BONNEVILLE POWER ADMINISTRATION

Residential HVAC Market Model Methodology

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Introduction

Anyone who pays household utility bills knows that heating and cooling a residential home can consume a significant amount of energy. In the Pacific Northwest, space heating represents the largest residential end use in the Northwest Power and Conservation Council's (the Council's) Seventh Power Plan (Seventh Plan) load forecast. This large end use has significant potential for energy savings, but accurately estimating total regional energy consumption for complex heating, ventilation, and air conditioning (HVAC) systems has proven challenging due to the many highly variable factors that influence HVAC energy consumption. In its continued market research efforts to improve the regional body of knowledge about energy consumption and savings, Bonneville Power Administration (BPA) decided to face this challenge and build a quantitative model representing the regional residential HVAC market.

This report describes the Cadeo team's (the research team, or the team) methodology for estimating total residential HVAC electric consumption and Momentum Savings for the Seventh Power Plan Action Plan period (2016-2021; hereafter referred to as the Action Plan Period). BPA's modeling goals for this market are twofold:

1. Understand how total residential HVAC electric consumption is changing over the Action Plan period; and
2. Estimate draft electric Momentum Savings for the Action Plan period (2016-2021)

BPA designed this model to represent the Action Plan period, which is currently underway. The team provides associated spreadsheets that show both actual results from calendar years 2016 and 2017 and forecast values for 2018 through 2021. Prior to finalizing the estimates of energy consumption and Momentum Savings for the Action Plan period, BPA will update the model with the latest available data.

This report includes three major sections. First, it describes in detail the team's methodology for developing the model using BPA's Four Question Framework, including data sources the team used, important analytical decisions, and the assumptions underpinning this methodology. The second section briefly summarizes the model results. Next, the report discusses sources of uncertainty and model sensitivities. Finally, it describes the team's recommendations for future model updates and future residential HVAC market research.

In addition to this memo, the team developed detailed spreadsheets that present the model inputs and outputs.

Methodology

This section describes the team's methodology, developed in close collaboration with BPA's market research and engineering teams. The team also received input from the Regional Technical Forum's (RTF's) Market Analysis Subcommittee while developing this methodology.[1]

Momentum Savings Analysis Framework

The methodology follows the Four Question Framework,[2] BPA's standard analytical framework for estimating Momentum Savings. The Four Questions, answered in greater detail in the following sections, are:

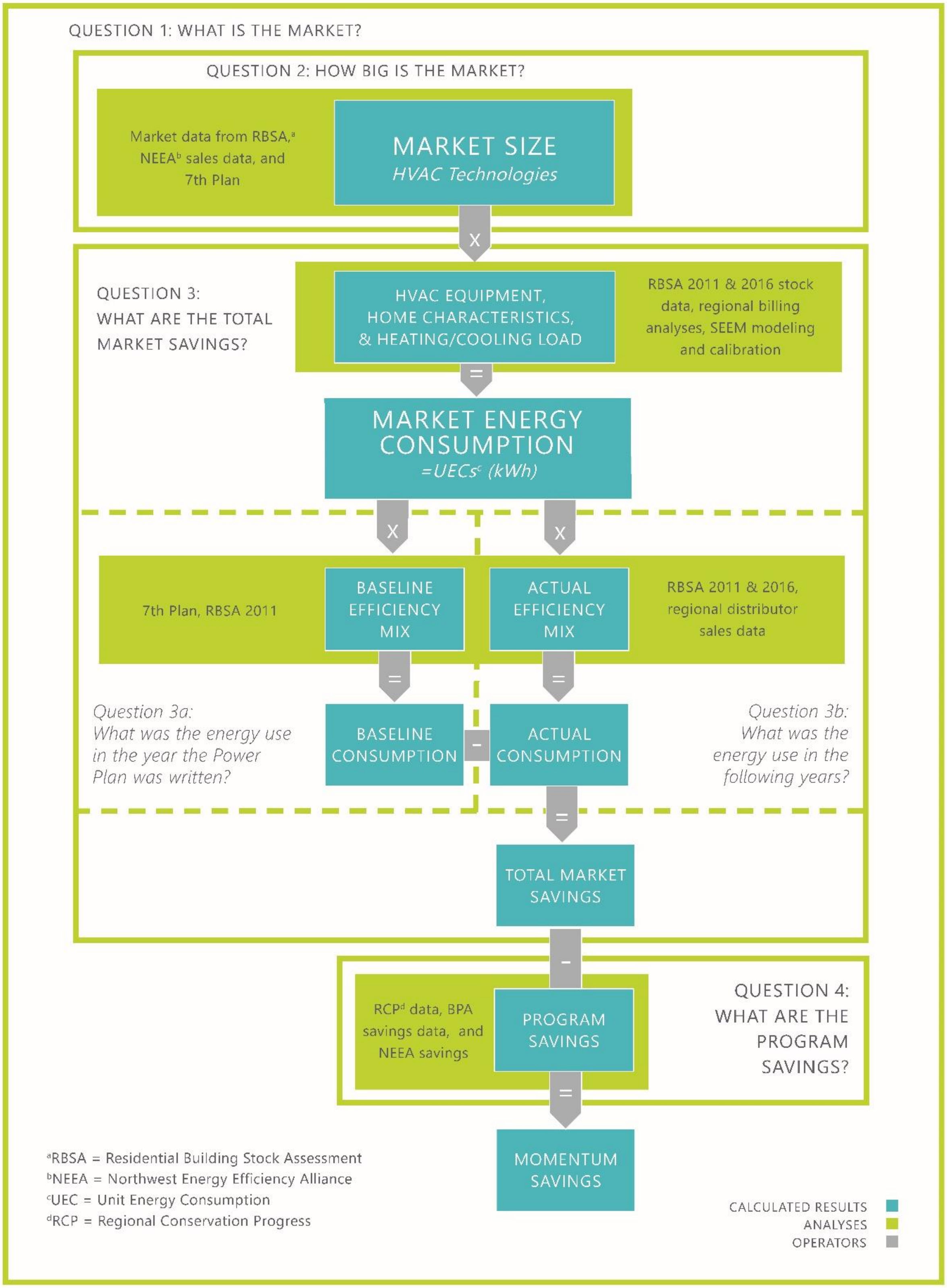
1. What is the market?
2. How big is the market?
3. What are the total market savings?
    a. What was the energy use in the year the Power Plan was written?
    b. What was the energy use in the following years?
4. What are the program savings?

Answers to these questions provide the information necessary to estimate Momentum Savings. Momentum Savings are energy savings above the Council's Seventh Plan frozen baseline programs do not claim or the Northwest Energy Efficiency Alliance (NEEA) does not include in its net market effects. Figure 1 summarizes how the Four Questions fit together, including details specific to residential HVAC market analysis and relevant data sources. The following sections describe how the team answered these questions in relation to the residential HVAC market.

[1] Presentation materials from the RTF Market Analysis Subcommittee meetings are linked on BPA's website at https://www.bpa.gov/EE/Utility/Momentum-Savings/Pages/HVAC.aspx

[2] Available at https://www.bpa.gov/EE/Utility/research-archive/Documents/Momentum-Savings-Resources/Methods_for_calculating_Momentum_Savings.pdf

Figure 1: Overview of the Momentum Savings Analysis Framework for Residential HVAC



Question 1: What is the market?

Question 1 defines the analysis scope; it does not have any specific data sources or methodology, but rather presents decisions the team made in collaboration with BPA about how to define the residential HVAC market. The team presents market sizing data sources and methods in Question 2, energy consumption in Question 3, and program savings in Question 4.

The research team defined the HVAC market by technology, sector, building type, and geography. Table 1 summarizes each of these dimensions, and the following sections provide further detail.

Table 1: Market Definition

Element	Description	Notes
Geographic Scope	Oregon, Washington, Idaho, and Western Montana	Includes the four-state region, consistent with the Seventh Plan
Unit of Account	Dwelling unit (i.e., household)	The model accounts for heating and cooling electric consumption by dwelling unit.
Sector and Building Type Scope	All housing types in the residential sector (single family, manufactured homes, and multifamily units)	Includes low-, mid-, and high-rise multifamily buildings with in-unit HVAC systems
Technology Scope	All in-unit technologies that affect electric heating and cooling consumption	Includes all RTF and Seventh Plan measures; excludes central (non-in-unit) HVAC systems in multifamily buildings and HVAC equipment in common areas of multifamily buildings
Fuel Type Scope	Electric heating and cooling, plus electric consumption from non-electric heating	The model accounts for the equipment stock of non-electric HVAC technologies and includes a per-unit electric UEC that accounts for the fan loads and electric secondary heating in dwellings with non-electric HVAC technologies.

*An example of supplemental, non-electric secondary heat is a woodstove providing supplemental heat in a home that relies on electric resistance baseboard as its primary heating system. The model reflects the impact of such supplemental heat in its UECs.

Geographic Scope

The HVAC market includes Oregon, Washington, Idaho, and Western Montana, which is consistent with the Seventh Plan's geographic scope. The model excludes housing stock in Eastern Montana, consistent with the scope of the Seventh Plan. The team does not report state-level results for energy consumption or Momentum Savings.

Some model inputs disaggregate the model's geographic area into heating and cooling zones, also consistent with the Seventh Plan. The heating zones' designations are applicable to heating technologies and the cooling zones' designations are applicable to cooling technologies.

Unit of Account

The unit of account describes the metric by which the research team quantifies the model's market. The team uses **dwelling unit** (i.e., a household) as the unit of account to provide a consistent basis for modeling and technology analysis.[3] The team defines primary heating and cooling technology saturation for each dwelling unit type in the region, which varies based on climate zone, building types, and other factors.[4]

The modeling approach accounts for primary heating and primary cooling equipment separately. That is, the model treats dwelling unit heating energy consumption separately from dwelling unit cooling consumption. Question 3 provides further detail on unit energy consumption (UEC) methodology.

Sector and Building Type Scope

The market for this analysis includes all HVAC technologies installed in the **residential sector**. This sector comprises three building types: single family homes, manufactured homes, and multifamily units with in-unit HVAC systems. The specific scope of multifamily units included in the model is described in more detail below.

In addition to building types, the model also segments the market into new and existing building vintages, where existing construction represents buildings constructed before 2011 and new construction represents buildings constructed in 2011 or later. The team selected 2011 to align equipment saturations with the first Residential Building Stock Assessment (RBSA).[5]

Multifamily Buildings

Multifamily buildings present many complexities, and the research team determined its approach to modeling multifamily HVAC consumption with input from BPA and the RTF Market Analysis Subcommittee.

First, the model only includes multifamily *units* and excludes common areas in multifamily buildings because common area usage differs from typical residential use.

Second, as the model is focused on residential HVAC technologies, the model excludes multifamily dwelling units in buildings with central HVAC systems because these systems are generally non-residential technologies.[6] This market definition is consistent with the Seventh Plan, as well as with

[3] Dwelling units can be single-family detached homes, manufactured homes, or a unit within a multifamily dwelling (e.g., the model represents an apartment building containing 10 separate apartments as 10 dwelling units).
[4] See discussion of cells in Question 3.
[5] RBSA available at https://neea.org/data/residential-building-stock-assessment
[6] Some multifamily buildings include central HVAC equipment that serves the common areas and non-residential portions of the building. The model includes only in-unit HVAC equipment, regardless of whether the building also has central HVAC equipment for other non-residential uses.

regional, residential sector utility program definitions, both of which exclude non-in-unit HVAC systems from the residential sector.

Finally, multifamily buildings fall into one of three segments based on the physical size of the building: low-rise (1-3 stories), mid-rise (4-6 stories) and high-rise (7 or more stories). The research team's scope includes all multifamily buildings, regardless of size, to provide a comprehensive view of residential HVAC energy consumption. Regional utility programs and the Seventh Plan's regional conversation potential assessment do not focus on mid- and high-rise dwelling units; however, the majority of multifamily building HVAC systems, including mid- and high-rise structures, are in-unit systems as shown in Table 2.

Table 2. Summary of Percentage of In-Unit HVAC Systems

Building Type	Total # of Dwelling Units (Regional, 2016)	% In-Unit HVAC Systems
Single Family (1-4 units)	4,254,405	100%
Manufactured Homes	440,356	100%
Low-Rise Multifamily (1-3 stories, 5+ units)	621,990	93%
Mid-Rise Multifamily (4-7 stories, 5+ units)	250,802	98%
High-Rise Multifamily (4+ stories, 5+ units)	39,216	65%

Source: Cadeo analysis of RBSA 2016.

In total, these multifamily in-unit systems—which are residential HVAC technologies, such as electric baseboards or ductless heat pumps (DHPs)—represent approximately 14% of the residential HVAC market. Therefore, to be comprehensive, the team included all multifamily building in-unit technologies in the model's scope.

The inclusion of mid- and high-rise multifamily buildings introduces uncertainty into the model's regional HVAC energy consumption estimate because the Simplified Energy Enthalpy Model (SEEM)[7] building simulation software the team used to develop UECs is not designed to model large multifamily (i.e., mid- and high-rise) buildings. Later in this document, the team describes its approach for determining multifamily UECs and assesses the magnitude of Momentum Savings uncertainty associated with the multifamily UECs.

[7] The SEEM program models small-scale residential building energy use. The program consists of an hourly thermal simulation and an hourly moisture (humidity) simulation that interact with duct specifications, equipment, and weather parameters to calculate the annual heating and cooling energy requirements of the building. SEEM, written at Ecotope, was developed by and for the Northwest Power and Conservation Council and NEEA. SEEM is used extensively in the Northwest to estimate conservation measure savings for regional energy utility policy planners. For more information, see http://rtf.nwcouncil.org//measures/support/seem/.

