Pacific Northwest Pathways to 2050

Achieving an 80% reduction in economy-wide greenhouse gases by 2050

November 2018

Energy+Environmental Economics

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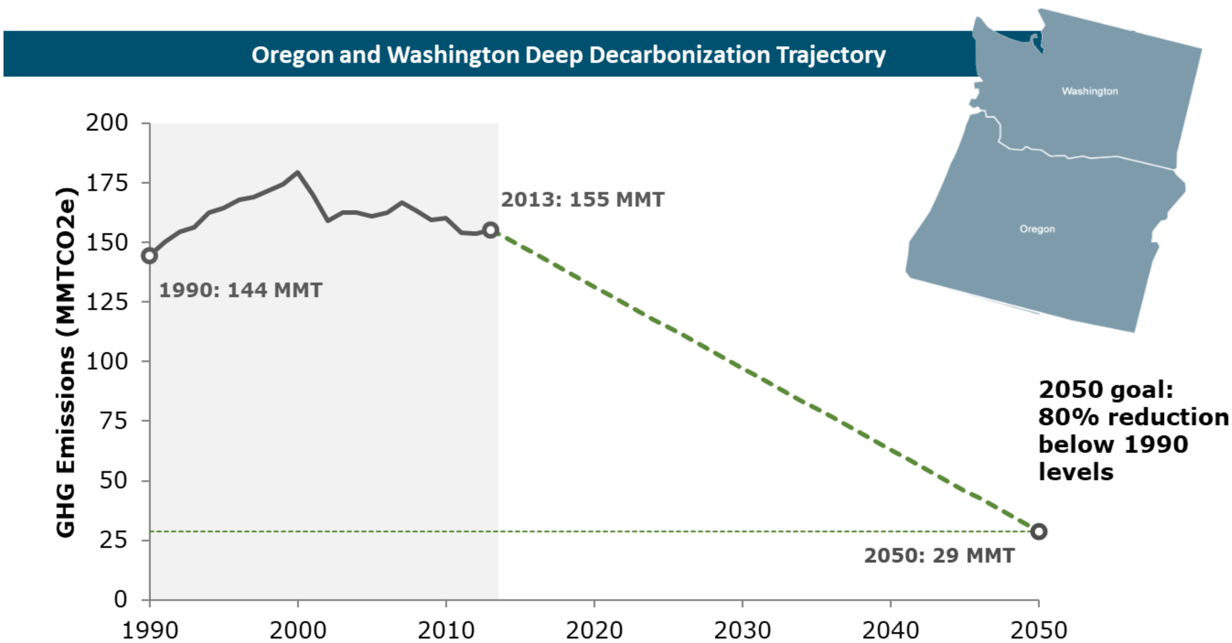
Executive Summary

Study Background

To help limit the worst impacts of climate change, Oregon and Washington have both committed to achieving significant reductions in greenhouse gas (GHG) emissions by 2050. Policymakers and the public are also contemplating new policies and programs to achieve steep regional GHG reductions.

This study evaluates the technology implications, and potential costs and savings, of different strategies to achieve long-term, economy-wide GHG reductions in Oregon and Washington. This study considers GHG emissions reductions of 80 percent below 1990 levels by 2050, a level of reduction often called "deep decarbonization." Achieving an 80 percent reduction goal across the two combined states would bring total regional economy-wide emissions down to 29 million metric tons CO_2-equivalent by 2050, compared to approximately 155 million metric tons CO_2e in 2013 (Figure 1).

Figure 1. Pacific Northwest historical greenhouse gas emissions and 2050 greenhouse gas target



This is an ambitious target. Achieving the carbon reductions envisioned in this analysis has implications for all residents, companies, and economic sectors in the region. NW Natural, as the gas distribution business serving most of Oregon's population and the Vancouver, Washington, area, has an abiding interest in both understanding the role of a natural gas company in achieving this low-carbon vision, and in helping to achieve the sustainability goals of its customers and the broader region. To address this, NW Natural contracted Energy and Environmental Economics, Inc. (E3) to perform an independent analysis of deep decarbonization scenarios for the Pacific Northwest.

This study builds on an existing body of research. Prior studies have evaluated options to achieve deep decarbonization in the United States as a whole, and in states like Washington and California. Similar studies have also been done at the sub-state level, including a recent deep decarbonization study of the Portland General Electric service territory. However, none of these prior studies, to our knowledge, has investigated the costs and implications of meeting winter peak energy needs during the region's coldest periods.

This study focuses on the role of buildings in meeting broad, economy-wide carbon reductions, and pays special attention to the performance of building space heating technologies under cold temperature conditions, and the costs of reliably serving those loads. The region's natural gas and electric systems are built to serve peak heating loads during cold temperatures that fall well below average winter conditions. Both the gas distribution system and the electric generation system experience the highest peak demands concurrently, during the winter. During the coldest days of the year, the natural gas system provides a large amount of energy to meet the region's heating needs.

A key question in this study is how the existing gas distribution system could be used to help achieve economy-wide deep decarbonization goals, while continuing to reliably meet regional peak energy demands. This low-carbon future is compared to what would be required of the region's electric system – already a winter-peaking system – if it were to take on the gas system's substantial winter peak heating loads. under a future where natural gas space and water heating were electrified.

Approach

The modeling approach applied in this project is based on E3's deep decarbonization scenario tool, called PATHWAYS. The economy-wide PATHWAYS framework is supplemented by tools tailored to specifically analyze the electricity sector, biofuel supply and conversion paths, and building energy performance. The Northwest version of the PATHWAYS model is tailored to regionally-specific energy demands, energy supply, and existing building types, vehicles, and other energy-consuming equipment, using local data whenever possible. The tool is also benchmarked to the Oregon and Washington state greenhouse gas emissions inventories.

PATHWAYS is an economic energy and greenhouse gas emissions accounting tool. A key feature of the PATHWAYS model is its detailed treatment of the Northwest's energy infrastructure. Energy infrastructure includes equipment that produces, delivers, and consumes energy, such as power plants, industrial facilities, trucks, cars, buses, and building equipment. While each sector and type of equipment consumes energy and produces emissions differently, collectively they determine the region's GHG emissions trajectory.

Costs, emissions, generation, and peaking capacity needs in the electricity sector are modeled in more detail using a separate electricity-sector tool called RESOLVE. RESOLVE is a power system operations and investment model that uses linear programming to identify optimal long-term resource investments in the electric system, subject to electric reliability and policy constraints. RESOLVE layers capacity expansion logic on top of a production cost model to determine the least-cost electric sector investment plan, accounting for both upfront capital costs and variable costs to operate the grid. This project uses a Northwest-specific version of RESOLVE that was initially developed for the Public Generating Pool in 2017 and described in the "Pacific Northwest Low Carbon Scenario Analysis" report.[1]

Biofuels are an important component of long-term decarbonization plans because they represent carbon-neutral fuels that can be transported and used with existing infrastructure and equipment. Assumptions around biofuel costs and supply receive detailed treatment using the E3 PATHWAYS Biofuels Module. This tool generates biofuel supply curves that determine the availability and cost of renewable liquid and gaseous biofuels, and optimizes the selection of combinations of feedstocks, conversion pathways, and final fuels based on regional fossil fuel demands.

Finally, we evaluate the hourly performance of different types of electric heat pump space heating equipment, using regionally appropriate winter temperature conditions. E3 worked with building science

[1] E3, "Pacific Northwest Low Carbon Scenario Analysis: Achieving Least-Cost Carbon Emissions Reductions in the Electricity Sector," December 2017. Available at: **http://www.publicgeneratingpool.com/wp-content/uploads/2017/12/E3_PGP_GHGReductionStudy_2017-12-15_FINAL.pdf**

consultants at Big Ladder Software to simulate the performance of several different types of buildings and heat pump equipment configurations in two climate zones in the Northwest, using the building simulation software EnergyPlus. After accounting for load diversity and building shell improvements, we use hourly load shapes to modify the base, system-wide hourly load profiles in the RESOLVE model. This creates a more realistic picture of how hourly electricity demands, and winter peak electricity demands, could change under a high building electrification future.

This suite of modeling and analytical tools allows us to combine a least-cost scenario design approach for the electricity sector, with a detailed understanding of electric building performance, with an economy-wide, technology-specific perspective of costs, energy consumption and greenhouse gas emissions using the PATHWAYS model.

Scenarios and Key Findings

Four scenarios to 2050 are evaluated, which differ in their consideration of technology pathways to serve space heating needs in buildings. Two of the scenarios maintain the direct use of natural gas[2] in buildings (relying on gas furnaces or natural gas powered heat pumps), while two of the scenarios assume a large-scale transition and retrofitting of buildings to electric end-uses (relying on electric air source heat pumps or cold-climate electric air source heat pumps) (Table 1). All scenarios are constrained to achieve an 80 percent reduction in GHGs by 2050 for the Pacific Northwest regional economy, while assuming continued economic and population growth.

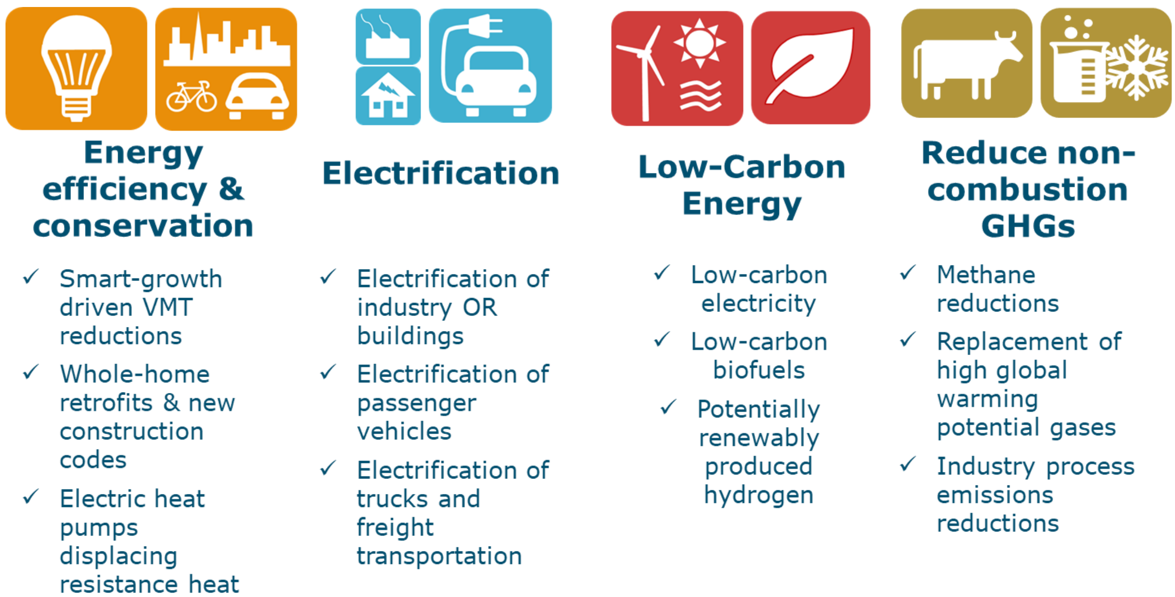
[2] Direct use of natural gas is defined as all gas that is not used to generate electricity.

Table 1. Key 2050 metrics by scenario

2050 metrics	Gas Furnace Scenario	Gas Heat Pump Scenario	Electric Heat Pump Scenario	Cold-Climate Heat Pump Scenario
Share of Natural Gas Space and Water Heating Electrified (fuel switching)	0%	0%	96%	96%
Industry Electrification (fuel switching, % total industry energy demand)	30%	30%	5%	5%
Carbon Free Electricity Generation	97%	97%	95%	95%
Biofuel Development (Share of available resource)	100%	97%	73%	73%
Hydrogen Mix in Gas Pipeline	7%	0%	0%	0%

These scenarios demonstrate that deep decarbonization in the Pacific Northwest will require transformative change to the energy economy of the region, across every sector of the economy. Four strategies, or "pillars," are identified as a common finding across deep decarbonization studies: energy efficiency and conservation, electrification (i.e., switching from fossil fuels to electricity), low-carbon energy, and reductions in non-combustion emissions (Figure 2).

Figure 2: Pillars of Deep Decarbonization

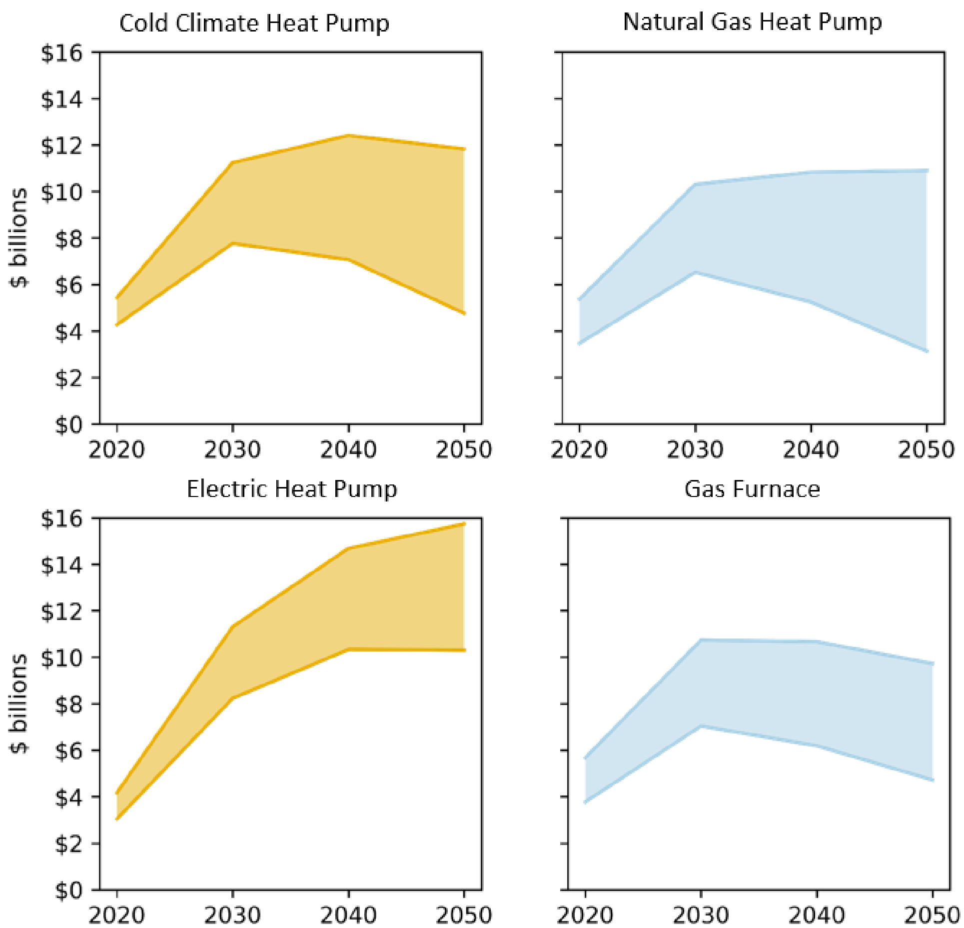


While all of the scenarios contain elements of each of these four pillars, not every measure is required in every scenario. The relative emphasis on each pillar differs by scenario. All of the scenarios evaluated in this study include high levels of building energy efficiency, including building shell improvements and deep energy efficiency retrofits, as well as reductions in vehicle miles traveled. All of the scenarios evaluated here include nearly complete electrification of the transportation sector as well as high levels of renewable and low-carbon electricity. All scenarios assume the same level of reductions in non-combustion GHGs. However, the scenarios differ in their levels of biofuels, renewable hydrogen, and in building and industrial electrification levels.

Total economy-wide scenario costs in 2050, relative to a reference or business-as-usual future, are similar between scenarios with one exception: the conventional (non-cold climate) electric heat pump scenario is most expensive, due to the high cost of serving winter peak demand (Figure 3). Overall, total scenario costs represent less than 1 percent of regional projected Gross Domestic Product (GDP). The average scenario costs range from $40/ton to $190/ton CO_2e in 2050 (in real 2017 dollars), relative to the Reference scenario depending on the future capital costs and fuel prices assumed. The average cost per ton metric means that some measures are far less expensive than this, while other measures are more expensive. This range reflects the wide range of uncertainties in projecting future scenario costs. Overall, these average GHG abatements costs ($40/ton to $190/ton CO_2e) are generally lower than the most recent estimates of the global social cost of carbon, which has a median cost of $417/ton CO_2, (and ranges from $177 to $805/ton CO_2).[3] The global social cost of carbon represents the expected economic damages to be incurred by climate change, per ton of CO_2 emitted.

[3] Ricke, K., L. Drouet, K. Caldeira, M. Tavoni, "Country-level social cost of carbon," *Nature Climate Change*, Vol. 8, October 2018 895-900. Available at: **https://www.nature.com/articles/s41558-018-0282-y.pdf**

Figure 3. Annual mitigation scenario costs relative to Reference scenario, including capital and fuel cost sensitivities, 2020 - 2050



We find that all scenarios that achieve deep decarbonization face significant challenges, but the types of challenges are different. Scenarios that maintain gas heat in buildings require:

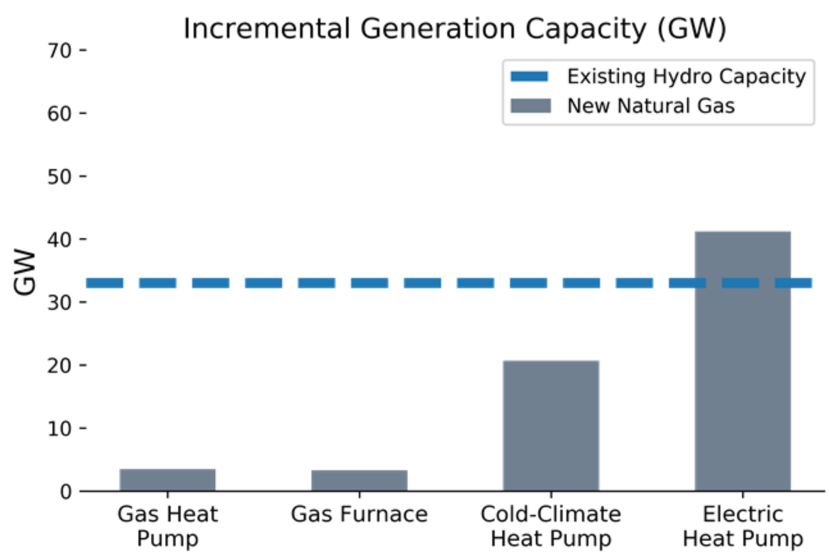
+ ***Reducing the carbon intensity of natural gas use in buildings by blending in low-carbon alternatives, including up to 30% carbon-neutral renewable natural gas and hydrogen.*** While all of the scenarios evaluated here rely on carbon-neutral biofuels to meet the 2050 GHG goal, the use of renewable natural gas is of higher importance in the scenarios that maintain gas in buildings. Renewably-produced hydrogen or synthetic methane blended in the gas pipeline are also options to displace fossil natural gas.
+ ***High levels of energy efficiency in buildings***, potentially with higher efficiency natural gas-powered heat pumps.
+ ***Additional reductions in other sectors to offset higher emissions in the building sector.*** In these scenarios, additional reductions are achieved primarily through 30 percent of industrial sector energy switching to electricity.

The scenarios that switch to electric heat in buildings require:

+ ***Rapid consumer adoption of electric heating technologies, including retrofits of existing buildings and broader commercialization and market transformation of cold-climate heat pump technologies.*** Conventional electric heat pump technologies are designed to maximize comfort and annual savings for the building occupants. This means that they require supplemental heat, typically electric resistance heat, during cold temperatures. At high levels of adoption, these heat pumps will place significant demands on the electric grid. In a high building electrification future, greater attention to heat pump installation practices and standards would be needed to mitigate the impact on the electricity system of meeting increased winter peak heat demands. Cold-climate electric heat pumps perform better during cold snaps than heat pumps not designed for cold climates, but they are less common today and have higher upfront costs. Absent other load management strategies, cold climate heat pumps do not eliminate the need for new winter peak electric generation and delivery capacity in a high building electrification future in the Pacific Northwest.
+ ***Significant new investments to address winter peak demand from electric space heating,*** including an expansion of the electricity system in the form of upgraded distribution systems as well as winter peak capacity resources. In the scenarios that transition to electric heat in

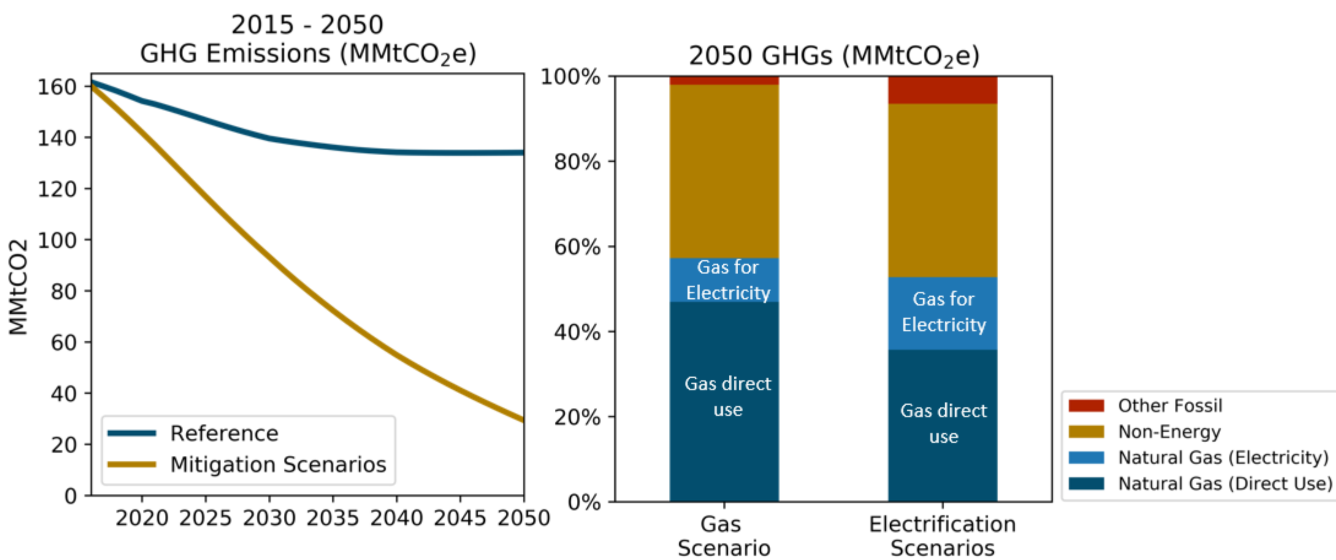
buildings, the widespread deployment of electric heat pumps leads to a five- to 10-fold increase in the incremental natural gas generation capacity build by 2050, relative to the Direct Use of Natural Gas Scenarios. This is equivalent to an additional 17,000 to 37,000 megawatts (MW) of additional peaking capacity need by 2050. Some of this winter peaking, gas-fired electric generation need could be displaced by energy storage, demand response, or technology innovation. But the cost of using batteries and other forms of electricity storage to meet winter peak heating needs is still unclear. For comparison, the entire hydroelectric system in the Pacific Northwest represents approximately 33,000 MW of installed capacity (Figure 4). Ensuring winter peak reliability will be a key planning challenge to address if building heating needs are increasingly electrified.

Figure 4. 2050 new firm natural gas capacity build by scenario, compared to existing regional hydroelectric capacity (gigawatts)



In all of the decarbonization pathways considered here, a combination of fossil and renewable natural gas, whether used in homes or in power plants, continues to serve winter peak heating needs in the Pacific Northwest (Figure 5). This study does not include an exhaustive investigation of alternative options to meeting peak heat demands. Potential alternative options are higher cost or more speculative as a peak capacity resource during extreme cold events in the region (e.g., geothermal heat pumps, energy storage, or incremental demand response).

Figure 5. Greenhouse Gas Emissions Over Time and 2050 GHG Emissions by Source and Scenario



Achieving a low-carbon future in the Pacific Northwest will require policies that encourage the development and deployment of next-generation energy technologies. Key areas for technology development and deployment highlighted in this study include:

- Deep energy efficiency and shell retrofits in buildings;
- Transportation electrification and electric vehicle charging infrastructure;
- Advanced forms of sustainable, carbon-neutral fuels, including renewable natural gas, renewable diesel, and renewable jet fuel;
- High efficiency space heating technologies, such as cold-climate heat pumps and natural gas heat pumps, that mitigate or manage winter peak impacts; and

- Industrial sector GHG mitigation options, including energy efficiency, electrification, and fuel-switching, as well as renewably produced hydrogen.

Many pathways exist to achieving decarbonization in the Pacific Northwest. The challenge lies in the development and sustained deployment of the advanced technologies needed to transform the region's energy economy to a lower-carbon future over the next two to three decades.

