Memorandum

To: Massachusetts Program Administrators and Energy Efficiency Advisory Council

From: Decker Ringo and Theo Kassuga; Navigant Consulting Inc.

Date: October 9, 2018

Re: Energy Optimization Study (RES 21)
Task 4: Report Findings

This memo summarizes the evaluation team's efforts to characterize the savings and costs of a variety of fuel-switching measures included in the draft implementation plan for the 2019 – 2021 program cycle. The evaluation team created and revised a spreadsheet model, submitted with this memo, that calculates the consumption and savings of different measures for three scenarios: (1) full/early replacement, (2) partial displacement, and (3) replace on failure. The consumption and savings estimates are presented in detail in the spreadsheet model submitted with this memo. The sections below describe the sources and methodology used in this Energy Optimization Study.

Summary

This study focuses on measures that remove oil and propane systems from service, and on fuel displacement measures that install electric systems alongside oil and propane systems.
In Task 1 of this study, the evaluation team developed a list of fuel-switching measures to characterize in this study, and defined efficiency levels for each measure at the baseline, code, and efficient measure levels. The list includes measures that add an electric heat pump to a household with an existing oil- or propane-fueled space heating system, measures that replace an oil- or propane-fueled space heating system with an electric heat pump, and measures that replace oil- or propane-fueled space heating and/or water heating equipment with gas-fired equipment.

This study considered three replacement scenarios: (1) a Full/Early Replacement scenario where high-efficiency equipment is installed to replace less efficient equipment prior to the failure of the existing equipment; (2) a Partial Displacement scenario where high-efficiency heat pump equipment is installed to operate alongside existing oil- and propane-fired heating equipment; and (3) a Replace-on-Failure scenario where an existing piece of less-efficient equipment has failed and is replaced by a more efficient piece of equipment.

In Task 2, the team developed a draft model to demonstrate the calculations and assumptions that were used to characterize each measure. After receiving comments from the PAs and EEAC, the team refined the input assumptions and built additional functionality into the model. For each measure considered in this study, the spreadsheet model provided with this memo calculates the annual energy cost savings, incremental measure costs, annual consumption savings (of electricity, natural

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gas, propane, and oil), peak demand savings, annual carbon emissions savings, and annual source fuel consumption savings.

The results of our analysis are as follows:

- All of the measures considered in this study result in annual energy cost savings for the customer.
- The early replacement measures with the highest annual energy cost savings were the measures involving the replacement of propane and oil boilers with gas-fired combination boilers.
- All of the measures considered in this study result in reduced CO_2 emissions. The CO_2 emissions reductions are comparable for the early replacement scenario (with measure savings ranging from 0.32 to 6.40 tons CO_2/year) and the replace-on-failure scenario (ranging from 0.22 to 6.96 tons CO_2/year).

Background

The goal of this study is to estimate the savings, costs, peak demand, and lifetimes for a focused group of energy optimization measures for space heating and water heating end uses. The Massachusetts Program Administrators (PAs) recently completed and submitted their draft implementation plan for the 2019 – 2021 program cycle, which includes several energy optimization measures. In general, these measures pertain to the installation of new electric heat pump equipment or new gas equipment in homes that are now or were previously heated using oil or propane. Electric heat pumps are generally more carbon and primary energy efficient than fossil fuel heating systems because heat pumps use electricity to transfer heat from one space to another, while fossil fuel systems generate heat through fuel combustion. Typically, when a customer switches from a fossil fuel system to an electric heat pump system (or when a customer installs and operates a heat pump system alongside a fossil fuel system), the customer's fossil fuel consumption decreases while their electricity consumption and peak electric demand increases.

Data Sources

The evaluation team used the following publicly-available data sources throughout the analyses conducted for this study.

- **Massachusetts Technical Reference Manual (TRM)**
  Link: http://ma-eeac.org/wordpress/wp-content/uploads/2016-2018-Plan-1.pdf
  The Massachusetts TRM describes the efficiency of different residential equipment at the baseline, code, and high efficiency levels of performance. The team referenced the TRM to determine equipment performance at the different efficiency levels considered in this study.
- **Energy Information Administration (EIA) Fuel Price Data**
  Link: https://www.eia.gov/dnav/pet/PET_PRI_WFR_DCUS_SMA_W.htm
  The EIA publishes residential price data for a variety of fuel types by U.S. state on a weekly basis. The evaluation team used this data to estimate the annual energy costs associated with different measures.
- **EIA Carbon Dioxide Emissions Factors**
  Link: https://www.eia.gov/tools/faqs/faq.php?id=73&t=11
  The EIA publishes the amount of carbon dioxide released from the combustion of different fuels. The evaluation team used these factors to estimate the amount of CO_2 emissions

associated with different equipment types and the amount of CO_2 emissions reductions associated with different measures.

- **EIA Electricity Generation and Heat Value Data for Massachusetts**
  Link: https://www.eia.gov/electricity/state/massachusetts/
  The EIA publishes summary statistics for the electricity generation sector in Massachusetts, including the heat value of different fuels and the total electricity generation by fuel type. The team used these data to calculate the source fuel consumption savings associated with different measures.

- **EIA 2015 Residential Energy Consumption Survey (RECS)**
  Link: https://www.eia.gov/consumption/residential/data/2015/index.php
  The EIA RECS reports energy consumption by end use, fuel type, and geographic region. The evaluation team estimated the water heating load for Massachusetts households using RECS data for gas- and propane-fired water heater energy consumption for the New England region.

- **Residential Cost and Evaluation Studies Conducted on Behalf of the EEAC**
  Link: http://ma-eeac.org/studies/residential-program-studies/
  The EEAC sponsored several recent studies that examined the total installed costs and annual loads of various types of residential heating and cooling equipment. The team referenced these studies to estimate the total installed costs of different equipment types at different efficiency levels. Specifically, the team referenced equipment costs in the RES 19 Water Heating, Boiler, and Furnace Cost Study, the RES 28 Ductless Mini-Split Heat Pump Cost Study, and the RES 23 Cost Study of Heat Pump Installations for Dual Fuel Operation. The team referenced heating loads in the RES 34 Home Energy Services (HES) Impact Evaluation and the 2015 High-Efficiency Heating Equipment (HEHE) Impact Evaluation. The team referenced equivalent full-load hours (EFLH) for cooling and peak load coincidence factors (CFs) from the RES 1 Baseline Study.