Technology Scope

The model includes two HVAC technology groups based on how they impact energy use associated with heating and cooling.

1. **HVAC equipment** refers to the physical HVAC systems that heat and/or cool dwelling units.
2. **Non-equipment factors**, such as building shell or occupancy, that impact the amount of energy needed to condition each home.

The following sections describe the two groups in more detail and how each is treated in the model.

HVAC Equipment

Table 3 lists the model's HVAC technologies and indicates whether the technologies provide heating, cooling, or both. In defining these technologies, the team grouped similar technologies together when they had similar electric energy consumption characteristics, especially for technologies with limited market saturation.

Table 3: List of HVAC Equipment Included in the Model

Technology	Heating	Cooling
Air Source Heat Pump (ASHP)	✓	✓
Ductless Heat Pump (DHP)	✓	✓
Central Air Conditioner (CAC)		✓
Electric Zonal Heat (Baseboard & Electric Boiler)	✓	
Electric Forced Air Furnace (eFAF)	✓	
Gas Forced Air Furnace (gFAF)	✓	
Ground Source Heat Pump (GSHP)	✓	✓
Packaged Terminal Heat Pump (PTHP)	✓	✓
Room and Portable Air Conditioners (RAC/PAC)		✓
Packaged Terminal Air Conditioners (PTAC)		✓
Evaporative Cooler		✓
Non-Electric Zonal Heating Sources: All Boilers (oil, gas) and Heating Stoves (wood, pellets, propane, oil, fireplaces, etc.)	✓	

Key Decision

Table 3 does not explicitly list secondary (supplemental) heating and cooling equipment. **The research team elected to not specify secondary heating and cooling equipment regional market size. Instead, the team accounted for secondary heating and cooling use in its estimate of per-dwelling UEC, described later in this document.** Heating UECs represent average total dwelling unit heating energy consumption, including secondary heating equipment impact, as well as factors such as occupancy. Similarly, the cooling UECs represent average total dwelling unit cooling energy consumption, including secondary cooling equipment use.

For some equipment, the model tracks specific efficiency levels discretely, while for others the model estimates only a single efficiency level. The specific equipment efficiency levels accounted for in the model are summarized below in Table 4.

Table 4. Summary of HVAC Equipment Efficiency Levels Included in the Model

HVAC Equipment Type	Efficiency Level(s)	Rationale/Description
ASHP	Heating = HSPF 7.2, 7.7, 8.2, 8.5, 9.0, and 10.0+ Cooling = SEER 10, 13, 14.5, 18+	These efficiency levels balance granularity with simplicity, while capturing the meaningful breaks in ASHP efficiency due to federal standards, current market practices, or technology improvements (e.g. variable capacity heat pumps).
DHP	DHP with Electric Zonal; DHP with eFAF; Full DHP	Only a single efficiency level of DHP is modeled, but in three different configurations. The team determined that the difference in efficiency between DHP models has a small impact on consumption[8] and cannot be reliably estimated.
CAC	SEER 10, 13, 14.5, 18+	These efficiency levels balance granularity with simplicity, while capturing the meaningful breaks in CAC efficiency due to federal standards, current market practices, or technology improvements (e.g., variable capacity CAC).
Electric Zonal Heat	All	Electric zonal heating systems do not vary meaningfully in efficiency.
eFAF	All	Electric furnaces do not vary meaningfully in

[8] The RTF DHP measures analyze savings for three different efficiency tiers of DHPs: HSPF between 9.0 – 11.0, 11.1 – 12.5, and ≥12.6, as well as a combined level for all DHP ≥9.0 (ResSFExistingHVAC_v4_2.xlsx). In analyzing the measures, the research team determined that the average energy consumption for DHPs of different efficiency levels were all within 5% of each other. Furthermore, there is currently some uncertainty regarding the ability of the test procedure to accurately differentiate energy consumption for variable speed heat pumps, including DHPs. As such, and because the addition of a DHP was the primary driver of changes in energy consumption, the team elected to model a single DHP efficiency level that was representative of the average efficiency of regional sales and stock saturation, based on data 2017 NEEA DHP sales data and RBSA 2016, respectively. For more information on the efficiency of the modeled DHP unit, see the UEC Summary workbook accompanying this memo.

HVAC Equipment Type	Efficiency Level(s)	Rationale/Description
		efficiency.
gFAF (Electric Fans)	All	Only accounts for electric fan energy. The team does not use multiple efficiency levels, such as Electronically Commutated Motors (ECM) or permanent, split-capacitor motors (PSC) due to uncertainty of savings associated with ECM.
GSHP	All	Differences in GSHP efficiency are not expected to materially impact consumption due to low saturation.
PTHP	All	Differences in PTHP efficiency are not expected to materially impact consumption due to low saturation.
Zonal Cooling Technologies	All	Data is not available to reliably estimate changes in energy consumption from efficient zonal cooling technologies.
Evaporative Cooler	All	Differences in evaporative cooler efficiency do not materially impact consumption due to low saturation in the region.
Non-Electric Zonal Heating Sources	All	Only accounts for electric energy associated with pumps or fans. The team does not use multiple efficiency levels (ECM vs PSC) due to uncertainty of savings associated with ECM and lack of data related to electrical energy consumption of non-electrical zonal heating technologies in general.

Other Factors That Impact HVAC Energy Consumption

In addition to the factors previously discussed, the approach accounts for factors that affect residential building heating and cooling load and HVAC equipment energy use. Table 5 lists HVAC energy consumption impacts the team includes in its HVAC market analysis.

Table 5. Other Factors that Impact HVAC Energy Consumption

Non-Equipment Factors	Description
Thermostat Type	Includes baseline and "advanced smart"[9] thermostats
Building Shell (Weatherization)	Includes insulation, windows, and air sealing (all factors that affect shell UA[10])
Installation Practices (Commissioning, Controls and Sizing)	Includes HVAC controls, airflow, refrigerant charge, and equipment sizing for ASHPs and CACs
Duct Losses (for applicable HVAC equipment)	Includes supply and return duct leakage for ducted HVAC systems, as well as conduction losses and induced infiltration[11]
Occupancy	Addresses occupancy patterns (occupied all day vs vacant during working hours), as well as partial occupancy associated with, for example, vacation homes
Presence of Secondary Heating or Cooling	Addresses use of secondary sources for heating and cooling, including non-utility fuels

This section lists the factors and introduces the approach to modeling their impact within the region. Question 2 focuses on market sizing and estimating each factor's saturation in the region. Question 3 describes the team's approach to accounting for the factors' impact on HVAC energy consumption.

[9] The team only quantifies savings from certain thermostats with specific features that meet the definition of "advanced smart," as defined in BPA's Thermostat Market Characterization study (https://www.bpa.gov/EE/Utility/Momentum-Savings/Documents/181016_BPA_Smart_Thermostats_Market_Characterization.pdf).

[10] UA represents the total heat loss through building shell. Energy-efficiency measures like insulation, windows, and air sealing improve a home's UA by reducing heat loss.

[11] Note, due to lack of data, the team only models improvements in duct tightness (supply and return duct leakage). Duct insulation and duct system inefficiencies are included in the UECs based on their presence in the RBSA 2011 prototype homes, but do not change over time or between the baseline and actual case.

Modeling Approach for HVAC Equipment and Other Factors

The research team took one of three approaches in the model to account for HVAC equipment and each of the other factors listed above based on data availability, likelihood of market change, and each factor's potential impact on market savings.

- **Primary factors:** model market change directly via stock-turnover using product flow data.
- **Secondary factors:** model market change by evaluating changes in the stock (i.e., no product flow information is available).
- **Tertiary factors:** assume no market change over the analysis period (i.e., no reliable stock information is available).

Table 6 presents the research team's primary, secondary, and tertiary designation factors. For future model updates, the team may elect to change a factor's designation if additional data sources suggest significant or important market change.

Table 6. Factors Impacting HVAC Consumption and Their Modeling Approaches

Factor	Primary: Directly Modeled via Stock Turnover	Secondary: Modeled via Stock-to-Stock	Tertiary: Hold Constant
HVAC Equipment & Efficiency Level	✓		
Thermostat Type		✓	
Building Shell (Weatherization)		✓	
Installation Practices (Commissioning, Controls and Sizing)		✓	
Duct Tightness		✓	
Occupancy			✓
Presence of Secondary Heating and/or Cooling			✓

The research team models HVAC equipment type and efficiency level as **primary factors**, which means the model directly analyzes changes in market saturation and stock efficiency mix via a stock-turnover approach for equipment technologies. The model disaggregates HVAC equipment type and efficiency level by climate zone, building type, and building vintage and represents stock-turnover for each segment of the HVAC market uniquely.

For the **secondary factors,** thermostat type (i.e., advanced smart thermostats), weatherization, installation practices, and duct sealing, product flow data are not available to inform a stock turnover model. Instead, the team estimates market change for these technologies based on modeling changes in stock saturation over time, based on RBSA 2011 and RBSA 2016, in addition to data from regional energy efficiency programs. The team discusses data sources and approaches to estimating market change for each of these factors in more detail in Question 2 below.

There are also other, primarily behavioral, non-equipment factors that affect regional HVAC energy consumption, for which the team does not currently have enough data to model changes in saturation over time, such as occupancy and use of supplemental heating and/or cooling. The research team has identified these as **tertiary factors** and has modeled their impact on HVAC energy consumption as fixed over the analysis period.

The team's residential HVAC market modeling approach is comprehensive related to the study's scope; other factors that impact HVAC energy consumption fall outside the scope of this study. For instance, the increasing saturation of electric appliances decreases the home heating load. The state of the economy also has an unknown impact on heating and cooling loads as residents may adjust their space conditioning behavior based on their economic circumstances.

Fuel Type Scope

The analysis focuses on residential HVAC market **electricity consumption** changes. However, the market definition also includes gas technologies insomuch as they impact electric consumption, either directly through fan loads or by impacting total electric HVAC consumption through changes in fuel preferences over time. The research team used equipment saturations from RBSA 2011 and RBSA 2016 to account for fuel saturation changes and their overall residential HVAC market electric consumption impact.

Question 2: How big is the market?

To estimate residential HVAC market energy use, the team must first define the market size in the Seventh Plan baseline year (2015) and in each subsequent Seventh Plan year (2016-2021). The market size, in this case, consists of the annual regional number of installed units of each in-scope HVAC technology. The research team's approach uses two overarching assumptions

- Use the RBSA 2011 to estimate equipment saturations and number of dwelling units in 2011.
- Calibrate the model's assumptions such that the modeled HVAC equipment saturations in 2016 align with the observed HVAC equipment saturations in the RBSA 2016.[12]

From these assumptions, the research team determines the HVAC equipment saturation for all other years in its model. The Seventh Plan baseline year (2015) is an interpolation between the two RBSA years (2011 and 2016), and the team's forecast for the remaining Seventh Plan years (2017-2021) is a forward projection of the trend between the RBSA years.

[12] The calculated RBSA 2016 saturations are based on the most recent RBSA 2016 dataset and updated weights, provided by NEEA on April 17, 2019. See NEEA's RBSA II Update Memo (https://neea.org/img/documents/RBSA-II-Update-Memo.pdf) and other resources on NEEA's RBSA Data Resources page (https://neea.org/data/residential-building-stock-assessment) for more information.

While the time period of this study is the same as the Seventh Plan, there are three factors that differentiate this model's market sizing from the Seventh Plan:

- **Data availability:** The team aligned the HVAC equipment saturations to those found in RBSA 2016, which was not available at the time of Seventh Plan development.
- **Level of resolution:** The team's approach is more detailed than the baseline for the Seventh Plan energy efficiency supply curves in that the team expects to account for the full HVAC market, rather than limiting the market sizing to the combinations of building types and HVAC equipment included in RTF measures.
- **Equipment turnover rates:** The research team's equipment turnover rates, as described in this section, take a different functional form than they do in the Seventh Plan energy efficiency supply curves.

This section describes two methods the research team uses to estimate the HVAC equipment market size beyond 2011: (1) a detailed stock-turnover approach based on annual HVAC equipment additions and retirements; and (2) stock-turnover result calibration based on updated saturations captured in the RBSA 2016.

Estimating Market Size for Primary Factors: HVAC Equipment & Efficiency

The research team's market sizing approach for the primary factors described above is to multiply the number of dwelling units in the region in a given year by the saturation of HVAC equipment observed in that year to estimate the market size of residential HVAC technologies in the model (Equation 1). The team divided the market into segments using four factors to accurately estimate the HVAC equipment distribution throughout the region:

- **Building vintage:** existing construction (2011 and earlier) and new construction (new homes in 2012 and later).
- **Building type:** single-family homes, manufactured homes, and multifamily units
- **Climate zone:** heating zone 1, 2, and 3; cooling zone 1, 2, and 3
- **HVAC equipment type & efficiency level**: primary heating and cooling technologies in Table 3 and Table 4

The first three segmentation variables physically define the unit of account (i.e., a dwelling unit).

