
Exploring Pathways to Deep Decarbonization for the Portland General Electric Service Territory

April 24, 2018

PREPARED FOR



PREPARED BY

Gabe Kwok
Ben Haley



EVOLVED
ENERGY
RESEARCH

Contents

Executive Summary.....	3
I. Background.....	8
A. Motivation and Context.....	8
B. Study Scope.....	9
C. Study Emissions Target.....	10
II. Study Assumptions and Approach.....	12
A. EnergyPATHWAYS Modeling Framework.....	12
B. Electricity Sector Modeling.....	14
C. Energy Demand and Supply.....	18
D. Biomass.....	20
E. Key Data Sources.....	21
III. Scenarios.....	22
A. Overview.....	22
B. Energy Supply.....	23
1. Electricity Resources.....	23
2. Liquid and Pipeline Gas Fuel Blends.....	25
C. Energy Demand.....	26
1. Buildings and Industry.....	26
2. Transportation.....	27
IV. Results: Energy System.....	29
A. High-Level Summary.....	29
B. Energy Demand.....	31
C. Energy Supply.....	34
1. Electricity.....	34
2. Pipeline Gas.....	35
3. Liquid Fuels.....	36
D. Energy-related CO ₂ Emissions.....	36
E. Energy System Costs.....	38
F. Transportation Electrification Sensitivity Analysis.....	40
V. Results: Electricity System.....	41
A. Load.....	41
B. Resources.....	43

1.	Installed Capacity	43
2.	Generation	45
C.	System Operations	47
1.	Load and Net Load	47
2.	Hourly System Load Shape	49
3.	Month-Hour Electricity Dispatch.....	51
4.	Curtailement	53
D.	Sensitivity Analyses	56
VI.	Summary	58
VII.	Bibliography.....	59

Executive Summary

Background

Portland General Electric (PGE) retained Evolved Energy Research to undertake an independent study exploring pathways to deep decarbonization for its service territory. This study comes amidst a broad interest in decarbonization from customers and stakeholders, as well as policies and goals to promote clean energy and emissions reductions.

Since 2007, Oregon has had a goal of reducing statewide greenhouse gas (GHG) emissions by 75 percent below 1990 levels by 2050. Recently proposed legislation seeking to establish a cap-and-trade program in Oregon also proposes to tighten the statewide GHG reduction goal to 80 percent below 1990 levels by 2050. At the local level, the City of Portland and Multnomah County passed resolutions in June 2017 committing to 100 percent renewable electricity by 2035 and a complete transition to carbon-free energy by 2050.

These drivers to deeply decarbonize the economy would require a transformation of the energy system, and major choices will need to be made about which technologies play a role and how aggressively to pursue carbon reductions across different sectors. A substantial body of existing technical work shows that the electricity sector plays a pivotal role in a low-carbon transition, but the extent and type of role depends on choices made in other sectors.¹ For example, the level of electrification pursued in buildings and the decision to produce fuels from electricity, such as hydrogen from electrolysis, will have implications for electricity demand and the quantity of renewable electricity generation that will need to be developed.

Due to the potential impact on long-term planning, PGE sponsored this study to inform its Integrated Resource Planning (IRP) efforts. This study is intended to provide an understanding of: (1) the opportunities and challenges of achieving economy-wide deep decarbonization; and (2) the resulting implications for electricity system operations and planning.

Approach

The overarching emissions target for this study is an 80 percent reduction below 1990 levels by 2050 in energy-related CO₂ emissions. CO₂ emissions from fossil fuel combustion have been the predominant source of Oregon's historical GHG emissions, and, since 1990, they have accounted for approximately four-fifths of total GHG emissions in the state. This target would allow for fossil fuel combustion emissions of no more than 9.2 MMTCO₂ in 2050 for the state of Oregon. We allocate the statewide carbon budget to PGE's service territory using its projected share of Oregon's population, which is estimated to be 47 percent in 2050.² This results in a carbon budget of 4.3 MMTCO₂ in 2050 for the PGE service territory.

We designed three future energy scenarios that reduce emissions to comply with the 4.3 MMTCO₂ target. These scenarios are referred to as "deep decarbonization pathways" or "pathways", and they provide alternative blueprints for achieving deep decarbonization of the energy system.

¹ For example, see Williams, et al. (2014) and Haley, et al. (2016).

² Population growth rate projections from OEA (2013).

For each sector of the energy economy, we developed a range of measures to replace today's energy infrastructure with efficient and low-carbon technologies over the next three decades. For example, passenger travel currently provided by a gasoline vehicle is replaced by an electric vehicle, and a compact fluorescent (CFL) light bulb is replaced by a light emitting diode (LED) light bulb. Each pathway combines measures across sectors at the scale and rate necessary to meet the study's emissions target.

We use EnergyPATHWAYS, a bottom-up energy systems model, to estimate energy demand, emissions and costs for each pathway. Our analysis starts with the same model and approach we have previously used to evaluate deep decarbonization for the United States, the State of Washington and other jurisdictions. We developed a detailed representation of the PGE service territory energy system, including infrastructure stocks and energy demands for buildings, industry, and transportation. Our analysis incorporates an hourly dispatch of PGE's electricity system, which allows us to better understand fundamental changes to electricity supply and demand, such as how to balance very high levels of intermittent renewables and the impact of electrification on hourly electricity demand.

Pathways

Our study aims to provide an understanding of the broad choices available to achieve deep decarbonization across the economy and the potential implications on the electricity sector. To inform this understanding, we develop three plausible energy futures for PGE's service territory that achieve steep reductions in energy-related CO₂ emissions between now and 2050. These future energy scenarios outline: (1) potential sources and demands for energy types over time; and (2) the scale and timing of change over the next three decades.

Table 1 provides a high-level summary of the three pathways included in this study, where each scenario incorporates alternative emissions reduction strategies and technologies. One of the primary objectives of our scenario design was to reflect a broad range of outcomes for the electricity sector. The High Electrification pathway relies on electrifying space and water heating in buildings and deploying bulk energy storage to balance high levels of renewable generation. Passenger transportation is characterized by high levels of battery electric vehicles (BEV), while freight transportation includes both battery electric and hybrid diesel trucks. The Low Electrification pathway decarbonizes energy supply with a variety of renewable fuels, and electrolysis and power-to-gas facilities provide both electricity balancing services and decarbonized pipeline gas. Passenger transportation is primarily BEV, while compressed and liquefied natural gas trucks are incorporated in the freight transportation sector. The High DER pathway is highly electrified and distributed, with increased rooftop solar PV and distributed energy storage in buildings and industry. The Reference Case projects business-as-usual conditions, including the Oregon Clean Electricity and Coal Transition (OCEP) and Clean Fuels Program (CFP).