1 Introduction

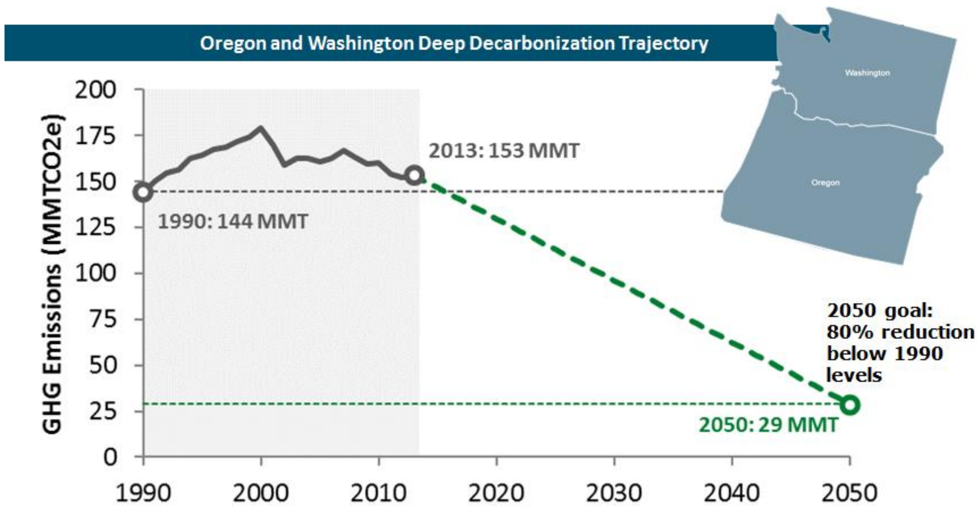
1.1 The Climate Context in the Pacific Northwest

1.1.1 CLIMATE GOALS IN OREGON AND WASHINGTON

Oregon and Washington are leaders on climate and clean energy policy. Both states are taking steps to reduce emissions with a portfolio of policies that encourage energy efficiency, expand renewable energy and support the deployment of battery electric vehicles. In 2007, the Oregon legislature passed House Bill 3543 which calls on the state to achieve greenhouse gas (GHG) levels that are at least 75 percent below 1990 levels by 2050. The Oregon legislature is now considering the development of a cap and trade program to reduce GHG emissions in the state further. In 2008, the Washington state legislature passed a law requiring a reduction in GHG emissions of at least 50 percent below 1990 levels by 2050, but in 2016, the Department of Ecology recommended a stricter limit. In the "Washington Greenhouse Gas Reductions Limit" report, the Department called for an overall GHG reduction of 80 percent below 1990 levels by 2050.

This study evaluates pathways for the Pacific Northwest, Oregon and Washington combined, to achieve an 80% reduction in greenhouse gases by 2050 (Figure 6). State-specific results for Oregon and Washington are included in the Appendix. This level of climate mitigation is often referred to as "deep decarbonization" and is consistent with the global reduction in greenhouse gas emissions that are necessary to limit global warming to 2 degrees Celsius.

Figure 6. Pacific Northwest historical greenhouse gas emissions and 2050 greenhouse gas goal



1.1.2 GREENHOUSE GAS EMISSIONS IN OREGON AND WASHINGTON

The largest share of greenhouse gas emissions in Oregon and Washington are from the transportation sector. Buildings represent the second largest source of GHG emissions in the region, nearly evenly split between emissions from electricity generation and the direct use of natural gas and petroleum-based fuels, such as propane. The remaining greenhouse gasses in the region come from both direct and fugitive emissions in industry, agriculture and waste.

Figure 7. 2015 Greenhouse Gas Emissions in Oregon and Washington by sector and fuel (source: PATHWAYS model)

1.2 Pathways to Achieve Deep Decarbonization

1.2.1 FOUR PILLARS

A common finding across the deep decarbonization studies completed in the US, globally, and in the Pacific Northwest is the use of four broad emissions reduction strategies to achieve deep decarbonization.

These strategies, or “pillars”, include: energy efficiency and conservation, electrification (switching fossil fuel powered infrastructure to electricity), low-carbon fuels, and reductions in non-combustion emissions. Any successful mitigation scenario will include reductions from each of these pillars, but not every scenario must include every measure from within a pillar. Scenario analysis offers the opportunity to consider how different strategies within, and emphasis between, these pillars affect the plausibility and cost of deep decarbonization.

Energy efficiency and conservation

Energy efficiency means providing the same energy service (e.g. hot water, mobility, lighting) with less input energy required. Energy efficiency is both an important measure from the perspective of both emissions reductions and cost. Less energy efficiency means that a larger quantity of more expensive measures will be needed, increasing the societal cost of deep decarbonization. Conservation is a change in behavior to reduce energy demands. For example, bicycling or walking rather than driving. The scenarios we use in this study focus on energy efficiency and assume only a very small amount of conservation.

Electrification

Electrification strategies shift energy usage from on-site combustion of fossil fuels in vehicles and buildings to power from the electric grid. Electrification can be an effective emissions reduction strategy because of the relatively high efficiency of electric end-uses and the complementarity with efforts to decarbonize the electric sector. However, some electrification measures are more cost effective than others, so like other emission reduction opportunities, electrification must be used strategically. An important consideration when evaluating the costs of electrification are the potential impacts to the electric system’s peak demand and associated infrastructure costs.

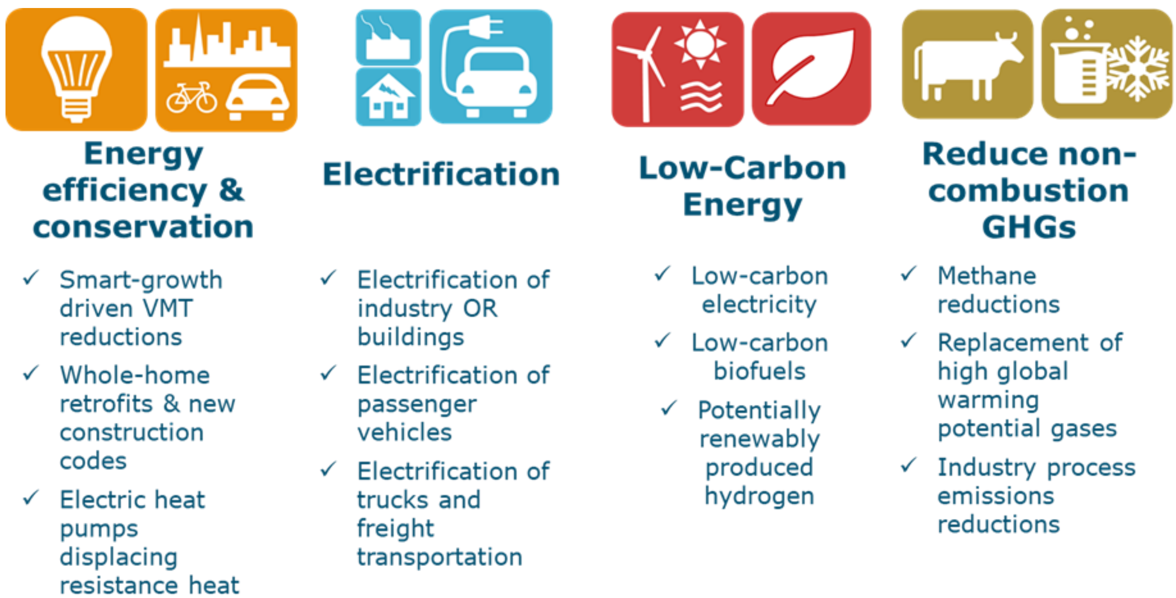
Low-Carbon Energy

Low carbon energy strategies substitute fossil fuels like gasoline, diesel, coal, and natural gas with low emission alternatives like renewable electricity, renewable natural gas and biodiesel. The advantage of low-carbon energy is that they can be formulated as a ‘drop in’ fuel and used in existing equipment with little modification. For example, biodiesel used in trucking. However, the available supply of sustainable biofuels is limited, falling far short of existing demands for liquid and gaseous fossil fuels in the Northwest, and the costs are higher than the fossil-fuel they replace. Therefore, the limited supply of sustainable biofuel resources must be used strategically, targeted to where they provide the highest value.

Reduction in non-combustion emissions

Non-combustion emissions include several different greenhouse gasses that are released or generated via non-combustion processes. Some non-energy emissions are produced through biogenic processes (e.g. urban wastes or manure), others occur because of industrial processes, while some are the result of the extraction or transportation of fossil fuels. Non-energy emissions often come in the form of greenhouse gasses with high global warming potential like methane or nitrous oxide. Strategies that reduce these emissions are important components of economy-wide decarbonization.

Figure 8: Pillars of Deep Decarbonization[4]



1.2.2 PRIOR DEEP DECARBONIZATION STUDIES AND ANALYSES OF "PEAK HEAT" NEEDS

While there is support for decarbonization in the Northwest, many questions remain about how to achieve this transformation of the region's energy economy. Several existing studies have evaluated different scenarios to achieve an 80% reduction in greenhouse gas emissions:

+ In 2014, the "Pathways to Deep Decarbonization in the United States" published by E3, in collaboration with Lawrence Berkeley National Laboratory and Pacific Northwest National Laboratory, evaluated scenarios with different electricity generation mixes, including renewables, nuclear power, and carbon capture and sequestration. In that study, the Pacific Northwest was

[4] VMT = vehicle miles traveled

grouped with the broader U.S. census region for the Pacific, including Alaska, Washington, Oregon, California, and Hawai'i.

- In 2016, the Obama White House published the "United States Mid-Century Strategy for Deep Decarbonization" evaluating several scenarios with a focus on the role of carbon sinks and carbon dioxide removal technologies in achieving the 2050 GHG goal.
- In 2017, the Office of Governor Inslee published a study evaluating decarbonization options for Washington State, and in 2018, Portland General Electric (PGE) published decarbonization scenarios for their service territory. Both the Washington state and PGE studies were performed by Evolved Energy and evaluated high building electrification scenarios and scenarios without building electrification.

However, none of these prior studies, to our knowledge, have investigated the costs and implications of reliably meeting winter peak energy needs during the coldest days experienced in the region. This study evaluates the cost implications of serving winter peak heating needs in the context of achieving an 80 percent reduction in GHGs by 2050.

In addition, this study evaluates the potential role and impact of natural gas heat pumps, an emerging technology which has not been evaluated in prior deep decarbonization studies, to our knowledge. Finally, a wide range of electric heat pump performance and cost assumptions are considered, reflecting some of the uncertainties in both technology innovation and regionally-specific building retrofit and installation costs. Prior studies appear to have relied primarily on national cost estimates and have not explicitly accounted for heat pump performance characteristics with changes in temperature.

1.2.2.1 Peak heat needs

This study focuses in particular on the capacity needs to serve space heating loads and builds on an emerging area of research that is evaluating incremental peak loads if natural gas heating load converted to electricity using air-source heat pumps for space heating and water heating. Though the electricity system in the Northwest is currently winter peaking, the natural gas system in the region provides the bulk of peak-space heating energy. NW Natural estimates that electrifying winter peak natural gas heating loads would increase the region's peak by nearly 30 GW (Northwest Natural 2017). Other utilities and researchers in the Northwest have also begun to examine this issue. For instance, Avista estimates that electrifying its gas loads would increase electric peak in its service territory by over 1,600 average megawatts (aMW) per day, just short of its current peak load of 1,681 aMW per day (Avista 2018). The Northwest Power and Conservation Council estimates that a high electrification case for the region could lead to a winter peak of over 65 GW, an 85% increase over today (Jourabchi 2018).

These regional findings are consistent with findings elsewhere in the world. Researchers at the University of Central London find that that the electric sector peak would more than double under large-scale deployment of electric heat pumps in the United Kingdom (Strbac et al 2018). Indeed, 'heat decarbonization' has been an ongoing policy and research question in the United Kingdom, with a variety of analyses examining the infrastructure implications of reducing emissions in buildings (Howard and Bengherbi 2016, MacLean et al 2016). These studies consider the heat required not only in average conditions, but also in peak conditions, usually defined as a historical '1 in 10' or '1 in 20' heating event. A key take-away from the existing literature on decarbonizing heat, both in and outside the Northwest, is the importance of accounting for peak conditions.

1.2.3 STUDY GOALS AND QUESTIONS

This study seeks to evaluate deep decarbonization strategies in buildings, within the context of an economy-wide pathway to 2050. This study evaluates scenarios that achieve the 2050 climate goal while continuing to rely on the region's existing gas distribution system, and scenarios that switch to a reliance on electric heat pumps for space and water heating. The scenarios that continue to rely on the direct use of natural gas blend low-carbon fuels into the gas pipeline, including renewable natural gas and in one case, renewably produced hydrogen. The electrification scenarios evaluate the implications of serving peak heat needs with electric heat pumps, together with a broader economy-wide evaluation of greenhouse gas mitigation options and costs. Furthermore, these scenarios seek to balance a reasonable set of GHG mitigation measures across sectors, avoiding the most expensive mitigation options where possible.

The key research questions include:

+ What are viable pathways to achieve deep decarbonization in the Northwest, focusing on different strategies in buildings?
+ How can NW Natural, and the natural gas system, contribute towards achieving the region's GHG goals?
+ What are the potential electric load impacts of electrifying buildings in the region?
+ What key factors affect the cost of different decarbonization strategies?

2 Study Approach

This report builds on prior deep decarbonization analyses from other regions and other states but uses an expanded analytical toolkit to draw out the implications of different decarbonization strategies, with a focus on the role of the buildings sector in achieving an economy-wide emissions reduction goal.

The core analytical tool used to evaluate long-term carbon reduction scenarios is an economy-wide energy and emissions accounting model developed by E3 called PATHWAYS. This model ensures that the long-term scenarios evaluated all achieve the economy-wide 2050 GHG emissions constraint. The Northwest version of the PATHWAYS model is tailored to region specific energy demands, supply and technology stocks, using local data whenever possible. The tool is also benchmarked to the existing Oregon and Washington state greenhouse gas emissions inventories.

PATHWAYS is an economic energy and greenhouse gas emissions accounting tool. A key feature of the PATHWAYS model is its detailed treatment of the Northwest's energy infrastructure. Energy infrastructure includes, but is not limited to, power plants, industrial facilities, trucks, cars, buses and building end use equipment. Each type of infrastructure consumes energy to meet projected energy services demands for the regions needs including transportation, heating, cooling, lighting, industry, agriculture and other uses spanning the entire energy system. Depending on the equipment stock, its fuel, and its efficiency this energy use results in different fuel consumption, emissions, and costs for the region.

Within this framework, there are three key areas that receive more detailed analysis: 1) Biofuels supply and costs, 2) Building performance, and 3) the Electricity sector, as described in more detail below.

+ **Biofuels supply and costs:** Carbon-neutral biofuels are a key strategy to reduce greenhouse gas emissions in the scenarios evaluated here. However, the sustainable biomass feedstocks that are needed to produce carbon-natural biofuels are also a fundamentally limited resource, and thus valuable. Examples include biogas from landfills, waste water treatment facilities or dairies, as well as wood from forestry plantations or waste wood. In order to evaluate the supply constraints and costs of producing sustainable biofuels, we augment the PATHWAYS model with a Biofuels Optimization Module. This tool accounts for the limited biofuel feedstocks and allocates them to final fuels to maximize emissions reductions at least cost.

+ **Building performance:** This study evaluates how the performance of electric air source heat pump space heating technologies might perform under a range of cold temperatures across the Pacific Northwest using a building simulation model, EnergyPlus. EnergyPlus estimates the hourly energy requirements of space heating in different building types across the region at different temperatures.
+ **The electricity sector:** In order to reflect the potential costs and carbon implications of decarbonizing the electricity sector we apply an electricity sector capacity expansion model called RESOLVE. This tool is designed to identify least-cost electricity generation portfolios under carbon constraints. The model includes historical hourly load shapes which are modified to reflect the impacts of scenario-based assumptions about energy efficiency and electrification in transportation, industry and buildings, to the extent applicable. After accounting for load diversity and building shell improvements, the hourly load shapes from the EnergyPlus building simulations are used to modify the base hourly load profiles in the RESOLVE model. This creates a more realistic picture of how hourly electricity demands, and winter peak electricity demands, could change under a high building electrification future.

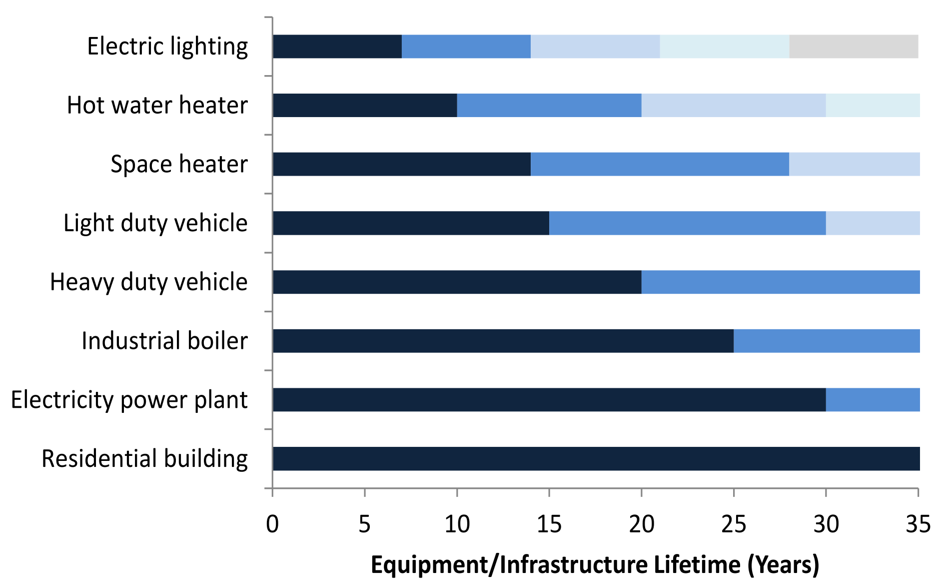
A list of key data sources used to develop this analysis can be found in the Appendix.

2.1 Economy-wide Energy and Emissions Scenarios

The core analytical tool used in this analysis is the Northwest PATHWAYS model. E3 first developed the PATHWAYS framework in 2008 to help policy-makers, policy implementers and businesses better understand plausible decarbonization scenarios. The model has since been modified and improved on over time in projects that analyze deep decarbonization at the national level, in several states, as well as sub-state jurisdictions.

A key feature of the PATHWAYS model is its detailed treatment of the Northwest's energy infrastructure. Energy infrastructure includes, but is not limited to, power plants, industrial facilities, trucks, cars, buses and home equipment. Each type of infrastructure consumes energy and produces emissions differently, but collectively they determine the direction of the region's emissions trajectory. Many of these technologies are long-lived. For instance, a home built today will likely still be in use by mid-century. Because investments made in the near-term shape the energy system of the future, the PATHWAYS model includes a detailed, bottom-up stock accounting treatment of the region's energy infrastructure on a technology-specific level (Figure 9). By accounting for vehicle and equipment lifetimes, PATHWAYS identifies the pace of change necessary to deploy decarbonization strategies while avoiding costly early retirement, and captures potential path dependencies of near-term decisions.

Figure 9: Infrastructure lifetimes in PATHWAYS



A second key feature of the PATHWAYS model is its ability to link sectors. By linking sectors, PATHWAYS identifies where aggressive action in one sector can enable emissions reductions elsewhere in the economy. For instance, the detailed treatment of the electricity sector is explicitly tied to the carbon savings associated with electric vehicles.

Demands for energy in PATHWAYS are driven by forecasts of population, building square footage, vehicle miles traveled, and other drivers of energy services. The rate and type of technology adoption and energy supply resources are all user-defined scenario inputs. PATHWAYS calculates energy demand, greenhouse gas emissions, the portfolio of technology stocks in selected sectors, as well as capital costs and fuel costs for each year between 2015 and 2050.

2.2 Biofuels Supply and Costs

Sustainable Biomass and Biofuel Resource Availability

The availability of carbon-neutral biofuels as a GHG reduction option is limited by the supply of sustainable biomass feedstocks. The United States Department of Energy’s 2016 Billion Ton Study (BTS) estimates the supply of biomass feedstocks by county and by type, at different price points (USDOE 2016). The DOE BTS study also estimates the potential supply of both biomass wastes and residues, as well as purpose grown crops such as plantation forests, switchgrass and miscanthus. This analysis assumes a transition away from current, food-based biofuel feedstocks such as corn and soy, and towards a more advanced and sustainable supply of biofuels. In addition to the U.S. DOE BTS study, NW Natural provided additional estimates of the resource potential for regional biogas supplies from landfills, waste water treatment facilities and other sources of biogas that are not well represented in the BTS data set, based on U.S. EPA data and a Washington

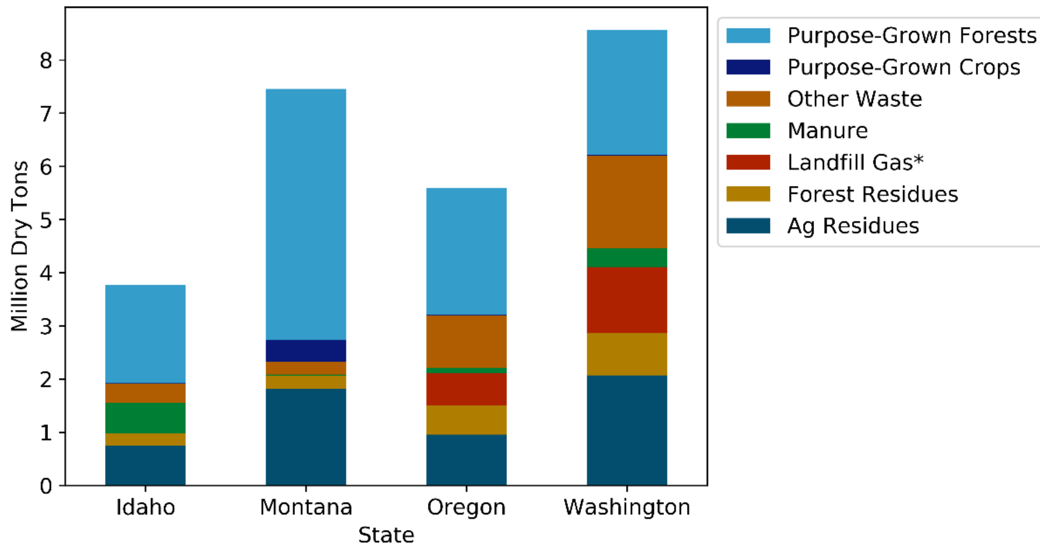
State University Energy Program study.[5] This data was reconciled with the DOE BTS study by adding 27 TBtu of biomethane potential from landfill gas and wastewater treatment plants and 0.14 million dry tons of manure feedstock.

In this study, we assume that biomass used to produce carbon-neutral biofuels are limited to wastes, residues and purpose-grown energy crops within the regional Northwest: Idaho, Montana, Oregon and Washington. We also assume that Oregon and Washington have access to their population share of the four-state region (80.7%). This represents a moderate quantity of biofuels compared to alternative approaches, resulting in a total of 25 million dry tons of biomass supply available to Oregon and Washington (Figure 10). This is in contrast to Washington State's deep decarbonization study which assumed 23.8 million dry tons available to the state. The Portland General Electric Pathways to Deep Decarbonization study also assumed a larger per capita share of biomass for biofuels compared to this study. Applying the PGE study methodology to the Oregon and Washington region would result in an assumption of 46.7 million dry tons of biomass available to the region, almost double the amount available in this study.[6]

[5] Oregon landfill gas data was based on the U.S. EPA Landfill Methane Outreach Program (LMOP) database. Washington data on biogas feedstocks was based on the Energy RNG Roadmap for Washington (Washington State University Energy Program 2017).

[6] PGE's share of the U.S. biomass supply is assumed to be 7.3 million dry tons (MDT), which is equal to the U.S. supply of biomass of 1,300 MDT multiplied by the region's population share (1.8 million people in PGE/320.9 million people in the U.S.). Applying this same method to Oregon and Washington would result in 46.7 MDT: 1,300 MDT of biomass supply in the U.S., multiplied by the region's population share (11.5 million people in Oregon and Washington/320.9 million people in the U.S.). See: **https://www.portlandgeneral.com/our-company/energy-strategy/resource-planning/integrated-resource-planning**

Figure 10. Biomass feedstock supply by type, 2050



*Tons of landfill gas are weighted by a factor of 3 to account for the approximate relative energy yield.

Biofuels Costs and Supply

The E3 PATHWAYS Biofuels Module generates supply curves that determine the availability and cost of renewable liquid and gaseous biofuels. The model optimizes the selection of feedstocks, conversion pathways, and final fuels. The optimization is flexible and can be configured to select a least-cost portfolio given final fuel demands, maximum carbon abatement given available feedstock, or some combination of these and other policy drivers. When multiple conversion pathways are available for a given feedstock and fuel pairing (for instance, pyrolysis vs. Fischer Tropsch for conversion of wood to diesel), the selection criterion is also flexible: the model can be configured to choose either the cheapest conversion process or the one with the highest yield.

E3's biofuels conversion pathway assumptions are drawn from work done as part of a California Energy Commission grant (E3, 2018). E3 worked with a combination of published literature and external expert consultations to develop estimates of conversion efficiencies and costs, assuming biofuels can be produced more cheaply in the future through industry learning.

2.3 Building Performance

EnergyPlus is a building energy simulation model that models energy consumption for heating, cooling, ventilation, lighting and plug loads in both residential and commercial buildings. E3 worked with Big Ladder Software (Big Ladder) to develop a set of building simulations to identify the hourly load impacts of electric space-heating.[7] Big Ladder simulated four building types: a small single-family home, a large single-family home, a multi-family building and a small commercial building. Each building type included two vintages (older and new construction) and two climate zones (West of the Cascades, represented by Portland, OR and East of the Cascades, represented by Spokane, WA), both of which determine building performance. Three different heating technologies were simulated in each building: an electric resistance heater, an air-source electric heat pump and a cold-climate air-source heat pump. Table 1 lists the different parameters simulated in this analysis.

[7] The hourly usage of natural gas equipment was not modeled in EnergyPlus since the peak impact of natural gas equipment is relatively simple to estimate.