- **White Box Technologies, Inc**
  Link: http://weather.whiteboxtechnologies.com/
  White Box Technologies provides weather data for building energy simulations. The team used hourly temperature data for Worcester, MA from 2005 to 2017 to calculate the annual heating loads at different outdoor air temperatures for measures involving heat pump equipment.

- **U.S. Department of Energy (DOE) Appliance Standards Technical Support Documents**
  Link: https://www.energy.gov/eere/buildings/standards-and-test-procedures
  The DOE publishes detailed analyses of the energy consumption of various residential equipment at different efficiency levels. The team referenced these analyses to estimate the electrical consumption associated with the furnace, boiler, and water heating equipment considered in this study.

- **Northeast Energy Efficiency Partnerships (NEEP) Cold Climate Air-Source Heat Pump Database**
  Link: http://www.neep.org/initiatives/high-efficiency-products/emerging-technologies/ashp/cold-climate-air-source-heat-pump
  NEEP hosts the Cold Climate Air-Source Heat Pump (ccASHP) Specification and a database of products that meet the specification. The ccASHP Specification was developed to address concerns regarding the HSPF metric, especially in cold temperature conditions. The ccASHP

database provides performance data for approved products at outdoor test temperatures of 47 °F, 17 °F and 5 °F.

Energy Efficiency Measure Definitions

Each measure considered in the analysis is defined by a baseline equipment type and a replacement equipment type. The evaluation team solicited input from the PAs and EEACs to develop the list of energy optimization measures to model in this study. Table 1 presents the full list of measures considered in this study, including measures considered in the draft 2019-2021 Implementation Plan. For several measures, the baseline cooling component is described as a “Baseline A/C Blend” or “2-Part Baseline A/C Blend.” These blended baselines are calculated as weighted averages that represent the mix of air conditioning technologies that customers use, including central A/C, room A/C, and no A/C. The Methodology section of this memo provides more details on the blended A/C baselines.

Table 1. Measures Considered in the Energy Optimization Study

Measure ID*	Baseline Equipment Type	Replacement Equipment Type
1	Baseline A/C Blend (CAC, RAC, No A/C)+Oil Furnace	Central HP+Oil Furnace
2	Baseline A/C Blend (CAC, RAC, No A/C)+Propane Furnace	Central HP+Propane Furnace
5	Baseline A/C Blend (CAC, RAC, No A/C)+Oil Furnace	Central HP
6	Baseline A/C Blend (CAC, RAC, No A/C)+Propane Furnace	Central HP
9	2-Part Baseline A/C Blend (RAC, No A/C)+Oil Boiler	DMSHP+Oil Boiler
10	2-Part Baseline A/C Blend (RAC, No A/C)+Propane Boiler	DMSHP+Propane Boiler
11	2-Part Baseline A/C Blend (RAC, No A/C)+Electric Baseboard	Electric Baseboard+DMSHP
12	Tankless Coil WH (oil)	Electric Heat Pump WH
13	Oil Boiler	Gas Boiler
14	Propane Boiler	Gas Boiler
15	Oil Boiler+Indirect WH	Gas Boiler+Indirect WH
16	Propane Boiler+Indirect WH	Gas Boiler+Indirect WH
17	Oil Furnace	Gas Furnace
18	Propane Furnace	Gas Furnace
19	Oil Boiler+Tankless Coil WH	Gas Combination Boiler
20	Propane Combination Boiler	Gas Combination Boiler
21	Oil Boiler+Storage WH	Gas Combination Boiler
22	Propane Boiler+Storage WH	Gas Combination Boiler
23	Oil Storage WH	Gas Storage WH
24	Propane Storage WH	Gas Storage WH
25	Oil Storage WH	Gas On-Demand WH
26	Propane Storage WH	Gas On-Demand WH
27	Tankless Coil WH (oil)	Gas On-Demand WH
28	Propane On-Demand WH	Gas On-Demand WH
29	Central A/C+Oil Boiler	Central HP+Oil Boiler
30	Central A/C+Propane Boiler	Central HP+Propane Boiler
31	2-Part Baseline A/C Blend (RAC, No A/C)+Oil Boiler	DMSHP
32	2-Part Baseline A/C Blend (RAC, No A/C)+Propane Boiler	DMSHP
33	Oil Boiler+Indirect WH	Gas Combination Boiler

* Measure ID numbers are not sequential in some cases because the team combined several measures in the original spreadsheet to model a blended A/C baseline.

Methodology and Assumptions

Incremental Analysis

In general, the costs and savings associated with energy efficiency measures are the incremental costs and reduced consumption of a more efficient technology relative to a baseline technology. The evaluation team applied this principle in our analysis of fuel switching measures.

This analysis considered three replacement scenarios: (1) a Full/Early Replacement (ER) scenario where high-efficiency equipment is installed to replace less efficient equipment prior to the failure of the existing equipment; (2) a Partial Displacement (PD) scenario where high-efficiency heat pump equipment is installed to operate alongside existing oil- and propane-fired heating equipment; and (3) a Replace-on-Failure (ROF) scenario where an existing piece of less-efficient equipment has failed and is replaced by a more efficient piece of equipment.[1] The evaluation team treated these scenarios differently in two respects:

(1) **Baseline**. For the ER scenario, the evaluation team assumed that the customer would replace their existing equipment at the end of the equipment's useful life with a code-level piece of equipment using the same fuel type. The team estimated savings separately for the retirement portion of the ER measure and the energy efficiency portion of the ER measure. The savings associated with the retirement portion of the measure are the difference between the code-level equipment using the original fuel and the baseline equipment using the original fuel, with a measure life equal to the remaining useful life of the existing equipment. The savings associated with the energy efficiency portion of the measure are the difference between the high-efficiency equipment using the new fuel and the code-level equipment using the original fuel, with a measure life equal to the lifetime of the replacement equipment. For the ROF scenario, the team calculated costs and savings for the life of the measure relative to a code-level piece of equipment using the original fuel (oil or propane). These assumptions are illustrated in Table 2.