Table 1 Scenario Summary

Scenario	Description
High Electrification	Fossil fuel consumption is reduced by electrifying end-uses to the extent possible and increasing renewable electricity generation
Low Electrification	Greater use of renewable fuels, notably biofuels and synthetic electric fuels, to satisfy energy demand and reduce emissions
High DER	Distributed energy resources proliferate in homes and businesses, which also realize higher levels of electrification
Reference	A continuation of current and planned policy, and provides a benchmark against the deep decarbonization pathways

We are not choosing or recommending a pathway to 2050, and the scenarios presented above are not exhaustive. However, the pathways we have included in this study illustrate possible routes to a deeply decarbonized energy system and provide an understanding of trade-offs between complex decisions made by consumers and producers across the energy economy.

Key Findings

The three pathways evaluated in this study demonstrate that achieving deep decarbonization is both possible and there are multiple ways of doing so. Through this analytical exercise, we have identified a number of key findings, which we describe in detail below.

Common Elements to Achieve Deep Decarbonization

Although our pathways demonstrate that a variety of technologies and approaches are possible to realize a low-carbon economy, they also share common strategies, including: energy efficiency, decarbonization of electricity generation and electrification. These *three pillars* are common themes in all pathways, and the energy transformation from today to 2050 reflects: (1) a decline in per capita final energy consumption by approximately 40 percent; (2) a decrease in the carbon intensity of electricity generation to near zero; and (3) an increase in the share of energy coming from electricity or fuels produced from electricity from approximately one-quarter today to at least half by 2050. All three strategies are required and pursuing only one is insufficient.

Planning for a 2050 Energy System

In order to facilitate a pathway to 2050, new energy infrastructure will be required that is low-carbon and efficient. Transformation is required across all sectors with consumers and energy suppliers both playing a key role. The analysis identifies the scale and rate of change for each pathway, and highlights trade-offs between choices made to achieve deep decarbonization. One example is the choice of decarbonizing heat in buildings. Electrification of heat with heat pumps may require electricity distribution network upgrades to allow for growth in electricity demand, but they also provide a source of flexibility and efficient cooling services during the summer. The alternative is decarbonized pipeline gas that requires new central-station fuel production facilities, additional renewable generation and

transmission network upgrades. *Both* choices require new infrastructure and highlight how long-term planning will need to address several uncertainties.

Energy Demand and Electricity Demand

Energy efficiency plays a crucial role in all pathways, and *total energy demand* in 2050 is approximately 10 to 20 percent below today's level, while the population grows by more than 40 percent. Despite overall energy demand decreasing, *electricity consumption* increases in all pathways. By 2050, retail electricity sales are projected to increase by 60 to 75 percent relative to today's level. As a result, electricity's share of overall energy demand is projected to increase in a deeply decarbonized future.

Transportation Electrification

Electrification of passenger transportation is a critical component of decarbonizing the energy system, and passenger vehicles are at least 90 percent BEV by 2050 across all pathways. To ensure these vehicles are on the road by 2050 requires consumer adoption to be near 100 percent of vehicle sales during the mid-2030s. Delays in adoption increase the likelihood of missing the 2050 target.

Widespread adoption of electric vehicles (EVs) is projected to be the largest source of increased electricity consumption, and, left unmanaged, would increase peak demand. However, the fleet of EVs across PGE's service territory can employ smart charging by shifting their demand to more efficient times of day. Charging off peak, such as when renewable generation is high or during the middle of the night can mitigate peak load impacts while ensuring that passengers complete all of their intended trips.

Scale of Renewable Resources

Oregon's existing renewable portfolio standard (RPS) requires half of the energy PGE delivers to its customers to come from qualifying renewable resources by 2040. Deep decarbonization extends that ambition in two ways. First, the overall electricity generation mix is more than 90 percent carbon-free by 2050, including onshore wind, solar PV, hydro and geothermal resources. Second, the total quantity that must be generated (in average megawatts) increases due to: (a) electrification of end-use demand, such as heating and transportation; and (b) producing fuels from electricity, such as hydrogen and synthetic natural gas. As a result, the installed capacity of renewables is substantially higher than what's anticipated in any current planning proceedings and is more than double the quantity we would expect under current RPS policy.

Rooftop solar PV can play a key role in electricity supply, but its share of the overall electricity generation mix in a deeply decarbonized energy system is limited by the resource quality in Northwest Oregon (i.e., low capacity factors) and growth in electricity consumption. Distributed solar reduces the need for, but does not completely replace, transmission-connected renewables. Although the Low Electrification pathway has the lowest retail energy deliveries by 2050, the pathway requires the highest level of transmission-connected renewable generation due to electric loads from producing hydrogen and synthetic natural gas.

The scale of renewable resource development present in all scenarios highlights the need for proactive planning to ensure that these resources are available to come online in a timely fashion. This includes identifying promising areas for resource development, possible transmission network upgrades to

ensure renewable generation is delivered to load, and operational considerations to balance a highly renewable electricity grid.

Balancing the Electricity System

Electricity systems must be continually balanced across several timescales, from seconds to daily, weekly and seasonal changes. Today, generation from thermal and hydro resources is varied to meet changes in demand. However, balancing electricity supply and demand becomes more challenging when inflexible, variable renewable generation is the principal source of electricity supply. For example, renewable generation exceeds load in approximately half of all hours in 2050 in our pathways.

This operational paradigm necessitates a transition to new forms of balancing resources to integrate renewables and avoid curtailment. New sources of flexibility, including energy storage and flexible demand, can complement traditional sources of flexibility. Flexible demand includes both: (a) flexible end-use loads, such as smart EV charging and water heating; and (b) flexible transmission-connected loads, such as electrolysis and power-to-gas facilities that produce low-carbon fuels. The portfolio of available balancing options depends on choices made across the energy economy.