Equation 1: Market Size by Granular Segmentation Variables

$$\text{MarketSize}_{t,vbze} = \text{\# Dwelling Units}_{t,vbz} \times \text{Saturation}_{t,vbze}$$

Where:

t = analysis year

v = building vintage

b = building type

z = climate zone

e = equipment type[13]

This document uses the term "cell" to represent each of the many possible combinations of building type, climate zone, and primary HVAC equipment type to simplify the notation in Equation 1. Using cells in place of the more granular segmentation variables in the equation notation yields:

Equation 2: Market Size by Cell

$$MarketSize_{t,vc} = \#\ Dwelling\ Units_{t,vc} \times Saturation_{t,vc}$$

Where

t = analysis year

v = vintage

c = cell

The team estimates market size for each HVAC equipment type with a stock-turnover approach that accounts for the factors that affect total market size during the analysis period: growth in the housing stock through new construction, differences in saturation in subsequent years from new construction or remodels, and retirements of failed equipment not replaced by a similar technology. Equation 3 shows the calculation of market size based on all these factors.

Equation 3: Annual Market Size

$$AnnualMarketSize_t = \sum_{Cell\ c} \#\ Dwelling\ Units_{t-1,Ex,c} \times Saturation_{t-1,Ex,c} + \#\ Dwelling\ Units_{t,NC,c} \times Saturation_{t,NC,c} - Retirements_{t,c} + Replacements_{t,c}$$

Note: Retirements and Replacements are expressed as a number of units of HVAC equipment

Where:

t = analysis year

Ex = existing vintage

NC = new construction vintage

c = cell[14]

The research team uses Equation 3 to calculate annual market size for each year of the analysis period and capture how the stock changes year-to-year; this approach requires the inputs listed in Table 7 and described in further detail below.

[13] For the purposes of estimating energy consumption, the team further segmented equipment type by efficiency level and heating versus cooling.

[14] Note, as discussed previously, vintage (new construction versus existing) is part of the cell definition. However, the team is breaking out that variable uniquely for this equipment to describe the stock-turnover logic. In this case, the "cell" describes the unique combination of primary variables besides vintage.

Table 7. Stock Turnover Inputs and Sources

Description	Data Sources
Pre-2011 dwelling units	Cadeo analysis of RBSA 2011, Northwest Residential Lighting model*
Rate (%) at which dwelling units are demolished	Seventh Power Plan
New construction dwelling units: 2011 through 2021	Seventh Power Plan
HVAC system saturation in 2011	Cadeo analysis of RBSA 2011
Equipment age distribution in 2011	Cadeo analysis of RBSA 2011
Annual turnover rate	Cadeo analysis of DOE Weibull parameters and ASHRAE lifetime
Annual HVAC equipment efficiency share	Cadeo analysis of RBSA 2011 and RBSA 2016, Cadeo analysis of NEEA sales data
Annual product flow	Cadeo analysis of RBSA 2011 and RBSA 2016, Cadeo analysis of NEEA sales data

*BPA developed this model, which NEEA now maintains.

Pre-2011 Dwelling Units. The team used a combination of the RBSA 2011 and previous BPA market model research to estimate the total number of 2011 single-family homes, manufactured homes, and multifamily buildings as a basis for the total number of homes/units in the residential sector. This approach to estimating the number of dwelling units in 2011 aligns with the Northwest residential lighting model and the BPA residential hot water model.

In order to track this vintage of homes over time, the team does use the demolition rate assumption directly from the Seventh Plan to account for dwelling unit-teardown.

New Construction Dwelling Units: 2011 through 2021. The stock-turnover model begins in calendar year 2011 and requires new construction estimates for years 2011 through 2021 to cover the full analysis period.[15] The model uses new construction growth estimates from the Seventh Plan for each of the three housing types: single family, manufactured homes, and multifamily units. This approach aligns with the other Northwest residential market models (lighting and hot water).

The Seventh Plan was completed in calendar year 2016, thus its housing stock estimates are projections for the Action Plan period years (2016-2021). For future model updates impacting the Action Plan period, the BPA team can use more up-to-date information, such as the U.S. Census Bureau's Building Permits Survey,[16] to update the housing stock values as better annual data become available during the Action Plan period.

[15] While the Action Plan period consists of the years 2016 through 2021, the Seventh Plan contains estimates of new construction spanning back to 1985.
[16] Available at https://www.census.gov/construction/bps/

HVAC Equipment Saturation in 2011. The team conducted an analysis of the RBSA 2011 to determine saturation (percentage of dwelling units with each specific type of primary HVAC equipment) by building type, climate zone, and construction vintage.

Equipment Age Distribution in 2011. The number of units of each HVAC equipment type in existing construction that are replaced each year is a function of the age distribution in its regional stock. The research team developed an age distribution of the installed HVAC equipment stock in the initial year of the stock turnover model (2011) based on the year of manufacture in the RBSA 2011 information.

Annual Turnover Rate. The team derived equipment turnover rate assumptions come from one of two sources (See Table 8). Regardless of the equipment turnover rate assumption source, the team used professional judgment to adjust the modeled equipment retirement rates so the 2016 equipment saturation in its stock turnover model aligned with RBSA 2016.

Where possible, the team uses a Weibull curve to define what proportion of the existing stock turns over in a given year. This requires equipment age data from the RBSA 2011, and Weibull parameters from the U. S. Department of Energy (DOE) 2011 technical support document.[17]

Where those data are not available, the team uses an annual turnover rate of one divided by the assumed median equipment lifetime, as determined by ASHRAE,[18] to inform what proportion of the existing stock turns over in a given year.

Table 8. Source for Annual Replacement Rates, by HVAC Equipment

Technology	Single Family and Manufactured Homes	Multifamily Units*
Air Source Heat Pump (ASHP)	DOE Weibull	ASHRAE
Ductless Heat Pump (DHP)	DOE Weibull	ASHRAE
Central Air Conditioner (CAC)	DOE Weibull	ASHRAE
Room Air Conditioner (RAC)	ASHRAE	ASHRAE
Electric Zonal Heat (Baseboard)	ASHRAE	ASHRAE
Electric Forced Air Furnace (eFAF)	DOE Weibull	ASHRAE
Gas Forced Air Furnace (gFAF)	DOE Weibull	ASHRAE
Electric Boiler	ASHRAE	ASHRAE
Ground Source Heat Pump (GSHP)	ASHRAE	ASHRAE
Packaged Terminal Air Conditioner (PTAC)	ASHRAE	ASHRAE
Packaged Terminal Heat Pump (PTHP)	ASHRAE	ASHRAE
Other heating sources	ASHRAE	ASHRAE

*Note: the RBSA 2011 does not have equipment ages for HVAC equipment in multifamily buildings, therefore the team uses the ASHRAE lifetime in the turnover rate assumption.

[17] Available at https://www.regulations.gov/contentStreamer?documentId=EERE-2011-BT-STD-0011-0012&attachmentNumber=9&contentType=pdf
[18] Available at https://www.scribd.com/document/324263299/ASHRAE-Chart-HVAC-Life-Expectancy-1

The team used RBSA 2011 and RBSA 2016 saturation data to guide the development of equipment efficiency shares and product flows, as described here.

Key Decision

Annual HVAC Equipment Efficiency Share. The research team used NEEA's annual HVAC distributor sales data for sales occurring during 2016 and 2017.[19] **The team leveraged the sales data, which only covered a portion of the total market, by developing and applying an HVAC-specific extrapolation approach to estimate regional 2016 and 2017 HVAC equipment efficiency shares.** Additional detail on that analysis can be found in the 2016-2017 HVAC Sales Data Executive Summary report. This extrapolation approach is subject to uncertainty; the team discusses this topic in more detail in the Uncertainty Sources and Sensitivity Analysis section of this report.

The team developed efficiency shares for years 2011 through 2015 such that the modeled stock in 2016 aligns with that reported in RBSA 2016.[20] At this time, the team assumes that the HVAC equipment sold in 2018-2021 has identical efficiency shares to 2017. The team will update this assumption as data become available.

Key Decision

Annual HVAC Equipment Product Flow. The team developed its modeled annual product flows (i.e., the number of HVAC equipment units sold each year by technology) for years 2011 through 2015 to align with RBSA 2016 for stock-turnover HVAC equipment saturation. In addition to aligning its modeled stock to RBSA 2016, the team also used market intelligence on annual sales by equipment type and an analysis of energy savings reported by regional utility programs[21] to inform its product flow assumptions. This approach uses multiple sources, each subject to uncertainty; the team discusses this topic in more detail in the Uncertainty Sources and Sensitivity Analysis section of this report.

At this time, the team assumes that the mix of HVAC equipment sold in 2018-2021 is identical to 2017 and will update as data become available.

Estimating Market Size for Secondary Factors

This section describes the team's method for accounting for market changes for the secondary and tertiary factors (Table 6) that impact HVAC energy consumption for each technology. The team accounts for changes in the market saturation of these factors by using a stock-to-stock approach. Saturation changes for these factors impact UECs; Question 3 provides details on the UEC approach.

Building Shell. Building shell addresses the heat loss characteristics of residential units in the Region, including insulation, air-sealing, and window improvements. The Northwest region has numerous, ongoing weatherization programs that provide customers financial incentives to improve their home's shells and the research team believes these programs could have a meaningful impact on per-home HVAC energy consumption. The team originally anticipated comparing building shell quality from RBSA

[19] The research team assumes that NEEA will continue to collect annual sales data throughout the Action Plan period (2016-2021).
[20] RBSA 2016 is subject to sampling error – the team's modeled saturations in year 2016 are within the RBSA's error band.
[21] The team derived the number of incented units from total, reported energy savings. See the discussion on program savings in Question 4 for more information on the derivation of number of units going through programs.

2011 and RBSA 2016 databases to determine if changes over time are apparent in the data. However, there appear to be peculiarities in the RBSA 2016 shell data that make it difficult to compare the RBSA 2016 shell data to the RBSA 2011 shell data to determine this change in shell heat loss characteristics over time. As such, this study has disregarded RBSA 2016 data related to shell quality at this time. The Regional Technical Forum is currently reviewing the RBSA 2016 UA data related to revisiting the SEEM Calibration based on the new RBSA 2016 dataset. If they are able to resolve these issues, the team will consider incorporating the RBSA 2016 shell data into future model updates to inform any market changes in shell quality outside of programs.

Key Decision

Instead, **the model conservatively estimates market change based solely on the increased saturation of more efficient shells resulting from weatherization program activity**. The methodology for deriving the increase of weatherization saturation due to program activity is described in more detail in Question 4. This is a source of uncertainty in the model, as there may be shell improvements occurring outside of programs the model is not accounting for. However, the team currently lacks reliable data to estimate the extent of market change happening outside of utility programs. For future model updates, the team may explore acquiring additional data to estimate building shell improvements occurring outside of programs.

Thermostats. "Advanced smart" thermostat market adoption is a recent trend in the HVAC market, and many regional utilities provide rebates for these measures. Advanced smart thermostats incorporate specific features, including:

- Programmability and temperature/operating mode display,
- Wi-fi connectivity and an online dashboard or mobile app,
- Proximity sensing via on-board occupancy sensing,
- Basic demand response capabilities,
- Heat pump optimization, and
- Algorithms to "learn" typical setpoint schedules and optimize thermostat settings accordingly.[22]

Recent evaluations show some advanced thermostats reduce heating and cooling energy consumption by adjusting temperature setpoints when homes are unoccupied and reduce use of back-up (electric resistance) heating in heat pump homes. For the purpose of estimating impacts on total HVAC energy consumption, the team differentiates these advanced smart thermostats from other thermostats in the market.

The team uses a stock-to-stock approach to determine the thermostat saturation rate assumptions using the following data:

[22] BPA defines "advanced smart" thermostats as "Thermostats that incorporate all features of programmable, connected, and smart thermostats but also have: occupancy sensing directly onboard the device, heat pump optimization, algorithms that learn occupants' behaviors and characteristics of the structure and adjusts the device accordingly to improve scheduling and performance, and proven energy efficiency savings." For more information, see: "Smart Thermostat Market Characterization to Inform Market Modeling" at https://www.bpa.gov/EE/Utility/Momentum-Savings/Documents/181016_BPA_Smart_Thermostats_Market_Characterization.pdf.

- The RBSA 2011 database does not include advanced smart thermostats; the team assumes a market saturation of 0% for all HVAC system types because advance smart thermostats were not available in the market at that time
- The research team conducted an analysis of RBSA 2016 and other market data to determine advanced smart thermostat saturation in 2016 and 2017 by HVAC system type. Not all HVAC systems in the model can use advanced smart thermostats (e.g., these thermostats are typically incompatible with DHPs). For non-compatible system types, the team also assumed a 2016 market saturation of 0%.
- The research team then uses the assumptions above to project smart thermostat saturation for years 2018-2021.

Looking ahead, the team will use a combination of market research, sales and shipment data, and program data to inform advanced smart thermostat saturations in 2018-2021, rather than wait until the next RBSA. The research team is currently exploring sales data sources and sales data requirements in tandem with BPA but has not yet identified a specific vendor.

Duct Sealing and Commissioning, Controls, and Sizing. The Northwest has ongoing incentive programs aimed at HVAC installers to improve the Commissioning, Controls, and Sizing (CC&S) installation practices for ASHPs. The research team believes these programs could have a meaningful impact on average, per-home HVAC energy consumption. Like building shell, there is no reliable, time-variant data on CC&S saturation or duct sealing available through the two RBSA surveys. Therefore, **the team assumes that all regional duct sealing and CC&S activity occurs through energy-efficiency programs.**

Key Decision

The research team anticipates using the findings from the BPA's forthcoming 2019 HVAC Field Study to develop CC&S-specific saturation estimates and appropriate SEEM inputs. In a future Momentum Savings model update, the team will evaluate the findings from the field study and consider updating its treatment of CC&S.

