BONNEVILLE POWER ADMINISTRATION

Residential HVAC Northwest Market Model

AUGUST 2022

EXECUTIVE SUMMARY

Quantifying the Northwest Residential HVAC Market

Space heating and cooling represents the largest proportion of residential electric energy consumption in the Northwest. As the region experiences more extreme weather events, residential heating, ventilation, and air conditioning (HVAC) energy consumption has changed as well, with increased prevalence of cooling, shifts in heating technologies, and improvements to HVAC and building shell efficiency.

This report contains the methodology and findings from the Bonneville Power Administration's (BPA) modeling of the Northwest residential HVAC market between 2016 and 2021, corresponding with the Northwest Power and Conservation Council's (the Council) Seventh Power Plan's (Seventh Plan) action plan period.

BPA's market model has three primary goals:

1. **Understand** how the stock of residential HVAC technologies and factors that impact HVAC consumption changed between 2015 and 2021.
2. **Estimate** residential HVAC electric energy consumption over the same period.
3. **Calculate** residential HVAC electric Momentum Savings from 2016 to 2021.

The rising demand for cooling and the increase in new construction homes in the region has increased Northwest residential HVAC electric energy consumption every year since 2015. Consumption grew 7%, or 169 average megawatts (aMW), between 2015 and 2021. Our research shows that increase would have doubled were it not for the installation of efficient heating and cooling technologies like air source heat pumps (ASHP) and ductless heat pumps (DHP), upgrades to building shell, and the installation of energy-saving smart thermostats that occurred from 2015 to 2021. Together, these energy efficiency activities produced 140 aMW of total regional market savings over the past six years. Momentum Savings, which are cost-effective energy savings above the Council's Seventh Plan frozen baseline not directly paid for by regional utility programs or part of the Northwest Energy Efficiency Alliance's (NEEA) net market effects, account for 84 aMW of the total market savings.

QUICK HITS

2,696 average megawatts (aMW) of total Northwest residential HVAC consumption in 2021

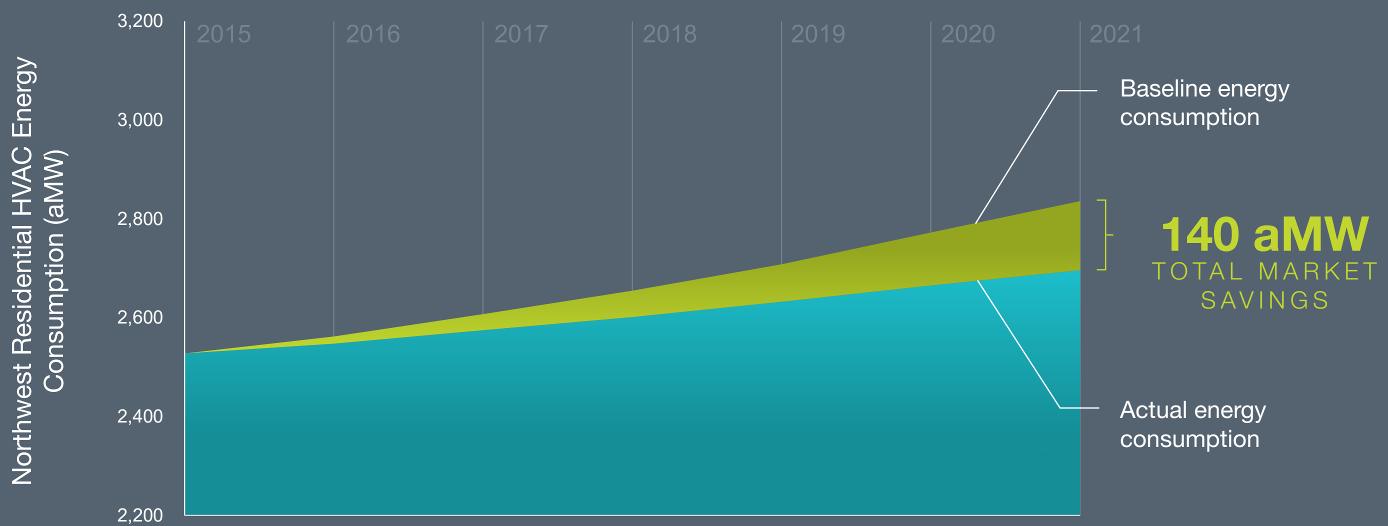
7% increase in residential HVAC consumption since 2015

46% of 2021 Northwest homes have whole-home cooling systems

26% of 2021 Northwest homes use a heat pump technology for primary heating

140 aMW total market savings

84 aMW Momentum Savings



MODEL METHODOLOGY

Leveraging the Best Available Data

The Northwest residential HVAC market is changing rapidly, so BPA sought to characterize this market's technology trends and electric energy consumption with an analytical market model. The model uses numerous regional best available data sources, including NEEA's annually collected full-category HVAC sales data, confidential annual thermostat shipments data from thermostat manufacturers, annual insulation sales volume from Principia, the Residential Building Stock Assessments (RBSA), the Regional Technical Forum's (RTF) measure research and savings estimates, the Council's Regional Conservation Progress reports, and Home Innovation Research Labs' new construction data.

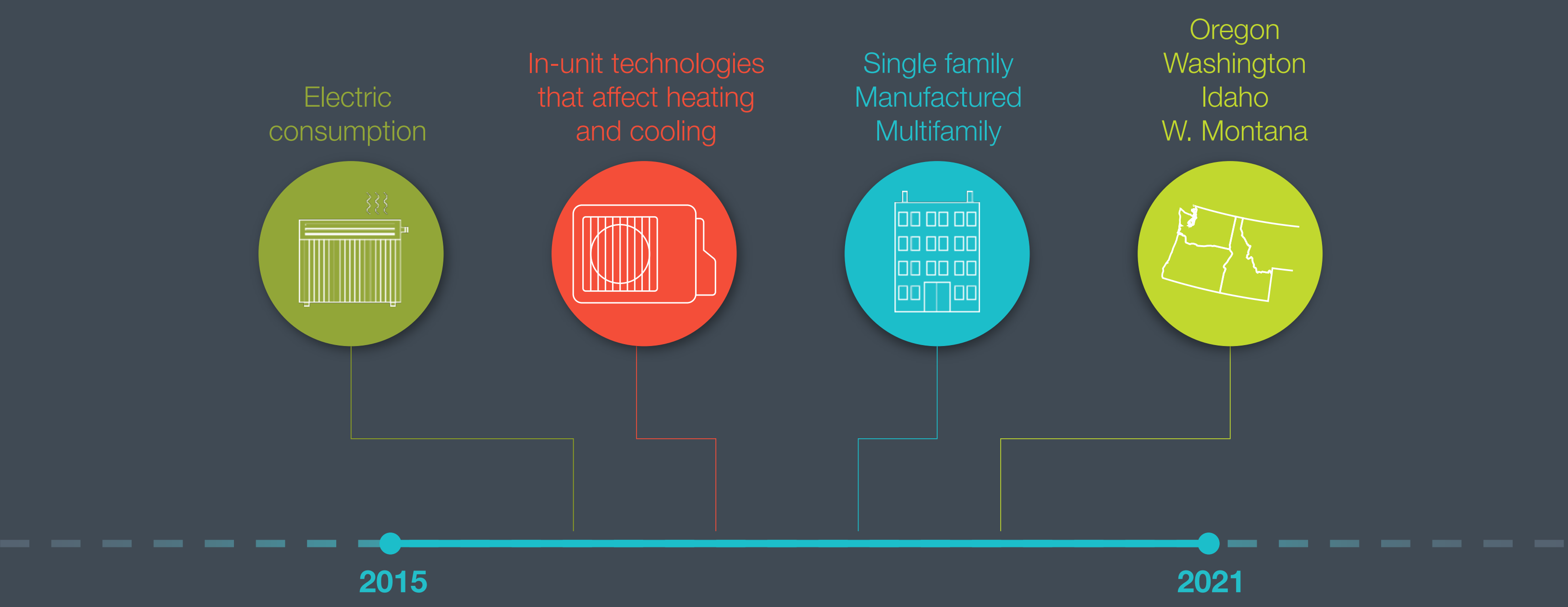
BPA also engaged directly with a panel of regional industry experts and stakeholders representing the Council, the RTF, and NEEA to provide feedback on the model's methods, inputs, and results throughout the modeling process.

BPA and Cadeo (the research team) designed the market model to comprehensively track the Northwest's stock of residential HVAC technologies and the non-equipment factors that impact electric heating and cooling energy consumption. The model includes in-unit technologies that affect electric heating and cooling in single-family homes, manufactured homes, and multifamily units with in-unit heating installed in Oregon, Washington, Idaho, and Western Montana.

Several independent market research studies commissioned by BPA also supplement the model's inputs:

- 2018 Smart Thermostat Market Characterization
- 2018 HVAC Installer Survey
- 2019 Air Source Heat Pump Commissioning, Controls & Sizing Baseline Field Study Report
- 2020 Air Conditioning, Heating, Refrigerating (AHR) Expo Findings
- 2021 Insulation Installer Survey
- 2021 HVAC Market Actor Interviews

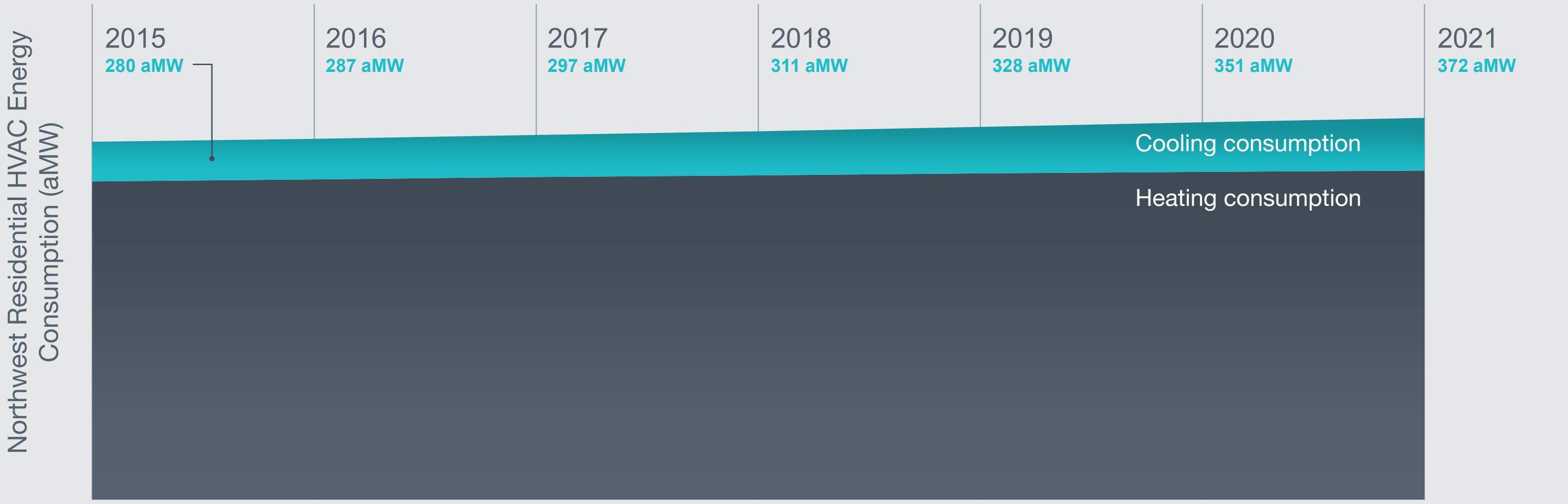
Model Scope



RESULTS

Northwest Homes Added Significant Cooling

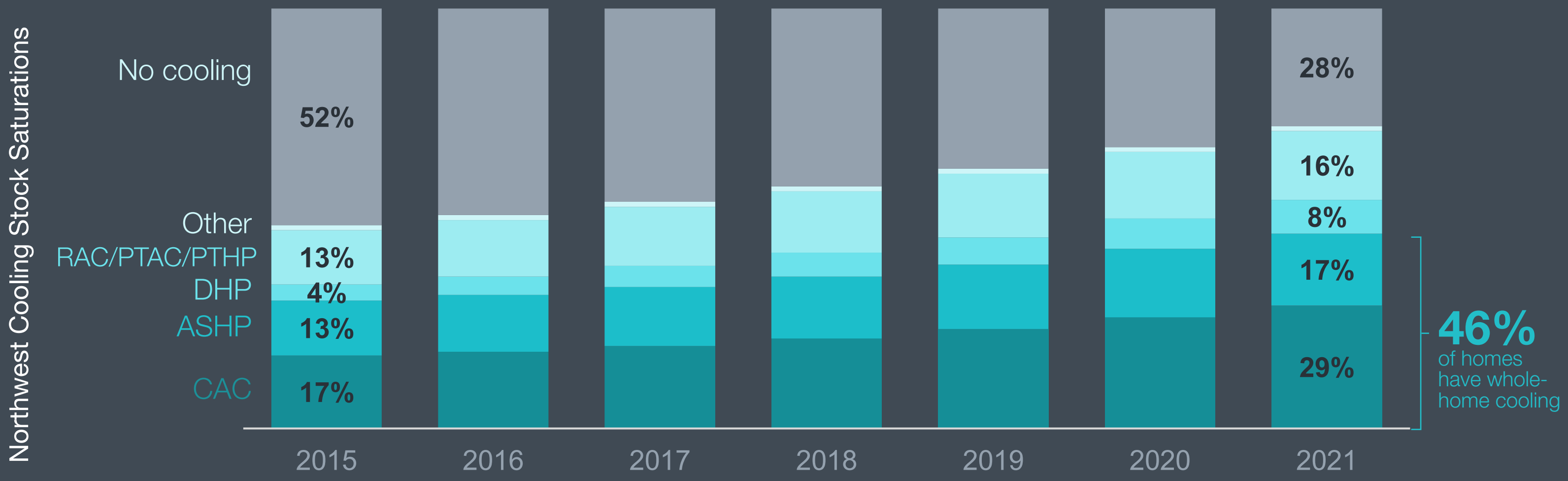
The increase in consumption comes from added cooling



Much of the growth in Northwest residential electric HVAC consumption comes from the rising prevalence of cooling in homes. Regional cooling consumption increased by 33% between 2015 and 2021. Northwest homes went from 48% with a form of cooling (including whole-home cooling and zonal cooling like room or portable air conditioners) in 2015 to 72% in 2021.

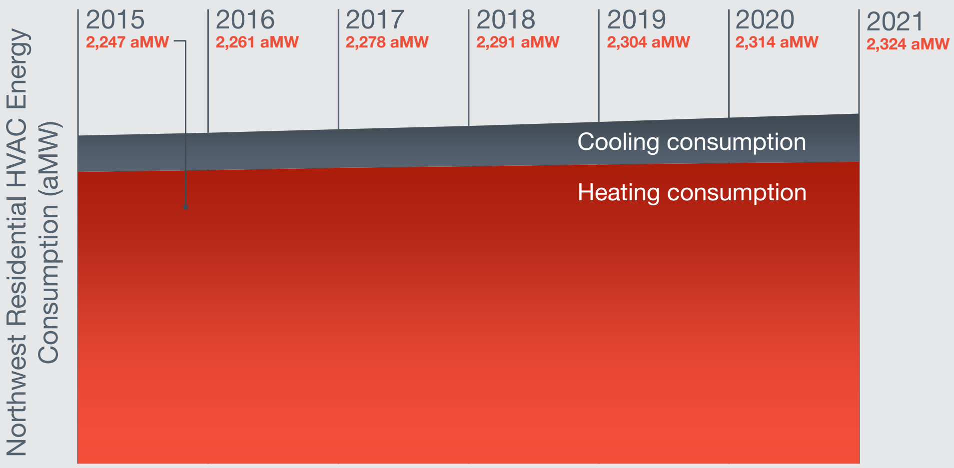
Fortunately, the efficiency mix of new cooling equipment entering the region has improved year-over-year, which helped offset consumption increases. The market average efficiency of central air conditioners (CAC) improved from a Seasonal Energy Efficiency Ratio (SEER) of 14 in 2015 to SEER 14.5 in 2021. With CAC federal standards set at SEER2 13.4 in 2023 (equivalent of SEER 14), the region has already surpassed the future standard.

ASHP saw efficiency improvements as well, with the market average increasing from SEER 14.8 in 2015 to SEER 15.5 in 2021, which also surpasses the future federal standard. These efficiency gains come from a growing share of variable capacity heat pump (VCHP) and single- and two-stage SEER 18+ ASHP sales, which make up 30% of ASHP units sold in 2021.



Residential Electric Heating Consumption Holds Flat as Heat Pump Stock Grows

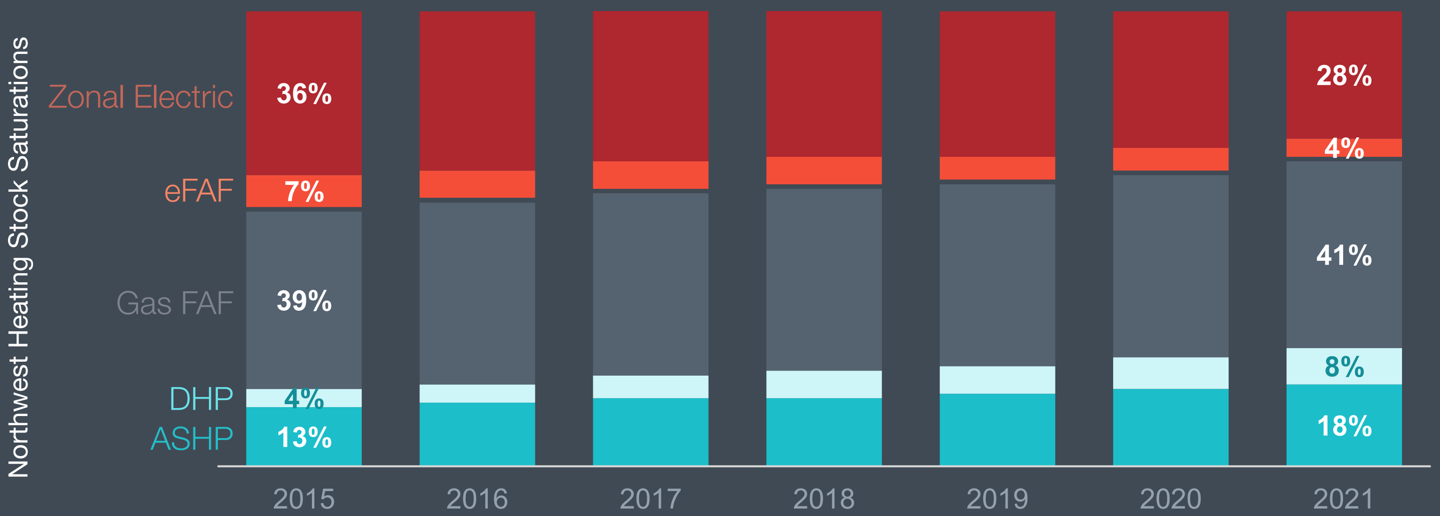
Even with the growth in cooling in the region, the Northwest is still a heating-dominant region, with heating composing 86% of the residential HVAC electric energy consumption in 2021. While cooling energy consumption has increased over the past six years, heating electric energy consumption has held relatively flat in part because of the proliferation of efficient heating technologies.



From 2015 to 2021, the number of homes using ASHPs and DHPs for primary heating climbed steadily to 18% and 8% of the stock, respectively. These increases are a result of rapidly growing sales, with an average annual growth rate of 10% over the past six years. By 2021, our model estimates that ASHP and DHP sales serving as primary heating have reached 114,000 and 60,000, respectively. Northwest utility programs and NEEA played a large part in the expanded use of ASHPs and DHPs by familiarizing distributors, installers, and customers with the technologies. When these new efficient technologies enter the stock, some replace less efficient technologies leaving the stock. As a result, the saturation of zonal electric systems (also known as electric baseboards) and electric forced-air furnaces (eFAF) have declined in the total housing stock, from 43% in 2015 to 32% in 2021.

