Meeting the Challenge of Our Time: Pathways to a Clean Energy Future for the Northwest

An Economy-Wide Deep Decarbonization Pathways Study • June 2019

Clean Energy
Transition Institute

> "Limiting global warming to 1.5°C would require 'rapid and far-reaching' transitions in land, energy, industry, buildings, transport, and cities. Global net human-caused emissions of carbon dioxide (CO_2) would need to fall by about 45 percent from 2010 levels by 2030, reaching 'net zero' around 2050."
>
> — IPCC Special Report on Global Warming of 1.5°C, October 8, 2018.

Cover: Bullitt Center, Seattle, Washington.
Photo credit: Ben Benschneider

Umpqua National Forest fire, Oregon, 2018.
Photo credit: U.S. Forest Service–Pacific Northwest Region

About the Clean Energy Transition Institute

The Clean Energy Transition Institute is an independent, nonpartisan Northwest research and analysis nonprofit organization with a mission to accelerate the transition to a clean energy economy by identifying deep decarbonization strategies, advancing urban clean energy, and building a clean energy workforce. The Institute provides information about the pathways to a clean energy economy and convenes stakeholders to accelerate the shift to a low-carbon economy.

Idaho Falls wind farm. Photo credit: Daxis

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EER brings tried and tested expertise in planning for least-cost decarbonization, using a tool kit built to answer technical and economic questions about deep decarbonization, including the EnergyPATHWAYS and RIO models. EER's integrated approach to holistic energy planning finds the lowest-cost pathways to future policy goals by co-optimizing investments in the electric and non-electric energy sectors, which is essential for finding realistic and least-cost solutions for a clean energy future.

Decarbonization Pathways Work Group

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Technical Advisory Group

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Design Firm

One Visual Mind designed *Meeting the Challenge of Our Time: Pathways to a Clean Energy Future for the Northwest*. Founded in 2004, One Visual Mind has offices in Boston, MA, and in Portland, OR, and aims to provide functional design solutions that have an impact.

Seastack, Oregon Coast. Photo credit: Clean Energy Transition Institute

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Terms and Definitions

100% Clean Electricity: Electricity infrastructure that produces no greenhouse gas emissions during the production, transmission, and distribution of electricity.

Bioenergy Potential: A measure of the energy stored within organic materials, such as wood, crops, or solid waste, and their usefulness as fuel sources.

Biofuel/Biomass Feedstocks and Infrastructure: A biofuel/biomass feedstock is a renewable source of organic matter, such as sugarcane, cornstarch, woody plants, crop residues, etc., that can be either used as fuel or converted into fuel. Biofuels require distinct infrastructure: equipment that converts feedstocks into fuel, as well as specialized storage facilities, transportation methods, and pumps.

Biogas: A combustible gas composed predominantly of methane that is collected from waste streams, such as landfills and manure lagoons, for use as fuel. As a fuel, it is virtually identical to conventional natural gas.

Biomass Resources: Sources of organic materials that can be converted into fuel, including dedicated energy crops, agricultural crop residues, forestry residues, algae, wood processing residues, municipal waste, industrial waste, and food waste.

Built Environment: Human-made surroundings, especially buildings.

Capacity Factor: A measure of an electricity resource's utilization; the ratio of actual electrical energy output to maximum possible output.

Carbon-Beneficial Biomass: Sources of biomass that when used for fuel result in net reductions of carbon dioxide emissions.

Carbon Capture: Technology that prevents carbon emissions from escaping into the atmosphere from power plant or industrial waste gas streams and stores it in geological formations or in biological material such as forests, or that converts the carbon into fuel for reuse and recapture. Also called carbon capture and sequestration, carbon capture and storage, carbon capture sequestration and utilization.

Carbon Feedstock: The reservoir of available carbon dioxide in the atmosphere or produced by burning fossil or biofuels that can be captured and converted back into useful fuels and products.

Compressed Natural Gas: A fuel produced by compressing natural gas into a liquid form so that it can be used in place of other liquid fuels such as gasoline.

Cross-Sectoral Decarbonization/Cross-Sectoral Integrated Energy Economy: In the case of deep decarbonization, integrating low-carbon solutions across the transportation, built environment, and electricity.

Demand-Side Scenario: Decarbonization strategies that involve decisions and technologies that affect energy demand.

Diesel Hybrid Vehicle: Much like gasoline hybrid vehicles, a diesel hybrid vehicle is powered by both a diesel engine and a rechargeable electric battery.

Direct Air Capture: Technology that removes carbon dioxide from the atmosphere.

Electric Boiler: A water tank containing electrical heating elements that heat water.

Electricity System Reliability: The ability for utility operators to deliver electricity to consumers with adequate generation and available operating capacity even after outages or equipment failure. Reliability is measured by frequency, duration, and magnitude of adverse effects on service.

Electrolysis, Power-to-X: Power-to-X is a term that describes a variety of different technologies and processes that enable production of fuels using electric power. See Appendix B for detailed description.

Energy Crops: Plants grown specifically for use in producing biofuels.

Energy Density: Energy density is a measure of how much energy a fuel can store in a given amount of space. Energy-dense fuels include most liquid petroleum fuels such as gasoline, jet fuel, and diesel.

EnergyPATHWAYS Model: Evolved Energy Research's analysis tool that evaluates energy consumption across all end-use sectors and models final energy demand for fuels (electricity, pipeline gas, diesel fuels, gasoline, etc.), as well as the hourly demand for electricity.

Energy-Related Carbon Dioxide Emissions: Carbon dioxide produced from burning carbon-based fuels for energy.

Energy Resource: A source of energy; something that can be burned, harvested, extracted, or processed in order to generate energy.

Flexible Loads/Controllable Loads: A flexible load is an appliance or device with power consumption that can be directly controlled or varied.

Fuel-Switching: In the case of deep decarbonization, substituting fuels with cleaner, less carbon-intense alternatives (e.g., replacing gasoline with electricity).

Gaseous Fuel: Fuel that is stored as a vapor, rather than as a liquid or a solid, such as methane, propane, or hydrogen. Gaseous fuels take up more space but weigh less per unit of energy than liquid or solid fuels.

Generation Mix: The proportion of energy sources used to generate electricity in a given geography or jurisdiction (e.g., coal, natural gas, hydropower, wind, solar, etc.).

Grid Flexibility: The ability for an electrical system to balance power supply and demand under changing or uncertain conditions.

Grid Integration: The process of introducing and connecting new energy resources into an existing power system. Often used in reference to renewable energy, as renewables must be added into an existing grid powered by coal, natural gas, etc.

Grid Reliability: The ability of the power system to deliver electricity to consumers without interruption.

Heavy-Duty Vehicle (HDV): Usually used in reference to non-passenger vehicles, heavy-duty vehicles are freight vehicles, such as large trucks and trains, that weigh more than 8,501 pounds and are powered by diesel.

High-Capacity Factor: A highly utilized electricity resource; an electricity resource that produces almost as much energy during operation as its maximum theoretical energy output.

Hurdle Rates: Costs applied to imports and exports between transmission zones. These represent the transaction costs of trading between regions, wheeling charges, GHG charges associated with California imports, and any additional frictions of trading across borders.

Installed Capacity/Nameplate Capacity/ Maximum Effect: Installed capacity is the intended, maximum, sustained output of a power plant or electrical generator.

Interties: Connections that allow the flow of electricity between two balancing areas or transmission zones.

Least-Cost Optimization Framework: Method used in this study to determine the most cost-effective strategies for maximum carbon emissions reductions.

Light-Duty Vehicles (LDV): Vehicles that weigh less than 8,500 pounds; for example, standard passenger automobiles.

Liquefied Natural Gas: Natural gas that has been cooled to -260°F to compress it into a liquid state for storage and transportation. As a liquid, natural gas takes up 600 times less space than as a vapor.

Lithium-Ion Batteries: Energy storage method that provides a way to generate electricity and save it for use later. Lithium-ion batteries contain solid metal electrodes and allow charged lithium atoms to move in order to generate electricity.

Load: The amount of electricity drawn from the electrical grid.

Load Balancing: Matching supply to demand of electricity, including increasing and decreasing production of power plants, storing electrical power when demand is low and releasing it when demand rises, and adjusting loads through flexible load technologies.

Low-Quality Solar: Electricity produced in areas with relatively low levels of annual sunlight, or on rooftops that are shaded or at a poor angle.

Medium-Duty Vehicle (MDV): A passenger vehicle weighing between 8,501 and 10,000 pounds.

Natural Gas–Fired Generation: Producing electricity by burning natural gas. Combustion of the gas turns a turbine. The hot exhaust (carbon dioxide and water vapor) is redirected to heat water, producing steam, which also turns a turbine.

Non-Energy-Related Carbon Dioxide Emissions: Carbon dioxide emitted from sources other than the burning of fossil fuels, such as deforestation, methane from livestock, soil carbon, landfills and wastewater, and permafrost.

Optimal Electricity Supply Mix: The mixture of energy resources that produce the most efficient, lowest-cost energy with minimal carbon emissions.

Operational Integration: Integration of system dispatch activities across currently separated or only partially integrated balancing areas, lowering costs by using resources and transmission more efficiently.

Overall End-Use Energy Demand: The energy needed by all consumers on the grid.

Overgeneration: When power supply exceeds power demand, resulting in excess or wasted power. Typically, this manifests as curtailed renewable resource output.

Pipeline Gas: Gaseous fuel transported to consumers via pipelines. Today, the vast majority of pipeline gas is fossil natural gas, but in a decarbonized future it may also consist of large quantities of biogas or synthetic gas.

Regional Investment and Operations Model (RIO): Evolved Energy Research's computational tool that finds least-cost resource investments and operations for all energy-supply options and fuel types, including electricity, pipeline gas, gasoline, diesel, jet fuel, hydrogen, and other fuels. The model decides which technologies will be used over time to meet annual emissions targets and other constraints.

Regional Integration/Regional Grid Integration: Strengthening interconnection between transmission zones; a key strategy to resolve issues of overgeneration, undergeneration, or high electricity demand.

Renewable Diversity: Using varied sources of renewable energy to meet electricity demand.

Resource Adequacy: A regulatory construct developed to ensure that there will be sufficient resources to serve electric demand under all but the most extreme conditions.

Residual Fuels: The by-products of crude oil after gasoline and other fuels have been extracted during the refining process; used in thermal power plants and large engines, such as marine vessels.

Scenario-Based Pathways Approach: One of the methodologies used in a pathways study, involving specific sets of economic and policy conditions in order to determine the optimal route and tools to accomplish emissions reduction goals.

Sensitivities/Sensitivity Analyses: A measure of how changes in one resource or condition will impact other resources and conditions in an energy modeling analysis.

Sustainable Biomass: Biomass harvested from renewable resources, such as from forestry and agricultural residues, where waste products are reused to fertilize future biomass feedstocks.

Thermal Power Plants: A power station in which heat energy is converted into electricity, usually using coal or natural gas.

Undergeneration: The production of less electricity than is needed; when the load (demand) exceeds the production (supply).

Waste and Wood Feedstocks: Sources of organic material that can be converted into biofuels derived from waste (e.g., landfills) and wood (e.g., forestry residues).

Vanadium Flow Batteries: Vanadium flow batteries contain salt solutions that interact through a membrane. Flow batteries use both an electrochemical cell and a liquid electrolyte stored in separate tanks, which flow through the cell when the battery is operating. Vanadium flow battery capacity and power can be scaled independently.

Zero-Carbon Electricity/Zero-Carbon Sources: Electricity production that emits no carbon dioxide.

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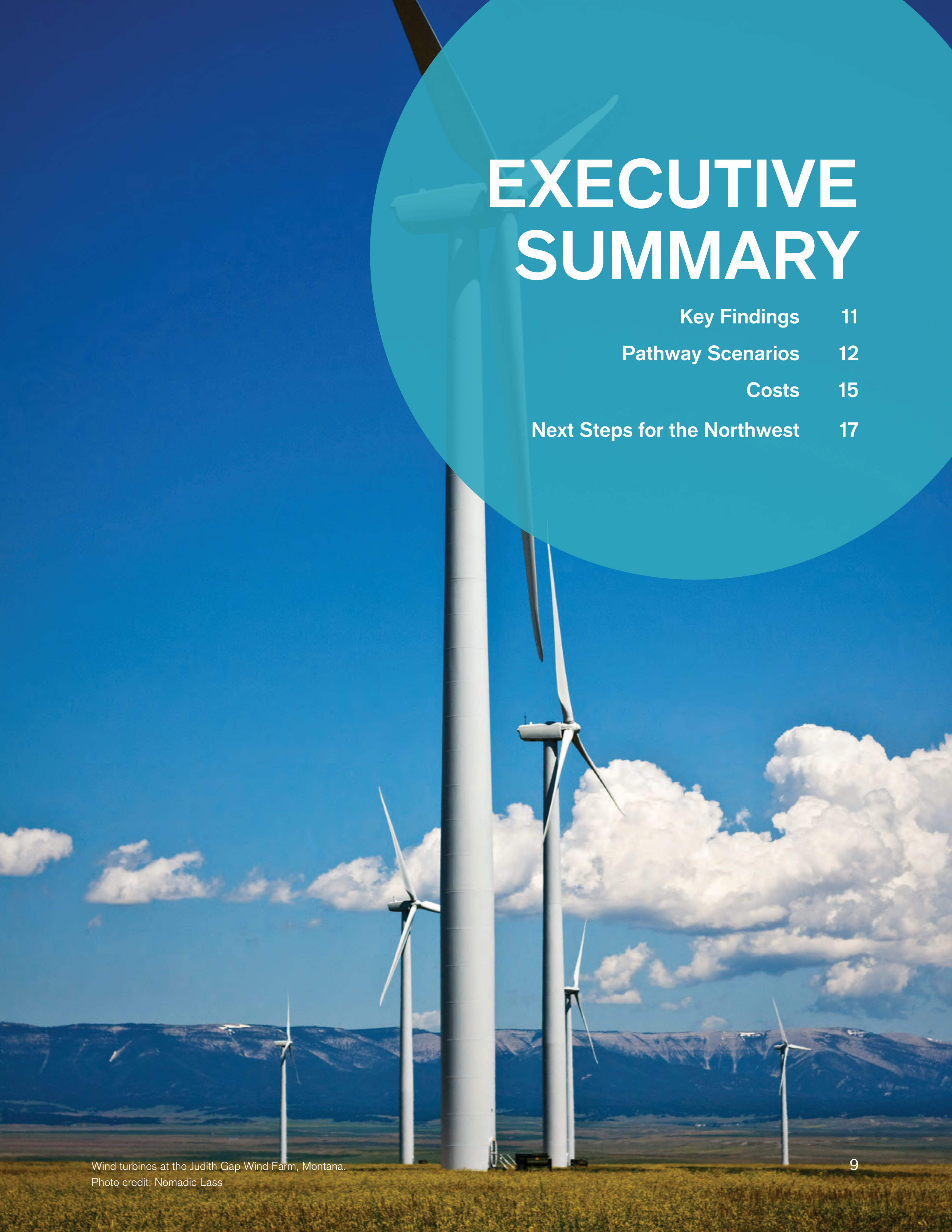


Wind turbines at the Judith Gap Wind Farm, Montana.
Photo credit: Nomadic Lass

Executive Summary

The Clean Energy Transition Institute commissioned this economy-wide deep decarbonization pathways study to serve as a blueprint for how Idaho, Montana, Oregon, and Washington might achieve a low-carbon, clean energy economy over the next three decades. The study, *Meeting the Challenge of Our Time: Pathways to a Clean Energy Future for the Northwest*, examines alternative pathways to achieving an 86% reduction of carbon emissions below 1990 levels in the built environment, transport sector, and electricity grid by 2050. A pathways approach enables an understanding of the most economically and technically efficient means of realizing this mid-century decarbonization goal.

The study models the energy systems in each of the four Northwest states to identify the interdependencies, efficiencies, and trade-offs that must be considered when pursuing deep decarbonization. The study's purpose is to provide guidance to policymakers, advocates, leaders, and investors as decisions are made to catalyze the clean energy transition in the Northwest over the coming three decades.

Since the fall of 2017, several regional studies have been conducted for different stakeholders and with varying assumptions that offer insights into different aspects of the Northwest's decarbonization puzzle. *Meeting the Challenge of Our Time: Pathways to a Clean Energy Future for the Northwest* is the first economy-wide analysis to examine the most likely decarbonization scenarios mapped to the region's economic and institutional realities. Prior studies looked only at the electricity grid, at one state or one utility service territory, or at the role of one fuel in specific sectors or subsectors of the economy as Figure 1 shows.

FIGURE 1. This study is the only four-state and sector-wide decarbonization analysis of the Northwest.

Year	Study	Energy Sectors	WA	OR	ID	MT
2016	State of Washington Office of the Governor	All sectors	●	○	○	○
2017	Public Generating Pool	Electricity sector only	●	●	◔	◔
2018	Portland General Electric	All sectors	○	◐	○	○
	Climate Solutions	Electricity sector only	●	●	◔	◔
	Northwest Natural Gas Company	All sectors; optimized decisions limited to electricity sector only	●	●	○	○
2019	Public Generating Pool	Electricity sector only; reliability study	●	●	●	●
	Clean Energy Transition Institute	All sectors; optimized decisions across entire energy supply side	●	●	●	●

Geographic Coverage: WA, OR, ID, MT

Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 9.

Each of these studies had a narrower purpose and answered questions of more limited scope than those posed by *Meeting the Challenge of Our Time: Pathways to a Clean Energy Future for the Northwest*. For example, none has looked at the impact of constraining biomass, the use of natural gas in transport, limited electrification, or greater integration of the Northwest and California electric grids. This study is unique in offering a blueprint that broadly frames the opportunities and trade-offs for the Northwest to achieve economy-wide deep decarbonization between 2020 and 2050.

Olympic National Forest. Photo credit: Clean Energy Transition Institute

Key Findings

The study demonstrates how the Northwest can rapidly deploy strategies to reduce carbon emissions in the energy sector efficiently and at least cost for the electricity grid, the built environment, and transportation. The region's relatively clean electricity grid and proximity to California, where climate policies aim to achieve a massive transition to clean energy within the coming three decades, are key assets.

Consistent with prior decarbonization pathways efforts, this study demonstrates that the low-carbon system of the future must have four primary features: (1) energy must be used more efficiently than it is today; (2) electricity generation must be as clean as possible; (3) liquid fuels must be as low-carbon as technically and economically feasible; and (4) clean electricity must be used for as many purposes as possible.

The study's key findings include:

- **Deep decarbonization is achievable in the Northwest.** Multiple strategies exist to achieve a deeply decarbonized energy system in the Northwest using today's technologies. Policymakers must decide how to achieve a low-carbon energy system at an acceptable cost.

- **Energy efficiency is a key strategy to reduce costs and meet goals.** Decreasing the demand for energy through efficiency reduces the need for new energy supply and associated infrastructure, and therefore also reduces the cost of decarbonization.

"Clean electricity is the backbone for deep decarbonization and the cross-sectoral role that electricity will play in the coming decades is key to the low-carbon future."

- **A nearly 100% clean electricity grid is needed.** A Northwest electric grid nearly free of fossil fuels efficiently achieves mid-century climate targets. Carbon emissions from electricity generation were reduced by 96% in the study's Central Case, the core decarbonization pathway. While coal is eliminated in a deep decarbonized future, a small amount of natural gas–generated electricity (just 3.7% of annual energy in the study's Central Case by 2050) ensures that the grid can reliably deliver power during periods of low generation from hydroelectricity and other renewable sources.

- **Demand for clean electricity will continue to grow.** A low-carbon future hinges on an integrated energy economy where power sources—and electricity in particular—play a cross-sectoral role in transportation and the built environment. Widespread transportation electrification (100% of light-duty, 60% of medium-duty, and 40% of heavy-duty vehicles in the study's Central Case) will be crucial to reduce emissions at least cost and avoid using either scarce biofuel supplies or relatively expensive electric fuels for transport. Clean electricity also needs to replace oil and gas to heat and cool buildings in a low-carbon future. Finally, clean electricity will be used to produce synthetic gas and liquids as additional energy sources.

- **Increased grid integration and transmission between the Northwest and California is cost-effective.** Significant cost savings can be realized if the Northwest and California electric grids are expanded and operations are better integrated. Building additional transmission lines between the Northwest and California electricity grids could reduce the costs of decarbonization by an estimated $11.1 billion in net present value over the 30-year study period accrued to the combined California and Northwest region.

- **Sustainable biomass is best used for jet and diesel fuel.** The best use for sustainable biomass is creating liquid fuels to power the hardest-to-electrify subsectors within transportation, namely aviation and long-distance freight shipping.

- **Emerging technologies will play a critical decarbonizing role.** With the correct mix of regulatory guidance, investment, and research it is likely that a range of technological developments will emerge to solve some of the most challenging deep decarbonization problems in the years beyond 2030. These technologies, which include electrolysis, direct air capture, hybrid boilers, hydrogen, synthetic fuels, and carbon capture, will provide economic value for excess renewables, displace conventional gas and liquid fuels, and help balance the grid.

This study is designed to show the trade-offs between different deep decarbonization pathways, but it does not take into account equity considerations for different communities. The study demonstrates that we can decarbonize our economy, but the critical work ahead must focus on how to do so equitably.

Pathway Scenarios

The study examined eight cases, starting with:

- **Business as Usual Case** based on existing policies and the scenario against which the seven deep decarbonization cases are compared; and

- **Central Case** that represents the study's core optimal deep decarbonization pathway.

The Central Case is the most flexible pathway to achieve emissions reductions because it is technology neutral. Six additional scenarios representing demand and supply variables relevant to current discussions in the Northwest energy community were modeled off the Central Case to understand the energy system trade-offs that occur as a result of different constraints or policies.

- **100% Clean Electricity Grid Case**, where all electricity generation must be zero-carbon in 2045.

- **Limited Electrification and Efficiency Achieved Case**, in which the aggressive electrification and energy efficiency assumptions in the Central Case do not materialize.

- **No New Gas Plants for Electricity Case**, which prohibits any new gas-fired power plants from being built across the region after 2020 and retires existing gas plants at the end of their economic lifespan.

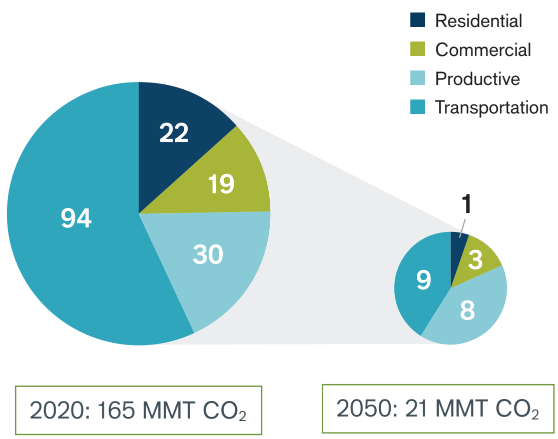
- **Increased Northwest-California Transmission Case**, where unconstrained construction of additional transmission is allowed between the Northwest and California for better grid integration.

- **Limited Biomass Available for Liquid Fuels Case**, where each state's bioenergy potential is limited to only waste and wood feedstocks, and no energy crops or biomass resources outside of the region are permitted.

- **Pipeline Gas Used for Freight Vehicles Case**, where compressed and liquefied pipeline gas replace renewable diesel fuel for freight vehicles in the Central Case.

Northwest CO_2 emissions decrease in the Central Case from 165 million metric tons (MMT) in 2020 to 20.8 MMT in 2050.

FIGURE 2. Comparison by sector of Northwest CO_2 emissions decrease from 2020 to 2050 in the Central Case.



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 63.

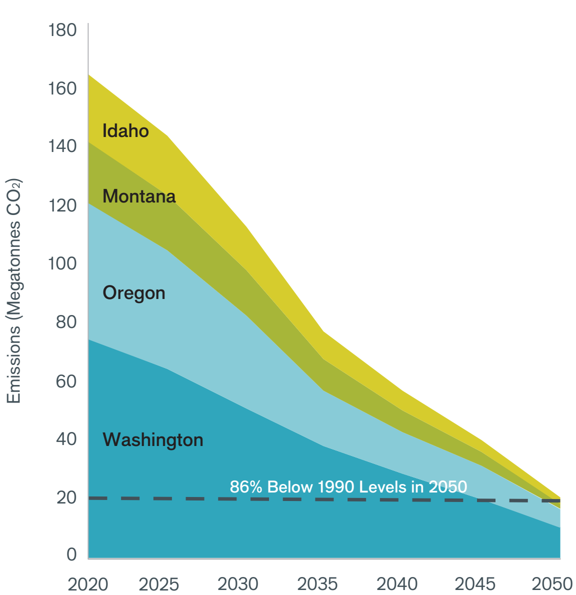
Figure 2 shows that Northwest CO_2 emissions decrease in the Central Case from 165 million metric tons (MMT) in 2020 to 21 MMT in 2050. Emissions in the residential sector decline by 95%; in the commercial sector by 86%; in the productive (industrial) sector by 72%; and in the transportation sector by 91%.

Figure 3 shows the emissions decline from 2020 to 2050 by each state, as well as by fossil fuel type. These emission reductions are achieved through five key decarbonization strategies: energy efficiency; decarbonizing electricity; decarbonizing gas and liquid fuels; fuel-switching in industry, transportation, and buildings; and carbon capture. The cost of achieving these reductions is offset by avoided fossil fuel purchases.

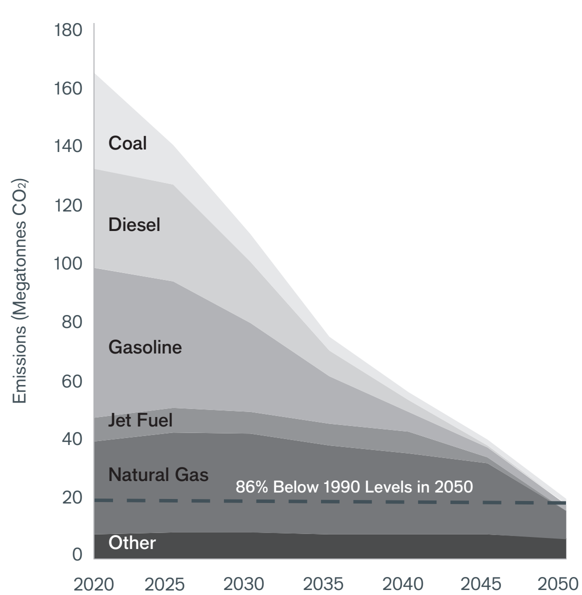
This study is unique in offering a blueprint that broadly frames the opportunities and trade-offs for the Northwest to achieve economy-wide deep decarbonization between today and 2050.

FIGURE 3. Declining emissions by state and by fossil fuel type 2020–2050.