I. Background

Portland General Electric (PGE) retained Evolved Energy Research to undertake an independent study exploring pathways to deep decarbonization for its service territory. This study comes amidst a broad interest in decarbonization from customers and stakeholders, as well as policies and goals to promote clean energy and emissions reductions at the state and local level. Transitioning towards a low-carbon energy economy will have significant implications for electricity supply and demand, and the various technologies and strategies deployed during this transformation can result in broad outcomes for the electricity sector. Due to the potential impact on long-term planning, PGE sponsored this study to inform its Integrated Resource Planning (IRP) efforts and provide an understanding of: (1) the opportunities and challenges of achieving economy-wide deep decarbonization across its service territory; and (2) the resulting implications for electricity system operations and planning.

A. Motivation and Context

Oregon has long been at the forefront of recognizing the risks imposed by climate change. In 2007, the Oregon legislature passed House Bill 3543 (HB 3543), which established GHG reduction goals, including: (a) 10 percent reduction below 1990 levels by 2020; and (b) 75 percent reduction below 1990 levels by 2050. The Oregon Global Warming Commission (OGWC) was established through the same bill, and later recommended an interim goal of a 40 percent reduction below 1990 levels by 2035.

Recently proposed legislation seeking to establish a cap-and-trade program in Oregon also proposes to tighten the statewide GHG reduction goal. The proposed legislation would require a reduction in statewide GHG emissions to: (a) a goal of 20 percent below 1990 levels by 2025; (b) a limit of 45 percent below 1990 levels by 2035; and (c) a limit of 80 percent below 1990 levels by 2050.

Oregon has existing climate policies targeting specific sectors. The Clean Fuels Program requires the average carbon intensity of transportation fuels to be reduced by 10 percent between 2015 and 2025. The state adopted a Renewable Portfolio Standard (RPS) in 2007, which requires a percentage of retail electricity sales to be met by qualifying renewable electricity generation. This policy originally required 25 percent of load to be met by renewables by 2025. Senate Bill 1547 (SB 1547), also known as the Oregon Clean Electricity and Coal Transition (OCEP), was passed in March 2016 and requires: (1) an increase in the RPS to 50 percent renewables by 2040; and (2) removing coal-fired electricity generation from the state's electricity supply by 2035.

PGE's 2016 IRP reflected the increase in renewable energy requirements and transition from coal generation called for in the OCEP. Throughout the IRP process, stakeholders and customers have expressed interest in low-carbon portfolios and exploring deep emissions reductions. In addition, the City of Portland and Multnomah County passed resolutions committing to ambitious clean energy goals shortly after, including: (a) 100 percent renewable electricity by 2035; and (b) a complete transition to carbon-free energy by 2050.

These drivers to deeply decarbonize the economy would require ambitious energy system transformation. Prior studies examining similar levels of GHG reductions for the states of Washington and California, the United States and countries representing more than 75 percent of global GHG emissions have all identified the following required changes to their future energy systems: (1) highly efficient use of energy; (2) generating electricity with low- and zero-carbon resources; and (3)

substituting fossil fuels with electricity and electricity-derived fuel.³ Pursuing only one change, such as decarbonizing electricity generation, is insufficient to meet economy-wide goals and all three strategies are needed.

In addition to these common themes, there are a range of alternative strategies that make it possible to achieve the same GHG goal. Different technologies and fuels can be deployed to decarbonize energy supply and demand, and the extent of decarbonization by end-use sector may vary. Key differences between pathways identified in prior studies include the level of end-use electrification and the allocation of limited bioenergy resources to decarbonize gaseous and liquid fuels.

As a result, long-term planning for the electricity sector will need to account for decarbonization efforts in other sectors and the complex mix of choices that may be pursued. Examples of actions that would affect long-term electricity planning include: (a) adoption of high levels of electric vehicles in the transportation sector, which affects overall electricity demand and its shape; (2) production of synthetic electric fuels, such as hydrogen from electrolysis, which will increase the demand for clean electricity generation; and (3) deployment of distributed energy resources across homes and businesses. However, the likelihood and timing of these developments and other potential decarbonization efforts is uncertain.

Our study aims to provide an understanding of the broad choices available to achieve deep decarbonization across the economy and the potential implications on the electricity sector. To inform this understanding, we develop a range of plausible energy futures for PGE's service territory that achieve steep reductions in energy-related CO₂ emissions between now and 2050. These future energy scenarios outline: (1) potential sources and demands for energy types over time; and (2) the scale and timing of change over the next three decades.

B. Study Scope

Our study scope includes designing and evaluating three future energy scenarios that deeply decarbonize the PGE service territory's energy system. We refer to these scenarios throughout the report as "deep decarbonization pathways" or simply "pathways". We also developed a Reference Case reflecting current policy to provide a benchmark against the pathways scenarios.

The primary results of our study include projections from today to 2050 of: (1) energy demand by sector and type; (2) energy supply; (3) energy-related CO₂ emissions; and (4) energy system-related costs. This is supplemented by detailed results for the electricity sector, including electricity demand, installed capacity, generation, and hourly dispatch results for PGE's bulk power system.

Given our focus on exploring energy system transformation, we account for all forms of energy (e.g., gasoline, pipeline gas, hydrogen) and our analysis is not limited to electricity. We include CO₂ emissions from energy use, but we do not track non-energy CO₂ and non-CO₂ GHGs. The geography for our analysis is confined to PGE's service territory and excludes the rest of Oregon. Since one of the primary objectives of the study is to explore economy-wide compliance with a GHG target, we include load from customers that are currently under direct access to account for all energy use.

³ These strategies are commonly referred to as the "three pillars".