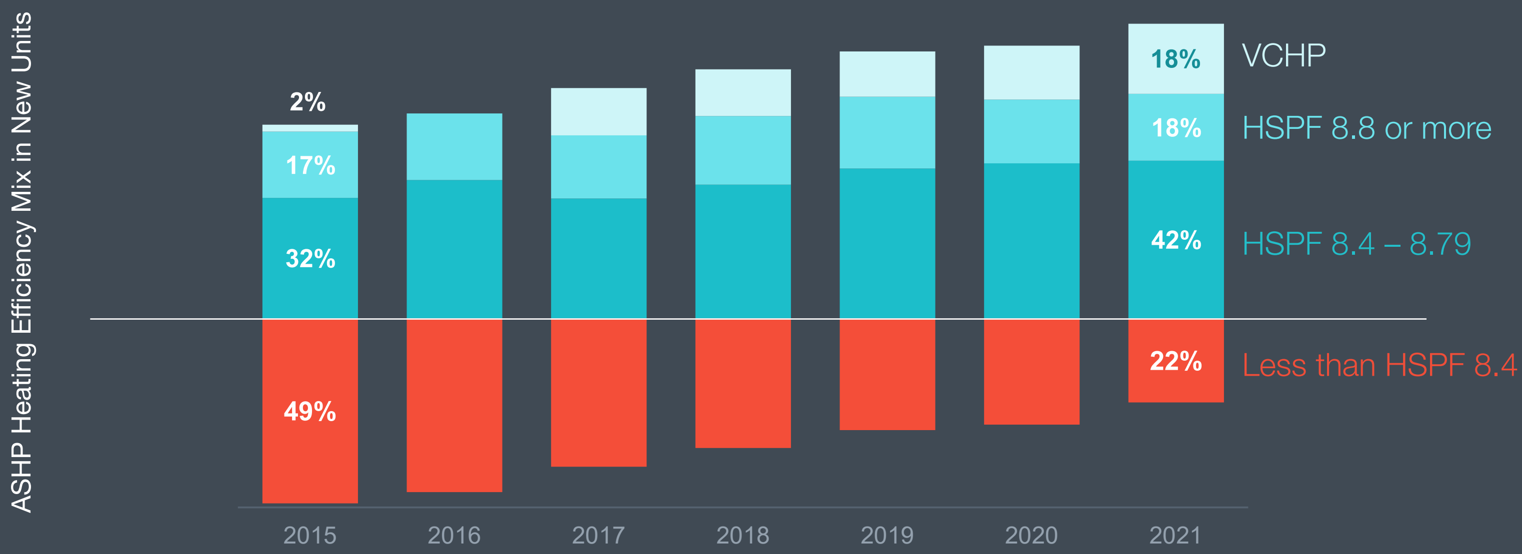
Though the region has seen a growth in heat pumps, the regional saturation of gas furnaces has held steady throughout the past six years due to a significant increase in gas furnace sales. This trend could change in the future, but as of 2021, gas furnaces remain the primary heating technology in 41% of homes in the Northwest.

Heat pumps primarily replace eFAF and zonal electric, gas furnaces holding steady



RESULTS

Growth in VCHPs Leads ASHP Heating Efficiency Improvements



The market is seeing heating efficiency improvements from the replacement of less efficient systems with ASHP and DHPs and from new ASHPs being more efficient in general. NEEA's annually collected sales data show the sales of lowest efficiency units (heating seasonal performance factor [HSPF] of 8.2 or lower) rapidly declining, while the share of single- and two-stage heat pumps with HSPF 9 and above and VCHP has doubled. These efficiency improvements drove the 2021 market average up to HSPF 8.8, which meets the upcoming 2023 federal standard of HSPF2 7.5 (equivalent to HSPF 8.8).

These higher efficiency heat pumps, combined with building shell and thermostat improvements, are bringing average per-dwelling ASHP energy consumption down.

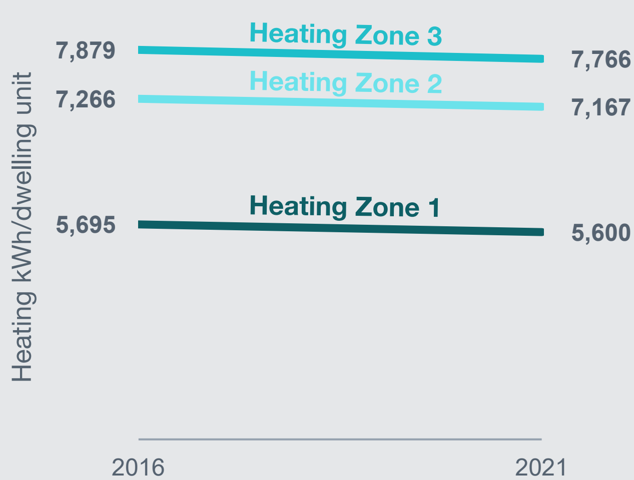
Variable Capacity Heat Pumps

The model includes six heating efficiencies and four cooling efficiencies for single and two-stage ASHP units based on Seasonal Energy Efficiency Ratio (SEER) and Heating Seasonal Performance Factor (HSPF) levels, and a separate efficiency tier for VCHPs (also called variable speed).

VCHPs vary the speed of the compressor based on the demand for heating or cooling, rather than staged or on/off cycling.

VCHPs are not identified based on HPSF or SEER levels but by specific model numbers with presence of a variable speed compressor. VCHP sales increased from 2% of all ASHP sales in 2015 to 18% in 2021.

Average single family ASHP heating consumption is decreasing



RESULTS

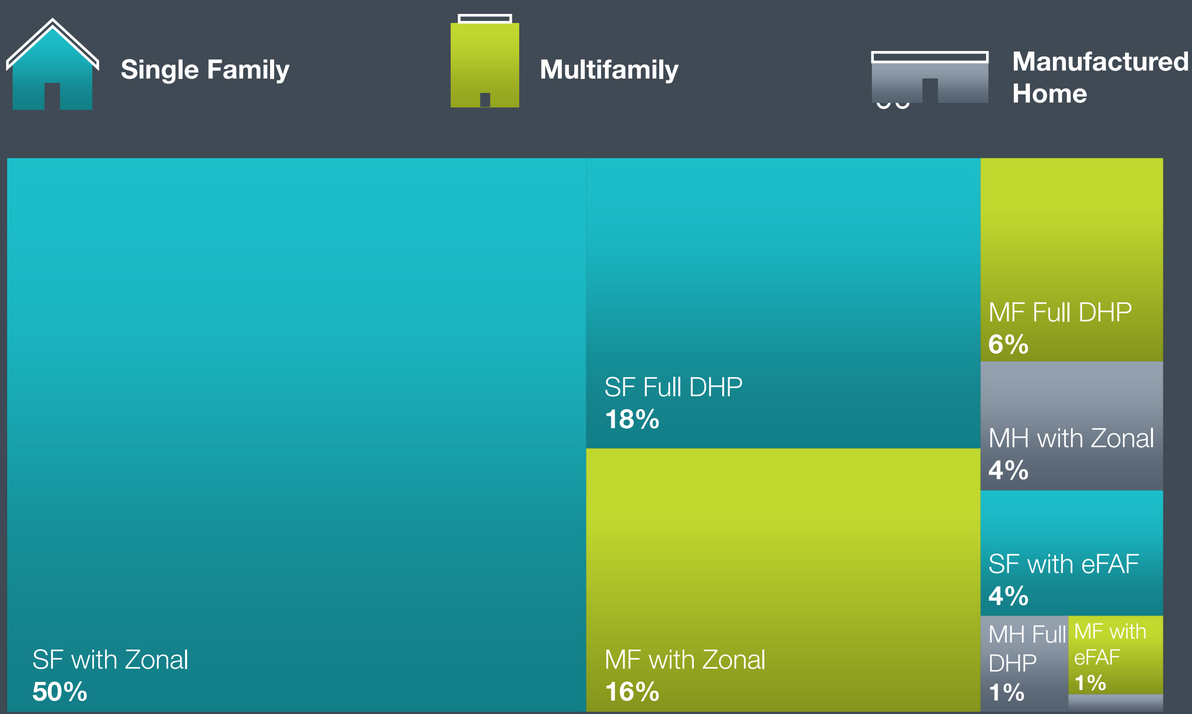
DHP Installations Popular in the Northwest

The Northwest saw large growth in DHP installations, with 277,000 more homes using DHPs as the primary heating system in 2021 than 2015. By 2021, 8% of homes use DHPs in one of the three common primary configurations: DHP with electric zonal systems (DHP with zonal), DHP with eFAFs (DHP with eFAF), and DHPs serving as the only heating or cooling system (full DHP). When DHPs are added to homes with electric zonal and eFAF systems, a large portion of the electric resistance heating is displaced by the more efficient DHP, resulting in regional heating savings. DHPs also serve as secondary applications, such as conditioning a previously unconditioned space. The model's total residential HVAC energy consumption estimates account for consumption of DHPs in secondary applications, but all data summarized here are specific to DHPs providing primary heating and cooling.

The research team allocates DHPs serving as primary heating and cooling systems to each building type and configuration based on the 2016 RBSA. The RBSA indicates 70% of primary DHP systems are installed into homes with zonal systems, where Northwest utilities and NEEA have focused their program efforts over the past several years. In terms of building types, the majority (72% of primary DHP systems) are installed in single-family homes. Interestingly, primary DHP systems are installed at a faster rate in multifamily units than in manufactured homes. Multifamily units represent 18% of the housing stock and have 23% of all installed primary DHP systems, while manufactured homes represent 10% of homes and only have 5% of all installed primary DHP systems.

Looking into the future, new DHP configurations like DHPs connected to a home's ductwork are emerging in the market.

Most DHPs providing primary heating are in single family homes with electric zonal heat



RESULTS

Abundant Opportunities Remain for Building Shell Upgrades & Thermostats

Efficient electric heating and cooling technologies bring efficiency gains that decrease overall residential HVAC energy consumption, but other non-equipment factors in a home also influence HVAC energy consumption. The research team created a robust market model that captures all the characteristics in a home that impact electric HVAC energy consumption, including building shell quality. Insulation, windows, and air sealing all affect heating and cooling consumption—and all have improved in the Northwest.

These upgrades make homes more comfortable as the Northwest experiences more extreme weather conditions. They also help offset the increased consumption associated with new cooling equipment. Weatherization will become an increasingly important upgrade if more electric heating and cooling loads are added to the grid in the future.

How is Northwest shell quality changing?

- Measured in total improved building shell as product of U-value change and area (UA)
- UA improvements doubled in existing homes, from 5% to 9% between 2015 and 2021
- Plenty of opportunities remain, with 91% of UA in existing homes available for improvements

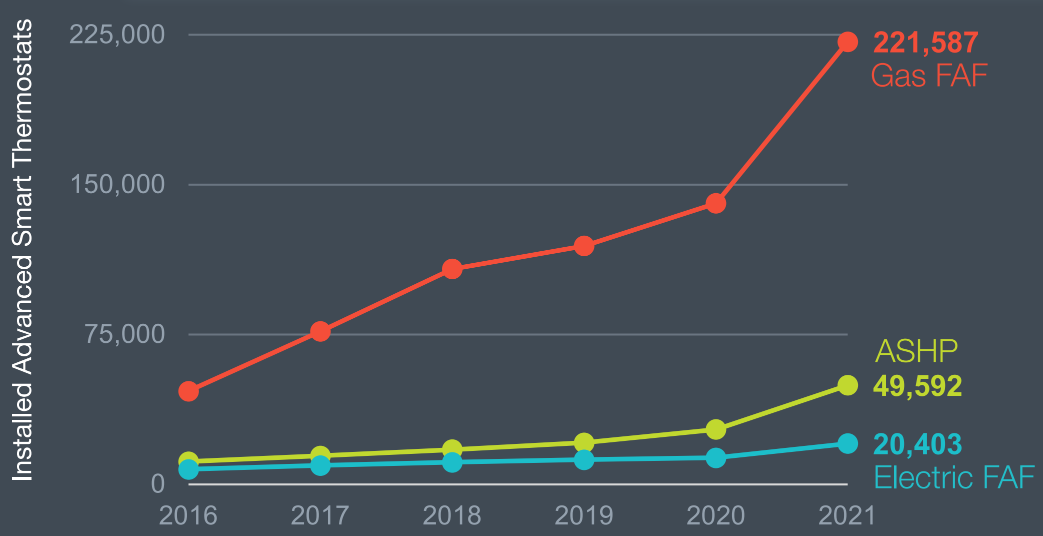
Data Sources

- Regionally representative survey of insulation installers (61 across four states)
- Insulation sales data from Principia
- 2011 and 2016 RBSAs
- Insulation, window, and air sealing program data

The presence of a thermostat also impacts how much energy an HVAC system consumes. The Northwest saw dramatic rises in the use of advanced smart thermostats, with more than 226,000 new installations on heating systems since 2015. The model uses RTF's v3.0 measure and BPA's definition of advanced smart thermostats, which includes programmability, Wi-Fi connectivity, occupancy sensing, demand response capabilities, heat pump optimization, and learning algorithms, to derive savings.

Advanced smart thermostats play a vital role in the Northwest. They make HVAC equipment operate more efficiently through scheduling, setbacks, and heat pump optimization, and they enable homes to participate in demand response programs. Only 4% of ASHPs and 8% of electric furnaces use an advanced smart thermostat in 2021, so installing more advanced smart thermostats on ASHPs and eFAFs in the future can help manage peak loads in the winter and summer.

We've seen growth in Advanced Smart Thermostats, but could see more



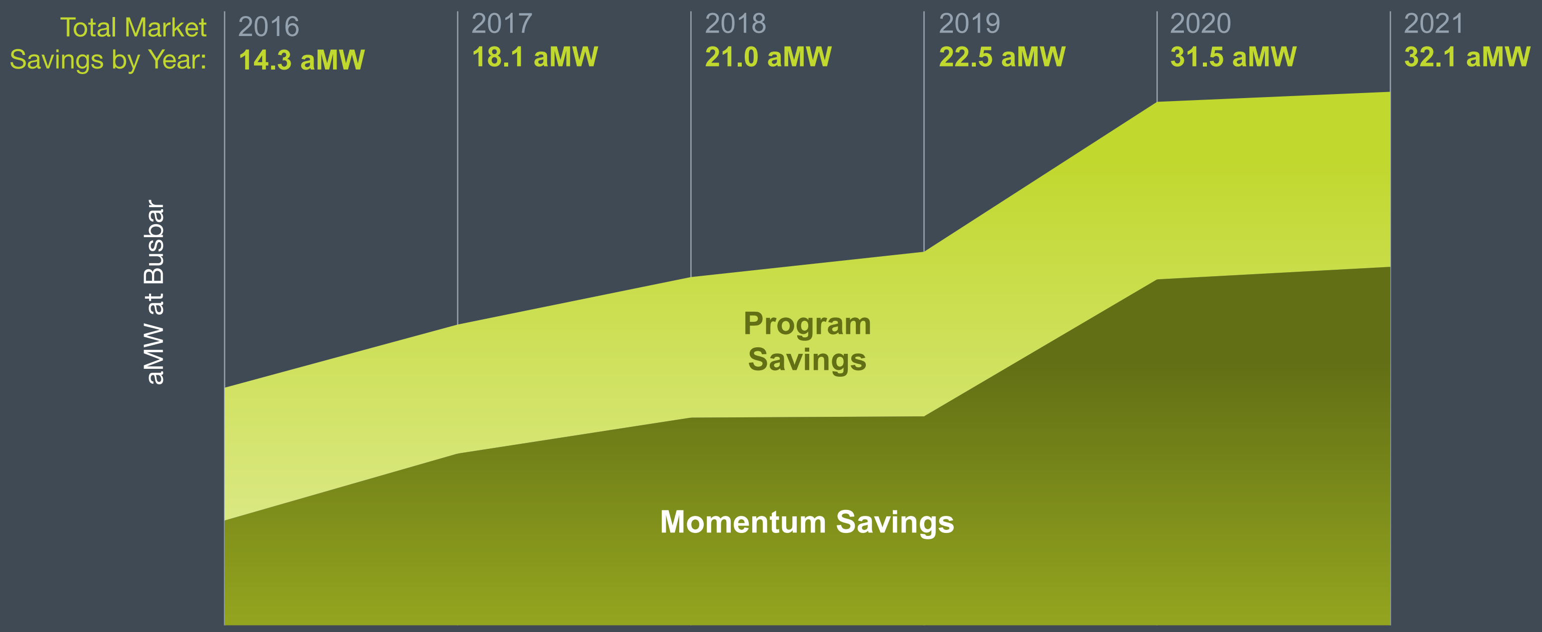
PROGRAMS PAVED THE WAY

Northwest residential HVAC program activity has steadily increased over the past six years. These program efforts, including NEEA's residential HVAC initiatives, drive energy savings in the region. Programs play a crucial role in generating momentum in the market, resulting in increased total market savings each year. Programs steer the market by familiarizing installers with emerging technologies, spurring growth in higher efficiency technologies, and informing consumers about the non-energy benefits that come with efficient technologies.

Programs Drive Savings

- Northwest initiatives promoted ASHPs and DHPs, leading to more heat pump installation as the preferred cooling solution.
- Weatherization programs improved insulation, windows, and air sealing practices.
- Programs spearheaded adoption of advanced smart thermostat technologies, which are now commonly installed for mobile controllability and improved comfort.

Northwest utility programs and NEEA generate market momentum



WHAT'S NEXT FOR RESIDENTIAL HVAC?

While there have been significant HVAC, building shell, and thermostat improvements since 2015, many energy efficiency opportunities still exist for residential HVAC. Opportunities to influence choice in efficient heating and cooling technologies will increase as the Northwest adds cooling solutions and shifts from zonal cooling to whole-home cooling. For example, the region can encourage consumers desiring cooling to consider ASHP and DHPs, which can also increase heating efficiency.

ASHPs will remain an important technology in the Northwest, particularly if the interest in cooling and electric heating continues. The region can leverage these trends to encourage people to purchase the most efficient options and to ensure equipment is installed properly and operates efficiently.

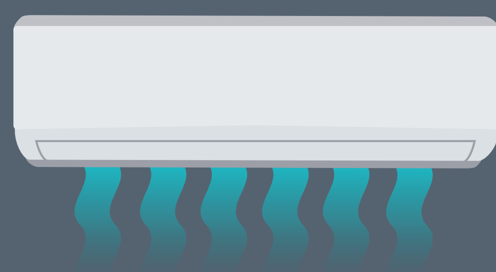
DHPs also present opportunities for additional heating and cooling efficiency, especially as DHP configurations and offerings expand beyond traditional electric zonal and eFAF pairings. Regional experts indicate new DHP trends are emerging, including DHPs paired with a home's existing ductwork.

Changes in the residential HVAC market will continue to present new insights and opportunities. Future Northwest residential HVAC activities can provide opportunities such as enable demand response activities and support the management of winter and summer peak loads. To meet these future goals, the research team will continue to prioritize residential HVAC as a key market by pursuing additional market research and refining the residential HVAC market model.

WANT TO LEARN MORE?