Declining Emissions by State



Declining Emissions by Fossil Fuel Type



Five Key Decarbonization Strategies

Transitioning the Northwest to a low-carbon energy system relies on five decarbonization strategies:

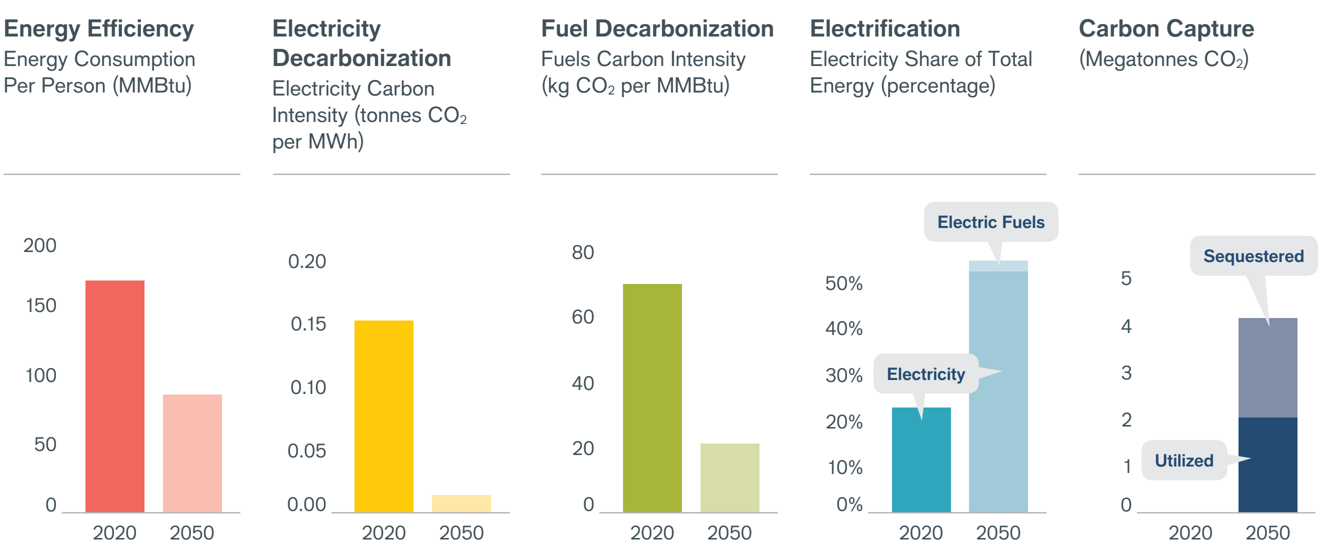
1. **Energy Efficiency:** reducing energy consumed to provide an energy service
2. **Electricity Decarbonization:** reducing the emissions intensity of electricity generation
3. **Fuel Decarbonization:** reducing the emissions intensity of liquid and gaseous fuels
4. **Electrification:** switching end uses from fuel to electricity
5. **Carbon Capture:** capturing CO_2 from a facility or removing CO_2 from the atmosphere

The purpose of the fifth strategy, carbon capture, is twofold: the captured CO_2 can either be used as a carbon feedstock for electric fuel production or sequestered.

Figure 4 shows metrics for the five strategies in the Central Case. Per capita energy consumption decreases from approximately 170 MMBtu per person today to 85 MMBtu per person in 2050, a 50% decrease. The average carbon intensity of electricity generation, which is already relatively low in the Northwest due to the hydroelectric system, decreases to near-zero by 2050.

The carbon intensity of fuels (liquid and gas) decreases by 70% primarily using biofuels. The share of total final energy served by electricity or electrically produced fuels (e.g., hydrogen and synthetic natural gas) more than doubles from approximately 23% today to 55% in 2050. Four million metric tons of CO_2 are captured in 2050, with about half of the CO_2 being utilized to produce synthetic fuels and the other half being sequestered (e.g., in saline aquifers in Montana).

FIGURE 4. Five decarbonization strategies.



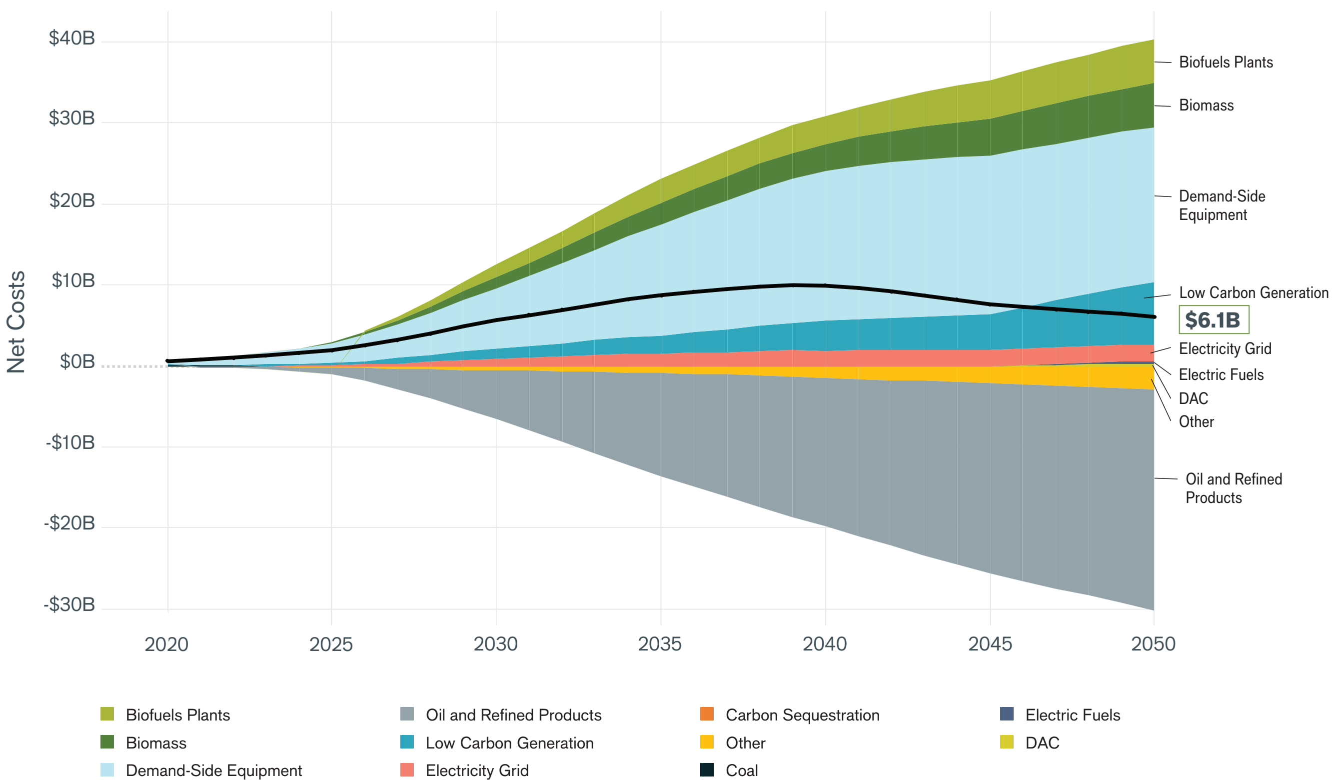
Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 65.

Costs

The study models the annual energy system costs of producing, distributing, and consuming energy, comparing the annual costs of the Business as Usual Case and the Central Case from 2020 to 2050. Net annual costs of the Central Case vary over the modeled period based on the timing of infrastructure investments, peaking at 16.1% ($9.8 billion) above the Business as Usual Case in 2038 and decreasing to 8.3% ($6.1 billion) higher than the Business as Usual Case in 2050. The cumulative costs of decarbonizing the energy system in the Central Case are 9.5% higher than the capital and operating expenses of the Business as Usual Case's energy system, roughly 1% of the region's total GDP in 2017 of more than $870 billion.[1] (See Figure 5.)

ZHome, Issaquah, Washington. Photo credit: City of Issaquah

FIGURE 5. Annual net energy system costs for the Central Case relative to the Business as Usual Case 2020–2050.



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 106.

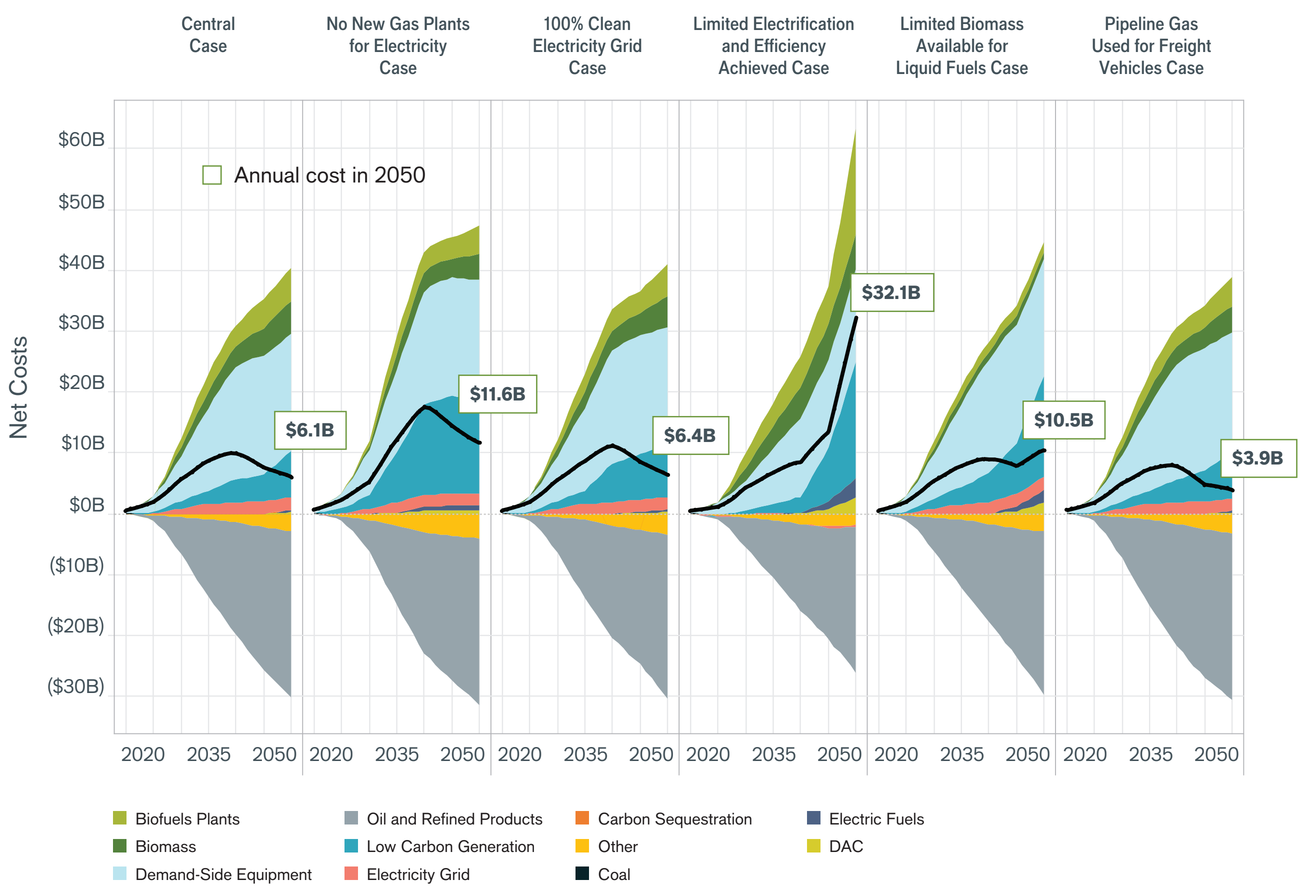
Increased costs in a decarbonized system consist primarily of biofuel feedstocks and infrastructure, demand-side electrification and efficiency investments, and renewable power plants and supporting electricity infrastructure. These costs are mitigated by the savings from reduced spending on fossil fuels, primarily liquid petroleum products such as gasoline, diesel, and jet fuel.

Costs for each scenario were modeled and compared to the Business as Usual Case. All cases performed worse than the Central Case, with the exception of the 100% Clean Electricity Grid scenario, which was only a marginal change from the Central Case and therefore has only a minimal impact on costs. The Pipeline Gas for Transport Case was $2 billion less than the Central Case. While this is a more cost-effective result, there are two issues that must be considered: (1) the model does not take into account the upstream emissions of pipeline gas production, and (2) there are significant technical challenges with using gas in the transport sector.

The Limited Electrification and Efficiency Achieved, No New Gas Plants for Electricity, and Limited Biomass Available for Liquid Fuels scenarios differ the most from the Central Case in terms of an increase in net systems costs. (See Figure 6.)

In 2050, the average cost of avoided carbon is $48/tonne and declining. The model makes conservative assumptions about the costs and scalability trends of clean energy technologies. A future report will explore in greater depth details on costs and emissions reductions, the assumptions that returned these results, and what these results mean for how the Northwest should consider investing in transitioning the region to a low-carbon economy.

FIGURE 6. Annual net energy system costs for six cases compared to the Business as Usual Case.



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 107

Next Steps for the Northwest

Meeting the Challenge of Our Time: Pathways to a Clean Energy Future for the Northwest aims to represent potential energy futures in enough technical detail to be used as blueprints to develop a future of the Northwest's choosing. While this analysis offers a functional technical representation of low-cost deep decarbonization pathways, successful implementation is more uncertain. Implementation challenges include the following:

- A nearly 100% clean grid is a key feature of low-cost decarbonization in the region. Policymakers and utilities must focus on overcoming the policy, technical, business model, and economic barriers to cleaning the grid well in advance of 2050.
- The level of transportation electrification called for by 2050 requires immediate attention to accelerating the widespread adoption of electric vehicles, investing in the essential charging infrastructure, and determining how the grid will handle the additional load required to serve this new demand. Not only must we move quickly to electrify transportation, we also need to invest in solutions that promote greater equity, especially for people historically least served or most impacted by fossil fuel–based transportation systems.
- New grid infrastructure and operational integration are needed to leverage renewable development efficiently and cost-effectively in California and across the West. Achieving this integration and installing the needed grid capacity is complicated politically and technically, so planning must get underway now to ensure successful integration of these markets.

Further work is needed to develop the policies that will accelerate a deep decarbonization path in the Northwest that is affordable, equitable, and meets reliability standards.

There are several areas of additional examination that the study suggests pursuing, including changing assumptions about hydroelectricity and nuclear availability, coal plant retirement dates, and natural gas pricing and carbon intensity. Further examination is needed of the role of natural gas and the decentralization of the electricity grid, as is work on the key policy drivers that are needed to accelerate decarbonization in the Northwest.

This study is designed to show the trade-offs between different deep decarbonization pathways, but it does not take into account equity considerations for different communities. The study demonstrates that we can decarbonize our economy, but the critical work ahead must focus on how to do so equitably.

Meeting the Challenge of Our Time: Pathways to a Clean Energy Future in the Northwest is the only independent and rigorous deep decarbonization analysis framing the choices we must make in the coming decade to achieve a deeply decarbonized future in the next 30 years. Stakeholders can use the results of this and other decarbonization studies to formulate policies and make investments and operational decisions to accelerate the clean energy transition and put the Northwest on a deep decarbonization path that is sustainable, affordable, equitable, and meets reliability and security needs.

Electric bus charging station, Seattle, Washington. Photo credit: SounderBruce

INTRODUCTION

Ivanpah Solar Electric Generating System, California. Photo credit: National Renewable Energy Lab

Introduction

Humanity has a small window in which to reduce greenhouse gas emissions. According to the October 2018 UN Intergovernmental Panel on Climate Change (IPCC) report,[2] "rapid and far-reaching" transitions in worldwide land use, energy, industry, building, transport, and cities are required to keep global warming temperatures to a maximum of 1.5 degrees Celsius (1.5°C) above pre-industrial global temperatures. Scientific consensus indicates that there is a critical 12-year window in which to bring global net human-caused carbon dioxide (CO_2) emissions down by approximately 45% below 2010 levels by 2030, and that the world must be net-zero emitting by 2050.

Just 11 days after the IPCC report was released, an International Energy Agency (IEA) analysis concluded that the world is on a path to build so many fossil fuel power plants and energy-inefficient factories and buildings in the next five years that it will become impossible to hold global warming to safe levels.[3] "The chances of meeting [a 1.5°C target] are becoming weaker and weaker every year, every month,"[4] IEA's executive director Fatih Birol declared to an audience gathered in Paris in late 2018.

The Northwest region of the United States is uniquely suited to lead the country in accelerating a path to deep decarbonization with its longstanding environmental ethic, abundant supply of clean hydroelectricity, and decades-long investment in energy efficiency. The region's built-in advantages suggest that the Pacific Northwest could take the lead in achieving a nearly 100% clean electricity grid by piloting the technologies and strategies required to decarbonize the transportation sector and buildings.

Northwest residents believe that global warming is happening by overwhelming majorities and express concern about climate change impacts.[5] The Northwest's close economic and historical energy linkages to California, as well as that state's ambitious carbon emission reduction policies, offer an opportunity to embrace new technologies that could drive change in Western energy markets, with an eye toward capturing additional efficiency and deeper carbon reductions.

Grand Coulee Dam. Photo credit: U.S. Bureau of Reclamation

According to the Yale Program on Climate Communication, 73% of Washington, 72% of Oregon, 65% of Montana, and 63% of Idaho believe that global warming is happening; 63% of Washington, 62% of Oregon, 55% of Montana, and 56% of Idaho are worried about global warning.

Now is the time for the Northwest to determine the path to a low-carbon future. The Clean Energy Transition Institute, a Northwest research and analysis nonprofit organization, developed *Meeting the Challenge of Our Time: Pathways to a Clean Energy Future for the Northwest* to offer a roadmap for how to achieve deep greenhouse gas emission reductions across the economy at a reasonable cost.

Study Objective

An analytical blueprint for decarbonizing the Northwest's economy offers a common set of assumptions to guide the region in making informed decisions about how the clean energy transition could unfold regionally over the coming three decades.

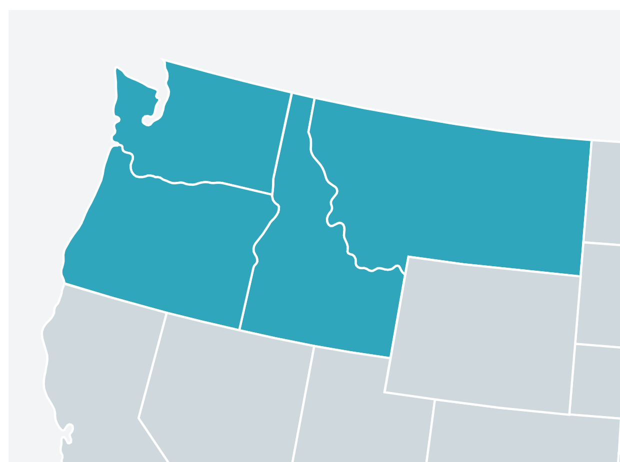
The study aims to provide unbiased analysis of decarbonization strategies for the region and, by doing so, demonstrate a variety of pathways to lower carbon emissions in the Northwest. The study also serves to illuminate the practical implications of achieving mid-century climate targets and broaden conversations about the actions we need to take to get there.

Proterra electric bus. Photo credit: Eric Wheeler, Metro Transit

Study Differentiation

The study is an economy-wide analysis that models the technical and economic implications of different decarbonization choices for the Northwest from now through 2050 for Washington, Oregon, Montana, and Idaho's energy systems—the network of all infrastructure that produces, converts, delivers, and consumes energy. This analysis contributes to an existing body of technical work related to decarbonization in the Northwest but is the first to optimize energy supply decisions for all four Northwest states, revealing new low-cost pathways to decarbonization.

The study includes a detailed representation of residential and commercial buildings and stocks, electricity demand, industrial energy demand, and vehicle fleets and transportation demand for freight and passenger transport to provide a full picture of the Northwest's energy systems. The study does not account for emissions from agriculture nor from industrial processes that are separate from the energy directly consumed by these sectors of the economy, due to data limitations associated with these sectors.



Several studies of decarbonization for the Northwest have been conducted since November 2016 and each of them provides slices of the decarbonization picture for the Northwest. (See Figure 1.)

FIGURE 1. This study is the only four-state and sector-wide decarbonization analysis of the Northwest.

Year	Study	Energy Sectors	WA	OR	ID	MT
2016	State of Washington Office of the Governor	All sectors	●	○	○	○
2017	Public Generating Pool	Electricity sector only	●	●	◔	◔
2018	Portland General Electric	All sectors	○	◑	○	○
	Climate Solutions	Electricity sector only	●	●	◔	◔
	Northwest Natural Gas Company	All sectors; optimized decisions limited to electricity sector only	●	●	○	○
2019	Public Generating Pool	Electricity sector only; reliability study	●	●	●	●
	Clean Energy Transition Institute	All sectors; optimized decisions across entire energy supply side	●	●	●	●

Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 9.

The five key differentiators between this study and prior studies are:

Scope: Each of the prior studies had a narrower purpose and answered questions of more limited scope than those that this study poses. None looked at the impact of constraining biomass, the use of natural gas in transport, limited electrification, or greater integration of the Northwest and California electric grids.

Economy-Wide: Looking economy-wide at all energy systems—not just at the electricity grid—yields a better understanding of how the whole energy system could work together to decarbonize and how the sectors interconnect. Evaluating only one source of emissions at a time provides an incomplete assessment of decarbonization. For example: should biomass be used to produce biogas for gas-fired power plants or for renewable jet fuel for aviation? Approaching deep decarbonization holistically provides an understanding of cross-sectoral advantages, impacts, and trade-offs.

Geography: Of the seven studies, only this study and the Public Generating Pool's 2019 study consider all four states in the region, while the other five include only parts of each state.

Energy Sectors: Four of the seven studies are electricity-sector focused only, while the other three, including this study, look at all energy sectors.

Models: The study combines detailed demand-side scenario development using a bottom-up energy system model called EnergyPATHWAYS, with optimal decision-making of the supply side done by an optimal-capacity expansion tool called the Regional Investment and Operations (RIO) model. Prior studies either optimized only for the electricity grid or only used a scenario-based pathways approach. (See Appendix A for a detailed description of the modeling approach.)

Greenhouse Gas Emissions Context

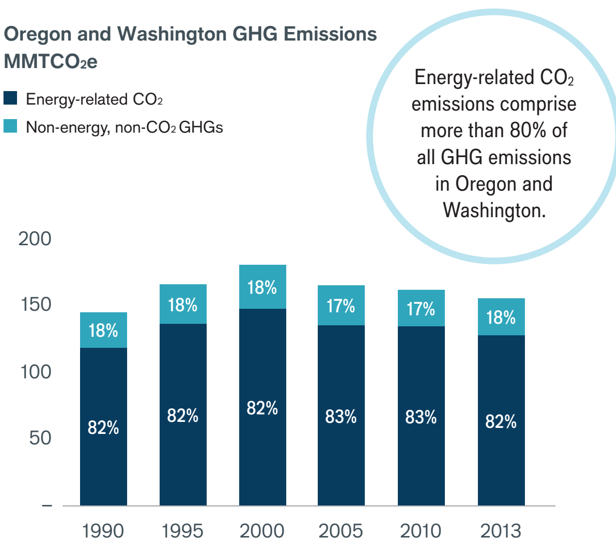
Energy-related CO_2 emissions have historically dominated greenhouse gas emissions in the Northwest, including emissions from fossil fuel combustion in buildings, industry, transportation, and electricity consumption. As Figure 2 shows, energy-related CO_2 emissions comprise more than 80% of all GHG emissions in Oregon and Washington.[6]

The remaining GHG emissions, colored light blue on the chart, include non-energy CO_2 and non-CO_2 greenhouse gas emissions from agriculture and industrial processes, such as methane from agriculture and waste, as well as hydrofluorocarbons and other high-intensity industrial emissions.

Energy CO_2 emissions are spread across three major sectors: electricity, transportation, and buildings and industry. The transport sector accounts for nearly half of all energy-related CO_2 emissions in Washington and Oregon primarily because of liquid fuel consumption: gasoline in passenger vehicles, diesel fuel in freight transport, fuel for marine transport, and jet fuel for aviation. Figure 3 depicts the breakdown of emissions by sector.

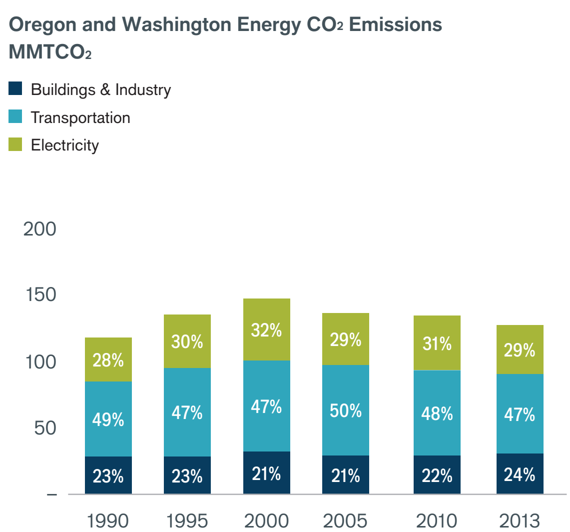
Marine shipping. Photo credit: Pixabay

FIGURE 2. Energy GHG emissions dominate in Washington and Oregon.



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 11. Data are from Oregon's Department of Environmental Quality and Washington's Department of Ecology.

FIGURE 3. Transportation emissions are nearly half of all energy-related CO_2 emissions in Washington and Oregon.



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 12. Data are from Oregon Department of Environmental Quality and Washington Department of Ecology.

Study Emissions Target

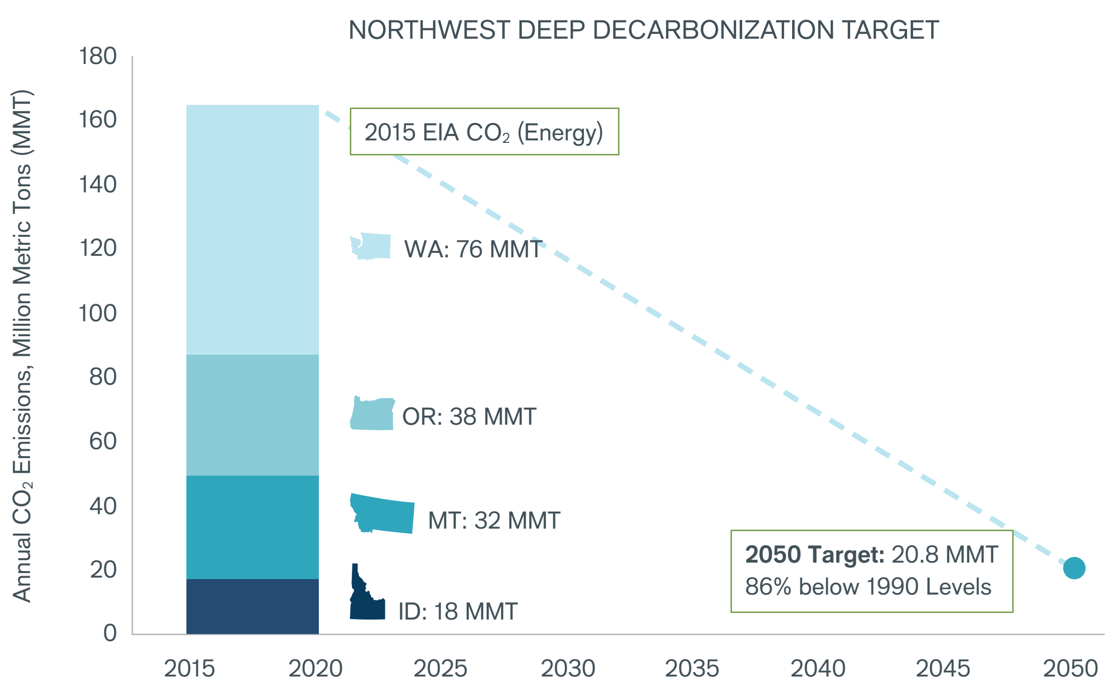
Two of the four Northwest states have set mid-century greenhouse gas emissions reduction targets. Washington established limits on emissions in 2008, including a 50% reduction below 1990 levels by 2050, which the Department of Ecology has recommended strengthening to 80%. Since 2007, Oregon has had the goal of reducing GHG emissions by 75% below 1990 levels by 2050.