Table 2. Fuel Types Modeled for Early Replacement and Replace-on-Failure Scenarios

	Early Replacement			Replace on Failure	
	Baseline	Code-Level (Applied at end of existing equipment useful life)	High-Efficiency	Code-Level	High-Efficiency
Fuel Type	Original Fuel (oil or propane)	Original Fuel (oil or propane)	Replacement Fuel (electricity or gas)	Original Fuel (oil or propane)	Replacement Fuel (electricity or gas)

(2) **Incremental cost calculation.** For the ROF scenario, the incremental cost of a measure is the difference between the total installed cost of the high-efficiency equipment and the total installed cost of the lowest-efficiency equipment allowed by code. In contrast, the PD and ER scenarios involve taking some or all of the baseline equipment out of service before its useful life is finished. Without the measure, the customer would continue using the baseline-level

[1] In the Full/Early Replacement scenario, the spreadsheet model also calculates and reports a separate output: the amount of energy savings associated with just the fuel-switching portion of each measure. This output is calculated as the difference in total MMBtu consumption between the code/ISP-level product in the replacement fuel type (gas or electric) and the code/ISP-level product in the original fuel type (oil or propane).

equipment until the end of its useful life, and then they would replace it with a code-level piece of equipment. For ER and PD measures, the customer would pay the total installation cost of the high-efficiency equipment, but they would defer the future cost of replacing their equipment with a code-level piece of equipment. Under the ER and PD measures, this deferred future cost of replacement is considered as a benefit, and the incremental cost is calculated as the total installed cost for the high-efficiency equipment less the deferred replacement cost of code-level piece(s) of equipment.[2,3]

Equipment Types and Efficiency Levels

The evaluation team modeled each equipment type at four or five efficiency levels, depending on the number of efficiency levels that are eligible for program rebates.

- **Original Fuel – Baseline Efficiency Level** represents the efficiency of equipment currently installed in the field.
- **Original Fuel – Code Efficiency Level** represents the minimum efficiency available to customers today for equipment using the original fuel (oil or propane). This is the larger of the minimum federal efficiency standard, the minimum efficiency available in the market, or the negotiated industry standard practice (ISP) level efficiency selected by the PAs.
- **Replacement Fuel – Code Efficiency Level** represents the minimum efficiency available to customers today for equipment using the replacement fuel (electricity or gas). This is the larger of the minimum federal efficiency standard, the minimum efficiency available in the market, or the negotiated ISP-level efficiency selected by the PAs.
- **Replacement Fuel – PA Program Low Efficiency Tier** represents the lowest efficiency level incentivized by the program. This is the larger of either the rebated measure level or the lowest efficiency equipment available in the market that meets the rebated level.[4]
- **Replacement Fuel – PA Program High Efficiency Tier** represents the highest efficiency level incentivized by the program, if the program incentivizes multiple efficiency levels.

The efficiency ratings at each efficiency level were referenced from the Massachusetts TRM, the minimum efficiency standards in the U.S. Code of Federal Regulations,[5] and recent cost studies sponsored by the EEAC that identified the market baseline levels for various equipment types. The equipment and efficiency ratings considered in this study are presented in Table 3.

[2] The evaluation team used a discount rate of 0.46% at the recommendation of the PAs. The discount rate can be changed in the spreadsheet model.

[3] For partial displacement measures (measures in which the baseline heating equipment is kept in operation), the model accounts for only the deferred cost of the code cooling equipment (if the baseline includes cooling equipment). For replacement measures, the model accounts for both the deferred cost of the heating equipment and of the cooling equipment (if the baseline includes cooling equipment).

[4] For some equipment types, such as electric heat pump water heaters, there are no products on the market at the exact level rebated by the program. In these cases, the measure level consumption and savings are modeled at the lowest efficiency equipment available on the market that meets the rebate threshold.

[5] 10 CFR 430.32. "Energy and water conservation standards and their compliance dates." Available at: https://www.ecfr.gov/cgi-bin/retrieveECFR?n=pt10.3.430