Read the model methodology memo below or visit BPA's website for additional detail including:

- **Model Results**
- **Market Model (Analytica)**
- **Input Documentation Workbooks**



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Bonneville Power Administration Residential HVAC Market Model Methodology

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Acknowledgements

This model is a direct result of the diligent and thoughtful engagement from numerous stakeholders and regional subject matter experts. Bonneville Power Administration's Market Research Team would like to thank everyone who provided thorough review, meaningful feedback, and recommendations throughout model development, including Expert Panel facilitators Tyler Mahone, Brielle Bushong, and Andrew Wood and members of the Expert Panel: David Baylon, Ryan Brown, Abram Conant, Bob Davis, Christian Douglass, Christopher Dymond, Michael Flatt, Havala Hanson, Tina Jayaweera, Mark Jerome, Mitt Jones, Jennifer Light, Kevin Madison, Chris McKinney, and Robert Weber. The panel's feedback and the team's responses are available on BPA's website: https://www.bpa.gov/energy-and-services/efficiency/market-research-and-momentum-savings/hvac-market-research.

Table of Contents

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) 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 market 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 from 2016 to 2021, corresponding with the Seventh Plan Action Plan period (hereafter referred to as the Action Plan period). Momentum Savings are energy savings above the Council's Seventh Plan frozen baseline which programs do not claim or the Northwest Energy Efficiency Alliance (NEEA) does not include in its net market effects. BPA's modeling goals for this market are twofold:

1. Understand how total residential HVAC electric consumption is changing from 2015 to 2021
2. Estimate residential HVAC electric Momentum Savings from 2016 to 2021

BPA completed the Interim Model in 2019 and received input from the Regional Technical Forum's (RTF) Market Analysis Subcommittee. In 2021, BPA subsequently began to update the model and inputs to produce and finalize the estimates of energy consumption and Momentum Savings for 2016-2021. To ensure the updated model is as robust as possible, BPA engaged with a panel of 15 industry, market analysis, and technology experts (the Expert Panel) to provide independent feedback on the model updates. Based on the Expert Panel's collective feedback, the team refined model inputs and key assumptions, which increased the team's confidence in the model results.[1]

This report includes three major sections. First, it describes in detail the team's approach to developing the market model's methodology 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 market 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 workbooks that present the market model inputs and outputs.

[1] The panel's feedback and the team's responses are available on BPA's website: https://www.bpa.gov/energy-and-services/efficiency/market-research-and-momentum-savings/hvac-market-research.

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 BPA's Expert Panel while developing this methodology.

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:

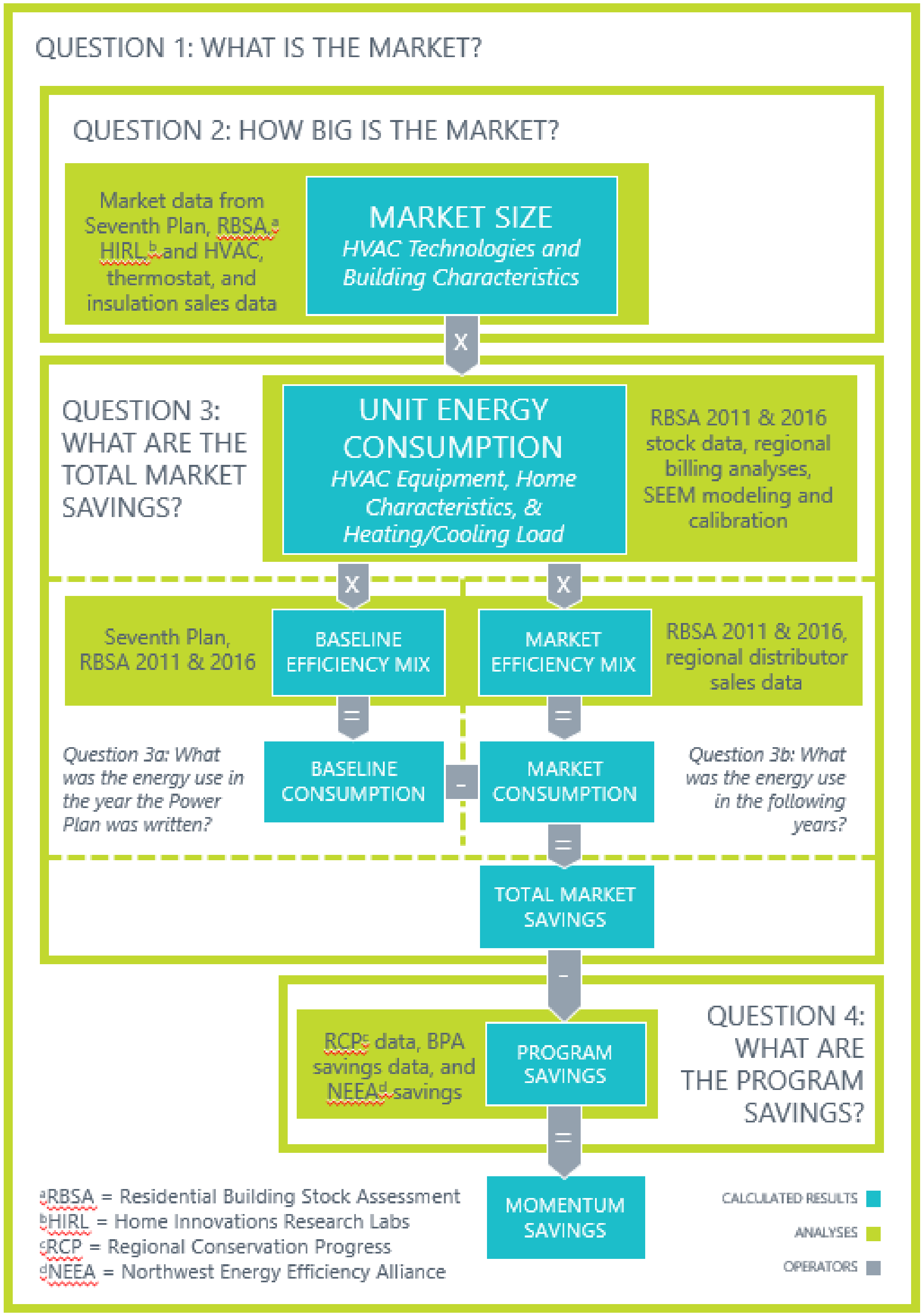
1. What is the market?
2. How big is the market?
3. What are the total market savings?
    a. What was the energy use in the year the Power Plan was written?
    b. What was the energy use in the following years?
4. What are the program savings?

Answers to these questions are necessary interim steps of the methodology to estimate Momentum Savings and are shared in this memo for transparency. These steps are not used for other reporting purposes. The market model also produces other valuable insights into residential HVAC market trends and how the region's residential HVAC equipment consumes electric energy. The

[2] Available at https://www.bpa.gov/energy-and-services/efficiency

Market Model Results section summarizes these insights. 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 as steps to estimating Momentum Savings.

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 contain any specific data sources or methodology. Rather, it 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.

As summarized in Table 1, the research team defined the residential HVAC market by various elements.

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.
Analysis Period	2011-2021	The model estimates energy consumption from 2011 to 2021, enabling the estimation of Momentum Savings during the Seventh Plan Action Plan period (2016-2021).
Unit of Account	Dwelling unit (i.e., household)	The market 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	Accounts for the equipment stock of non-electric HVAC technologies and includes a per-unit electric unit energy consumption (UEC) that accounts for the fan/pump loads and electric secondary heating in dwellings with non-electric HVAC technologies*.
Total Market Savings Scope	Savings associated with electric heating *technology* improvements, electric heating *efficiency* improvements, and cooling *efficiency* improvements in ASHP and Central Air Conditioner (CAC), and building shell and thermostat improvements in existing homes	Excludes savings associated with fuel switching, technology or efficiency improvements in new construction, and changes in cooling technology saturation.

*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, as with the Seventh Plan, excludes housing stock in Eastern Montana. 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.

Analysis Period

The analysis period refers to the timeframe over which this model characterizes energy consumption, **2011-2021**. The analysis period begins in 2011 using the building stock data in the first Residential Building Stock Assessment (RBSA).[3] To calculate Momentum Savings for 2016-2021 (the Action Plan period), the model uses 2015 as the baseline year.

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.[4] 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.[5]

The modeling approach accounts for primary heating and primary cooling equipment separately. That is, the market model treats dwelling unit heating energy consumption separately from dwelling unit cooling consumption. The approach also includes secondary (supplemental) heating and cooling equipment consumption in its estimate of per-dwelling UEC. Question 3 provides further detail on 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 (including attached homes up to four units), manufactured homes, and multifamily units (from buildings with five or more units) with in-unit HVAC systems. The specific scope of multifamily units included in the market model is described in more detail below.

In addition to building types, the market model also segments the market into new and existing building vintages, where existing homes represent those constructed before 2011 and new construction represent

[3] RBSAs available at https://neea.org/data/residential-building-stock-assessment

[4] Dwelling units can be single-family detached homes, manufactured homes, or a unit within a multifamily building (e.g., the model represents an apartment building containing 10 separate apartments as 10 dwelling units).

[5] See discussion in Question 3.

homes constructed in 2011 or later. The team selected 2011 to align equipment saturations with the RBSA.

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 market model only includes multifamily *units*. It excludes common areas in multifamily buildings because common area usage differs from typical in-unit usage. The majority of multifamily building HVAC systems across low-, 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 (4-6 stories, 5+ units)	250,802	98%
High-Rise Multifamily (7+ stories, 5+ units)	39,216	65%

Source: Cadeo analysis of RBSA 2016.

Second, as the market 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 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.

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

[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.

[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 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 https://rtf.nwcouncil.org/simplified-energy-enthalpy-model-seem.Error! Hyperlink reference not valid.

simulation software the team used to develop UECs is not designed to model large multifamily (i.e., mid- and high-rise) buildings. The RBSA sampling for multifamily buildings also introduces uncertainty, which the team mitigates by using additional data where available. Later in this document, the team describes its approach for determining multifamily UECs.

Technology Scope

The market 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, refers to factors that impact the amount of energy needed to condition each dwelling unit.

The following sections describe the two groups in more detail and how each is treated in the market 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 research 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 Market 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.)	✓	

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

Air Source Heat Pumps

The model includes six heating efficiencies and four cooling efficiencies for single and two-stage Air Source Heat Pump (ASHP) units, and a separate efficiency tier for Variable Capacity Heat Pumps (VCHPs).

Although many factors contribute to an ASHP's electric consumption, the team chose to use the heating seasonal performance factor (HSPF) and the seasonal energy efficiency ratio (SEER) as heating and cooling efficiency bins in absence of better efficiency metrics. VCHPs are not identified based on HPSF or SEER levels but by specific model numbers with presence of a variable speed compressor. The HSPF and SEER levels apply only to single and two-stage heat pumps.

The model implicitly includes ASHPs with gas furnaces as backup (or "dual fuel heat pumps") and treats them as ASHPs because the model tracks dwelling units by their primary heating and cooling systems. Gas furnaces as backup to ASHPs are considered a secondary system. The UECs include the impact of non-electric consumption on the electric consumption of an ASHP within SEEM's phase II calibration factors.

team accounted for secondary heating and cooling use in its estimate of per-dwelling UEC, described in detail later in this document. Heating UECs represent average total dwelling unit heating energy consumption, including secondary heating equipment impact and factors such as occupancy. Similarly, the cooling UECs represent average total dwelling unit cooling energy consumption, including secondary cooling equipment use.

For ASHPs and CACs, the market model tracks specific efficiency levels discretely with seven heating and five cooling efficiencies, including Variable Capacity Heat Pumps (VCHPs). While VCHPs, have a range of rated efficiency levels, the model treats VCHP as a unique efficiency level with its own average UEC. For DHPs the model includes three unique configurations[8] but does not disaggregate consumption by the efficiency of the DHP itself. The three configurations include DHPs installed in dwelling units with electric zonal heating (DHP with Electric Zonal) or electric forced air furnaces (DHP with eFAF), or DHPs installed as the primary heating and cooling system (Full DHP). The model does not differentiate efficiency levels for the remaining HVAC technologies. Table 4 summarizes the specific equipment efficiency levels accounted for in the model and the team's rationale for making those selections.

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

HVAC Equipment Type	Efficiency Level(s)	Rationale/Description
ASHP	Heating: HSPF 7.2, 7.7, 8.2, 8.5, 9.0, 10.0+, and VCHP Cooling: SEER 10, 13, 14.5, 18+, and VCHP	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 such as VCHP.

[8] The team considered additional configurations, such as DHPs paired with indoor air handling units or other ducted systems but chose to exclude them from this model due to the low prevalence of these systems during the analysis period.

HVAC Equipment Type	Efficiency Level(s)	Rationale/Description
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 the difference in efficiency between DHP models has a small impact on consumption[9] 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.
Electric Zonal Heat	All	Electric zonal heating systems do not vary meaningfully in efficiency.
eFAF	All	Electric furnaces do not vary meaningfully in 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 (RAC/PAC/PTAC)	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.

[9] The RTF DHP with Zonal measure uses a single efficiency level, HSPF ≥9.0 (ResDHPforZonal_v5_1.xlms). Past RTF DHP measures analyzed 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 past measures, the research team determined that the average energy consumption for DHPs of different efficiency levels were all within 5% of each other. As such, and because the addition of a DHP (as opposed to higher efficiency DHPs) was the primary driver of changes in energy consumption, the team elected to model a single DHP efficiency level representing the average efficiency of regional sales and stock saturation, based on data from 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
Non-Electric Zonal Heating Sources: Boilers (oil, gas) and Heating Stoves (wood, pellets, propane, oil, fireplaces, etc.)	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.

Non-Equipment Factors That Impact HVAC Energy Consumption

In addition to the characteristics of HVAC equipment previously discussed, the team's approach accounts for other factors that affect residential building heating and cooling load and HVAC equipment energy use. Table 5 lists non-equipment factors impacting HVAC energy consumption the team includes in its HVAC market analysis.

Table 5. Non-Equipment Factors that Impact HVAC Energy Consumption

Non-Equipment Factors	Description
Thermostat Type	Includes "advanced smart"[10] thermostats versus baseline thermostats (or all thermostat types other than "advanced smart").
Building Shell (Weatherization)	Includes insulation, windows, and air sealing (all factors that affect shell UA[11]).
Installation Practices (Commissioning, Controls and Sizing)	Includes HVAC controls, airflow, refrigerant charge, and equipment sizing for ASHPs.
Duct Losses (for applicable HVAC equipment)	Includes supply and return duct leakage for ducted HVAC systems (ASHP, eFAF, gFAF, GSHP, CAC), as well as conduction losses and induced infiltration.[12]
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.

[10] 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/-/media/Aep/energy-efficiency/momentum-savings/181016-bpa-thermostat-market-characterization-memo.pdf). This definition generally aligns with the RTF's thermostat measure, with some minor differences.

[11] U-factor x Area, or 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.

[12] 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 market case.

Fuel Type Scope

The analysis focuses on residential HVAC market **electricity consumption** changes. However, the research team's market definition also includes natural 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 market model only estimates Momentum Savings for electric efficiency improvements, not from fuel choice. Therefore, the research team makes the saturation of gas and electric technologies in the baseline equal to the market scenario to avoid reporting savings associated with fuel switching.

Total Market Savings Scope

The market model estimates residential HVAC consumption over time and the total market and Momentum Savings associated with efficiency improvements in the stock. In order to best align with the Seventh Plan baselines and conservation targets, the model structures the baseline and market scenarios to only derive total market savings from specific stock improvements, described here and in subsequent sections. The model derives total market savings from the following:

- Increased stock saturation of efficient electric heating technologies such as ASHPs, DHPs, and other types of heat pumps and decreased stock saturation of eFAF and zonal electric
- Heating and cooling efficiency improvements above the current practice baseline in ASHPs and CACs entering the stock as new units
- Building shell, advanced smart thermostat, commissioning, controls, and sizing (CC&S), and duct sealing improvements in existing homes (for CC&S, duct sealing, and some types of building shell improvements the total market savings equal program savings because there are no available data suggesting improvements outside of programs)

The model does not derive total market savings from the following areas:

- Changes in electric consumption associated with fuel switching because it makes the saturation of gas and electric technologies in the baseline equal to the market scenario
- Efficiency improvements installed in new construction associated with energy code requirements, including building shell, ASHP and DHP installations, and duct sealing
- Changes in cooling technology saturation (e.g., increased or decreased saturation of RACs, CACs, etc.)

Question 2: How big is the market?

To estimate total regional residential HVAC electric consumption during the analysis period, the research team first estimates the market size in each year of the analysis period. The team's definition of market size is the total number of dwelling units installed with each type of primary HVAC technology in each year. The research team's market sizing approach is to multiply the number of dwelling units in the region in each year by the saturation of HVAC equipment observed in that year (Equation 1). The team segmented the market using five factors to accurately estimate the HVAC equipment distribution throughout the region:

1. **Building vintage:** existing home (constructed in 2011 and earlier) and new construction (home constructed in 2012 and later)
2. **Building type:** single-family home, manufactured home, and multifamily unit
3. **Climate zone:** heating zone 1, 2, and 3; cooling zone 1, 2, and 3
4. **HVAC equipment type and efficiency level**: primary heating and cooling technologies in Table 3 and Table 4
5. **Non-equipment factors:** non-equipment factors in Table 5 that impact HVAC energy consumption

The first three segmentation variables physically define the unit of account (i.e., a dwelling unit), while the remaining two variables define the HVAC technology that exists in that unit and other factors impact the technology's energy consumption.

Equation 1: Market Size by Granular Segmentation Variables

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

Where:

t = analysis year

v = building vintage

b = building type

z = climate zone

e = equipment type (including the efficiency levels tracked)

f = non-equipment factors

This document uses the term "cell" to represent each of the thousands of possible combinations of building vintage, building type, climate zone, primary HVAC equipment type and other non-equipment factors to simplify the notation in Equation 1. Using cells in place of the more granular segmentation variables in the equation notation yields Equation 2:

Equation 2: Market Size by Cell

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

Where:

t = analysis year

c = cell

This section describes how the market model estimates the number of dwelling units and the saturation of HVAC technologies and non-equipment factors, as well as the approach to estimating change over time.

Number of Dwelling Units

The number of dwelling units is a fundamental variable used in calculating the market size for all HVAC equipment and non-equipment factors included in the model. The team first calculates the number of dwelling units in 2011 to estimate the existing stock of residential dwelling units in the region. The team then determines the number of dwelling units that are demolished each year and added to the stock via new construction to update the number of dwelling units in each subsequent year. The data sources the team uses for each of these inputs are described below.

Number of Existing Dwelling Units. The team uses the RBSA 2011 to estimate the total number of 2011 single-family and manufactured homes in the region. For multifamily units, the team uses the number of units in BPA's Residential Lighting market model, which relies on a combination of RBSA 2011 and Seventh Plan estimates.[13]

Rate at Which Dwelling Units are Demolished. The team uses the demolition rate assumption directly from the Seventh Plan to account for dwelling units leaving the existing stock.

Number of New Construction Dwelling Units: 2011 through 2021. The stock turnover model begins in calendar year 2011 and requires new construction estimates for single family, manufactured homes, and multifamily units for years 2011 through 2021 to cover the full analysis period. The team uses new construction growth estimates from three sources to derive new construction estimates, based on the time period of interest:

1. The Seventh Plan estimates for new construction dwelling units constructed from 2011 through 2014.
2. For 2015 through 2020, the US Census Bureau's Building Permits Survey (BPS) estimates of completed new construction, rather than forecasted values from the Seventh Plan.[14]
3. For 2021, the Council's 2021 Power Plan new construction forecast because the US Census Bureau's BPS for calendar year 2021 was not available at the time the research team collected these data. The Council's 2021 Power Plan also represented more current data than the Seventh Plan.[15]

Determining Saturation for HVAC Equipment and Non-Equipment Factors

After estimating the number of dwelling units in each year of the analysis period, the second component in determining the market size is estimating the saturation of HVAC technologies and non-equipment factors in each year. The research team took one of three approaches in the market model to account for the saturation, and any changes in saturation, of primary HVAC equipment and each of the non-equipment factors based on data availability and likelihood of market change. The three factor categories and their associated market sizing approaches are:

1. **Primary factors,** whose market change is directly modeled via stock turnover

[13] BPA residential lighting market model documentation available at https://www.bpa.gov/-/media/Aep/energy-efficiency/momentum-savings/2017-residential-lighting-final-report.pdf
[14] https://www.census.gov/construction/bps/stateannual.html for single family and multifamily, and https://www2.census.gov/programs-surveys/mhs/tables/time-series/shipmentstostate14-21.xlsx for manufactured homes
[15] https://www.nwcouncil.org/2021-power-plan-technical-information-and-data

2. **Secondary factors,** whose market change is modeled by evaluating annual changes in the stock using a range of data sources
3. **Tertiary factors,** which assume no market change over the analysis period, either due to a lack of market data or market data indicating little or no change during the analysis period

Table 6 presents the research team's primary, secondary, and tertiary designation factors.