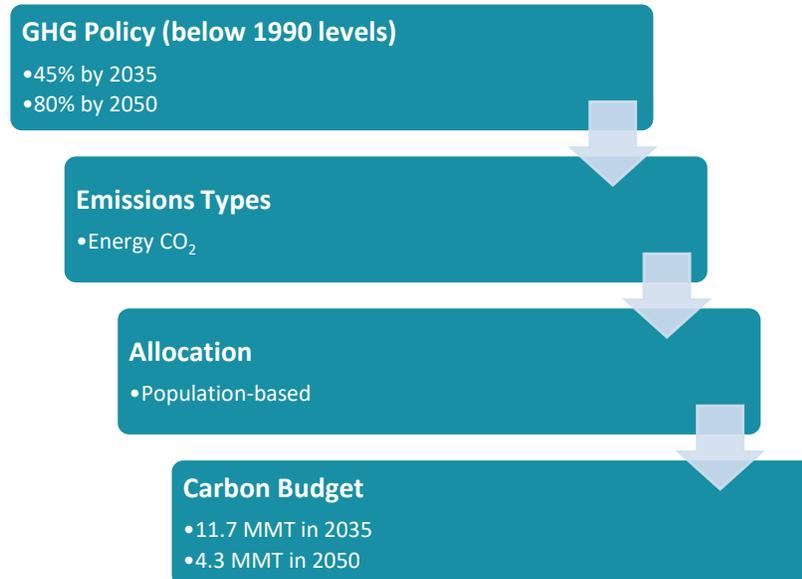
Given the exploratory nature of this study, it is important to emphasize what this study *is not*:

- Our scenarios are not a forecast of the future;
- We are not predicting future outcomes or assigning probabilities to scenarios;
- We are not choosing or recommending a pathway to 2050;
- Scenarios assessed here are not exhaustive and thousands of plausible alternatives exist;
- Scenarios do not reflect PGE’s business plan or future resource acquisitions; and
- This study’s modeling approach and results do not replace existing tools or processes used in IRP, such as defining “need” for resource adequacy or identifying optimal portfolios, nor do they replace cost-effectiveness evaluation, etc.

C. Study Emissions Target

For the purposes of this study, the energy-related CO₂ emissions budget for PGE’s service territory is 11.7 million metric tons (MMT) in 2035 and 4.3 MMT in 2050. Developing an appropriate emissions budget to evaluate deep decarbonization requires numerous assumptions to account for: (a) the fact that currently there is no binding, economy-wide GHG policy covering PGE’s service territory; (b) any state-wide emissions limit must be translated into a budget for PGE’s service territory; and (c) the scope of our work includes energy-related CO₂ emissions and excludes non-energy CO₂ and non-CO₂ GHGs. Our approach for deriving the study’s emissions budget is summarized in Figure 1 and further described below:

Figure 1 Approach to Develop Study’s CO₂ Target



- **GHG Policy.** The context for emission reductions, discussed in the proposed cap-and-trade legislation, requires a reduction in statewide GHG emissions to: (a) 45 percent below 1990 levels by 2035; and (b) 80 percent below 1990 levels by 2050.

- **Emissions Types.** CO₂ emissions from fossil fuel combustion have been the predominant source of Oregon’s historical GHG emissions, and, since 1990, energy-related CO₂ emissions have accounted for four-fifths of total gross GHG emissions in the state. For simplicity, we apply the emissions reductions from the above GHG policy to Oregon’s 1990 energy-related CO₂ emissions, which were approximately 46 MMTCO₂.⁴ This results in a state-wide budget for CO₂ emissions from fossil fuel combustion of approximately 25.2 MMTCO₂ in 2035 and 9.2 MMTCO₂ in 2050. Based on a state population forecast of 5.59 million in 2050, this results in a per capita emissions budget of 1.6 tCO₂ per person, which is consistent with prior decarbonization studies.
- **Budget Allocation.** We allocate the state-wide emissions budget to PGE’s service territory using its projected share of Oregon’s population. In 2015, the PGE service territory included approximately 1.8 million people or 45 percent of Oregon’s population. Projections of long-term population growth show counties within PGE’s service territory growing at a slightly faster rate than the state as a whole. PGE’s share of the state’s population is projected to increase to 46.3 percent in 2035 and 47 percent by 2050. This translates into a carbon budget of 11.7 MMTCO₂ in 2035 and 4.3 MMTCO₂ in 2050.

The carbon budget we have developed for PGE’s service territory is specific to this study. Any future policy mechanisms used to achieve emissions reductions, such as a price on carbon or complementary measures, may result in alternative emissions outcomes than those modeled here. In other words, the *total* statewide GHG emissions target may be compliant in the future, but *where* mitigation occurs is not definite. For example, more or less mitigation may occur between: (a) PGE’s service territory and the rest of Oregon; (b) buildings and the industrial sector; and (c) sources of energy CO₂ and other GHGs.

⁴ We note that our approach implicitly assumes that non-energy CO₂ and non-CO₂ GHGs will be reduced on an equivalent percentage basis in order to achieve the overall GHG targets. Historical emissions data from DEQ (2016).