Table 3. Equipment List and Efficiency Levels

Equipment	Baseline	Code / ISP	Low Efficiency Tier Measure	High Efficiency Tier Measure
Room A/C	8 EER	10 EER	-	-
Oil Furnace	78% AFUE (78.9% actual)	83% AFUE	-	-
Propane Furnace	78% AFUE (78.9% actual)	85% AFUE	-	-
Gas Furnace	-	85% AFUE	95% AFUE (95.4% actual) w/ ECM fan motor	97% AFUE (97.2% actual) w/ ECM fan motor
Baseline A/C Blend +Oil Furnace	CAC:10 SEER/8.5 EER, Room A/C: 8 EER 78% AFUE (78.9% actual)	CAC: 13 SEER/11 EER Room A/C:10 EER 83% AFUE	-	-
Baseline A/C Blend + Propane Furnace	CAC:10 SEER/8.5 EER, Room A/C: 8 EER 78% AFUE (78.9% actual)	13 SEER/11 EER 85% AFUE	-	-
Oil Boiler	75% AFUE	84% AFUE	-	-
Propane Boiler	75% AFUE	82% AFUE (79.3% actual)	-	-
Gas Boiler	-	82% AFUE (79.3% actual)	90% AFUE (87.2% actual)	95% AFUE (89.4% actual)
Central A/C+ Oil Boiler	10 SEER/8.5 EER 75% AFUE	13 SEER/11 EER 84% AFUE	-	-
Central A/C+ Propane Boiler	10 SEER/8.5 EER 75% AFUE	13 SEER/11 EER 82% AFUE (79.3% actual)	-	-
Central HP	-	14 SEER/11.7 EER/8.2 HSPF	16 SEER/8.5 HSPF	18 SEER/9.6 HSPF
Central HP+Oil Furnace	78% AFUE (78.9% actual)	14 SEER/11.7 EER/8.2 HSPF 83% AFUE	16 SEER/8.5 HSPF	18 SEER/9.6 HSPF
Central HP+Propane Furnace	78% AFUE (78.9% actual)	14 SEER/11.7 EER/8.2 HSPF 85% AFUE	16 SEER/8.5 HSPF	18 SEER/9.6 HSPF
Central HP+Oil Boiler	75% AFUE	14 SEER/11.7 EER/8.2 HSPF 84% AFUE	16 SEER/8.5 HSPF	18 SEER/9.6 HSPF
Central HP+Propane Boiler	75% AFUE	14 SEER/11.7 EER/8.2 HSPF 82% AFUE (79.3% actual)	16 SEER/8.5 HSPF	18 SEER/9.6 HSPF
DMSHP	-	15 SEER/12 EER/8.2 HSPF	18 SEER/10.0 HSPF	20 SEER/12.0 HSPF
DMSHP+Oil Boiler	75% AFUE	15 SEER/12 EER/8.2 HSPF 84% AFUE	18 SEER/10.0 HSPF	20 SEER/12.0 HSPF
DMSHP+Propane Boiler	75% AFUE	15 SEER/12 EER/8.2 HSPF 82% AFUE (79.3% actual)	18 SEER/10.0 HSPF	20 SEER/12.0 HSPF
Electric Baseboard	1 COP	1 COP	-	-
Electric Baseboard+DMSHP	1 COP	15 SEER/12 EER/8.2 HSPF 1 COP	1 COP, 18 SEER/10.0 HSPF	1 COP, 20 SEER/12.0 HSPF
Oil Boiler+Indirect WH	75% AFUE, UA 4.1 Btu/hr-F	84% AFUE UA 4.1 Btu/hr-F	-	-
Propane Boiler+Indirect WH	75% AFUE, UA 4.1 Btu/hr-F	82% AFUE (79.3% actual) UA 4.1 Btu/hr-F	-	-
Gas Boiler+Indirect WH	-	82% AFUE (79.3% actual)	90% AFUE (87.2% actual)	95% AFUE (89.4% actual)
Oil Boiler+Tankless Coil WH	75% AFUE	84% AFUE	-	-
Gas Combination Boiler	-	90% AFUE	90% AFUE	95% AFUE
Propane Combination Boiler	80% AFUE (77.4% actual)	90% AFUE	-	-
Oil Boiler+Storage WH	75% AFUE, 0.58 UEF	84% AFUE, 0.62 UEF	-	-

Equipment	Baseline	Code / ISP	Low Efficiency Tier Measure	High Efficiency Tier Measure
Propane Boiler+Storage WH	75% AFUE, 0.58 UEF	82% AFUE (79.3% actual) 0.62 UEF	-	-
Oil Storage WH	0.58 UEF	0.62 UEF	-	-
Propane Storage WH	0.58 UEF	0.63 UEF	-	-
Gas Storage WH	-	0.58 UEF	0.64 UEF	0.80 UEF
HPWH	-	0.92 UEF	2.45 UEF	-
Propane On-Demand WH	0.711 UEF	0.80 UEF	-	-
Gas On-Demand WH	-	0.80 UEF	0.87 UEF	-

Heating, Cooling, and Water Heating Loads

The evaluation team characterized many of the measures in this study using engineering calculations that use the load and efficiency of a given piece of equipment as inputs. As such, the savings results calculated for each measure depend on the heating, cooling, and water heating loads that are input to the model. Higher load values lead to higher consumption estimates and, in turn, to greater savings potential from measures that improve energy efficiency. With this in mind, the team took care to reference heating, cooling, and water heating loads that have been recently measured and reported for households in Massachusetts. The load assumptions are specified in the "Inputs" tab of the spreadsheet that accompanies this memo, and these assumptions are described below:

- **Heating Load.** The model specifies separate heating load values for households equipped with furnaces and households equipped with boilers. The RES 34 HES Impact Evaluation Study reported heating loads based on a 2014-2016 billing analysis of HES participants by fuel type. The spreadsheet model uses the loads reported in the RES 34 study: 68.4 MMBtu/year for households with furnaces and 76.7 MMBtu/year for households with boilers. For households equipped with combination boilers, the heating load is estimated based on a finding reported in the 2015 HEHE Impact Evaluation, which found that the heating load for combination boilers is 19 percent lower than the load for standard boilers.[6] The heating load assumption for households with combination boilers is estimated at 62.1 MMBtu/year.

- **Cooling Load.** The cooling load assumed for this study is calculated by multiplying the typical cooling capacity for cooling systems in Massachusetts by the equivalent full load hours (EFLH) for cooling equipment. The typical cooling capacity reported in the Massachusetts TRM is 30 kBtu/h.[7] The RES 1 Baseline Study reported the EFLH of central A/C and heat pump equipment based on calculations using the weather-normalized annual energy and peak demand measured in RES 1 and the relevant name plate data (size and efficiency) from the measured equipment. RES 1 reported EFLH of 419 hours/year for central A/C and heat pump equipment. The cooling load is estimated as the product of cooling capacity and EFLH, at 13.1 MMBtu/year.

- **Water Heating Load.** Prior studies of water heating energy consumption in Massachusetts have used water heating loads reported in a 2009 Potential Study by GDS Associates[8] or water heating load calculations from the U.S. Department of Energy (DOE) test procedure for

[6] Cadmus (2015). "High Efficiency Heating Equipment Impact Evaluation." p.6. Available at: http://ma-eeac.org/wordpress/wp-content/uploads/High-Efficiency-Heating-Equipment-Impact-Evaluation-Final-Report.pdf
[7] Massachusetts Technical Reference Manual, 2016-2018 Program Years – Plan Version. p.60.
[8] GDS Associates, Inc. (2009). "Natural Gas Energy Efficiency Potential in Massachusetts."

residential water heaters. However, recent evaluation studies and residential surveys have reported water heating consumption values that indicate water heating loads that are significantly lower than those assumed in prior studies. The RES 1 Baseline Study used end use metering to estimate consumption of 2,550 kWh/year for electric resistance water heaters, indicating a load of 8.0 MMBtu/year for electric resistance WH, assuming a typical efficiency of 0.92 UEF. The Energy Information Administration's 2015 Residential Energy Consumption Survey (RECS) reports consumption by end use and by fuel for households in New England.[9] The RECS results show water heating consumption of 21.0 MMBtu/year for average gas-fueled households in New England, indicating a water heating load of 13.9 MMBtu/year assuming a baseline efficiency of 0.66 EF.[10] The spreadsheet model uses the RECS-derived water heating load of 13.9 MMBtu/year for WH measures with gas-fired baseline equipment. The RECS results show water heating consumption of 17.1 MMBtu/year for average propane-fueled households in New England, indicating a water heating load of 11.3 MMBtu/year assuming a baseline efficiency of 0.66 EF. The spreadsheet model uses the RECS-derived water heating load of 11.3 MMBtu/year.