Table 6. Factors Impacting HVAC Consumption and Their Modeling Approaches

Factor	Primary: HVAC Equipment Modeled Directly via Stock Turnover	Secondary: Other Factors Modeled via Change in Stock	Tertiary: Held Constant
Primary HVAC Equipment and Efficiency Level	✓		
Building Shell (Weatherization)		✓	
Thermostat Type		✓	
Installation Practices (Commissioning, Controls and Sizing)		✓	
Duct Tightness		✓	
Occupancy			✓
Presence of Secondary Heating 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 stock turnover model simulates changes in the stock of HVAC equipment over time as a function of its initial state (the number of units of each equipment type in 2011), a retirement rate (the rate at which units leave stock in each subsequent year), and product flow (how many units of each equipment type enter stock in each subsequent year). The team uses both the RBSA 2011 and RBSA 2016 to inform its stock turnover model, as well as product flow data, information on retirement rates, and new construction HVAC saturation information. The market model disaggregates HVAC equipment type and efficiency level by climate zone, building type, and building vintage and calculates stock turnover for each segment of the HVAC market uniquely.

For the non-equipment **secondary factors,** the team estimates market change by modeling annual changes in stock saturation over time, informed by market data sources that include proprietary thermostat and insulation sales, stock saturations (RBSA 2011 and RBSA 2016), regional energy efficiency program reporting, and additional market research. The team discusses data sources and approaches to estimating market change for each of these secondary factors (thermostat type, building shell, installation practices, and duct tightness) in more detail below.

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

The following sections describe in more detail the team's modeling approaches for each of the three factors.

Estimating Saturation for Primary Factors

As described above, the research team uses a stock turnover approach to model primary factors, which includes the following overarching assumptions, in addition to the number of dwelling units, in its market size estimate:

1. Use the RBSA 2011 to estimate HVAC equipment saturation in 2011.
2. Use HVAC equipment lifetime data to estimate the retirement of HVAC equipment in existing homes from 2012 through 2021.
3. Use HVAC sales data, new construction data, and additional data sources to estimate the product flow and efficiency mix of equipment entering the stock and allocate those HVAC units to new construction homes (as new units) and existing homes (as replacements) from 2012 through 2021 via a stock turnover approach.
4. Calibrate the market model's assumptions such that the modeled HVAC equipment saturations and product flows align with the best available data, including the observed HVAC equipment saturation in the RBSA 2016[16] and secondary data for 2017–2021.

Equation 1 and Equation 2 demonstrate, at a high-level, how the model estimates market size for any given cell in any given year. However, as discussed previously, the market model includes multiple years and focuses on how those saturations and number of dwelling units change over time. To simulate this change, the team uses 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 major remodels, and retirements of equipment not replaced by the same technology. Equation 3 shows the calculation of the market size primary factor based on all these variables.

Equation 3: Annual Market Size for Primary Factors

$$\text{AnnualMarketSize}_t = \sum_{\text{Cell } c} \begin{array}{c} \#\ \text{Dwelling Units}_{t-1,Ex,c} \times \text{Saturation}_{t-1,Ex,c} + \#\ \text{Dwelling Units}_{t,NC,c} \times \text{Saturation}_{t,NC,c} \\ - \text{Retirements}_{t,c} + \text{Replacements}_{t,c} \end{array}$$

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

Where:

[16] 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.

t = analysis year

Ex = existing vintage

NC = new construction vintage

c = cell[17]

The approach presented in Equation 3 requires several data sources to calculate the necessary inputs of dwelling units, HVAC equipment and cell saturation, retirements, and replacements. The data sources the team uses in calculating these inputs are listed in Table 7 and described in further detail below. These data represent the best available data at the time of the market model.

Table 7. Stock Turnover Inputs and Sources

Input	Description	Data Sources	Model Use
Dwelling Units (Existing), 2011	Existing dwelling units built pre-2011	Cadeo analysis of RBSA 2011, Northwest Residential Lighting model (developed by BPA and maintained by NEEA)	Direct input, analysis starting point
Dwelling Units (Existing), 2012-2021	Existing dwelling units built pre-2011 in years 2012-2021	2011 dwelling units minus units demolished based on Seventh Plan demolition rate	Direct input, number of existing dwelling units in subsequent years
Saturation in 2011	HVAC equipment saturation in 2011	Cadeo analysis of RBSA 2011	Direct input, analysis starting point
Saturation, 2012-2016	HVAC equipment allocation in existing dwelling units	Cadeo analysis of RBSA 2011 and RBSA 2016 (pre-2011 homes only)	Calibration point, used to triangulate product retirements and replacement flows
Dwelling Units (New Construction), 2011-2021	New dwelling units in years 2011-2021	2011-2014: Seventh Plan 2015-2020: US Census Bureau Building Permits Survey (BPS) 2021: 2021 Power Plan forecast	Direct input, number of new construction homes

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

Input	Description	Data Sources	Model Use
Saturation (New Construction), 2016-2021	HVAC equipment allocation in SF & MF new construction dwelling units	Home Innovation Research Lab's Builder Survey, Regional code compliance studies	Direct input, used to allocate new HVAC equipment added to stock in new construction homes
	HVAC equipment allocation in MH new construction dwelling units	Cadeo analysis of RBSA 2016	
Efficiency Saturation	Annual HVAC equipment product flow efficiency share	Cadeo analysis of RBSA 2011 and RBSA 2016, Cadeo analysis of NEEA HVAC sales data	Direct input, applied to new construction and replacement product flows to disaggregate efficiency levels for applicable equipment
Retirements	Equipment age distribution in 2011	Cadeo analysis of RBSA 2011	Direct input as lifetime and age, which produces annual retirements in the stock turnover
	Annual turnover rate	ASHRAE and DOE lifetime estimates	
Replacements	Annual product flow of equipment to existing homes	Cadeo analysis of NEEA HVAC sales data minus model-calculated new construction sales, Cadeo analysis of RBSA 2011 and RBSA 2016 (pre-2011 dwelling units only)	Adjusted to align the stock turnover approach with RBSA stock data.

In addition to the data listed in Table 7, the team uses several additional data sources to corroborate the magnitude and rate of change seen in the modeled annual product flow for specific equipment, including:

- NEEA DHP Market Progress Evaluation Reports[18] to corroborate the model's estimated DHP product flows
- Confidential 2016–2018 HVAC sales data used as a comparison and calibration point
- The US Census American Housing Survey[19] to corroborate the model's estimated primary cooling saturation

The next sections describe the four steps the team uses to incorporate all data sources as inputs into the stock-turnover model to estimate the market size for primary factors.

[18] https://neea.org/resources/northwest-ductless-heat-pump-initiative-market-progress-evaluation-8
[19] https://www.census.gov/programs-surveys/ahs.html

Step 1: Use the RBSA 2011 to estimate HVAC equipment saturation in 2011

The team's analysis of the RBSA 2011 determines the primary HVAC equipment saturation (i.e., percentage of dwelling units with each specific type of primary HVAC equipment) by building type, climate zone, and construction vintage in 2011, the start of the analysis period. The team then multiplies this value by the number of dwelling units in 2011, as discussed in the Number of Dwelling Units section, to determine the quantities of primary HVAC equipment in each cell in 2011.

Step 2: Use HVAC equipment lifetime data to estimate the retirement of HVAC equipment in existing dwelling units from 2012 through 2021

The team uses equipment age and lifetime data as a model input, which the stock turnover uses to calculate the number of retirements leaving the existing stock in each year.

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

Annual Turnover Rate. National lifetime data, which range from 10 to 24 years by technology, form the basis for the research team's equipment turnover rate assumptions.[20] However, the HVAC equipment product flow data, described below, and the change in HVAC stock between the 2011 RBSA and the 2016 RBSA provide actual, empirical evidence for how many HVAC units are being replaced in each year. Thus, the team adjusts the annual turnover rate assumptions such that the 2016 equipment saturation in the stock turnover model aligns with RBSA 2016. These adjustments also ensure the market model's estimate of annual HVAC equipment product flow aligns with observed market data sources.[21]

Step 3: Estimate and allocate HVAC units entering the stock to new construction homes (as new units) and existing homes (as replacements) from 2012 through 2021

As shown in Table 7, new equipment enters the market to both serve new construction dwelling units and replace the stock turnover's retiring existing equipment. The team creates product flow estimates (i.e., the number of primary HVAC equipment units sold each year by technology) that the model first allocates to new construction homes, then to existing homes, either as units replacing retired units (like for like replacements) or units replacing different equipment types (conversions). This step also includes estimating the efficiency mix of the product flow entering the stock.

Annual HVAC Equipment Product Flow. For 2011 through 2016, the stock turnover determines the magnitude of product flow needed to maintain retirements and new construction additions. The team calibrates the stock turnover model to align with the HVAC equipment saturation with RBSA 2016.

[20] The team relies on three data sources for lifetime estimates by technology: ASHRAE (https://www.ifmaorlando.org/docs/ASHRAE_life_expectancy_chart.pdf), DOE's Office of Scientific and Technical Information National Survey (https://www.osti.gov/biblio/1182737), and DOE's Technical Support Documents (https://www.regulations.gov).

[21] In the Interim Model, the team used a Weibull curve to define the proportion of the existing stock that turned over in a given year, however in the Final Model, the team chose to remove Weibull curves to allow for the addition of annual sales data, improve the model's calibration capabilities, and reduce unnecessary complexity.

For 2017, the team estimates product flows for four key technologies (CAC, gFAF, ASHP, and DHPs) in the region with an analysis of regional HVAC sales data collected by NEEA. These data have sales by year, state, and technology for key residential technologies, but only represent a portion of overall regional sales compiled from a confidential number of regional suppliers. Thus, the team scales those sales to product flow estimates for 2017 using the magnitude of replacements needed by the stock turnover model. The team compared the resulting product flow estimates against confidential sales data sources to corroborate and calibrate the model inputs, discussed more in Step 4.

To estimate product flows for 2018, the team multiplies the 2017 product flow estimates for each technology by a scalar value that represents the percentage increase (or decrease) in sales from 2017 to 2018 based on NEEA's annual HVAC supplier sales data.[22] The team repeats this process to calculate 2019 and 2020 product flows. Finally, the team forecasts 2021 product flow as equal to 2020, to be conservative, since 2021 data were not available at the time of model finalization.

The product flow estimates are subject to uncertainty, as discussed in more detail in the Uncertainty Sources and Sensitivity Analysis section of this report.

Product Flow Allocation to New Construction. The research team estimates the number of HVAC units entering the stock of new construction homes using a number of building type-specific data sources to model the saturation of each equipment type and efficiency level in new construction:

Single-Family new construction allocation relies primarily on Home Innovation Research Lab's (HIRL) Builder Survey.[23] For gas furnace saturation, the team uses the average saturation between regional code compliance studies[24] and HIRL's estimates based on feedback from the Expert Panel and allocates the remaining share of HVAC systems proportionally between the remaining heating system types.[25] Additionally, the team uses RBSA 2016 to fill HIRL data gaps for uncommon HVAC system types (e.g., PTHPs, PTACs, and RACs) and to disaggregate electric resistance technologies (i.e., eFAF and electric zonal), which HIRL groups together.

Multifamily new construction allocations also rely on HIRL's data as a primary data source but use regional code compliance studies to fill gaps in HIRL's multifamily data.

Manufactured Homes new construction allocations rely on the extrapolated trend between RBSA 2011 and RBSA 2016 in absence of HIRL data or alternative data sources.

The allocation of HVAC equipment within new construction dwelling units assumes a regional average across all four states. The team considered allocating the state-specific data to climate zones given the lack of climate zone-specific data, however, states do not precisely align with weather-based climate zones and state is not a disaggregation variable in the model. Thus, based on feedback from BPA's Expert

[22] Additional detail on that analysis can be found in the 2016-2019 HVAC Sales Data Executive Summary report available at https://www.bpa.gov/-/media/Aep/energy-efficiency/momentum-savings/bpa-hvac-sales-data-report-2016-2019.pdf. At the time of this report, BPA had not yet published the 2020 report, but the model does incorporate NEEA's 2020 data.
[23] HIRL's Builder Survey is an annual, national survey of home builders that includes approximately 100 builders in the Northwest, accounting for 2-4% of regional new construction activity. The research team purchased the survey data product, which includes HVAC installation data in single family and multifamily new construction. See https://www.homeinnovation.com/trends_and_reports/data/new_construction/hvac_systems for further detail.
[24] https://neea.org/img/documents/2019-2020-Washington-Residential-New-Construction-Code-Study.pdf, https://www.energycodes.gov/residential-energy-code-field-studies
[25] Panelists had varying opinions on the HVAC saturations in the HIRL data and code compliance studies. All feedback and the team's rationale for final model approaches are available at BPA's website: https://www.bpa.gov/energy-and-services/efficiency/market-research-and-momentum-savings/hvac-market-research.

Panel,[26] the team elected to use regional average saturation for HVAC systems in new construction units. Note that the model does not derive any savings associated with new construction by setting the baseline saturation equal to the market in new construction homes.

Finally, due to the variability in HIRL's 2016-2020 year-by-year data, the team chose to average HIRL's data across all years to apply a single new construction HVAC saturation by technology to each year from 2016 to 2021.

[26] The team reviewed two options with the panel, each with pros and cons. The panel provided varying feedback on each approach. All feedback and the team's rationale for final model approaches are available at BPA's website: https://www.bpa.gov/energy-and-services/efficiency/market-research-and-momentum-savings/hvac-market-research.

Ductless Heat Pumps

Consumers install DHPs, or mini-splits, in a variety of applications for a number of uses. This model uses three configurations to categorize DHPs and allocates new DHPs from the product flow to those three configurations (in both existing and new construction) based on the saturation observed in the RBSA 2016, corroborated with BPA's 2018 HVAC Installer Survey* and Energy Trust of Oregon's 2021 DHP study:** 70% DHP with Zonal, 25% Full DHP, and 5% DHP with eFAF.

Expert Panel feedback indicates the number of ways DHPs are being used is changing, but because of limited saturations and data on these new configurations, BPA's model is currently limited to the three primary configurations.

The model avoids attributing DHPs used in secondary applications as primary systems by establishing stock saturations and product flow estimates based only on DHPs in primary applications (defined by the three configurations), as observed in RBSA. Future DHP growth is then modeled by applying the year-over-year growth rate in the sales data to the primary systems. The does, however, account for the consumption of DHPs in secondary applications in the model UECs.

*https://www.bpa.gov/energy-and-services/efficiency/market-research-and-momentum-savings/hvac-market-research.

**https://www.energytrust.org/wp-content/uploads/2019/10/Residential_Ductless_Heat_Pump_Study_Report.pdf.

Product Flow to Existing Homes. After allocating the product flow estimates to new construction, the model allocates the remaining units to the existing stock, first replacing retiring units as like-for-like replacement. Any remaining units then replace different retiring equipment types as conversions. The model does not specifically replace an individual system with another individual system. Rather, the model replaces retiring units with the total number of units entering the stock through the product flow. For example, in any given year, 300,000 units might retire based on their lifetime and age. The product flow data replaces those retired units, in aggregate, creating overall changes in technology saturation. The model balances retirement of the stock with entering product flow by leveraging default replacement categories. For heating, ducted systems (e.g., ASHPs) generally replace eFAF, while zonal technologies (e.g., DHP) generally replace zonal electric (except in the case of DHPs replacing eFAF). This logic is supported by and aligned with the decreasing saturation of those technologies in the RBSAs. For cooling, more units enter the stock than are retiring, so units not replacing retirements transition from no cooling to the entering cooling technology.

For both heating and cooling technologies, the model allocates units to building types and climates zones based on the saturation of equipment in the RBSA 2016. For example, if single-family in heating zone 1 homes account for 70% of a given technology in the 2016 stock, 70% of the units entering the stock as new units for that technology are allocated to single family in heating zone 1.

The product flow includes both gas and electric technologies, which can replace gas or electric technologies in the stock. When the gas or electric saturation of the stock changes as a result of incoming product flow, the model's baseline scenario mirrors the market scenario to hold the saturation of gas versus electric technologies the same in each case, avoiding attributing any savings to changes in consumption associated with fuel switching. Then, to implement a Frozen Efficiency Baseline consistent with the Seventh Plan definition, the saturation among electric heating technologies is held constant across 2016–2021 within the electric proportion of the stock. For example, if 25% of electric heating technologies in the 2015 stock are ASHP, the absolute number of

ASHPs in stock will increase or decrease to maintain 25% of the electric heating technologies as ASHP from 2016 to 2021, as the gas saturation increases or decreases. This implies that, in the specific case of a gas furnace switching to an ASHP (with the gas furnace as a secondary system), the baseline is modeled as an electric technology and is represented by the mix of electric heating technologies in the baseline stock.

Efficiency Mix. The model's efficiency mix refers to the mix of efficiencies of ASHP and CAC in the product flow. The team developed the efficiency mix for years 2011 through 2015 such that the modeled stock in 2016 aligns with that reported in RBSA 2016.[27] Between 2016 and 2020, the research team used NEEA's annual HVAC supplier sales data to estimate the annual, regional HVAC equipment efficiency mix. To accomplish this, the team developed an HVAC market-specific approach to extrapolate total market trends from the sample of distributors found in NEEA's sales data.[28] This extrapolation approach is subject to uncertainty, as discussed in more detail in the Uncertainty Sources and Sensitivity Analysis section of this report.

Finally, the team uses a simple linear regression model to project the efficiency mix for HVAC equipment sold in 2021 based on the observed efficiency mix for years 2016 through 2020, since 2021 data were not available at the time of model finalization. Analysis of the 2020 sales data relative to prior years indicates COVID impacts on the market did not affect efficiency share trends in 2020, and that 2021 residential HVAC sales are likely to follow trends established in prior years.

Step 4: Calibrate the market model's assumptions to align with RBSA 2016 and additional data sources

Calibration serves a crucial step in the stock turnover approach by using multiple data sources and aligning inputs and outputs to produce results that align with available data. For 2012-2016, the team calibrates the existing stock and product flow such that the modeled HVAC equipment saturation in 2016 aligns with the observed HVAC equipment saturation in the RBSA 2016.[29] For 2017-2021, the team uses four primary calibration steps, together, to produce results that align with regional data sources, where available, and engineering judgement and market knowledge where data is not available.