Table 2: Building simulation parameters

Building types	Vintages	Climate zones	Heating technology
• Small single-family • Large single-family • Multi-family • Commercial	• Existing (built in 1990) • New (Most recent building energy codes)	• West of Cascades (Portland) • East of Cascades (Spokane)	• Electric heat pump • Cold climate electric heat pump • Electric resistance

Weather assumptions

In order to capture the inter-year variation in peak heating requirements in buildings, NW Natural worked with E3 to develop a range of temperature conditions for the building simulations. Building usage was simulated using weather data for Portland and Spokane[8] so that the resulting annual energy demands are representative of normal weather conditions. However, this representative weather data was supplemented with an imposed a 3-day cold-snap representing a 1- in 10 year cold event.[9] This represents a more extreme, but still within the historical experience, heating event for the region. The average minimum 7am temperature in a given year in NW Natural's service territory over the last decade was 18° Fahrenheit (F), while the '1 in 10' year cold-snap included in the weather used in this study dips to 10° F. This 10° F cold-snap event represents a heuristic for the types of inter-year variation in heating needs that could be experienced by buildings across the region.[10]

[8] Weather from 2012 was found to be representative, so the hourly weather from 2012 was used as an input to the simulation.
[9] Using the methodology in NW Natural's 2018 IRP, a 1-in 10 year cold event in Portland includes a day with an average temperature of 17.09°F. Consequently, the hourly temperature profile from the December 7 through December 9, 2013 cold event was added to the data to represent a 1-in 10 year event. The average temperature of the coldest day of this cold event (December 8th, 2013) was 17.42°F.
[10] Note that these figures for Portland are representative and adjustments were made to account for regional diversity in weather conditions.. See Section 6.4 in the appendix for more information on the treatment of weather.

2.4 Electricity Sector

In order to simulate the costs and performance of the electric grid under a very low-carbon future, this study uses a tool called RESOLVE. This tool is an electricity-sector resource investment model that uses linear programming to identify optimal, long-term generation and transmission investments, subject to reliability, technical, and policy constraints. RESOLVE layers capacity expansion logic on top of a production cost model to determine the least-cost electric sector investment plan, accounting for both upfront capital costs and variable costs to operate the grid. This project uses a Northwest specific version of RESOLVE first developed for the Public Generating Pool in 2017 (E3 2017).

RESOLVE selects from a wide range of potential new generation resources. The options for new investments considered in this study are limited to those technologies that are commercially available in the Pacific Northwest today. New nuclear power and carbon capture and sequestration are not considered in these scenarios.

RESOLVE includes a variety of Northwest specific inputs, including hydro dispatch informed by historical operations. RESOLVE captures the constraints on the dispatch of the hydroelectric system by deriving constraints from actual operational data. Three types of constraints govern the operation of the hydro fleet as a whole: 1) daily energy budgets, 2) maximum and minimum hydro-electric generation levels and 3) maximum multi-hour ramp rates. Collectively, these constraints limit the generation of the hydro fleet to reflect seasonal limits on water availability, downstream flow requirements, and non-power factors that impact the operations of the hydro system. RESOLVE incorporates a number of other constraints including a planning reserve margin (PRM) that requires a minimum quantity of firm capacity, and the ability to impose a GHG cap on electricity emissions over time.

RESOLVE is a complementary model to both PATHWAYS and EnergyPlus. PATHWAYS identifies the annual electric loads that the electric sector must serve and the emissions budget that constrains RESOLVE's capacity expansion and operational linear optimization problem. EnergyPlus provides hourly load shapes for individual buildings, that when aggregated and diversified, can be used to inform changes to the system-level building load shape, which determine both the annual peak capacity requirements in RESOLVE and operational requirements of the electric system.

3 Northwest PATHWAYS Scenarios

PATHWAYS is a user-defined scenario analysis framework. Scenarios are not forecasts. They do not represent an expectation of what a future energy system will look like. Nor are they mere speculation. Instead, scenarios are opportunities to ask “what if?” questions about plausible decarbonization trajectories for Oregon and Washington. This scenario analysis approach is meant to draw out potential implications and trade-offs between different approaches to achieve deep decarbonization.

3.1 Scenario Design

This analysis develops four decarbonization scenarios that examine trade-offs between and within different strategies for providing heat in buildings, as well as a Reference scenario, representing a “current policy” trajectory. The tradeoffs between building heating strategies in the decarbonization scenarios have implications for the rest of the economy as well as total scenario costs, since all scenarios are constrained to meet the same long-term carbon reduction goal.

Four variations of building heating equipment are considered: gas furnaces, electric air-source heat pumps, gas-powered heat pumps and cold-climate air source heat pumps. These four scenarios can be binned into two scenario categories: Direct Use Gas Scenarios and Electric Heat Pump Scenarios.

3.1.1 REFERENCE SCENARIO

The PATHWAYS Reference scenarios is a representation of current policy in the Northwest as of Summer 2018. Key policies include the Oregon Clean Fuels Program, Oregon’s participation as a ZEV State, a 20%

regional RPS target by 2045,[11] and energy efficiency savings consistent with the Northwest Power and Conservation Council's 7th Power Plan.

3.1.2 DIRECT USE GAS SCENARIOS

In these scenarios the gas distribution pipeline system continues to provide heat to residential and commercial buildings in the Northwest. The proportion of homes in Oregon and Washington that are served by gas are held constant through time, though the total number of gas homes increases as the region's population expands. In each of the Direct Use Gas Scenarios, natural gas is blended with renewable gases like biomethane and hydrogen to decrease the carbon content of energy provided via the existing pipeline infrastructure.

3.1.2.1 Gas Furnace Scenario

In the Gas Furnace Scenario, the primary heating equipment in homes transitions to high efficiency versions of gas furnaces and water heaters, both of which are commonly used technologies today. By 2030, nearly all gas space-heaters sold are 98% efficient condensing gas furnaces while air conditioning needs continue to be met with high efficiency air conditioners.

3.1.2.2 Gas Heat Pump Scenario

In the Gas Heat Pump scenario, natural gas fired air-source heat pumps, an emerging technology, are assumed to become the primary space heating and water heating equipment in buildings that typically use natural gas today. Gas heat pumps operate similarly to electric heat pumps, except that they are powered by gas rather than electricity. The Northwest Energy Efficiency Alliance (NEEA) is working to commercialize gas heat pumps in the region and provided E3 with estimates of the performance

[11] This is a regional weighted figure representing the combination of the 50% RPS by 2040 in Oregon and the 15% RPS by 2020 in Washington.

characteristics and potential costs of natural gas heat pumps. Gas heat pumps have improved efficiencies compared to gas furnaces, achieving a coefficient of performance (COP) of 1.4 for space-heating and 1.3 for water-heating. NEEA believes natural gas heat pumps may be well suited to provide both space- and water-heating in a combined unit, which could lead to cost savings relative to the cost of an individual water heater and gas heat pump heater.

3.1.3 ELECTRIC HEAT PUMP SCENARIOS

The electric heat pump scenarios examine futures where the bulk of heat in buildings is provided by electric air-source heat pump space heaters and water heaters. Electrification paired with a 95% decarbonized electric sector achieves a near-complete decarbonization of heat in buildings.

3.1.3.1 Electric Heat Pump Scenario

This scenario replaces both existing gas and electric technologies with a high efficiency (HSPF 9) electric air-source heat pump for space heating, representing an efficiency option that is readily available today.[12] This scenario does not assume installations of higher efficiency systems on the upper-end of the heat pump market, nor does it assume any technology innovation. An HSPF 9 heat pump system is relatively efficient in terms of annual energy but becomes less efficient at cold temperatures. At 34°F these heat pump systems "lock-out" and switch to the use of electric resistance back-up heat.[13] This scenario represents a future where the region proceeds with building electrification using a commonly-available

[12] Heating Season Performance Factor, or HSPF, is a measure of the seasonal efficiency of heat pump equipment in the winter. The Federal minimum for air source heat pumps is an HSPF rating of 7.7. In Oregon, to qualify for an Oregon residential energy tax credit, a ducted air source heat pump system must have an efficiency of 9.5 HSPF or greater. The Energy Trust of Oregon offers incentives for systems that have an HSPF of 8.5 or higher. High efficiency mini-split heat pumps may have an HSPF efficiency rating of 12.5 but may not be suitable in larger homes or some applications.

[13] Energy Trust of Oregon provides an incentive to set a compressor lock-out temperature to 35°F (or "as close as possible"). High efficiency mini-split heat pumps do not "lock-out" at temperatures experienced in the Pacific Northwest but may not be suitable in larger homes or some applications.

heat pump technology and common HVAC installation procedures without accounting for the system-wide peak impacts of electrification.

3.1.3.2 Cold-Climate Electric Heat Pump Scenario

Cold-climate air-source heat pumps are commercially available products, though still relatively uncommon in today's market, that perform better at cold temperatures than more common heat pumps. Their improved performance at cold temperatures is due to their having an inverter driven, variable-speed compressor, and more advanced control systems. The Northeast Energy Efficiency Partnerships (NEEP) has established a product specification for cold-climate heat pumps and provides a listing of systems that meet that specification. To qualify, a system must have a variable speed compressor, a coefficient of performance (COP) at 5° F higher than 1.75, and an HSPF of at least 10.

For this analysis, Big Ladder simulated a ducted cold-climate heat pump with an HSPF of 10.5. The system uses supplemental heat once the temperature drops below 20° F.[14] Below that temperature, the heat pump can still provide a portion of the heat, with electric resistance heating providing the additional heat needed to maintain building comfort. Note that we did not model the hourly performance of ductless heat pumps in this study, assuming that homes that fuel-switch from natural gas to electric heating would already have duct-work. We do assume for costing purposes only that ductless heat pumps are installed in homes that currently have electric resistance heat.

[14] For comparison with NEEP's cold-climate heat pump specifications the modeled system has a COP of 2 at 5°F.

3.2 Common Scenario Assumptions

The scenarios in this analysis examine different strategies to deliver heat in buildings while achieving the same level of economy-wide carbon reduction. However, there are many shared features and common assumptions across the scenarios, which are described below:

+ **Energy efficiency and conservation**: High levels of energy efficiency and conservation in buildings and industry are critical to reduce energy demands and save carbon in all scenarios. In all scenarios, ductless heat pumps replace nearly every electric resistance heater in buildings, while deep building shell retrofits reduce the heat required in residential and commercial buildings, and smart-growth measures decrease per-capita vehicle-miles travelled in the region.
+ **Electrification in transportation, and industry OR buildings**: All scenarios assume nearly complete electrification of passenger vehicles, trucks and off-road vehicles by 2050. The amount of electrification in industry and buildings varies by scenario, as discussed in more detail below.
+ **Low carbon fuels: biofuels and renewable natural gas:** All scenarios include renewable natural gas and renewable jet fuel to decarbonize fuels that may be otherwise difficult to electrify. The total quantity of biofuels varies between scenarios, ranging from 73% of the available biofuel supply in the Electrification scenarios, to 97% to 100% of the available supply in the Direct Use of Natural Gas scenarios.
+ **Low-carbon electricity:** All scenarios assume nearly complete decarbonization of the electricity sector through expanded reliance on renewable generation, and continued reliance on hydropower and nuclear energy, achieving between 95% and 97% zero-carbon electricity generation by 2050. All of the scenarios consider additional demand response, electricity storage, wind, and solar generation, but do not consider the development of carbon capture and sequestration, new nuclear power, or new large-scale hydropower as zero-carbon technology options. In all scenarios, the electricity sector is allocated a carbon budget that allows the overall scenario to meet the 2050 carbon reduction goal.
+ **Reductions in non-combustion GHG emissions**: Each scenario assumes concerted efforts to reduce non-combustion emissions, achieving approximately a 53% reduction in non-combustion

emissions by 2050, relative to 1990 levels. This means that a higher share of reductions is required in the energy sector, in order to achieve an economy-wide goal of 80% below 1990 levels by 2050. Methane emissions from manure, landfills and wastewater are captured in each scenario and converted to biomethane. Fluorinated (F)-gases are replaced with lower cost refrigerants throughout the economy. The scenarios also assume efforts to reduce fugitive and process emissions in industry.

All of these common mitigation assumptions represent major shifts from a business-as-usual world.

3.3 Key Differences between the Scenarios

The different building strategies applied in each scenario result in different implications for other sectors of the economy. These differences are summarized by sector, and in the table below:

+ **Electrification in Industry:** The Direct Use Gas Scenarios assume that 30% of industrial energy demand currently served by other fuels is electrified by 2050. This quantity of electrification is consistent with a near-complete electrification of industrial HVAC equipment, as well as high levels of process heating and boiler electrification. No industrial electrification is assumed in the Electric Heat Pump Scenarios, beyond a limited switching of HVAC electricity demand to electric heat pumps.
+ **Electrification in Buildings:** As discussed above, the Direct Use Gas Scenarios do not assume any new building electrification, beyond the current market share of electric heat in existing buildings in the Pacific Northwest. Buildings with existing electric resistance space heating are assumed to switch to electric heat pumps in all scenarios. In the Electric Heat Pump Scenarios, 90% of all buildings are assumed to use electric heat pumps for space heating and water heating by 2050. This assumes a rapid transition towards electric heat pump adoption in both new construction and existing buildings, requiring major retrofits of existing space and water heating equipment.
+ **Low Carbon Fuels: Biomethane and Renewable Hydrogen:** All of the scenarios include substantial use of carbon-neutral, advanced biofuels to achieve the 2050 GHG targets. In the Direct Use of

Natural Gas Scenarios, up to 25% biomethane is blended into the natural gas pipeline by 2050, based on the assumed available regional supply of sustainable biomass. This is equivalent to 72 TBtu of renewable natural gas by 2050 in the Gas Heat Pump Scenario, and 84 TBtu of renewable natural gas in the Gas Furnace Scenario. The total quantity is higher in the Gas Furnace Scenario because the total gas demand is higher in this scenario. In the Gas Furnace scenario, an additional 6.5% of the energy in the gas pipeline is provided by renewably-produced hydrogen from electrolysis.

+ **Zero-Carbon Electricity:** In all scenarios, electricity is nearly decarbonized by 2050. The Electric Heat Pump scenarios assume that 95% of electricity generation is provided by zero-carbon resources, mostly from renewable energy and hydro-power by 2050. This is equivalent to a 5 MMtCO2 carbon budget in 2050 for the electric sector. The Direct Use Natural Gas Scenarios assume that 97% of electricity generation is provided by zero-carbon resources by 2050, equivalent to a 3 MMtCO2 carbon budget for the electricity sector.

These key scenario design differences are illustrated in Table 3.

Table 3. Key assumptions by scenario

2050 metrics	Gas Furnace Scenario	Gas Heat Pump Scenario	Electric Heat Pump Scenario	Cold-Climate Heat Pump Scenario
Share of Natural Gas Space and Water Heating Electrified (fuel switching)	0%	0%	96%	96%
Industry Electrification (fuel switching, % total industry energy demand)	30%	30%	5%	5%
Carbon Free Electricity Generation	97%	97%	95%	95%
Biofuel Development (Share of available resource)	100%	97%	73%	73%
Hydrogen Mix in Gas Pipeline	7%	0%	0%	0%

4 Results

In all four PATHWAYS scenarios, achieving deep decarbonization will require transformative change to the energy economy of the Northwest in just over 30 years. This is a relatively short period of time compared to the investment decision timeframe and average lifetimes of energy infrastructure and equipment. A low-carbon energy transition for the Northwest region will only occur if investment decisions shift towards prioritizing higher efficiency options, and the development and use of low-carbon fuels. Those investment decisions range from small choices, like consumer purchases of LED light-bulbs, to large capital investment decisions by industrial facilities in the region.

4.1 Greenhouse Gas Emissions in a Low Carbon Future

Each scenario achieves the same 80% below 1990 target emissions budget of 29.3 MMtCO2 in 2050 and have very similar emissions trajectories over time. However, by 2050 the scenarios diverge in the allocation of emissions between sectors of the economy (Figure 11). The Gas Scenarios leave a larger share of the economy-wide budget to the buildings sector while the Electric Heat Pump Scenarios allocate more of the emissions budget to electricity and industry (Figure 12). The bulk of remaining energy emissions in both cases come from natural gas combustion, though the scenarios differ in where that gas is used. The Gas Scenarios rely more on direct-use of natural gas, while the Electric Heat Pump Scenarios use relatively more gas in the electricity sector, although the total use of natural gas is greatly reduced by 2050 in all scenarios relative to today.

Figure 11. Greenhouse Gas Emissions Over Time by Scenario and by Source in 2050

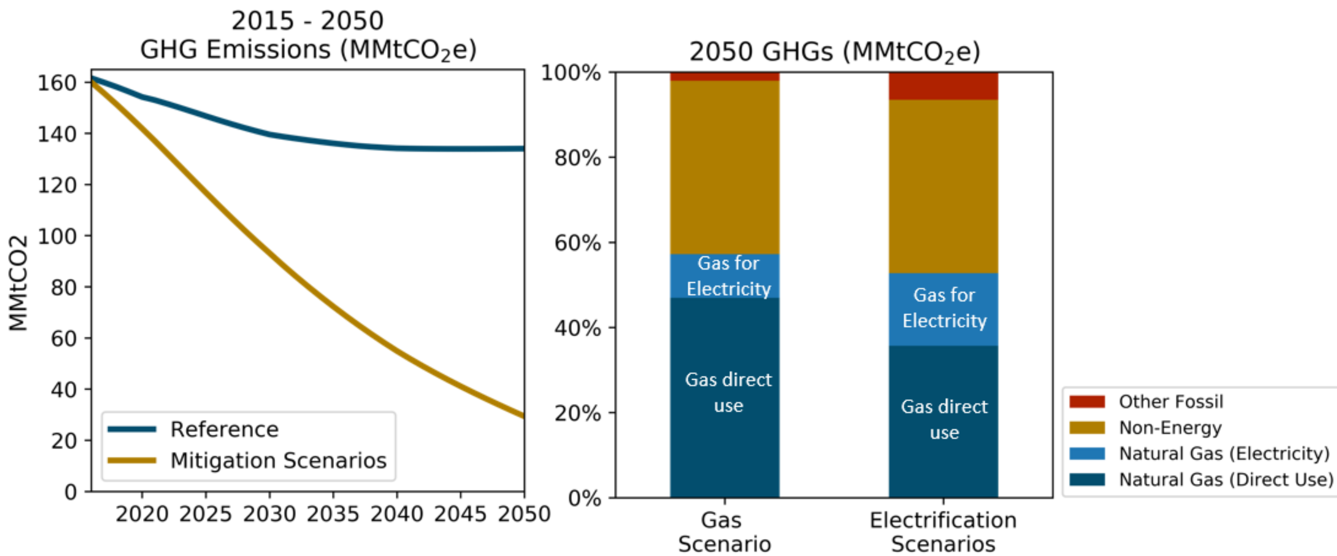
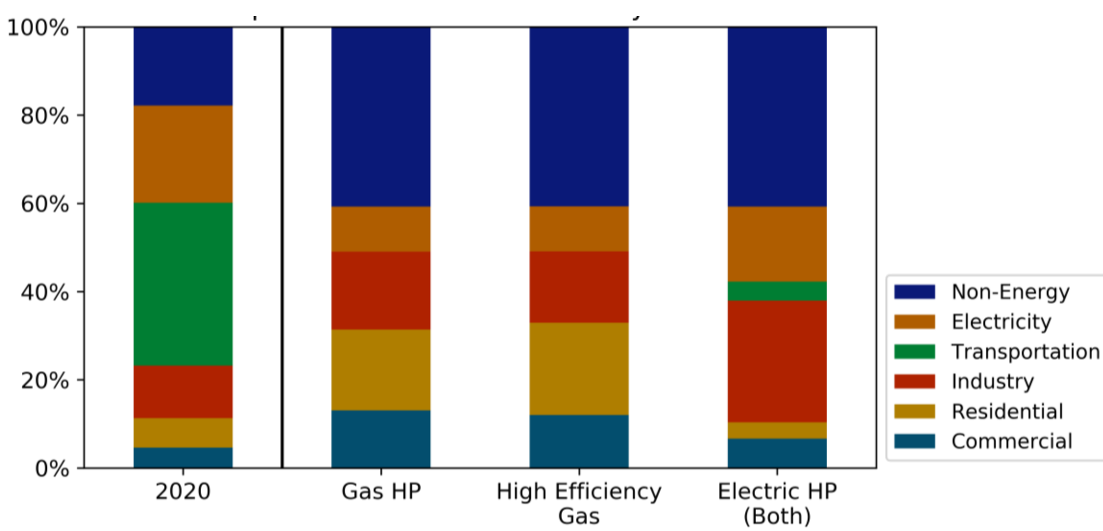


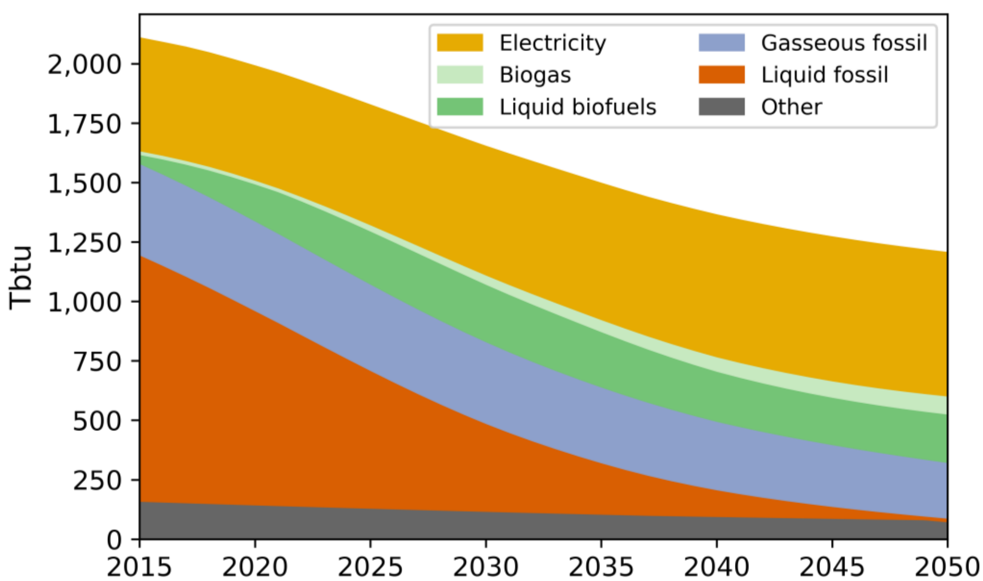
Figure 12. Share of Greenhouse Gas Emissions by Sector in 2020 and by Scenario in 2050



4.2 Energy Demand in a Low Carbon Future

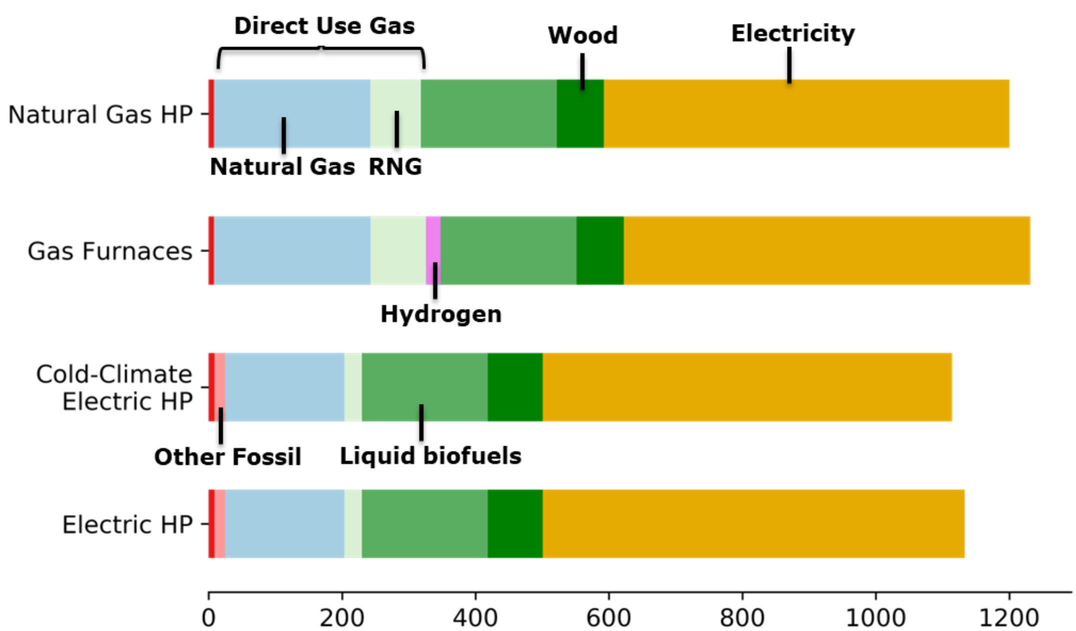
Delivered energy in the Northwest is dominated by the use of liquid fossil fuels (mostly gasoline and diesel in the transportation sector) and gaseous fossil fuels (mostly natural gas use in buildings and industry). Electricity is currently provided by a mix of coal, natural gas, hydropower, nuclear and renewables. In every mitigation scenario considered in this analysis, final energy demands are lower by 2050 than today, despite continued population and economic growth (Figure 13). The lower final energy demand is due to the combined impact of energy efficiency in all sectors (buildings, industry and transportation), as well as the efficiency savings from switching from internal combustion engines in vehicles (~20% efficient) to electric motor drive-trains in the transportation sector (~60% efficient).

Figure 13. Energy demand by fuel type, Gas Heat Pump Scenario



By 2050, low-carbon electricity is assumed to provide the largest share of final energy demands in all scenarios. The remaining liquid and gaseous fuels in the economy are blends of biofuels and conventional fossil fuels. Biofuels account for between 19% and 24% of final energy consumption in 2050 in all scenario. In the Gas Furnace Scenario, an additional 6% of pipeline gas energy comes from renewably-produced hydrogen (Figure 14).