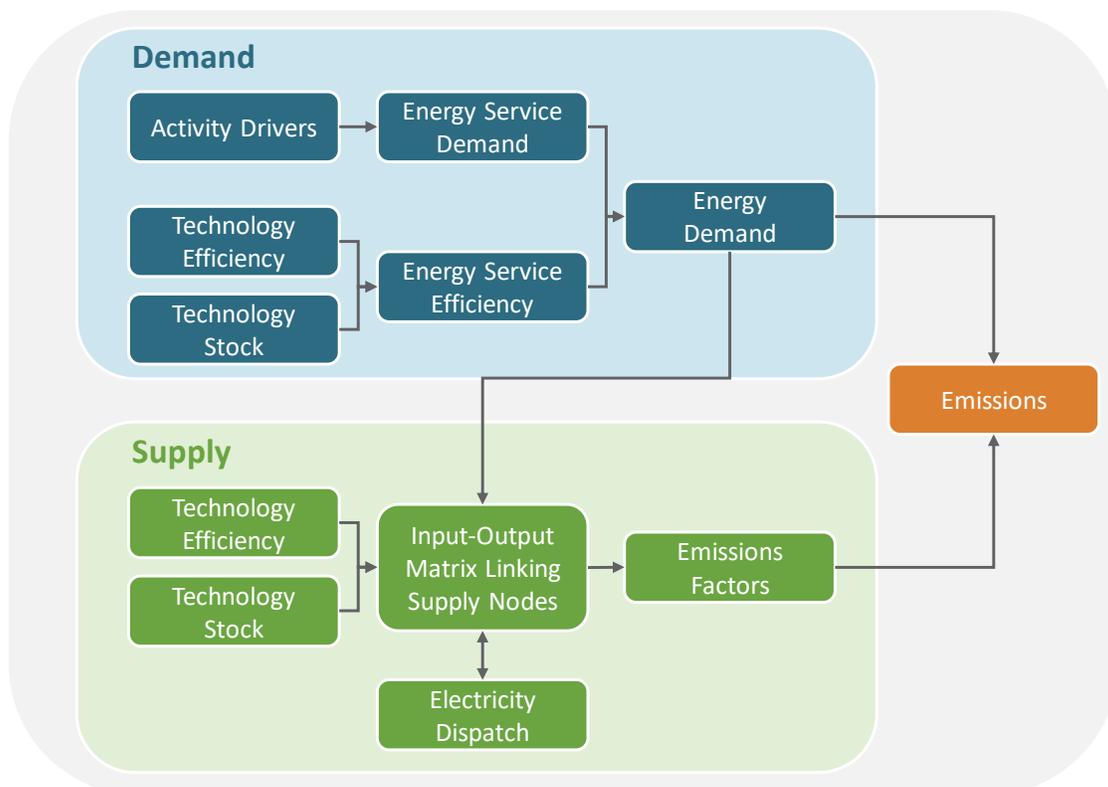
II. Study Assumptions and Approach

A. EnergyPATHWAYS Modeling Framework

We use EnergyPATHWAYS, a bottom-up energy systems model, to estimate energy demand, emissions and costs for each future energy scenario. Our analysis starts with the same model and approach we have previously used to evaluate deep decarbonization for the United States, the State of Washington and other jurisdictions. We developed a detailed representation of the PGE service territory’s energy system, including infrastructure stocks and energy demands for buildings, industry, and transportation. Our analysis incorporates an hourly dispatch of PGE’s electricity system, which allows us to better understand fundamental changes to electricity supply and demand, such as how to balance very high levels of intermittent renewables and the impact of electrification on hourly load.

Figure 2 depicts the general structure of EnergyPATHWAYS with the demand- and supply-side of the energy system shown separately. The demand-side calculates the quantity of energy demanded by different services at the technology level, such as the kWh of electricity and therms of pipeline gas demanded by water heaters in the residential sector. The supply-side determines how energy demand is met, such as the share of electricity provided by gas-fired combined cycle power plants, onshore wind power plants and rooftop solar PV. The energy system is simulated in sequence with the demand-side run prior to the supply-side.

Figure 2 General Structure of EnergyPATHWAYS



The demand-side starts with exogenous projections of activity drivers, such as population, households, commercial floorspace and industrial value of output. These drivers serve as the basis for projecting demand for energy services. For example, as the number of total residential households and square footage increases, then the demand for lighting will similarly increase. The technology composition of the stock along with the efficiency of each technology creates a service efficiency. In the lighting example, a transition from incandescent to CFL and LED light bulbs would improve service efficiency. Energy service demand and service efficiency are then combined to calculate the demand for energy, while the fuel type depends on the stock of technologies used to satisfy the demand for energy services.⁵

The supply-side is characterized by an input-output (IO) matrix that specifies the flow of energy between “supply nodes” that produce or deliver energy. Examples of supply nodes include power plants and transmission and distribution infrastructure. The coefficients in the matrix specify the amount of input energy required to produce one unit of output energy. For example, a gas-fired combined cycle power plant with a heat rate of 6,824 Btu/kWh (50% efficiency) would require 2.0 units of natural gas to generate 1.0 unit of electricity. These coefficients are dynamic and reflect: (1) changes in the composition and efficiency of supply-side technologies; and (2) outputs from an hourly electricity dispatch (i.e., the generation mix). From this process, emission factors are developed for each fuel. Finally, the emission factors from the supply-side are combined with final energy demand from the demand-side to estimate system-wide emissions.

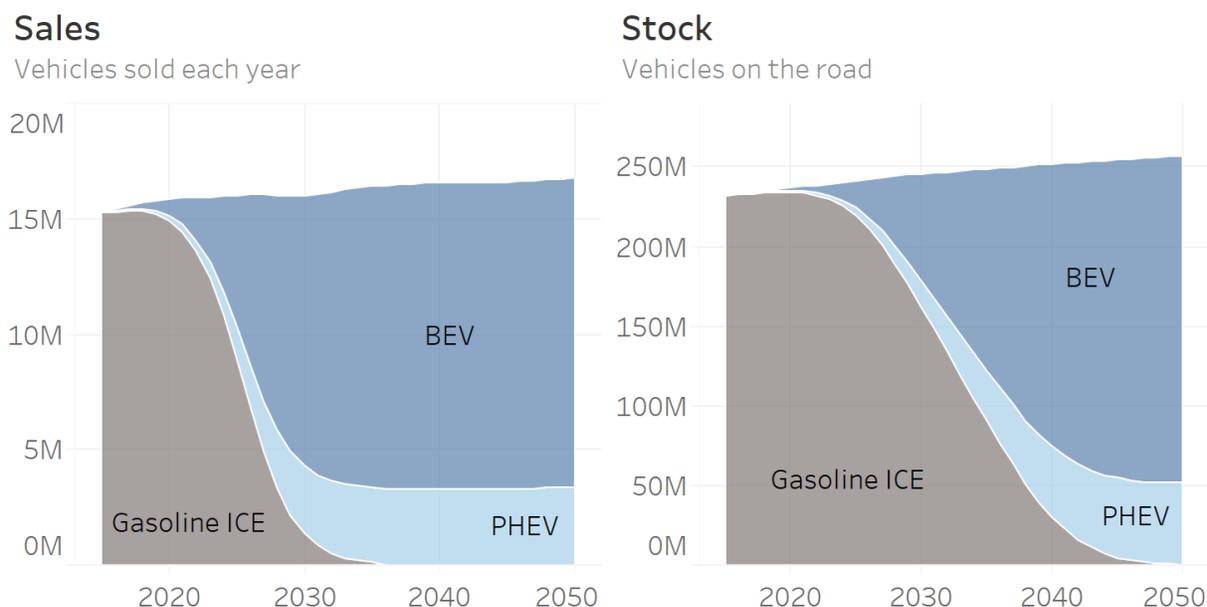
To reduce emissions, we develop measures to replace existing demand- and supply-side equipment and infrastructure with efficient and low-carbon technologies. For example, passenger travel currently provided by a gasoline vehicle is replaced by an EV, and a CFL light bulb is replaced by an LED light bulb. Future energy scenarios are designed by combining measures across sectors at the scale and rate necessary to meet the study’s emissions target.