Estimating Market Size for Tertiary Factors

The research team does not have sufficient data to model temporal changes in market size for the tertiary factors (Table 6) that impact HVAC energy consumption for each technology.

Occupancy and Sources of Secondary Heating & Cooling. As described in more detail in Question 3, the team is relying on information from the RBSA 2011 and associated RTF RBSA 2011 SEEM Calibration to estimate the impact of secondary heating and/or cooling sources and partial occupancy on HVAC energy consumption. Specifically, as described in more detail in Question 3, the RTF SEEM Calibration based on the RBSA 2011 data incorporates a "Phase II" factor that adjusts modeled energy consumption to account for behavioral and occupancy patterns, as well as sources of secondary heating & cooling.[23] The RTF is conducting a similar effort to calibrate SEEM to the RBSA 2016 data, but this activity is not yet final at the time of this analysis. As such, the team currently lacks data to estimate how the presence of supplemental heating and/or cooling sources varies over time and its commensurate impact on HVAC

[23] For more information on the RTF's SEEM Calibration work, see Rushton & Hadley. 2014. "Where Did It Go? Lost Savings Found in Real-World Data." Presentation at the 2014 ACEEE Summer Study on Buildings in Energy Efficiency. https://nwcouncil.app.box.com/s/bzbtdrczjpu8vu4q0v7sdpaayamrtjzs

energy consumption. After the RTF completes its RBSA 2016 SEEM calibration, the team will review the data to determine if either of these factors have changed significantly over time and warrant updating in the model.

Question 3: What are the total market savings?

Total market savings represent the difference between baseline energy consumption and actual energy consumption in aMW. Therefore, the team answers the following two questions:

> **Question 3a.** What was the energy use in the year the Seventh Plan was written?
>
> **Question 3b.** What was the energy use in the following years?

The installed stock and efficiency mix in the year the Seventh Plan was written (2015) informs the baseline (Question 3a). Verified (or projected) installed stock, shipments, and efficiency mix in each year of the analysis period (2016-2021) informs the actual scenario (Question 3b). The section on calculating total market savings describes the detailed inputs and assumptions for each of these scenarios.

In both the baseline and the actual case, the first step is to develop a method to estimate energy consumption for the residential HVAC market (as defined in Questions 1 and 2) in a given year. The research team uses this method to estimate baseline and actual energy consumption for each year of the analysis period. The team then compares the baseline energy consumption to the actual energy consumption for each year of the analysis period to arrive at total market savings. The following sections describe the method for estimating energy consumption in a given year.

Calculating Annual Energy Consumption

The research team's approach for estimating total residential HVAC market consumption in a given year hinges on two primary components, market size and UECs, as shown in Equation 4:

Equation 4. Regional HVAC Energy Consumption

$$\text{Total Annual Energy Consumption}_t(\text{kWh/yr}) = \sum_c \left(\text{Market Size}_{cv,t} \text{x UEC}_{cv,t}(\text{kWh/yr}) \right)$$

Where:

UEC = Energy Consumption for a dwelling unit with primary HVAC system (kWh/yr) in given *cell* and *year*

t = analysis year

c = One of multiple, distinctly defined cells of the total residential HVAC market.

The market size for each type of HVAC equipment and secondary non-equipment factor considered in the model was discussed in Question 2. This section discusses the derivation of the various UECs for each cell in the model.

Distinct UECs are necessary for all combinations of primary and secondary factors discussed previously in Question 1 and shown in Table 9, below. Table 9 also shows that the method for deriving the UEC, which varies based on the status of the factor, as well as the data available. The team primarily used the SEEM building simulation tool to develop the UECs, which provides a consistent and reliable framework for estimating UECs across all cells. To the extent possible, the research team corroborated the modeled UEC estimates with empirical data like the RBSA billing analysis or other regional studies, to ensure the results were as accurate and reliable as possible. However, in some cases, SEEM modeling does not adequately estimate a given system's energy consumption, so the team used adjustments to SEEM outputs to develop more reliable estimates. For example, zonal systems, such as ductless heat pumps, packaged terminal heat pumps and air conditioners, and portable air conditioners are difficult to accurately model in SEEM. For these cases, the team relied on available empirical data to provide reasonable estimates of UECs for these technologies. The team describes the specific modeling approach and assumptions that it made for each HVAC system in detail in the UEC Summary workbook.

Finally, for each primary and secondary factor, the team determined the level of granularity, or dimensions, to include in the model. In defining the dimensions, the team sought to balance simplicity with comprehensiveness. The team prioritized accurate and reliable savings capture using market changes and minimizing overall model complexity. Table 9 also summarizes each primary and secondary factor included in the model. All of the assumptions underlying each factor and dimension definition are summarized in detail in the associated "UEC Summary" workbook.

Table 9. Factors Impacting HVAC Consumption and Their UEC Development Approaches

Factor	Factor Status	Modeling Approach	Dimensions
Building Vintage	Differentiator*	Modeled either: • directly based on calibrated SEEM results or • with adjustments applied to SEEM results**	New Construction, Exisiting
Building Type			Single-Family, Manufactured Homes, Multifamily (Low-rise, mid-rise, and high-rise)
Climate Zone			HZ 1, 2, 3 (for heating), CZ 1, 2, 3 (for cooling)
Primary HVAC Equipment & Efficiency Level	Primary		Various, see Table 3 & Table 4
Thermostat Type	Secondary	Developed indirectly based on study findings applied to adjust SEEM results	Baseline, Advanced Smart
Building Shell (Weatherization)	Secondary	Modeled directly based on validated SEEM results	As Is (representative of current stock), Full Upgrade (i.e., fully weatherized)
Installation Practices (Commissioning, Controls and Sizing)	Secondary		Standard Practice (without CC&S), PTCS Installation (with CC&S)
Duct Tightness	Secondary		As Is (representative of current stock), Tight
Occupancy	Tertiary	Captured in UEC based on Phase II SEEM Adjustments	N/A
Presence of Secondary Heating and/or Cooling	Tertiary		N/A

* Building Vintage, Building Type, and Climate Zone are not specific technologies or factors that are accounted for in the model and do not change over time. Instead, they are used as additional variables to differentiate UECs for each primary and secondary factor combination. That is, for each unique combination of primary and secondary factors, there is a unique set of UEC for each specific combination of differentiating factors (vintage, building type, and climate zone).

** The method for estimate UECs varied by HVAC system and climate zone, based on the available data, this is discussed in more detail below.

As mentioned earlier, the research team's UEC development approach is based on the following three tenets:

1. It is grounded in empirical data whenever possible
2. It relies on a physics-based simulation to create a consistent and robust way of estimating energy consumption over a broad range of current and future scenarios
3. It avoids complexity, where possible, without sacrificing accuracy

To implement these tenets, the team developed a unique UEC for each combination of primary and secondary HVAC factors, or cells, based on a combination of SEEM building simulations and empirical energy consumption data, where available.

The UEC development process comprises the following steps for the primary HVAC factors:

1. Develop calibrated SEEM models for a representative population of homes for each building type
2. Validate the SEEM model results based on available measured data to confirm the model predictions
3. Apply the calibrated SEEM simulations to other cells where sufficient empirical data do not exist
4. Apply additional assumptions or adjustments to modeled SEEM results to generate estimates for particular cells that are not able to be modeled accurately in SEEM

The following subsections describe these steps in more detail.

Step 1. Developing Calibrated SEEM Models

SEEM building energy simulation software uses heat transfer equations to estimate heat losses (or gains) from the interior of the home to the exterior.[24] The heat transfer depends on the home's specifications (e.g., its size and shape, the number of windows and their insulation value, the amount of wall and ceiling insulation, etc.). SEEM outputs describe, among other things, an estimate of the heating (or cooling) system energy consumption based on the given specifications and HVAC equipment parameters.

The first step in the process involves developing, for any given cell, a representative set of homes and weights such that the weighted average SEEM-derived mean energy consumption accurately reflects the actual, regional average energy consumption, as described by billing analysis or other empirical estimates.

Key Decision

For single-family and manufactured homes, the team developed the representative set of homes based on the modellable homes in the RBSA 2011 stock assessment.[25] **The team chose to develop the UECs based on the RBSA 2011 homes because they provided the most accurate and granular description of the characteristics of homes in the region and in each climate zone available at the time of modeling.** Specifically, home characteristics consist of a number of key variables, including home geometry, square footage, construction type, and shell efficiency levels, all of which vary independently and are carefully captured in the RBSA 2011 dataset. The team originally considered using the RTF SEEM single-family prototype homes to model the homes in the region, but this sample did not sufficiently capture the range of home characteristics and variability observed in the RBSA 2011 sample. The team did not incorporate the RBSA 2016 homes at this time because the data were not available to map to SEEM inputs at the time of model development. This effort is currently underway, as part of the RTF's RBSA 2016 SEEM Calibration process. The research team will consider adjusting the model to include these homes in future model updates, although the RBSA 2016 home

[24] SEEM documentation can be found here: https://rtf.nwcouncil.org/simplified-energy-enthalpy-model-seem

[25] The team included all homes in RBSA 2011 that could be modeled in SEEM as the prototype set. For details on which homes were included or excluded, see the "UEC Summary" workbook.

characteristics are not expected to be significantly different than the RBSA 2011 sample and are not expected to significantly affect the results.

In addition, as Table 10 summarizes, the team developed a specific set of representative homes for ducted and unducted HVAC systems in each climate zone to capture differences in residential building construction characteristics between ducted and unducted homes and among the climate zones.

Table 10. Summary of Approaches to Develop a Representative Set of Homes for SEEM Modeling

Building Type	Sub-set	Representative Homes	Number of Homes	
Single-Family	Ducted	All homes in RBSA 2011 with central systems, by climate zone	HZ 1 = 626 HZ 2 = 147 HZ 3 = 82	CZ 1 = 596 CZ 2 = 162 CZ 3 = 97
	Unducted	All homes in RBSA 2011 with zonal systems, by climate zone	HZ 1 = 626 HZ 2 = 147 HZ 3 = 82	CZ 1 = 157 CZ 2 = 69 CZ 3 = 12
Manufactured Homes	Ducted	All homes in RBSA 2011 with central systems, by climate zone	HZ 1 = 168 HZ 2 = 76 HZ 3 =54	CZ 1 = 40 CZ 2 = 12 CZ 3 = 9
	Unducted	All homes in RBSA 2011 with zonal systems, by climate zone	HZ 1 = 7 HZ 2 = 8 HZ 3 = 2	CZ 1 = 0 CZ 2 = 1 CZ 3 = 0
Multifamily Units	N/A	RTF Prototypes	4	

To create UECs based on the modeled SEEM outputs for each prototype home requires an approach to weight the results of each individual SEEM run in a given cell such that the weighted average within the cell accurately approximates the measured consumption for that cell, based on empirical energy consumption data. Each home in the RBSA 2011 sample already includes a weight that represents the number of homes in the region that particular home represents. [26] For single-family homes, the team used these weights, normalized within each ducting subset and climate zone, to weight the results of each home. For manufactured homes, although these weights also exist, the team did not apply these weights in the current analysis. The difference between the calculated UECs for single family homes calculated with the site weights versus a straight average were within 1% of each other, so the team determined that the site weights would not be expected to make an appreciable difference in the manufactured home results either. For multifamily units, the prototypes were weighted based on the foundation type of the individual RTF Prototypes and the typical foundation types observed in RBSA 2011.

[26] The sample weights derived in RBSA 2011 are based on the specific sample frames defined in RBSA 2011, which were based on geographic subregion and utility service type (private vs public).

Accounting for Non-HVAC Equipment Factors in UECs

As described in Question 1, shell level, installation practices, duct tightness, occupancy, and the presence and use of secondary heating systems are non-HVAC-Equipment factors that affect overall residential HVAC load. To account for these factors, the team developed specific UECs and SEEM inputs for each of the factors and dimensions noted in Table 9. For more details on the assumptions and inputs used to determine the designated shell level, duct tightness, and installation characteristics (for heat pumps), see the UEC Summary workbook. For the tertiary factors of occupancy and use of secondary heating fuels, the team captures these impacts by employing the RTF's Phase II adjustment factors, which accounts for these impacts. That is, the empirical heating energy consumption data in the RBSA 2011 includes some homes that use secondary heating sources (e.g., wood stoves), or experience partial-year occupancy. The team cannot attribute how much these tertiary factors influence energy consumption, but their influence is embedded in the empirical consumption data. Therefore, adjusting SEEM outputs to that empirical data (based on the RTF Phase II adjustments) implicitly accounts for the influence of these tertiary factors. For future model updates, the team will consult the updated RTF SEEM calibration based on RBSA 2016 billing data, when available, to determine if any of these factors show significant change over time.