Central Heat Pump and Ductless Mini-Split Heat Pump Analysis

Several measures in this study involve the installation of electric heat pumps that will operate in conjunction with existing oil- or propane-fired furnaces or boilers. These measures required a specialized analysis to determine how the heating load will be shared between these different equipment types, and how much consumption may be expected from each piece of equipment. This section details the analysis conducted to estimate the energy consumption and demand for the heat pump measures in this study.

Consumption of Heat Pump-Only Systems

The performance of air-source heat pumps changes with outdoor temperature. Heat pumps generally perform at a lower efficiency in colder outdoor temperatures, and at a higher efficiency in warmer outdoor temperatures. This fact can have a significant effect on the cost-effectiveness of heat pump installations, especially in places such as Massachusetts, where cold winters are frequent. Considering that issue, the evaluation team developed an outdoor temperature-based analysis for heat pumps. The objective of that analysis was to obtain outdoor temperature-dependent estimates of consumption for a reference heat pump, which can then be scaled to match each of the energy efficient measures under consideration in this study.[11]

The evaluation team started by analyzing the Northeast Energy Efficiency Partnerships (NEEP) database of cold-climate air-source heat pumps. The NEEP database lists the coefficient of

[9] 2015 RECS Table CE4.7. Available at: https://www.eia.gov/consumption/residential/data/2015/index.php

[10] The team calculated an average installed base efficiency of 0.66 EF for gas-fired WH using on-site characterization results from the RES 1 Baseline Study. The team assumed the average baseline efficiency is the same for propane-fired WH and gas-fired WH.

[11] Energy consumption analyses frequently use the Heating Seasonal Performance Factor (HSPF) to calculate the consumption of heat pumps when operating without supplemental heat from a different piece of equipment. Because this analysis requires calculating and comparing the performance of heat pumps with and without electric, oil or propane supplemental heat, the HPSF metric does not provide enough information to accurately estimate energy consumption in each case under consideration. An advantage of the COP-based method used here is that it allows for estimates of heat pump performance in different climates simply by replacing the weather data in the analysis with data from other weather stations.

performance (COP) of each heat pump at three outdoor test temperatures: 5°F, 17°F, and 47°F. The evaluation team used those COP values to create two curves for COP as a function of outdoor temperature: one curve for central heat pumps (CHP) and one curve for ductless mini-split heat pumps (DMSHP). The heat pumps under consideration in this study range from 8.2 HSPF to 11 HSPF, so the evaluation team selected 10 HSPF (the lowest value available on the NEEP database) as the representative value for creating the COP-temperature curves. Therefore, the team used only NEEP-listed heat pumps rated at 10 HSPF to create COP temperature curves and estimate electrical consumption of a reference model. The team then scaled the consumption of the 10-HSPF reference model to estimate consumption at other HSPF values, as explained later in this subsection.

Some heat pumps contain a resistance heater which is used to provide backup heat in particularly cold conditions where the heating demand cannot be met by the vapor compression cycle alone. In those conditions, the resistance heater may provide all of the heat delivered by the heat pump, or the resistance heater may operate alongside the vapor compression cycle. In either case, the evaluation team conservatively estimated that the heat pump operates with an efficiency of COP=1.0 when the resistance heater is engaged. This was accounted for in the consumption calculation in two ways: (1) for cold temperatures in which the COP-temperature curve gives a value below 1.0 COP, the COP was set to 1.0; and (2) the consumption model allows users to select a resistance heat threshold temperature below which the COP is set to 1.0 regardless of the COP-temperature curve.[12]

After developing reference COP-vs.-temperature curves based on models in the NEEP database, the evaluation team moved on to estimating the number of hours spent at each outdoor temperature during the heating season. To estimate the annual number of hours at each outdoor temperature, the evaluation team used historical hourly temperature data from a weather station in Barnstable, MA, as described in the Data Sources section of this memo.[13]

Next, the evaluation team estimated the heating load at each outdoor air temperature. The evaluation team calculated the heating-degree hours at each temperature using 65 °F as the heat pump setpoint temperature. Then, the reference heating load was split between each outdoor air temperature using the heating-degree hours as a weighting factor.[14] Consequently, one hour at a colder temperature received a greater heating load apportionment than one hour at a milder temperature, which is consistent with the increased building heat loss in colder temperatures.

With the heating load and the COP calculated for each outdoor air temperature, the evaluation team divided the heating load by the COP to obtain the estimated electricity consumption at each outdoor air temperature. Then, the consumption values at each outdoor air temperature were summed to obtain the reference annual heating consumption for each reference heat pump (one CHP and one

[12] Heat pumps are generally expected to require supplemental heating at temperatures below freezing, but this varies depending on the equipment. Since the COP-temperature curve uses data as low as 5°F and any resistance heat usage would be included in that data, the evaluation team set the switchover temperature to 5°F. For a more conservative assumption, users of the model may increase the switchover temperature.

[13] The evaluation team plans to replace the Barnstable data with a more representative weather station in the next model update.

[14] The reference heating load used in this analysis is 1 MMBtu/year. However, this reference load value does not impact the results of the analysis because all measures scale the consumption results to match the applicable heating load for each measure. Selecting a different reference heating load would merely change the multiplier that is applied when calculating the consumption of a given heat pump measure.

DMSHP). The evaluation team calculated the annual heating consumption of the resistance heater and of the vapor compression cycle separately.

To estimate the annual heating consumption of each heat pump measure, the evaluation team scaled the reference annual heating consumption by the appropriate variables, as listed below:

- **Vapor compression cycle operation:** the reference consumption during vapor compression cycle operation was scaled by the heating load and the HSPF.
- **Resistance heater operation:** because the efficiency of resistance heaters is independent of HSPF, the reference consumption was only scaled by the heating load for resistance heaters.
- **Total electric heating consumption:** the increase or decrease in total electric consumption depends on the two scaled values above, since total electric consumption is the sum of the consumption using the vapor compression cycle and the consumption using the resistance heater.