We implement measures through a stock rollover process, where a portion of energy infrastructure retires in each year and must be replaced by new energy infrastructure. In a baseline scenario, retiring infrastructure is generally replaced with the same category of technology, but the cost and performance characteristics reflect the more recent installation year (e.g., a retiring reference dishwasher is replaced by a new reference dishwasher). Alternatively, measures specify the composition of new energy infrastructure (e.g., half of vehicle sales are plug-in hybrid electric vehicles by 2025).

The stock rollover process is illustrated for light-duty vehicles in Figure 3, where the measure shown on the left-hand side of the chart specifies that sales of new light-duty vehicles are 80 percent BEV and 20 percent PHEV by 2035. Changes to the vehicle stock, shown on the right-hand side, are moderated by this process and BEV/ZEV vehicles do not make up all vehicles on the road until 2050. All scenarios in this study assume that infrastructure is retired naturally (i.e., at the end of its lifetime), and there are no early retirements.

⁵ A portion of electric energy can be dispatched (i.e., flexible load), and this process is modeled on the supply-side.

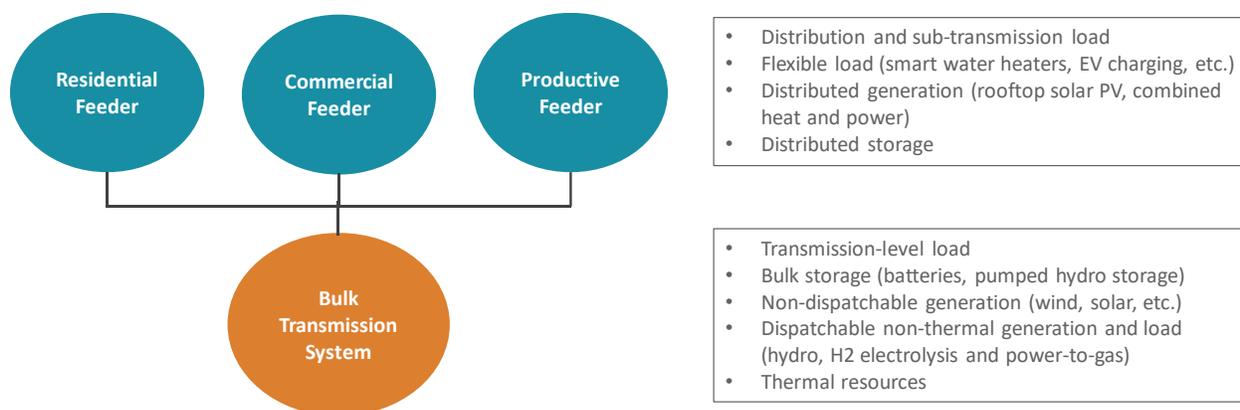
Figure 3 Illustrative Example of Stock Rollover in EnergyPATHWAYS



B. Electricity Sector Modeling

Electricity system operations in EnergyPATHWAYS are modeled on an hourly basis for each year through 2050. This includes a detailed representation of loads and resources at the feeder-level and the bulk transmission system. The structure of the electric system is shown in Figure 4 below, with the boxes illustrating the type of resources included within each node. Electricity dispatch and the development of load shapes are further described below, and we illustrate our approach for a three-day period (February 6-8, 2050).

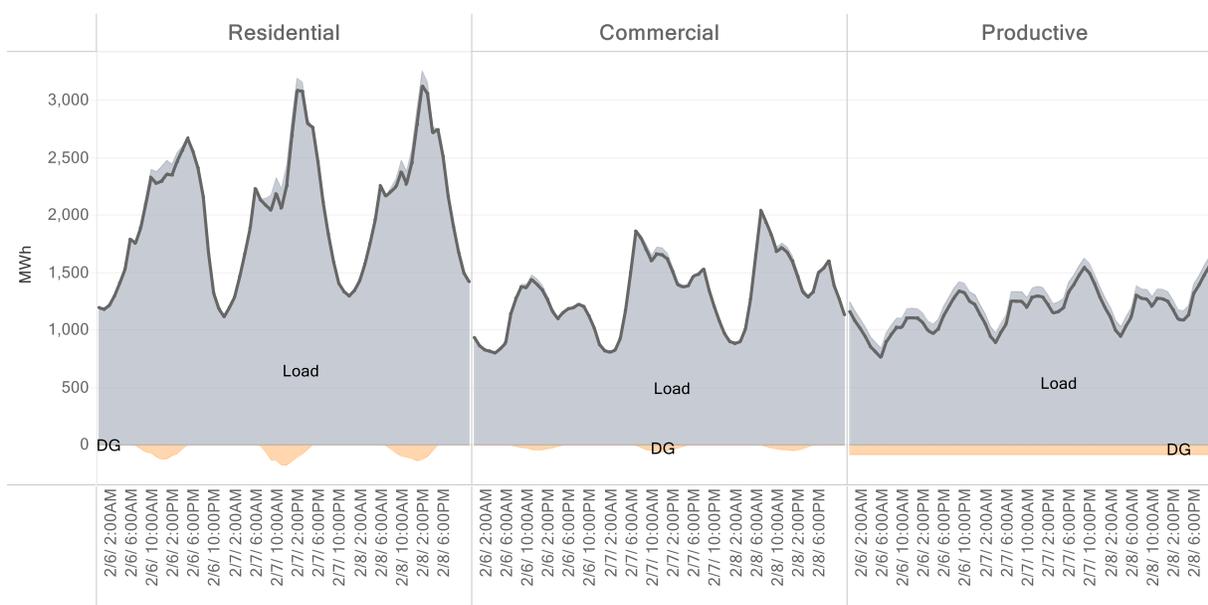
Figure 4 EnergyPATHWAYS Electricity System Structure



System load shapes are developed from the “bottom-up” by multiplying hourly sector, sub-sector, and technology-specific load shapes by the associated annual electricity consumption.⁶ The bottom-up shape is then calibrated against a historical, top-down system load shape. Going forward, the system load shape changes in each year as the contribution from end-uses evolves. For example, as LED lighting penetration increases, then night-time demand will decrease due to their higher efficiency relative to incandescent and CFL light bulbs. In addition, the electrification of space heating will increase electric load during winter hours to account for the contribution of heating during winter months.