This study's analysis uses the carbon emissions reduction target of 80% below 1990 levels by 2050 for all emissions (the global target established by scientific consensus) and assumes that the energy system will need to achieve reductions of 86% in energy-related CO_2 emissions below 1990 by 2050 to achieve the overall target that includes other sources of carbon emissions, such as forestry, agriculture, waste management practices, and others. This target was applied to each Northwest state independently. Targeting an 86% reduction in energy-related CO_2 emissions allows for fewer reductions of non-energy CO_2 emissions and non-CO_2 GHG emissions, where reduction strategies are less well understood.

While achieving the economy-wide target of 80% below 1990 levels by 2050 does not put the Northwest on track to do its part to limit the rise of global temperatures to 1.5°C, it is the standard target that most deep decarbonization pathways studies have modeled to date. An 80% reduction target provides a baseline against which deeper reductions could be measured in future studies.

This study, therefore, represents a floor and not a ceiling for responsible climate action, and while it develops an important pathway, further analysis should be conducted to achieve the targets that scientists recommend for the world to address global warming. Figure 4 depicts the deep decarbonization target for the Northwest energy system to attain.

FIGURE 4. An 86% reduction in energy-related CO_2 emissions below 1990 levels by 2050 is required to achieve an overall Northwest deep decarbonization target.



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 15.

Deep Decarbonization Pathways Framework

To decarbonize energy supply—electricity, pipeline gas, liquid fuels—the study applies a least-cost optimization framework that chooses the most cost-effective investment in resources to develop low-carbon energy supply portfolios. The model determines the fuel and energy supply-side infrastructure simultaneously while also considering constraints, such as the need to maintain electricity system reliability, or how much of a given resource, such as biomass, is available.

The deep decarbonization pathways framework for energy includes these strategies:

1. Use Less Energy

Energy efficiency and conservation reduce energy so fewer resources are needed, less carbon is emitted, and consumers pay less. Buildings, appliances, and vehicles all must become far more efficient to dramatically reduce energy consumption.

2. Decarbonize Electricity

By 2050, low-carbon technologies must replace nearly all fossil fuel electricity generation. A nearly 100% clean electric grid is essential to achieving required emission reductions.

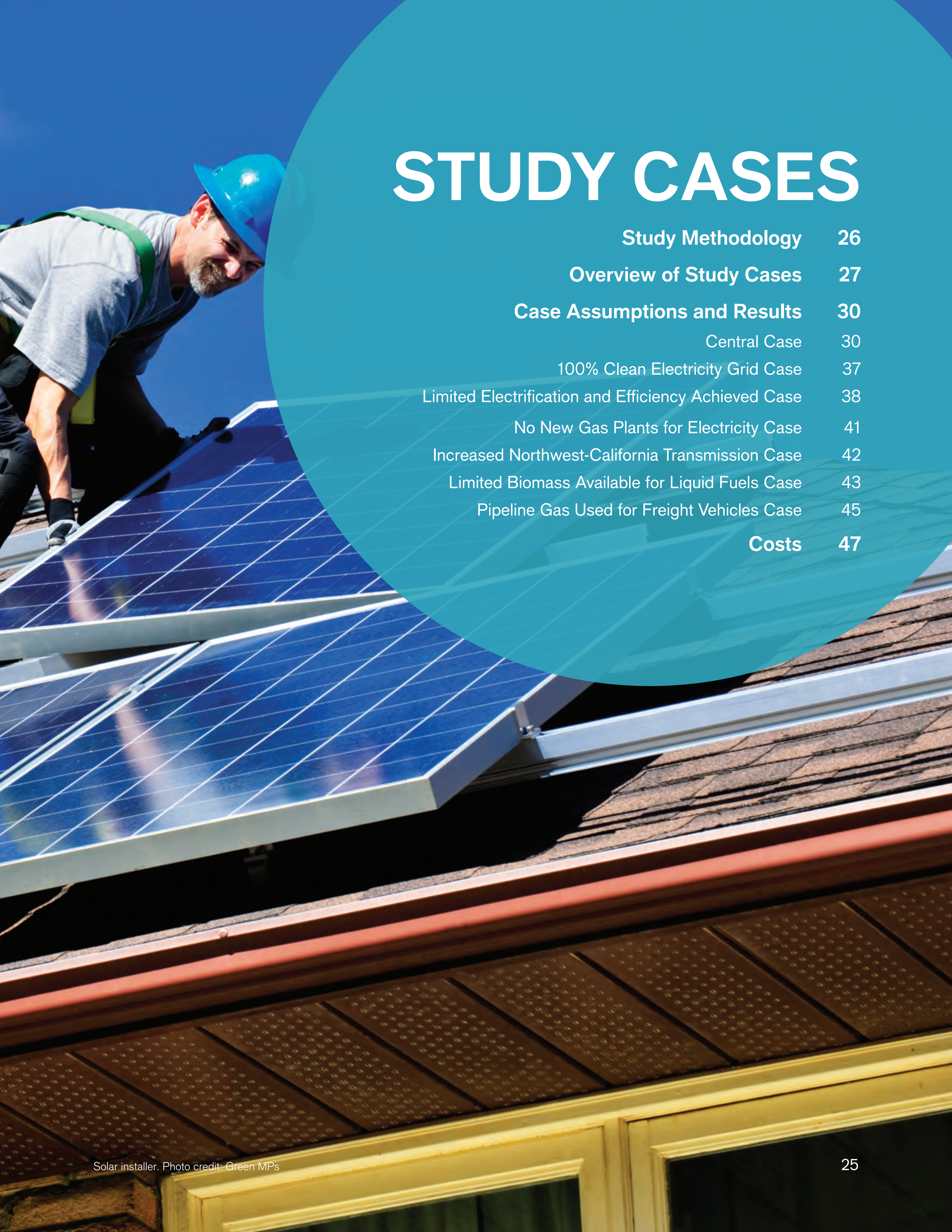
3. Decarbonize Liquid Fuels and Gas

For energy-dense transportation, such as aviation, long-haul trucking, and some industrial heat processes, carbon-beneficial biomass and synthetic fuels may be used.

4. Fuel-Switch

Transportation is currently powered by petroleum, while buildings and industry are currently fueled by a mix of natural gas, petroleum, and electricity. All must switch to cleaner fuels, principally clean electricity.

Photos clockwise: Infrared home detector. Photo credit: iStock; Wind turbines. Photo credit: iStock; Large commercial jet airplane. Photo credit: Cory Hatchel; Under the hood of a Nissan LEAF, Photo credit: Green Energy Futures



STUDY CASES

Solar installer. Photo credit: Green MPs

Study Methodology

Prior to commissioning *Meeting the Challenge of Our Time: Pathways to a Clean Energy Future for the Northwest*, the Clean Energy Transition Institute convened a Deep Decarbonization Pathways Working Group (see page 4 for the list of participants) and conducted numerous interviews with Northwest stakeholders about the value of conducting an economy-wide pathways study.

This stakeholder process revealed a clear need for a common set of facts about the decarbonization pathways for the Northwest that legislators and the advocacy community could agree to. (See Appendix E for the questions that stakeholders developed.) The Clean Energy Transition Institute commissioned Evolved Energy Research (EER) to develop the pathways to deep decarbonization for the four Northwest states with the following study parameters:

- Explore how energy sectors and energy supply need to transform in the most technologically and economically efficient way.
- Examine the extent to which electricity generation needs to be decarbonized to achieve economy-wide carbon reduction goals.
- Estimate the most cost-effective use of biomass for decarbonizing fuels.
- Assess the impacts of alternative assumptions and constraints, such as the limits of available biomass or the failure to achieve a high rate of electrification.
- Explore the value of increased electricity grid transmission between the Northwest and California.

The modeling process began by creating representations of each of the four state energy systems, incorporating state-specific energy infrastructure data and existing policies and creating benchmarks against historical energy use and emissions. The modelers then defined the deep decarbonization pathways by identifying plausible technologies for energy supply and demand and creating multiple scenarios that were designed to address the specific regional decarbonization questions, cases, and sensitivities that the Clean Energy Transition Institute wanted to explore.

King County Cities Climate Collaboration summit, January 2015.
Photo credit: Clean Energy Transition Institute

The model ran scenarios for each pathway through 2050, optimizing energy supply-side decisions within the constraints of the scenario being run and producing outputs of energy, emissions, cost, and infrastructure for different pathways to achieve steep reductions in energy-related CO_2 emissions by 2050. Modeling involved two different models that Evolved Energy Research developed: EnergyPATHWAYS (EP) and the Regional Investment and Operations model (RIO). (See Appendix A for detailed discussion of the modeling approach.)

The deep decarbonization target was applied to each Northwest state independently and assumes that each state complies with the target individually, although each can also use regional energy resources by importing or exporting clean energy to achieve compliance. One advantage of this study methodology is that it produces deep decarbonization pathways for each state individually.

Overview of Study Cases

The study explores multiple pathways for decarbonizing the region's energy system, while addressing policy questions and potential implementation challenges in the context of economy-wide carbon limits. The modeling exercise involved eight cases: the Business as Usual Case and the Central Case, two cases that examine different levels of energy demand, and four cases that assume varying sources of energy supply.

The Business as Usual Case is based on existing policies and is the scenario against which the seven deep decarbonization cases are compared. The Central Case represents the optimal deep decarbonization pathway, and the remaining six pathways cases are developed off the Central Case to draw out insights from alternative assumptions and policies. (See Appendix C for a list of all study assumptions and Appendix D for a list of key references.)

Wind turbine technicians. Photo credit: Pinnacle Career Institute

This approach allows for a better understanding of the trade-offs across the energy system when we assume alternative levels of electrification, mandates to use 100% clean electricity generation or prohibit new gas power plants, constraints on the use of biomass, and further electricity sector integration between the Northwest and California.

FIGURE 5. Overview and descriptions of the eight cases in this study.

Case	Description
Business as Usual Case	• A continuation of current and planned policy • Provides a benchmark against the deep decarbonization pathways
Central Case	• Represents the core pathway to achieve deep decarbonization • Flexible pathway to achieve emissions reductions (e.g., technology agnostic in the electricity sector)
100% Clean Electricity Grid Case	• 100% of electricity generation in the Northwest must come from zero-carbon sources in 2045 • Allows gas-fired generation to burn biogas and synthetic electric fuels
Limited Electrification and Efficiency Achieved Case	• Aggressive electrification fails to materialize • Adoption of electrification is half of the Central Case
No New Gas Plants for Electricity Case	• Pathway prohibits any new gas-fired power plants across the region throughout the study horizon • Existing gas plants retire at the end of their natural life, which effectively results in zero gas plants by 2050
Increased Northwest-California Transmission Case	• NW and CA power systems are currently connected by approximately 8,000 MW of interties • Pathway allows for transmission interties to be expanded as both regions strive to achieve decarbonization
Limited Biomass Available for Liquid Fuels Case	• Each state's bioenergy potential is limited to waste and wood feedstocks without access to energy crops or resources outside of the region • Biomass supply is 60% less than Central Case
Pipeline Gas Used for Freight Vehicles Case	• Freight vehicle fleet has a large composition of compressed and liquefied pipeline gas trucks • Increased pipeline gas use in freight transportation supplants diesel fuel demand in the Central Case

The eight cases studied are as follows:

Business as Usual Case

The Business as Usual Case assumes the continuation of current and planned policy for the four Northwest states, serves as the benchmark case, and demonstrates that existing policies are not enough to attain the deep decarbonization target.

Central Case

The Central Case is the optimal low-carbon pathway for the Northwest and shows that a diverse set of unconstrained technologies and strategies (including significant energy efficiency and electrification) will achieve deep decarbonization. It is structured to answer multiple questions: How clean must electricity generation be to realize a deep decarbonization target? What is the cost-optimal allocation of biomass? How quickly must we electrify transportation? What is the role of natural gas for electric power generation in 2050?

100% Clean Electricity Grid Case

The 100% Clean Electricity Grid Case puts the grid on a trajectory to zero-carbon sources for all electricity generation starting in 2020, and constrains electricity generation to be 100% clean in 2045 and beyond to align with California's clean energy mandate. Gas-fired power plants are allowed to burn biogas and synthetic electric fuels to meet the target. This case demonstrates how more aggressive decarbonization in the electricity sector can make up the balance with harder-to-mitigate sectors.

Limited Electrification and Efficiency Achieved Case

In this case, the aggressive electrification and efficiency assumed in the Central Case fail to materialize. It explores the strategies needed to achieve deep decarbonization if electrification is only half of that achieved in the Central Case.

No New Gas Plants for Electricity Case

This case prohibits any new gas-fired power plants in the region after 2020 and has existing gas plants retire at the end of their economic lives, which means no gas plants operate on the grid by 2050. This case reveals the options that electric grid managers have for maintaining resource adequacy and flexibility as renewables are added, as well as the role that storage would need to play in maintaining grid reliability.

Increased Northwest-California Transmission Case

In this case, unconstrained construction of additional transmission between the Northwest and California electric grids allows better integration than currently exists. This case reveals how a more efficient use of electricity sector infrastructure can reduce costs and grid-balancing challenges.

Limited Biomass Available for Liquid Fuels Case

For this case, each state's bioenergy potential is limited to waste and wood feedstocks with no access to energy crops or to biomass resources outside of the region, which means 60% less biomass than in the Central Case. This case tests the impact of limiting biomass to see what other strategies would be required to meet deep decarbonization if a sustainable biomass supply fails to materialize.

Pipeline Gas Used for Freight Vehicles Case

Here hybrid diesel vehicles in the Central Case are powered by compressed natural gas for medium-duty vehicles and liquefied pipeline gas for heavy-duty vehicles. The total vehicle fleet has the same proportion of battery electric vehicle fleets as in the Central Case, which helps illuminate the potential role for pipeline gas in transportation.

Case Assumptions and Results

Central Case

The Central Case was designed to probe how clean the electric grid must be to achieve the economy-wide carbon reduction target and how biomass would be cost-optimally allocated. On the demand side, the Central Case incorporates aggressive levels of efficiency and electrification across all sectors.

On the supply side, the Central Case allows for cost-optimal decarbonization of energy supply without explicitly constraining which fuels are decarbonized. In other words, in the Central Case there is no explicit requirement that all electricity must be 100% clean or an explicit prohibition on building new gas plants.

Figure 6 below shows the demand-side assumptions that the modelers chose for transportation, buildings, and industry.

Electric smart car. Photo credit: Green Energy Futures, David Dodge

FIGURE 6. The assumptions for demand in the Central Case.

Sector	Subsector	Assumption
Transportation	Light-duty vehicles	90% battery electric 10% plug-in hybrid electric
	Medium-duty trucks	60% battery electric 40% hybrid diesel
	Heavy-duty trucks	40% battery electric 60% hybrid diesel
	Aviation	48% reduction in energy intensity
Buildings	Space conditioning	Primarily air source heat pump
	Water heating	Primarily heat pump water heater
	Lighting	LED
	Appliances	Best available technology
Industry	Industrial curing, processing, boilers, machine drives, and process heat	Electrification adoption similar to NREL Electrification Futures Study “High scenario”
	Other subsectors	20% reduction from baseline

Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 49.

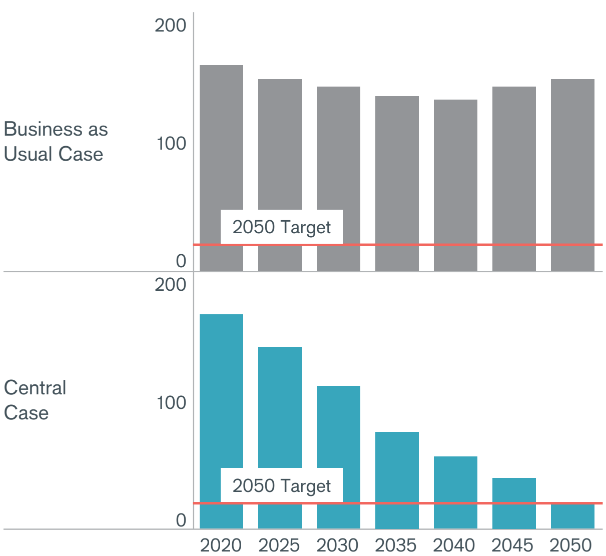
As Figure 7 shows, the Business as Usual Case's emission trajectory falls far short of the 2050 reduction goal, while in the Central Case, electrification, energy efficiency, and decarbonizing the energy supply enable each Northwest state to meet the mid-century energy CO_2 emission target of 86% below 1990 levels.

As Figure 8 demonstrates, overall end-use energy demand in 2050 is more than one-third less than today, in spite of population increase and economic growth; electricity consumption increases by more than 50% and comprises one-half of all end-use demand by 2050; and liquid fuels decrease from one-half of today's demand to one-fifth by 2050 as on-road vehicles transition to electricity.

Traffic on the Alaskan Way Viaduct. Photo credit: Tony Webster

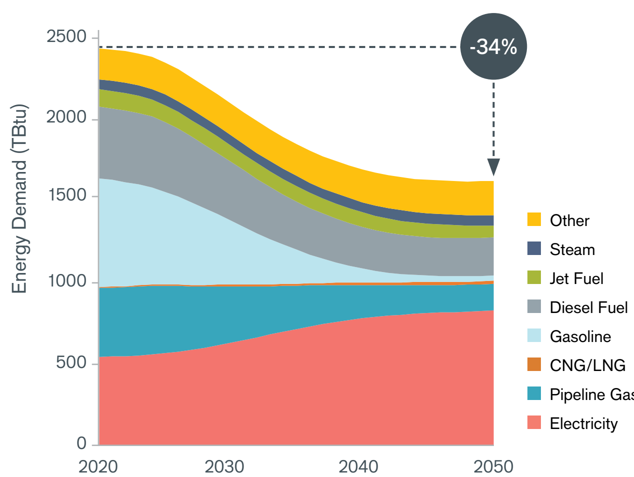
FIGURE 7. In the Business as Usual Case emissions trajectory falls far short of the 2050 reduction goal, while the Central Case meets the mid-century energy CO_2 emission target of 86% below 1990 levels.

Energy CO_2 Emissions (MMT)



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 62.

FIGURE 8. In the Central Case energy demand is down 34% and electricity consumption is up more than 50% in 2050.

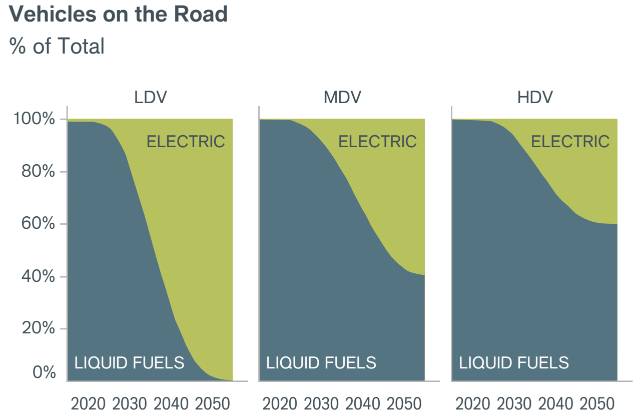


Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 67.

The primary reason for the net increase in electricity consumption in the Central Case is that by 2050 all passenger vehicles (LDVs), 60% of medium-duty vehicles (MDVs), and nearly half of all freight trucks (HDVs) are electric. The freight trucks that continue to use liquid fuels mostly consume renewable diesel in 2050. Figure 9 shows the increasing proportion of electric to liquid fuels for the three vehicle classes in 2020, 2040, and 2050.

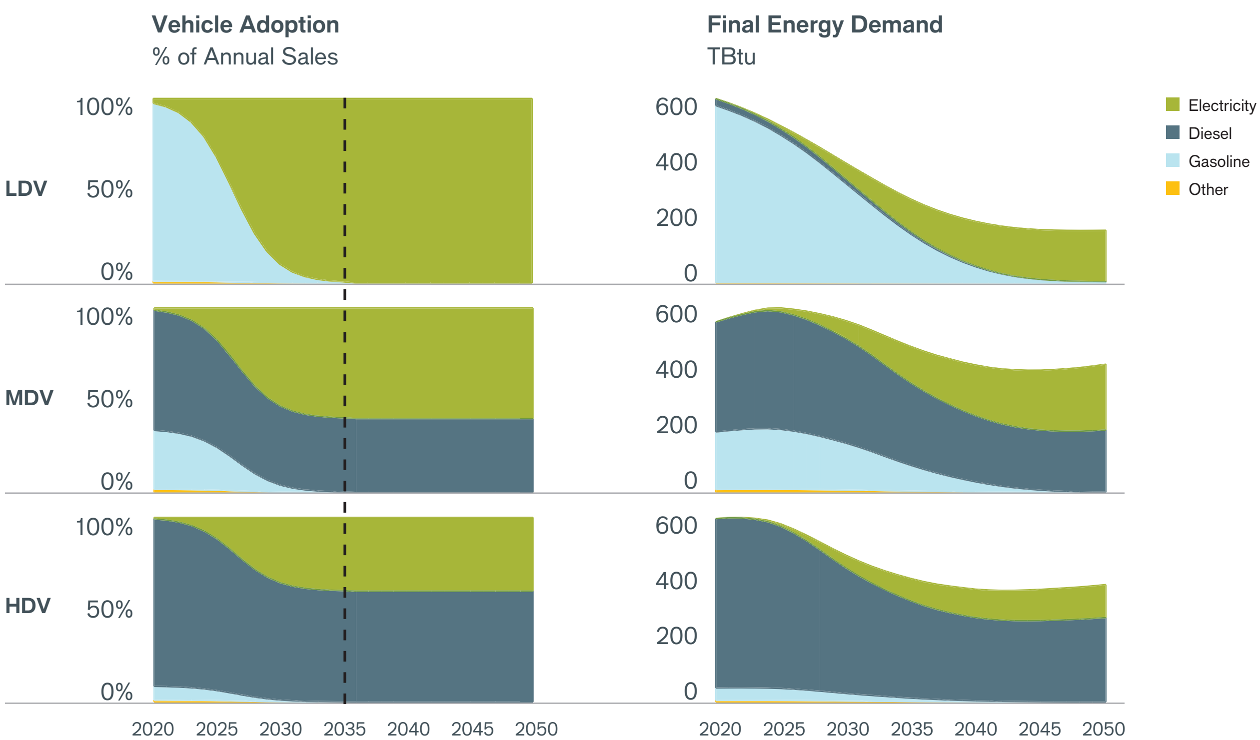
As Figure 10 shows, in the Central Case all LDV (passenger car) sales are electric by 2035 (note the dotted line in the Vehicle Adoption graph). The figure also shows the proportion of electric versus renewable diesel versus gasoline to meet energy demand over the 30-year span. Gasoline is out of the fuel mix in the Central Case. The significant decrease in energy demand for LDVs is all met with clean electricity in 2050 and the freight truck fleet uses a combination of electricity and renewable diesel by 2050.

FIGURE 9. The increasing proportion of electric to liquid fuels for vehicles from 2020 to 2050.



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 68.

FIGURE 10. The rate of vehicle adoption as a percentage of annual sales by fuel type from 2020 to 2050 in the Central Case.



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 69.

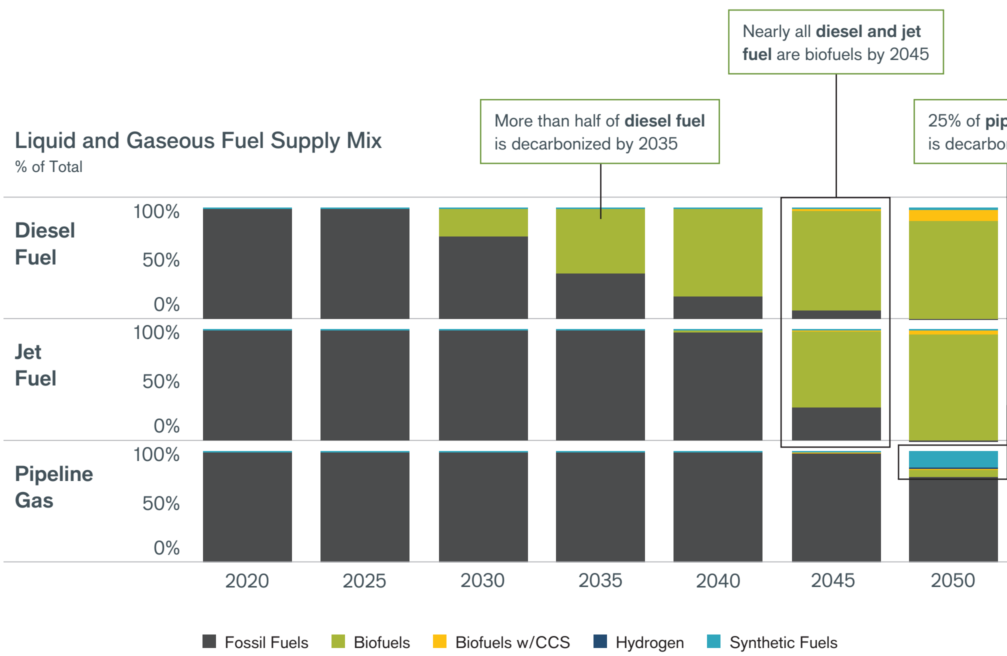
Figure 11 shows the composition of the liquid and gaseous fuel supply mix from 2020 to 2050 in five-year increments, divided among fossil fuels, biofuels and biofuels with carbon capture and sequestration (CCS), hydrogen, and synthetic fuels. Biofuels begin replacing fossil fuels for diesel fuel in 2030, and by 2035 more than half of diesel fuel is decarbonized.

In 2050, biofuels begin decarbonizing jet fuels and nearly all diesel and jet fuel are biofuels by 2045. By 2050, diesel and jet fuel are decarbonized, largely by biofuels, but synthetic electric fuels also make up more than 10% of pipeline gas in 2050, and 25% of pipeline gas is decarbonized, mostly with synthetic electric fuels.

Electricity sector load increases by more than 60% between 2020 and 2050, largely due to the net increase of higher fixed loads from transportation and building electrification. However, producing hydrogen, capturing CO_2, and using electric boilers to produce steam also create significant new load.

Incremental wind and solar photovoltaics (PV) are the principal sources of supply to decarbonize electricity generation and meet the growing demand for electricity in the Central Case from 2020 to 2050. Wind generation is nearly the same as hydroelectricity generation by 2050, while the share of gas-fired generation is only 3.7%, and coal-fired generation is completely eliminated by 2050. The model extends Columbia Generating Station (CGS)'s nuclear power beyond its current 2043 end date through 2050, the study's time horizon.

FIGURE 11. The composition of the liquid and gaseous fuel supply mix in the Central Case in five-year increments from 2020 to 2050.



KEY TAKEAWAYS:

Biomass is largely allocated to liquid fuels

Synthetic electric fuels make up more than 10% of pipeline gas in 2050

Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 71.

Figure 12 shows electricity generation in gigawatt hours on the left, and the generation mix as a percentage of total generation on the right.