Step 2. Validating SEEM Results Based on Empirical Data

As described previously, the team attempted, to the extent possible, to develop and validate UECs based on empirical data. The first way the team implemented this was by grounding the SEEM modeling in the RBSA 2011 billing data, using the RTF's RBSA 2011 SEEM Calibration approach. The RTF SEEM Calibration analyzed the raw SEEM model outputs alongside regional billing data, and developed calibration factors. These calibration factors, applied to raw SEEM model outputs, improve the alignment of SEEM outputs with regional billing information. The two calibration factors (Phase I and Phase II) serve the following purposes, for specific HVAC types (eFAF or Zonal, gFAF or ASHP, and DHP):

- Phase I adjustment serves to better match consumption for fully occupied homes in the region.
- Phase II adjustment serves to account for partial occupancy and the use of non-utility fuels

The RTF SEEM Calibration was determined by modeling the RBSA 2011 homes in SEEM and adjusting the results to match RBSA 2011's empirical energy consumption data for *individual* homes.[27] Since both the RTF SEEM Calibration and the model leverage the RBSA 2011 homes[28] and the RBSA 2011 billing data, the RTF's SEEM Calibration factors should result in UEC estimates that are similar to the RBSA billing analysis results for a given cell. As such, by relying on the RTF's SEEM Calibration factors and following

[27] For more information on the RTF's SEEM Calibration work, see Rushton & Hadley. 2014. "Where Did It Go? Lost Savings Found in Real-World Data." Presentation at the 2014 ACEEE Summer Study on Buildings in Energy Efficiency. https://nwcouncil.app.box.com/s/bzbtdrczjpu8vu4q0v7sdpaayamrtjzs

[28] The team's RBSA 2011 prototype homes include some homes that were not included in the RTF's Phase I and II calibration work, due to the differences in the purposes of the two efforts. Specifically, the RTF calibration work was focused on electrical energy consumption in program-eligible homes, while this effort in interested in all homes in the region.

the modeling guidelines associated with the calibrated SEEM model,[29] the team presumes that the UEC results align with the RBSA 2011 billing data within the bounds of the SEEM calibration.

To validate this result, especially for the slightly different prototype homes and scenarios included in this model, as compared to the SEEM calibration work, the research team also compared the weighted average UEC results to empirical data for particular cells with sufficient billing data. These comparisons were possible for:

- ASHPs in heating zones 1 and 2
- Electric zonal in all heating zones
- Electric forced air furnace in all heating zones
- DHP with Zonal Electric Heat in all heating zones

While comparisons are possible for all heating zones for most heating systems, as noted below, the comparisons for heating zone 1 are more robust than heating zones 2 and 3. The comparison for each of these equipment types is described below and in more detail in the team's UEC Summary workbook.

Air Source Heat Pumps. For ASHPs, Figure 2 compares the model estimates to the RBSA 2011 and RBSA 2016 billing data,[30] as well as billing data from the 2005 Heat Pump Installation Practices Study.[31] The modeled UEC results for heating zones 1 and 2 align reasonably well with the available empirical data, although they are slightly lower (on average) than the measured data (which represents a mix of ASHP efficiencies). There are a number of possible explanations for the slightly lower modeled UECs, including house size differences or other normalization issues. The alignment between the model estimates and the empirical data in heating zone 3 is expected to be unreliable due to the low sample size and is, therefore, not shown. In heating zone 3, the team is relying on the calibrated SEEM model to adjust consumption by climate and believes that data to be more reliable than the limited empirical estimates.[32]

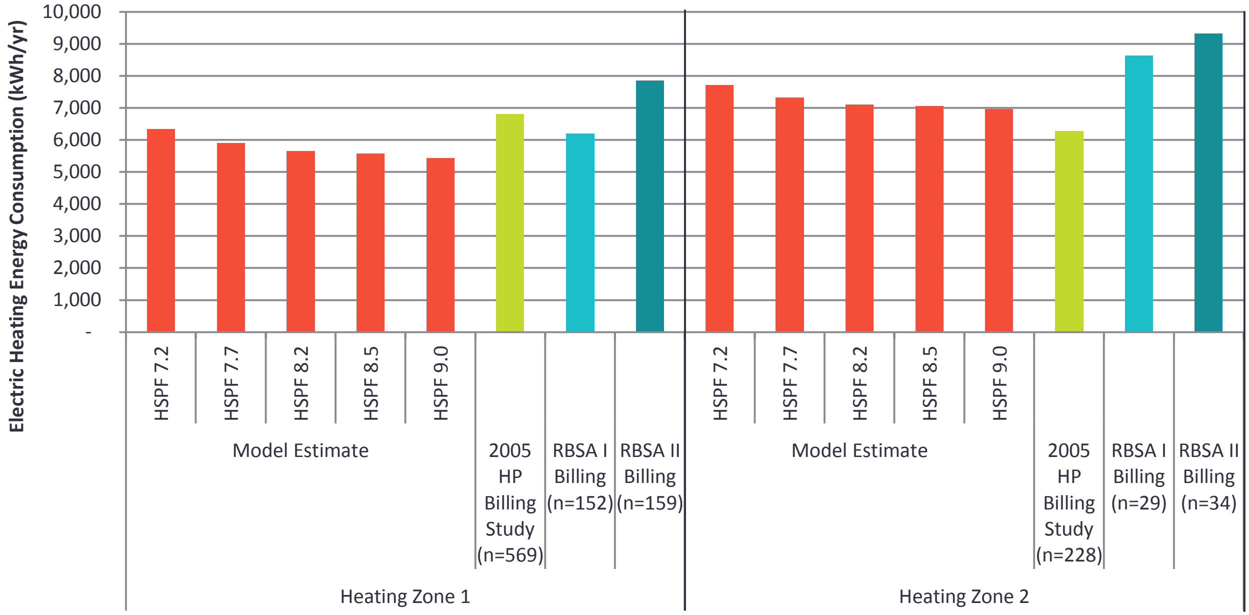
[29] The SEEM calibration is only applicable to certain heating systems and house types, requires certain SEEM inputs to match the original calibration (e.g., thermostat set points), and the application of calibration factors need to match calibration (e.g., estimation of u_o). Note that the team adjusted the ASHP control parameters from what was originally modeled in the RTF calibration to better account for the impact of CC&S in the model. The team subsequently adjusted the calibration factor for ASHPs to account for this. See the UEC Summary workbook for more information.

[30] The RBSA 2016 billing data is available through the RTF SEEM calibration work based on RBSA 2016.

[31] Baylon, David. et. al. "Final Report: Analysis of Heat Pump Installation Practices and Performance." Ecotope and Stellar Processes. December 2005. https://ecotope-publications-database.ecotope.com/2005_002_AnalysisHeatPumpInstallation.pdf

[32] Note, this approach is similar to the approach taken by the RTF in assigning the SEEM Calibration factors initially.

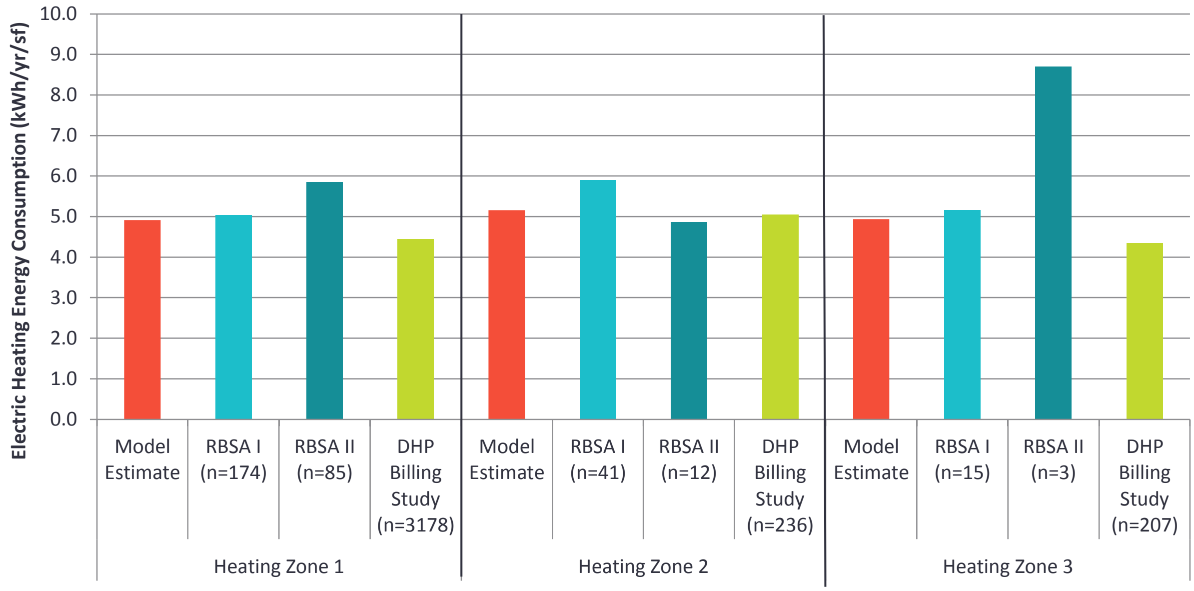
Figure 2. Comparison of ASHP UECs in the Model to Empirical Data from the RBSA 2011, RBSA 2016, and the 2005 Heat Pump Study



Note: RBSA I refers to RBSA 2011 and RBSA II refers to RBSA 2016

Electric Zonal. For electric zonal heat, the model estimates match well with RBSA 2011 in all heating zones, especially when normalized by square footage, as shown in Figure 3. Energy use per home for the model is somewhat lower than RBSA 2016 on a per square foot basis, potentially due to the small home sizes in RBSA 2016. In heating zone 3, the RBSA 2016 estimate is much higher than the model result or other estimates from RBSA 2011 and the DHP Billing Study. However, this difference is not significant due to the small sample size in RBSA 2016 (n=3).

Figure 3. Comparison of Electric Zonal UECs in the Model to Empirical Data from RBSA 2011, RBSA 2016, and the DHP Billing Study[33] on a Normalized Basis (kWh/yr/square footage of conditioned floor area)

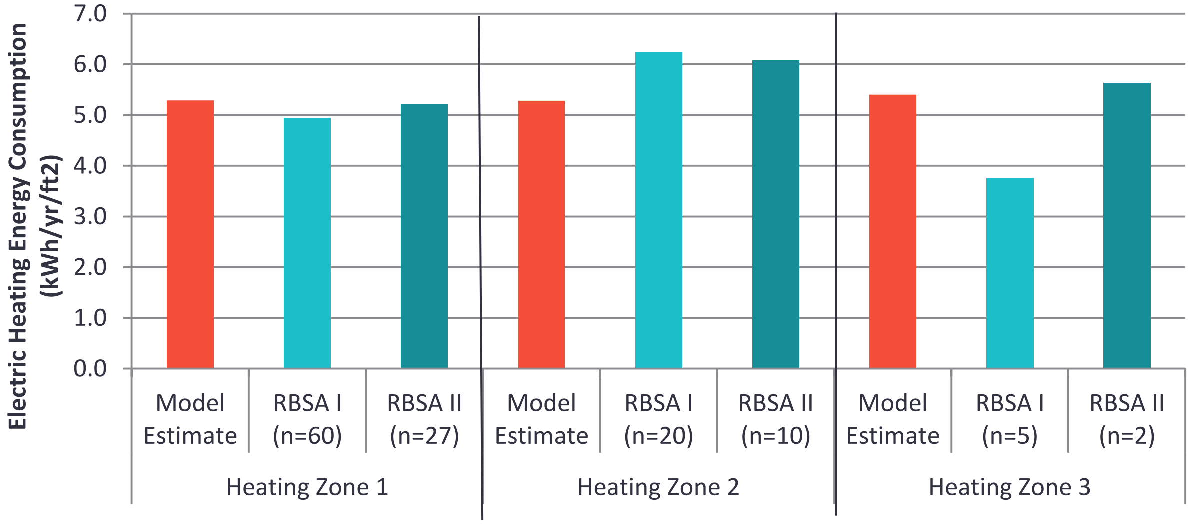


Note: RBSA I refers to RBSA 2011 and RBSA II refers to RBSA 2016

[33] Baylon et al. "Ductless Heat Pump Impact & Process Evaluation: Field Metering Report." Ecotope. May 2012. https://neea.org/resources/ductless-heat-pump-impact-process-evaluation-field-metering-report.

Electric Forced Air Furnace. For forced air furnaces, the model results match well with RBSA 2011 and 2016 in heating zone 1, especially when the results are normalized for conditioned floor area, similar to electric zonal. In heating zones 2 and 3, limited sample sizes make comparison less reliable, although the values still appear reasonable. Figure 4 displays these results.