Sub-sector loads are aggregated to sectors and mapped to a “stylized” residential, commercial and/or productive (industrial) feeder, which models customer type at the distribution level. This is primarily to allocate electric vehicle charging, which could take place at home or at the workplace, onto the electricity distribution system. Distributed generation, such as combined heat and power (CHP) and rooftop solar PV resources are modeled across feeders. Figure 5 shows load and distributed generation for three feeders with the net load shown as the black line.

Figure 5 Distribution System: Net Load

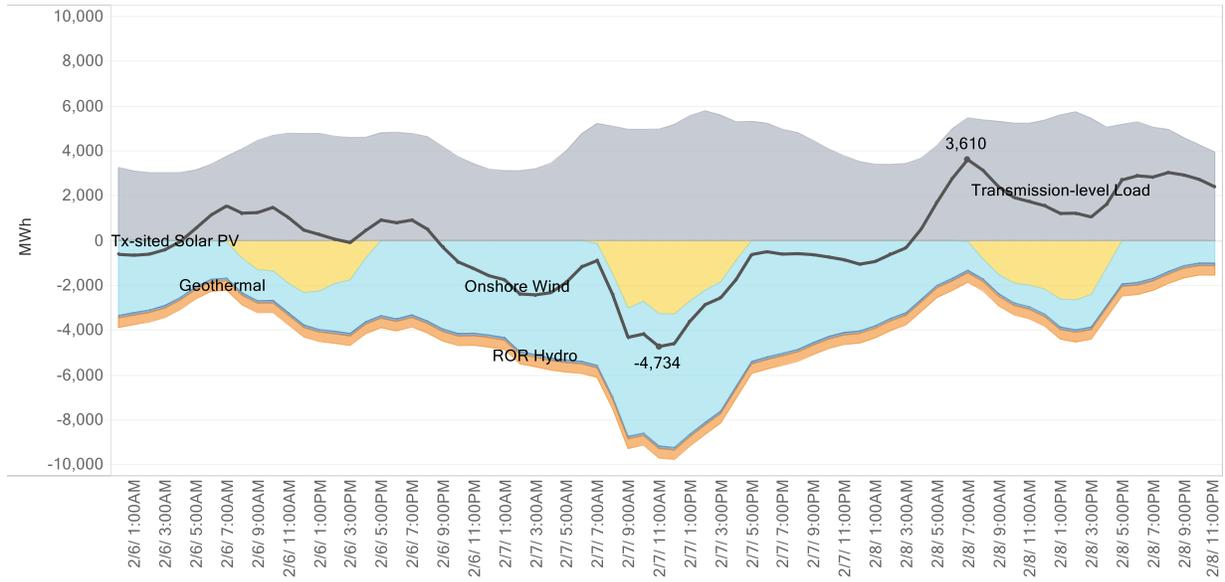


Note: figure is illustrative.

The bulk transmission system receives the distribution-level net load and combines them with transmission-level loads, such as electrolysis and power-to-gas facilities. Output from non-dispatchable resources on the transmission system, such as wind, solar, geothermal and run-of-river hydro, is then accounted for to produce an initial system net load signal, as shown in Figure 6 below. During this three-day snapshot, the minimum net load in a single hour is -4,734 MW due to the coincidence of high wind and solar generation.

⁶ Load and resource shapes reflect 2011 weather conditions.

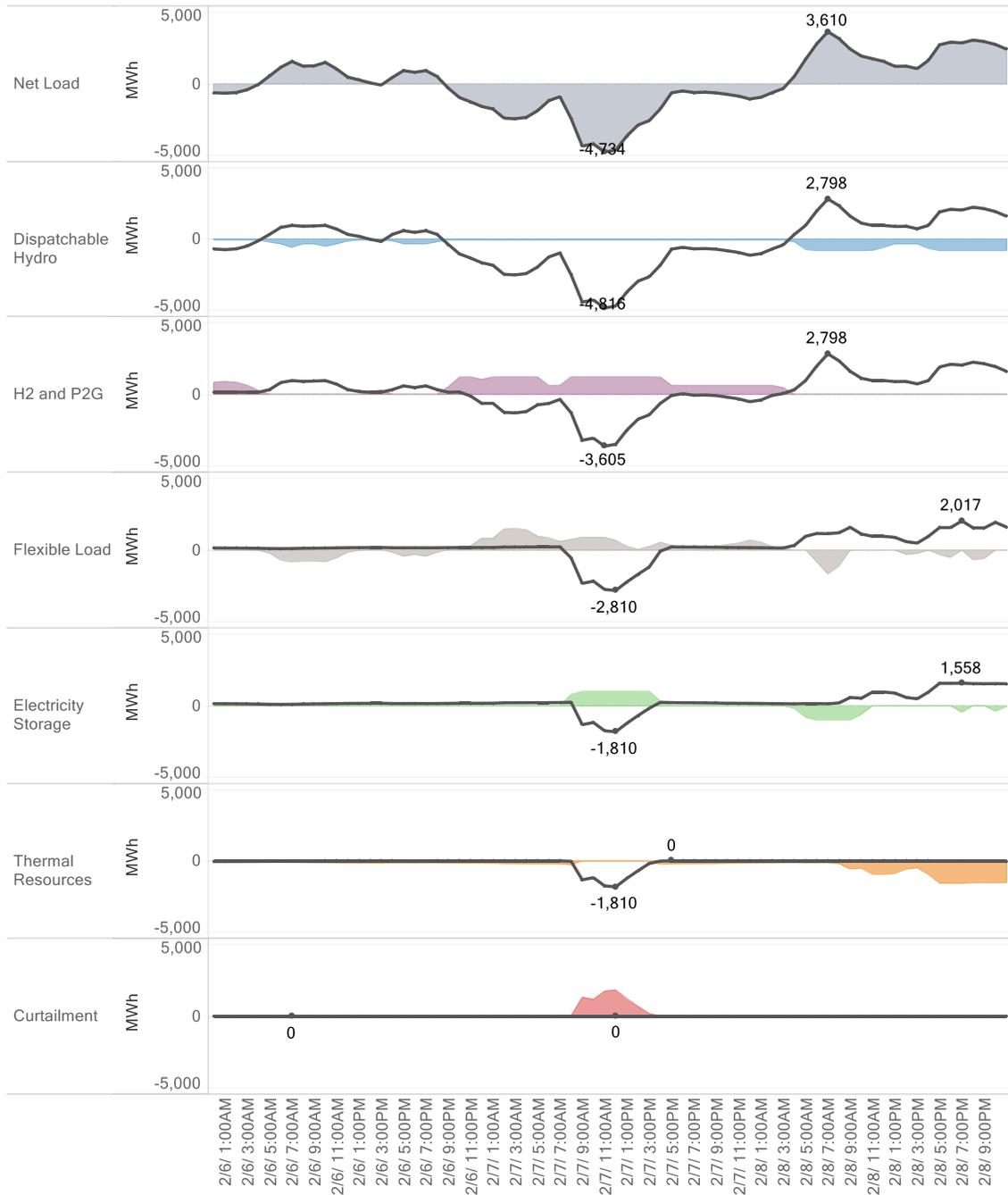
Figure 6 Transmission System: Net Load



Note: figure is illustrative.