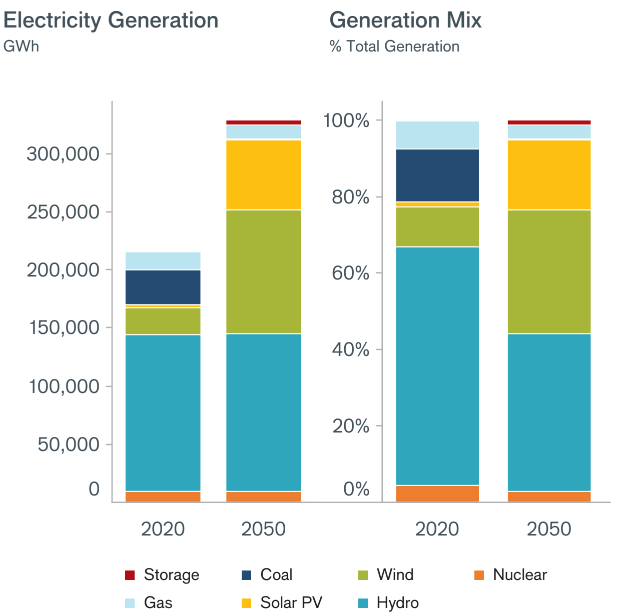
New electricity power generation to be built in the Central Case is significant: nearly 100 gigawatts of new electricity supply resources by 2050, shown in Figure 13. Renewable energy dominates the new capacity, with more than 40 gigawatts of new onshore wind and 35 gigawatts of solar photovoltaic.

Gas and storage resources are added primarily to ensure that the grid has adequate resources to serve demand for energy and that different power sources are balanced; however, the share of gas-fired generation is 3.7% in 2050.

The large percentage of wind and solar resources is non-dispatchable generation, which creates electricity balancing challenges. In many low-carbon electricity systems studies, thermal and energy storage resources are used for balancing the grid. But these are either not able or too expensive to address grid imbalances that persist over days or weeks. This study expands the portfolio of options available to address balancing challenges by including flexible electric fuel production (electrolysis) as a resource.

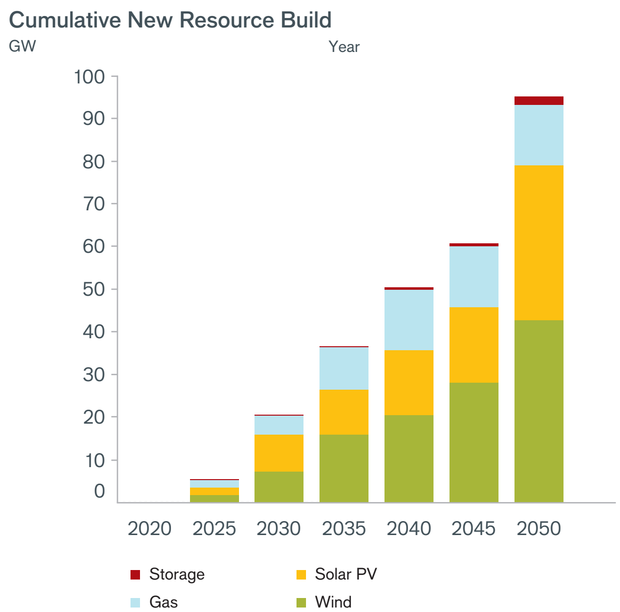
Installing solar panels. Photo credit: Oregon Department of Transportation

FIGURE 12. Amount of electricity generation and the generation mix for electricity supply in the Central Case.



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 72.

FIGURE 13. The Northwest region would build 95 gigawatts of new electric generation in the Central Case.

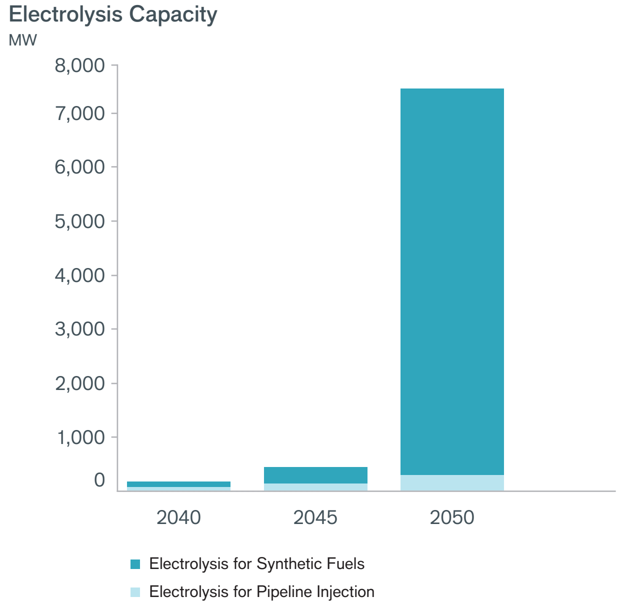


Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 73.

Electrolysis produces hydrogen that can be used in two principal ways: (1) as a feedstock to combine with a source of CO_2 to produce synthetic electric fuels; and (2) to be used as synthetic gas to inject directly into the gas pipeline. In the Central Case, 7,500 megawatts of electrolysis capacity is added in the Northwest by 2050, most of which is used to produce synthetic gas and uses existing gas delivery mechanisms, thereby avoiding new infrastructure expense. This electrolysis capacity is mostly added in 2050, as Figure 14 shows. (See Appendix B for a description of power-to-X, hydrogen electrolysis, and direct air capture.)

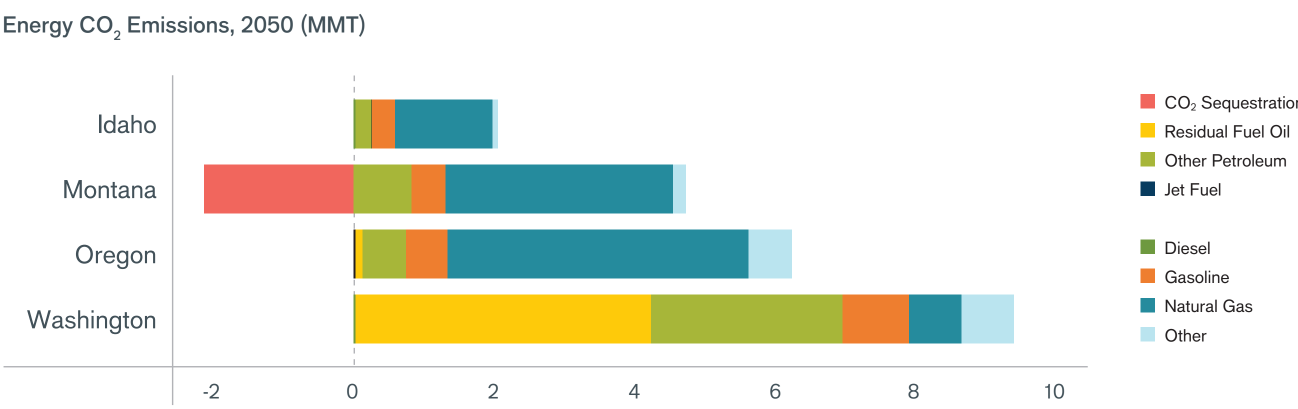
Jet fuel and diesel are almost completely displaced by biofuels and therefore barely register in Figure 15 below, which shows the remaining emissions in 2050 in the Central Case. In three of the four states, the majority of remaining emissions in 2050 are from natural gas combustion. The exception is Washington State, which is home to 75 ports and where residual fuel oil used in shipping is the largest remaining source of emissions. Montana is the only state with enough geological CO_2 sequestration potential to allow for the CO_2 capture and storage in saline aquifers.

FIGURE 14. Flexible electrolysis capacity is added starting in 2040 in the Central Case to address balancing challenges and produce synthetic fuels and gas.



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 76.

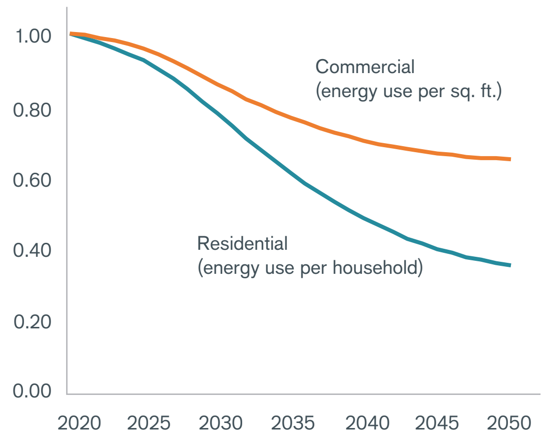
FIGURE 15. In three of the four states, the majority of remaining emissions in the Central Case in 2050 are from natural gas combustion.



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 79.

FIGURE 16. Decline in building energy intensity for commercial and residential buildings from 2020 to 2050.

Building Energy Intensity (2020=1.0)



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 70.

In terms of energy efficiency, residential and commercial energy intensity drop significantly over time (See Figure 16.) This means that even as the number of households and commercial square footage grow over time, total energy use in the built environment declines and contributes to the Central Case's 34% decrease in overall energy use.

The decline in energy intensity is due to aggressive efficiency in electricity end-uses, such as lighting, clothes washers, and ventilation. The efficiency of heat pump technology relative to the best-in-class combustion equipment also translates into deep energy-use reductions in electrification of space and water heating.

Energy efficiency worker. Photo credit: Consumers Union

Lackland Airforce Base, San Antonio, Texas. Photo credit: William Belcher

100% Clean Electricity Grid Case

In the 100% Clean Electricity Grid Case, the Northwest states achieve economy-wide deep decarbonization with the mandate that all electricity generation must be zero-carbon by 2045, permitting no fossil fuel combustion in electricity generation. Thermal power plants can continue to operate, but pipeline gas consumption must be 100% decarbonized with either biogas or synthetic gas.

Requiring 100% of electricity generation in the Northwest to come from zero-carbon sources produces marginally different results from the Central Case. The share of gas-fired generation decreases from 3.7% to 1.7% due to incremental renewables and energy storage deployment and, by 2050, all of the gas burned for electricity is either clean synthetic or biofuels in the 100% Clean Electricity Grid Case.

Even though biofuels and synthetic gas are expensive, it is still cost-effective to burn them during times when it is challenging to supply adequate power, such as when low renewable generation coincides with periods of high load and low hydro.

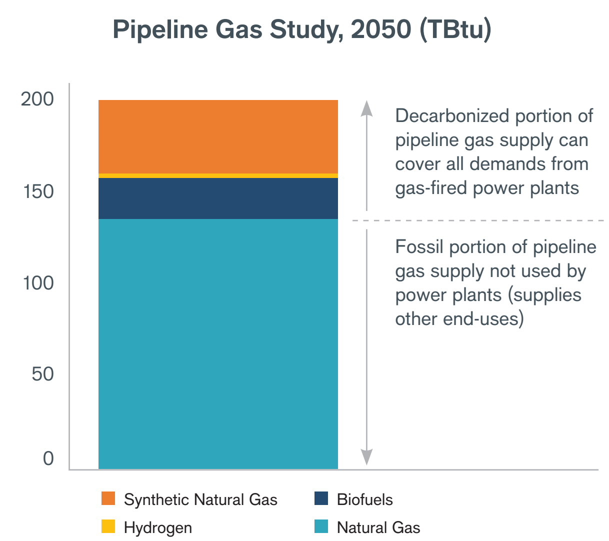
Seen in Figure 17, decarbonized pipeline gas supply (biofuels [dark blue], hydrogen [yellow], and synthetic natural gas [orange]) covers all demand from power generation in 2050. The majority of incremental decarbonized pipeline gas is from synthetic gas.

To achieve deep decarbonization of the energy system, the Central Case is 96% (nearly 100%) clean without a specific mandate, so a relatively small quantity of additional synthetic fuels and biofuels are needed to bridge the gap between 96% and 100% clean electricity in the Northwest. It is easier to obtain 100% clean electricity when the electricity sector is integrated with other parts of the supply-side energy economy that serve fuel demands. Producing fuels from electricity decarbonizes fuel supplies, replacing fossil fuels for transportation, industry, and buildings.

Producing fuels from electricity also provides valuable benefits that reduce investment costs in the electricity sector at high renewable penetrations in two ways: 1) producing flexible electric fuels increases load flexibility and makes it easier to balance the electricity system; and 2) clean synthetic gas can be used to generate electricity during challenging system-balancing conditions.

Furthermore, there are economic benefits with 100% clean electricity that come from sharing a border with California and the resulting renewable resource diversity: The Northwest has excellent wind, California has excellent solar, and both regions benefit economically from running clean electrons through the interties between them. (See the description of the Increased Northwest-California Transmission Case on page 40 for additional discussion of the technical and economic benefits of 100% clean electricity.) By sharing the same clean energy standard, the two regions could more easily take advantage of these resource diversity benefits.

FIGURE 17. In the 100% Clean Electricity Grid Case, decarbonized pipeline gas can fully supply power plants.



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 81.

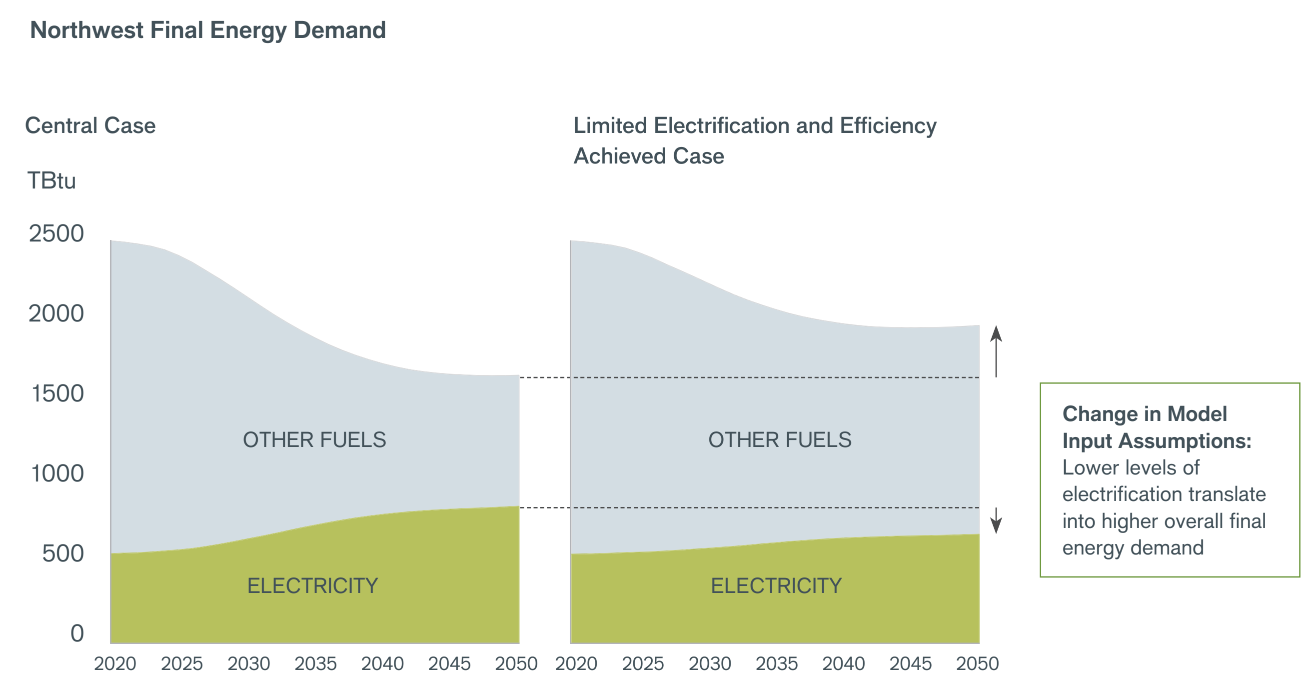
Limited Electrification and Efficiency Achieved Case

The Central Case relies almost completely on clean, efficient electricity replacing gasoline in vehicles, and biofuels replacing diesel and jet fuel, with a very small amount of synthetic fuels providing the remaining decarbonized source for the transportation sector. The Limited Electrification and Efficiency Achieved Case assumes that aggressive electrification fails to materialize and shows that removing clean electricity as a replacement for liquid and gaseous fuels requires using more of the other fuel sources in varying degrees, which results in significant added cost as discussed in the Cost section. (See page 45.)

In the Limited Electrification and Efficiency Achieved Case, adoption of electrification is one-half that of the Central Case (only 50% of passenger cars, 30% percent of medium-duty vehicles, and 20% of trucks are electric) and half of the electrification is achieved for buildings and industry. The demand for fuels shifts from 49% of the final energy demand in the Central Case to 66% in the Limited Electrification and Efficiency Achieved Case, as Figure 18 shows.

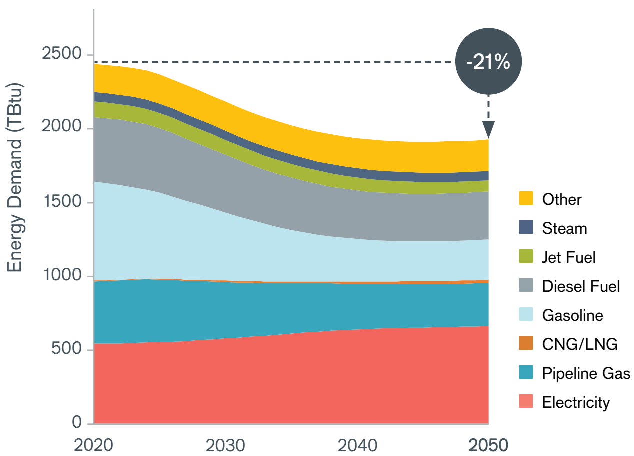
The lower levels of electrification also translate into higher overall final energy demand in the Limited Electrification and Efficiency Achieved Case. Overall end-use energy is 21% less than today's levels but 7% more than in the Central Case, as Figure 19 shows. With more energy demand to meet than in the Central Case, the supply side faces a higher mitigation burden to achieve the emission reduction target.

FIGURE 18. Assumptions for final energy demand in the Central Case vs. the Limited Electrification and Efficiency Achieved Case.



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 52.

FIGURE 19. Energy demand declines by 21% in the Limited Electrification and Efficiency Achieved Case vs. 34% in the Central Case.

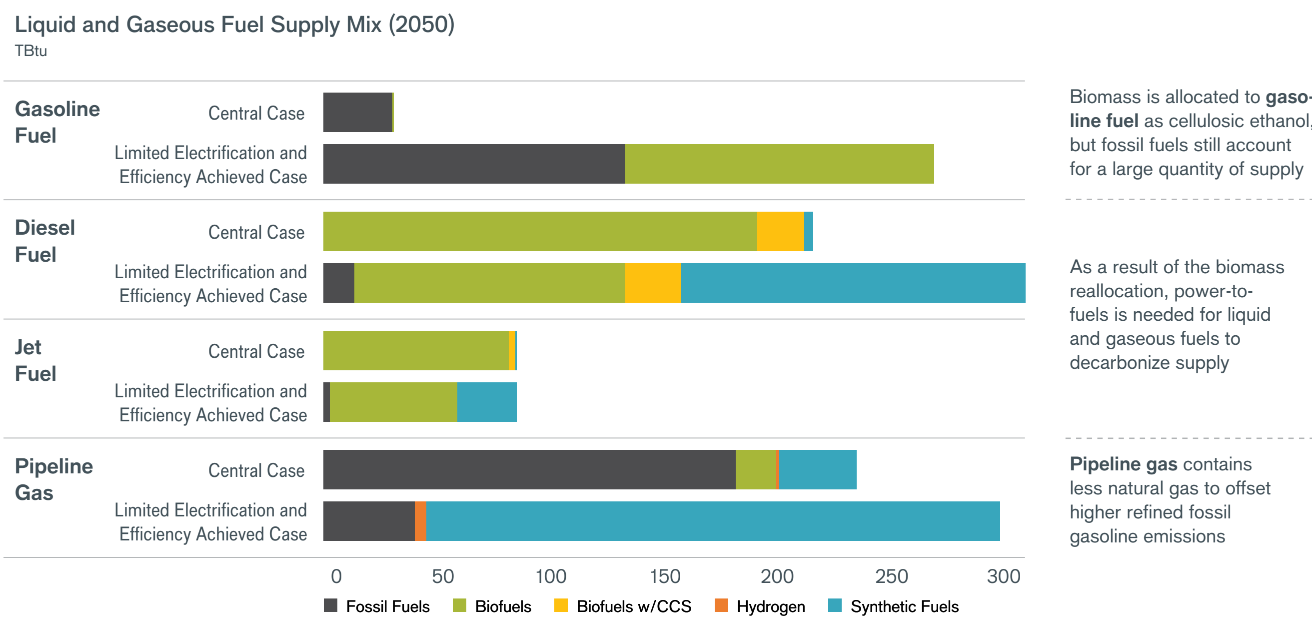


Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 83.

Achieving lower electrification, particularly in the transportation sector, means that large volumes of diesel fuel, jet fuel, and gasoline remain in the energy system during the 30-year study period, unlike in the Central Case where we saw that biofuels largely decarbonize these fuels.

Here, biofuels replace gasoline (which electricity replaced in the Central Case, thus saving biofuels for the harder fuels to decarbonize) and significantly more expensive synthetic fuels are required to decarbonize diesel fuels, jet fuels, and pipeline gas. Figure 20 shows the changes to fuel supply and biomass allocation in the Limited Electrification and Efficiency Achieved Case compared to the Central Case.

FIGURE 20. Changes to fuel supply and biomass allocation in the Limited Electrification and Efficiency Achieved Case.



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 84.

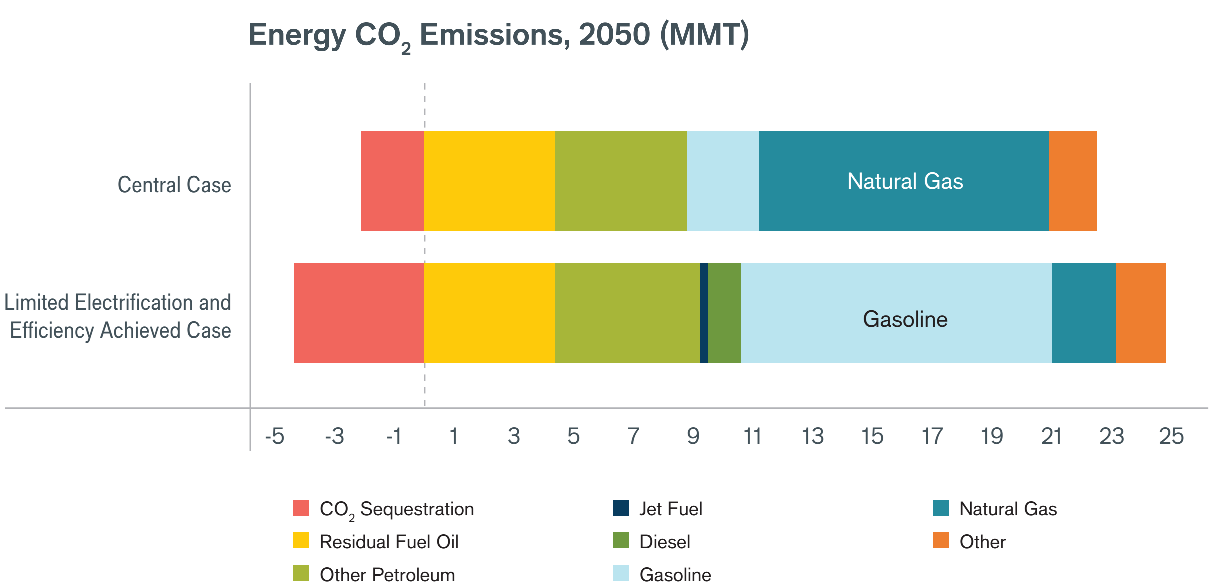
With lower levels of end-use electrification, the Limited Electrification and Efficiency Achieved Case has significantly higher emissions in the transportation fleet, primarily from gasoline, than in the Central Case. To compensate for these higher emissions, pipeline gas must be decarbonized to a greater extent than in the Central Case.

With all available biofuels being used to displace transportation fuels in the Limited Electrification and Efficiency Achieved Case, pipeline gas largely consists of synthetic gas and some hydrogen. Figure 21 shows that the remaining emissions in the Limited Electrification and Efficiency Achieved Case compared to the Central Case are largely in gasoline, jet and diesel fuel, and other petroleum, which includes kerosene, liquefied petroleum gas, and other petroleum products used in industry.

The large quantity of additional synthetic fuels required in the Limited Electrification and Efficiency Achieved Case to decarbonize pipeline gas, diesel, and jet fuel increases the need for CO_2 feedstocks, thus increasing investment in direct air capture (DAC) technology to provide them. In the Central Case, DAC technology captures approximately 2 million metric tons (MMT) of carbon in 2050, whereas in the Limited Electrification and Efficiency Achieved Case, 27 MMT must be captured in 2050.

The bottom line: not replacing gasoline with electricity means both that significantly more fuel is needed with the Limited Electrification and Efficiency Achieved Case than the Central Case and that there are not enough biofuels for jet and diesel fuels, so expensive synthetic fuels are required to decarbonize the fuel supply. In general, the study shows that achieving deep decarbonization in the transportation sector requires either widespread electrification or substantial increases in DAC-produced synthetic fuels.

FIGURE 21. Remaining energy CO_2 emissions in the Limited Electrification and Efficiency Achieved Case vs. the Central Case.



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 85.

No New Gas Plants for Electricity Case

For the No New Gas Case, new gas-fired resources cannot be developed anywhere in the Northwest from 2020 to 2050. Existing gas resources retire at the end of their economic lives and cannot be extended or replaced, which means that there are no gas-fired resources online in 2050 in the region. There are no constraints on pipeline gas outside of the electricity sector.

Even though gas-fired resources comprise a small portion of generation in 2050 in the Central Case (3.7%), the resource adequacy value they provide to the system is significant and expensive to replace with other resources. Prohibiting the development of new gas-fired generating resources in the electricity sector results in 12 gigawatts of additional energy storage resources—dominated by lithium-ion batteries—to maintain resource adequacy. In addition to the 75 gigawatts of new renewables required in the Central Case, the No New Gas Case requires an additional 35 gigawatts of wind, solar, or geothermal resources. Figure 22 shows the change in installed capacity in the No New Gas Case relative to the Central Case in 2050.

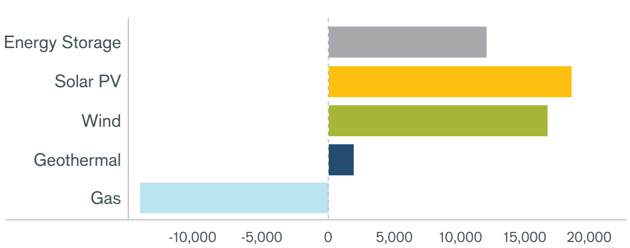
Electrical apprentice works on solar reference array. Photo credit: Northern Alberta Institute of Technology

The constraint on gas-fired resources in the electricity sector also has spillover effects on the rest of the energy system. Higher penetrations of renewables—and resulting overgeneration—incentivize the production of additional electric fuels, notably power-to-diesel and power-to-jet-fuel.

As a result, fewer biofuels are used. In fact, the No New Gas Case is the only case that does not fully use available biomass (biomass use is 30% below the Central Case). Figure 23 shows the impact on the liquid and gaseous fuel supply mix in 2050 when gas is constrained.

FIGURE 22. The No New Gas Case requires installing nearly three times as much renewable generation capacity.