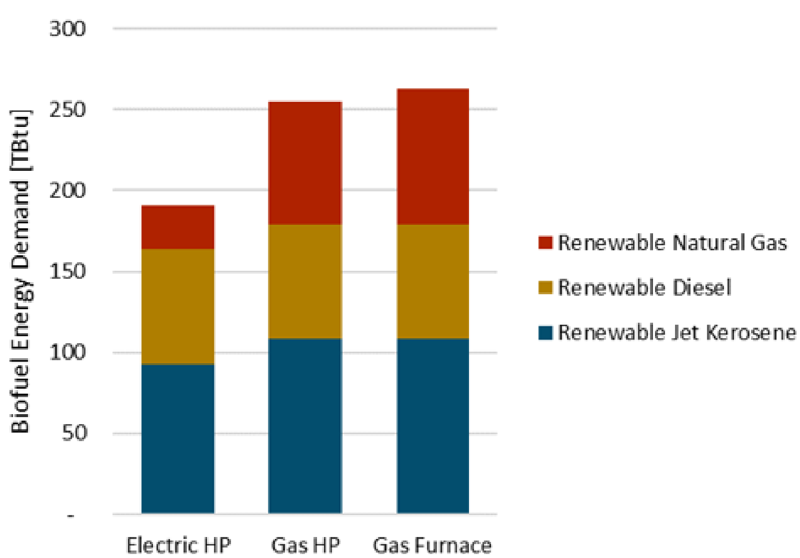
Figure 14. Final energy demand by fuel type and scenario, 2050 (Tbtu)



4.2.1 BIOFUELS

Carbon-neutral, advanced biofuels are a limited, but important, source of carbon reductions in all mitigation scenarios. The PATHWAYS biofuels module allocates biomass feedstocks to fuels, based on energy demands remaining after electrification and energy efficiency measures have been applied in each scenario. Most of the biomass is allocated to producing liquid fuels, largely renewable diesel and renewable jet kerosene to displace fossil fuel emissions in off-road transportation and aviation, both sectors which may be difficult to electrify (Figure 15). The allocation in these scenarios was selected by optimizing to maximize cost-effective GHG reduction from a societal perspective (e.g. consumer incentives and electric rate design options are not considered). For cellulosic and woody feedstocks, liquid fuels result in lower net cost CO_2 displacement than biomethane because of the high cost and CO_2 intensity of the displaced fossil fuels, but this result is sensitive to a number of uncertain model inputs, including projected biofuel conversion efficiencies. Biomethane is an important tool to decarbonize remaining pipeline gas in each scenario, with blends as high as 25% of total throughput in the Direct Use Natural Gas Scenarios. Biofuel demands are identical in both of the Electric Heat Pump Scenarios.

Figure 15. Biofuel Energy Use by Scenario, 2050



The PATHWAYS biofuels module determines a market-clearing price for biofuels on an economy-wide basis. The same market-clearing price for biofuels is assumed in all scenarios, based on an assumption that the market price will be set by regional, economy-wide supply and demand (Table 4).

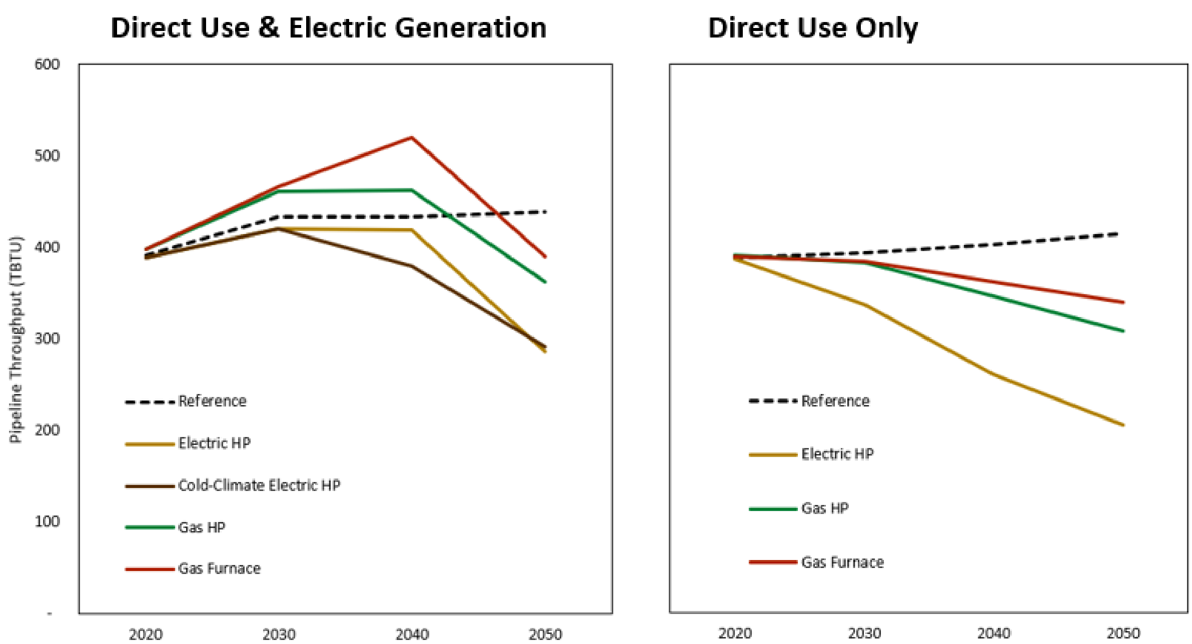
Table 4. 2050 estimated market clearing price for biofuels, by fuel type

Final biofuel	$ / MMBtu
Biomethane	$23
Renewable diesel	$51
Renewable jet kerosene	$49

4.2.2 DEMAND FOR PIPELINE GAS

Demand for natural gas decreases in every case relative to Reference (Figure 16). Direct use gas demand begins decreasing in 2020 due to aggressive energy efficiency in all cases. Further reductions in direct use gas occur in the Electric Heat Pump Scenarios as fuel-switching from gas to electric equipment in buildings occur. Total pipeline gas use in the region increases in the Gas Scenarios and is close to Reference in the Electric Heat Pump scenarios through 2040. This result is largely driven by a switch from coal-fired generation to natural gas combined cycle power plants. Later in the study period, the emissions cap for the electricity sector, achieved largely through additional renewable generation, leads to a sharp drop in gas use in the electricity sector between 2040 and 2050.

Figure 16: Pipeline gas throughput by scenario

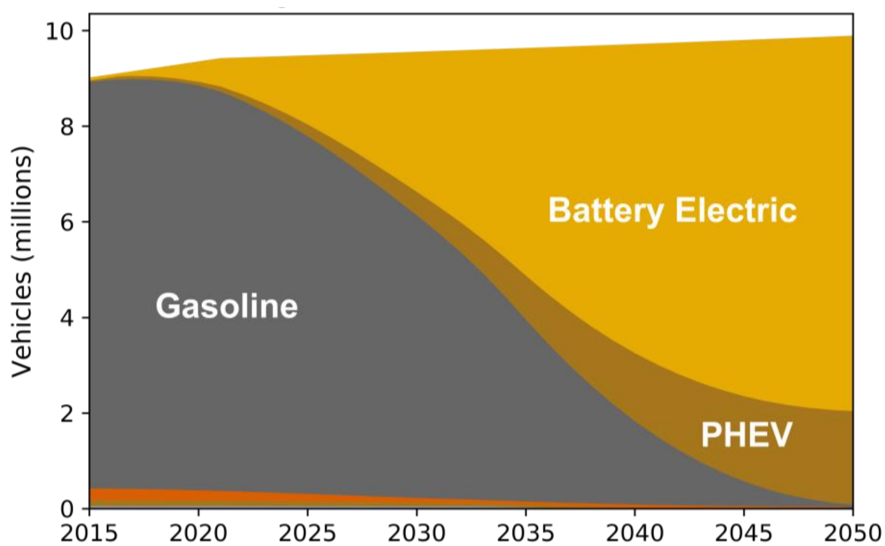


4.3 Transportation Sector

4.3.1 PASSENGER VEHICLES

Across all scenarios, passenger vehicle electrification is a core strategy to decarbonize the region's transportation sector, the largest source of GHG emissions in the Northwest region. In all scenarios, over 70% of passenger vehicle sales are from either battery electric or plug-in hybrid technologies in 2030, and by 2035, 100% of sales are either battery electric or plug-in hybrids. This translates to 3.4 million electric or plug-in electric passenger vehicles by 2030 and 9.8 million electric or plug-in electric vehicles by 2050 (Figure 17). Achieving this scale of light-duty vehicle electrification will require a complete transformation of consumers' vehicle purchase decision within the next two decades. In 2017, 2.5 percent of light-duty vehicle sales in Washington and 2.3 percent of sales in Oregon were battery electric or plug-in hybrid vehicles (Alliance of Auto Manufacturers 2018).

Figure 17. Millions of Passenger Cars and Trucks by Type, All Scenarios, 2015 – 2020



Barring a ban on fossil-fueled vehicles, consumer decisions will determine the pace of passenger vehicle electrification. Even under optimistic cost projections, electric vehicles are expected to be more expensive from an upfront cost perspective than fossil alternatives for at least the next decade (Bloomberg New Energy Finance 2018). This means that an increasing proportion of consumers will have to opt for vehicles with a higher upfront cost or will continue to require subsidies to drive ZEV sales.

Barriers to widespread adoption of electric vehicles must also be addressed, even as ZEVs move towards cost-parity with fossil alternatives. Non-cost considerations—for example, anxiety over range or the opportunity to refuel—may reduce consumers' propensity to adopt a new vehicle technology. Public charging infrastructure will be needed to address range anxiety concerns and ensure equitable access to electric vehicles for lower income drivers who may not have access to at home chargers.

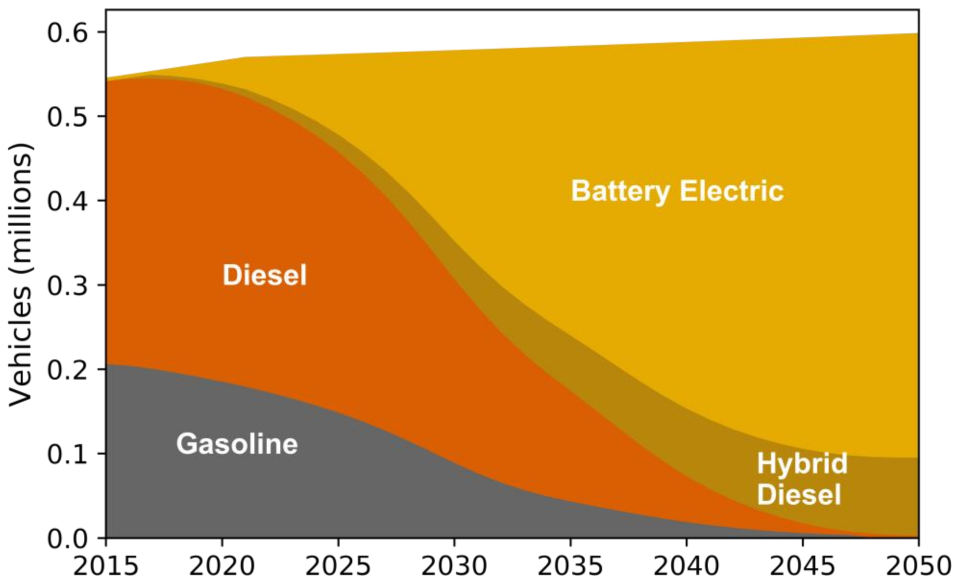
4.3.2 MEDIUM- AND HEAVY-DUTY TRUCKS

Like passenger vehicles, medium and heavy-duty trucks must undergo a transition from GHG intensive fossil fuels to a mix of low-carbon alternatives. There are a range of plausible technologies that can be used to decarbonize trucks, including: hybrid electric (diesel hybrid), battery electric (BEV), hydrogen fuel cell (HFCV), and biofuel derived diesel and compressed natural gas (CNG). In this analysis, we focus on electrification as the primary strategy to reduce emissions in medium-and heavy-duty trucks. Battery electric trucks have not yet been produced at scale but could represent an important transportation decarbonization technology. We assume that battery electric trucks are most immediately useful in the medium-duty trucking sector.

Major owners of medium duty fleets like UPS have begun to pilot battery electric parcel trucks (Winston 2018). Heavy duty truck electrification is more speculative. Barring substantial improvements in battery technology, the energy densities of renewable diesel and hydrogen may be attractive options for trucking services that involve heavy loads or long-distances.

In all scenarios over 80% of medium duty trucks and over 70% of heavy-duty trucks are electrified. This view of the future is premised on electric technologies being capable of serving all but the highest load and longest trips. The remaining trucks in the economy are powered by hybrid diesel drive-trains, fueled with 100% renewable diesel (Figure 18).

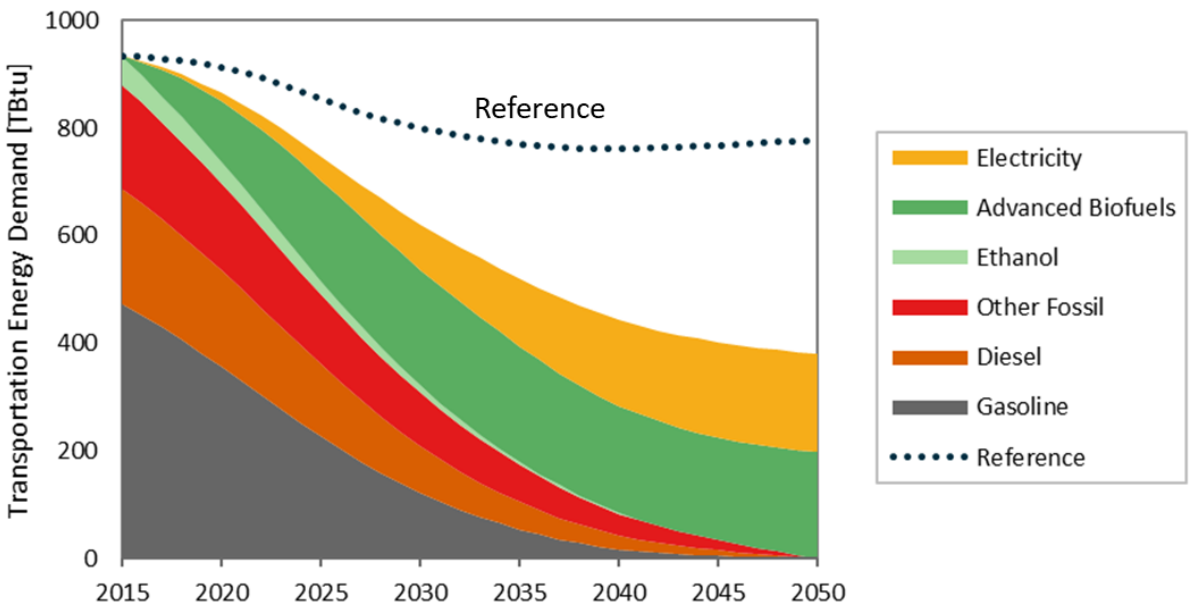
Figure 18. Millions of Freight Trucks by Type, All Scenarios, 2015 - 2050



4.3.3 ENERGY DEMAND IN THE TRANSPORTATION SECTOR

By 2050, in all scenarios, energy demands in the transportation sector are assumed be served entirely with electric or hybrid electric vehicles, with the remaining liquid energy demands provided by advanced, carbon-neutral biofuels. Total transportation energy demands in the mitigation scenarios are about half of the energy demands in the Reference scenario, due to the efficiency gains from electric drive trains in vehicles (Figure 19). Energy demands fall even in the Reference scenario due to the assumed efficiency gains of continued implementation of the federal corporate average fuel economy standards for vehicles.

Figure 19. Energy demand in the Transportation Sector, All Scenarios, 2015 - 2050



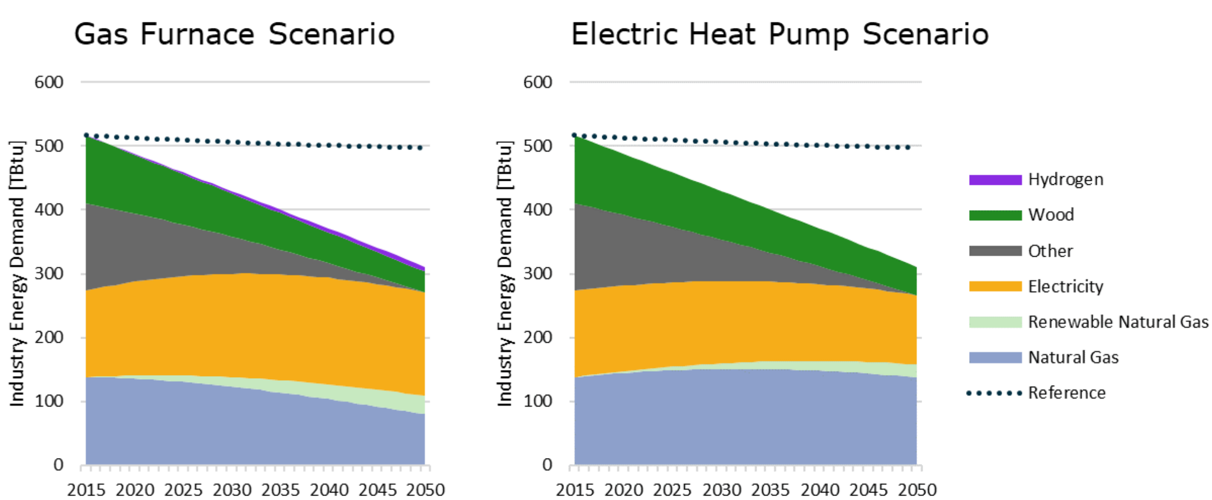
4.4 Industrial Sector

Greenhouse gas reductions from industrial energy emissions are achieved in these scenarios via three mechanisms: 1) energy efficiency, 2) decarbonization of fuels, and 3) electrification. Non-energy emissions reductions are also an important component of decarbonizing industry, particularly in sectors like cement, and are applied based on current research suggesting realistically achievable reductions.

Energy efficiency is assumed to reduce industrial demands for pipeline gas, diesel and electric power. Each scenario assumes a 30% reduction in total industrial energy demand via energy efficiency, relative to the Reference scenario. We assume that the petroleum refining industry in the region sees sharp decreases in output given the very low demand for refined petroleum products in all mitigation scenarios. Today, all refining in the Northwest occurs in Washington. We estimated the share of industry energy usage associated with refining using Washington State Emissions Inventory Reporting System data for 2014 (Washington Department of Ecology 2014). Based the emissions in that report, we assume that retired refinery capacity is equivalent to an additional 20% reduction in total industrial demand in Washington in 2050 relative to the Reference scenario.

The remaining energy demands in industry can be served in one of three ways: electrification, low-carbon fuels, and fossil-fuels. All scenarios use low-carbon fuels, primarily biomethane, to displace fossil natural gas in the pipeline. The renewable natural gas in the pipeline contributes to reducing emissions from the industrial sector. A distinction between the Electric Heat Pump and Direct Use Gas Scenarios is industry electrification. The Gas Scenarios rely on 30% electrification of industry natural gas to meet the 2050 emissions gap, reducing the direct use of natural gas in industry compared to the Electric Heat Pump scenarios (Figure 20). Industry electrification includes converting HVAC equipment to electric heat pumps, using electric resistance heaters in process heating and boiler applications, as well as using emerging electric technologies like ultraviolet pasteurization or induction melting.

Figure 20. Energy Demand in Industry by Scenario and Fuel Type, 2015 - 2050



The electrification of industrial energy usage in the Gas Scenarios is a transformational change in the sector. There may be emerging use cases where some industrial processes will experience productivity gains by converting to electric technologies, but cost per unit of heat will probably be the most salient feature for most of industry.

4.5 Buildings Sector

4.5.1 ENERGY EFFICIENCY

In all scenarios, carbon reductions are achieved in the buildings sector through high levels of energy efficiency. Conventional forms of energy efficiency that are applied in all scenarios include a complete transition to efficient LED lighting, as well as more efficient plug loads and equipment, ranging from refrigeration to dishwashers. High efficiency appliances achieve an Energy Star standard or beyond.

All scenarios assume substantial improvements in the building shells of buildings in the Northwest. In the PATHWAYS model, building shell improvements are modelled as a ‘stock’ measure. Building shell improvements are assumed to reduce space-heating energy services demand by 40% relative to today in individual retrofit of buildings. By 2050, almost 75% of buildings are assumed to have this more efficient building shell. We also assume that behavioral conservation measures, such as smart use of programmable thermostats, decrease energy services demand by 5% per building. The result is a 35% decrease in heat required to keep buildings warm across the entire Northwest building stock by 2050. These energy efficiency gains are an important tool to contain costs for the Gas Scenarios and the Electrification Scenarios.

4.5.2 SPACE HEATING

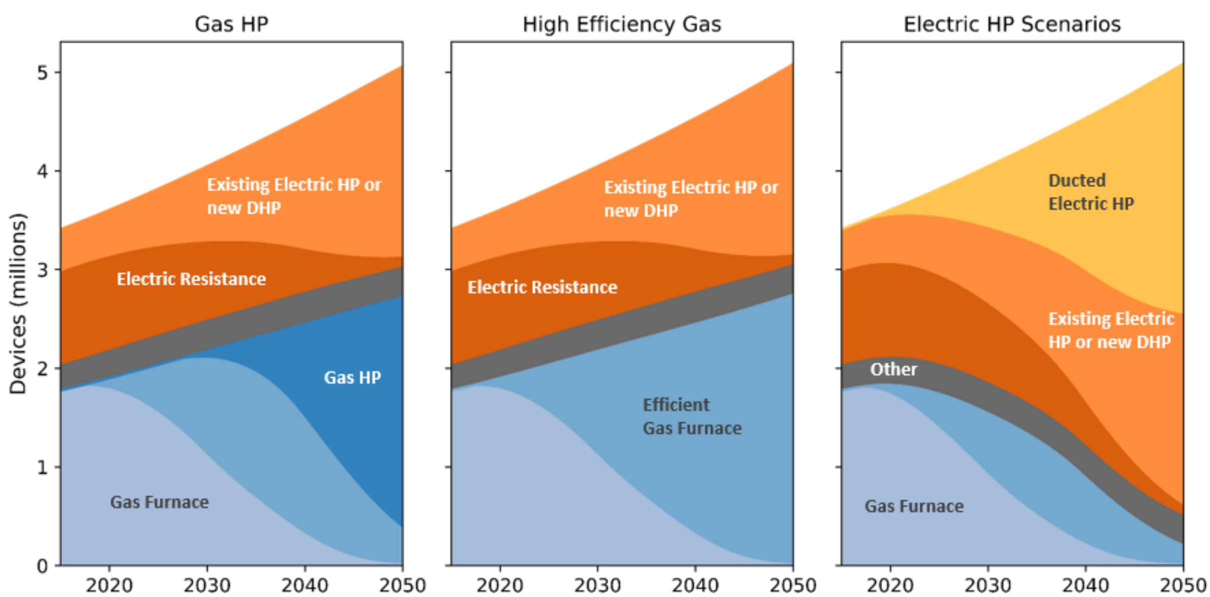
In nearly all scenarios, a transformation of space heating technology sales is envisioned as part of a low-carbon future. There are a wide variety of space-heating technologies in use in the Northwest today, ranging from natural gas furnaces to wood-fired stoves. All scenarios assume that electric resistance, diesel, and propane (LPG) heaters are replaced with ductless electric heat pumps, given that the lifecycle economics for such a replacement would be generally positive in all cases. Policy intervention may still be needed for this transition to overcome market barriers such as limited access to credit or split incentives for renters.

In the Direct Use Natural Gas Scenarios, continued use of the Northwest's existing natural gas distribution infrastructure is assumed to heat existing proportions of homes and businesses. The Electric Heat Pump Scenarios replace existing gas space- and water-heaters with electric air source heat pump technologies (Figure 21).

- In the Gas Furnace Scenario, all new furnaces sold have an efficiency of 98% or greater by 2030, compared to an approximate 90% efficiency for a typical furnace installed in Northwest today (NEEA Residential Building Stock Assessment [RBSA]).
- The Natural Gas Heat Pump scenario is an innovation case, where gas-powered heat pumps are brought to market on a wide scale by 2025. Natural gas heat pumps operate under similar principles as electric heat pumps and can achieve annual COPs of over 1.4 annually for space heating and 1.3 for water heating, without relying on electric resistance heating during extreme cold temperatures. E3 consulted with NEEA—a regional energy efficiency organization working to commercialize the technology—to better understand the characteristics of natural gas heat pumps (Interview). One notable feature of NEEA's preferred natural gas heat pump technology is that it may be well suited to provide both space- and water-heating from a single system.
- The Electric Heat Pump Scenarios assume a near complete electrification of space-heating in the Northwest. The Electric Heat Pump Scenario assumes that, by 2030, 60% of the sales of space heating equipment in buildings are high efficiency air source heat pumps with an HSPF of 9.0. By 2040, 100% of sales of all space heating equipment in the region is assumed to be electric heat pumps. The Cold-Climate Heat Pump Scenario assumes that, by 2030, 60% of the sales of space heating equipment are higher performing, but more expensive, cold climate heat pumps, with an HSPF of 10.5. This share of new sales increases to 100% by 2040. Over time, homes that have, or

would have, installed gas heating equipment instead install an air-source heat pump. By 2050, almost every building in the region is heated by electric heat pumps or cold climate heat pumps. The scale and pace of this transition highlights the role of the consumer in achieving deep decarbonization. To achieve this transition, the purchase decisions of both homes and business must shift to electric alternatives. That trend would run counter to recent experience, where the share of gas heated buildings in the region is increasing (NEEA RBSA). The electric sector implications of space-heating electrification are discussed below, in section 4.7.