Figure 4. Comparison of Electric Forced Air Furnace UECs in the Model to Empirical Data from RBSA 2011 and RBSA 2016 on a Normalized Basis (kWh/yr/square footage of conditioned floor area)

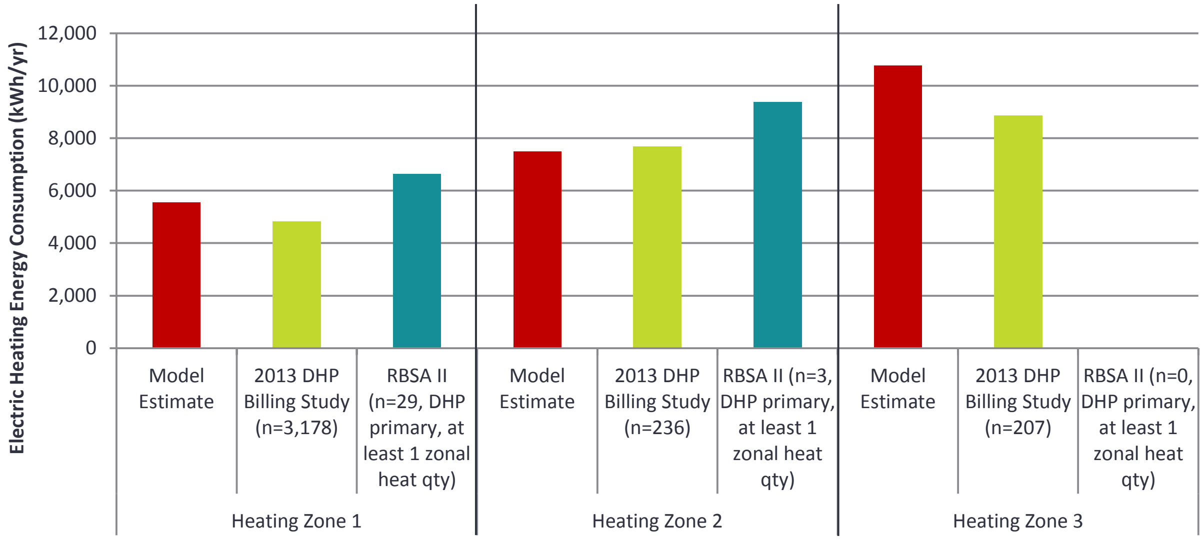


Note: RBSA I refers to RBSA 2011 and RBSA II refers to RBSA 2016

Ductless Heat Pumps. For DHPs with zonal electric heat in heating zone 1, as shown in Figure 5, the model estimates fall neatly between both empirical data sources. In heating zone 2, the estimate also aligns well with the 2013 DHP Billing Study. In heating zone 3, the modeled UEC is higher than the DHP billing study estimate, however heating zone 3 is particularly challenging to model due to supplemental fuel usage and variability in how the DHP systems were controlled, with respect to the existing electric zonal systems.[34]

[34] The team also looked into using data from additional studies (the 2012 Field Metering Study and the 2018 BPA/Navigant Impact Evaluation) but determined that those studies were not applicable or granular enough to include here.

Figure 5. Comparison of Ductless Heat Pump with Zonal Electric UECs in the Model to Empirical Data from 2013 DHP Billing Study and RBSA 2016 on an Absolute Basis (kWh/yr)



Note: RBSA II refers to RBSA 2016

Based on these comparisons, the team determined that the calibrated SEEM results were reliable and agreed with the available empirical data as well as could be expected. In addition, the team notes that the inputs to the SEEM models were developed based on the best available data and consistent with data and methodologies used in other regional programs, including the Seventh Plan and RTF measures. As such, the team prefers not to change key assumptions or methodologies that have been vetted within the region without significant reason to do so.

Step 3. Apply Adjusted SEEM Simulations to Other Cells

Based on the calibrated SEEM results, the research team also created UECs for all other technologies and climate zones that are able to be modeled in SEEM, including:

- Gas forced air furnaces (electric fan energy only)
- Ground source heat pumps
- Central air conditioners
- Whole-home ductless heat pump (referred to as "Full DHP" in the model)

These SEEM estimates are deemed to be reliable and consistent with the validated SEEM models but are more uncertain because no significant empirical data is available to compare the consumption estimates. However, the method for generating the UECs (based on SEEM and relevant inputs) is consistent with the Seventh Plan and regional program savings estimates and, therefore, any uncertainty that exists is not unique to BPA's model.

Step 4. Accounting for Factors that cannot be Modeled in SEEM

There are also several HVAC equipment types and non-equipment factors that cannot be reliably modeled in SEEM but are expected to contribute to or impact total residential HVAC energy consumption. These factors include zonal cooling technologies, DHP with eFAF, non-electric zonal heating technologies, PTHPs (which are primarily installed in multifamily buildings), evaporative coolers, and thermostats. To capture these HVAC technologies, the research team made adjustments to the SEEM results as summarized in Table 11 and Table 12. These adjustments are, to the extent possible, also based on empirical data, especially for important HVAC technologies that have a larger impact on regional consumption and savings. These include DHP with eFAF and thermostats, as discussed below.

Preparation of UEC estimates for other technologies, which are less common or less-well-characterized zonal heating and cooling technologies, are based on engineering judgement informed by any available data, as summarized in Table 11. These UEC estimates are clearly the most uncertain, but mostly pertain to HVAC equipment with low market share and which do not meaningfully contribute to total market savings or Momentum Savings. For that reason, they do not significantly impact the overall uncertainty in the model results.

Table 11. Summary of Method for Determining UECs for HVAC Equipment not Compatible with SEEM

HVAC Technology	Method for Estimating UEC	Basis
DHP with Electric Forced Air Furnace	Model as fixed savings amount subtracted from SEEM eFAF result, consistent with RTF approach for these measures[35]	Empirical data
Zonal Cooling (RAC/PAC/PTAC)	Scale DHP result based on relative efficiency of RAC/PAC/PTAC compared to DHP, as well as assumed lower usage due to temporary nature of appliance (1.75 x DHP UEC)	Engineering judgment
Non-electric Zonal Heating Equipment	Modeled as 0.50 UEC of gas FAF to account for pumps (associated with boiler), fans, or any ancillary electrical consumption.	Engineering judgment
Packaged Terminal Heat Pump	Model as equivalent to DHP energy consumption because these technologies have similar COPs.	Engineering judgment
Evaporative Coolers	Model as 0.25 of Zonal Cooling UEC, based on literature citing evaporative coolers can save 75% over RAC/PAC.[36]	Engineering judgment

Thermostats. Average annual energy use is expected to decrease as saturation of advanced smart thermostats increase. The research team modeled the energy impact from specific advanced smart thermostats consistent with the RTF savings estimates for connected thermostats, which are shown in Table 12 below. The team based this assumption on the results of a market study conducted by BPA,[37] which found that only specific thermostats with certain features (referred to as advanced smart thermostats) consistently save energy. BPA's research found that the RTF connected thermostat measure relies on the best available data to inform its savings estimates. Additionally, the BPA research found that, although the RTF connected thermostat definition differs slightly from the definition of advanced smart thermostat established by BPA and referenced in this model, all studies referenced in the RTF analysis are advanced smart thermostats, as defined by BPA.

[35] See https://rtf.nwcouncil.org/measure/ductless-heat-pump-forced-air-furnace-sf-and-mh and https://rtf.nwcouncil.org/measure/ductless-heat-pumps-multifamily

[36] https://phoenixmanufacturing.com/evaporative-cooling-how-it-works-and-why-it-saves-you-money/

[37] BPA Market Research Team. "TO17 – Smart Thermostat Market Characterization to Inform Market Modeling." Research Into Action and SBW Consulting. October 2018. https://www.bpa.gov/EE/Utility/Momentum-Savings/Documents/181016_BPA_Smart_Thermostats_Market_Characterization.pdf

Table 12. Summary of Advanced Smart Thermostat Savings

Equipment Types	Savings % of Home Heating Load (kWh/yr)	Notes
eFAF, GSHP, ASHP (w/ CCS, Heating, non-VCHP), ASHP (non-VCHP, Cooling), gFAF, CAC	6%	Original RTF values were only for eFAF and ASHP cooling. Applies to all ducted systems and ASHP w/CC&S (since higher savings rate for ASHPs accounts for compressor lock out, which is already accounted for in equipment with CC&S).
ASHP (w/o CC&S, Heating, non-VCHP)	14%	
Others (DHP, Zonal, VCHP, "Other" categories)	0%	Advanced smart thermostats are not currently compatible with zonal technologies; therefore the team assumes no savings.

Calculating Total Market Savings

The difference between the baseline energy consumption and the actual energy consumption determines total market savings in each year of the analysis period. Therefore, to estimate total market savings in any given year, the research team answered the following two questions:

- **Question 3a:** What was the energy use in the year the Seventh Plan was written?
- **Question 3b:** What was the energy use in the subsequent years?

The research team determined the energy consumption in each year by multiplying the number of units in each cell with each cell's UEC value. It is necessary to calculate total, regional HVAC energy consumption under two different scenarios and take their difference to calculate market savings:

- A **baseline scenario** that represents the equipment and stock efficiency mix in the year the Power Plan was written for all technologies.
- An **actual scenario** that represents the stock efficiency of each technology as it occurred and was observed in subsequent years after the Power Plan was written.

Structurally, these total energy calculations are identical, though the inputs change from scenario to scenario, as Equation 5 and Equation 6 show.

Equation 5. Regional HVAC Energy Consumption - Baseline Scenario

$$\text{Total Annual Energy Consumption}_{t,\ baseline}(\text{kWh/yr}) = \sum_{c}\left(UEC_{cv,\ baseline}(\text{kWh/yr}) \times MarketSize_{Cv,t,\ baseline}\right)$$

Equation 6. Regional HVAC Energy Consumption - Actual Scenario

$$\text{Total Annual Energy Consumption}_{t,\ actual}(\text{kWh/yr}) = \sum_{c}\left(UEC_{cv,actual}(\text{kWh/yr}) \times MarketSize_{Cv,t,\ actual}\right)$$

The total market size, in terms of overall number of dwelling units, is constant in Equation 5 and Equation 6, so the only driver for total market savings is changes in the saturation of different efficient technologies in the baseline and actual scenarios. In other words, the baseline and actual scenarios reflect the same assumptions around the number of dwelling units in the stock in each year, but they reflect different assumptions about the mix of HVAC equipment and non-equipment factors in the stock.

Question 3a: What was the energy use in the year the Seventh Plan was written?

The research team uses the Seventh Plan baseline for the model baseline. The Council describes its Seventh Plan describes as follows[38]:

"Conditions of the electricity-using buildings, systems, and devices at the start of the plan....

For new and replacement equipment, baseline conditions are the more efficient of either (1) minimum applicable code or standard or (2) market conditions at the start of the planning period."

In the model, the baseline represents how the stock of equipment would have **most likely changed** in lieu of program and associated momentum activity. For most technologies, these means frozen efficiency of product flow in the year the Power Plan was written (2015). However, there are two cases where the assumption of frozen product flow is adjusted (both in the Seventh Plan baseline and the model):

- Updated product flow to account for current or new federal standards in the analysis period; and
- No new energy efficiency measures are implemented in the baseline. (i.e., stock saturation is held constant at 2015. This applies to advanced smart thermostats and DHPs.)

The specific baselines described in the Plan and implemented in the model are summarized in Table 13 and described in more detail in the Baseline Summary workbook. In Table 13 the team differentiates measures that employ a static stock (pre-conditions) baseline versus a current practice baseline. Note that the "Model Implementation" column simply provides details on how the Seventh Plan assumptions were translated into model inputs and assumptions, not deviations from the Seventh Plan assumptions; the team has implemented the Seventh Plan baseline directly in the model.

[38] https://www.nwcouncil.org/reports/appendix-g-conservation-resources-and-direct-application-renewables, pg 8.

Table 13. Summary of Baseline in the Seventh Power Plan and Implementation in the Model

Seventh Power Plan Res HVAC Measures	Seventh Plan Baseline Summary	Model Implementation Notes
ASHPs - Conversions	**Static stock (pre-conditions) baseline** based on RBSA 2011; savings based on eFAF baseline with baseline mix of cooling techs (for cooling)	Hold saturation of eFAF constant in 2015 (no conversions), different saturations for existing and new construction (based on Seventh Plan assumptions and RBSA penetration); allocate "additional" ASHP to eFAF with cooling mix in RBSA 2011
ASHPs - Upgrades	**Current practice baseline** (market average of ASHP efficiency levels) of 8.5 HSPF based on RTF analysis.[39]	Hold efficiency constant at 2015 levels (no upgrades)
DHP added to Electric Zonal	**Static stock (pre-conditions) baseline** based on adding DHP to existing HVAC system; savings based on electric zonal with baseline mix of cooling technologies	No implementation of DHP beyond that already in the stock in 2015 (freeze stock saturation); allocate "additional" DHP to Zonal electric with cooling mix in RBSA 2011
DHP added to Electric FAF	**Static stock (pre-conditions) baseline** based on adding DHP to existing HVAC system; no cooling savings estimated due to difficulty with RAC/CAC interaction	No implementation of DHP beyond that already in the stock in 2015 (freeze stock saturation); allocate "additional" DHP to eFAF with cooling mix in RBSA 2011
GSHP	**Static stock (pre-conditions) baseline** based on conversion from ASHP (HSPF 9.0)	No increase in GSHP stock; freeze 2015 GSHP stock saturation
Weatherization (SF, MH and Low-rise MF only)	**Static stock (pre-conditions) baseline** based on insulation, fenestration, and infiltration parameters per RBSA 2011.	100% "As Is" shell per RBSA 2011: applies to mid-rise and high-rise MF also
Duct Sealing	**Static stock (pre-conditions) baseline** based on RBSA 2011 duct sealing levels	Model as 100% "As Is" ducts per RBSA 2011
Thermostats	**Static stock (pre-conditions) baseline** of "existing" thermostat mix (<1% penetration)	Model as constant saturation of advanced smart thermostats in 2015 based on interpolating RBSA 2011 and 2016

[39] From ResSFExistingHVAC_v4_2.xlsx. The RTF value is derived from a 2009 Energy Trust of Oregon study: "Air Source Heat Pump Market Transformation Model Development and Market Research." Prepared by Summit Blue Consulting, LLC. December 29, 2009.

CC&S	**Current practice baseline** based on "standard practice heat pump installation" as defined by RTF[40]	100% standard practice CC&S installation

The two technologies included in the model where there is no savings baseline specified in the Seventh Plan are: CACs and zonal cooling technologies (e.g., RAC, PAC, and PTAC). For these technologies the team assumed the baseline case had the same saturation in the stock as the actual case, so that the saturation of these cooling technologies would be the same between the baseline and actual case. This ensures that the presence or absence of cooling does not result in differences in regional electric consumption between the baseline and actual scenario. For CAC, the team freezes product flow (sales) in 2015, consistent with the intent of the Seventh Plan stated above. For zonal cooling technologies, the team is not modeling multiple efficiency levels, so no assumptions regarding efficiency distribution are required.