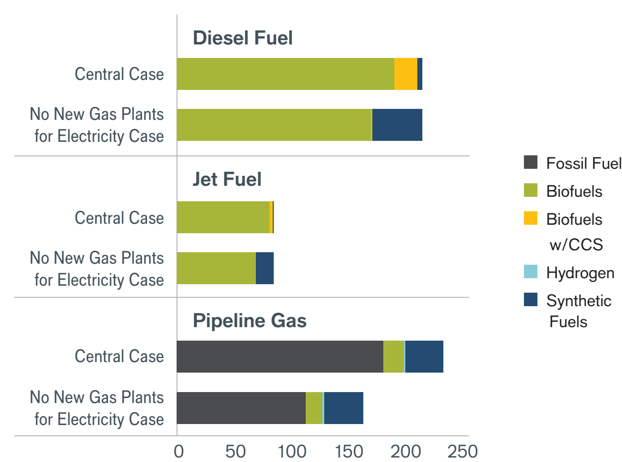
Change in Installed Capacity Relative to Central Case, 2050 (MV)



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 87.

FIGURE 23. Liquid and gaseous fuel supply mix in the No New Gas Case vs. the Central Case.

Liquid and Gaseous Fuel Supply Mix, 2050 (TBtu)



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 88.

Increased Northwest-California Transmission Case

The Increased Northwest-California Transmission Case explores how increased transmission between the Northwest and California could allow both regions to achieve deep decarbonization at potentially lower costs. The Northwest's and California's electricity systems are currently connected by approximately 8,000 MW of interties, including the California-Oregon Intertie (COI) and Pacific Direct Current Intertie (PDCI). The model economically expands transmission, relaxes California's net export limit over time, and removes hurdle rates between the two regions starting in 2030.

Approximately 4,500 MW of incremental transmission capacity is developed between the Northwest's and California's power systems. With this infrastructure in place, there are increased exports from California to the Northwest during daylight hours, while the Northwest increases exports to California during traditionally off-peak hours. Net exports from the Northwest increase by approximately 7,000 GWh in 2050.

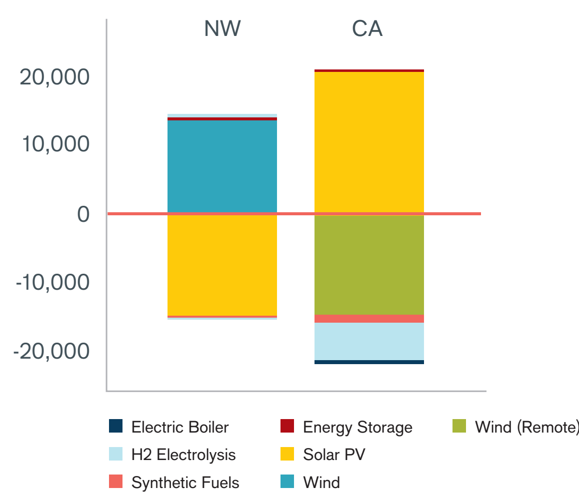
Expanded interties change the optimal electricity supply mix, with each region avoiding the development of local, low-quality renewables and expanding the development of high-quality resources that are more efficiently shared across both areas. Figure 24 shows the difference in resource build between the Central Case and the Increased Northwest-California Transmission Case by region. Those resources shown with positive megawatt changes increase in capacity versus the Central Case, whereas those on the negative side of the scale decrease in capacity.

By allowing greater transfer between regions, the Northwest and California can focus on building their best-quality resources. The Northwest avoids developing low-quality solar and increases wind development, and California avoids procuring remote wind generation from other Western states (New Mexico and Wyoming) and develops additional high-quality solar. In total, it is estimated that increased integration between California and the Northwest could save $11.1 billion in net present value over the 30-year study period (accrued to the combined California and Northwest region), with resource cost savings offsetting higher transmission investment costs.

Electricity transmission wires. Photo credit: Emilian Robert Vicol, Pixabay

FIGURE 24. The Increased Northwest-California Transmission Case means that the Northwest builds more wind and less solar relative to the Central Case.

Change in New Resource Build (MW)

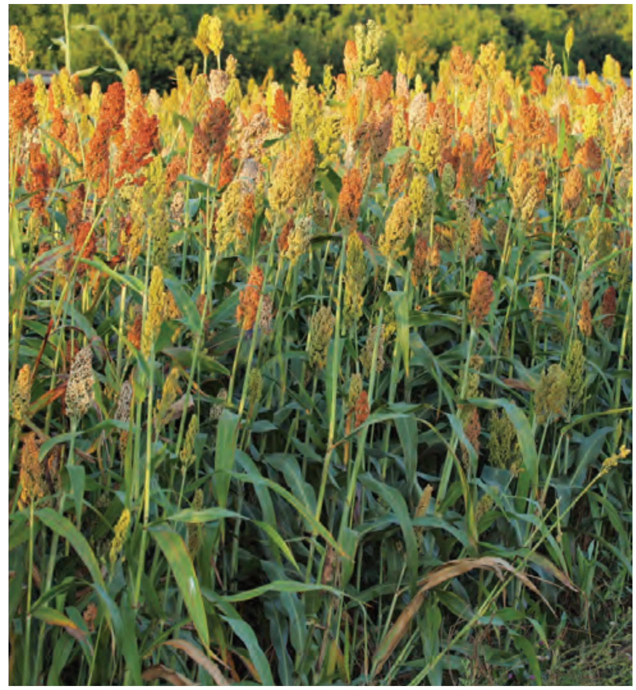


Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 90.

Limited Biomass Available for Liquid Fuels Case

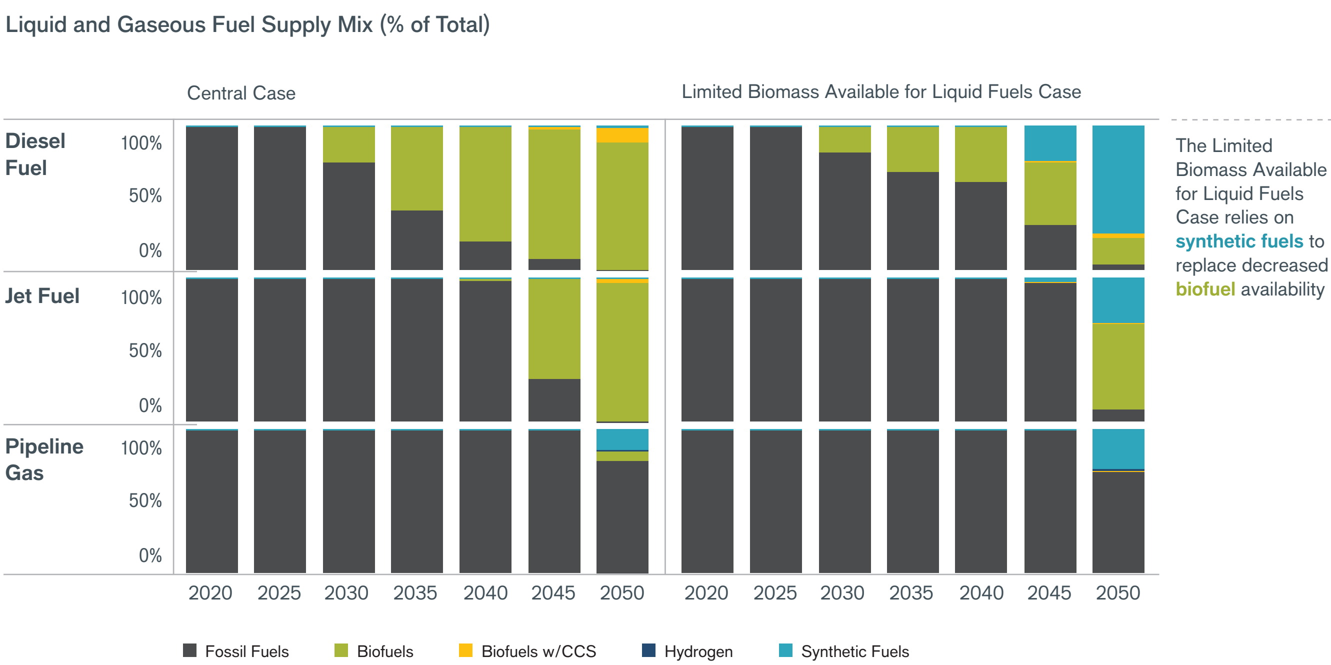
The Limited Biomass Available for Liquid Fuels Case addresses concerns about biomass availability, particularly crops grown expressly for energy. In this case, each state's bioenergy potential is restricted to in-state waste and its population-weighted share of regional wood. This constraint results in an overall biomass supply that is 60% less than the Central Case biomass assumptions.

Figure 25 shows how the fuel supply mix evolves over time for diesel fuel, jet fuel, and pipeline gas. The Limited Biomass Available for Liquid Fuels Case relies on synthetic fuels (seen in teal) to replace the lost biofuels (seen in green) present in the Central Case. The diesel fuel supply mix is impacted the most, shifting from almost 100% biofuels in the Central Case to predominantly synthetic fuels in the Limited Biomass Available for Liquid Fuels Case, which are more expensive.



Sorghum field. Photo credit: Hermann Falkner

FIGURE 25. The Limited Biomass Available for Liquid Fuels Case requires more expensive fuel sources.



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 91.

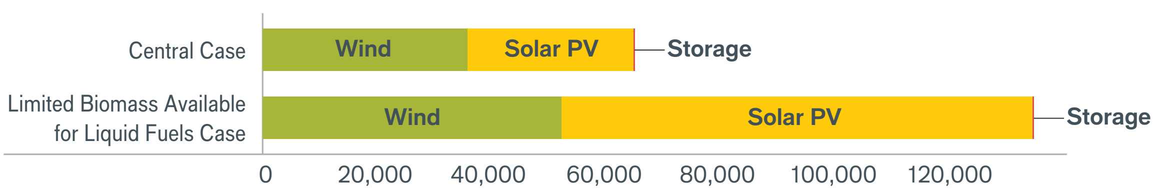
Producing high volumes of synthetic electric fuels to replace biofuels means building considerably more infrastructure, including two times the installed capacity of wind and solar resources, five times the requirement for electrolysis capacity, and six times the direct air capture capacity.

Hence, on top of the 40 gigawatts of new onshore wind and 35 gigawatts of solar PV already built in the Central Case, substantial investments in generation to power synthetic gas production would be required to offset the lack of biofuels. (See Figure 26 to understand the infrastructure implications of a constrained biomass supply.)

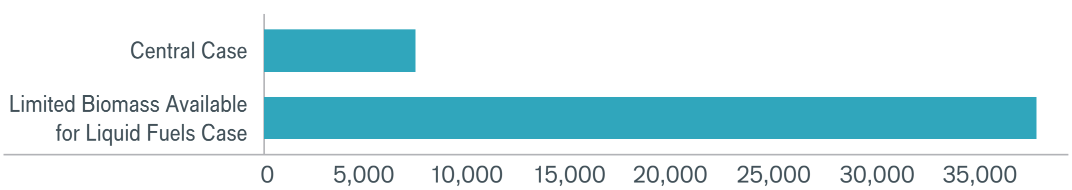
Biofuels work at Argonne. Photo credit: Argonne National Laboratory

FIGURE 26. The substantial infrastructure implications of the Limited Biomass Available for Liquid Fuels Case.

Renewables: Installed Capacity, 2050 (MW)



Hydrogen Electrolysis, 2050 (MW)



Direct Air Capture, Total Capacity, 2050 (MMT per year)

Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 92.

Pipeline Gas Used for Freight Vehicles Case

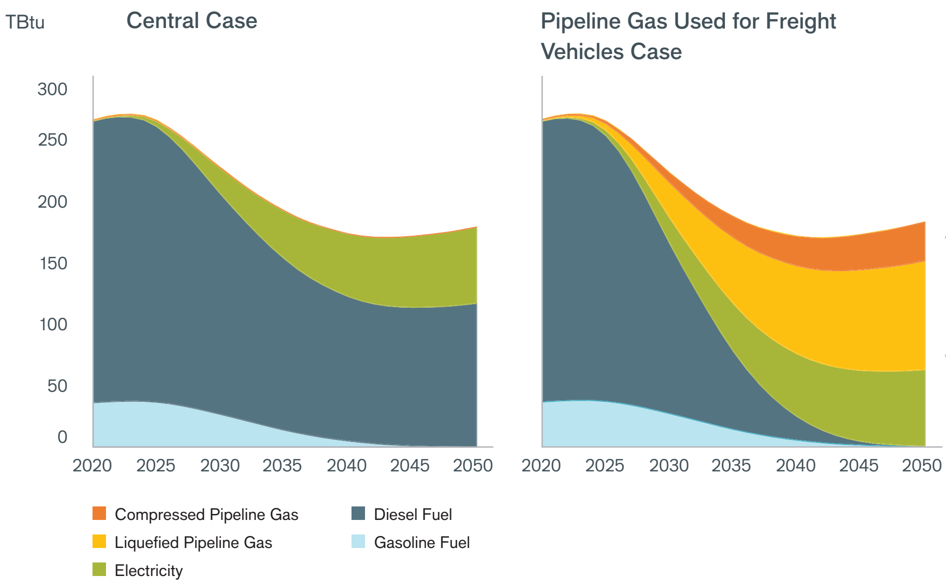
The freight vehicles in the Central Case that are not electric are diesel hybrid vehicles and in the Pipeline Gas Used for Freight Vehicles Case, compressed and liquefied pipeline gas substitute for diesel hybrid vehicles. Specifically, the Central Case assumes that medium-duty vehicles (MDVs) are 60% battery electric and 40% are diesel hybrid vehicles. In the Pipeline Gas Used for Freight Vehicles Case, the same number of MDVs are electric, but the remaining 40% of MDVs are powered by compressed natural gas.

Similarly, the 40% of heavy-duty trucks (HDVs) in the Central Case that are electric remain electric in the Pipeline Gas Used for Freight Vehicles Case, while the remaining 60% of HDVs are fueled by liquefied natural gas. Compressed and liquefied pipeline gas make up approximately two-thirds of freight truck final energy demand by 2050 as Figure 27 shows.

United Parcel Service truck fuels with compressed natural gas.
Photo credit: U.S. Department of Energy

FIGURE 27. Final energy demand for medium-duty and heavy-duty vehicles in the Central Case vs. the Pipeline Gas Used for Freight Vehicles Case.

FINAL ENERGY DEMAND: MDV AND HDV



Change in Model Input Assumptions: Increased sales share of CNG and LNG trucks results in compressed and liquefied pipeline gas making up approximately two-thirds of freight truck final energy demand by 2050

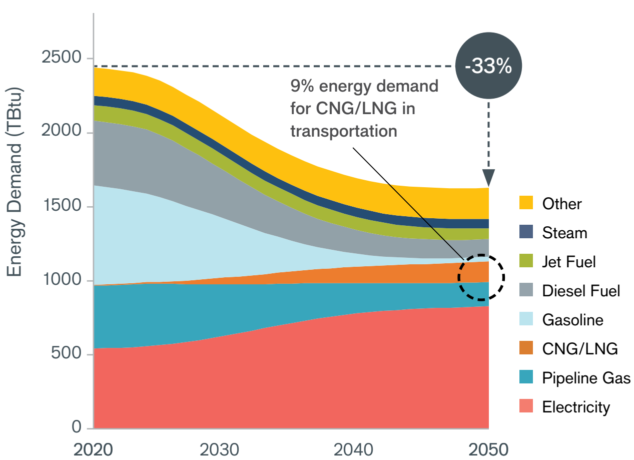
Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 58.

Compressed and liquefied pipeline gas are nearly 10% of end-use demand by 2050 in the Pipeline Gas Used for Freight Vehicles Case, with half of freight trucks consuming compressed or liquefied gas. Demand for diesel fuel is further reduced relative to the Central Case. (See Figure 28.)

As Figure 29 shows, freight trucks in the Pipeline Gas Used for Freight Vehicles Case consume more pipeline gas, which is supplied by increasing biofuels to pipeline gas and decreasing biofuels to diesel fuel. The main impact across energy systems in the Pipeline Gas Used for Freight Vehicles Case is the reallocation from liquid fuels to gaseous biofuels, as Figure 29 indicates.

Important Note: The study does not take into account the carbon emissions from methane leakage or upstream emissions in the production of natural gas. Hence, the carbon benefit in the Pipeline Gas Used for Freight Vehicles Case is likely over-estimated and further study is required to investigate higher carbon emissions in the production and transport of pipeline gas.

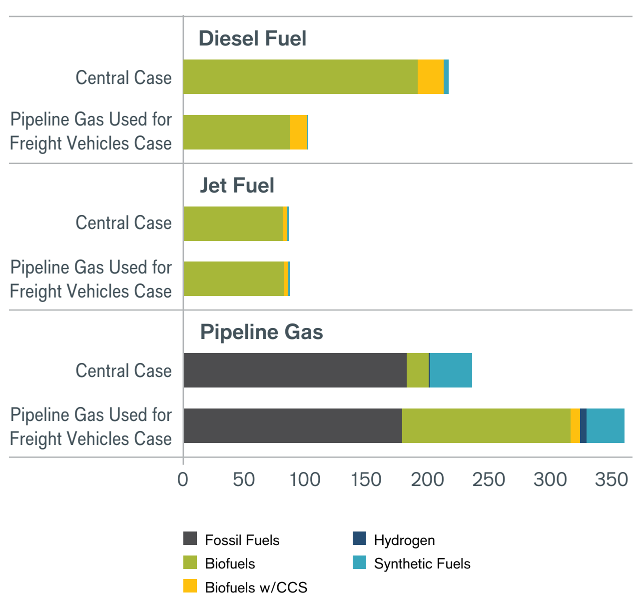
FIGURE 28. Final energy demand in the Pipeline Gas Used for Freight Vehicles Case is down 33%, with compressed and liquefied pipeline gas constituting 9% of end-use demand in 2050.



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 94.

FIGURE 29. The changes in the liquid and gaseous fuel supply mix in the Central Case vs. the Pipeline Gas Used for Freight Vehicles Case.

Liquid and Gaseous Fuel Supply Mix, 2050 (TBtu)



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 95.

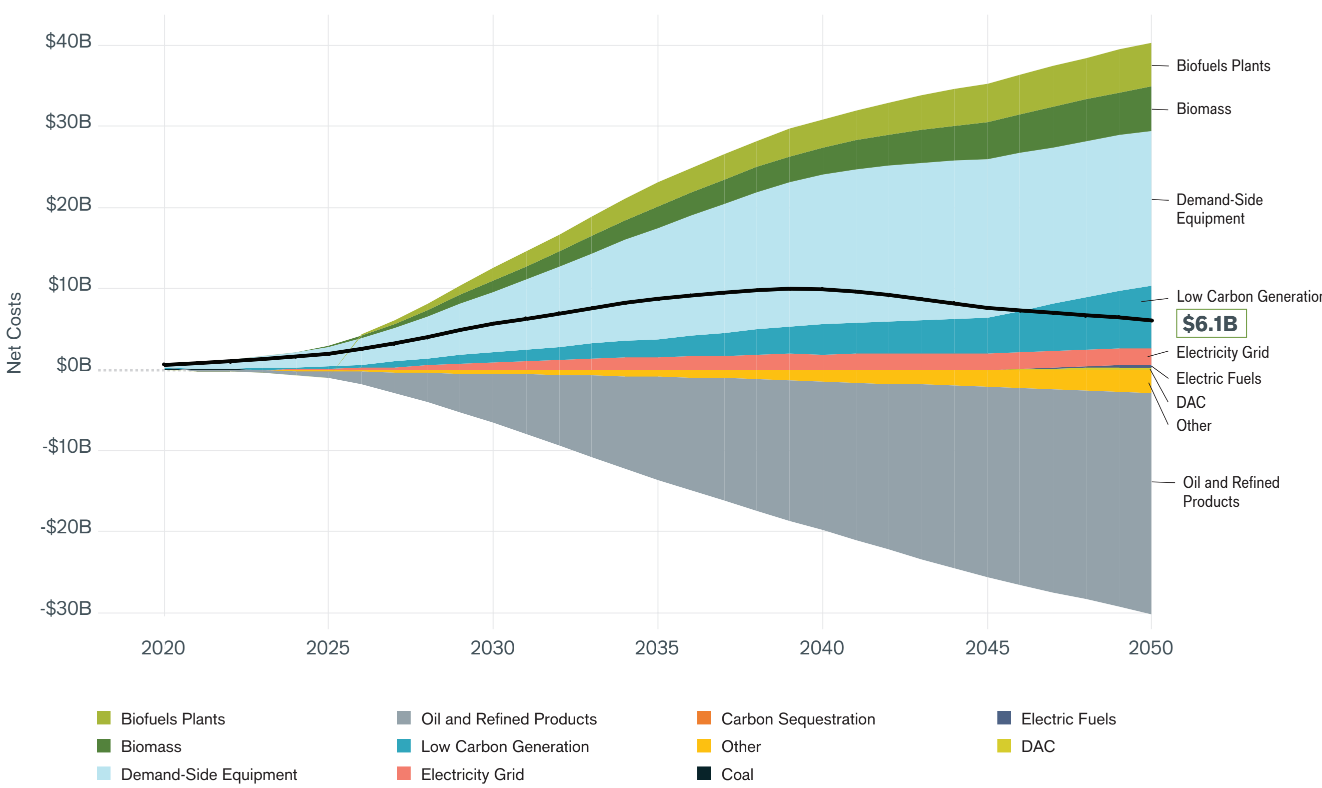
Costs

The scope of costs in this study is limited to energy system costs, which represent the annual cost of producing, distributing, and consuming energy. This study considered the annualized capital costs of equipment (both supply and demand), fixed and variable operations and maintenance (O&M) costs, and fuel costs. (See Appendix C for details on the cost assumptions used in this study.) The study excludes costs outside of the energy system or benefits from avoiding climate change and air pollution.

The study compares the annual costs of the Business as Usual Case and the Central Case from 2020 to 2050. Net annual costs of the Central Case vary over the modeled period based on the timing of infrastructure investments, peaking at 16.1% ($9.8 billion) above the Business as Usual Case in 2038 and decreasing to 8.3% ($6.1 billion) higher than the Business as Usual Case in 2050. The cumulative costs of decarbonizing the energy system in the Central Case are 9.5% higher than the capital and operating expenses of the Business as Usual Case's energy system, roughly 1% of the region's total GDP in 2017 of more than $870 billion. (See Figure 30.)

The increased costs in a decarbonized system consist primarily of biofuel feedstocks and infrastructure, demand-side electrification and efficiency investments, and renewable power plants and supporting electricity infrastructure. These increased costs are mitigated by the savings from decreased fossil fuel use, primarily expensive liquid petroleum products.

FIGURE 30. Annual net energy system costs for the Central Case relative to the Business as Usual Case 2020–2050.



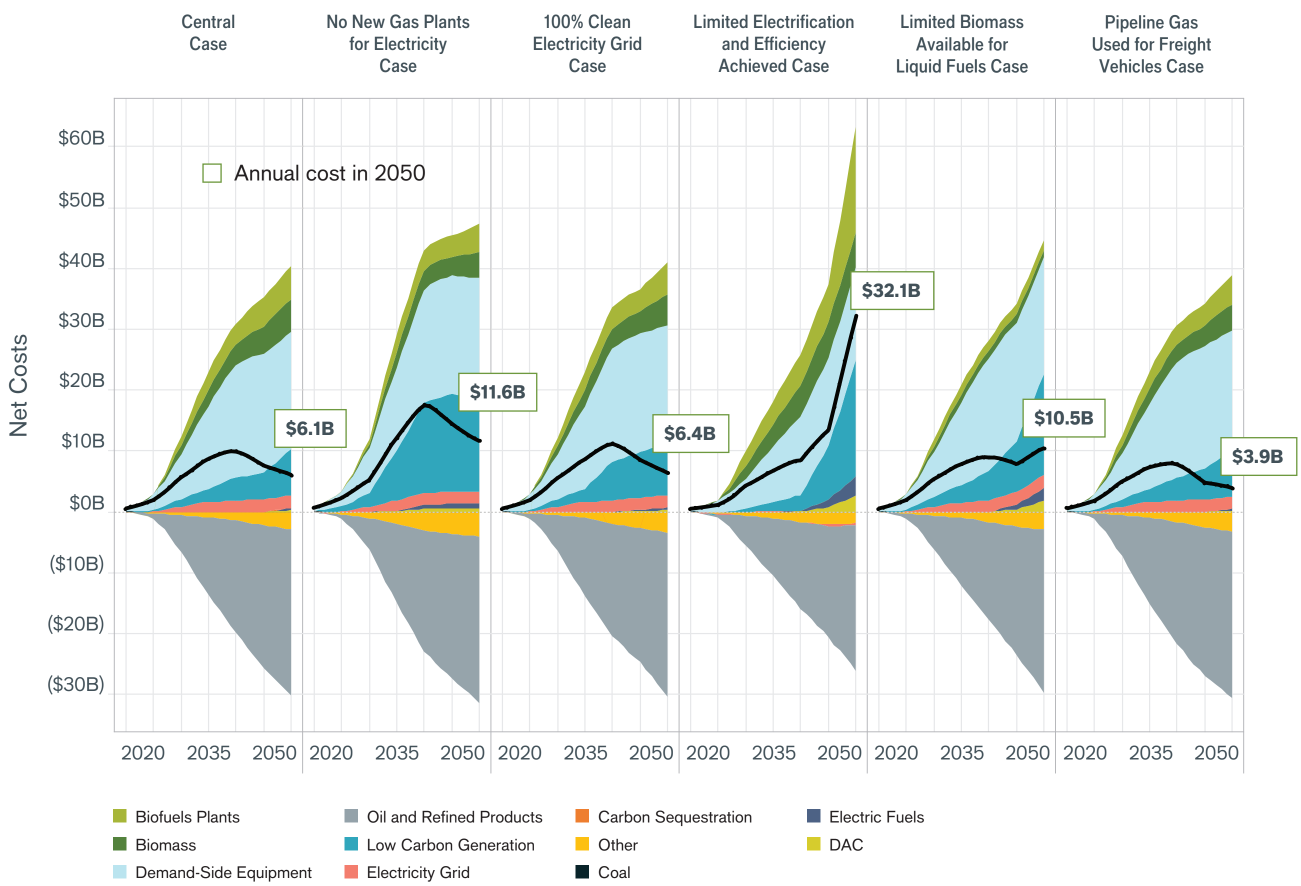
Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 106.

In Figure 31, the black line shows the net annual energy system costs as the difference in cost between each of the cases (except the Increased Northwest-California Transmission Case) and the Business as Usual Case. The stacked areas show the differences in investment by category between each case and the Business as Usual Case. Investments in additional clean energy measures (positive cost differences) are offset by avoided fuel purchases (negative cost differences).

The most impactful sensitivities in terms of net system costs include prohibiting new gas assets, not achieving demand-side transformation, and constrained biomass. Because 100% clean electricity has only a marginal change from the Central Case, it has minimal impact on costs.

City of Eugene, Oregon, transit service. Photo credit: City of Eugene, Oregon

FIGURE 31. Annual net energy system costs for six cases compared to the Business as Usual Case.