1. **RBSA 2016 Saturation.** As described previously, the team calibrates the stock turnover to align with RBSA 2016 saturation estimates. RBSA 2016 includes error bounds, so the team calibrates the stock turnover model within the RBSA error bounds to ensure the inputs are within reasonable ranges supported by the data. The team calibrated the stock turnover to the lower end of the RBSA 2016 error bounds for gFAF and ASHP to align with secondary data sources and moderate the impact product growth has on the stock.
2. **Product Lifetime.** Equipment lifetimes determine how slowly or quickly a unit will retire, which, in turn, informs the magnitude of product flow needed to maintain the stock turnover. The team adjusts product lifetimes within the range of empirical lifetime data to ensure the product flow

[27] RBSA 2016 is subject to sampling error – the team's modeled saturations in year 2016 are within the RBSA's error band.
[28] Additional detail on that analysis can be found in the 2016-2019 HVAC Sales Data Executive Summary report available at https://www.bpa.gov/-/media/Aep/energy-efficiency/momentum-savings/bpa-hvac-sales-data-report-2016-2019.pdf. At the time of this report, BPA had not yet published the 2020 report, but the model does incorporate NEEA's 2020 data.
[29] 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.

inputs produce results that are realistic (e.g., the stock does not run out of eFAF units), reasonable (e.g., the stock will not see drastic shifts in technologies over a short period of time), and mathematically feasible. The team adjusted ASHP lifetimes from 17 to 15 years and gFAF lifetimes from 24 to 21 years. As a result of expert panel feedback on 2020 and 2021 trends, the team further adjusted 2020 and 2021 ASHP, DHP, and gFAF lifetimes down an additional 10% to account for a higher rate of replacement in those years.

3. **Product Flow.** While NEEA's annual HVAC supplier sales data informs the growth or decline of a technology in the stock, the team does not assume each unit sold goes to a unique dwelling unit in the stock. Some sales serve as secondary systems. During the calibration process the team increased the assumption of gas furnaces serving as secondary applications to ASHP from 10% to 20% of ASHP.[30]

Estimating Saturation for Secondary Factors

As described earlier in this section, the model estimates the saturation of non-equipment factors, or secondary factors, that impact HVAC energy consumption, with an approach unique to each factor. The four secondary factors—building shell, thermostat type, installation practices, and duct tightness—each rely on different data sources to estimate changes in stock over the analysis period. Since these factors do not use a stock turnover approach, this section describes the team's method for accounting for secondary factor market changes. In general, the team accounts for this by estimating the stock saturation of the technology in 2015 and using market data to estimate the saturation of the technology in 2016–2021.

Building Shell

The model addresses the heat loss characteristics of dwelling units in the region, including building shell improvements through insulation, air-sealing, and window upgrades. The Northwest has many ongoing weatherization programs that provide utility customers financial incentives to improve their home's shell, and these programs have a meaningful impact on per-home HVAC energy consumption. Additional building shell upgrades occur outside of these programs as well. To model this market, the team used three sources of market data to estimate regional building shell improvements for each year across 2016-2021: Principia (a market data analytics firm specializing in the construction products market)[31] supplemented by a regional insulation installer survey,[32] the two RBSA surveys (2011 and 2016), and program data. To effectively combine and compare these data sources, the data must be converted into a common unit of building shell upgrade, UA. UA is the product of the change in U-value, which measures heat loss through a building component, and the area of the building that receives the upgrade in units of square feet. The team applies each data source to the appropriate building type and component using the approach described below.

[30] https://www.bpa.gov/-/media/Aep/energy-efficiency/momentum-savings/181214-res-hvac-installer-survey-findings-memo.pdf
[31] https://www.principiaconsulting.com/
[32] The BPA Insulation Installer Survey and Supply Chain Interviews report can be found on BPA's website. https://www.bpa.gov/-/media/Aep/energy-efficiency/momentum-savings/2021-insulation-installer-survey-and-supply-chain-interviews.pdf

Fully Weatherized Building Shell

The team calculates building shell upgrades in terms of total UA improvement (U-factor x Area) per year, converted to an equivalent number of "Fully Weatherized" homes for the purposes of modeling, similar to describing greenhouse gas emissions from multiple sources in terms of CO_2-equivalent tons.

"Fully Weatherized" represents a home with all envelope measures installed from average shell conditions in 2015 to regional program specifications, including insulation, windows, and air sealing. Since individual homes rarely receive a full upgrade, a fully weatherized home represents a normalized value equivalent to multiple homes receiving a combination of insulation, window, and air sealing upgrades and is calculated based on the total UA improvement in the region observed by multiple data sources.

The team assumes all new construction homes are fully weatherized and only derives total market savings from improvements in existing homes.

Principia Insulation Sales and Installer Survey. The research team purchased data from Principia on single family residential retrofit and remodel building insulation sales for 2016–2019 for the four Northwest states. Data are organized by insulation type and application (e.g., floor, wall, ceiling).[33] Principia uses extensive quantitative and qualitative research to develop its market estimate, which the team corroborated by conducting additional primary research in 2021: distributor and manufacturer interviews and a statistically representative survey of installers representing all four Northwest states.[34]

Principia does not differentiate its sales data by heating fuel (electric versus gas). Therefore, the team allocated insulation sales to both electrically and gas heated homes based on the distribution of homes by fuel type in the model. The team converts the insulation sales data (provided in pounds) into annual units of UA improvement from single family insulation. This calculation uses standard starting and target R-values specific to each applicable building component as reported by installers in BPA's survey, along with material-specific assumptions around R-value per inch and density. The "WxInputs" workbook includes additional detail on the Principia data and the allocation to model inputs.

RBSA Surveys. The two RBSA surveys completed in 2011 and 2016 define a trend in improving building component U-values. However, analysis based on two rounds of data collected by building auditors is subject to measurement and consistency issues. To make the best use of the RBSA data without risking overstating savings, the team only applies RBSA data for building type and measure category (floor, wall and ceiling insulation, air-sealing, and window) combinations that are statistically significant at a 95% confidence level, where no better market data are available (e.g., Principia) and where RBSA trends exceed program savings estimates. These building type and measure category combinations are single family air sealing, manufactured home wall insulation, and manufactured home windows.

[33] Principia provided data in both remodel/retrofit and new construction categories. The team only uses the remodel/retrofit data to analyze improvements in existing homes, and assumes all new construction homes are fully weatherized.
[34] Ibid.

For these specific building type and measure category combinations, the team allocates UA improvement between the two RBSA surveys evenly across the five intervening years to establish a linear rate of annual UA improvement. The UA improvements include improvements in both electrically and gas heated homes. The model continues that linear rate as a projection into the years following 2016.

Program Data. Regional utility energy efficiency programs provide an additional data source where market estimates from Principia or the RBSA analysis do not sufficiently describe the market. For the building segment and measure category combinations without market data, program data represent a conservative estimate of the market activity. These building type and measure category combinations are single family windows, manufactured home air sealing, manufactured home attic insulation, manufactured home floor insulation, and all multifamily measures.

The team converts the reported aMW savings in the Council's Regional Conservation Progress (RCP) Report to a total annual UA improvement and disaggregates the reported value at the Technology, Application, or Practice (TAP) level to the more detailed building type and measure category (e.g., wall insulation, attic insulation, etc.). The conversion and disaggregation rely on BPA's more detailed program data as representative of the region's average savings per UA. Question 4: What are the program savings? details the process for calculating program savings.

The associated "TO41_ResHVACModel_WxInputs" workbook includes additional detail on the methodology and implementation of the weatherization inputs.

Thermostats

Advanced smart thermostat market adoption is a recent trend in the HVAC market, and many regional utilities provide rebates for these measures. The model's definition of advanced smart thermostats require the following specific features proven to save energy, consistent with BPA's definition:[35]

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

Thermostat evaluations show that some advanced smart thermostats reduce heating and cooling energy consumption by adjusting temperature setpoints when the home is unoccupied and reduce the use of back-up (electric resistance) heating in homes with heat pumps. To estimate impacts on total HVAC energy consumption, the team differentiates these advanced smart thermostats from other thermostats in the market.

[35] For more information, see: "Smart Thermostat Market Characterization to Inform Market Modeling" at https://www.bpa.gov/-/media/Aep/energy-efficiency/momentum-savings/181016-bpa-thermostat-market-characterization-memo.pdf.

The team estimates annual smart thermostat saturation using the following approach:

- The RBSA 2011 database does not include advanced smart thermostats; the team assumes a market saturation of 0% in 2011 for all HVAC system types because advanced smart thermostats were not available in the market at that time.
- The research team conducted an analysis of RBSA 2016 and other confidential market data to determine advanced smart thermostat saturation in 2016 and 2017 by HVAC system type, building type, and climate zone. For 2012-2015, the team interpolated between the two RBSAs.
- Not all HVAC systems in the model can use advanced smart thermostats. DHPs, VCHPs, and GSHPs typically have manufacturer-specific thermostat controls and are typically incompatible with advanced smart thermostats. For these system types, the team assumes a market saturation of 0% in all years of the analysis period (2011-2021).
- The research team then incorporates confidential sales and installation data collected from advanced smart thermostat manufacturers to estimate advanced smart thermostat saturation for years 2018-2021. These data lack granular information on building type, climate zone, and building vintage, so the team distributes thermostats proportionally between these segments based on the distribution of dwelling units by building type, climate zone, and building vintage.

Question 3 describes the savings by system type associated with advanced smart thermostats.

Commissioning, Controls, and Sizing and Duct Tightness

The Northwest has ongoing incentive programs aimed at HVAC installers to improve the CC&S installation practices for ASHPs. The research team believes these programs could have a meaningful impact on average, per-home HVAC energy consumption. There is no reliable time-variant data for the analysis period on CC&S saturation or duct sealing available through the two RBSA surveys. Therefore, BPA conducted a CC&S study[36] in 2019 and found evidence of CC&S occurring outside of programs. However, the study's sample size was too small to extrapolate to a regional level for market model purposes. Therefore, the team assumes that all regional CC&S and duct sealing activity occurs through energy efficiency programs.[37] As such, the primary data source for CC&S and duct sealing improvements in the region is the RCP, which reports aMW savings attributed to these programs. The team converts the aMW savings from the RCP into number of dwelling units that receive duct sealing and CC&S using the approach described in detail in Question 4.

Estimating Saturation for Tertiary Factors

The research team considered modeling temporal changes in the market for occupancy and the presence of secondary heating and/or cooling, but existing data (listed below) indicates there is little change over time. The market model, therefore, treats these two factors as tertiary factors that impact HVAC energy consumption for each technology, but does not change over time.

[36] https://www.bpa.gov/-/media/Aep/energy-efficiency/momentum-savings/2019-bpa-heat-pump-field-study-final-report.pdf
[37] The team considered removing CC&S completely from the model based on expert panel feedback but chose to include it since programs reported activity associated with CC&S, and BPA's study indicated a difference in controls practices within programs versus outside of programs. The panel's full feedback and the team's rationale for final model approaches are available at BPA's website: https://www.bpa.gov/energy-and-services/efficiency/market-research-and-momentum-savings/hvac-market-research.

The team is relying on information from the RBSAs and associated RTF 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 2 based on the RBSA 2011 and RBSA 2016 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.[38] The RTF's Phase II factor changed 1-2% depending on the heating zone between Calibration 1 and 2, indicating very little change in secondary heating presence between the two RBSAs.

Question 3: What are the total market savings?

Question 2 describes the number of dwelling units in the region, the saturation of technologies in those dwelling units, and the flow of new products entering the stock during the analysis period. Question 3 estimates how much HVAC energy those dwelling units consume, on average, in both a baseline and market energy consumption scenario. The difference between baseline and market energy consumption in each year across 2016-2021 (in aMW) results in total market savings, which are a necessary calculation to determine Momentum Savings. Total market savings are not used for any reporting purposes.

Question 3 of the Four Question Framework has two sub-questions that address the baseline and market scenarios:

> **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). Modeled installed stock, shipments, and efficiency mix in each subsequent year (2016-2021) informs the market scenario (Question 3b).

In both the baseline scenario and the market scenario, the first step is to develop a method to estimate total energy consumption for the residential HVAC market in a given year. The following sections describe the method for calculating this energy consumption estimate and how the team uses the modeled annual energy consumption to estimate total market savings.

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

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

[38] 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

Where:

Market size = total number of dwelling units with a specific primary HVAC system as defined by the model cells, as estimated in Question 2

UEC = energy consumption for a dwelling unit with primary HVAC system (kWh/yr) in given cell

t = analysis year

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

This section discusses the derivation of the various UECs for each cell in the market model. Distinct UECs are necessary for all combinations of primary and secondary factors discussed previously in Question 1 and shown in Table 8 below. For each primary and secondary factor, the team determined the level of granularity, or dimensions, to include in the market model. In defining the dimensions, the team sought to balance simplicity with comprehensiveness. The team prioritized accurate and reliable savings while minimizing overall model complexity. Table 8 also summarizes each primary and secondary factor included in the model. All the assumptions underlying each factor and dimension definitions are summarized in detail in the associated "UEC Summary" workbook.

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 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 circumstance. The team considered adjusting UECs because of the global COVID-19 pandemic that began in 2020, but the team's analysis of the U.S. Energy Information Administration's consumption data of consumption did not indicate major consumption differences that would significantly affect the results of the analysis.[39] Further, the Council's 2021 regional load analysis came to similar conclusions.[40]

Table 8. 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 (Step 1. Developing Calibrated SEEM Models and Step 2. Apply Adjusted SEEM Simulations to Other below) or with adjustments applied to SEEM results** (Step 3. Accounting for Factors Modeled Outside of SEEM below)	New Construction, Existing
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 and Efficiency Level	Primary		Various, see Table 3 and Table 4

[39] https://www.eia.gov/electricity/data/browser/#/topic/5.
[40] https://www.nwcouncil.org/sites/default/files/2021_11_p4.pdf.

Factor	Factor Status	Modeling Approach	Dimensions
Thermostat Type	Secondary	Developed indirectly based on study findings applied to adjust SEEM results (Step 3. Accounting for Factors Modeled Outside of SEEM below)	Baseline, Advanced Smart
Building Shell (Weatherization)	Secondary	Modeled directly based on calibrated SEEM results (Step 1. Developing Calibrated SEEM Models and Step 2. Apply Adjusted SEEM Simulations to Other below)	As Is (representative of the 2015 stock), Full Upgrade (i.e., fully weatherized), New Construction
Installation Practices (Commissioning, Controls and Sizing)	Secondary		Standard Practice (without CC&S), PTCS Installation (with CC&S)
Duct Tightness	Secondary		As Is (representative of the 2015 stock), Tight
Occupancy	Tertiary	Captured in UEC based on Phase II SEEM Adjustments (Step 1. Developing Calibrated SEEM Models below)	N/A
Presence of Secondary Heating or Cooling	Tertiary		N/A

* Building Vintage, Building Type, and Climate Zone do not change over time and are not specific technologies or factors that are accounted for in the model. 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 estimating UECs varies by HVAC system and climate zone, based on the available data, which is discussed in more detail below.

Table 8 also shows the method for deriving the UEC, which varies based on the status of the factor as well as the data available. The research team's UEC development approach is based on the following three tenets:

- It is grounded in empirical data whenever possible.
- 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.
- 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 and segment differentiators, or cells, based on SEEM building simulations and empirical energy consumption data. 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. 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, typically consistent with the RTF approach for such technologies. For example, zonal systems, such as packaged terminal heat pumps, room air conditioners, and portable air conditioners are difficult to accurately model in SEEM. For these technologies, the team relied on available empirical data to provide reasonable estimates of UECs. In all cases, the research team corroborated the modeled UEC estimates with available empirical data like the RBSA billing analysis or other regional studies, to ensure the results were as accurate and reliable as possible. The specific modeling approach and assumptions the team made for each HVAC system, as well as empirical data comparisons, is described in detail in the UEC Summary workbook.

The UEC development process comprises the following steps:

1. Develop calibrated SEEM models for a representative population of dwelling units for each building type
2. Apply adjusted SEEM simulations to other equipment types where sufficient empirical data do not exist
3. Account for factors that SEEM cannot accurately model using additional data and engineering judgement
4. Validate the SEEM model results based on available empirical data to confirm the model predictions

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.[41] 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). 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 team uses SEEM to directly model ASHP, DHP, electric zonal, and eFAF electric heating and cooling consumption.

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 energy consumption accurately reflects the typical, average energy consumption of HVAC equipment in a given cell in the region, comparable to billing data or other empirical estimates.

For single family and manufactured homes, the team developed the representative set of homes based on the modelable homes in the RBSA 2011 stock assessment (shown in Table 9).[42] 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 when the team built the model in 2019. Specifically, home characteristics consist of a number of key variables, including home geometry, square footage, building construction materials, and shell efficiency levels, all of which vary independently and are carefully captured in the RBSA 2011 dataset. The team also 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

[41] The RTF maintains SEEM documentation here: https://rtf.nwcouncil.org/simplified-energy-enthalpy-model-seem

[42] 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.

2011 sample. The team did not incorporate the RBSA 2016 homes because analysis showed similar geometry, square footage, and building construction materials, and minimal impact on energy consumption by adding the RBSA 2016 homes.

The RBSA does not include modelable units in multifamily buildings, so the team uses the RTF multifamily prototypes to model and weight the UECs, based on the foundation type of the individual RTF prototypes and the typical foundation types observed in RBSA 2011. The RTF's four multifamily prototypes are Woody Walk-up, Double-Loaded Apartment, Townhome with Crawlspace, Townhome with Slab-on-Grade. The team uses the SEEM models to "stack" units to represent a proportion of the whole building, then combines those stacks to represent low-rise, mid-rise, and high-rise multifamily buildings. Finally, the team weights the low-rise, mid-rise, and high-rise UECs based on the RBSA 2016 distributions to create a single weighted multifamily unit UEC by the model's cells.

As Table 9 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 9. Representative Set of Homes Used for SEEM Modeling

<table>
<tr><th>Building Type</th><th>Sub-set</th><th>Representative Homes</th><th colspan="2">Number of Homes</th></tr>
<tr><td rowspan="2">Single Family</td><td>Ducted</td><td>All modelable single family homes in RBSA 2011 with central systems, by climate zone</td><td>HZ 1 = 626
HZ 2 = 147
HZ 3 = 82</td><td>CZ 1 = 596
CZ 2 = 162
CZ 3 = 97</td></tr>
<tr><td>Unducted</td><td>All modelable single family homes in RBSA 2011 with zonal systems, by climate zone</td><td>HZ 1 = 247
HZ 2 = 64
HZ 3 = 63</td><td>CZ 1 = 157
CZ 2 = 69
CZ 3 = 12</td></tr>
<tr><td rowspan="2">Manufactured Homes</td><td>Ducted</td><td>All modelable manufactured homes in RBSA 2011 with central systems, by climate zone</td><td>HZ 1 = 168
HZ 2 = 76
HZ 3 =54</td><td>CZ 1 = 40
CZ 2 = 12
CZ 3 = 9</td></tr>
<tr><td>Unducted</td><td>All modelable manufactured homes in RBSA 2011 with zonal systems, by climate zone</td><td>HZ 1 = 7
HZ 2 = 8
HZ 3 = 2</td><td>CZ 1 = 0
CZ 2 = 1
CZ 3 = 0</td></tr>
<tr><td>Multifamily Units</td><td>N/A</td><td>RTF Prototypes</td><td colspan="2">4 (Woody Walk-up, Double-Loaded Apartment, Townhome with Crawlspace, Townhome with Slab-on-Grade)</td></tr>
</table>

Creating 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 for the number of homes in the region that particular home represents.[43] The team used these weights, normalized within each ducting subset and climate zone, to weight the results of each home.

Accounting for Non-Equipment Factors in UECs

As described in Question 1, building shell, installation practices, duct tightness, occupancy, thermostat type, and the presence and use of secondary heating or cooling systems are non-equipment factors that affect overall residential HVAC load. To account for these factors, the team develops specific UECs and SEEM inputs for each of the factors and dimensions noted in Table 8. For more details on the assumptions and inputs used to determine the designated shell level, duct tightness, thermostat type, 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 and RBSA 2016 includes homes that use secondary heating sources (e.g., wood stoves) or experience partial-year occupancy. The team cannot attribute precisely and specifically how much each of 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.