Figure 21. Millions of Residential Space Heaters, by Scenario, 2015 - 2050

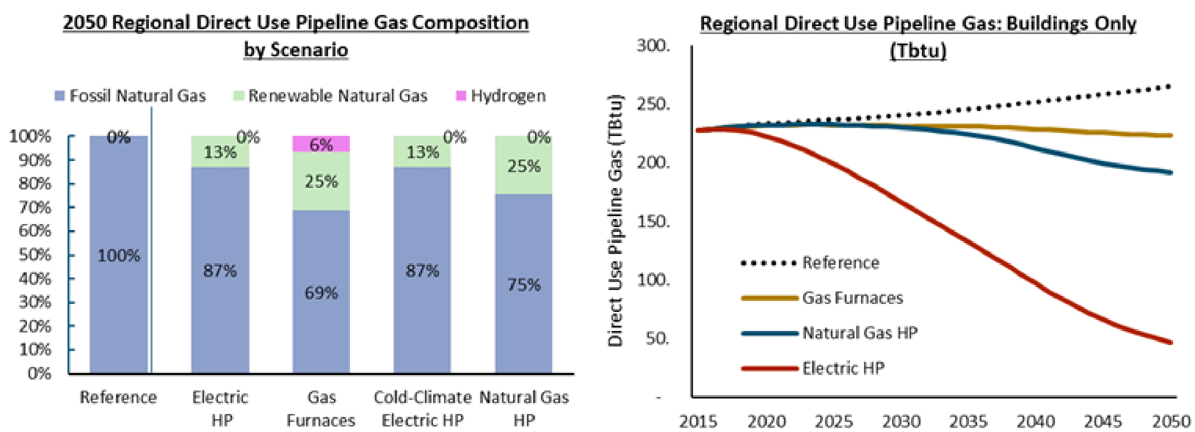


4.5.3 GAS USE IN BUILDINGS

A key element of greenhouse gas reductions in the Gas Scenarios is energy efficiency. Wide-spread adoption of efficient gas technologies—paired with the same aggressive shell measures used in the Electrification Scenarios—decreases gas throughput relative to Reference by between 18 and 26 percent compared to the Reference scenario.

The remaining pipeline gas throughput is partially decarbonized in the Gas Scenarios. The Gas Furnaces scenario uses a combination of biomethane and blended hydrogen to decarbonize 31% of direct use natural gas. The Natural Gas Heat Pump Scenario has a similar quantity of biomethane, but with its lower denominator has a higher blend of biomethane at 25% of direct use of natural gas. The Natural Gas Heat Pumps scenario avoids the use of relatively expensive hydrogen because of the additional energy efficiency this technology enables.

Figure 22. 2050 Composition of the Natural Gas Pipeline by Scenario, and Direct Use of Gas in the Buildings Sector Over Time, by Scenario



4.5.4 WATER HEATING

Both of the Electric Heat Pump Scenarios include wide-spread adoption of electric heat pump water heaters in Oregon and Washington. The heat pump water heater load shapes are derived from Ecotope, and are primarily driven by occupant use schedules, with some impact from outdoor air temperatures (Larson and Hannas 2014). While heat pump water heaters are larger than traditional tank water heaters and require more clearance around the unit, it is assumed that they can be installed in nearly all homes and businesses by 2050.

The Gas Furnaces scenario assumes wide-spread adoption of 85% efficient gas condensing storage tank water heaters. The Natural Gas Heat Pump scenario assumes that natural gas heat pump "combi" systems are installed to provide both space- and water-heating services to buildings. This is an important feature of the Natural Gas Heat Pump scenario, allowing customers to realize not only energy efficiency gains from adopting this technology, but also cost savings relative to the cost of purchasing a separate water heater and space heater.

4.5.5 PEAK HEATING LOADS IN THE NORTHWEST

Heating loads are the largest source of energy demand in a typical residential and commercial building in the Northwest. The importance of heating loads only increases as the temperature drops. E3 worked with Big Ladder Software to conduct building simulations in Energy Plus for three different building types using air source heat pumps. Results from that modelling show that electrification can cause large new loads in buildings. After accounting for weatherization and displaced electric resistance heat, electrification of space-heating adds incremental loads of between 17,000 and 37,000 megawatts to the region's peak electricity demand. For context, the region's entire hydroelectric system is about 33,000 MW, with an estimated peak capacity of 24,000 MW over a four-hour period.[15]

The Gas Scenarios examine cases where the proportion of homes[16]and businesses served directly by pipeline gas (inclusive of natural gas, renewable natural gas, and hydrogen) does not change over time. A

[15] Northwest Power and Conservation Council 7th Power Plan, Chapter 9: Existing Resources and Retirements: https://www.nwcouncil.org/sites/default/files/7thplanfinal_chap09_existresources_2.pdf

[16] The share of gas heating is based on housing unit type, where there are 3 categories, including large-single family, small single-family attached, and multifamily.

combination of low-carbon gases and energy efficiency reduces the direct-combustion emissions per gas home by between 42% and 50% by 2050.

The Gas Furnaces Scenario assumes the installation of condensing gas furnaces and condensing gas storage tank water-heaters to reduce demand over time. Both technologies are commonly installed today. In order to achieve the economy-wide emissions target this scenario also includes a blend of both RNG and hydrogen in the pipeline to reduce the emissions intensity of pipeline gas. The Gas Heat Pump Scenario assumes the installation of natural gas-powered heat pumps, a technology which is not widely available today. Natural gas-powered heat pumps have an efficiency rating, or COP, of 1.3 to 1.4, creating a large enough reduction in demand that hydrogen blending into the gas pipeline is not necessary in this scenario to meet the 2050 economy-wide GHG reduction goal.

4.5.5.1 Building Stock in the Pacific Northwest

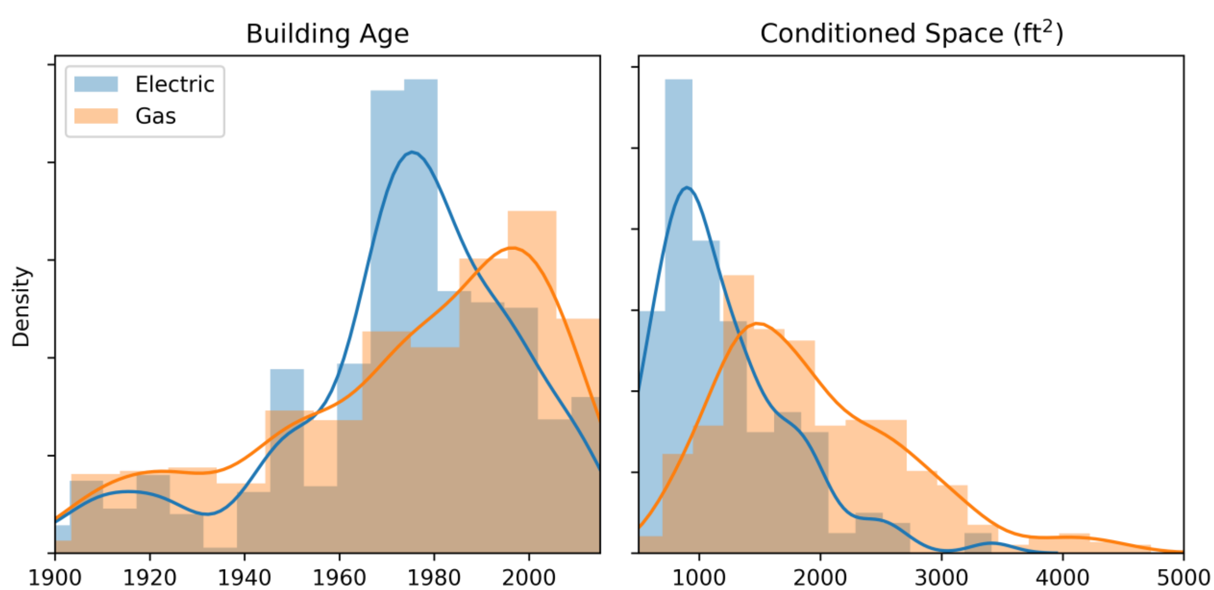
Most buildings in the Northwest are heated by either natural gas furnaces or electric resistance heaters. In Oregon, 58% of homes use natural gas as their primary source of space-heating, 33% of homes use electric heat and the remaining homes use a combination of oil, propane and wood. The current distribution of space-heating equipment in Washington is similar to Oregon (Table 5).

Table 5. Share of space heating and water heating by fuel type and state (%) (Source: NEEA RBSA)

Appliance	Fuel Type	Oregon	Washington
Space heating	Gas	58%	52%
	Electric	33%	42%
	Other	9%	6%
Water heating	Gas	50%	48%
	Electric	50%	51%
	Other	<1%	1%

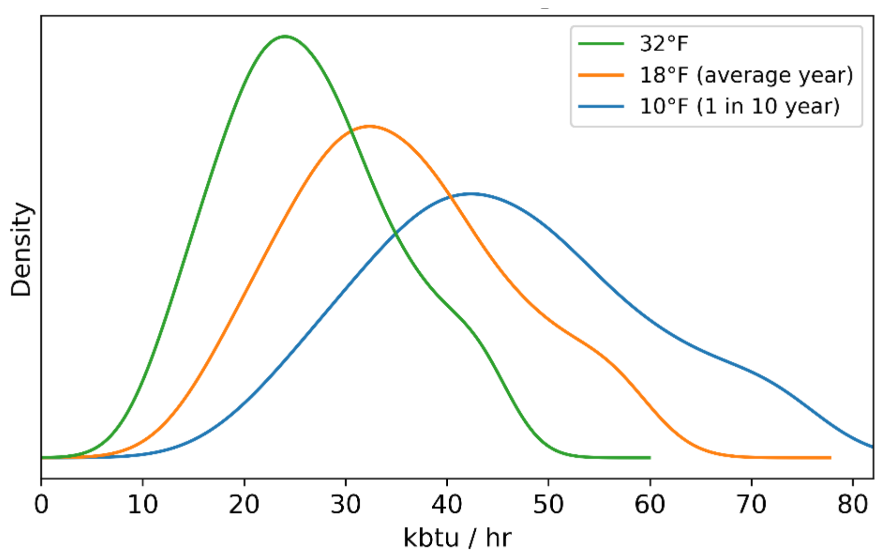
In the Northwest, approximately 35% of homes use electric heat. In general, these homes tend to be smaller and older than gas homes in the region (Figure 23). Whereas the average gas home in Oregon and Washington is almost 2,000 square feet and most likely was built in the 1990s or 2000's, an average electric resistance home in the region is 1,200 square feet and was most likely built in the 1970s. Gas equipment tends to serve larger loads, so its share of heating energy is higher than the stock shares in Table 2. For instance, natural gas serves 68% of regional space-heating needs despite being the primary source of heating for just over half of the residential housing units in Oregon and Washington.

Figure 23. Existing distribution of Pacific Northwest homes by vintage and heating fuel type, and by square footage and heating fuel type (Source: NEEA RBSA 2016)



Space heating and cooling loads are weather dependent. As the temperature drops, building heating requirements increase. Figure 24 shows the distribution of hourly space-heating demand for the gas-heated building stock within Northwest Natural's service territory at three different temperatures. At freezing, the median home requires 25 kbtu per hour (kbtu/hr) to maintain comfort. The average heating requirements increase to a peak of 37 kbtu/hr during an average winter (18° F) and 44 kbtu/hr during a particularly cold, “1 in 10 year”, winter at 10° F. For reference, the largest residential heat pump widely available is 5 tons, rated to provide 60 kbtu/hr at 47° F and that output that decreases with temperature.

Figure 24. Distribution of heating requirements across NW Natural’s housing stock at 7am, across three different temperatures (Source: NW Natural)



4.5.5.2 Performance of Electric Heat Pumps in the Pacific Northwest

Electrification of space-heating creates a large new weather dependent load for the Northwest electricity system to serve. This analysis considers the impact of a ‘1 in 10’ cold-snap as a heuristic for the type of heating event that the electric sector will need to plan for in a high electrification regime.

This analysis considers two types of centrally-ducted electric heat pumps for residential and commercial buildings: a conventional air source heat pump system and an electric air source heat pump designed for better performance in cold-climates. The first heat pump system has an efficiency rating, or HSPF, of 9, equivalent to an annual COP of 3.2 (estimated regional average). These types of systems are commonly available in the Pacific Northwest region. For context, these systems are more efficient than the federal code minimum requirements of an HSPF of 7.7. The minimum requirements to receive an incentive from The Energy Trust of Oregon for an air source heat pump is an HSPF of 8.5 or greater, while the state of Oregon offers an incentive for ducted air source heat pumps with an HSPF of 9.5 or greater. The cold-climate system has an HSPF of 10.5, equivalent to an annual COP of 4 (estimated regional average). These systems are both more efficient overall and more expensive than the heat pumps with an HSPF of 9. Cold climate heat pumps are also currently less common and as a result are less well understood by some contractors and HVAC installers.

Both electric heat pump systems are efficient on an annual basis, requiring less on-site energy to heat buildings than gas furnaces or electric resistance heaters. The systems are most distinct in their performance during cold weather events. Consistent with the standard installation practices for heat pumps in cold climates, each system is assumed to be installed with electric-resistance back up heat. At the “lock-out” temperature, the heat pump operation is entirely replaced with less efficient electric resistance back-up heat to ensure that desired building temperature is maintained. The Electric Heat Pump scenario assumes that this temperature is 34 degrees Fahrenheit, while the Cold Climate Electric Heat Pump scenario sets that temperature at 5 degrees Fahrenheit. Table 6 lists the key parameters of the heat pump systems.

The Electric Heat Pump scenario represents a worldview where relatively efficient air source heat pump systems are adopted, but where installers and building occupants select and install the electric heat pumps systems to reduce the upfront capital costs, and do not have an incentive to optimize the performance of the systems for the broader electric grid during cold weather. The Cold Climate Electric

Heat Pump scenario is more consistent with a market-transformation future where cold climate heat pumps are specifically incentivized or required, or customers' economic interests are aligned with reducing system-wide winter peak demands.

Table 6. Comparison of electric heat pump performance assumptions by scenario

	Electric Heat Pump	Cold-Climate Heat Pump
Annual Efficiency (heating seasonal performance factor, HSPF)	9	10.5
Annual coefficient of performance, regional average estimate (Heat pump/ System)	3.0 / 2.5	4.0 / 3.8
Peak coefficient of performance (System)	1.0	2
Lock-out temperature (F)	34F	5F

Electric heat pumps both lose efficiency and produce less heat as the outdoor temperature drops. When there is a gap between building heating requirements and the maximum output of a heat pump, supplemental heat is required. The most common form of supplemental heat is an electric resistance element, though natural gas or propane furnaces can also provide supplemental heat (Center for Energy and Environment 2017, Wales & West Utilities 2018). For the purposes of this study, electric heat pumps are assumed to be supplemented by electric resistance heat.

After accounting for energy efficiency improvements and load diversity, we find that switching from gas to cold-climate electric heat pumps adds an incremental peak of 4.3 kW per home during a '1 in 10' heating event. Similar incremental peak loads occur in the commercial sector, where conversion to air source heat pumps increases electric load by 2 W/ft^2. These loads are offset, somewhat, by replacing electric resistance heaters with electric heat pumps. The Appendix provides additional detail on how building electrification loads were built up in this analysis. Table 7, below, outlines some key conditions under which actual building electrification peak load impacts could either be higher our lower than our findings.

Table 7: How peak load estimates could change

Winter peak could be higher with:	Winter peak could be lower with:
+ Less progress on building shell retrofits and improvements in new buildings + Winter temperatures colder than the 1-in-10 heuristic used in this analysis + Less diversity in building heating loads during cold temperatures + More reliance on supplemental heat during cold weather (e.g. HVAC installation practices that are not focused on meeting peak heat needs, or poor equipment maintenance) + Higher coincidence of space heating, water heating and electric vehicle charging	+ Market transformation that reduces the cost of non-weather dependent ground source heat pumps + Technology improvements that improve the performance of cold-climate heat pumps + More diversity in building heating loads at cold temperatures + Demand response & flexible loads in industry, electric transportation and other non-weather dependent end-uses + Heat storage in buildings, including pre-heating buildings + Duel-fuel heating systems: electric heat pumps paired with a furnace or boiler powered by gas or propane that provides supplemental heat + Increased winter minimum temperatures due to climate change + New electric transmission could also help to address winter peaks

4.6 Electric Sector Capacity Expansion and Operations

The electric sector is the lynchpin of deep decarbonization. In each scenario, clean electric generation displaces fossil fuels, both directly in the electric sector and through electrification of end uses elsewhere in the economy. As discussed in the methods section of the report, the electricity sector is modeled using the RESOLVE model to evaluate the costs and generation mix associated with meeting a given set of electricity demands and an electricity sector carbon constraint, as defined in each scenario.

For this analysis, we simulate the electricity sector under a carbon budget. The carbon budget defines a maximum amount of carbon which the electricity sector can emit. The greenhouse gas accounting convention reflects a consumption-based approach, in which the emissions attributed to the region includes in-region generation, external resources owned by utilities which serve load within the region, and "unspecified" imports to the region, based on a deemed emissions rate of 0.43 tons/MWh. This accounting convention is based on rules established by the California Air Resources Board – for further details see the E3 "Pacific Northwest Low Carbon Scenario Analysis" Study.[17] The carbon budget is an upper bound on emissions, not an emissions target; if it is economic to procure more zero-carbon energy, meeting a lower emissions target than the required budget, RESOLVE will do so.

This study models a suite of scenarios to investigate strategies to deep decarbonization. A Reference Scenario reflecting current policies and trends serves as a point of comparison for the decarbonization scenarios. This Reference Scenario models existing statutory Renewable Portfolio Standard (RPS) goals, including Oregon's 50% RPS requirement for large IOUs and Washington's 15% RPS by 2020. This results in a region-wide, weighted RPS goal of 20% by 2040, which is held constant through 2050. Under the various decarbonization scenarios, the carbon budget for the electricity sector is set such that the total

[17] E3, "Pacific Northwest Low Carbon Scenario Analysis: Achieving Least-Cost Carbon Emissions Reductions in the Electricity Sector," December 2017. Available at: http://www.publicgeneratingpool.com/wp-content/uploads/2017/12/E3_PGP_GHGReductionStudy_2017-12-15_FINAL.pdf

scenario will achieve the 80% by 2050 carbon target. Table 8 below reflects the RPS assumption and carbon budget requirement by scenario.

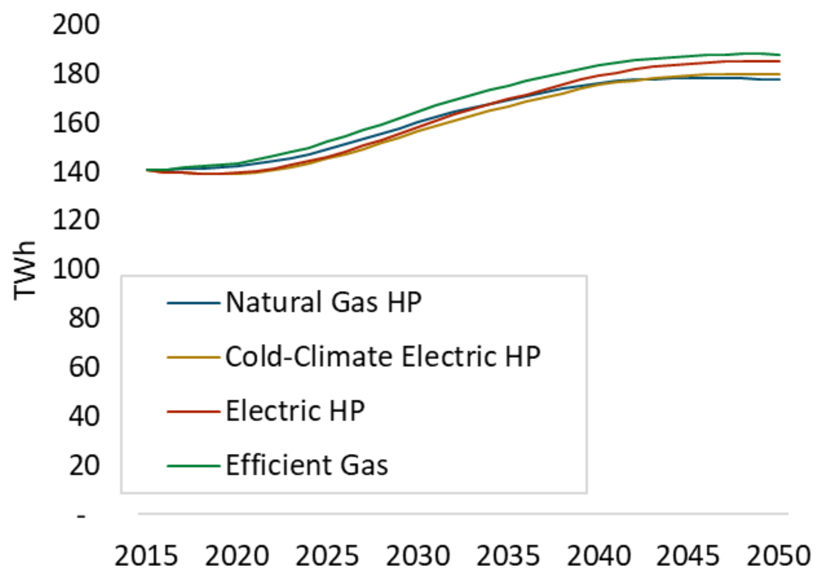
Table 8. Electricity sector RPS and carbon budget assumptions by scenario

	Regional RPS	Carbon Budget / Constraint (2050)
Reference	20% by 2040	None (unlimited)
Direct Use Gas Scenarios	20% by 2040	3 MMT (97% zero-carbon)
Electric Heat Pump Scenarios	20% by 2040	5 MMT (95% zero-carbon)

4.6.1 ELECTRICITY DEMAND

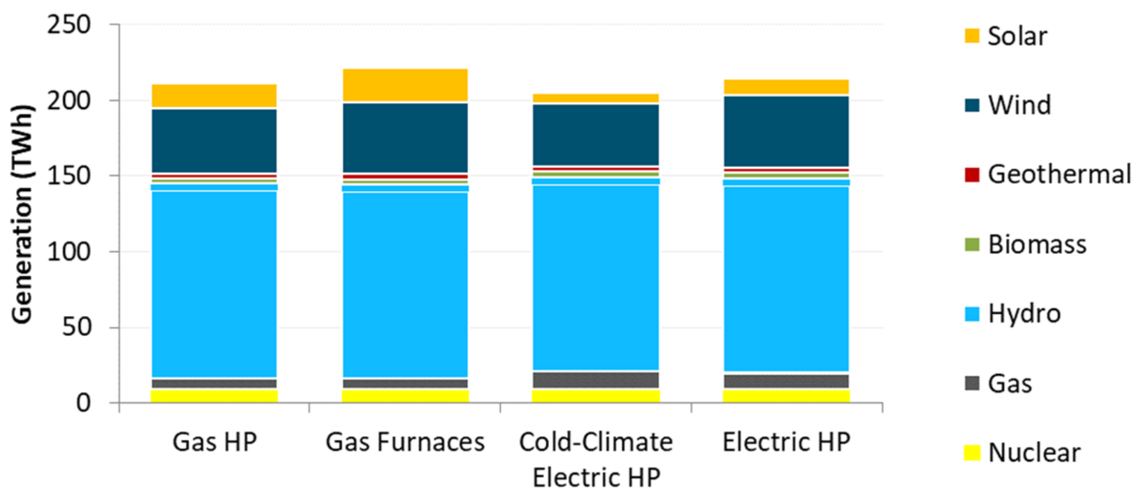
Electric demand increases through 2050 in all decarbonization scenarios. Population growth and decarbonization driven electrification are the primary drivers of load growth in each scenario. Load in PATHWAYS Reference case is expected to grow at 0.2% per year after energy efficiency, while the mitigation scenarios see load growth of 0.67% to 0.84% per year. The Direct Use Gas Scenarios see higher load growth than the Electric Heat Pump Scenarios due to industrial electrification (both Direct Use Gas Scenarios) and due to electricity loads associated with the production of hydrogen via electrolysis in the Gas Furnace scenario. By 2050, the Gas Furnace Scenario has the largest electricity loads due to energy intensive hydrogen electrolysis (Figure 25).

Figure 25. Annual Electricity Demand by Scenario, 2015 - 2050



While the hourly loads look quite different between the scenarios, each of the scenarios has a similar magnitude of annual electric loads in 2050, served by an electric generation mix that is 95% to 97% zero carbon. The largest source of energy in the region continues to be hydropower. Renewables displace most existing fossil generation in the region—including all coal—leaving 3% to 5% of generation from natural gas to balance the system (Figure 26). There is only a modest amount of renewable curtailment in this analysis, falling around 5% of generation in each case.

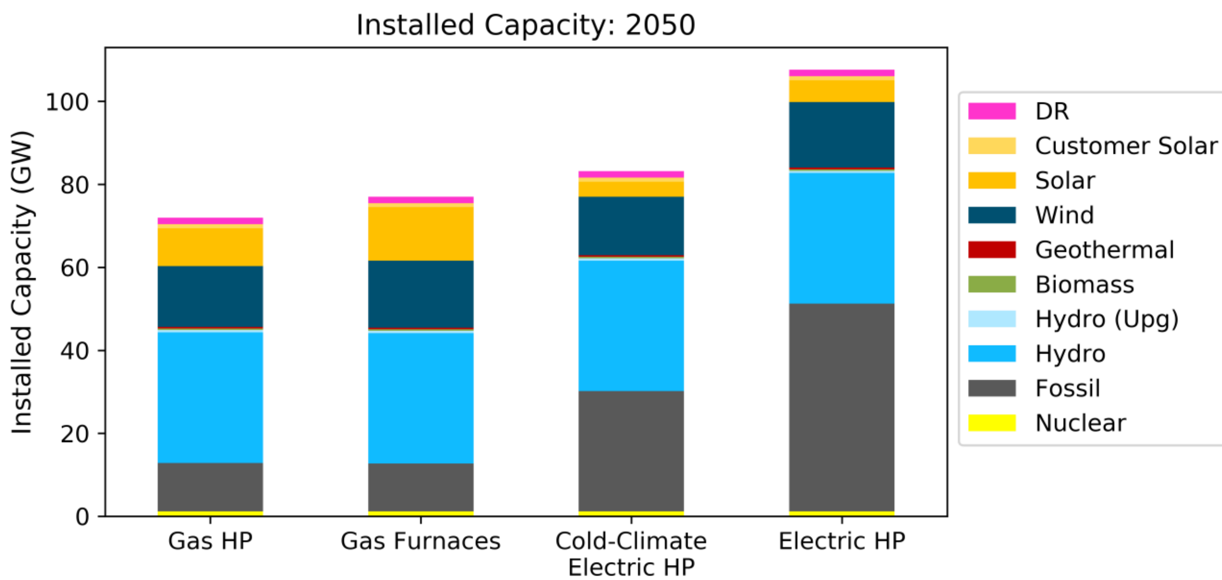
Figure 26. Electricity Generation Mix by Scenario, 2050



4.6.2 ELECTRICITY GENERATION CAPACITY

The Northwest electricity system must expand in every scenario to meet higher electricity demands. There are three main reasons for that expansion: natural growth in loads due to population and economic growth (which is offset by energy efficiency in the mitigation scenarios), greenhouse gas constraints which require new zero-carbon resources to be built, and electrification measures that increase electricity demands, particularly winter peak demands. The 2050 installed resource capacity assumptions by scenario are shown in Figure 27 below. For context, across the Pacific Northwest, the total installed capacity for renewables in 2016 was approximately 10,000 MW, mostly wind. In this analysis, the installed capacity of renewable resources approximately doubles by 2050, to 19,000 MW in the Cold Climate Heat Pump Scenario and to 30,000 MW in the Natural Gas Furnace Scenario, including a mix of solar and wind. The 11,000 GW of additional renewable capacity in the Natural Gas Furnace Scenario compared to the Cold Climate Heat Pump Scenario is used to provide low-carbon power to produce hydrogen from electrolysis, which is blended into the natural gas pipeline. Higher levels of renewable capacity are also built in the Natural Gas Heat Pump scenario to power industrial electrification.