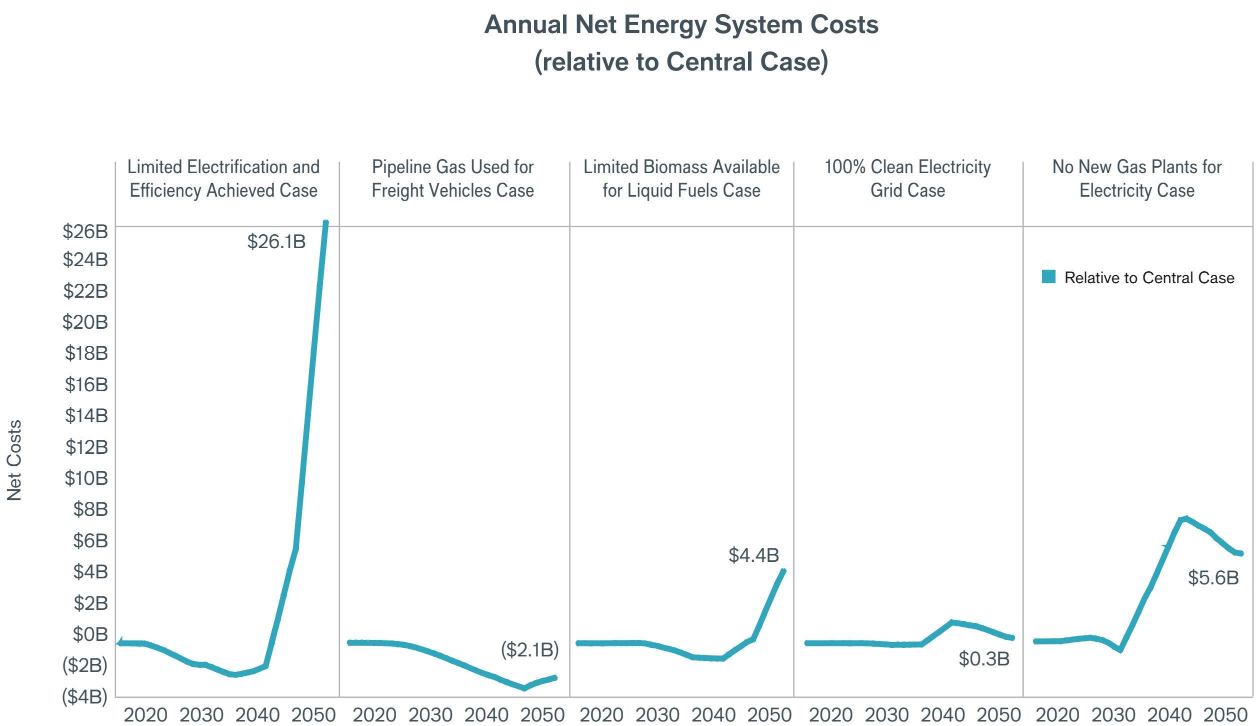
Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 107

Increased gas in transportation allows access to a lower-emissions/lower-cost fossil fuel than diesel, but as previously noted, this result does not consider the carbon emissions of methane leakage, so its lower cost must be viewed in light of its uncounted higher carbon emissions. Further, there are technical challenges with using pipeline gas for heavy-duty trucks. (See Figure 32.)

Most cases show a slight increase in household expenditures in the 2030 time frame—roughly $25 per month. But by 2050, most cases show small monthly savings, due to the increasing cost-effectiveness of electric vehicles and the elimination of gas costs.

Fort Dix solar panels. Photo credit: U.S. Army Environmental Command

FIGURE 32. Annual net energy system costs for the cases (not including the Business As Usual Case and the Increased Northwest-California Transmission Case) relative to the Central Case.



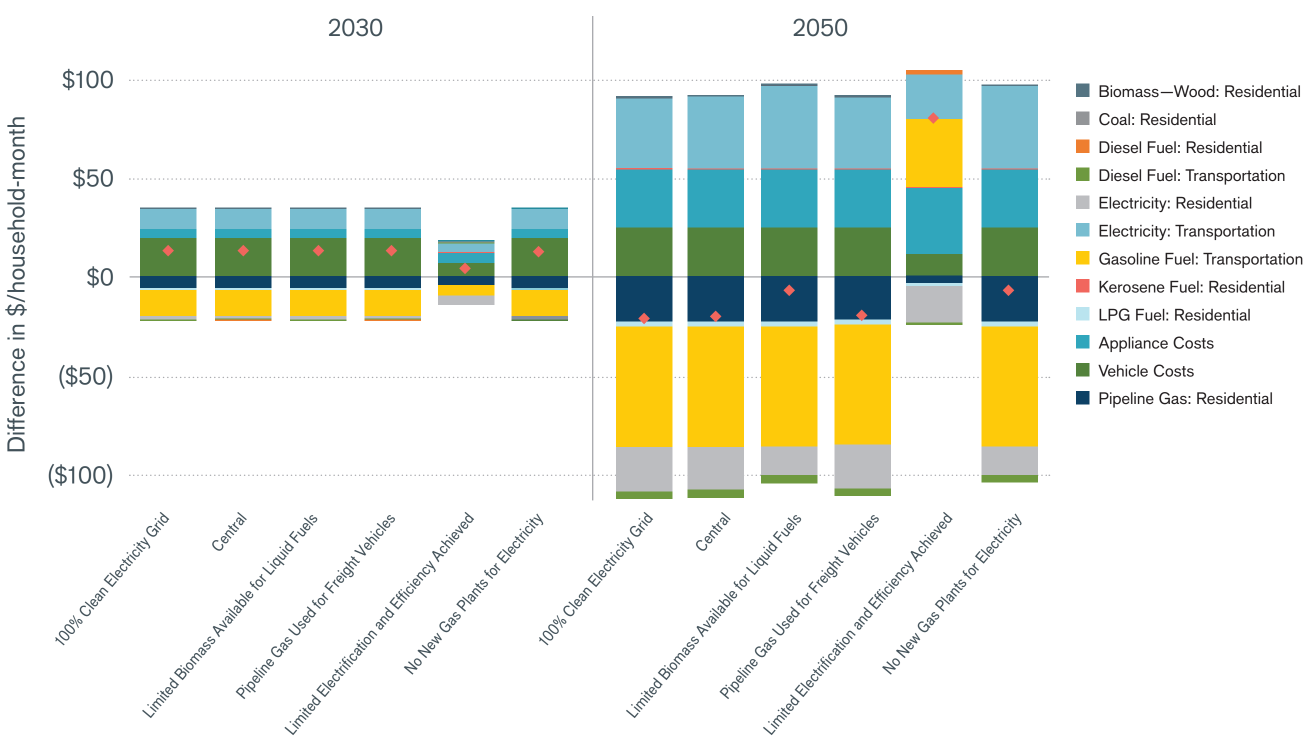
Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 108.

The Limited Electrification and Efficiency Achieved Case has the lowest cost in the 2030 time frame as it does not have to incur as much in incremental costs for electric vehicles and other electrified appliances. But by 2050, limited electrification necessitates huge investments in electric sector infrastructure for electrolysis and direct air capture to produce electric fuels and biofuels to offset the increased fuel usage, driving up costs. (See Figure 33.)

In 2050, the average cost of avoided carbon in the Central Case is $48/tonne and declining. The model makes conservative assumptions about the costs and scalability trends of clean energy technologies. A future report will explore in greater depth details on costs and emissions reductions, the assumptions that returned these results, and what these results mean for how the Northwest should consider investing in transitioning the region to a low-carbon economy.

2016 Chevrolet Volt. Photo credit: Green Energy Futures, David Dodge

FIGURE 33. Residential cost impacts across six cases.



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 109.

STUDY CONCLUSIONS AND CASE COMPARISONS

Aerial view of the Cascade Range. Photo credit: Clean Energy Transition Institute

Study Conclusions and Case Comparisons

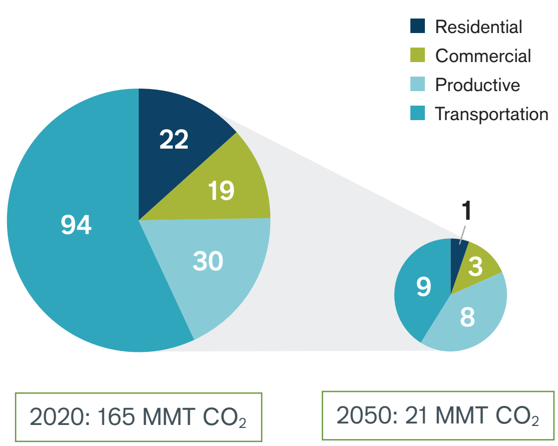
The results of *Meeting the Challenge of Our Time: Pathways to a Clean Energy Future for the Northwest* demonstrate the feasibility of Northwest states to achieve deep decarbonization by mid-century, even if we postulate several potential implementation challenges, such as lower levels of electrification and constraints on biomass availability.

This study incorporates several new and unique analytical approaches to assess deep decarbonization in the Northwest, including developing cost-optimal energy supply portfolios, incorporating new electric loads (direct air capture, fuel production, steam production), and accounting for changing dynamics outside of the region (California energy policy).

The study's Central Case is a flexible pathway to achieve emissions reductions, and highlights several key findings:

- Electricity generation approaches 100% clean.
- Aggressive electrification on the demand side is required, particularly in the transportation and building sectors. All passenger transportation is electric by 2050.
- Biomass is primarily allocated to jet fuel and diesel fuel even after partial electrification of freight trucks.
- Flexible electricity demand, notably from facilities that produce hydrogen and synthetic gas, plays a large role in electricity balancing and energy system–wide carbon mitigation.

FIGURE 34. Comparison by sector of Northwest CO_2 emissions decrease from 2020 to 2050 in the Central Case.

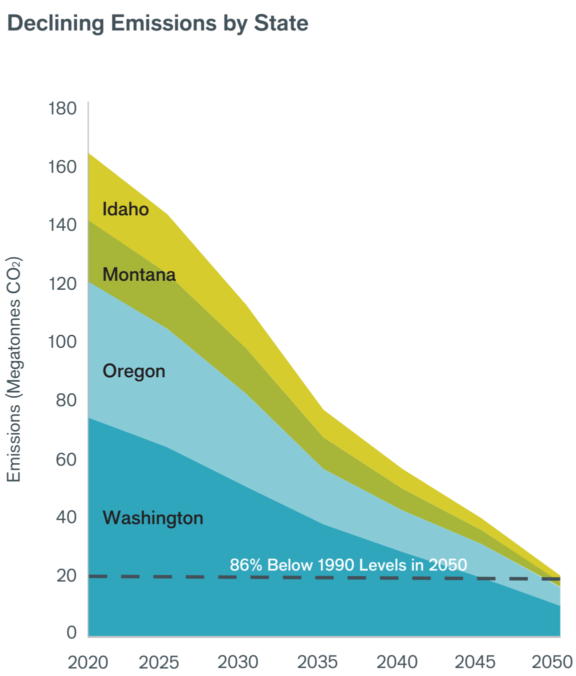


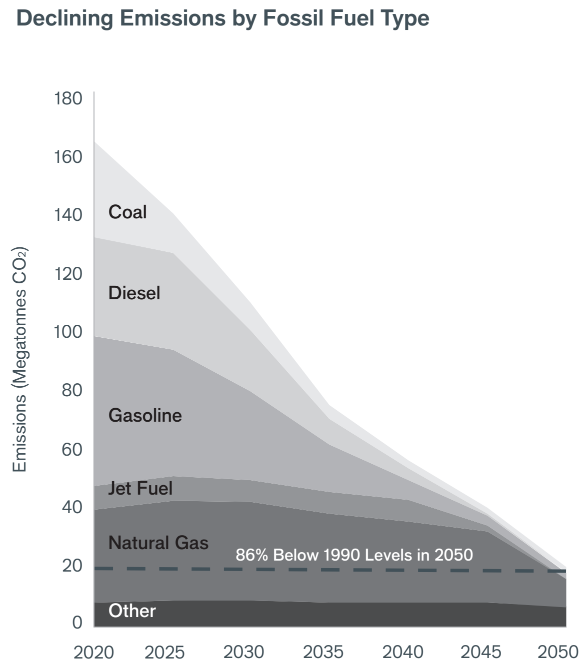
Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 63.

Northwest CO_2 emissions decrease in the Central Case from 165 million metric tons (MMT) in 2020 to 21 MMT in 2050. Emissions in the residential sector decline by 95%; in the commercial sector by 86%; in the productive (industrial) sector by 72%; and in the transportation sector by 91%. Relatively inexpensive abatement measures for the built environment (residential and commercial sectors) and transportation enable a greater percentage of emission decreases for those sectors. The difficulty and expense of decarbonizing industrial end uses explains the increase in the productive sector. (See Figure 34.)

Figure 35 shows the emissions decline from 2020 to 2050 by each state, as well as by fossil fuel type. These emission reductions are achieved through five key decarbonization strategies: energy efficiency; decarbonizing electricity; decarbonizing gas and liquid fuels; fuel-switching in industry, transportation, and buildings; and carbon capture. The cost of achieving these reductions is offset by avoided fossil fuel purchases.

FIGURE 35. Declining emissions by state and by fossil fuel type 2020–2050.





Nissan LEAF license plate. Photo credit: Washington State Department of Transportation

Five Key Decarbonization Strategies

Transitioning the Northwest to a low-carbon energy system relies on five decarbonization strategies:

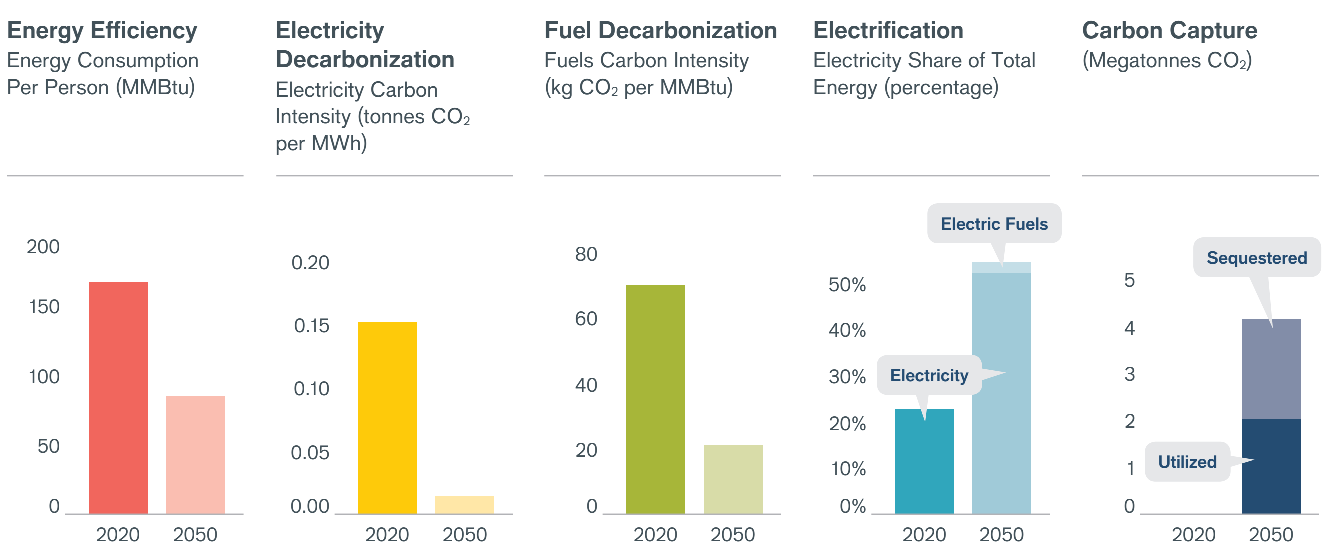
1. **Energy Efficiency:** reducing energy consumed to provide an energy service
2. **Electricity Decarbonization:** reducing the emissions intensity of electricity generation
3. **Fuel Decarbonization:** reducing the emissions intensity of liquid and gaseous fuels
4. **Electrification:** switching end uses from fuel to electricity
5. **Carbon Capture:** capturing CO_2 from a facility or removing CO_2 from the atmosphere

The purpose of the fifth strategy, carbon capture, is twofold: the captured CO_2 can either be used as a carbon feedstock for electric fuel production or sequestered.

Figure 36 shows metrics for the five strategies in the Central Case. Per capita energy consumption decreases from approximately 170 MMBtu per person today to 85 MMBtu per person in 2050, a 50% decrease. The average carbon intensity of electricity generation, which is already relatively low in the Northwest due to the hydroelectric system, decreases to near-zero by 2050.

The carbon intensity of fuels (liquid and gas) decreases by 70% primarily using biofuels. The share of total final energy served by electricity or electrically produced fuels (e.g., hydrogen and synthetic natural gas) more than doubles from approximately 23% today to 55% in 2050. Four million metric tons of CO_2 are captured in 2050, with about half of the CO_2 being utilized to produce synthetic fuels and the other half being sequestered (e.g., in saline aquifers in Montana).

FIGURE 36. Five decarbonization strategies.



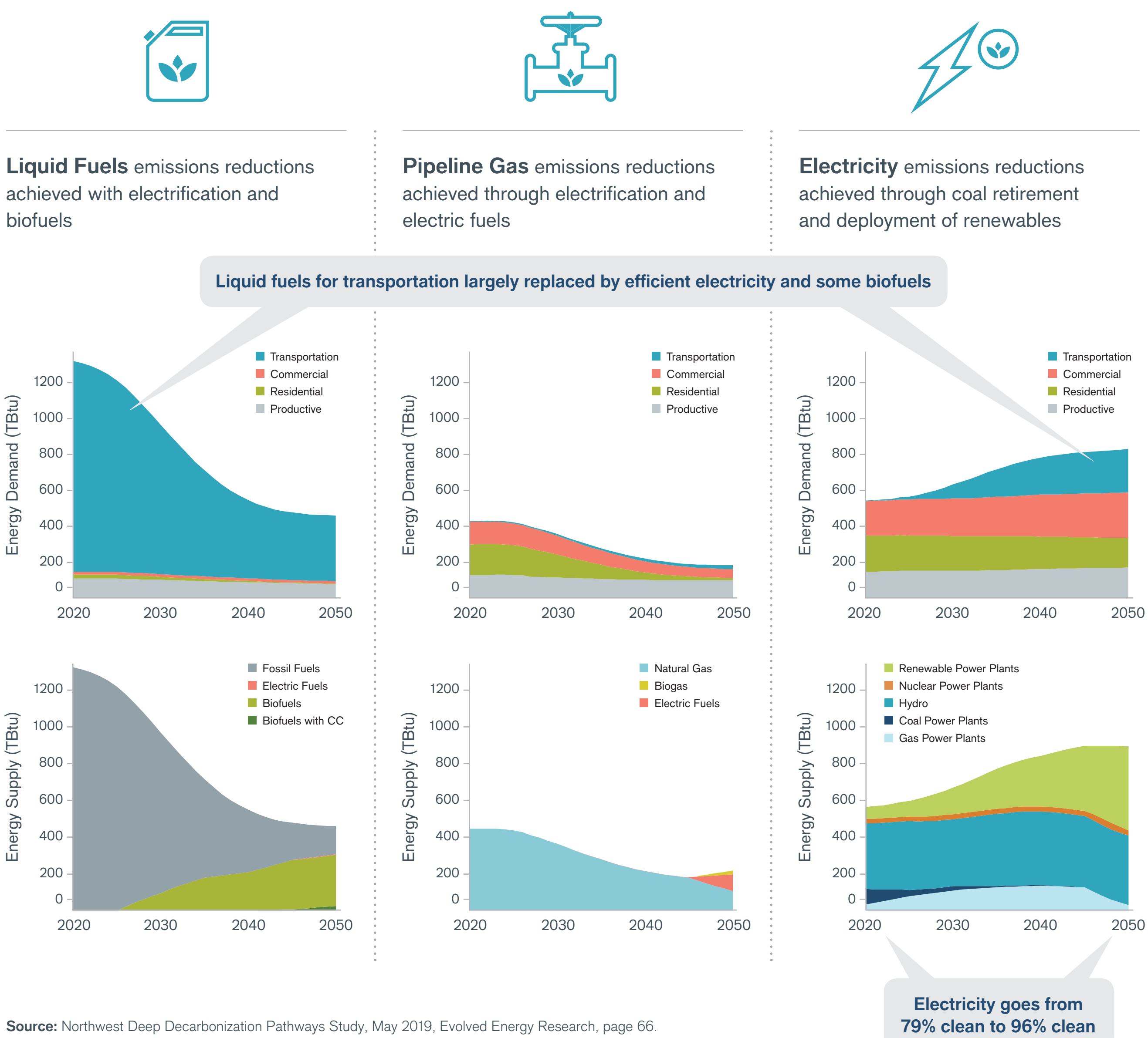
Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 65.

Figure 37 combines all of the results of the Central Case in one graphic to show the changes in energy demand and supply for the three energy sources—liquids, gas, and electricity—from 2020 to 2050 by sector. The right-hand side of the graphic shows the overall emissions decrease by energy source over the 30-year period of the study, demonstrating the significant drop in the carbon intensity of liquid fuels.

The graphic clearly shows the critical role of electrification for all three sources. Electrification decreases liquid fuel and gas demand for the transport, building, and productive (industrial) sectors. The increased demand for electricity across the sectors is also displayed.

On the supply side, biofuels, along with synthetic liquids produced with clean electricity, significantly reduce the carbon intensity of liquid fuels, while synthetic gas decarbonizes pipeline gas. Coal retirement and renewable deployments decarbonize the electricity supply. Overall demand and supply for clean electricity increase substantially.

FIGURE 37. Central Case emissions reduction for liquid fuels, gaseous fuels, and electricity from 2020 to 2050.



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 66.

Study Highlights

Critical Role of Electricity

Clean electricity is the backbone for deep decarbonization, and the cross-sectoral role that electricity will play in the coming decades is vital to achieving a low-carbon future. A clean grid decarbonizes all existing electricity uses, including industrial processes powered by electricity and buildings heated and cooled by electricity in the years to come.

In the low-carbon energy future, clean electricity must include electrifying as many transportation operations as possible to replace petroleum-generated liquid fuels, as well as substitute for the oil and natural gas that heats and cools buildings.

Electrifying the Northwest transportation sector is critical to achieving deep decarbonization and provides the least-cost path to reducing fossil fuels in transportation. Hence, the interactions between the fuel and electricity sectors in long-term planning processes is paramount.

Electricity Sector Insights

The difference between the 100% Clean Electricity Grid Case and the Central Case is much smaller than anticipated, where a nominal quantity of additional synthetic fuels and biofuels is needed to bridge the gap. Economy-wide decarbonization involving the fuel supply sectors and not just the electricity grid brings two benefits that make it easier to attain 100% clean electricity. First, flexible electric fuels increase load flexibility and make balancing the electricity system easier, and second, the clean synthetic gas that is produced can be used to generate electricity during challenging system-balancing conditions.

In addition, California's 100% clean electricity requirement encourages the Northwest to export power to California that would otherwise be curtailed, thus giving that resource economic value, and makes it possible for there to be fewer requirements for California to build storage or additional resources to balance its California grid.

Significant cost savings ($11.1 billion in net present value from 2020 to 2050 accrued to the combined California and Northwest region) could be realized if interties between the Northwest and California were expanded (Northwest-California Transmission Case). But further investigation is required to understand the benefits fully.

Prohibiting new gas plants (No New Gas Case) would require additional energy storage and renewable generation facilities to provide reliable supply. Electric fuels using excess renewables implement this pathway, which would otherwise involve a large amount of curtailment, but at a significantly higher cost than the Central Case.

New Sources of Clean Electric Fuel

Emerging technologies that can deploy hydrogen, carbon capture, and synthetic gas to create very low-carbon fuels will be important in the out-years. Clean electric fuels can be produced using renewable electricity. Splitting water molecules through electrolysis produces hydrogen that can constitute up to 7% of the gas in pipeline gas or be used as a feedstock in other processes. Combining that feedstock with carbon dioxide can create synthetic gas or liquid fuels that are as clean as the energy used to produce them.

Carbon dioxide as a feedstock can be captured via industrial waste streams, direct air capture, or from biorefineries that use carbon capture. Synthetic gas can be used for either heating or cooling instead of natural gas, or for powering transport as compressed liquefied gas, while synthetic liquid fuels can substitute for conventional transportation fuels.

Flexible Electric Loads

The study highlights the important cross-sectoral role that new technologies and flexible electric loads could play in making economic use of renewable overgeneration and with balancing the grid in two key ways. First, the Northwest's reliance on hydroelectric and wind resources means that periods of sustained overgeneration may become common. This is a component of a least-cost decarbonized energy economy. However, when considering all possible system-balancing options, it is important to limit costs. Electric storage solutions, outside of limited pumped hydro, do not yet economically address long-duration balancing and system reliability when renewable energy production is low.

The mismatch between load and intermittent supply and the subsequent curtailment of generation is a lost opportunity to use that energy to decarbonize the economy. Hence a key challenge is how to minimize the costs of a deeply decarbonized, intermittent, renewable-dominant system, recognizing the many cross-sectoral opportunities that exist at high levels of decarbonization.

Transmission lines. Photo credit: Mike Wilson

Electricity that would otherwise be curtailed is put to good use when the electricity system is integrated with fuels production for the rest of the energy economy, and electric loads can more flexibly respond to levels of renewable production. Gas and liquid transportation fuels can be stored far more cheaply than energy in electrochemical storage and large quantities of storage for these fuels exist today.

The lowest-cost pathways to deep decarbonization include electric fuels production, moderating the variability in intermittent renewables by increasing production in periods with high renewable and hydro output, and decreasing production during periods of low output.

Second, Northwest grid planners need to address the challenge of interannual variability in hydroelectric and wind resources. Achieving high percentages of renewables is a fundamentally different challenge in years of low hydro and wind production than in high hydro and high wind years.

Several nontraditional solutions exist for electricity balancing: electrolysis that uses renewable overgeneration to produce hydrogen, steam production with electric boilers, and direct air capture technologies that supply energy or feedstocks for synthetic gas. Models and approaches that don't incorporate this sectoral integration and the potential for this portfolio of solutions tend to be suboptimal, as they result in higher cost for renewables systems and large amounts of unused energy.

Limited Thermal Generation Needed

The inverse of overgeneration in high-renewables systems is rare periods of undergeneration, when hydro and other renewable energy production is diminished, typically during the winter. Renewable diversity and regional integration could help address this issue, while storage can be used for short (4- to 8-hour) periods of undergeneration.

These rare undergeneration events are most economically served by thermal generators that operate only for a very limited number of hours each year and can be fueled by biofuels, electric fuels, or fossil gas depending on policy design. In the study, gas and storage are added as new resources to provide resource adequacy and balancing, and the share of gas-fired generation is 3.7% in 2050.

Role for Carbon Capture

In modeling regional 80% of 1990 levels by 2050 emissions targets, it is important to note the long-term role of carbon capture, either for high-capacity factor biofuels facilities or in the use of direct air capture facilities. This captured carbon may be used to provide a feedstock for power-to-fuels production or directly sequestered.

The study does not project a significant use of carbon capture and sequestration in the Northwest's power sector (where the role of carbon capture has traditionally been most closely examined), due to the low-capacity factors at which thermal generators would operate in highly renewable systems.

Carbon capture and sequestration infrastructure is expensive, and low utilization makes it too costly to be part of a least-cost resource solution. As carbon reduction targets become even more stringent—with some even contemplating net-zero emissions futures—developing this technology will become more important.

Regional Electricity Collaboration

Understanding California's electricity policy landscape is critical for cost-effective electricity planning in the Northwest. California lacks non-solar renewable resources and requires off-peak renewable energy to meet its 100% clean electricity goal, which is driving renewables development across the Western grid.