The research team has also held the saturation of gas versus electric technologies consistent between the baseline and actual scenario, to ensure that changes in fuels (e.g., the conversion from a gas furnace to an electric ducted system, or vice versa) is not a source of market savings. The Council does not treat fuel conversions as energy efficiency; the model results are aligned with that position.

Question 3b. What was the energy use in the subsequent years?

Energy consumption in the years since the Seventh Plan described the actual scenario, or what happened in the market during the Action Plan period (2016-2021). In the actual scenario, the stock saturations and efficiency mixes of HVAC technologies and non-equipment factors vary due to energy-efficiency program activity and other market changes that occur over time. Therefore, in the model, the actual scenario stock and product flow saturations are allowed to vary over time, as defined by the available market data. The method for modeling market change and the market data used to inform these estimates for each technology/factor are described in Question 2.

Cumulative Savings

The total market savings in each plan year (2016-2021) is the difference between the baseline and actual case consumption in that year, as Equation 7 illustrates.

Equation 7: Total Market Savings in Each Year

$$TotalMarketSavings_N = (BaselineStockConsumption_N - ActualStockConsumption_N) \times BusbarFactor$$

Where:

N = analysis year

All UECs in the model and any available energy consumption data stem from calibrations to metered consumption at the home site. The team converted site-level metered market savings to savings at the

[40] From ResHeatingCoolingCommissioningControlsSizingSF_v3_6.xlsx. The RTF value is derived from a 2005 Ecotope Study: "Analysis of Heat Pump Installation Practices and Performance." Prepared for the Heat Pump Working Group by Ecotope. December, 2005.

generation source by applying a busbar factor (Equation 7) to account for transmission and distribution system losses. The team applies a busbar adjustment factor of 1.0749, based on a weighted average busbar adjustment analysis conducted by BPA.

The research team also notes that direct comparisons of stock energy consumption in any given year, as Equation 7 illustrates, yield **cumulative** energy savings (i.e., savings that include efficiency improvements in prior years). To calculate annual Momentum Savings (i.e., **first-year** savings in each year), the team calculates the difference in cumulative Momentum Savings from year-to-year, so that the model does not overestimate Momentum Savings based on accrued savings from prior years (Equation 8).

Equation 8: Annual Momentum Savings

$$FirstYearSavings_{N} = CumulativeSavings_{N} - CumulativeSavings_{N-1}$$

Where:

N = analysis year

Question 4: What are the program savings?

The final step in the Momentum Savings Analysis Framework corresponds to Question 4: What are the program savings? The actual energy consumption, described in Question 3, reflects total market energy consumption, including that associated with high-efficiency units. Some high-efficiency units receive program incentives or are associated with NEEA initiatives. Therefore, the last step in the Momentum Savings analysis involves subtracting all reported regional residential HVAC program savings from the total market savings calculated in Question 3. After subtracting the program savings, the remaining savings are regional Momentum Savings.

Calculating regional program savings is complex because different program-funders may use different baselines from which they calculate their program savings; not all programs use the RTF's savings values or the same data sources. Funders also structure their program values as average kWh *savings* per unit, while the Momentum Savings model calculates HVAC energy *consumption*.

Therefore, to accurately represent savings associated with regional program activity, the research team performed an analysis to true-up program savings against a single consistent baseline—the Seventh Power Plan baseline. This avoids double counting of Momentum Savings and program savings. The team's approach consisted, in general, of reviewing any sources of regional program savings activity and then calculating the number of units incented by programs in each of the model cells described in Question 3. The data sources and methodology the team employed are described in more detail in the following sections.

Sources of Regional Program Savings

In order to quantify regional program savings and account for it in the model, the team must first identify all sources of utility program activity. Utility program activity includes all incentives provided by utility-funded programs in the Northwest relevant to the residential HVAC market, including both HVAC equipment and envelope measures. These programs are run by several entities, which include BPA's public customer utilities, private investor-owned utilities (IOUs), Energy Trust of Oregon, and NEEA.

The research team primarily relies on the Council's annual Regional Conservation Progress (RCP) survey and report to describe regional utility program activity. The RCP survey and report provide a broad snapshot of regional program activity, which assesses progress toward Seventh Plan goals. The RCP reports the region's energy efficiency savings for each funding source (BPA, IOUs, Mid-C, and NEEA programs) and by specific Technology, Application, or Practice (TAP) categories. Table 14 lists the technologies currently reported in the RCP data that are available to the research team and relevant to the residential HVAC market.

Table 14. RCP Residential HVAC Savings Categories and Technologies (2016 & 2017)

Category	Technology, Application, or Practice (TAP)	Total Regional Program Savings (aMW @ Busbar)	
		2016	2017
Envelope	Air Sealing	0.10	0.17
	Windows	1.44	1.27
	Insulation	1.49	0.70
HVAC System	Air Conditioners	0.12	0.25
	ASHPs with Duct Sealing	0.03	0.00
	ASHPs without Duct Sealing	2.08	1.70
	Variable Speed Heat Pumps without Duct Sealing	0.24	0.39
	CC&S	0.18	0.18
	Duct Sealing	0.73	0.57
	Ductless Heat Pumps*	4.26	4.86
	GSHPs with Duct Sealing	0.03	0.01
	GSHPs without Duct Sealing	0.12	0.07
	Thermostats	0.05	0.25
	Interactive HVAC System Improvements	0.01	0.00
Unknown	Unknown	0.40	0.53

* Note, DHP savings reflect the "Total Regional Savings" submitted by NEEA to the sectors for which NEEA tracks savings. This does not include shipments of DHP units to new construction and multifamily.

The RCP only reports total energy savings per TAP category; they do not include efficiency assumptions or total units. In addition, the TAPs identified in RCP are not granular enough to understand or compare the baseline or category measure detail to the model framework and assumptions.

The team also relies on data from BPA's IS2.0 database to break down the RCP data into more granular segments that better match the team's UEC definitions. This database is a central repository of detailed program savings information that member utilities report to BPA: detailed measure information, claimed energy savings, and unit counts. The research team used export tables from the BPA IS2.0 database to disaggregate the RCP TAP categories into more granular segments that better map to the team's UEC and cell definition, assuming that BPA activity is representative of total regional activity.[41] To test this assumption, the team also analyzed the percentage of regional activity reported in the RCP that is also reflected in the BPA IS2.0 dataset.[42] The team's analysis methodology is described below in the Program Savings Methodology section and in more detail in the Program Savings workbook.

NEEA Initiatives

The program activity reported in the RCP also includes savings from NEEA's Initiatives. However, NEEA also tracks market savings for some of its initiatives, so it is important consider how NEEA's Initiative saving models relate to BPA's Momentum Savings model. The research team accounted for savings from the NEEA's active residential DHP initiative, RAC and PACs included in NEEA's Retail Product Portfolio (RPP), and NEEA's Code and above-code programs in the regional program savings analysis.

Specifically, for NEEA's DHP Initiative, NEEA actively tracks distributor DHP sales within the region and reports total market DHP savings for certain applications to the RCP. However, NEEA only reports savings for certain DHP applications—specifically retrofit DHPs in single family and manufactured homes that are installed in homes with existing zonal or electric forced air furnace systems. Conversely, the research team's model includes *all* DHP units that are sold in the region, including units that are sold into multifamily and new construction applications. NEEA's reported savings include only units within their Initiative areas, which are reflected in the RCP as "NEEA Alliance" savings and are treated equivalently to other utility-reported program savings in the model—they are not included in BPA's estimate of regional Momentum Savings. The remaining DHP units included in the research team's model that are not reflected in regional program activity, including NEEA Initiatives, are reported as regional Momentum Savings.

NEEA also reports savings for ENERGY STAR®-certified RACs and PACs as part of their RPP. However, the BPA Momentum Savings model does not track RAC or PAC efficiency variation. As a result, the model does not currently include any RAC or PAC market savings and the team does not account for NEEA's RPP-reported RAC/PAC savings, since there is no overlap. BPA could, in future updates, pursue adding market and potential Momentum Savings from RACs and PACs to the model, but left them out of this initial draft due to the uncertainty in the savings.

Finally, NEEA reports savings associated with NEEA's Certified Homes and Manufactured Homes programs, as well as building code improvements. These programs address more efficient new construction homes. The team modeled all new construction homes based on typical construction practices for new vintage homes, as captured in RBSA 2011 (for homes built since 2000), to avoid overlap with these programs. This represents the as-built stock of new vintage homes, without accounting for

[41] The team used BPA IS2.0 export tables, also referred to as the BOOM report, to characterize 2016 and 2017 savings recorded in BPA's database through May 2018.

[42] There is a small percentage of the BPA IS2.0 savings that were reported after the RCP's reporting date cutoff. These "post-reported" BPA savings were calculated and added to the total RCP savings by measure to avoid double counting these as Momentum Savings.

future code improvements or new homes programs. While this approach could slightly overstate consumption related to extremely efficient new homes, it is unlikely to have an impact on BPA's model results due to the small percentage of affected units. The team prefers this simpler approach, despite its slight conservatism, rather than attempting to estimate improvements from code and above-code programs that are already accounted for in other regional savings estimates.

Program Savings Methodology

In order to subtract program savings from total market savings, the two savings values must have a consistent baseline and calculation methodology. This section describes the team's approach to recalculating program savings to fit BPA's consumption modeling framework. The research team notes that this approach, at an aggregate level, yields a total program savings estimate similar to what the RCP reported.

The research team uses the same UECs and calculation methodology described in Question 3 for the total market baseline and actual scenario to account for the model's program savings on a consistent basis. The team treats program activity as a separate and equivalent scenario in the consumption model, where program activity saturations are equivalent to the baseline scenario saturations, except for where program activity has occurred.

To implement this approach, the team requires information on the number of efficient units delivered via programs, ideally at the same level of granularity the team used to derive the baseline and actual case consumption (i.e., by cell). However, as noted above, the RCP reported program savings represent all regional program activity, but only report total savings by general TAP category. Additionally, the RCP database does not provide unit quantity, which is critical to this analysis. The team developed assumptions based on BPA's more granular IS2.0 database to disaggregate the RCP-reported savings into more granular segments that better map to the model's cells and UECs, and to derive the unit quantity incented in each segment (i.e., cell). Specifically, using BPA's detailed measure reporting, the team takes the following steps:

1. Map each program measure to the applicable model cell or cells.[43]
2. Then, apply BPA total reported savings and number of units to derive an average "kWh savings per unit" for each specific program measure application and program savings segment.
3. Calculate the relative total savings for each specific measure application within a given RCP TAP category.
4. Translate the total RCP savings for each TAP to unit quantities per specific model cell based on the relative savings amount and savings per unit from the BPA data.

This process leverages the best available data as well as certain assumptions to obtain the level of detailed information needed to calculate regional utility program savings. For more detail on the

[43] In many cases, the BPA IS2.0 data is still not as granular as the model's cell definitions. For example, a particular measure category may apply to both new construction and existing homes or may not be differentiated by heating zone. In these cases, once the applicable "cells" are identified, the identified units are allocated to the cells based on the relative population of eligible homes within each of those cells for the program data segment. For example, if a given measure applied to ASHP upgrades in heating zones 1, 2, and 3. The program units would be allocated to heating zones 1, 2, and 3 based on the relative population of eligible homes in each heating zone.

program savings mapping and calculation, see the Program Savings workbook (and associated Envelope Savings workbook). To check the reasonableness of this approach, the team compared the BPA-derived per-unit savings values (from step 2 in the process described above) to the model-derived per-unit savings values (based on the UECs developed by the research team) and the per-unit savings calculated by the RTF. In all cases, the values were in alignment and any larger differences could be explained by logical differences in methodology or assumptions. For more details, see the "UEC Comparison" tab in the UEC Summary workbook.

Forecasting Program Savings Beyond 2017

After applying the methodology described above to estimate total program savings for 2016 and 2017, the team forecasted savings for the years 2018-2021 by holding the ratio of program savings to total market savings from year 2017 constant. The team's approach assumes that programs evolve with the market through time and capture a constant portion of available savings.

Model Results

Once the team has developed regional program savings estimates that align with the model methodology, the final step is to subtract all reported regional residential HVAC program savings from the total market savings calculated in Question 3. After subtracting these program savings, remaining savings are Momentum Savings, which are described in the following section.

At the time of this report's publication, the model provides draft results for 2016 and 2017, and forecasted results for 2018 through 2021. These results are the currently reviewed values, but are not yet final estimates of savings, since future model updates may improve these results. This section briefly describes the results from the research team's analysis. The team has provided BPA with the underlying model[44] and a workbook with a detailed extract of model results; both documents are available upon request.

The research team estimates 44.2 average megawatts[45] (aMW) of regional, residential HVAC market savings in 2016 and 2017 (see Table 15). Of that, the team estimates 18.5 aMW of regional, residential HVAC Momentum Savings in 2016 and 2017. These savings include all residential HVAC systems, as described in Question 1 of this document. The cumulative regional total for market savings and Momentum Savings over the Action Plan period of 2016-2021 is 119.1 aMW and 54.3 aMW, respectively.