Figure 27. Installed electric generation capacity, 2050



4.6.3 ELECTRIC HEAT PUMP LOAD SHAPES AND CONTRIBUTION TO WINTER PEAK

The largest cause of capacity expansion in the Electric Heat Pump scenarios are the peak loads associated with the electrification of building heat. A critical feature of these loads is that they are inherently weather-dependent and weather varies both within and between years.

Current electricity sector peak planning practices consider a variety of weather conditions, generator outages and other contingencies to establish a planning reserve margin (PRM). A PRM is expressed as an incremental percentage of capacity that is needed on top of expected loads in an average year to ensure electric reliability through a range of contingencies ranging from generator outages to variations in weather dependent loads. Today, a PRM of 15% is typical in many jurisdictions across the Western United States, including in the Pacific Northwest (NERC 2017). Adding weather dependent space-heating loads to a winter-peaking electricity system will, all else equal, increase the variance of plausible load conditions beyond those seen in studies that are the basis for current planning standards.

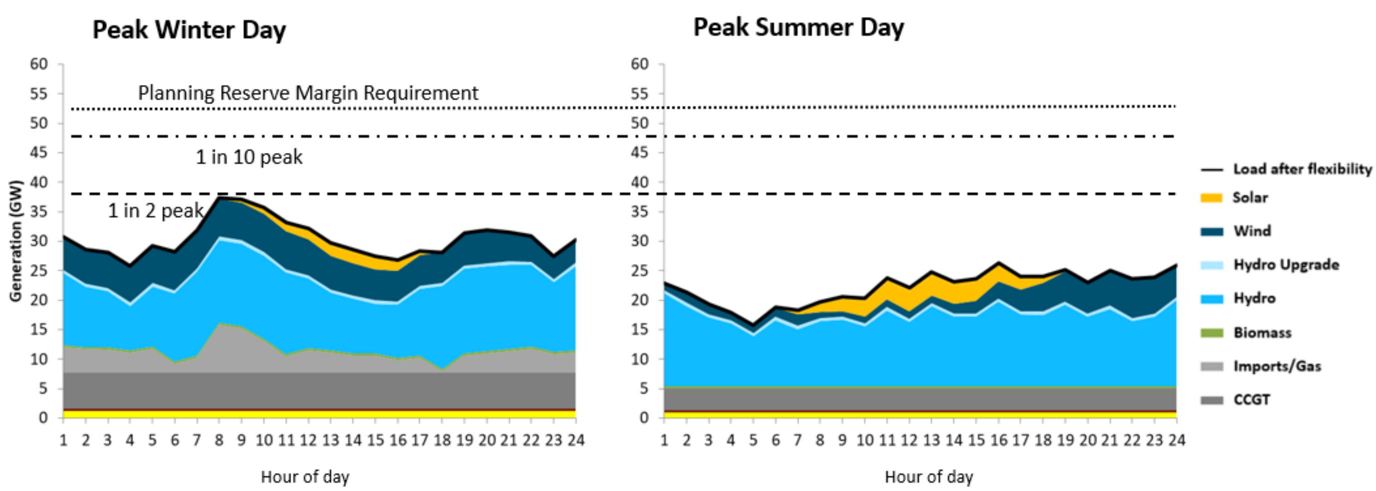
E3 used a ‘1 in 10’ year cold weather event to help evaluate the type of peak event that electricity sector planners would need to account for in a high building electrification future. The difference in peak heating loads between a 1-in-10 weather year and an average ‘1 in 2’ weather year exceeds 9 GW for the Cold-Climate Heat Pump Scenario in 2050, highlighting the sensitivity of load from heat pumps at cold temperatures. Put differently, the system-wide coincident peak loads for the Cold-Climate Heat Pump Scenario are 25% higher in a ‘1-in-10’ winter than in a ‘1-in-2’ winter. Based on this information, we derive an estimated requirement of a 35% planning reserve margin (PRM) in the Cold-Climate Heat Pump Scenario. This PRM is then applied to the ‘1-in-2’ peak loads.

The estimated 35% PRM figure incorporates the 25% inter-annual variation in load under cold temperatures, with the remaining 10% of the PRM accounting for contingencies ranging from generator outages to forecast uncertainty. The estimated 35% PRM was applied to the ‘1-in-2’ peak loads in the RESOLVE model. We compared this approach to an alternative method of applying a 10% PRM to the ‘1-in-10’ peak loads in RESOLVE and the RESOLVE model peak capacity requirements between these two approaches were within 200 MW.

It is important to note that both methods are a heuristic for how a PRM would be calculated and applied in a more detailed electricity resource planning process. To develop a more detailed analysis of the peak capacity needs under a high building electrification, high renewables future, a loss-of-load probability analyses would be needed that accounted for many more contingencies and weather conditions than are included in this study. However, for the purposes of this kind of long-range, scenario planning exercise, we believe that this heuristic-based approach provides an appropriate estimate of the peak capacity requirements.

Figure 28 below illustrates the hourly load shape and generation supply during a peak demand day in the winter and in the summer, under 1-in-2 winter weather conditions, 1-in-10 winter weather conditions and the planning reserve margin that is applied in this analysis.

Figure 28: Hourly loads, peak winter day and peak summer day in 2050, Cold-Climate Heat Pump Scenario

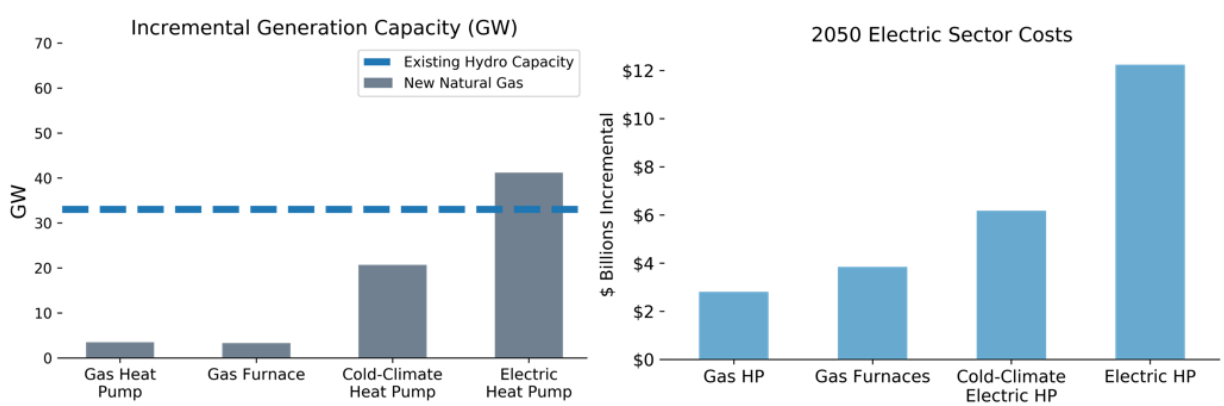


Variable renewables can provide a portion of peak capacity requirements, but that contribution is de-rated by these resources' effective load carrying capacity (ELCC). ELCC metrics capture the outage rate of a given resource. For thermal plants that is equivalent to a period of maintenance or refueling, but for variable resources the ELCC also captures periods of low wind or solar output. There are 18,000 MW of variable renewable energy installed in the Cold-Climate Heat Pump scenario, but after the ELCC adjustment these resources only contribute 3,500 MW towards the region's peak planning requirement.

The remaining incremental peak load—between 17,000 MW and 37,000 MW in the Electrification Scenarios—are served by firm resources, meaning natural gas combustion turbines, hydro-electric power and battery energy storage. In all scenarios, the RESOLVE model selects natural gas combustion turbines to provide the bulk of the firm capacity not met by variable renewable energy (Figure 29). The incremental cost to the region's electric grid of serving peak heating loads—that is the difference in electric peak in an average year versus a 1-in-10 heating year—exceed $1.9 billion annually.

An alternative source of capacity to serve peak loads could be battery or pumped-hydro energy storage. These technologies can provide firm capacity insofar as they are able to reliably charge and discharge during peak demand events. A determinant of these technologies' ability to provide reliable power during peak demand events is the storage duration of batteries and pumped-hydro resources.

Figure 29. 2050 incremental firm capacity build by scenario and 2050 electricity sector cost by scenario



We tested a "no new gas" sensitivity, in which only new energy storage could be selected to meet capacity needs in the RESOLVE model, and new gas capacity is not allowed to be built. This sensitivity assumes that a 10-hour energy storage duration could achieve the full capacity value needed to meet the winter peak, and that renewable resources would be available to charge the energy storage during the peak demand times in the winter. The incremental cost of using 10-hour energy storage, rather than combustion turbines to meet the peak demand, adds an additional $2 billion per year to the electricity sector costs in 2050, in the Cold Climate Heat Pump Scenario.[18]

However, this study did not include a detailed loss-of-load probability analysis to evaluate the expected load carrying capacity of battery storage under these conditions. As a result, this “no new gas”, energy storage sensitivity may underestimate the cost of reliability serving winter loads if significantly more low-carbon resources (wind and solar) are needed to fully-charge the energy storage facilities during the winter. capacity contribution of energy storage under these future high-load, high renewable energy systems are very uncertain, especially in a winter-peaking system when extended periods of low hydro (drought), wind, and solar output are taken into account. While chemical battery technologies have been improving, it may not be possible for batteries and pumped storage to provide sufficient energy to serve loads during extended periods of low renewable output and high peak loads, especially during an extended cold snap, in which multiple days of peak or near-peak system loads can be expected to occur. A detailed analysis of the capacity value of energy storage under these future conditions is beyond the scope of this analysis.

The electric sector results from the RESOLVE model represent a limited subset of supply and demand conditions associated with deep decarbonization. These results inform the magnitude of low-carbon generation needed in the region to achieve deep decarbonization and the impacts of peak heating events on the region’s electricity system. These results are not a substitute for a more detailed reliability analysis to assess the ability of the region to serve loads under a variety of supply and demand conditions. A loss-of-load-probability analysis is needed to more fully explore the range of possible load conditions under high electrification and how these conditions coincide with available energy supply.

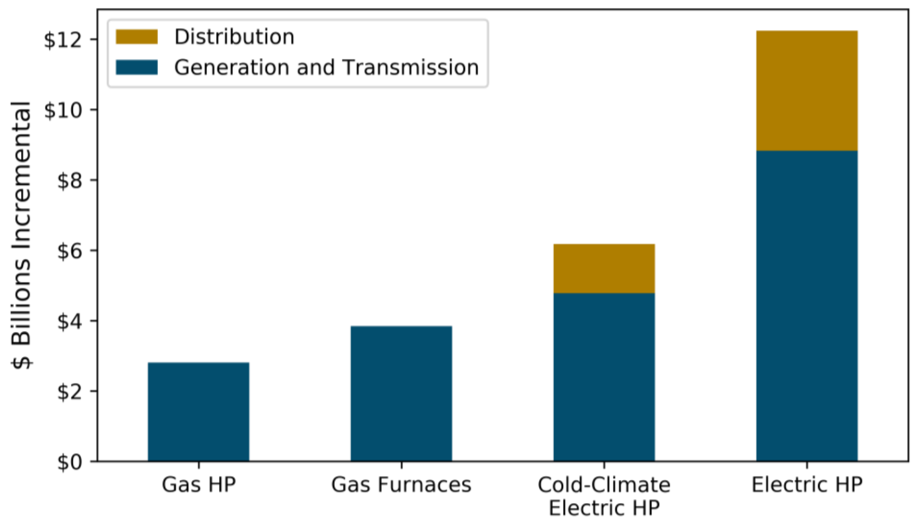
[18] The incremental cost would be higher in the Electric Heat Pump Scenario.

4.6.3.1 Incremental distribution costs

RESOLVE does not model electricity distribution system costs. Higher peak loads will require reinforcements of distribution infrastructure from the substation to the service drop. In fact, it is possible that the peak impacts of electrification could be more acute in the distribution system given that there will be less load diversity on any individual circuit or substation than for the region as a whole.

This analysis uses a single long-run marginal cost of service. That figure is in terms of $/kW-year, which is the annualized cost of individual distribution investments (i.e. similar to amortization of a home mortgage). A more granular figure would require a feeder by feeder analysis that assesses how much spare capacity is available in the region's distribution system, and what the grid upgrade costs would be under high electrification. No such analysis has been done in the region, but studies along those lines have been done in the United Kingdom (Delta Energy & Environment 2016). Those studies find that the grid upgrade costs under a high building electrification scenario exceed $100/kW-year when planning for a '1 in 20' heating event. We used that figure as a reference point to pick the highest distribution marginal cost listed in the Northwest Power and Conservation Council's 7th Plan. That cost is $76/kW-year (2012$) and is applied to all incremental peak load as an adder to the generation and transmission costs in RESOLVE (Figure 30). There are no incremental distribution costs in the Gas Scenarios, reflecting the aggressive energy efficiency measures in all mitigation cases. The incremental costs in the Electric Heat Pump Scenarios are largely driven by peak space-heating loads.

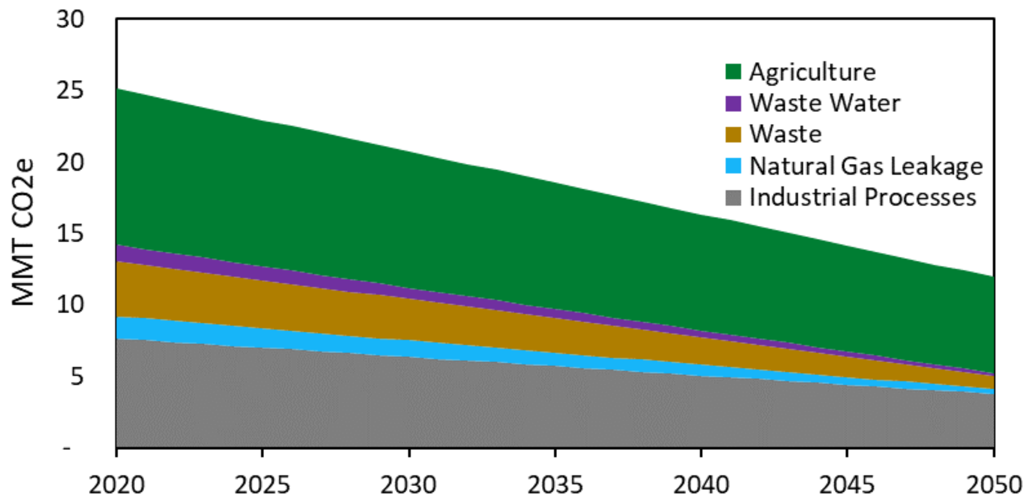
Figure 30: RESOLVE Costs, Including a Distribution Adder



4.1 Non-Combustion GHG Emissions

Each scenario assumes a 53% reduction in non-combustion emissions relative to 1990 (Figure 31). Non-combustion greenhouse gas emissions are gasses that contribute to global warming but are not directly the result of combusting fossil fuels. Examples include methane from biogenic and anthropogenic sources and other high global warming potential gases such as fluorinated gases used in refrigeration, air conditioners and heat pumps. The measures identified are consistent with the California Air Resources Board Short Lived Climate Pollutant Strategy (CARB 2017). Achieving these reductions will require action across multiple sectors of the economy, ranging from industry to agriculture. In some cases, these mitigation measures are complementary to energy system mitigation measures. A prime example is manure management, where we assume an 80% reduction in methane emissions and 452,000 dry tonnes of this feedstock is converted to advanced biofuels. Other non-combustion emissions reductions are potentially more challenging. For instance, we assume that emissions from enteric fermentation can be reduced by 80% and cement emissions reduced by 10%.

Figure 31: Non-combustion emissions



4.2 Scenario Costs

The total economy-wide costs for each scenario are calculated as the sum of the PATHWAYS model costs (all sectors except for electricity) and the RESOLVE model costs (electricity). Total costs are calculated on an annual basis including amortized capital costs for energy infrastructure in each sector, associated operations and maintenance costs, and fuel costs. The cost of each mitigation scenario is reported as an annual increment over the Reference case. These costs are meant to capture the direct incremental costs of the energy transition in terms of capital costs and fuel savings. The scenario costs do not include or reflect macroeconomic effects (e.g. jobs or structural changes to the economy), nor do they include avoided externality costs like the social cost of carbon or changes in health outcomes or costs due to changes in regional air quality.

4.2.1 COST UNCERTAINTIES

The economy-wide scenario costs calculated in this analysis are sensitive to input assumptions, particularly for measures that differ between scenarios. Key sources of cost differences between scenarios in this analysis include: the heating equipment deployed in buildings, the levels of industry electrification, and quantities of biofuels used. The costs of these measures are uncertain, particularly when projected out to 2050. The cost sensitivities and ranges presented below seek to capture some of that uncertainty.

4.2.1.1 Building equipment cost ranges

This analysis compares four different types of heating equipment in buildings. E3 evaluated a variety of sources to identify multiple cost estimates for each technology modelled. Ideally there would be a single data source that has a credible, comparable set of cost figures for each technology. To the best of our knowledge, no such data source currently exists. Table 9 lists the costs of space-heating equipment evaluated in this study. These costs define the low- and upper bounds of the capital cost sensitivities in Figure 32. All the heat pump technologies have a wide range of capital costs. Costs can vary for a variety of reasons, with the largest source of uncertainty being the non-equipment install costs associated with installing heat pump technologies. For example, if duct work is required to increase air flow throughout the home, or new electrical panel upgrades are required, the costs for a heat pump retrofit can be significantly higher than the capital cost of the equipment alone.

Table 9. Ranges of installed capital costs assumed for space heating plus water heating equipment, by type and data source

	Natural Gas Furnace	Natural Gas Heat Pump	Electric Heat Pump	Cold-Climate Electric Heat Pump	Ductless Air-Source Heat Pump
U.S. Department of Energy (National Energy Modelling System)	$3,000	$14,700	$5,100		
Energy Trust of Oregon			$10,200	$15,100	
Northwest Energy Efficiency Alliance		$7,000			$3,900
National Renewable Energy Laboratory	$2,500		$4,500	$6,000	$1,800

4.2.1.2 Biofuel cost uncertainty ranges

All scenarios in this analysis rely on biofuels to reduce the emissions intensity of remaining liquid and gaseous fuel demands. The PATHWAYS Biofuels Module simulates a regional market for biofuels, identifying a single clearing price for avoided CO2 emissions across all biofuels. That clearing price is sensitive to the cost of raw feedstocks, as well as the efficiency and costs of the conversion process from feedstocks to final biofuels. We estimate a high- and a low-end cost for biofuels by changing the final delivered fuel price for each final biofuel by plus or minus 20%.

4.2.1.3 Electrolysis and industrial electrification capital cost uncertainty ranges

There are also uncertainties in the capital costs of two key technologies—electrolysis and industrial electrification. Hydrogen electrolysis is a well understood process but has only been deployed at a limited scale. The capital costs of electrolysis today are assumed to be $1,127/kW, but these fall over time as demands for hydrogen fuels increase and learning-by-doing effects occur. The annual, or levelized, cost of hydrogen infrastructure also depends on its utilization. Hydrogen produced at a high capacity factor will cost less on a dollars per unit of energy produced basis than hydrogen produced at a low capacity factor, given the same electricity costs. The costs of converting from fossil fuel-powered to electric processes in industry are also uncertain, in part because the industrial sector is heterogeneous.

In this analysis both electrolysis and industry electrification capital costs are represented as a levelized ($/GJ) cost (Table 10). Costs in Table 10 do not capture cost of electricity associated with these mitigation measures. All electricity sector costs associated with industry electrification and hydrogen electrolysis are captured in RESOLVE. In 2050, RESOLVE costs in the Gas Furnaces scenario are $1 billion higher than in the Natural Gas Heat Pumps scenario.

Table 10: Hydrogen and industry electrification cost uncertainties

	Low - $/GJ	Mid - $/GJ	High - $/GJ
Hydrogen electrolysis capital cost uncertainty ranges	-20%	$35.3 (2018) $19.3 (2050)	+20%
Industrial electrification capital cost uncertainty ranges	$5	$5	$10

4.2.2 SCENARIO COST RESULTS AND DISCUSSION

PATHWAYS scenarios evaluate complex and uncertain futures. Results do not prescribe an optimal mitigation pathway, but instead test “what if” questions that can help inform future rounds of analysis and policy-making. Indeed, scenario results are sensitive to assumptions, many of which are fundamentally uncertain over the three-plus decades considered in this analysis.

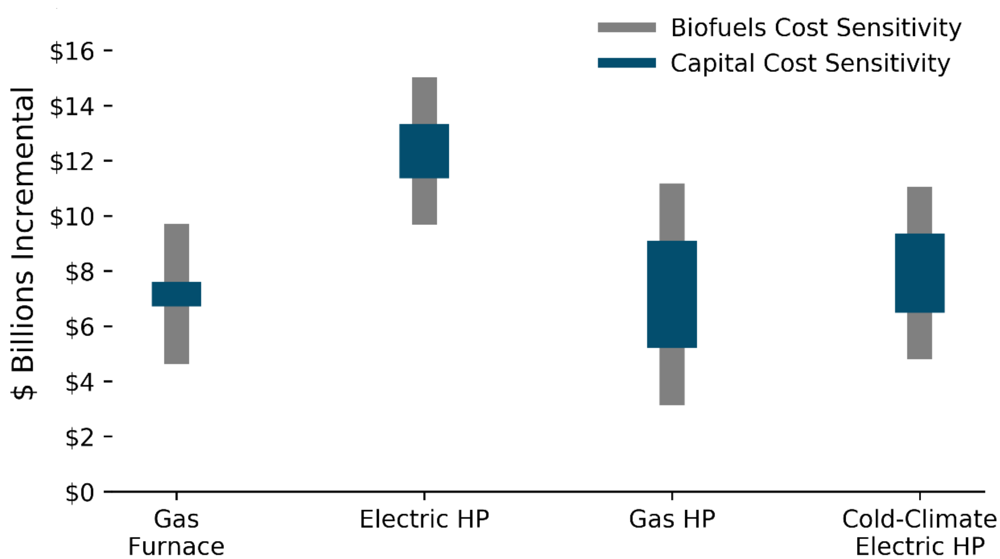
Figure 32 shows the range of scenario costs in 2050 relative to the Reference case. The cost ranges reflect two sensitivities. The cost ranges shown in the blue bars reflect uncertainty about the capital costs of building space-heating, industry electrification and hydrogen production costs. The narrow, grey portion layers the biofuels price uncertainty on top of the capital cost uncertainty, reflecting a biofuels cost range of +/- 20% compared to the results from the PATHWAYS biofuels module.

The 2050 costs of the Direct Use Gas Scenarios and Cold-Climate Electric Heat Pump scenario are similar in 2050, representing an incremental cost in the range of $4 to $10 billion per year in 2050. This range falls within 1% of the projected combined Gross State Product of Oregon and Washington. The Electric Heat Pump scenario shows the highest scenario costs due to the cost of serving the unmitigated, large winter peak load.

The average scenario costs range from $40/ton to $190/ton CO_2e in 2050 (in real 2017 dollars), relative to the Reference scenario depending on the future capital costs and fuel prices assumed. The average cost per ton metric means that some measures are far less expensive than this, while other measures are more expensive. This range reflects the wide range of uncertainties in projecting future scenario costs. Overall, these average GHG abatements costs ($40/ton to $190/ton CO_2e) are generally lower than the most recent estimates of the global social cost of carbon, which has a median cost of $417/ton CO_2, (and ranges from $177 to $805/ton CO_2). [19] The global social cost of carbon represents the expected economic damages to be incurred by climate change, per ton of CO_2 emitted.