The Northwest has an opportunity to create a complementary resource portfolio to meet California's clean energy needs. Expanding interconnection capacity to California would allow greater integration of resources, relieving California's overgeneration conditions and enabling the Northwest access to higher-quality California solar than what can be produced regionally.

Demand-Side Electrification and Biomass

Failure to electrify on the consumer side has enormous implications for energy supply, as depicted in the Limited Electrification and Efficiency Achieved Case. The scale of new wind, solar, direct air capture, electrolysis, and power-to-X facilities in this case (see Appendix B for a description and graphic of power-to-X) could be considered prohibitive in implementation and may ultimately require imports of electric fuels produced elsewhere.

Restricted availability of net-zero-carbon biomass as in the Limited Biomass Available for Liquid Fuels Case results in similar energy system impacts. If consumers don't electrify or biofuels are not available, then the "backstop" resource to decarbonize is synthetic electric fuels, which may face implementation challenges to develop at the necessary scale and are expensive.

Power County wind farm, Idaho. Photo credit: U.S. Department of Energy

Cross-Case Comparisons

Significant Positive Benefit Case

Expanded interties between the Northwest and California change the optimal electricity supply mix, with each region avoiding the development of local, low-quality renewables and expanding the development of high-quality resources that are more efficiently shared across both areas. The Northwest avoids developing low-quality solar and increases wind development, while California develops additional high-quality solar and avoids procuring remote wind generation from other Western states. Savings are estimated as $11.1 billion net present value over the 30 years of the study (accrued to the combined California and Northwest region).

Significant Negative Impact Cases

In the Limited Electrification and Efficiency Achieved Case, where deep electrification of building, transport, and industry does not occur, there are large volumes of residual liquid fuel demand for diesel fuel, jet fuel, and gasoline in the system. This necessitates squeezing the use of gas-fired resources out of electricity generation to reduce emissions as much as possible in non-transportation sectors, and substantially ramps up direct air capture. While 2 million metric tons (MMT) are captured in 2050 in the Central Case, the Limited Electrification and Efficiency Achieved Case requires 27 MMT of carbon to be captured in 2050.

In the No New Gas Plants for Electricity Case, more than 35 gigawatts of additional wind, solar, and geothermal resources are required—on top of the 75 gigawatts of new renewables built in the Central Case. In addition, 12 gigawatts of additional energy storage resources are needed to maintain resource adequacy. This higher penetration of renewables and associated overgeneration incentivizes the production of additional electric fuels, in the form of power-to-diesel and power-to-jet-fuel.

When biomass is constrained, high volumes of synthetic electric fuels must be produced to replace biofuels. This has considerable infrastructure implications, including two times the installed capacity of wind and solar resources, five times the electrolysis capacity, and six times the direct air capture capacity than what is needed in the Central Case.

Poplar harvest and swallows. Photo credit: Marcus Kaufman

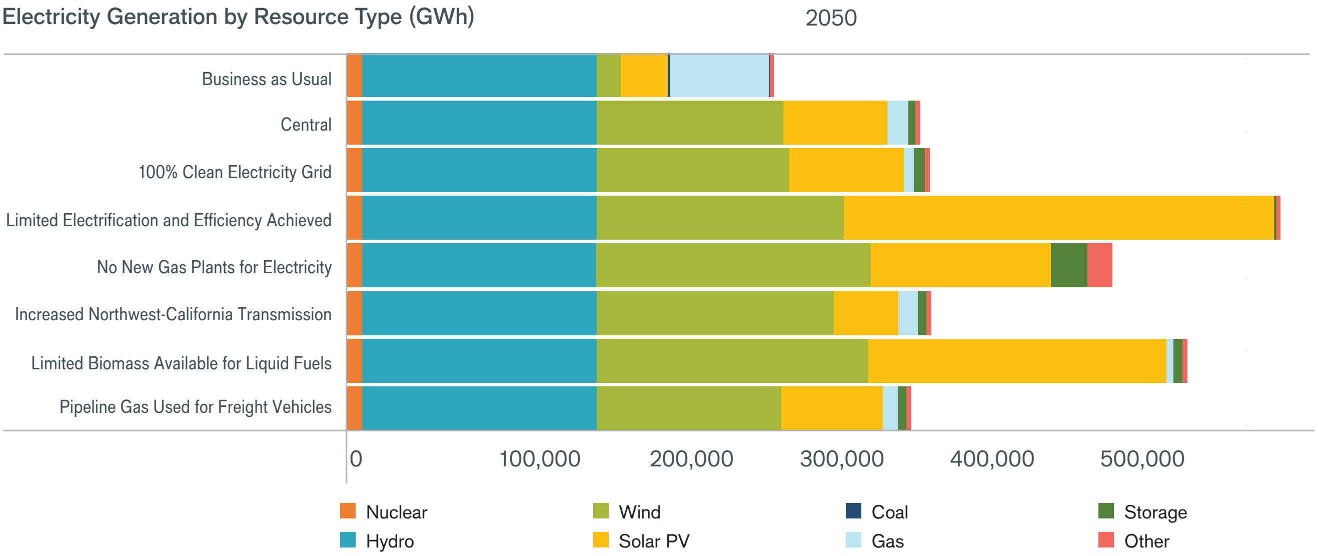
Marginal Impact Cases

The 100% Clean Energy case produces marginally different results from the Central Case. The share of gas-fired generation decreases from 3.7% to 1.7%, due to incremental renewables and energy storage deployment. Decarbonized pipeline gas supply (biofuels, hydrogen, and synthetic natural gas) covers all gas demand from power generation, and most of the incremental decarbonized pipeline gas is from synthetic gas.

Increasing gas in transport also has limited impact, but the study did not account for upstream methane leakage, so this result comes with a significant caveat. Freight trucks consuming higher pipeline gas means biofuels are not used to substitute for diesel fuel and are available for pipeline gas. This means minimal impacts across the energy system other than that reallocation from liquid biofuels to gaseous biofuels. But this case would be far less salutary if the full carbon accounting for methane leakage were considered.

Figure 38 combines all eight cases in one graphic to show the quantity and type of electricity generation (in GWh) required to achieve deep decarbonization in 2050.

FIGURE 38. There are significant impacts on total electricity generation for the Limited Electrification and Efficiency Achieved Case, Limited Biomass Available for Liquid Fuels Case, and No New Gas Plants for Electricity Case.



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 99.

Geyser Basin, Yellowstone National Park. Photo credit: Clean Energy Transition Institute

Conclusion

A principal goal of this deep decarbonization pathways study was to represent potential energy futures in enough technical detail to be used as blueprints to develop a future of the Northwest's choosing. There are several areas of additional examination that the study suggests pursuing.

Focus on Equity. This study is designed to show the trade-offs between different deep decarbonization pathways, but it does not take into account equity considerations for different communities. The study demonstrates we can decarbonize our economy, but the critical work ahead must focus on how to do so equitably.

Areas for Further Study. Understanding the dynamics of alternative fuel development on refinery activity and relative fuel prices is important for the Northwest. While it might be possible to predict the decline of certain fuels as electrification increases in buildings and transportation, the development of biofuels or electric fuels that also displace fossil fuels may be more challenging to foresee. This is an unanswered question in almost all deep decarbonization transformations and developing long-term strategies today could mitigate the clean energy transition's disruptive impacts and avoid unnecessary investments.

This study examined low, normal, and high hydro years; however, it held the likelihood of experiencing these hydro conditions constant through 2050 and did not consider even lower future water years, assumptions that require examination. Follow-on work should involve a scenario in which lower snowpack occurs more frequently, and seasonal dynamics are altered due to climate change.

Sensitivity analyses are needed to understand how a 10% to 20% lower hydro resource would impact other resources, as well as how removing the Lower Snake River dams and retiring the nuclear Columbia Generating Station before 2043 would affect clean power supply. Finally, a combination of all three of these changes in low-carbon resources should be modeled together.

Modeling the retirement of all coal-fired electricity generation by 2030 is an additional area for study, as is modeling natural gas at higher prices than the study assumed and, if possible, modeling natural gas with a higher emissions level to account for upstream emissions and methane leakage.

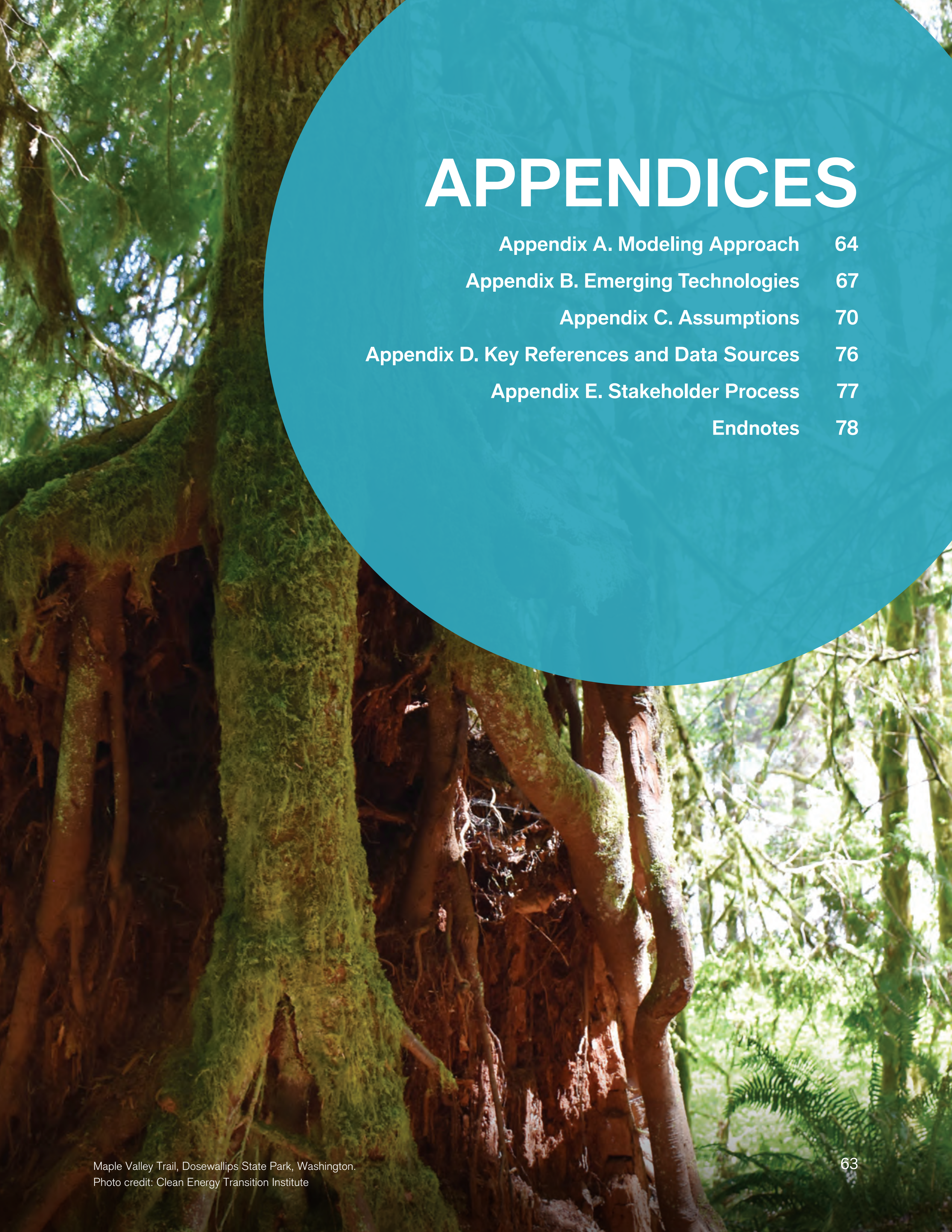
Focus on Implementation. While this study offers a functional technical representation of low-cost deep decarbonization pathways, successful implementation is more uncertain. Some implementation challenges include:

- A nearly 100% clean grid is a feature of low-cost decarbonization in the region. Policymakers and utilities must overcome the technical and economic barriers to cleaning the grid well in advance of 2050.
- The level of transportation electrification called for by 2050 requires immediate attention to overcoming barriers to massive adoption of electric vehicles, and to determining how the electric grid will handle the additional load required to serve new electricity needs.
- Grid infrastructure development and operational integration are needed to most efficiently leverage renewable development in California and across the West; this is complicated politically and technically and will take time. Planning must get underway now to ensure successful integration of these markets.

With several recent international and national reports clearly establishing that there is a small window of time within which to massively reduce fossil fuel dependence, and a U.S. federal government currently focused on increasing, not decreasing, the use of fossil fuels, it is imperative that states and regions in the United States step up to the decarbonization challenge.

Initiatives such as the Green New Deal, the Keep it in the Ground Movement, and 100% Clean Energy campaigns set forth a range of goals and strategies to reduce carbon emissions. Achieving these goals requires technology investment, smart policies, innovation, and regulatory reform to shape the low-carbon energy system of the future.

Solutions need time to be developed and implemented, so policymakers must anticipate them now. *Meeting the Challenge of Our Time: Pathways to a Clean Energy Future for the Northwest* provides support and direction for policy-makers, advocates, businesses, government leaders, and investors to begin implementing effective solutions for a deeply decarbonized future in the Northwest.



APPENDICES

Maple Valley Trail, Dosewallips State Park, Washington.
Photo credit: Clean Energy Transition Institute

Appendix A: Modeling Approach

Modeling involved two different models that Evolved Energy Research has created: (1) EnergyPATHWAYS, and (2) the Regional Investment and Operations model (RIO).

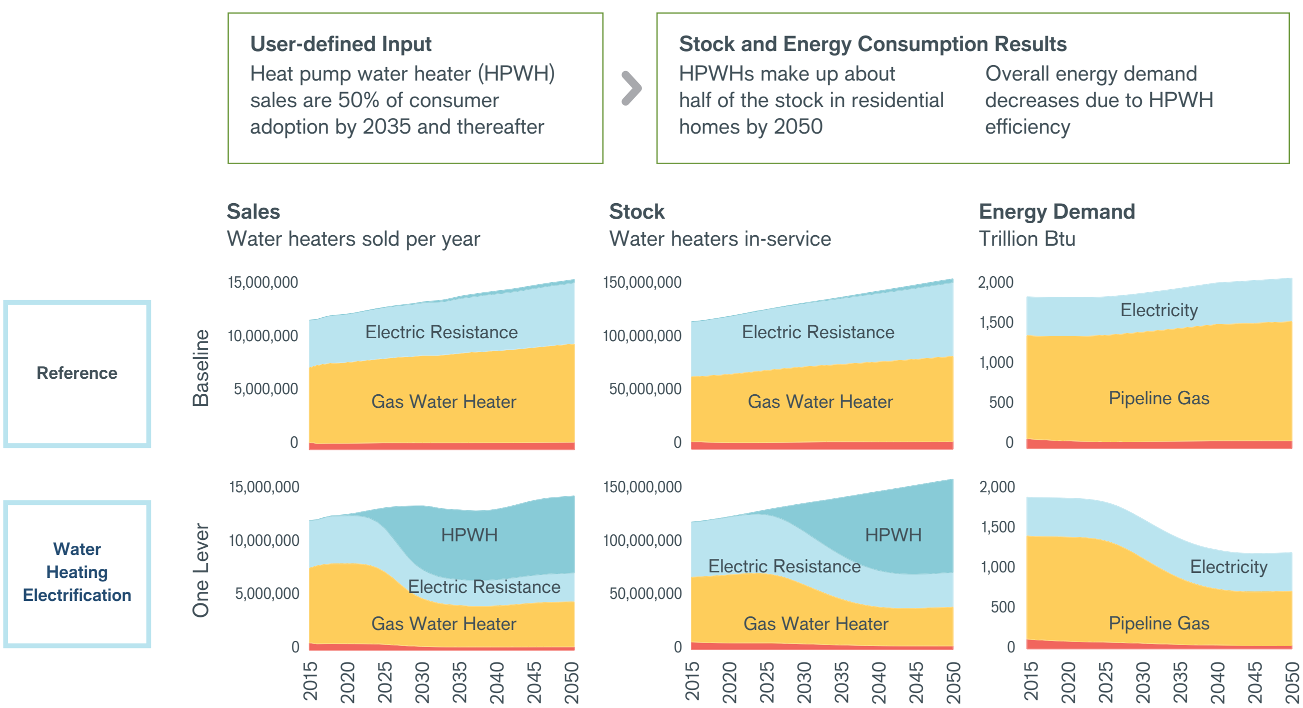
EnergyPATHWAYS

The EnergyPATHWAYS (EP) model is a bottom-up energy system scenario analysis tool that tracks energy infrastructure, including stocks for building, industry, and transportation infrastructure.

EP develops demand-side scenarios across all end-use sectors and produces annual final energy demand for electricity, pipeline gas, diesel fuels, gasoline, etc., as well as hourly electricity load shape demand.

User-defined measures specify low-carbon and efficient technologies to replace energy infrastructure over time. Specifically, modelers choose the scale and rate of adoption for new technologies for different sectors (e.g., the percent of light-duty car sales that are battery electric vehicles in each year). Figure 39 demonstrates how user-defined decisions for residential water heaters generate the stock and energy demand for heaters over time from now until 2050.

FIGURE 39. EnergyPATHWAYS: residential water heating example.



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 23.

EP represents approximately 80 demand subsectors for the residential, commercial, industrial, and transportation sectors, the major energy-consuming subsectors of which are displayed in Figure 40 below.

Regional Investment and Operations (RIO)

The Regional Investment and Operations (RIO) model is a capacity expansion tool that produces cost-optimal resource portfolios for all energy supply options and fuel types, including electricity, pipeline gas, gasoline, diesel, jet fuel, hydrogen, and other fuels. The model decides the suite of technologies that will be used over time to meet annual emissions targets and other constraints. RIO's optimization allows for trade-offs of limited resources across the energy system (like biomass) to be determined simultaneously.

For the electricity sector, RIO simulates sequential hourly system operations for every modeled year from now until 2050, incorporating long-duration energy storage logic that optimizes investment and operations of all types of energy storage, which is required to manage high renewable penetrations. RIO simulates operations and investment across the energy supply side, including electricity and fuels, while accounting for dynamically changing inputs and constraints across the energy system.

The model incorporated load, wind, solar, and hydro profiles from multiple weather years to capture a range of electricity system operating conditions because weather-driven or seasonal trends in load, hydro availability, and renewable production cause operational challenges that can persist over long periods. For load, wind, and solar, the modelers used hourly profiles from 2010, 2011, and 2012, and for hydro, the modelers represented conditions from three historical years—2001 (dry), 2005 (normal), and 2011 (wet).

RIO invests across a range of thermal, renewable, and energy storage technologies to satisfy energy, capacity, balancing, and environmental needs, as Figure 41 below demonstrates. RIO can select from three gas-fired resource alternatives.

FIGURE 40. Key energy-consuming subsectors.

Residential Sector
- Air-conditioning
- Space heating
- Water heating
- Lighting
- Cooking
- Dishwashing
- Freezing
- Refrigeration
- Clothes washing
- Clothes drying

Commercial Sector
- Air-conditioning
- Space heating
- Water heating
- Ventilation
- Lighting
- Cooking
- Refrigeration

Industrial Sector
- Boilers
- Process heat
- Space heating
- Curing
- Drying
- Machine drives
- Additional subsectors (e.g., machinery, cement)

Transportation Sector
- Light-duty autos
- Light-duty trucks
- Medium-duty vehicles
- Heavy-duty vehicles
- Transit buses
- Aviation
- Marine vessels

Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 24.

FIGURE 41. New electric sector resource options.

THERMAL
- Gas Combustion Turbine (CT)
- Gas Combined Cycle (CC)
- Gas CC with Carbon Capture and Sequestration (CC w/CCS)

RENEWABLE
- Onshore Wind
- Solar PV
- Geothermal

ENERGY STORAGE
- Pumped Hydro
- Lithium-ion
- Vanadium Flow

Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 36.

RIO invests across a range of thermal, renewable, and energy storage technologies to satisfy energy, capacity, balancing, and environmental needs

FIGURE 42. Conversion technology options.

BIOMASS-BASED

- Biomass feedstock can be converted into liquid or gaseous fuels using a variety of conversion technologies
- Biomass gasification technology can produce biogas
- Fischer-Tropsch can produce renewable diesel and renewable jet fuel

ELECTRIC-BASED

- **Power-to-X** processes convert carbon-free electricity into synthetic fuels (e.g., power-to-gas, power-to-liquids)
- Processes rely on:
  - Electrolysis to produce hydrogen
  - Carbon feedstocks either from CO_2 embodied in biomass or direct air capture

RIO represents a suite of conversion technologies to produce useful low-carbon fuels that depend on biomass- or electric-based feedstocks

Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 40.

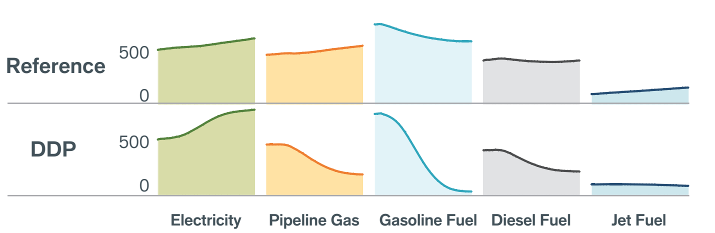
RIO represents a suite of conversion technologies to produce useful low-carbon fuels that depend on either biomass- or electric-based feedstocks, as Figure 42 shows.

Pairing EnergyPATHWAYS and RIO

The energy demand parameters that EP produces are then fed into RIO. Taking the demand projections aggregated from subsector loads that the EP model produced, RIO provides cost-optimal energy supply investments and operations for the electricity sector, biomass allocation for fuels, synthetic electric fuels, and direct air capture. Figure 43 below illustrates how EP and RIO are paired together.

FIGURE 43. Modeling framework: pairing EnergyPATHWAYS and RIO.

EnergyPATHWAYS: final energy demand projections (illustrative)



RIO: scenario inputs

- End-use energy demand
- Emissions budget
- Biomass supply curve
- RPS or clean energy constraints
- New resource constraints
- Technology and fuel cost projections

RIO: scenario outputs

Electricity sector
- Wind/solar build
- Energy storage capacity/duration
- Capacity for reliability
- Curtailment

Biomass allocation

Synthetic electric fuel production (H2/SNG)

Direct air capture deployment

Energy CO_2 Emissions

Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 21.

Appendix B. Emerging Technologies

Power-to-X

A major finding of *Meeting the Challenge of Our Time: Pathways to a Clean Energy Future for the Northwest* is the crucial role that power-to-X (either fuels or liquids) will play in the later years of this study. Power-to-X is a term that describes a variety of different technologies and processes that enable surplus electric power to be stored or used to produce fuels.

In this study, power-to-X is primarily referring to electrolysis that converts surplus electricity captured by power-to-X technology into hydrogen and then further converts it to methane gas or ammonia (e.g., power-to-gas). Carbon that is captured from power plants can also be recycled into synthetic fuels, which can replace the oil and gas that have been the traditional feedstocks for fuels used in transport.

Emmanouil Kakaras, senior vice president and the head of the department of innovation and new products at Mitsubishi Hitachi Power Systems Europe, told *Forbes* magazine in June 2018[10] that "gasoline produced by combining the captured carbon and hydrogen produced by renewable energy emits 90% less carbon than gasoline produced by conventional means."

Hydrogen Electrolysis

Using electricity to produce hydrogen by electrolyzing water plays a key role in balancing the electricity system during periods of renewable energy overgeneration. The hydrogen produced is used to create synthetic fuels that can be used for difficult-to-electrify applications. Electrically produced hydrogen is used as a feedstock to produce renewable liquid and gaseous fuels that already have existing delivery mechanisms.

Hydrogen can be combined with captured CO_2 to produce methane (the main component of natural gas). Chemical synthesis using the Fischer-Tropsch process can produce synthetic liquid fuels that are interchangeable with refined petroleum products, including diesel, gasoline, and jet fuel. Produced hydrogen can be injected into a natural gas pipeline directly, limited to 7% by energy, which research has shown can be blended with fossil-based or synthetic natural gas without damaging end-use equipment or the delivery infrastructure.

Electrical power lines. Photo credit: Public Domain

Producing electrolytic hydrogen and synthetic fuels provides a primary method of long-duration storage for systems with high penetrations of renewable generation. When peak electricity generation exceeds demand, the extra electricity is used to synthesize the hydrogen and synthetic fuels. These fuels in turn can be used directly to meet liquid and gaseous fuel demand and—to a limited extent—to produce electricity during times when renewable energy is not created.

The principal mechanism by which electric fuels balance the electricity system is not "round-trip" electricity storage in which energy is stored in one time period and discharged back to the electricity grid in another. Instead, the dominant economic means of balancing with electric fuels involves producing fuels that will be used to meet demand from hard-to-decarbonize end uses.[11]

Electric fuel production utilizes otherwise curtailed renewable energy, which means that electric fuels create value for electricity overgeneration. In doing so, electric fuels increase loads during times of renewable abundance and decrease them during low production periods. Because fuels can be stored far more cheaply than electrical energy, this method of balancing is the economic option for long-term balancing challenges.

Direct Air Capture

Direct air capture (DAC) removes CO_2 directly from the atmosphere. In this study, DAC created a carbon feedstock to be used for electric fuel production. Heightened emphasis on early commercialization of DAC is needed, as DAC can accelerate overall decarbonization and also serve as a technological backstop if widespread electrification does not take place or biomass for biofuels is constrained.

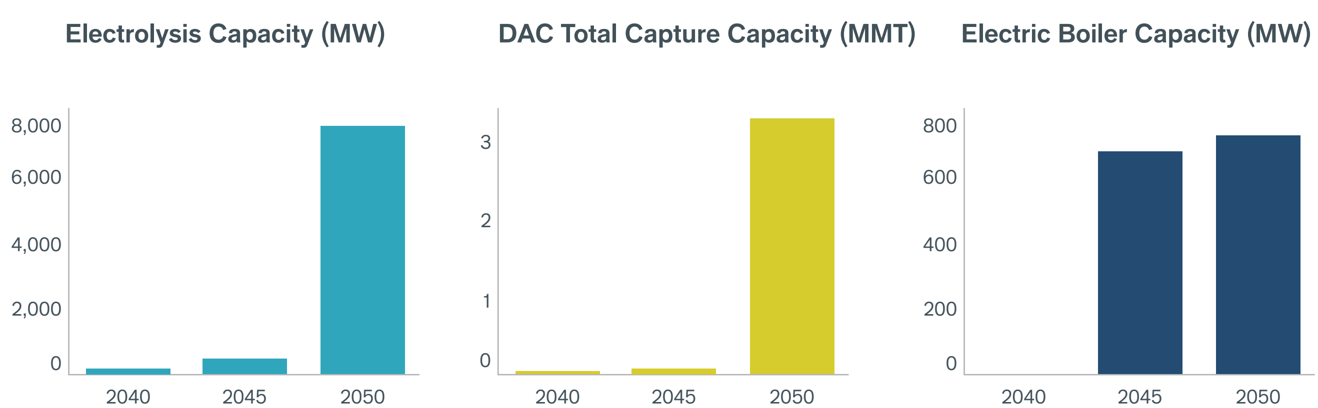
While there are legitimate concerns that DAC can be used to justify the continued development and combustion of fossil fuels, there is increasing understanding that DAC could play an important and complementary role in deep decarbonization. DAC pairs best economically with low-cost zero-carbon resources, such as wind or solar, because CO_2 feedstock (like hydrogen) can be stored and therefore DAC can operate flexibly to take advantage of periods of renewable overgeneration. Carbon capture scenarios where fossil fuels provide the grid electricity do not offer the same economic benefit.[12] Figure 45 illustrates how synthetic gas is produced from renewably generated hydrogen when methanated with captured CO_2.