The evaluation team also calculated the cooling-mode consumption of the heat pumps. The cooling consumption was calculated by dividing the cooling load by the rated Seasonal Energy Efficiency Ratio (SEER) of the heat pump. Then, the evaluation team calculated the overall annual electricity consumption as the sum of the cooling consumption and the heating consumption.

Consumption of Combined Systems (Heat Pump paired with Other Heating Equipment)
Some of the measures considered in this analysis are defined as a heat pump operating in conjunction with other heating equipment. Specifically, the evaluation team considered heat pumps paired with furnaces (oil and propane), boilers (oil and propane) and baseboard heaters (electric). In the consumption model, users may select a fuel switchover temperature between the heat pump and the supplemental heating equipment, with the heat pump assumed to run in milder temperatures while the supplemental heating equipment is assumed to run in colder temperatures.[15] The user can select different switchover temperatures for each type of fuel (oil, propane, natural gas and electricity). The method used to calculate consumption for both fuel types is described below. In addition, the user can select a contingency factor for the consumption of combined systems; this contingency factor is intended to account for sub-optimal use of the heat pump by the customer (*e.g.*, if the customer operates the heat pump below the ideal threshold temperature for fossil fuel operation, or if the customer operates the fossil fuel-fired equipment above the ideal threshold temperature when it would be more efficient to operate a heat pump.).

The evaluation team calculated the heat pump electrical consumption in the same manner as described above for heat pump-only systems, except that calculations for dual-fuel systems only sum the heating consumption for hours when the outdoor temperature is above the fuel switchover temperature.[16] For the hours when the outdoor temperature is below the fuel switchover temperature, the consumption calculation estimates the fuel consumption and electric consumption of the supplemental oil- or propane-fired heating equipment instead of the heat pump.

[15] Selecting lower switchover temperature values will lead to more heat pump usage, while higher switchover temperatures lead to less heat pump usage.
[16] None of the measures include supplemental cooling equipment, so the cooling consumption of the heat pump was always included in its entirety.

The electric consumption of the supplemental heating equipment comes from the operation of ancillary components such as fans, blowers, and water pumps. The team calculated the reference electric consumption at each outdoor temperature by multiplying the number of hours at that temperature by the reference power input of the electric components, which was assumed to be 1 kW with a capacity factor of 25%. The consumption values at each temperature were then summed to obtain the annual electric consumption of the fossil fuel equipment. Each measure tab in the spreadsheet model scales the electric consumption by the actual power input and capacity factor of the equipment under consideration, so the reference values used (1 kW and 25%) do not impact the results of the analysis.

The fuel consumption of the supplemental heating equipment comes from the operation of that equipment at temperatures below the fuel switchover temperature. The evaluation team calculated the consumption by dividing the heating load at temperatures below the switchover temperature by a reference efficiency of 100%. This yielded a reference fuel consumption that could then be scaled by the actual efficiency of the equipment and the actual heating load to obtain the actual fuel consumption.[17]

Peak Demand

The evaluation team calculated the winter peak demand by dividing the rated heating capacity of the heat pump by the HSPF, then multiplying the result by the coincidence factor. For the purposes of this analysis, the evaluation team assumed that the cooling capacity and the heating capacity of the heat pump are identical.[18] Heat pump-only systems were assumed to be rated at 4 tons of cooling and heating capacity. Heat pumps operating in conjunction with oil- or propane-fired equipment were assumed to be smaller because they do not need to meet the entire household heat load, especially in cold conditions. Thus, the evaluation team assumed that the heat pumps in dual-fuel systems were rated at 2.5 ton. In the consumption model, users have the option to select different capacities if they prefer.

Peak demand was calculated in the same manner for both heat pump-only systems and for dual-fuel systems. The evaluation team acknowledges that the heat pumps in combined systems may not operate while the fuel-burning equipment runs, such that the peak demand for combined systems may not occur at the same time as the peak demand for heat pump-only systems. However, the team calculated the peak demand for combined systems as if the heat pumps operated all the time, which is the worst-case scenario from the perspective of peak demand.

The evaluation team calculated the summer peak demand by dividing the rated cooling capacity (which, as previously mentioned, was assumed equivalent to the heating capacity) of the heat pump by the EER, then multiplying the result by the summer coincidence factor. The team used the same approach for estimated peak loads of air conditioners. In the case of room A/Cs, the calculation also accounted for the number of room A/Cs installed at the site.

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[17] While electric baseboard heaters do not technically use fuel onsite, the analysis calculates their consumption in the same way as fuel equipment, but with the necessary unit conversions to obtain the result in kWh as opposed to therms or MMBtu.

[18] The evaluation team investigated the NEEP database and found that on average the cooling capacity of a central heat pump is equivalent to the heating capacity at 47 °F. For DMSHPs, the heating capacity at 47 °F is on average approximately 10% greater than the cooling capacity.

Blended A/C Baseline

The evaluation team assumed that baseline households considered in this analysis either do not provide space cooling or provide space cooling using either a central A/C system or room/window A/C units. For measures in this analysis that include a cooling function, the team calculated the baseline cooling characteristics as a blend of these A/C types (Room A/C, Central A/C, and No A/C).[19] To characterize these baseline A/C blends, the team first estimated the consumption and costs associated with the baseline efficiency level of each separate A/C equipment type (Room A/C, Central A/C, and No A/C). Then, the team combined the consumption and costs of the separate A/C types into weighted averages, using the saturation[20] of the different A/C types as weights.

- For measures with furnace equipment in the baseline, the blended A/C baseline is a weighted average of all three cooling types (Room A/C, Central A/C, and No A/C).
- For measures with boiler equipment in the baseline, the team assumes that customers with a boiler and central A/C would most likely upgrade to a central HP (since they already have ductwork in place), and customers with a boiler and room A/C or no A/C would most likely upgrade to a DMSHP to avoid the cost of installing new ductwork. Based on this assumption:
    - Measures that upgrade from a boiler baseline to a DMSHP use a blended baseline that is a weighted average of two cooling types (Room A/C and No A/C).
    - Measures that upgrade from a boiler baseline to a central HP use a central A/C baseline without any blending.