[19] Ricke, K., L. Drouet, K. Caldeira, M. Tavoni, “Country-level social cost of carbon,” *Nature Climate Change*, Vol. 8, October 2018 895-900. Available at: **https://www.nature.com/articles/s41558-018-0282-y.pdf**

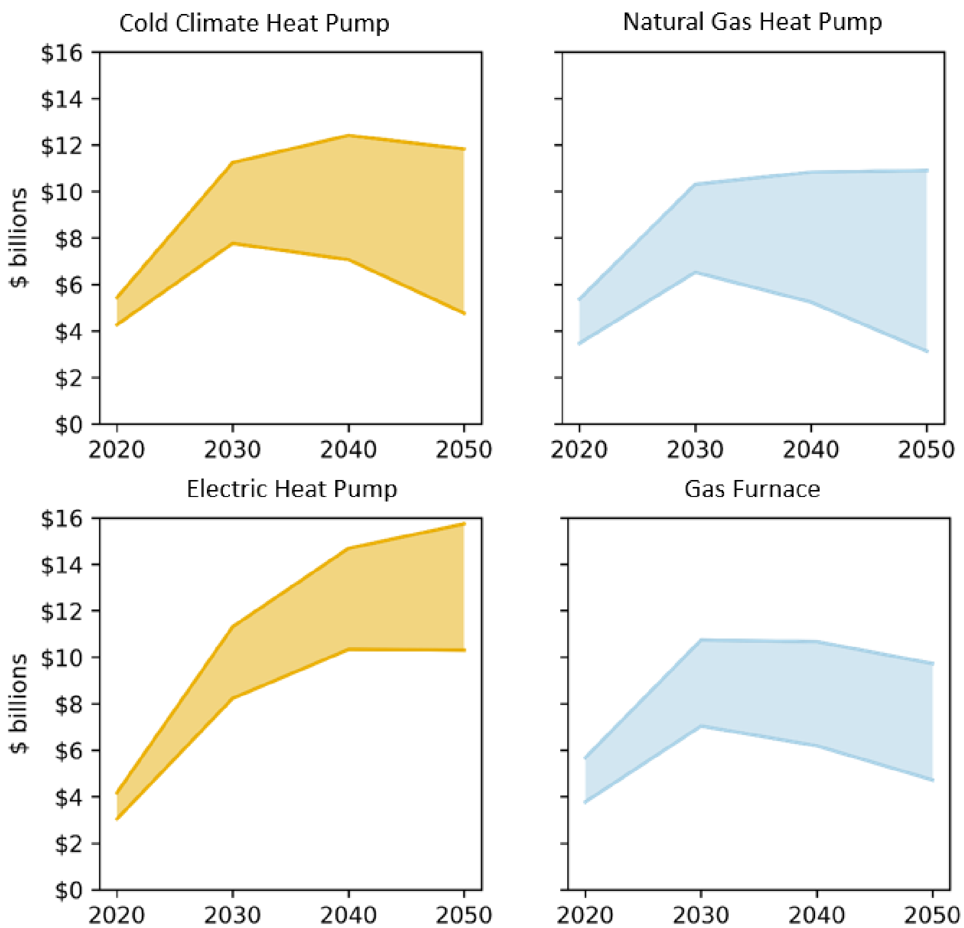
Figure 32. 2050 Mitigation scenario costs relative to Reference scenario, including capital and fuel cost sensitivities



Summary of Range of 2050 Mitigation Costs Relative to Reference Scenario:
Gas Furnace Scenario: $5 - $10 billion
Gas Heat Pump Scenario: $3 - $11 billion
Cold Climate Heat Pump Scenario: $5 - $11 billion
Electric Heat Pump Scenario: $10 - $16 billion

Each scenario carries incremental costs throughout the study period (Figure 33). These costs increase most rapidly between 2020 and 2030 as markets for biofuels scale and relatively more expensive technologies are deployed. Over time, the combined impact of technology cost decreases and continued energy efficiency progress stabilize scenario costs. In fact, in the lower end of the cost sensitivity ranges the cost of mitigation begins to drop post-2030. This result underscores the critical role of ongoing technology innovation and energy efficiency in achieving deep decarbonization.

Figure 33. Mitigation scenario costs relative to Reference scenario, including capital and fuel cost sensitivities, 2020 - 2050



5 Conclusions

The emissions reduction scenarios modelled in this analysis represent a transformation of the energy economies of Oregon and Washington. Rapid gains in energy efficiency, electrification and the development of low-carbon fuels are necessary for any strategy that reduces emissions by 80% below 1990 levels. This analysis takes an economy-wide view on regional decarbonization, with a focus on the role of buildings.

The results suggest multiple plausible technology pathways for the buildings sector in achieving economy-wide deep decarbonization, though each comes with risks and challenges. Indeed, no single strategy for buildings appears to be definitively the most cost-effective, when considered in the context of an economy-wide decarbonization strategy. Given this uncertainty, it would be prudent from a policy perspective to encourage the commercialization of renewable natural gas and hydrogen along with high efficiency space heating technologies in buildings. A number of "no regrets" decarbonization strategies are also identified including: 1) continued support for energy efficiency in buildings, 2) rapid electrification of the transportation sector, and 3) deployment of zero-carbon electricity generation.

In all scenarios, a combination of fossil and renewable natural gas, either used in homes or in new power plants, continues to serve winter peak heating, and is consistent with achieving an 80 percent reduction in greenhouse gases in the region.

5.1.1 MAINTAINING GAS HEAT IN BUILDINGS IS A FEASIBLE STRATEGY

In the Direct Use Gas Scenarios, space heating and water heating in buildings continue to be provided by pipeline gas, using a mixture of fossil natural gas and renewable natural gas, and in one scenario, a limited amount of renewably-produced hydrogen. These pathways are consistent with a future world that achieves an 80 percent reduction in GHG emissions by 2050. All of the scenarios evaluated here rely on technology innovation in producing and delivering renewable fuels at an industrial scale, this is true to a higher degree in the Direct Use of Natural Gas Scenarios. Compared to the electric heat pump pathways, maintaining gas heat in buildings doesn't require as many changes from consumers: no need for widespread investments and retrofits to existing buildings' space conditioning systems and water heaters or changes to contractor practices. The Gas Furnace Scenario assumes that consumers continue to purchase efficient versions of the same technologies for space heating and water heating that they already use.

The Natural Gas Heat Pump scenario envisions a more substantial change in how buildings are heated, through the use of natural gas heat pumps, but offers the potential for larger energy efficiency gains relative to the Gas Furnaces scenario. A further benefit of the 'drop-in' fuel feature of the Direct Use Gas Scenarios is that they avoid the need for the new electric sector infrastructure associated with meeting winter peak demands in the Building Electrification Scenarios.

The primary challenge associated with maintaining gas heat in buildings in a deeply decarbonized future is around the development and commercialization of new, low-carbon technologies: renewable natural gas, industrial electrification, renewable hydrogen and/or natural gas heat pumps. Since these scenarios use a relatively high share of the region's 2050 GHG emissions budget in the buildings sector, more mitigation efforts in other sectors of the economy are required, each of which face their own set of implementation challenges. In both of the Direct Gas Use scenarios, industry electrification is the primary mitigation measure to offset the additional emissions from the building sector. Industry electrification is an emerging opportunity for decarbonization, but more research is needed to understand the cost of industrial fuel switching.

In addition, the Direct Use Gas scenarios rely on about 30% more sustainable, carbon-neutral biofuels than the other scenarios. Research, development and investments will be needed to bring significant new quantities (between 255 and 263 tBtu by 2050)[20] of renewable natural gas and other sustainable biofuels to market. Finally, biomethane must be paired with either natural gas heat pumps or renewable hydrogen in these scenarios, neither of which are currently commercially prevalent technologies in the region. This list of technology challenges also presents a set of research, development, deployment and market transformation opportunities for NW Natural and other companies to invest in bringing to market.

5.1.2 SWITCHING TO ELECTRIC HEAT IN BUILDINGS IS A FEASIBLE STRATEGY

Building electrification, when paired with very low-carbon electricity, can displace nearly all emissions in the buildings sector using existing technologies, reducing the need for other mitigation strategies such as industrial electrification, renewable natural gas, or hydrogen. However, switching to electric heat in buildings also comes with its own challenges and risks.

Large-scale electrification of buildings depends on a transformation of the building HVAC and water heater market, accompanied by consumer acceptance and rapid adoption of electric heat pumps in place of gas equipment. In many existing homes, retrofitting to electric space heating and water heating may require expensive retrofits. Further, the building simulations and electricity sector modelling in this analysis indicate that, from a grid perspective, consumers should install cold-climate systems that perform well in cold weather to avoid the highest system-wide cost impacts to the electric grid. However, the cold-climate systems are currently more expensive than conventional electric heat pumps.

No matter what type of heat pumps are installed, the Building Electrification scenarios add large new weather-dependent loads to the Northwest Electricity system, estimated at 20,000 and 40,000 MW of

[20] In the building electrification scenarios the quantity of sustainable biofuels in 2050 is lower, at 191 tBtu.

incremental peak capacity needs by 2050. Those loads will require an expansion of the region's electric system, including additional generation, transmission and distribution infrastructure.

5.1.3 SCENARIO COSTS AND UNCERTAINTIES

Given the many uncertainties in projecting future technology costs, it appears that within a reasonable cost uncertainty range, three of the four scenarios evaluated in this analysis have similar total economy-wide costs: The Gas Furnace Scenario, the Natural Gas Heat Pump Scenario, and the Cold Climate Heat Pump Scenario. The Electric Heat Pump scenario is the highest cost scenario of the four evaluated, based on the relatively poor performance of the conventional heat pumps in cold weather.

5.1.4 POLICY IMPLICATIONS AND ONGOING RESEARCH NEEDS

Energy efficiency is critical in all scenarios

All scenarios depend on energy efficiency to enable emissions reductions at manageable costs, in buildings, industry and the transportation sector. Building shell measures reduce the annual amount of heat demanded by buildings, which is important for reducing the total cost of the Direct Use Gas Scenarios, given that there is a limited supply of carbon-neutral biomethane available. If natural gas demands were higher, then more expensive fuels like hydrogen or synthetic natural gas would be needed to meet the emissions target. Likewise, deep energy efficiency retrofits in buildings are important in reducing the total costs of the electrification scenarios because they reduce the peak heating requirements of space-heating in the region. Absent building shell improvements, the peak load impacts of electric heat pumps would be more pronounced than modeled here.

All scenarios rely on widespread electrification of the region's transportation sector

The transportation sector is currently the largest source of emissions in the Northwest. All scenarios in this analysis assume near-complete electrification of passenger vehicles by 2050, as well as high levels of truck and freight electrification. As the cost of light-duty electric vehicles declines, the deployment of public charging infrastructure will become increasingly important, particularly for those drivers who do not own their home and cannot install home-based EV chargers.

Given rapid declines in battery costs, electrification of trucks is an emerging strategy for freight transportation and was the primary decarbonization strategy assumed for trucks in these scenarios. Hydrogen fuel cell trucks represent an alternative technology pathway, but these were assumed to be higher cost than the electric options. Finally, advanced biofuels, such as renewable compressed natural gas trucks or hybrid trucks running on renewable CNG or renewable diesel represent alternative decarbonization strategies. In these scenarios, since biofuels are assumed to be relatively limited, advanced biofuels were used for aviation (renewable jet fuel) and in the gas pipeline, rather than for cars and trucks.

Advanced biofuels, such as renewable natural gas and renewable jet fuel, are needed in all mitigation scenarios

Both scenarios rely on advanced, carbon-neutral biofuels to displace remaining liquid and gaseous fuels in the economy. Oregon has already begun to promote advanced biofuels with its Clean Fuels Program. Expanding the region's policy to promote development of biomethane resources could be a worthwhile next step. It will be important to continue to refine estimates of the lifecycle emissions of biofuel resources, to ensure that they are indeed carbon-neutral resources. Using today's biofuel's technologies, the lifecycle emissions of ethanol, for example, can be comparable to fossil fuels. A transition away from current forms of biofuels, towards more sustainable, carbon-neutral biofuels is needed.

Focus research, development and deployment of space heating technologies that address or mitigate peak heat needs

This study suggests that continued use of the natural gas distribution system is a cost-effective strategy to meet the region's climate goals while also reliably serving winter peak demands. Advanced heat pump technologies could play an important role in decarbonizing heat in the Northwest at relatively low societal costs. The natural gas heat pumps modelled in this analysis are not yet commercially available in the Northwest, but NEEA staff indicate that the technology is expected to be available by the mid-2020s. In the interim, pilot programs and demonstrations would be very useful in validating the performance characteristics of natural gas heat pumps assumed in this report. Beyond 2025, market transformation and deployment programs will be needed to ensure the technology is available throughout the region.

In addition, cold-climate electric heat pumps with electric resistance back-up could provide winter heating services in the region. Cold climate heat pumps remain a relatively new technology but are available in the market today. From a societal perspective, cold climate heat pumps are preferable to standard electric heat pumps, but also have a higher upfront cost. Further, the benefits of cold-climate heat pumps will only be realized if HVAC contractors are trained and incentivized to install heat pumps that perform up to their rated efficiency, while minimizing the reliance on electric resistance supplemental heat. This implies a market transformation initiative is needed alongside ongoing technology development if widespread electrification of space heating were pursued.

A potential way to partially mitigate the peak load requirements of electrifying space heating load is to shift loads from peak to off-peak periods. Load flexibility is included in this analysis primarily through the assumption that light-duty electricity vehicles can be charged during off-peak periods. It is possible that, given the right price signals, additional electric sector load flexibility could be realized, for example, with flexible use of heat pump water heaters. However, water heaters represent only 7% of total electric loads in the Electrification scenarios, in 2050. Additional study is needed to characterize those resources' availability and costs.

Whether served by natural gas or electricity there could also be additional flexibility in buildings' heating systems. For instance, a combination of tighter shells and pre-heating of buildings could smooth morning peak loads. Alternatively, on-site heat storage systems could provide a similar service. Another source of flexibility could be hybrid electric and natural gas or propane heating systems. Those types of systems use an electric heat pump for the bulk of annual heating requirements but switch to natural gas or propane back-up during relatively cold hours[21]. These systems have the greenhouse gas benefit of displacing most fossil gas combustion, while also taking advantage of the large existing pipeline gas system as an energy storage system. Each of these alternatives comes with an incremental cost; this study did not attempt to evaluate how much these alternatives might cost relative to the incremental electricity sector expansion costs identified in this analysis.

Overall, this study focused on the economics of a deep decarbonization from a societal perspective. As a next step, it would be helpful to develop a better understanding of the consumer economics and consumer choices that may drive the adoption of different space heating technologies in the Pacific Northwest.

Strategies to deploy industry electrification and hydrogen electrolysis

A more granular characterization of the region's industrial sector could help decision-makers understand: 1) in what industries and end-uses in the Pacific Northwest a shift from fossil fuels to electricity is most plausible and, 2) what policy mechanisms would be most conducive to incentivizing a shift of the region's industrial sector towards electrification.

[21] These systems are being evaluated in Europe, see for example Wales and West Utilities 2018

Finally, renewably-produced hydrogen from electrolysis is a small portion of the energy used in the Gas Furnace Scenario, but it helps to close the emissions gap to meet the 2050 GHG goal. This scenario assumes that up to 6% hydrogen by energy, about 20% by volume, can be blended into the existing pipeline gas supply without a need for upgrades to end-use equipment or the region's gas transmission, storage and distribution systems. Further study of the impacts of hydrogen on those systems would be a valuable next step.

Many pathways exist to achieving decarbonization in the Pacific Northwest. The challenge lies in the development and sustained deployment of the advanced technologies needed to transform the region's energy economy over the next two to three decades.

6 Appendix

6.1 Baseline Key Drivers of Pathways Model Energy Demands

Sector	Key Driver	Compound annual growth rate [%]	Data Source
Residential	Housing Units	1.15%	NWPCC Projections
Commercial	Square Footage	1.11%	NWPCC Projections
Industry	Energy growth	Varies by fuel	EIA AEO 2018 growth rates 2017-2050
Industry	Natural Gas Energy growth	0%	NW Natural
On Road Transportation	VMT	0.35% average 2015-2050	State DOT forecasts
Off Road Transportation	Energy growth	Varies by fuel	EIA AEO 2018 growth rates 2017-2050
Electricity generation	Electric load growth	0.77% average 2015-2050	Built up from Pathways demands in Buildings, Industry, Transportation

6.2 Reference Scenario Key Assumptions

	Reference Scenario
Electricity generation	
Carbon-free generation	20% Weighted RPS target in 2040 (per 50% Oregon RPS requirement by 2040 and 15% Washington RPS by 2020) and85% Carbon-free by 2050
Buildings	
Energy Efficiency	50% of appliance sales are high-efficiency by 2030, reflecting NWPCC 7th Power Plan
Transportation	
Zero-Emission Vehicles	8% sales by 2025, 20% light-duty sales by 2030 (5% PHEV, 15% EV)
Efficiency	Federal CAFÉ standards for LDVs by 2026
Biofuels	
Conventional Biofuels	10% ethanol blend in gasoline (currently 7% E85 and 93% E10)
Other Sectors	
Energy Consumption	Grows at AEO 2017 reference scenario growth rates by fuel
Non Combustion GHG Emissions	Held constant at current GHG Inventory levels

6.3 Mitigation Scenario Key Assumptions

	Gas Furnace Scenario	Electric Heat Pump Scenario
Electricity generation		
Carbon-free Generation	97% Carbon-free by 2050	95% Carbon-free by 2050
Buildings		
Energy Efficiency	100% of appliance sales are high-efficiency by 2030 100% adoption of efficient building shell/weatherization measures by 2030	
Sales of Heat Pump Equipment	100% heat pump sales replacing electric resistance by 2040. 100% efficient gas furnaces by 2030	100% heat pump sales replacing electric resistance by 2040. 60% heat pump by 2030, 98% by 2050
Transportation		
Sales of Zero-Emission Vehicles	LDVs: 70% by 2030, 100% by 2050 MDVs: 85% by 2030, 85% through 2050 HDVs: 60% by 2030, 80% by 2050	
Efficiency	Federal CAFÉ standards for LDVs through 2026, Aviation efficiency of 40% below Reference Scenario by 2050	
Biofuels		
Advanced Biofuels	Advanced biofuels from wastes, residues and purpose grown crops, sourced from within the PNW region	Advanced biofuels from wastes, residues and purpose grown crops, sourced from within the PNW region (20% less than gas scenarios)
Other Sectors		
All Emissions	Reduction of 80% below 1990 Levels	
Industry Electrification	30% of Industry End Uses electrified by 2050	5% of Industry End Uses electrified by 2050

	Gas Heat Pump Scenario	Cold Climate Heat Pump Scenario
Electricity generation		
Carbon-free Generation	97% Carbon-free by 2050	95% Carbon-free by 2050
Buildings		
Energy Efficiency	100% of appliance sales are high-efficiency by 2030 100% adoption of efficient building shell/weatherization measures by 2030 100% sales of ductless heat pumps in place of resistance by 2040	
Sales of Heat Pump Equipment	20% Natural Gas HP sales by 2030, 100% by 2050	60% Cold Climate HP sales by 2030, 98% by 2050 (small amount of electric resistance in Commercial)
Transportation		
Sales of Zero-Emission Vehicles	LDVs: 70% by 2030, 100% by 2050 MDVs: 85% by 2030, 85% through 2050 HDVs: 60% by 2030, 80% by 2050	
Efficiency	Federal CAFÉ standards for LDVs through 2026, Aviation efficiency of 40% below Reference Scenario by 2050	
Biofuels		
Advanced Biofuels	Advanced biofuels from wastes, residues and purpose grown crops, sourced from within the PNW region	Advanced biofuels from wastes, residues and purpose grown crops, sourced from within the PNW region (30% less than gas scenarios)
Other Sectors		
All Emissions	Reduction of 80% below 1990 Levels	
Industry Electrification	30% of Industry End Uses electrified by 2050	5% of Industry End Uses electrified by 2050

6.4 Building Simulations and Evaluation of Electric Heat Pump Winter Peak Performance

This study focuses on the role of buildings in achieving the broader economy-wide deep decarbonization goal. Buildings contribute to GHG emissions through both consumption of electricity generated from fossil fuels and through direct, or on-site use of fossil fuels. The primary purpose of direct use of gas in buildings is to provide heat.

Space-heating loads are the largest source of natural gas use in buildings in the Northwest, followed by water-heating, cooking and clothes drying—in that order. Space heating loads are also weather dependent. As the outdoor air temperature drops, buildings require more heat to maintain a comfortable temperature for occupants. Today, space heating energy needs in the Northwest are met by a combination of natural gas (68%), electricity (24%), petroleum products (6%) and wood (2%).

The relatively high share of electric resistance space-heating in the region, combined with mild-summers, means that the region has historically seen the highest electricity demands in the winter, [22]The PNUCC estimates that the winter peak for the Northwest in 2019 will be 36.4 GW, while summer peak is forecasted at 35.2 GW.

The heating requirements of buildings increases and the output of electric air-source heat pumps decreases as the outdoor air temperature drops. When a heat pump can no longer provide sufficient heat to maintain a comfortable temperature of building occupants, supplemental heat is required. The most common type of supplemental heat installed is electric resistance. Where a heat pump may have a COP of over 2 or higher in cold temperatures, an electric resistance element has a COP of 1. Supplemental heat

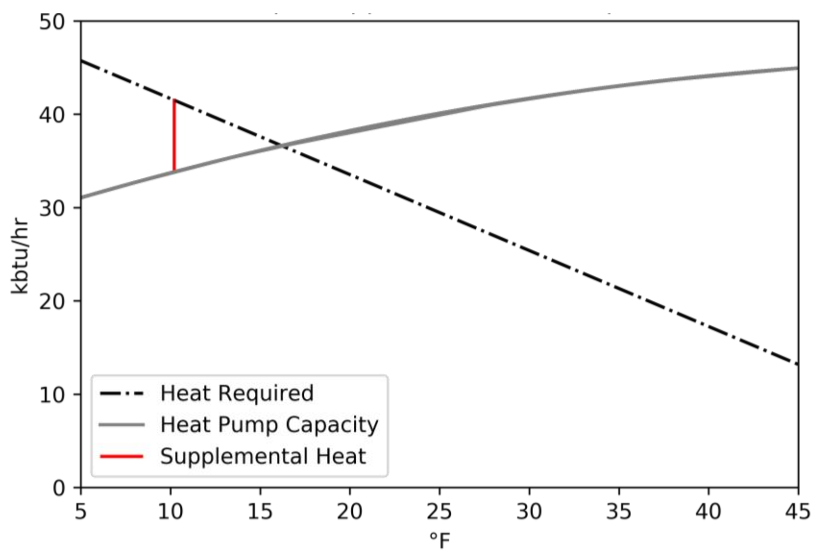
[22] The increased adoption of air conditioning in the region – which is nearly 100% electric – means that the summer peak is now catching up to the winter electric demand. The results of this study show that with electrification of a majority of non-electric space heating load that the region would become a heavily winter peaking region.

fills the gap between a buildings heating requirements and a heat pump's output until a 'lockout' temperature is reached, after which point only supplemental heat is used.

Buildings require the most space-heating energy during morning hours when there is little solar radiation and thermostats are set to daytime settings. Peak space-heating loads tend to occur during the coldest morning hours of the year. However, some years have lower minimum morning temperatures than others.

The amount of supplemental electric resistance heat required depends on the capacity of the heat pump and the heating load of the building. Figure 34 compares the maximum output of the 4-ton cold-climate heat pump simulated by Big Ladder to the hourly heating requirements of the median NW Natural residential customer. As the temperature drops the heat pump requires more input power per unit of useful heat produced. When the heat pump can no longer provide enough heat to heat the home—when the grey line is below the dotted black line—supplemental electric resistance heat is needed.

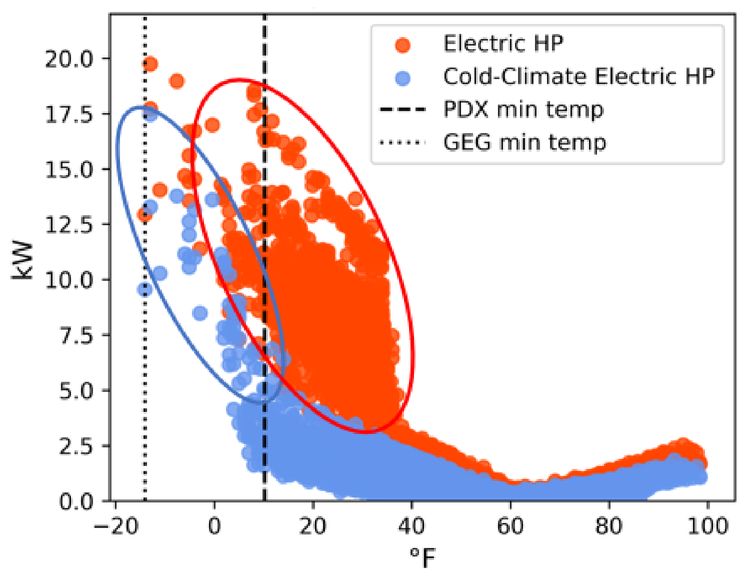
Figure 34: Air-source heat pumps and supplemental heat



The building simulations in this analysis show that supplemental electric resistance heat can markedly increase the load of homes served by cold-climate electric heat pumps. The share of electric resistance heat in the building simulation increases as the temperature drops. In the Portland simulations, a 4-ton ducted heat pump provides 34 kbtu/hr at 10.2°F, the coldest simulated temperature, but the building requires 42 kbtu/hr to stay warm. The gap between the heat pump's output and building heating demand is filled by 8 kbtu/hr of supplemental heat, equivalent to over 2.3 kW of additional electric load. The amount of energy required for the heat pump itself also increases as the temperature drops, with its COP dropping from 4 annually to 2.5 during the coldest hour simulated. The result is a combined load for the HVAC system—the heat pump, electric resistance heater and fans— of over 7 kW at 10.2°F.

Figure 35 shows HVAC demand over the same 8760 hours of weather in the representative year for both the conventional and cold-climate heat pumps simulated in EnergyPlus. The figure includes loads simulated for both Portland and Spokane. The conventional electric heat pump simulations (red) lock-out the heat pump compressor below 34°F,[23] relying entirely on electric resistance heat below that temperature. These results represent an estimate for the load impacts of electrifying space-heating in the Northwest with commonly installed systems today. The cold-climate heat pumps (blue) show a marked improvement in performance as the temperature drops. However, loads for these systems begin to increase more rapidly as the temperature drops below 20° Fahrenheit. This is especially true during the early morning heating hours when solar gains are at their minimum and homes recover from their night-time setbacks.

Figure 35. Simulated heat pump performance by temperature



Big Ladder also simulated the performance of a cold-climate heat pump in a smaller home, comparing its hourly load with that of a conventional electric furnace. The heat pumps in these homes also require supplemental heat at temperature below 18° Fahrenheit but exhibit a large improvement in performance

[23] The Energy Trust of Oregon provides a heat pump control incentive to new and existing heat pumps ($250) to set the lockout temperature at 35°F ("or as close as possible"). https://www.energytrust.org/wp-content/uploads/2016/09/HES_FM0320C.pdf

relative to a stand-alone electric furnace. Where conversions of gas homes to electric heat pumps create new electric loads, replacing electric resistance heat with an efficient electric heat pump puts downward pressure on peak loads.