Electric Boilers

Electric boilers produce steam for commercial and industrial activity. When used in conjunction with a fuel boiler at the same location, they can provide electric load flexibility. In periods of excess renewable energy, the electric boiler produces steam and the fuel boiler sits idle. In periods short of renewable energy, i.e., when the wind is not blowing, the fuel boiler takes over and the electric boiler sits idle, reducing electric loads. This functionality helps balance the electricity grid.

In the 2040s, new sources of electric load play essential roles for both the electricity system and the energy system as a whole. First, the new loads are flexible and can manage electricity imbalances across the year. Second, these new electric loads produce co-products that assist with energy system–wide decarbonization in the form of (1) hydrogen from electrolysis and CO_2 from DAC to produce synthetic natural gas, and (2) electric boilers that produce steam for commercial and industrial activity. Figure 44 shows the builds for each of these new sources of electric load in the Central Case.

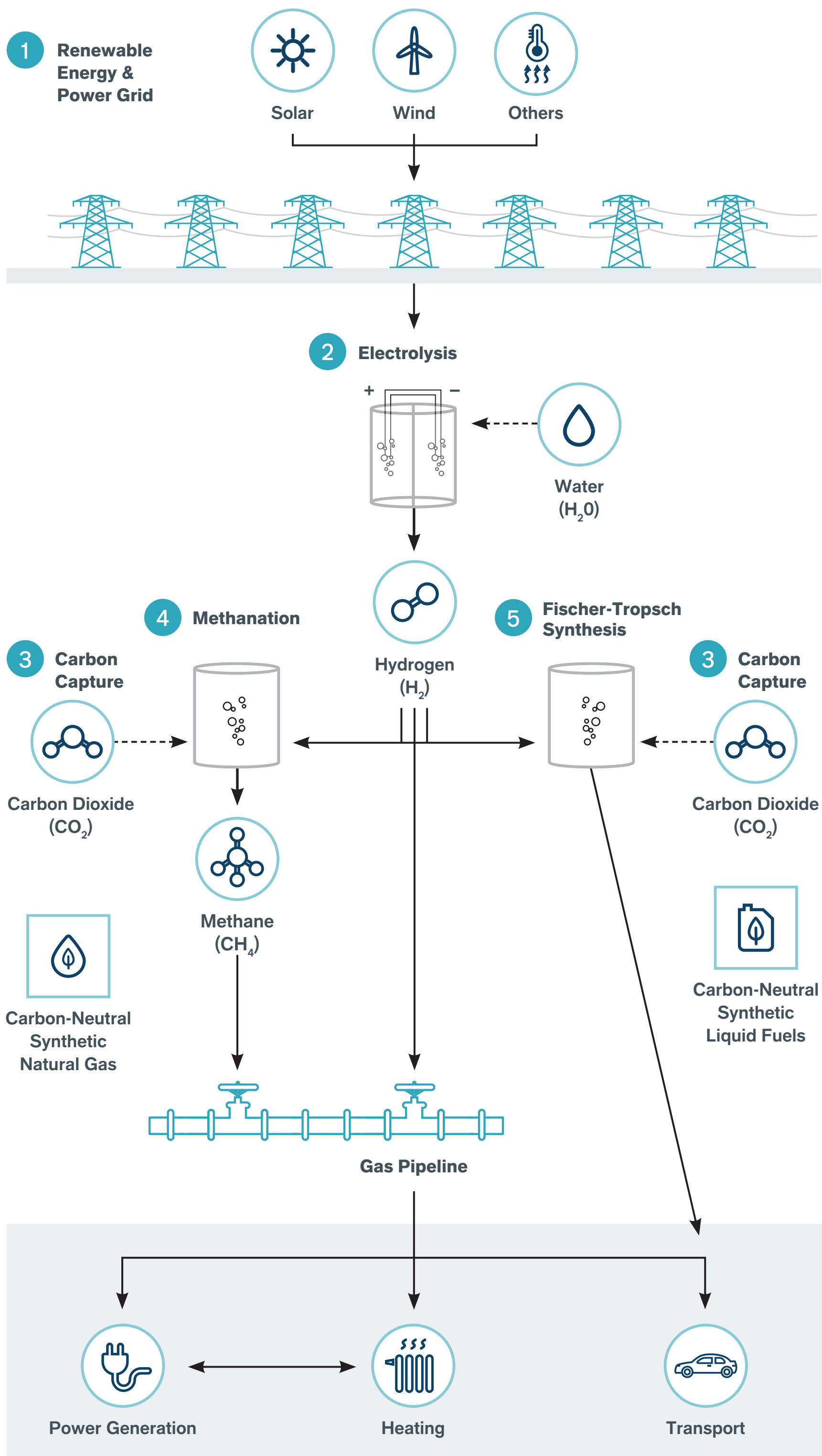
FIGURE 44. New sources of electric load.



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 77.

FIGURE 45. Illustration of power-to-gas and power-to-liquids (P2X).

A major finding of *Meeting the Challenge of Our Time: Pathways to a Clean Energy Future for the Northwest* is the crucial role that power-to-X will play in 2040–50 to create synthetic gas or synthetic liquid fuels. Power-to-X is a term that describes a variety of different technologies and processes that enable surplus electric power to be stored or used to produce fuels.



In the study, power-to-X refers to electrolysis that converts surplus electricity into hydrogen, which then is combined with carbon dioxide, captured either through direct air capture powered by carbon-free electricity, or from biorefineries to produce methane gas (power-to-gas). The Fischer-Tropsch synthesis process can also be used to create synthetic liquid fuels to replace conventional oil based transport fuels (power-to-liquids).

1 **Renewable Energy & Power Grid:** Clean electricity powered by sources such as solar, wind, and hydroelectricity supplies the power grid.

2 **Electrolysis:** The process of using electricity, in this case carbon-free, to split water into hydrogen and oxygen.

3 **Carbon Capture:** Carbon dioxide is captured either through direct air capture powered by carbon-free electricity or from biorefineries.

4 **Methanation:** Combines hydrogen with carbon dioxide to produce methane that can be injected into the gas pipeline as carbon-neutral synthetic gas.

5 **Fischer-Tropsch Synthesis:** Chemical reactions that change a mixture of carbon dioxide gas and hydrogen gas into liquid hydrocarbons, such as gasoline or kerosene, that can be used for transportation.

Appendix C. Assumptions

Deep decarbonization analyses require a wide variety of inputs and data sources to characterize current and future energy systems. This study relies on state and regional data sources where available, and leverages public sources primarily from federal government reports, including the U.S. Energy Information Administration (EIA), U.S. Department of Energy (DOE), and National Renewable Energy Laboratory (NREL).

This section describes how various assumptions were derived and the way the models incorporated those assumptions. The list of key references and data sources is provided in Appendix D. These sources tend to be conservative about the projected cost and performance of low-carbon technologies.

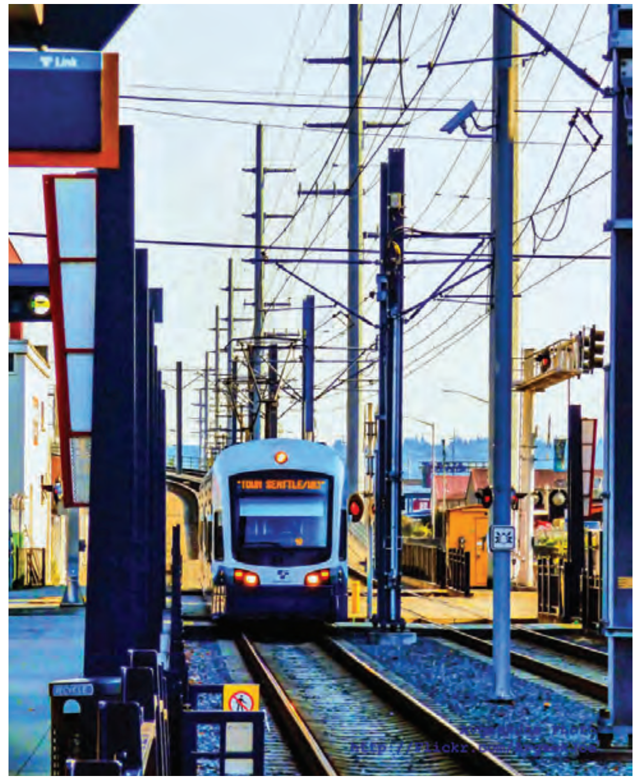
End-Use Stocks and Technologies Assumptions

Regional building stock assessments from Northwest Energy Efficiency Alliance (NEEA)[13] were used to characterize the existing building stocks in each of the four states.

Cost and performance for new end-use technologies were primarily derived from the NREL Electrification Futures Study,[14] which includes projections for:

- **Buildings Sector:** Air source heat pumps and heat pump water heaters
- **Transportation Sector:** Battery electric vehicles for light-duty cars and trucks, medium-duty battery electric trucks, heavy-duty battery electric trucks, and battery electric buses
- **Industrial Sector:** Air source heat pumps, electric machine drives, industrial heat pumps, electric boilers, and electric process heating

The Annual Energy Outlook (AEO) produced from the U.S. Energy Information Administration (EIA)'s National Energy Modeling System[15] was used to develop the demand-side database, including baseline and projected cost and performance for residential and commercial equipment, such as residential clothes dryers and commercial ventilation systems.



Link light rail train pulls into SoDo Station. Photo credit: Joe A. Kunzler

Electric Topology

Electricity sector operations and investment were modeled across the four Northwest states, California, and the rest of the Western Electric Coordination Council (WECC). Transfer capability between zones is based on major WECC paths and their line ratings. The capacity of Colstrip's major remote generation resources is allocated to the four states based on utility ownership.

Existing Generation Resources

The model derived the installed capacity of generation resources in each state from the U.S. Energy Information Administration's Form EIA-860.[16] Capacity from the existing hydroelectric system was assumed to remain constant through 2050.

Existing Coal Resources

The study incorporates planned retirement of coal-fired resources as the table below demonstrates.

Plants without a planned retirement year are assumed to retire at the end of their economic lifetimes.

Existing Nuclear Resources

The Columbia Generating Station (CGS) is the only operating nuclear power plant in the Northwest and its current license expires at the end of 2043. RIO allows CGS to retire or continue operations after 2043 to maintain dependable capacity and carbon-free energy.

The going-forward fixed costs of maintaining CGS are derived from Energy Northwest's Fiscal Year 2019 Long-Range Plan:[17]

- Fixed capital costs are assumed to equal $85/kW-yr
- Fixed operations and maintenance costs are assumed to equal $238/kW-yr
- Total going-forward fixed costs are equal to $323/kW-yr

Thermal Resource Options

Capital, fixed operations and maintenance (O&M), variable O&M, and heat rate characteristics are from NREL's 2018 Annual Technology Baseline (ATB).[18]

Fuel costs vary depending on the pipeline gas composition. Natural gas fuel costs are from the Annual Energy Outlook 2017[19] and the cost of decarbonized pipeline gas is solved for endogenously in RIO.

New coal and advanced nuclear resources were not considered.

Renewables Resource Options

Various state-level inputs characterizing renewable resources (potential, performance/capacity factor, transmission costs) are derived from NREL's Regional Energy Deployment System (ReEDS).[20]

Capital cost projections for wind, solar, and geothermal are from NREL's 2018 Annual Technology Baseline (ATB).[21]

Energy Storage Resource Options

Cost and efficiency inputs are derived from the International Renewable Energy Agency (IRENA) "Electricity Storage and Renewables: Costs and Markets to 2030" report. Costs are portioned into capacity ($/kW) and energy ($/kWh) components, where RIO selects the optimal duration of new resources over time.

New pumped hydro storage potential is limited to 2,000 MW in the Northwest based on a review of existing projects under development, which reflects the Gordon Butte, Goldendale, and Swan Lake pumped storage projects.

Table 1. Washington and Oregon coal plant retirement schedule.

Unit	Assumed Retirement Year (First Year Offline)
Boardman	2021
Centralia 1	2021
Centralia 2	2026
Colstrip 1 and 2	2022
Colstrip 3 and 4	▪ Avista and PSE share: 2028 (reflects accelerated depreciation schedule) ▪ PACW share: 2030 ▪ PGE share: 2035

Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 34.

Ludington Pumped Storage Plant. Photo credit: Consumers Energy

Supply-Side Resource Options

The model assumes the following supply-side energy resource options:

TABLE 2. Supply-side resource options.

Diesel Fuel	Jet Fuel	Pipeline Gas	Liquid Hydrogen	Gasoline Fuel
Power-to-Diesel	Power-to-Jet-Fuel	Power-to-Gas	Electrolysis	Corn Ethanol
FT Diesel	FT Jet Fuel	Hydrogen	Natural Gas Reformation	Cellulosic Ethanol
FT Diesel with CCS	FT Jet Fuel with CCS	Biomass Gasification	Natural Gas Reformation with CCS	**Steam**
FT Diesel with CCU	FT Jet Fuel with CCU	Biomass Gasification with CCS	Natural Gas Reformation with CCU	Fuel Boilers
		Biomass Gasification with CCU	**Direct Air Capture**	CHP
		Landfill Gas	DAC with CCS	Electric Boilers
			DAC with CCU	

Acronyms
CHP: combined heat and power
CCS: carbon capture and sequestration
CCU: carbon capture and utilization
DAC: direct air capture
FT: Fischer-Tropsch

Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 41.

Biomass Availability and Costs

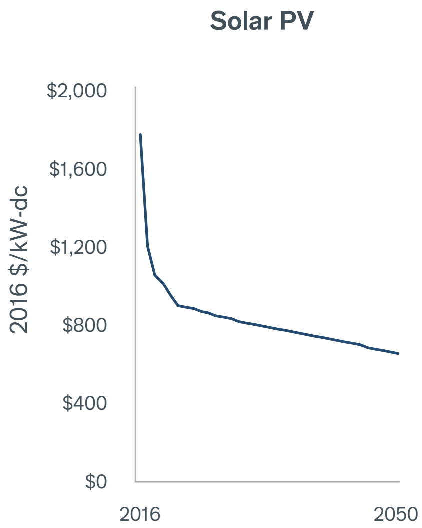
Prior deep decarbonization pathways studies have relied on the Department of Energy (DOE) Billion-Ton Study[22] for estimates of biomass availability and costs. This study includes feedstock potential by U.S. county at different price points for agricultural residues, forest residues, purpose-grown energy crops, and waste stream.

The Washington State and Portland General Electric deep decarbonization pathways studies assumed an allocation of biomass to the jurisdiction that is equal to its population-weighted share of national supply. This study follows the same approach as earlier work, where each state in the Northwest is allocated a share of national supply based on its relative population. RIO determines the application of biomass for the energy system by allocating limited supply to the most cost-optimal fuel type.

Electricity Supply Technology Cost Projections

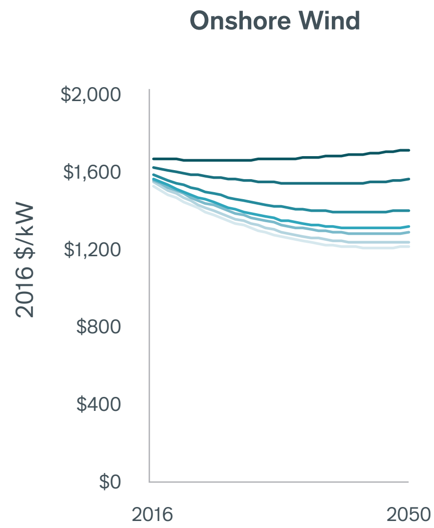
Onshore wind and solar PV cost projections were sourced from the NREL 2018 Annual Technology Baseline (ATB).[23] The different trajectories of onshore wind cost represent NREL resource bins that differ in wind speed. These map to the wind resource potential within the Northwest states and are derived from the NREL Regional Energy Deployment System (ReEDS) model database.[24]

FIGURE 46. Solar PV technology cost projections.



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 121.

FIGURE 47. Onshore wind technology cost projections.



Note: Lines represent separate resource bins. **Source:** Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 121.

Battery Electric Vehicles Technology Cost Projections

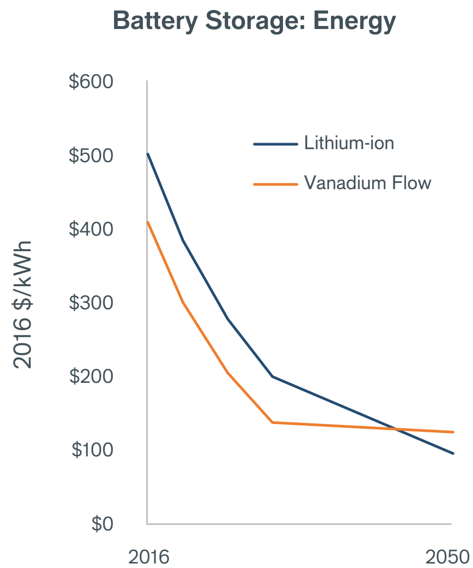
The energy storage costs used in the study were sourced from the International Renewable Energy Agency (IRENA) "2017 Electricity Storage and Renewables: Costs and Markets to 2030" report. IRENA projects battery costs only to 2030. We therefore assumed battery prices follow the IRENA baseline projection through 2030, then drop to the IRENA 2030 Low Cost Case projection by 2050.

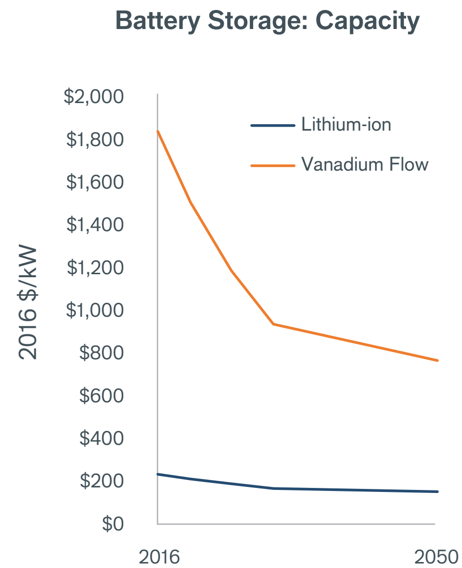
This assumes that the additional price declines due to various factors assumed in the IRENA Low Cost Case projection happen post-2030 and may be conservative depending on whether new battery chemistries become more competitive than the current market leaders.

Battery costs are separated by energy (kWh of storage) and capacity (kW of power) components. For example, the total kilowatt hours stored in a flow battery are driven by the quantity of electrolyte, whereas a flow battery's maximum discharge is driven by its membrane. Separation of the energy and capacity components allows the RIO model to optimally size new battery build.

The cost evolution of electric vehicles in each of the categories modeled in the study is shown in the figures below. These are sourced from the NREL Electrification Futures Study that provides price projections by vehicle class out to 2050.[26]

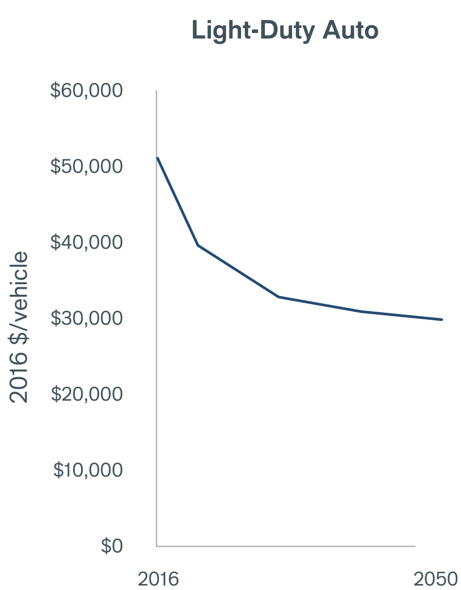
FIGURE 48. Battery storage energy and capacity technology cost projections.

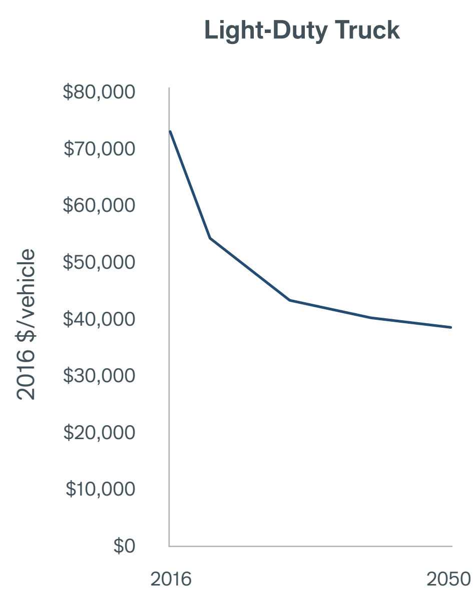




Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 121.

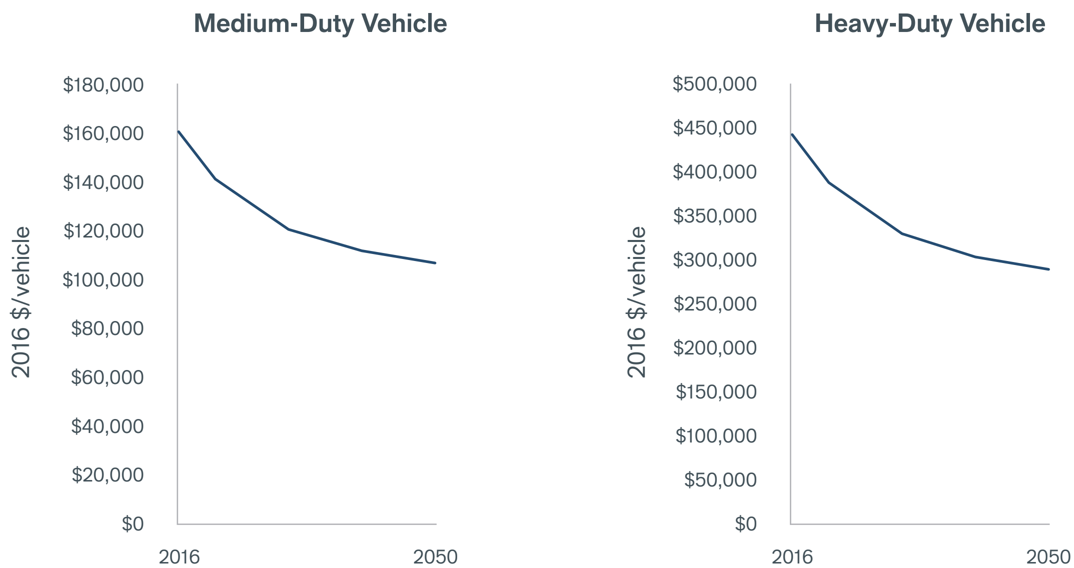
FIGURE 49. Light-duty auto and truck cost projections.





Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 122.

FIGURE 50. Medium- and heavy-duty vehicle cost projections.



Source: Northwest Deep Decarbonization Pathways Study, May 2019, Evolved Energy Research, page 122.

Freight truck. Photo credit: Rhys Moult

Appendix D. Key References and Data Sources

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Building Stock (Commercial): Northwest Energy Efficiency Alliance (NEEA). "Commercial Building Stock Assessment 2014." https://neea.org/data/commercial-building-stock-assessments

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Fossil Fuel Cost Projections: U.S. Energy Information Agency (EIA). "Annual Energy Outlook 2017." https://www.eia.gov/outlooks/archive/aeo17/

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Renewable Resource Potential and Transmission Costs: National Renewable Energy Laboratory (NREL). "Regional Energy Deployment System Model." https://www.nrel.gov/analysis/reeds/

Appendix E: Stakeholder Process

Prior to commissioning *Meeting the Challenge of Our Time: Achieving a Low-Carbon Future in the Northwest*, the Clean Energy Transition Institute convened a Deep Decarbonization Pathways Working Group (see page 4 for the list of participants) and conducted numerous interviews with Northwest stakeholders about the value of conducting an economy-wide pathways study.

This stakeholder process revealed a clear need for a common set of facts about the decarbonization pathways for the Northwest that legislators and the advocacy community could agree to. Stakeholders' questions were summarized as:

1. **What is the likely trajectory by which we will clean the electricity grid in the Northwest by 2030, 2040, and 2050?**
   - When looking at economy-wide decarbonization in the Northwest, how close to 100% clean does the electricity sector have to be, by when?
   - How quickly can we remove coal from the Northwest grid?
   - How realistic is it that we will not replace coal with natural gas to power the grid?

2. **How will electrification of the transportation and buildings sectors contribute to deep decarbonization in the Northwest?**
   - How will energy efficiency help in decreasing load and therefore contribute to decarbonization?
   - How much decarbonization can we achieve through electrifying the transport sector with a nearly 100% clean electricity grid?
   - How does demand management contribute to peak load reduction and decarbonization?
   - How does transportation electrification impact load in Washington and Oregon?

3. **What is the role of natural gas for power generation and other end uses, including transportation?**
   - How do trade-offs in natural gas infrastructure impact emission reductions? From a carbon emissions reduction point of view, should we replace old natural gas plants with peakers if storage prices are high?
   - Absent policy changes, how soon do we expect storage to directly compete with natural gas for peaking?
   - What is the role of compressed natural gas/liquefied natural gas in reducing emissions in the transport sector over the next 20–30 years? Are there transportation subsectors (maritime, freight) where the role may be more prominent, given technology trajectories? How would knowing the answer to this question inform our policy choices and our approach to this sector and to natural gas?

4. **What is the cross-sector role of biomass?**
   - What are the highest value allocations of biomass among fuels, electricity, and gas?
   - What is the role of renewable natural gas derived from biomass and used for power generation or transportation?

5. **How would greater integration between the Northwest and California contribute to deep decarbonization?**
   - How much could Northwest-California integration reduce energy infrastructure needs and costs?

Endnotes

1 U.S. Bureau of Economic Analysis, Total Gross Domestic Product for Washington, Oregon, Idaho, and Montana, retrieved from FRED, Federal Reserve Bank of St. Louis.

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3 Fiona Harvey. *The Guardian*. November 9, 2018. "World headed for irreversible climate change in five years, IEA warns." https://www.theguardian.com/environment/2011/nov/09/fossil-fuel-infrastructure-climate-change

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5 73% of Washington, 72% of Oregon, 65% of Montana, 63% of Idaho believe that global warming is happening; 63% of Washington, 62% of Oregon, 55% of Montana, 56% of Idaho are worried about global warning. Yale Climate Communications http://climatecommunication.yale.edu/visualizations-data/ycom-us-2018/?est=happening&type=value&geo=state&id=53

6 Figures 1 and 2 depict only Oregon and Washington data for the ratio of CO_2 emissions and the breakdown by sector because data for Montana and Idaho are not available.

7 Biofuels can either be burned with their emissions released into the atmosphere, in which case their CO_2 is cycled rather than removed. Biomass with CCS is similar to direct air capture (DAC) that removes CO_2 from the air, but plants remove the CO_2 and when burned they produce the same end-use fuel as DAC, but the process is different.

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26 National Renewable Energy Laboratory (NREL). “Electrification Futures Study: End-Use Electric Technology Cost and Performance Projections through 2050.” https://www.nrel.gov/docs/fy18osti/70485.pdf

Wind turbines in northern Montana. Photo credit: Mark Stevens

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