The “Inputs” tab of the spreadsheet enclosed with this memo contains the assumptions, calculations, and weights that the evaluation team used to define the blended A/C baselines.

Cost Assumptions

As described above, the incremental cost of each measure is the difference between the total installed cost of the high-efficiency equipment and either the total installed cost of code-level equipment (for the ROF scenario) or a credit for the deferred cost of installing code-level equipment at some point in the future (for the ER and PD scenarios). To estimate the total installed costs of different equipment types at different efficiency levels, the team referenced recent cost studies sponsored by the EEAC:

- RES19 – Water Heating, Boiler, and Furnace Cost Study
  Water heaters, boilers, and furnaces fueled by gas, propane, and oil; gas and propane combination boilers; indirect water heaters; electric water heaters

[19] Two measures do not use the blended A/C baseline: (1) Central A/C+Oil Boiler → Central HP+Oil Boiler, and (2) Central A/C+Propane Boiler → Central HP+Propane Boiler. The team assumed that the customers most likely to install a Central HP system would be customers who already have ductwork in place from an existing CAC installation. The team expects that other boiler users, with room A/Cs or no cooling, would be more likely to install a DMSHP than a central HP.

[20] Baseline A/C saturation describes the percent of households that are equipped with central A/C, window/room A/C, or no A/C. Baseline saturations are reported in the 2017 Baseline Study, Appendix C-1, p.6, available at: http://ma-eeac.org/wordpress/wp-content/uploads/Appendix-C-1-Saturation-Results-Plots-2018-04-12.pdf

- RES23 – Air Conditioner and Heat Pump (AC & HP) Cost Study
  Central air conditioners and central heat pumps[21]
- RES28 – Ductless Mini-Split Heat Pump Cost Study
  Ductless mini-split heat pumps[22]

To estimate the annual energy costs customers would experience with each equipment type, the team multiplied the annual consumption of each fuel type by the retail cost of the fuel type.[23] Then, the team estimated the annual energy cost savings associated with a given measure as the difference between the annual energy costs at the baseline and the high-efficiency levels of the measure.

Carbon Emissions Calculations

The evaluation team estimated the carbon emission savings associated with each measure considered in this study. First, the team referenced the carbon emissions generated by combustion of different fossil fuels from information provided by the EIA, and the team referenced the typical carbon emissions associated with electricity generation in New England from ISO New England's Electric Generator Air Emissions Report.[24] The team estimated the carbon emissions associated with each efficiency level of each equipment type considered in the analysis. The team estimated carbon emissions for a given equipment type and efficiency level as the carbon emissions per unit of fuel multiplied by the estimated fuel consumption (summed across all fuel types, for equipment that consumes more than one fuel). The team calculated the carbon emission savings for each measure as the difference between the carbon emissions of the baseline equipment and the carbon emissions of the efficient equipment.

Source Fuel Calculations

The evaluation team estimated the source fuel savings associated with each measure considered in the study. This calculation estimates the heat content and the physical amount of fuel savings that result from each measure. This calculation proceeds in several steps:

- The amount of source electricity savings is estimated by multiplying the site energy savings by a transmission and distribution (T&D) loss factor.
- The amount of source electricity savings associated with different fuel types (coal, gas, and oil) is estimated by multiplying the source electricity savings by the typical proportion of electricity generated from these fuel types in Massachusetts.
- The heat input savings for each fuel type is calculated by multiplying the kWh of source electricity savings from each fuel type by the heat rate of generation (Input Btu/Output kWh)

[21] The spreadsheet model uses total installed cost values for central heat pumps that represent the total installed cost of cold-climate certified systems.
[22] The spreadsheet model uses total installed cost values for ductless mini-split heat pumps that represent the total installed cost of cold-climate certified systems.
[23] Retail fuel costs in Massachusetts were sourced from the EIA Fuel Price Data, available at: https://www.eia.gov/dnav/pet/PET_PRI_WFR_DCUS_SMA_W.htm
[24] ISO New England Inc. (2018). 2016 ISO New England Electric Generator Air Emissions Report." Available at: https://www.iso-ne.com/static-assets/documents/2018/01/2016_emissions_report.pdf

for each fuel type. The team referenced the heat rates of generation from an analysis of electricity generation conducted by Eversource.

- The physical amount of fuel savings is calculated by multiplying the heat input savings for each fuel type by the heat value of the fuel (*e.g.*, Btu per gallon oil).

The electricity generation fuel mix in Massachusetts is expected to change under the new Clean Energy Standard, which was designed to increase the proportion of electricity generated from clean energy sources. To forecast the source fuel savings under the Clean Energy Standard, the team repeated the calculations described above for an electricity generation fuel mix forecast for 2025.[25] The "Inputs" tab of the spreadsheet model lists following assumptions associated with these source fuel calculations: T&D loss factor, electricity generation mix, heat rates of generation and heat values of different fuel types. The results of the source fuel savings calculations are reported in the "Measure List" tab of the spreadsheet model.

Results

The results of this analysis are available in the "Measure List" tab of the spreadsheet model enclosed with this memo. The results for each measure are presented at the following efficiency levels:

- Original Fuel – Baseline Efficiency Level (for example, an existing propane furnace)
- Original Fuel – Code Efficiency Level (for example, a new, code-compliant propane furnace)
- Replacement Fuel – Code Efficiency Level (for example, a new, code-compliant gas furnace)
- Replacement Fuel – PA Program Low Efficiency Tier (for example, a new, rebate-eligible gas furnace)
- Replacement Fuel – PA Program High Efficiency Tier, if the program offers rebates at two efficiency levels

The following variables are provided in each of those cases:

- Annual energy cost
- Total installed cost (presented as a deferred replacement cost for the code level with original fuel; not presented for the baseline level which, by definition, has no installed cost)
- Annual electricity, natural gas, propane, and oil consumption
- Peak demand
- Annual carbon emissions

These variables are combined to calculate the energy savings and incremental costs associated with the low and high measures under three different scenarios: full/early replacement, partial