6.4.1 FROM BUILDING SIMULATIONS TO SYSTEM-WIDE BUILDING LOAD SHAPES

Electrification of gas homes causes incremental annual and peak loads. The peak load in a typical Northwest gas home would be nearly 7kW during a ‘1 in 10 year’ winter cold-snap. East of the Cascades, where temperatures can drop below -10°F during a very cold winter, that figure rises to over 13kW per home. However, the cumulative electric-sector loads in a high electrification future depend on a variety of different factors, including:

+ The amount of electric resistance heat displaced;
+ The diversity of space-heating loads in the region; and
+ Improvements in the thermal efficiency of buildings.

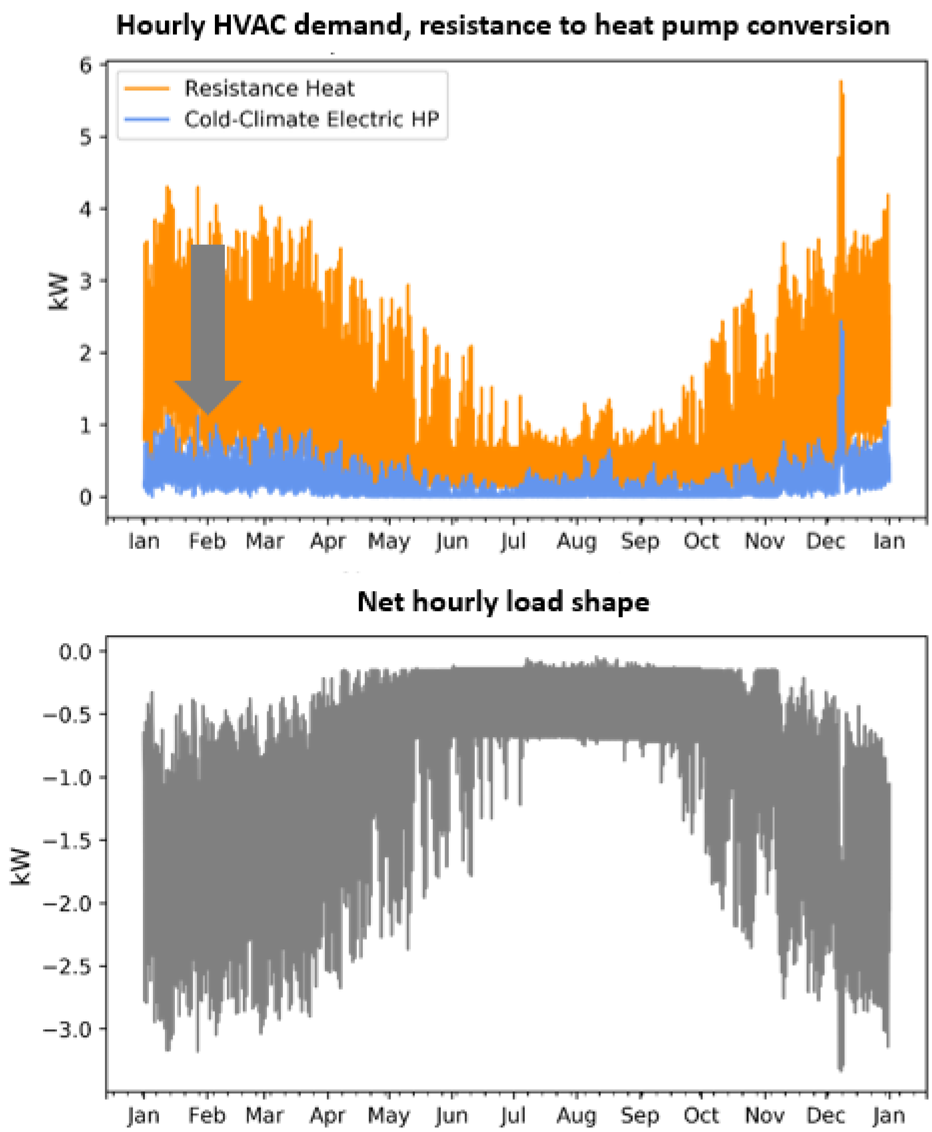
This study accounted for all three of these factors when defining electric-system peak loads in all of the mitigation scenarios, resulting in appreciably lower peak load estimates than if these adjustments were not made.

Displaced electric resistance heat

The Northwest has high levels of existing electric resistance heat relative to other moderate to cold climates in the country. High levels of electric resistance heat contribute to the region’s current winter electric sector peak. A key assumption made in this analysis is that most electric resistance heat in the region is replaced with electric air-source heat pumps. Electric resistance heat in the smaller housing units[24] save over 6 MWh in annual load and, importantly, also puts downward pressure on peak load. Building simulation results for the small single-family home during the coldest hour, show a peak savings of almost 3.5 kW (Figure 36).

[24] In the Pacific Northwest electric resistance heat is most commonly installed in multifamily housing units like apartment complexes, manufactured homes, and small single family homes.

Figure 36: Displaced electric resistance heat



Diversity of space heating loads across the region

No individual building load shape is an accurate representation of the system load that must be served by the electricity system. We consider two mechanisms through which diversity could occur for space-heating loads: 1) a behavioral effect, and 2) spatial variation of weather.

Behavioral diversity in space-heating loads occurs because occupants of buildings choose to heat their homes and businesses at different times. Diversity from spatial variation of weather occurs because the minimum temperatures will vary across population centers in the Northwest. For instance, during the '1 in 10' cold-snap simulated in this analysis, the temperature is almost 6 Fahrenheit warmer in Seattle than Portland during the coldest hour simulated in the latter city.

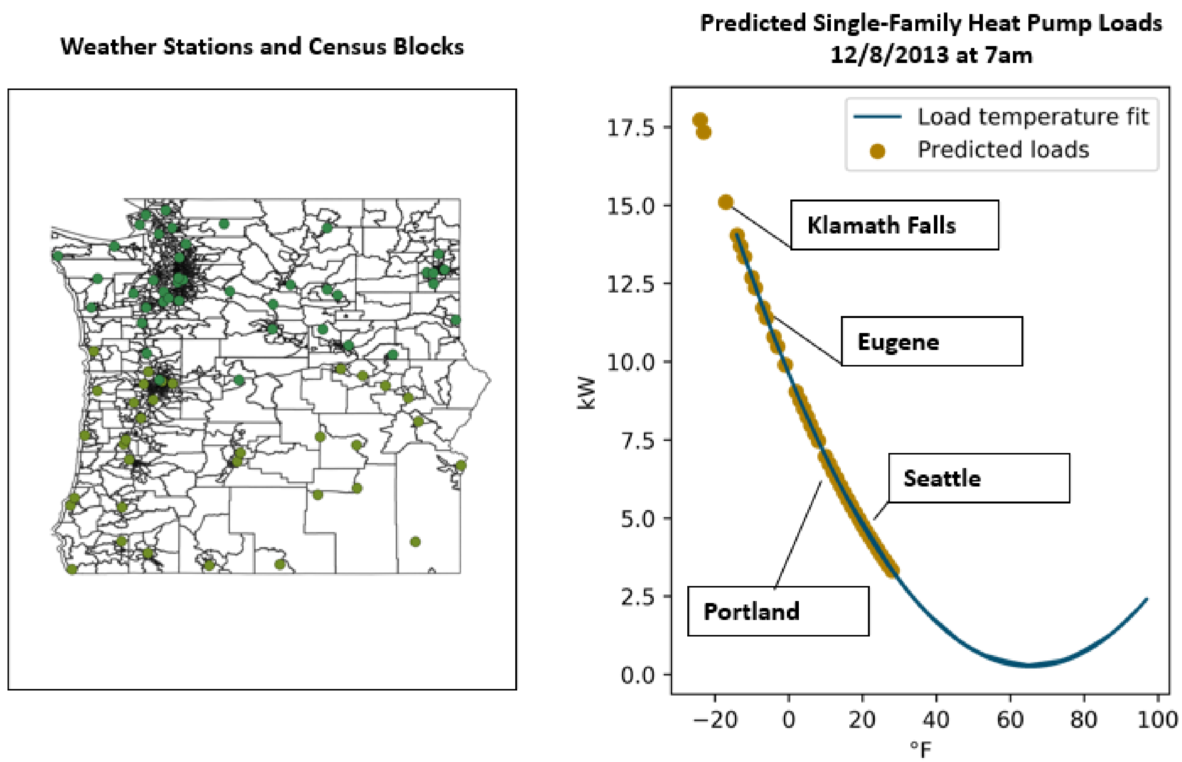
We account for behavioral diversity in the building simulations via two mechanisms. First, EnergyPlus returns electric loads on an hourly basis, so the hourly peak demand (kW) figures reported in this analysis are averaged hourly loads (KWh/h), not the instantaneous peak load for each building. A building simulation that provided heating estimates in shorter intervals would return higher peak values per building than those returned from EnergyPlus. However, variations in loads between hours also occur for behavioral reasons. Building heating is related to the behavioral choices and patterns of occupants. As a result, some buildings will start heating relatively early in the morning and some relatively late (Hanmer et al 2018). E3 and Big Ladder accounted for between hour variations in heating by allowing two hours for the simulated heat pump systems to meet the morning thermostat temperature[25] for each building. This modelling decision smooths out the morning heating period, lowering the peak load during the 7am hour compared to model results that only allow 1 hour to meet the morning thermostat set point.

E3 evaluated the potential for geographic diversity using a combination of the EnergyPlus load shapes, and temperature data from 76 airport weather stations in Oregon and Washington. Weather station data were paired with American Community Survey (ACS) estimates of where gas homes in each state are

[25] Representative thermostat heating setpoints were developed from the NEEA RBSA, and fall between 67.4- and 68.7-degrees Fahrenheit, depending on building type.

located. An hourly load shape for each weather station was estimated by using the relationship between HVAC load and temperature identified in EnergyPlus (Figure 37). This relationship was developed by fitting a 2nd-order polynomial to the temperatures and loads in Energy Plus during the 7am peak morning heating hour. Using that fit, a peak load was estimated for each fuel-switching single-family home in the region at 7am on December 8, 2013—the hour that drives peak planning requirements in this analysis.

Figure 37: Load diversity in Oregon and Washington



The average peak load for gas homes east and west of the Cascades simulated in Energy Plus during that hour was 6.8 kW. However, Washington was warmer than Oregon during that peak hour. As a result, the predicted loads using weather station data for Washington are 5.2 kW per home. In contrast, Oregon as a whole was colder than the temperatures simulated in Energy Plus during the peak heating hour. After accounting for the colder temperatures elsewhere in Oregon, the predicted average load per home for Oregon is 7.8 kW, or 1 kW higher than the figure returned by Energy Plus. There are more gas homes in Washington than Oregon, so the weighted average peak load per home using weather station data is 6.1 kW per home. We use the ratio of those weather-matched predicted loads and Energy Plus simulated loads as an estimate of weather-driven load diversity factor. That factor, equal to 0.9, decreases the peak capacity requirements associated with space-heating electrification by 10%.

Energy efficiency and weatherization

Peak heating requirements in buildings are driven by heat loss. One important strategy to reduce the annual and peak heating loads in buildings is to increase the ability of buildings to retain heat. Measures to weatherize a building might include installing more insulation, sealing bypasses, adding storm doors and replacing windows. In general, it is easier to install these measures in a new building, avoiding expensive retrofit costs. We assume that every new building has an efficient shell and that a substantial number of existing buildings undergo a retrofit. Accomplishing wide-spread retrofits will be a major challenge but is a critical measure for any strategy to reduce heat related GHG emissions.

PATHWAYS treats building shell improvements as a ‘stock’ measure that flows through the model like any other building equipment. Building shells are assumed to have a lifetime of 40-years. Effectively, this means that buildings undergo a major retrofit every 40-years, at which point a suite of weatherization measures are installed. An ‘efficient’ building shell in PATHWAYS decreases both the annual and peak heating requirements of buildings by 40%, and in 2050 73% of buildings are assumed to have an efficient shell. That is equivalent to 100% of new buildings being built with an efficient envelope and 60% of existing buildings receiving a retrofit. In sum, building shell measures reduce both annual and peak heating requirements in the region by 30% compared to loads that would have occurred without the measures.

6.5 Other End Use Load Shape Assumptions

Transportation Electrification Load Shapes

Electric vehicle charging load profiles are based on an EV charging model which translates travel behavior into EV load shapes by weekday/weekend, charging strategy, and charging location availability. This travel behavior is based on the 2009 National Household Transportation Survey, a dataset on personal travel behavior[26]. This study assumes that 60% of drivers have charging infrastructure available at home and work by 2050, while the rest have charging infrastructure available only at home. Furthermore, we let RESOLVE dynamically charge a certain percentage of cars that are plugged in; this is constrained by the number of cars that are plugged in, the instantaneous driving demand for that hour, and how much charge capacity is available. By 2050, 100% of electric vehicle charging is assumed to be flexible when plugged in. In 2050, this means that 100% of light duty electric vehicles flexibly charge outside of business hours, while 60% of light duty electric vehicles charge flexibly during business hours. This means that electric vehicles contribute very little to peak demand needs, despite increasing total electricity demands.

Hydrogen Electrolysis Load Shapes

In this study, hydrogen electrolysis facilities operate flexibility in RESOLVE, and thus avoid operating during system peak hours. While hydrogen electrolysis contributes significantly to total electricity demand in the Gas Furnaces scenario, it has no impact on incremental peak load. However, hydrolysis loads do spur additional renewable energy capacity expansion as additional solar resources are developed to provide

[26] http://nhts.ornl.gov/introduction.shtml

enough zero-carbon energy to power the hydrolysis and stay within the 3 MMtCO2e electric sector emissions budget for that scenario.

Industrial Load Shapes

Incremental industrial electrification loads are assumed to have a load shape that reflects the system-wide loads before electrification. This simplification was used because industrial loads are heterogenous in terms of both their base shape, their ability to be flexible and there is not sufficiently detailed public data available to translate annual electrification to a net change in annual electricity demands. There is reason to believe that much of this load could be flexible, however, given that most of the industrial load assumed to be electrified in these scenarios is currently served by natural gas; and the majority of natural gas industrial load in NW Natural's service territory elects to be on interruptible schedules. Interruptible schedules are a form of demand response where customers receive a discount on their rate for the option to be interrupted – or required to stop using gas – during peak cold events.

Electrified HVAC shapes will, insofar as they equate to air-source heat pumps, increase peak load requirements during cold weather. Other processes may be flexible, decreasing the capacity impacts of industry electrification. The Gas Scenarios have higher industry electrification levels than the Electric Heat Pump Scenarios and the incremental peak impact of industry in electrification in those scenarios is approximately 2 GW. While the exact capacity impact of industry electrification deserves further study, the order of magnitude does underscore the difference between electrifying more- and less-weather-dependent loads.

Water heating

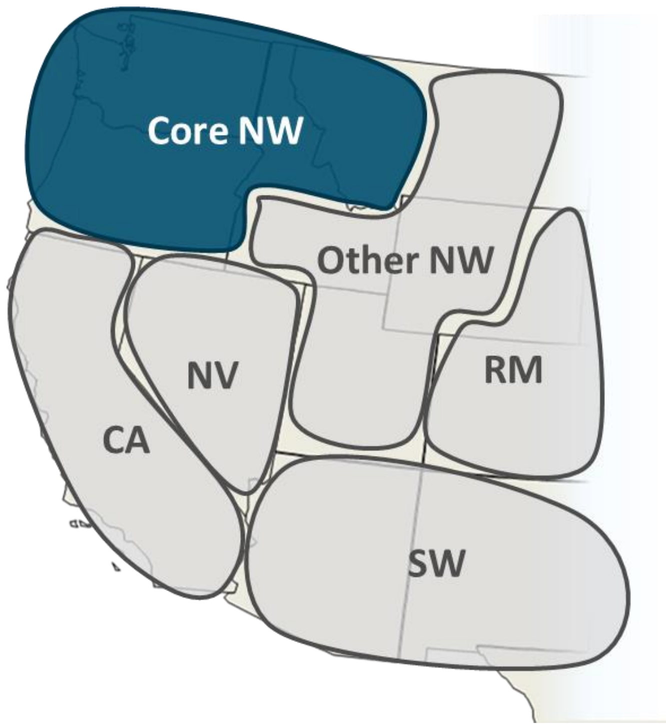
In addition to space heating electrification, we investigate the effect of water heating electrification on system peak. As part of a multi-year field metering study done on behalf of NEEA, Ecotope, Inc. created annual hourly load profiles for electric resistance and electric heat pump water heaters (Ecotope 2014).

Ecotope, Inc. developed representative shapes from 135 sites, encompassing a variety of installation locations, equipment brands, and climates. The day of week and time of year, in addition to hour of day, significantly affect water heating load. The change in water heating load over the year is affected by ground water temperature, which changes much more slowly than air temperature, and thus the daily air temperature is less impactful on water heating load shapes than on space heating load shapes. To incorporate the Ecotope calculated water heater load profiles into a system wide load shape, we match water heater load shapes from Ecotope with the day of week and month of year for the subset of days modeled in RESOLVE.

6.6 State cost results

The Northwest PATHWAYS model developed for this analysis models Oregon and Washington as two distinct regions of energy demand. Electricity supply in RESOLVE is modelled on a regional basis. RESOLVE costs were downscaled to each state by their 2017 load share of the “Core NW” region modelled in RESOLVE (Figure 38).

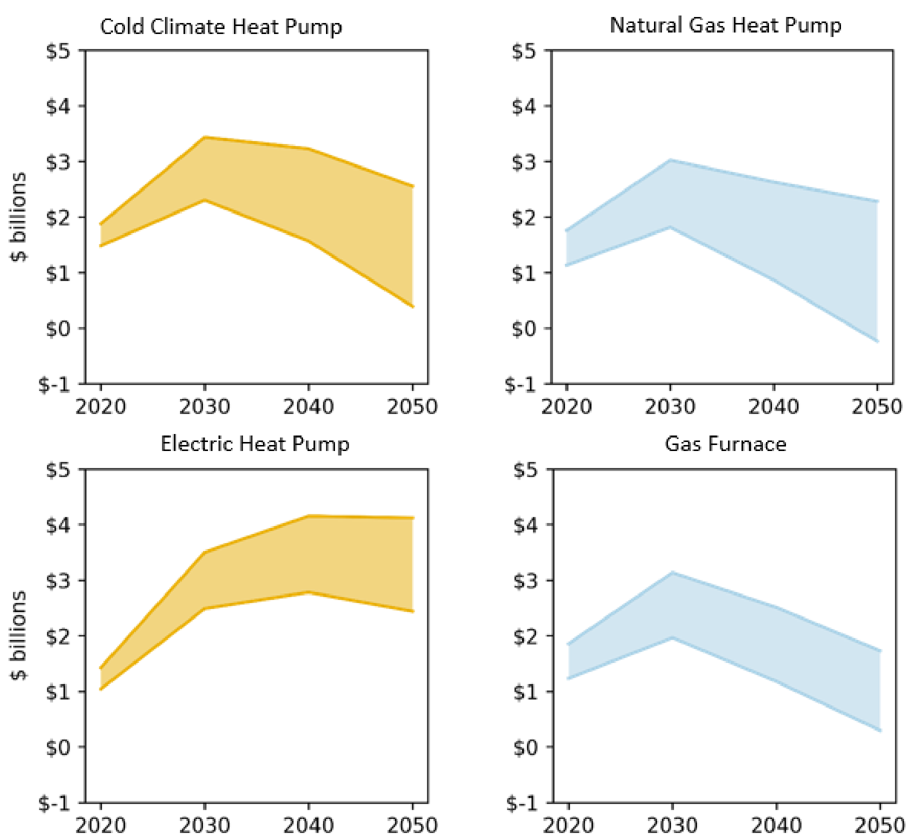
Figure 38: RESOLVE foot print



6.6.1 OREGON

Costs in Oregon are generally lower than those in Washington. This is partially due to Oregon being small relative to Washington. However, costs in Oregon are also proportionally lower relative to the Reference case because the state has lower biofuels demands than Washington. In fact, the lower bound of 3 of 4 mitigation scenarios in Oregon are near or below $0 incremental costs Figure 39.

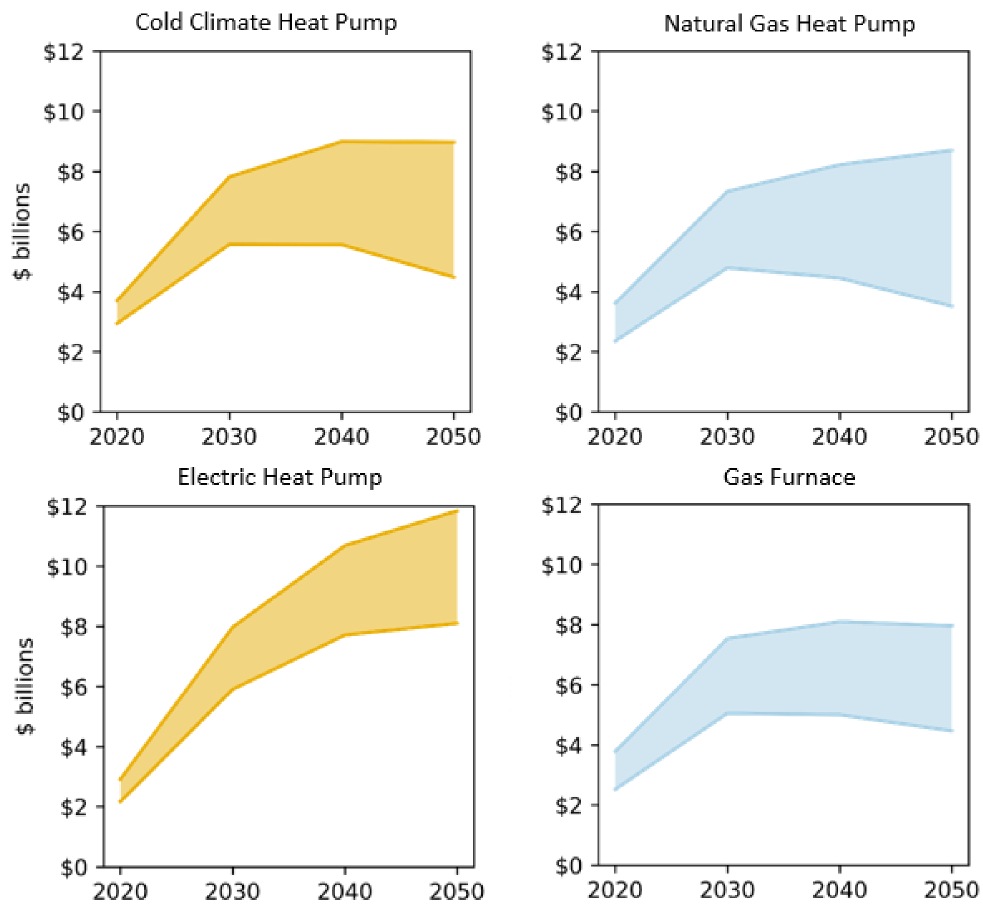
Figure 39: Scenario Costs in Oregon



6.6.2 WASHINGTON

Costs in Washington are higher than Oregon (Figure 40). These costs are partially driven by Washington having a larger energy economy than Oregon, though an additional driver of the cost differentials across scenarios are higher biofuels demands in Washington. Those higher biofuels demands are almost entirely attributed to Washington's aviation emissions. After aviation efficiency measures, the PATHWAYS model allocates a large share of the region's available biomass to displace remaining jet kerosene demands. Washington's emissions inventory includes per-capita aviation emissions above 1.1 MtCO2e. Per-capita aviation emissions in the Oregon inventory are approximately 0.5 MtCO2e, and nationally per-capita aviation emissions were 0.68 MtCO2e per person.

Figure 40: Scenario costs in Washington



6.7 Key data sources

6.7.1 GROWTH RATES AND DRIVERS

Sector	Key Driver	Compound annual growth rate	Data Source
Residential	Housing Units	1.15%	NWPCC Projections
Commercial	Square Footage	1.11%	NWPCC Projections
Industry	Energy growth	Varies by fuel	EIA AEO 2018 growth rates 2017-2050
Industry	Natural Gas Energy growth	0%	NW Natural
On Road Transportation	VMT	0.35% average 2015-2050	State DOT forecasts
Off Road Transportation	Energy growth	Varies by fuel	EIA AEO 2018 growth rates 2017-2050
Electricity generation	Electric load growth	0.77% average 2015-2050	Built up from Pathways demands in Buildings, Industry, Transportation
Fossil fuel price forecasts	$/GJ	Varies	EIA AEO 2018 growth rates 2017-2050

TECHNOLOGY COSTS

Technology	Source
Building heating equipment	Energy Trust of Oregon (ETO 2016) National Energy Modelling System (USDOE 2018) Northwest Energy Efficiency Alliance (NEEA 2016, 2018) National Renewable Energy Laboratory Efficiency Measures Database (NREL 2018)
Other building equipment (e.g. lighting, refrigeration, etc…)	National Energy Modelling System (USDOE 2018)
Battery electric vehicles	National Energy Modelling System (NEMS 2018) Ricardo Electric Vehicle Cost Forecast as Appendix C to PG&E EPIC DC Fast Charging Mapping Report (PG&E 2016)
Battery electric trucks	National Energy Modelling System (NEMS 2018) National Renewable Energy Laboratory Electrification Futures Study (NREL 2017)
Biofuels	United States Department of Energy Billion Tonnes Study (US DOE 2016)

Technology	Source
Hydrogen	UCI Advanced Power and Energy Program 2018 CEC Long-term Strategic View of the Use of Natural Gas in California. Publication Forthcoming
Electric sector	Public Generation Pool Carbon Study (PGP/E3 2017)
Electricity sector costs	PGP Carbon Study (E3 2017) Northwest Power and Conservation Council 7th Plan (NWPCC 2016)

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