[44] The team used Lumina Decision Systems' Analytica software (version 5.1) to develop the model. Lumina has a free, limited-functionality version of Analytica software available for download http://www.lumina.com/products/free101 that will allow read-only access to the model.

[45] 1 average megawatt = 8,760 megawatt hours

Table 15. Annual, Regional Residential HVAC Energy Savings Relative to Council 7th Power Plan Baseline (aMW at Busbar)

Savings Type	Currently Reviewed Values		Forecast Values				Total
	2016	2017	2018	2019	2020	2021	Total
Total Market Savings	22.1	21.1	20.8	19.5	18.0	17.6	119.1
Momentum Savings	8.6	9.9	9.8	9.2	8.5	8.3	54.3

Note: 2018-2021 are forecasts in which the team holds the ratio of Momentum Savings to total market savings constant.

Figure 6 and Figure 7 show the team's estimate of total market and Momentum Savings for the heating and cooling end uses. Over 90% of total market and Momentum savings comes from heating equipment.

Figure 6. Annual, Regional Total Market Savings by End Use

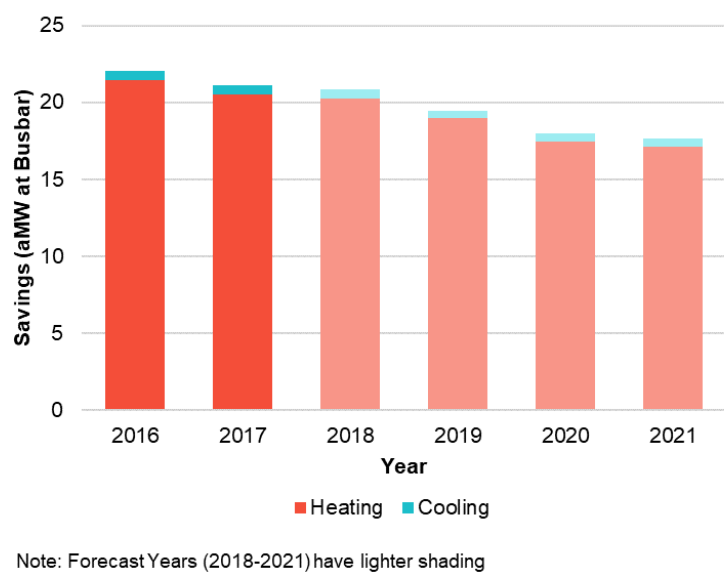
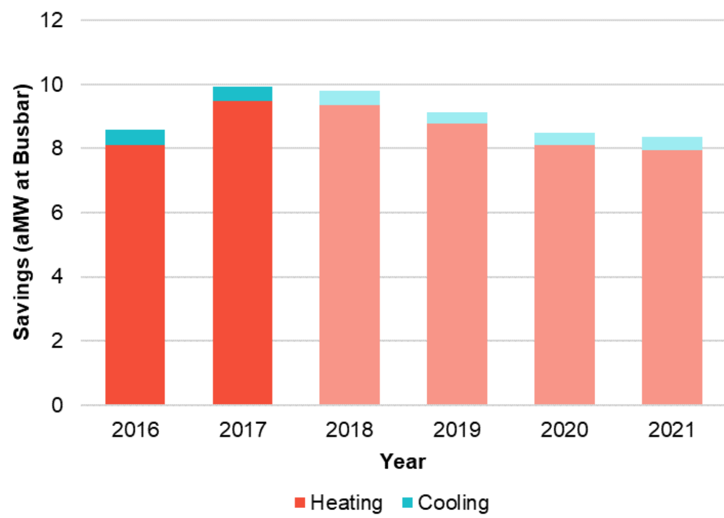


Figure 7. Annual, Regional Momentum Savings by End Use



Note: Forecast Years (2018-2021) have lighter shading

The forecasted results rely on three assumptions that the team will revisit and update as data become available:

- The efficiency mix of HVAC equipment sold in 2018-2021 is identical to 2017.
- The technology mix of HVAC equipment sold in 2018-2021 is identical to 2017.
- Program savings in 2018-2021 maintain 2017 levels, as a percent of total market savings.

The draft results and forecasts draw on the best available data, but still reflect uncertainty associated with those data sources, as described in the following section. BPA plans to update the model later in the Action Plan period when additional data become available. However, the team believes this model is an accurate and sound representation of regional HVAC stock, energy consumption, and market change over time.

Sensitivity Analysis

The team conducted a sensitivity analysis to quantify the impact on Momentum Savings for six key areas. This section describes the sensitivity analysis approach.

Sensitivity Analysis Approach

The team's Momentum Savings estimate relies on many data sources, each with its own level of uncertainty. Some model assumptions, like those derived from the RBSA, are subject to statistical uncertainty in that they involve sampling from a population of homes. Other assumptions, such as the advanced smart thermostat saturation, rely on the team's synthesis of data sources where statistical uncertainty is not known.

To analyze the effects these sources of uncertainty have on the model, the team developed and tested six sets of scenarios, each with specific sets of model inputs that represent uncertainty bounds. The analysis measured each input's effect on calculated Momentum Savings. This section describes the areas that the team considered in its sensitivity analysis:

- **Unit Energy Consumption.** The team's UEC estimates are subject to uncertainty in empirical inputs (billing analysis, SEEM, calibration), especially for less common technologies and less populous climate zones.
- **Product Flows in Sales Data.** The team noted product flow (annual sales) uncertainty for each HVAC technology based on its market research activities. There is substantial ASHP and DHP market activity and energy savings, so understanding the market size uncertainty impacts for these technologies is critical.
- **Efficiency Mix in Sales Data.** The team uses distributor sales data collected by NEEA to characterize the 2016 and 2017 ASHP and CAC systems efficiency mix. Although the team applied adjustments to improve representativeness, the efficiency mix observed in these data may not be representative of the entire region due to the low number of responders (i.e., extrapolation of smaller sample to region).
- **Building Shell Upgrades.** The team was unable to determine the saturation increase of homes with fully upgraded weatherization due to study methodology differences between the RBSA 2011 and RBSA 2016. The team wanted to assess how sensitive the Momentum Savings estimate would be if there were significant out-of-program regional weatherization activity.
- **Advanced Smart Thermostat Saturation.** Advanced smart thermostats are a significant contributor to market savings but are still an emerging technology without definitive data sources. At present, the team's assessment of the market is that saturation is low (4-5% of region). Furthermore, market saturation and product category definitions may evolve as new products continue to enter the market.
- **Advanced Smart Thermostat Energy Savings.** In addition to uncertainty in advanced smart thermostat regional quantity, regional advanced smart thermostat pilot program evaluation reports show a wide range of energy savings.

Sensitivity Analysis Results

The team tested each of the areas described above by creating test case scenarios and altering specific assumptions in its model. As noted in the results section above, the team estimates a total of 18.5 aMW of regional, residential HVAC Momentum Savings in 2016 and 2017. Table 16 shows how that Momentum Savings estimate would change if the team were to vary the specific assumptions noted for each sensitivity scenario.

Table 16. Sensitivity Analysis - Regional, Residential HVAC Momentum Savings

Scenario Description	Assumption	Low Momentum Savings (2016-2017 aMW at Busbar)	High Momentum Savings (2016-2017 aMW at Busbar)
Product Flows in Sales Data	Vary ASHP, DHP product flow by +/- 50% of market change*	3.2	34.3
Building Shell Upgrades	Vary saturation of building shell upgrades by +/- 50%	15.5	22.0
Efficiency Mix in Sales Data	Vary efficient sales of ASHP, CAC product by +/- 50%	17.4	20.2
Advanced Smart Thermostat Saturation	Vary saturation of advanced smart thermostats by +/- 50%	17.8	19.7
Advanced Smart Thermostat Savings	Vary energy savings from advanced smart thermostats by +/- 50%	17.9	19.7
UEC	Vary UEC for each technology by +/- 5% to 20%**	17.9	19.6

*Market change is the net increase in product flow between the team's Seventh Plan baseline and market scenarios.

** The team's technology-specific UEC variation follows:

- +/-5%: ASHP heating, eFAF, Zonal, DHP w/ Zonal heating
- +/-10%: DHP w eFAF heating, VCHP, GSHP, gFAF, AHSP cooling, CAC, DHP w/ Zonal cooling, DHP w/ eFAF cooling
- +/-20%: Full DHP heating, non-electric zonal heat, Full DHP cooling, PTHP cooling, PTAC, RAC

The team found that uncertainty in ASHP and DHP product flow could have the largest impact on regional Momentum Savings, with a range of approximately +/- 15 aMW. This means that the model is sensitive to variations in product flow. However, the model methodology mitigates this sensitivity: the model is calibrated to align with the results of RBSA 2011 and RBSA 2016. This provides two "anchor points" for the stock to ensure that the model's estimates align with the best available empirical data on building stock in the region. Due to the slow turnover cycle for HVAC equipment (as compared to lighting, for example, which has shorter measure lives), this alignment means the model's estimates of stock saturations and efficiency mixes will not diverge too far from measured results recorded in RBSA 2016.

Each of the remaining scenarios have a Momentum Savings impact of approximately +/- 1-2 aMW annually.[46] This means the model is not highly sensitive to any of the other sources of uncertainty examined through the sensitivity analysis. This finding suggests a potential substantial amount of Momentum Savings even with worst-case assumptions for each of these scenarios. It also suggests that if the team's market scenario assumptions are conservative, improving these assumptions would result in a modest Momentum Savings estimate increase.

Future Model Updates

Because the Action Plan period is ongoing at the time of this report, BPA intends to update this model later in the Action Plan period as more data become available. Over the course of this model build, the research team explored dozens of sources and conducted several concurrent market research studies to gather more information on the residential HVAC market. While each of these studies and sources provided valuable information to inform the market model, the research team has identified several topics that will allow the team to fill data gaps and confirm assumptions.

Ongoing Sales Data Collection

NEEA and BPA are continuing to collect HVAC distributors sales data on an annual basis. The team recommends continued use of this important data in future model updates. This will be important for updating future years 2018-2021 with actual data, as the team's current estimates for this timeframe at the time this report was published were forecasts. Further, BPA should review future data collection results to determine if improved 2016 and 2017 equipment sales estimates are possible. In its ongoing annual sales data collection efforts, NEEA may recruit new distributors to participate and ask them to provide sales going back to 2016. When analyzed in the context of the latest market intelligence to inform their accurate implementation in the model, these updates could improve the model's product flow accuracy. This input has a large impact on model results, so continued efforts to collect and analyze regional equipment sales data and market intelligence will be beneficial.

Non-Equipment Measures Outside Programs

The team's weatherization and CC&S model assumptions are conservative. BPA should revisit these assumptions when new data becomes available, or through additional research.

BPA is conducting a concurrent research effort on residential homes with recently installed ASHPs to gather information about the CC&S current practice baseline. The team recommends that BPA incorporate the study's results in future model updates. Potential uses include improving estimates of CC&S activity outside of programs and improving ASHP installation context stock-turnover assumptions.

[46] To confirm that the modeled sensitivity results were reasonable, the team used a savings rate analysis to independently validate the model results shown in Table 16. This analysis consisted of estimating the variation in the results associated with each scenario outside of the model, using estimates of the savings rate and change in number of units. This analysis confirmed that the modeled sensitivity results were reasonable.

The team recommends conducting additional weatherization research to determine whether significant and measurable activity is occurring outside of programs. As described below, the team recommends examining the RBSA 2016 data and the results of the RTF's assessment of differences between 2011 and 2016 measurement methods. These efforts could uncover additional market savings not currently included in the model.

Further Application of RBSA 2016 Data

At the time this report was written, the RTF was working on completing a SEEM calibration based on the RBSA 2016 billing data. Once this SEEM calibration is complete, the team recommends reviewing those data to determine if either the Phase I or Phase II calibration factors have changed significantly enough to warrant updating in the model. These calibration factors capture the impact of tertiary factors like secondary heating/cooling and occupancy. These updates could improve UEC Action Plan period accuracy if they have changed since the 2011 study.

Another element of the RTF's SEEM calibration effort is to map RBSA 2016 homes to SEEM inputs. The team also recommends considering a model update to include these homes once the calibration is complete. However, the team does not expect the RBSA 2016 home characteristics to be significantly different from the RBSA 2011 sample, and therefore would not expect them to significantly affect the results.

Finally, the RTF is also reviewing the RBSA 2016 insulation measurements, in comparison to RBSA 2011, to better understand how to compare the two values and address any inconsistencies found in the data. After the RTF completes its assessment, the team recommends revisiting this data to determine whether weatherization measures (windows, insulation, and air sealing) could be disaggregated and more accurately characterized in the model. This could result in weatherization activity identification outside of programs but may be uncertain due to remaining data collection methodological differences.

Adding RAC and PAC Savings to the Model

In this version of the model, the team included only one efficiency level for RACs and PACs. This allows the model to track increases in cooling penetration and energy consumption over the analysis period but does not allow for the model to track any change in the penetration of more efficient RACs and PACs. The research team elected to do this due to the uncertainty associated with the UECs for RACs and PACs, as discussed in Question 3. NEEA's RPP also tracks the installation of more efficient, ENERGY STAR-certified RACs and PACs, although their program may not cover the entire market of RACs and PACs installed in residential units in the Pacific Northwest. In the future, BPA could choose to explore the potential for additional market or Momentum Savings from more efficient RACs and PACs in the model, in conjunction with collecting better information to verify the energy consumption of this equipment.