[25] The team referenced the fuel mix forecast published in Synapse (2018) "Avoided Energy Supply Components in New England: 2018 Report." Figure 25. The team applied additional discounts of 0.5% to 1.5% to the oil and gas portions of the fuel mix, to account for Massachusetts' recent enactment of a law to accelerate adoption of clean energy sources. Available at:
http://www.synapse-energy.com/sites/default/files/AESC-2018-17-080.pdf

displacement, and replace-on-failure. The spreadsheet model contains separate sheets that report the incremental costs and savings of measures in each of these scenarios. In the ER and PD scenarios, the energy consumption and cost at the measure level is compared to the existing baseline equipment; the installation cost is compared to the deferred replacement credit associated with eventually having to install a code-level replacement that uses the original fuel. In the ROF scenario, the consumption and cost at the measure level is compared to a code-level replacement that uses the original fuel; the installation costs are compared directly (without deferred replacement considerations) because the customer must choose a piece of equipment for immediate purchase upon failure of the existing baseline.

Potential Improvements to the Energy Optimization Model

The evaluation team has identified the following potential improvements to the energy optimization model that could improve its accuracy and/or expand its applicability:

- **Improved measure definitions for heat pumps.** The measures used in the model are defined based on available rebate levels in the MassSave program. For heat pumps, the rebate levels require a certain efficiency in terms of SEER and HSPF. While this does incentivize purchases of more efficient equipment, it fails to capture the specifics of heat pump operation in cold climates. The evaluation team believes that greater focus on cold climate operation in defining the measures would be beneficial to the program.
- **Heating, cooling and water heating loads.** Due to the central role that these variables play in the analysis, they could also introduce significant error in the calculations. Fine-tuning these values would likely improve accuracy. Furthermore, using representative values for different building types and locations would lead to more accurate estimates of consumption.
- **Improvements to the cost-capacity trends and to line item cost estimates for central A/C and central HP installations.** In the Air Conditioner and Heat Pump (AC & HP) Cost Study (RES23), the evaluation team reviewed a sample of program invoices and developed installation costs for central A/C and HP equipment on a cost-per-ton basis. The sample frame for RES23 focused on the most commonly installed system capacities (from 2 to 3 tons of cooling capacity) and did not include many invoice records for higher-tonnage systems (at 4 tons capacity and above). A sample frame with more representation from higher-tonnage systems would improve the confidence of the model's cost-per-capacity estimates. Additionally, the records in the RES23 sample frame did not provide sufficient data to estimate line item costs for ductwork installation and/or modification or the line item costs for the replacement of air handlers and indoor heat exchanger coils. The evaluation team suggests reviewing a larger sample of program invoices (1) to better understand the relationship between installation cost and system capacity; and (2) to develop estimates of ancillary line item costs.
- **Improvements to specific installation cost components.** During the program invoice reviews conducted in the Air Conditioner and Heat Pump (AC & HP) Cost Study (RES23) and the Ductless Mini-Split Heat Pump Cost Study (RES28), the evaluation team attempted to estimate the costs of different line items associated with installing gas and electric equipment. Specifically, the team attempted to estimate the costs of removing and disposing of existing units and distribution systems, installing new gas service lines, upgrading home electrical systems for DMSHP installations, and integrating heat pump systems with existing heating equipment for dual-system operation. However, the team was unable to develop costs for

these items from invoice data because these costs are rarely itemized on contractor invoices. The Energy Optimization spreadsheet model uses cost assumptions for these items that are based on estimates from the evaluation team. The team suggests using a contractor survey to better understand the costs of these specific installation activities.

- **Update the relationship between heat pump cooling capacity and heating capacity.** The current version of the Energy Optimization spreadsheet model defaults to a 1:1 relationship between heat pump cooling capacity and heat pump heating capacity (*i.e.*, by default the model assumes that cooling capacity and heating capacity of heat pumps are equal). If the EEAC adopts the NEEP standard for cold-climate heat pumps, then the default assumption should be updated to reflect a relationship that is typical of cold-climate heat pumps.
- **Improvements to the COP calculations for heat pumps.** The current model utilizes NEEP data for cold climate heat pumps to estimate the COP-temperature curves at 10 HSPF, which are then scaled to other HSPF levels. This means that all of the heat pumps used to derive the COP-temperature curve meet the requirements of NEEP, such as a minimum COP at 5°F and having a variable compressor. These requirements are not present in the MassSave rebate level definitions, so in theory a customer could purchase, for example, a single-speed heat pump that still meets the MassSave rebate level. Therefore, a more accurate approach would be to develop COP-temperature curves that consider a wider selection of heat pump models.
- **Heat pump control patterns.** The model assumes that a heat pump can operate using either the vapor compression cycle or supplemental heat (electric or fuel-based). In practice, heat pumps with supplemental heat may be programmed to use both the compressor and the supplemental heater at the same time. This situation is partially accounted for due to the way the COP-temperature curves were developed. An even more complex situation occurs when the customer is responsible for selecting the type of heat, which may lead to switchovers at sub-optimal temperatures. This situation is accounted in the spreadsheet model by the Heat Pump Consumption Correction Factor. To improve the accuracy of the analysis, the evaluation team recommends accounting for the possibility of simultaneous resistance heat and compressor operation beyond what may be included in the COP-temperature curves. Additionally, the evaluation team suggests a careful review of usage data to determine the ideal value for the Heat Pump Consumption Correction Factor.
- **Switchover temperatures for heat pumps.** The fuel switchover temperature is either defined by the customer or programmed by the contractor. The model would be more accurate if the switchover temperature could be estimated more accurately. This could be done, for example, by conducting a survey with contractors to determine what they usually program into the equipment or what they suggest to customers.
- **Creation of a unified energy estimate application with standardized consumption and peak demand calculations.** This would allow for any piece of equipment to be compared to any other piece of equipment (measure or baseline) with greater simplicity and consistency across projects. For example, users would be able to create energy efficiency measures by selecting a baseline and a measure-level piece of equipment with only a few clicks. This kind of functionality would require a significant effort to develop a reliable back-end to the model, but it would pay off in the ease of application and the greater flexibility and scope.