Step 2. Apply Adjusted SEEM Simulations to Other Equipment Types

Based on the calibrated SEEM results, the research team also creates UECs for all other technologies and climate zones that are not modeled directly in SEEM, including gFAF (electric fan energy only), GSHP and CAC.

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 3. Accounting for Factors Modeled Outside of SEEM

There are also several HVAC equipment types that are better modeled outside of SEEM but are expected to impact total residential HVAC energy consumption. To model these HVAC equipment types, the research team adjusts the SEEM results as summarized in Table 10. These adjustments are based on empirical data for DHP with eFAF and DHP with zonal, which are important HVAC technologies that have a larger impact on regional consumption and savings. Preparation of UEC estimates for other 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 10. These UEC estimates are clearly the most uncertain, but mostly pertain to HVAC equipment with low market size and which do not meaningfully contribute to total regional HVAC energy consumption or Momentum Savings. For that reason, they do not significantly impact the overall uncertainty in the market model results.

[43] 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).

Table 10. UEC Summary for HVAC Equipment Modeled Outside of SEEM

HVAC Technology	Method for Estimating UEC	Basis
DHP with eFAF DHP with Electric Zonal	Model as fixed savings from empirical data subtracted from SEEM eFAF and electric zonal result, consistent with RTF approach for these measures.[44]	Empirical data
Zonal Cooling (RAC/PAC/PTAC)	Scale Full DHP Cooling UEC up based on relatively lower average efficiency of RAC/PAC/PTAC compared to average efficiency of Full DHP, but assume lower usage due to seasonal nature of cooling equipment (1.75 x Full DHP Cooling UEC).	Engineering judgment
Non-electric Zonal Heating Equipment: All Boilers (oil, gas) and Heating Stoves (wood, pellets, propane, oil, fireplaces, etc.)	Model as 0.50 UEC of gFAF electric fan consumption to account for pumps (associated with boiler), fans, or any ancillary electrical consumption.	Engineering judgment
Packaged Terminal Heat Pump	Model as equivalent to Full 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.[45]	Engineering judgment
Single Speed ASHP HSPF 10+	Model as an extrapolation of lower HSPF ASHPs. SEEM includes limited HSPF options and uses a similar extrapolation method to estimate consumption of other HSPF efficiency levels.	Engineering judgment

Accounting for Thermostat Type

Average annual HVAC energy use is expected to decrease as saturation of advanced smart thermostats increase. BPA's definition of advanced smart thermostats includes specific thermostat features

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

[45] The team did not find evaporative cooler consumption data specific to the Northwest. In absence of better data, the team used a study based in Southwest and assumes that the relatively small number of evaporative coolers in the region are primarily found east of the Cascades, which has some similar climate characteristics as the Southwest. https://phoenixmanufacturing.com/evaporative-cooling-how-it-works-and-why-it-saves-you-money/

consistently save energy.[46] Although the RTF connected thermostat definition differs slightly from the definition of advanced smart thermostat established by BPA and referenced in this market model, all studies referenced in the RTF analysis are advanced smart thermostats by BPA's definition. Therefore, the research team models the energy impact from advanced smart thermostats generally consistently with the RTF heating savings estimates for connected thermostats,[47] which are shown in Table 11. The model assumes no savings associated with cooling, consistent with the RTF measure.

The only measure where the team does not align with the RTF savings values is thermostats installed on ASHPs. The RTF measure gives 5% savings for thermostats that do not include "resistance heat optimization," and 10% savings for thermostats that do enable this feature. All advanced smart thermostats have the capability for resistance heat optimization, but not all thermostats set up the feature correctly when installed. Since ASHP with CC&S already have resistance heat optimization, they only realize scheduling and setpoint savings, so the team assumes thermostats on ASHP with CC&S receives 5% savings. For thermostats installed on an ASHP without CC&S, the team assumes that any thermostat incented by programs have resistance heat optimization enabled, and only some thermostats that do not go through programs will be resistance heat optimized. Using analysis of thermostat program data and confidential thermostat sales data, the team assumes 50% of thermostats on ASHP without CC&S include resistance heat optimization, and 50% do not, resulting in a weighted average savings of 7.5%.[48]

Table 11. Summary of Advanced Smart Thermostat Savings

Equipment Types	% Savings of Heating Load (kWh/yr)	Notes
eFAF	2.5%	Consistent with RTF v2.0 measure
gFAF	5%	Consistent with RTF v2.0 measure
ASHP w/ CCS (Heating, non-VCHP)	5%	Assumes thermostats on ASHP with CC&S receives 5% savings since ASHP with CC&S already have heat pump optimization
ASHP w/o CC&S (Heating, non-VCHP)	7.5%	Assumes weighted average savings between RTF savings values of 5-10%; assumes any thermostat incented by programs on an ASHP w/o CC&S includes optimization, and some (but not all) that do not go through programs will be optimized based on analysis of thermostat program data and confidential sales data
DHP, Zonal technologies, VCHP, GSHP	0%	Assumes no savings since advanced smart thermostats are not currently compatible with zonal technologies and technologies with manufacturer-specific controls

[46] 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/-/media/Aep/energy-efficiency/momentum-savings/181016-bpa-thermostat-market-characterization-memo.pdf
[47] https://rtf.nwcouncil.org/measure/connected-thermostats, based on savings in the v2.0 measure workbook.
[48] The team considered adding a dimension to the existing cells (thermostats with and without resistance heat optimization) to differentiate savings consistent with the RTF, but due to the timing of the model completion and the RTF measure update, the model could not accommodate new dimensions.

Step 4. Validating SEEM Results Based on Empirical Data

As described previously, the team attempted to develop and validate UECs based on empirical data to the extent possible. To do this, the team first grounds the SEEM modeling in the RBSA 2011 and RBSA 2016 billing data, using the RTF's SEEM Calibration approach. The RTF's 2019 SEEM Calibration analyzed the raw SEEM model outputs alongside regional billing data and developed calibration factors to apply to raw SEEM model outputs to 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 equipment types (eFAF or Zonal for zonal systems, gFAF or ASHP for central systems): [49]

- Phase I adjustment serves to better match consumption for fully occupied homes in the region with regular bill patterns
- Phase II adjustment serves to account for partial occupancy, irregular bill patterns, and the use of non-utility fuels

Since both the RTF SEEM Calibration and the model leverage the RBSA homes[50] and the RBSA 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 and within the bounds of the SEEM calibration. However, in some cases the results will differ due to differences in modeling approaches. The model uses a larger set of modelable homes than the RTF and models all ducted and zonal homes with all ducted and zonal technologies to produce a robust UEC data set. The team also models homes with some SEEM input modifications where newer data is available, such as BPA's CC&S Study[51], that would better align inputs with regional practices.

To validate the model's UEC results, the research team compares the weighted average UEC results to empirical data for particular cells with sufficient billing data. These comparisons were possible for single family and manufactured homes with:

- eFAF in all heating zones
- ASHPs in heating zones 1 and 2
- Electric zonal in all heating zones
- DHP with Zonal Electric Heat in all heating zones

This section includes comparisons for each of these equipment types in single family existing homes with as-is building shell and duct tightness, baseline thermostats, and without CC&S installation practices. The research team reviewed the final UECs with the Expert Panel, whose feedback confirmed the model uses the best available input data and empirical studies for comparisons.[52] The team's UEC Summary workbook includes additional detail as well as manufactured home comparisons.

[49] More information on the RTF's SEEM Calibration work can be found in the RTF meeting presentations posted on the RTF website: https://rtf.nwcouncil.org/subcommittee/seem-calibration-and-measure-interaction and https://rtf.nwcouncil.org/calendar?previous=1. The RTF discussed SEEM Calibration 2 factors during the May, July, August, September, and October 2019 RTF meetings.

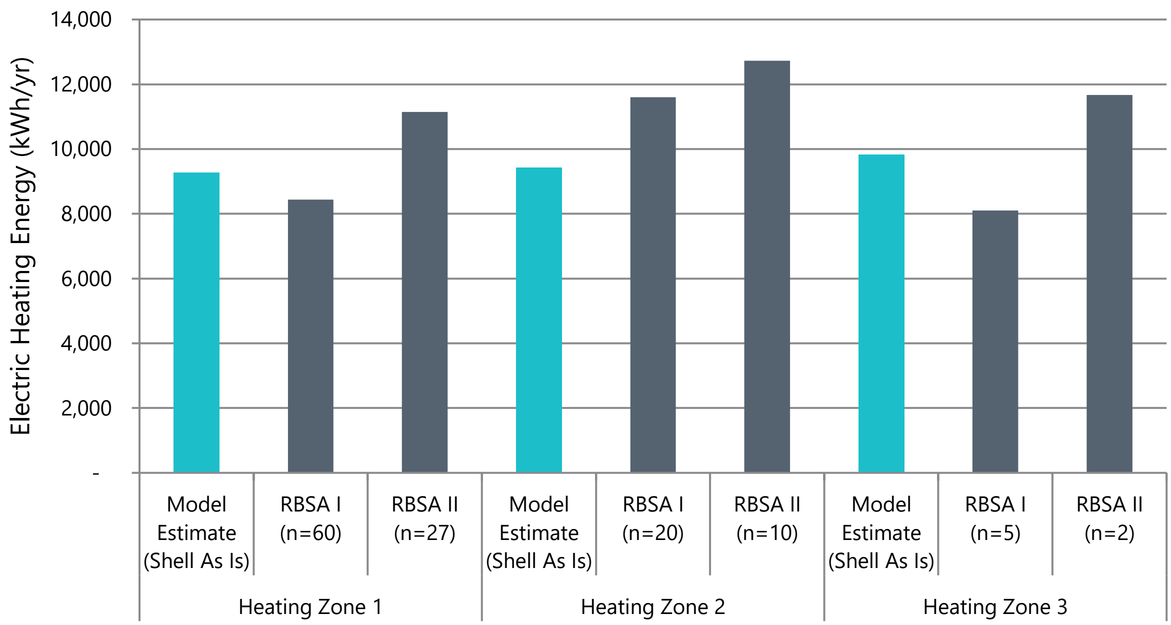
[50] The team's RBSA 2011 prototype homes include some homes that were not included in the RTF's Phase I and II calibration work due to the different purposes of the two efforts. Specifically, the RTF calibration work was focused on electrical energy consumption in program-eligible homes, while this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

[51] https://www.bpa.gov/-/media/Aep/energy-efficiency/momentum-savings/2019-bpa-heat-pump-field-study-final-report.pdf

[52] The panel's feedback and the team's responses are available on BPA's website: https://www.bpa.gov/energy-and-services/efficiency/market-research-and-momentum-savings/hvac-market-research.

Electric Forced Air Furnace. As shown in Figure 2, the eFAF SEEM model results fall between the two RBSAs in heating zones 1 and 3 but fall below both RBSAs in heating zone 2. The team uses caution when comparing data in heating zones 2 and 3 due to the small sample sizes. Overall, the results appear reasonable when comparing against the data and against each heating zone.

Figure 2: Comparison of the Model's eFAF UECs to Empirical Data



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

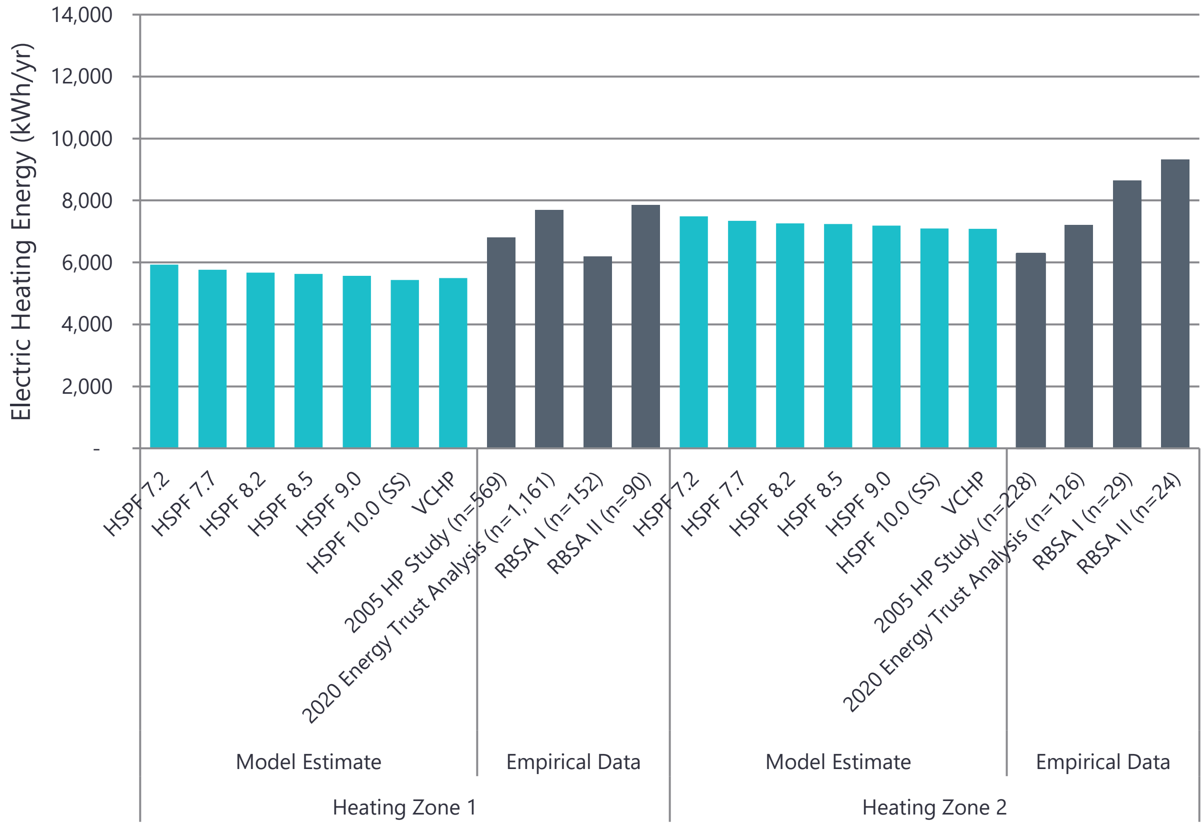
Air Source Heat Pumps. For ASHPs, Figure 3 compares the SEEM model estimates to the RBSA 2011 and RBSA 2016 billing data,[53] as well as billing data from the 2005 Heat Pump Installation Practices Study[54] and Energy Trust of Oregon's (Energy Trust) 2020 Billing Analysis.[55] The model's UEC results for ASHPs in heating zone 1 show lower consumption than any of the reported empirical data sets, most closely aligning with the RBSA 2011 billing data, but 15-20% lower than the 2005 HP billing study, Energy Trust billing analysis, and the RBSA II billing data.

In heating zone 2, the model results align fairly well with the average of empirical study results. RBSA 2011 and RBSA 2016 report higher consumption for heat pumps but represent a limited sample. The 2005 Heat Pump Installation Practices Study reports lower consumption, and the 2020 Energy Trust Billing Analysis aligns well with the model estimates.

Possible explanations of the model's lower ASHP UEC estimates compared to empirical data include differences in average house size, differences in weather, ranges of ASHP efficiencies in each study, and other normalization differences.

[53] The RBSA 2016 billing data is available through the RTF SEEM calibration work based on RBSA 2016.
[54] 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
[55] https://www.energytrust.org/documents/recurve-analysis-of-ducted-heat-pump-conversion-impacts-2013-2018/

Figure 3: Comparison of the Model's ASHP UECs to Empirical Data



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

When looking at ASHP energy savings (using ASHP HSPF 8.5 over the eFAF UEC as an example), the model's estimate results in lower savings compared to empirical studies, as shown in Figure **4**. The team considered adjusting ASHP consumption values to better align with empirical ASHP consumption estimates but found the resulting savings would stray further from empirical savings data. The team reviewed these results with BPA's Expert Panel, and the Expert Panel found the ASHP UECs reasonable as they do not overstate ASHP energy savings.

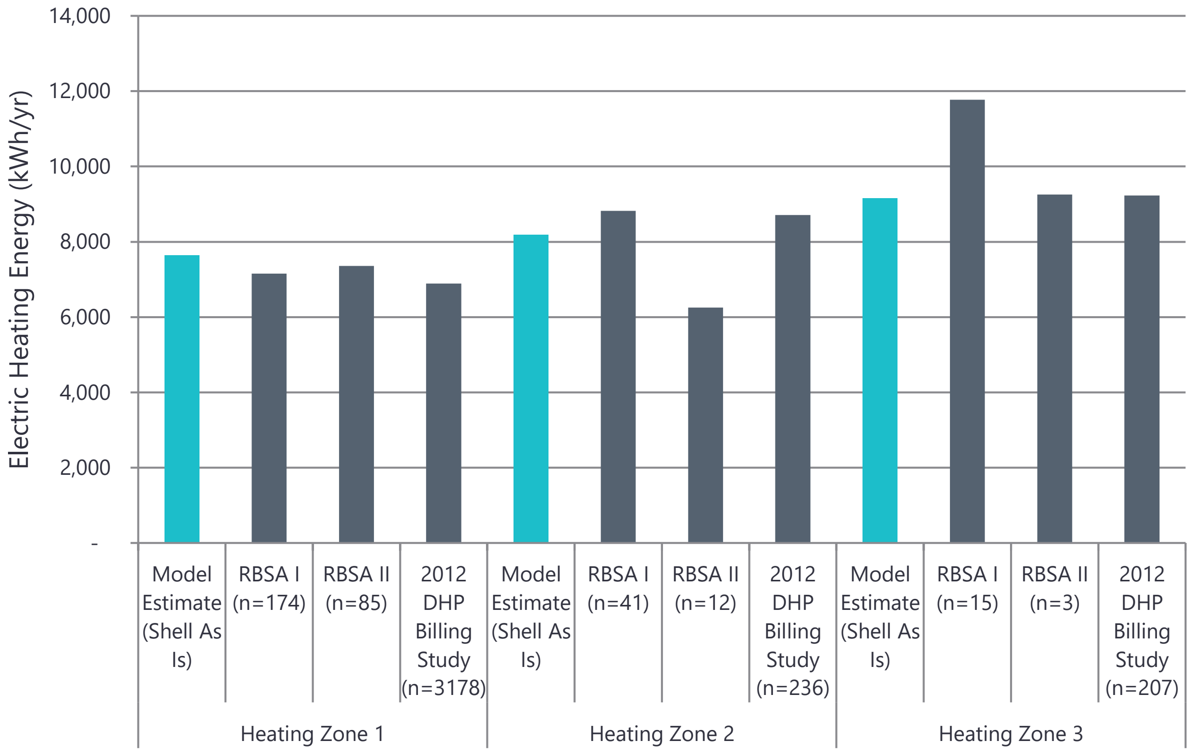
Figure 4: Comparison of the Model's Estimated ASHP Average Savings to Empirical Data

Note: This chart excludes Energy Trust's billing analysis, which did not distinguish heating savings from total savings and provided a less valuable comparison.

Electric Zonal. For electric zonal heat, the model estimates align reasonably well with the RBSA 2011 billing data, RBSA 2016 billing data, and the 2012 DHP Billing Study (which includes baseline consumption of electric zonal systems)[56], as shown in Figure 5. In heating zone 1, the model estimate is slightly higher compared to empirical data, but within a reasonable range. In heating zones 2 and 3, the model results fall between the empirical data and are particularly well aligned with the 2012 DHP Billing Study, which has the largest sample sizes.

[56] 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.

Figure 5: Comparison of the Model's Electric Zonal UECs to Empirical Data

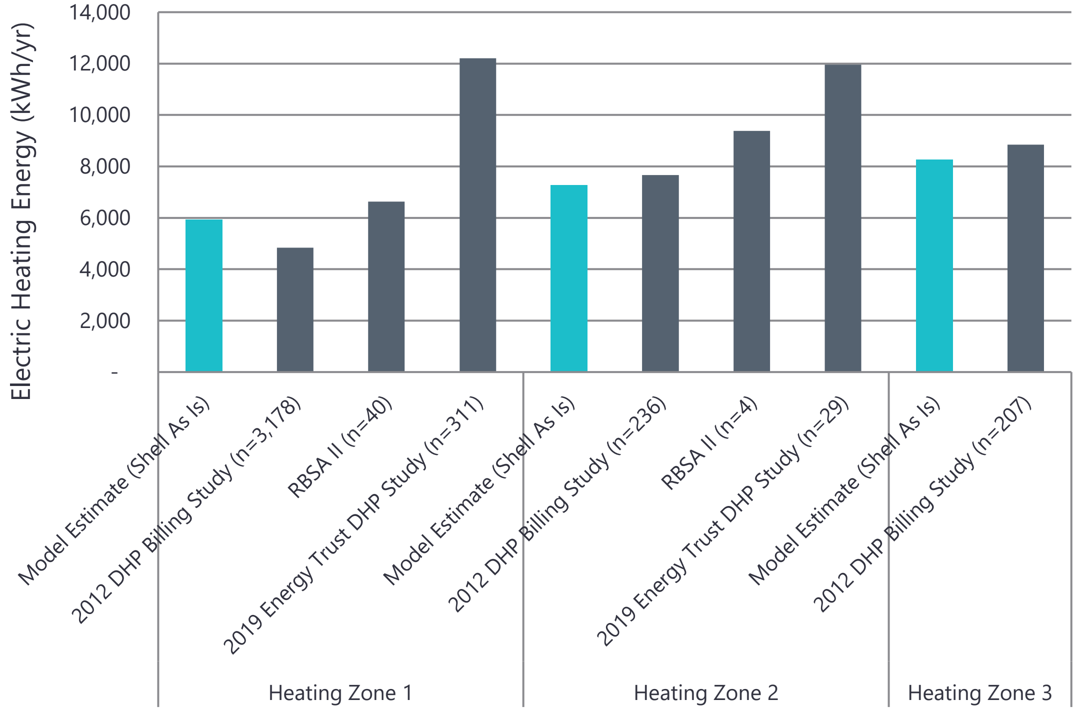


Note: RBSA I refers to RBSA 2011, and RBSA II refers to RBSA 2016.

Ductless Heat Pumps. The model estimated UECs for three DHP configurations: DHP with zonal electric heat, DHP with eFAF, and Full DHP. DHPs with zonal electric heat is the most prevalent DHP configuration in Northwest, therefore the team compared this configuration's UECs with empirical data to validate SEEM results. For DHPs with zonal electric heat in heating zone 1, as shown in Figure 6, the model estimate falls neatly between the RBSA 2016 and the 2012 DHP Billing Study, but falls well below the Energy Trust's 2019 DHP study.[57] Data reported by the 2019 Energy Trust DHP study revealed significantly higher consumption in heating zones 1 and 2 than the two other empirical studies. To align the RBSA 2016 billing data with the team's UEC estimates as much as possible, the team filtered the RBSA 2016 data to ensure that a mini-split is listed as the primary heating system and the zonal heat quantity is at least 1.

[57] https://www.energytrust.org/wp-content/uploads/2019/10/Residential_Ductless_Heat_Pump_Study_Report.pdf

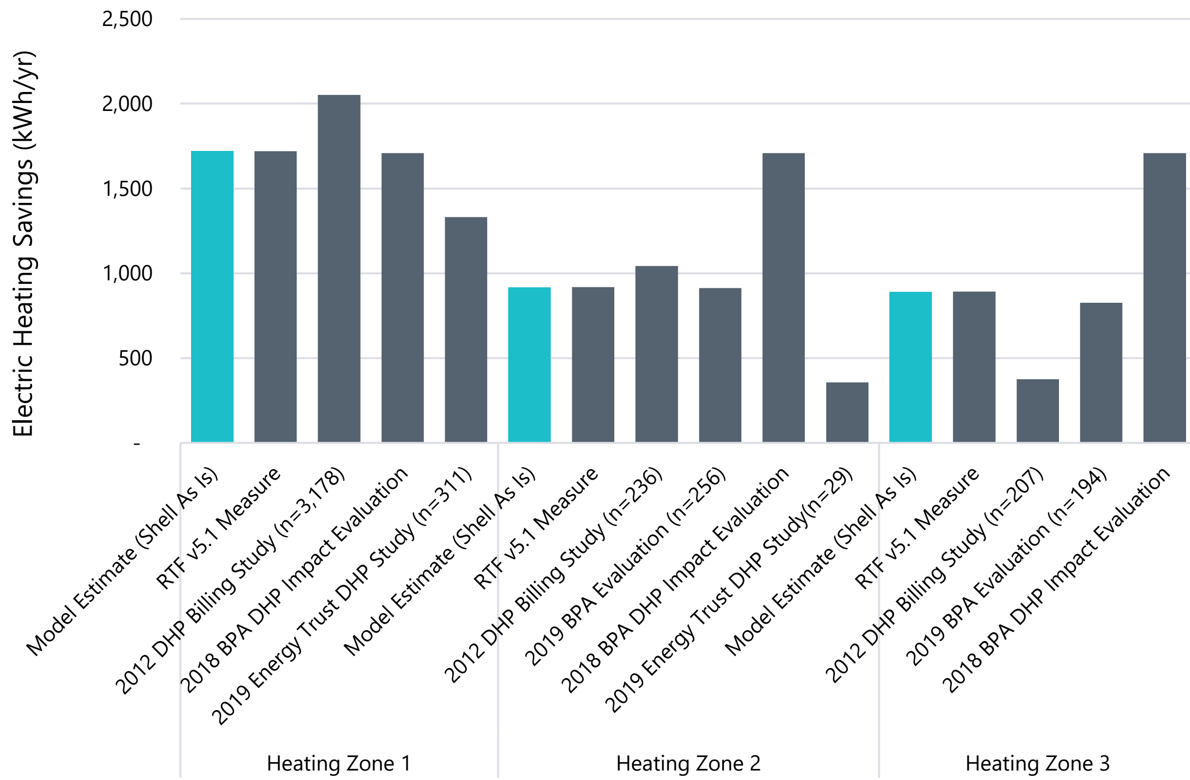
Figure 6: Comparison of the Model's DHP with Zonal Electric UECs to Empirical Data



Note: RBSA II refers to RBSA 2016.

When comparing DHP savings, the model's savings estimates (by adding DHP to zonal electric) is equal to the RTF's v5.1 measure savings since the model directly subtracts the RTF savings value from the electric zonal UEC to derive the DHP with zonal UEC. Figure 7 compares the model's average savings against empirical data. The team reviewed these results with BPA's Expert Panel, and the Expert Panel found the DHPs UECs reasonable since the savings align with the RTF's savings values.

Figure 7: Comparison of the Model's Estimated DHP with Zonal Electric Average Savings to Empirical Data



Note: The RTF's savings values are a weighted average of the other listed studies (in light gray), all of which can be found on the RTF website: https://rtf.nwcouncil.org/measure/ductless-heat-pumps-zonal-heat-sf

Based on these comparisons, the team determined that the model's calibrated SEEM UEC results were reliable and agreed with the available empirical data as well as possible. In addition, the team developed the inputs to the SEEM models based on the best available data and consistent with data and methodologies used in other regional programs, including the Seventh Plan and RTF measures.

Calculating Total Market Savings

As an interim step to derive Momentum Savings, the model calculates total regional HVAC energy consumption under two different scenarios and take their difference to calculate total regional market savings (which includes savings incented by programs and Momentum Savings):

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

The difference in energy consumption between the baseline and the market scenario determines total market savings from 2016-2021. Structurally, these total energy consumption 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

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

Equation 6. Regional HVAC Energy Consumption - Market Scenario

$$\text{Total Annual Energy Consumption}_{t,\ market}(\text{kWh/yr}) = \sum_{c}\left(\text{UEC}_{c}(\text{kWh/yr}) \times \text{MarketSize}_{c,t,\ market}\right)$$

Where:

t = analysis year

c = cell

The total market size in terms of overall number of dwelling units is constant in Equation 5 and Equation 6. In addition, the model holds the saturation of gas and electric technologies during 2016-2021 the same in both the baseline and market scenario, so the only driver for total market savings is changes in the saturation of different efficient electric technologies in the baseline and market scenarios. In other words, the baseline and market scenarios reflect the same number of dwelling units and number of electrically heated or cooled homes in the stock in each year, but they reflect different assumptions about the mix of electric 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 market model baseline. The Council describes its Seventh Plan baseline as follows:[58]

> *"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 market model, the baseline represents how the stock of equipment would have **most likely changed** in lieu of program and associated market activity. For some technologies, this means the baseline is the frozen efficiency of the product flow in 2015 (the year the Seventh Plan was written), aligning with the Council's definition of "market conditions at the start of the planning period." This baseline is also known as the current practice baseline. However, the team adjusts the frozen product flow assumption (both in the baseline and the market scenario) to account for current or new federal standards during 2016-2021 that were not known and accounted for in the Seventh Plan's baseline. Other technologies employ a static stock, or pre-conditions baseline, consistent with the Seventh Plan. HVAC technologies with a static stock baseline use the overall saturation of electric HVAC equipment installed in the 2015 stock as the baseline.

Non-equipment factors that use a static stock baseline use the 2015 stock conditions, specific to each technology. Table 12 summarizes the technologies described in the Seventh Plan, grouped by technologies that use a static stock or current practice baseline, and how the model implements each baseline.

[58] https://www.nwcouncil.org/energy/7th-northwest-power-plan/about-seventh-power-plan, Appendix G, pg 8.

Table 12. Summary of Baseline in the Seventh Plan and Implementation in the Model

Seventh Plan Res HVAC Measures and Baseline Summary		Model Implementation Notes
ASHPs - Conversions	**Static stock (pre-conditions) baseline** based on RBSA 2011; savings based on eFAF baseline (for heating) with baseline mix of cooling techs (for cooling)	Hold the 2015 stock saturation of electric HVAC technologies (eFAF, ASHP, DHP, GSHP) constant across 2015-2021, based on Seventh Plan assumptions, but updated with RBSA 2016 analysis to estimate 2015 saturation
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	
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	
GSHP	**Static stock (pre-conditions) baseline** based on conversion from ASHP (HSPF 9.0)	
Weatherization (SF, MH, and Low-rise MF only)	**Static stock (pre-conditions) baseline** based on insulation, fenestration, and infiltration parameters	Hold the 2015 stock saturation of "As Is" vs. "Fully Weatherized" shell constant from 2015-2021
Duct Sealing	**Static stock (pre-conditions) baseline** based on RBSA 2011 duct sealing levels	Model as 100% "As Is" ducts per RBSA 2011
Advanced Smart Thermostats	**Static stock (pre-conditions) baseline** of "existing" thermostat mix (<1% penetration)	Hold the 2015 stock saturation of advanced smart thermostats constant from 2015-2021, modeled by interpolating RBSA 2011 and RBSA 2016
ASHPs - Upgrades	**Current practice baseline** (market average of ASHP efficiency levels) of 8.5 HSPF based on RTF analysis[59]	Hold 2015 ASHP efficiency levels, as determined by the 2015 sales mix, constant from 2015-2021
CC&S	**Current practice baseline** based on "standard practice heat pump installation" as defined by BPA's 2019 Heat Pump Field Study[60]	100% standard practice installation

[59] 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.
[60] https://www.bpa.gov/-/media/Aep/energy-efficiency/momentum-savings/2019-bpa-heat-pump-field-study-final-report.pdf

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

The research team also holds the saturation of gas technologies in the baseline equal to the saturation in the market 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 total market savings. The Council does not treat fuel conversions as energy efficiency; the market model results are aligned with that position. When the saturation of gas technologies in the stock increases or decreases, the baseline is still the mix of electric HVAC technologies, but the saturation of the electric HVAC technologies adjusts proportionally so the total saturation adds to 100 percent.

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

Energy consumption in the years since the Seventh Plan describe the market scenario, or what happened in the market from 2016-2021. In the market 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 occurred over time. Therefore, in the market model, the market 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 during the Action Plan period is the difference between the baseline and market energy consumption in that year, as Equation 7 illustrates.

Equation 7: Cumulative Total Market Savings in Each Year

$$CumulativeTotalMarketSavings_t = (BaselineStockConsumption_t - MarketStockConsumption_t) \times BusbarFactor$$

Where:

t = analysis year

All UECs in the market model and any available energy consumption data stem from calibrations to metered consumption at the home site. The team converts site-level market savings to savings at the 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 savings (i.e., **first-year** savings in each year) for reporting purposes, the team calculates the difference in cumulative savings from year-to-year (Equation 8).

Equation 8: First-Year Total Market Savings in Each Year

$$FirstYearTotalMarketSavings_t = CumulativeTotalMarketSavings_t - CumulativeTotalMarketSavings_{t-1}$$

Where:

t = 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 total regional energy consumption in the market scenario, described in Question 3, reflects consumption 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 and NEEA savings from the total market savings calculated in Question 3. After subtracting the program savings, the remaining savings are regional Momentum Savings.

The team uses each regional utility's reported program savings as shown in the RCP to account for program savings in the model.[61] To do so, the research team translates the regional reported program savings (aMW) into quantity of incented units (e.g., number of incented DHPs). This translation ensures that both program savings and Momentum Savings are calculated using a single consistent baseline, the Seventh Plan baseline, as described in Question 3a. This alignment also ensures the program scenario incorporates the model's use of the most current UEC data that was not available to utilities at the time of reporting. Finally, the program scenario also includes NEEA and code-related activity so these savings would not be reported as Momentum Savings. Namely, these savings include NEEA's DHP initiative and efficient activity associated with new construction codes. The team calls the resulting program savings calculated by the model "adjusted program savings" and uses it solely as an interim step in calculating Momentum Savings, not for other reporting purposes.

The data sources and methodology the team employs are described in more detail in the following sections.

Program Savings Methodology

This section describes the team's approach to integrating the region's reported program savings in BPA's unique consumption modeling framework. The program scenario incorporates program-incented units into the baseline scenario so that program scenario energy consumption reflects what the baseline consumption would be, after accounting for program influence, shown in Equation 9 below. The difference in energy consumption between the baseline scenario and the program scenario represents the adjusted program savings.

[61] https://rtf.nwcouncil.org/about-rtf/conservation-achievements/

Equation 9. Regional HVAC Energy Consumption - Program Scenario

$$\text{Total Annual Energy Consumption}_{t,\ program}(\text{kWh/yr}) = \sum_c \left(\text{UEC}_c(\text{kWh/yr}) \times \text{MarketSize}_{c,t,\ program}\right)$$

Where:

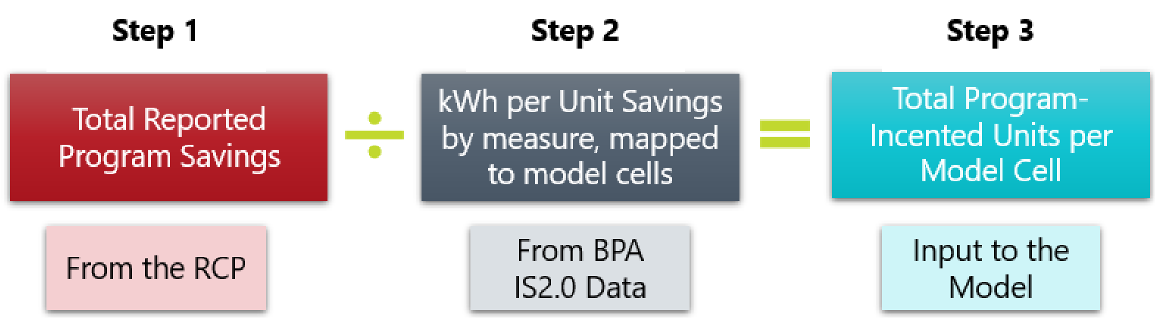
t = analysis year

c = cell

As indicated by Equation 9, the research team uses the same UECs and calculation methodology described in Question 3 for the baseline and market scenario to account for the program scenario in a consistent manner. Then, the team estimates market size for the program scenario with an analysis of the number of efficient units delivered via programs at the same level of granularity the team used to derive the market size in the baseline and market scenario (i.e., by cell). This results in a program scenario in which the only high-efficiency HVAC equipment and non-equipment factors entering the stock above the baseline come from program-incented units.

The number of program-incented units is the market size component of Equation 9, which the team translates directly from program savings reported in the RCP. The RCP tracks reported program savings by sector, end use, category, and TAP, which is not as granular as the model's cells. Thus, the team develops 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 cell. Specifically, the team implements three steps as illustrated in Figure 8.

Figure 8: Program Savings Approach Diagram



Step 1: Start with the total program savings by measure in the RCP. To quantify regional program savings and account for it in the market 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, including BPA's public customer utilities, private investor-owned utilities (IOUs), the Energy Trust of Oregon, and NEEA.

The research team primarily relies on the Council's annual RCP survey and report to describe regional utility program activity.[62] The RCP survey and report provide a broad snapshot of regional program

[62] The team's analysis relied primarily on the values reported in the 2020 RCP: https://rtf.nwcouncil.org/about-rtf/conservation-achievements/2020/

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 end use, category, and TAP. The Program Savings workbook includes the full list of technologies reported in the RCP data that are available to the research team and relevant to the residential HVAC market.

Step 2: Quantify kWh per unit savings and map each program measure to the applicable model cell or cells and. The RCP only reports total energy savings per TAP category; it does not include efficiency assumptions or total units incented. In addition, the TAPs identified in the RCP are not granular enough to understand or compare the baseline or measure detail to the model framework and assumptions. The BPA's IS2.0 database of detailed program savings information reported by BPA customer utilities include more granular measure information than the RCP. 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.[63] This analysis assumes that BPA's average savings per unit is similar to the values other utilities use in regional programs.

To check the reasonableness of this approach, the team compared the average kWh savings per unit derived from BPA IS2.0 database to the model-derived per-unit savings values (based on the UECs developed by the research team) and the per-unit savings in RTF measures. The team has confidence in BPA's program data being representative of regional program activity because the per-unit savings value falls within the range of savings values in RTF measures, which many regional utilities use for deemed savings. Any differences in unit savings values could be explained by logical differences in methodology or assumptions (e.g., BPA's per-unit savings value may not be updated as quickly as RTF measure updates). The team also analyzed the percentage of regional activity reported in the RCP and found that BPA represents more than 40% of regional savings for measures with the largest regional savings, further boosting confidence in this approach. For more details, see the "UES Comparison" tab in the UEC Summary workbook.

In many cases, the BPA IS2.0 data is still not as granular as the model's cell definitions. For example, a particular BPA 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 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.

For each BPA program measure, the team divides BPA total reported savings by BPA total reported number of units to derive an average kWh savings per unit. The team calculated two kWh/unit values for each BPA program measure, one for 2016-2017 and one for 2018-2020, to account for general shifts in RTF and BPA savings values over time.

Step 3: Calculate total program-incented units per model cell. Finally, the team translates 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. The team inputs these quantities into the model to calculate the program scenario.

[63] 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.

After applying the methodology described above to estimate total program-incented units for 2016 to 2020, the team forecasts program-incented units for 2021 by holding 2020 units constant by TAP.

This process leverages the best available data to obtain the level of detailed information needed to calculate number of program-incented units. For more detail on the analysis, see the Program Savings workbook (and associated weatherization workbook).

Accounting for Savings Associated with Energy Codes

The Seventh Plan baseline implicitly includes efficient practices required by energy codes and federal standards, existing or forthcoming, known to the authors at the time the plan was written. However, the team is aware of specific code updates enacted after the plan was written that NEEA influenced under their regional codes and standards efforts.[64] NEEA reports savings associated with energy code improvements to the RCP, but these savings include a range of non-HVAC-related improvements, so the model uses a tailored approach to comprehensively account for code-driven savings in the residential HVAC end use.

The team must account for permitted building shell improvements in the market model because they are included in market data and the model's estimate of total market savings from Question 3.

To ensure that this code-driven efficiency activity is not counted as Momentum Savings, the team models the code-driven energy savings as part of the adjusted program savings.

All Northwest state energy codes have required minimum building shell performance for both new construction homes and major remodels throughout 2016-2021. As discussed previously, the team models new construction building shells in SEEM as defined by new construction homes in RBSA 2011. As a result, the new construction UECs do not include shell improvements associated with newer energy codes during 2016-2021. For renovations and major remodels, however, some of the insulation activity included in the team's assessment of insulation market activity using Principia and RBSA data includes renovations where a permit is pulled. For permitted projects, the project must upgrade insulation to code levels for the square footage covered by the permit. In the regional installer survey mentioned in Question 3, a weighted average of 41% insulation projects in existing homes outside of programs was associated with a permit. [65] Therefore, the team attributes 41% of non-program upgrades to code-driven projects. This is a conservative estimate since renovation permits frequently cover only a portion of a home's area, but the analysis assumes that the home's full square footage is code-driven. To be conservative and not potentially overestimate Momentum Savings, the team adds 41% of non-program "Fully-Weatherized Homes" to the program units, thereby removing the savings associated with code-required building shell updates from the Momentum Savings calculation.

The model avoids other savings associated state and local energy codes, including ASHP and DHP installed in new construction homes in Washington, by holding the new construction HVAC saturation in the baseline the same as the market scenario.

[64] https://neea.org/our-work/codes-standards/codes

[65] The research team prefers to use insulation installer's estimated share of projects associated with a permit because renovation and alteration permits do not contain enough detail to ascertain if, and how much, insulation is installed.

Accounting for Savings from NEEA Initiatives

NEEA works to transform markets, including residential HVAC end uses. Because NEEA savings reported in the RCP represents total market savings for these technologies, the market model must account for savings from each NEEA initiative as part of the program scenario. There are three active NEEA initiatives related to residential HVAC: 1) the residential DHP initiative, 2) RACs and PACs included in NEEA's Retail Product Portfolio (RPP), and 3) NEEA's code and above code programs.

For NEEA's DHP Initiative, NEEA actively tracks distributor DHP sales within the region and reports total market DHP savings for 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, which include units that are sold into multifamily and new construction applications and "Full DHP" applications in addition to units in NEEA's scope. NEEA's reported DHP savings include only units within its DHP Initiative scope, which are reflected in the RCP as "NEEA Alliance" savings, but potentially result in a different quantity than estimated by the model. To avoid attributing Momentum Savings to units within NEEA's scope, the team includes all retrofit DHPs in single family and manufactured homes in DHP with zonal or eFAF applications calculated by the model as program savings. The remaining DHP units (outside NEEA's scope) included in the model that are not reflected in regional program activity are part of regional Momentum Savings.

NEEA also reports savings for ENERGY STAR®-certified RACs and PACs as part of its RPP. However, the BPA Momentum Savings model does not track RAC or PAC efficiency variation. As a result, the model does not include any RAC or PAC market savings (i.e., the stock saturation of RACs and PACs modeled in the market scenario is the same as the baseline scenario), and the team does not account for NEEA's RPP-reported RAC/PAC savings in the model.

Finally, NEEA reports savings associated with NEEA's Certified Homes and Manufactured Homes programs, as well as building code improvements.[66] These programs address savings associated with more efficient new construction homes constructed from 2016 and later. The team modeled UECs of all new construction homes based on typical construction practices for an average new home built between 2000 and 2011, as captured in RBSA 2011. This means the model does not report market savings or Momentum Savings associated with more efficient building characteristics associated with energy codes during 2016-2021 and avoids overlap with these programs. As a result, the team does not subtract NEEA's reported savings associated with these programs, as they are not a source of market savings in the model. However, as mentioned above, the team does account for savings associated with installation of efficient HVAC units and insulation installed as part of a permitted retrofit or remodel in the program scenario.

[66] https://neea.org/our-work/codes-standards/codes

Market Model Results

Once the team has developed regional program savings estimates that align with the model scope and methodology, the final step is to subtract all regional residential HVAC program savings from the total market savings calculated in Question 3. The remaining savings are Momentum Savings.

These model results represent Momentum Savings estimates for 2016-2021. This section briefly describes the results from the research team's Momentum Savings analysis. It also includes a high level summary of regional consumption and technology trends. The supplemental Model Export Tables includes the model's detailed results and the Analytica model itself provides the full underlying model.[67] Note, the model does not report savings by state due to market data limitations and overlap with heating and cooling zones. The model also does not report savings by measure due to the interactive effects of HVAC equipment and non-equipment factors.

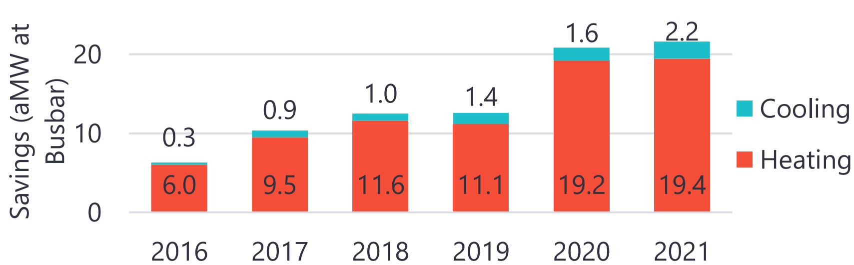
The research team estimates a total of 84.2 average megawatts[68] (aMW) of regional, residential HVAC Momentum Savings from 2016-2021 (see Table 13). These savings include all residential HVAC systems, as described in Question 1 of this document and represent first-year energy savings.

Table 13: Annual, Regional Residential First-Year HVAC Momentum Savings Relative to the Seventh Plan Baseline (aMW at Busbar)

Savings Type	2016	2017	2018	2019	2020	2021	Total
Regional Momentum Savings	6.3	10.4	12.5	12.6	20.8	21.6	84.2

Figure 9 shows total regional Momentum Savings by heating and cooling. Over 90% of total regional Momentum Savings are driven by changes in the heating end use. The model derives electric savings from the increased saturation of efficient HVAC heating equipment like ASHP, DHP, GSHP, and ASHP, increased heating and cooling efficiency of ASHP and CAC, and increased saturation of non-equipment factors like building shell improvements and advanced smart thermostats. The model does not derive Momentum Savings from heating fuel conversions, changes in cooling technology saturation, DHP savings within NEEA's target market, or savings associated with energy code improvements.

Figure 9: Annual, Regional Momentum Savings, by Heating and Cooling



[67] 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.
[68] 1 average megawatt = 8,760 megawatt hours

Uncertainty Sources and Sensitivity Analysis

The team believes this model is an accurate and sound representation of regional HVAC stock, energy consumption, and market change over time since the results draw on the best available data. However, even the best data sources are subject to uncertainty. Thus, the team conducted a sensitivity analysis to understand the relative impact that six key inputs have on total residential HVAC electric consumption and Momentum Savings, and more importantly, identify areas of future potential research.

The team conducted a similar analysis in the Interim Model to identify areas to improve the model. As a result, BPA pursued several areas of market research and data collection, including working with NEEA on HVAC sales data collection and analysis, gathering insulation and thermostat sales data, conducting insulation installer surveys, performing qualitative market research with HVAC market actors, and updating SEEM inputs and UEC estimates to reflect the best available studies in the region.

The results of this model's sensitivity analysis shows that research has improved the model and reduced areas of uncertainty. It also indicates there are still areas of further improvement BPA can pursue for future models. This section describes the sensitivity analysis approach and the results of the analysis.

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 product flows and advanced smart thermostat saturation, rely on the team's synthesis of data sources where statistical uncertainty is not known.

The team first identified these scenarios as the ones that could have the largest impact on energy consumption and savings. Then, the team developed alternate sets of model inputs that represented reasonable uncertainty bounds for a low and high scenario. Finally, the team measured each input's effect on calculated total residential HVAC electric consumption and resulting Momentum Savings.

The six scenarios follow:

1. **Product Flow.** The model shows substantial ASHP and DHP market activity and energy savings, so understanding the relative impacts of uncertainty around ASHP and DHP product flow estimates is critical. The team varies product flow growth (year over year percentage change) in 2017-2021 by +25% and -50% to represent the range of potential growth estimates from comparative data sources.
2. **Efficiency Mix in Product Flow.** The team uses distributor sales data collected by NEEA to characterize the efficiency mix of new ASHP and CAC systems entering the region. The collected sales data do not cover the entire market (they cover 25% and 30% of the model's product flow estimates for ASHPs and CACs, respectively), but they represent most major residential HVAC manufacturers and sales from all four Northwest states. Therefore, the team believes the efficiency mix observed in these data represent the best data covering the entire region. To create high and low uncertainty bounds for this input the team varies the ASHP and CAC efficiency mix by +/- 50% based on comparative analysis of HARDI data. For each efficiency bin,

the team adjusts 50% of the units to one efficiency bin higher or lower, with the exception of the lowest efficiency bins which no longer meet federal standards.

3. **Building Shell Upgrades.** The team uses a combination of three data sources to estimate regional weatherization activity: Principia insulation sales data, RBSA analysis, and regional program data. The model does not include any single family window market data, so assumes no window upgrades occur in single family homes outside of programs. The high scenario assumes there are window upgrades in single family homes outside of programs and that program activity represents 34% of total market activity. The insulation installer survey reported 34% of insulation activity occurs through programs, so this scenario assumes the same percentage might occur for windows.[69] For the low scenario, the team removes RBSA data to model the impact uncertainty around the RBSA data has on results. In the low scenario, and only uses Principia insulation sales and program activity to model building shell upgrades.
4. **Advanced Smart Thermostat Saturation.** The existing, confidential advanced smart thermostat data gives the team confidence the model does not overestimate thermostat installations, but the data only represent limited manufacturers and new manufacturers continue to enter the market. Therefore, the team varies advanced smart thermostat saturation by +25% in the high scenario and does not include a low scenario.
5. **Advanced Smart Thermostat Energy Savings.** In addition to uncertainty in advanced smart thermostat regional quantity, regional advanced smart thermostat studies and program evaluation reports show a wide range of energy savings. The largest uncertainty with thermostat savings lies with ASHP, which have small sample sizes in current data. As described in Question 3, the team uses a weighted average savings value for ASHP without CC&S (i.e., advanced smart thermostats reduce heating UEC by 7.5%), which assumes that half of ASHP without CC&S will include electric resistance optimization with an advanced smart thermostat, and half will not. The team's sensitivity analysis assumes that the RTF ASHP thermostat measure reduces the heating UEC by 10% in the high scenario and by 5% in the low scenario. Since ASHP with CC&S already include electric resistance optimization, and fewer units include CC&S than do not, the team did not include ASHP with CC&S in this scenario.
6. **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. The team uses a range of consumption estimates in empirical data compared to the model UECs to inform the variation in UEC sensitivity. Where empirical data does not exist, the team assumes +/- 25% variation:
    - +/-10%: ASHP heating, eFAF, Zonal, DHP w/ Zonal heating based on the average range empirical data
    - +/-15%: DHP w eFAF heating, VCHP, GSHP, gFAF, AHSP cooling, CAC, DHP w/ Zonal cooling, DHP w/ eFAF cooling based on the average range of empirical data
    - +/-25%: Full DHP heating, non-electric zonal heat, Full DHP cooling, PTHP cooling, PTAC, RAC

[69] The BPA Insulation Installer Survey and Supply Chain Interviews report can be found on BPA's website. https://www.bpa.gov/-/media/Aep/energy-efficiency/momentum-savings/2021-insulation-installer-survey-and-supply-chain-interviews.pdf

The team considered but did not implement additional scenarios that have potentially higher uncertainty but relatively small impact on consumption. These potential scenarios included:

- Multifamily UECs, which have uncertainty due to the lack of SEEM-modelable homes for mid- and high-rise buildings; however multifamily units have the lowest consumption of the three building types, and therefore the lowest impact on savings, and the UEC sensitivity analysis includes variation in multifamily UECs.
- RBSA sampling, which has statistical uncertainty, but this uncertainty is reduced by the comparative analysis between the two RBSAs and how the team uses data within the RBSA's error bounds.
- Specific technologies with higher uncertainty but lower prevalence in the market, such as GSHP, PTHP, and duct sealing.

Sensitivity Analysis Results

The team measured the impact of each of the uncertainties described above by running the model calculations with alternate inputs. Table 14 shows how total residential HVAC electric consumption and resulting Momentum Savings varies based on the specific assumptions and inputs noted for each sensitivity scenario. Each scenario includes a low and high range, with the low range representing the less efficient case and the high range representing the more efficient case. Note that the "high" scenarios have a negative impact on consumption (decreasing consumption by a specific percentage), which has a positive impact on Momentum Savings because the decrease in consumption from efficiency improvements results in increased savings.

Each scenario provides information about the relative impact on consumption and savings and should be evaluated independently rather than against other scenarios, particularly due to the interactive effects HVAC technologies and non-equipment factors like building shell and thermostats have on each other. The section following the table describes the results for specific scenarios in more detail.

As shown in the table below, the sensitivity analysis results indicate the overall impact of the six inputs have a relatively small impact on consumption, with most scenarios having less than 1% impact on total, residential HVAC consumption. This indicates the model has high stability given these inputs. The results also show minor changes in consumption can have relatively large impacts on Momentum Savings, which is expected given the scenarios chosen represent the model's largest drivers of savings. Naturally, varying the inputs that produce the most savings have the largest impact on Momentum Savings.

With each scenario, the results give BPA valuable insight on the relative impact uncertainty of inputs have on consumption and Momentum Savings. The next two sections summarize the team's findings for the two most impactful scenarios, product flow and building shell. All other inputs have relatively small impacts on consumption and Momentum Savings and produced expected results given the team's understanding of those inputs.

Table 14: Sensitivity Analysis Impact to Total Residential HVAC Consumption and Momentum Savings

Scenario Description	Assumption	Impact to Total Residential HVAC Consumption		Impact to Momentum Savings	
		Low Scenario	High Scenario	Low Scenario	High Scenario
Product Flow	Vary ASHP, DHP product flow growth in 2017-2021 by +25%/-50%	1.4%	<-1%	-30.8%	15.4%
Efficiency Mix in Product Flow	Vary ASHP, CAC product flow efficiency mix by +/- 50% by adjusting 50% of units to one efficiency bin higher or lower, with the exception of efficiency bins that no longer meet federal standards	<1%	<-1%	-13.4%	14.7%
Building Shell Upgrades	Vary saturation of building shell upgrades to include estimated window sales as the high estimate and only Principia and program data as the low estimate	1.4%	<-1%	-33.7%	36.2%
Advanced Smart Thermostat Saturation	Vary saturation of advanced smart thermostats by +25%	-	<-1%	-	1.0%
Advanced Smart Thermostat Savings	Assume 5% electric heating savings from advanced smart thermostats on ASHP w/o CCS as the low scenario and 10% savings as the high scenario	<1%	<-1%	<-1%	<1%
UEC	Vary UEC for each technology by +/- 10% to 25%*	10.8%	-10.8%	-8.1%	8.1%

* See Sensitivity Analysis Approach section above for the team's technology-specific UEC variation.

Product Flow

As described previously, the team has pursued several efforts to reduce the Interim Model's product flow uncertainty. These results indicate significant improvement over the Interim Model, attributed to the following research and data collection:

- BPA has supported NEEA's annual HVAC sales data collection effort for the past four years and has helped increase the quality and representativeness of the collected data by troubleshooting data quality issues with NEEA, developing quantitative approaches to fill temporal and geographic data gaps, sharing best practices on model-matching, and increasing regional awareness of the study.

  NEEA's 2016-2017 sales data collection had five reporting suppliers, which has increased to 11 reporting suppliers in 2020. In addition to having more suppliers, data collected now covers 2016 through 2020, which allowed the team to identify regional trends in HVAC sales. Each of the main technologies (ASHP, DHP, CAC, gFAF) include at least four reporting suppliers in each state, with improved reporting for Idaho and Montana. Finally, most of the top manufacturers of main technologies are represented in the sales data.

- The team used new data from HIRL's Builder Survey to identify the portion of product flow that builders are installing in new construction dwelling units.

- Most recently, BPA also developed a method to identify VCHPs in the sales data, which enabled the team to more accurately model VCHP market adoption and consumption.

- BPA conducted market actor interviews to understand market trends and market gaps and corroborate model findings. These interviews allowed the team to examine data in more detail to understand trends with variable capacity heat pumps and other inverter-driven technologies. Market actors have confirmed that sales are growing year-over-year.

- BPA also attended the 2020 International Air-Conditioning, Heating, and Refrigerating Exposition and conducted 27 qualitative interviews in 2021 to ground the team's data analysis and model findings in larger market trends. These market engagements confirmed the significant increase in cooling in the Northwest and trends toward inverter-driven technologies like ASHP and DHP, corroborating the model's product flow estimates and efficiency mix.

The sensitivity analysis results indicate these efforts have significantly improved the model's product flow inputs, which showed sensitivity ranges at 80% in the Interim Model. The results also show the region should continue to focus on recruiting more suppliers for sales data collection and gathering data on online and retail sales, which would further improve the model's product flow and efficiency mix. Finally, BPA can continue to pursue qualitative market research to further reduce uncertainty in future model updates.

Building Shell Upgrades

The Interim Model only included program data in its market estimate of building shell upgrades, due to lack of data on building shell upgrades occurring in the market. Since the Interim Model, BPA collected and analyzed single family insulation sales data from Principia, a market data analytics firm specializing in the construction products market.[70] The team also completed an analysis of the two RBSAs finding statistically significant insulation, air sealing, and windows improvements. Finally, the team conducted a statistically representative survey of 61 insulation installers representing all four Northwest states to corroborate the sales data and RBSA analysis.[71]

These estimates rely on multiple data sources and improve the model's reporting of HVAC energy consumption in the region by accounting for activity occurring outside of programs. These results boost the team's confidence in the model approach and help BPA identify areas of future research.

The sensitivity analysis results for the Building Shell Upgrades scenario show Momentum Savings could be significantly higher if BPA chooses to pursue single family window sales data in the future. The results also emphasize the importance of RBSA's building shell data; BPA's future model will greatly benefit from the next RBSA's findings, which will further reduce uncertainty in the model's building shell inputs.

Advanced Smart Thermostats

The Interim Model relied on RBSA and confidential data analysis of limited Advanced Smart Thermostat data, resulting in higher uncertainty for thermostat savings and saturation. The sensitivity analysis shows consumption and savings are not highly sensitive to input variation tested in these scenarios, in part due to BPA's efforts to better represent this technology. After the completion of the Interim Model, the team continued to collect data for thermostats, and while BPA cannot share the confidential data or the names of participating manufacturers due to confidentiality restrictions, the team is confident the data collected is representative of regional sales for qualifying products. Finally, the team incorporated the RTF's updated thermostat savings to reflect the most current available research.

UECs

The model incorporates several recent RTF measure updates and regional studies to improve the model's UECs and reduce uncertainty since the Interim Model. These updates include improved consumption (and therefore savings) estimates for ASHPs and DHPs, weatherization, CC&S, and advanced smart thermostats. While some uncertainty with UECs is expected given the range of empirical data by technology, the sensitivity analysis indicates improvements in the UECs as well as areas of future research with additional studies on technologies with fewer data.

[70] https://www.principiaconsulting.com/

[71] The BPA Insulation Installer Survey and Supply Chain Interviews report can be found on BPA's website. https://www.bpa.gov/-/media/Aep/energy-efficiency/momentum-savings/2021-insulation-installer-survey-and-supply-chain-interviews.pdf