Figure 7 illustrates the dispatch of flexible resources in sequence, with each resource dispatching to minimize the net load peaks and valleys. During the three-day period, net load starts with a maximum of 3,610 MW and a minimum of -4,734 MW. Flexible, carbon-free resources, including dispatchable hydro plants, electric fuel production facilities, flexible loads and energy storage, flatten the net load to a maximum of 1,558 MW and a minimum of -1,810 MW. Thermal generators are dispatched in order of marginal cost to serve the remaining positive net load, while the remaining negative net load is curtailed.

Figure 7 Flexible Resource Dispatch



Note: figure is illustrative.

We model all generation resources in PGE’s system, including existing power plants and contracts. The capacity of these resources was provided by PGE, and we developed plant heat rates (efficiencies) for thermal resources based on historical generation and fuel input data from Form EIA-923. Hydro resources are differentiated between dispatchable (e.g., Pelton-Round Butte) and run-of-river, and both resources types are constrained by a monthly energy budget. For imports, we use projected electricity

market prices (in \$/MWh) and natural gas prices (in \$/MMBtu) provided by PGE to develop market heat rates (in MMBtu/MWh) to both cost and assign an emissions intensity.

We use the following heuristic to ensure the quantity of installed generating capacity meets system load in every hour of the year. First, “annual capacity need” is estimated as the maximum hourly net load plus operating reserves. Next, the installed capacity of dispatchable resources is de-rated by their forced outage rate to estimate their contribution. Finally, generic capacity resources are added to fill any gap between “annual capacity need” and the contribution of dispatchable resources. We assume generic capacity resources have the cost and performance characteristics of a frame type combustion turbine, which is consistent with PGE’s IRP.

We note that our modeling results may differ from PGE’s IRP due to the use of alternative models and the inclusion of direct access loads in our scope. We describe the electricity resources for each scenario in Section III.B.1 below.

C. Energy Demand and Supply

EnergyPATHWAYS was originally developed to assess deep decarbonization for the United States, and most of the energy demand and supply inputs are drawn from the EIA’s National Energy Modeling System (NEMS) that produces the *Annual Energy Outlook*.⁷ NEMS input data is comprehensive of the U.S. energy system and internally consistent. The primary geography for energy demand in NEMS is the census division, which each include a collection of states. For example, the Pacific census division includes Washington, Oregon and California, while the Mountain census division aggregates the remaining states in the West.

Given the common input data and energy system representation, EnergyPATHWAYS also uses census division as the primary geography. However, the model is geographically flexible by accepting energy demand and supply input data at a variety of geographical resolutions (e.g., state-level) and mapping these together onto one consistent geography. We used this geographic mapping feature to develop the underlying energy system representation for PGE’s service territory. Figure 8 illustrates this process, where energy system data for a variety of geographies is mapped to PGE’s service territory. This “downscaled” energy data is combined with direct inputs of PGE’s service territory to characterize the entire energy system. To allocate input data at various geographical resolutions to PGE’s service territory, we used: (1) households by county in PGE’s service territory; (2) land area (in square miles) by county in PGE’s service territory; and (3) value of shipments of products by industrial sector by state of origin, which allows us to estimate the quantity of industrial activity within a given subsector and state.⁸

⁷ For example, see Risky Business Project (2016).

⁸ PGE provided county-level households and land area. Value of shipments data is from the Bureau of Transportation Statistics and Federal Highway Administration’s 2015 Freight Analysis Framework.

Figure 8 Geographic Downscaling



Table 2 summarizes the primary input data sources for energy demand by subsector. We use the 2013 PGE Residential Appliance Saturation Survey (RASS) to characterize the existing stock of the residential space heating, air conditioning and water heating subsectors. This includes the composition of technologies and fuels used in single-family, multi-family and manufactured homes. Energy use intensity (energy consumption per stock) is derived from the EIA’s Residential Energy Consumption Survey (RECS) and the Northwest Energy Efficiency Alliance’s (NEEA) Residential Building Stock Assessment. Energy demand for the remaining residential subsectors (e.g., refrigerators, dishwashers, etc.) is from the EIA AEO 2017. Vehicle miles traveled (VMT) for light-, medium- and heavy-duty vehicles are from Oregon’s 2017 Highway Cost Allocation Study (HCAS), while the remaining energy demand is primarily from the EIA’s AEO 2017.

Table 2 Summary of Energy Demand Input Data

Demand Subsector	Input Data Sources	Input Data Geography
Residential Space Conditioning and Water Heating	PGE 2013 RASS Study: existing stocks	Service Territory
	EIA RECS and NEEA: energy use intensity	State
Other Residential Subsectors	EIA AEO 2017: energy demand	Census Division
Commercial Subsectors	NWPCC 7 th Power Plan: square footage	State
	EIA AEO 2017: energy demand	Census Division
Industrial Subsectors	EIA AEO 2017: energy demand	Census Region
Passenger and Freight Transportation	2017 Oregon HCAS: vehicle miles traveled	State

We compared the initial bottom-up energy demand projections against top-down energy demand data from the EIA’s State Energy Data System (SEDS), which includes historical energy demand by fuel and sector. We calibrated EnergyPATHWAYS to reconcile any differences between our near-term modeling outputs and historical data by scaling energy service demand or energy demand. We further calibrated electricity consumption by sector to ensure consistency with PGE’s load forecast through 2050.

Energy demand projections are developed separately for a variety of final energy types, which can broadly be categorized as: (1) electricity; (2) pipeline gas; and (3) liquid fuels.⁹ Table 3 summarizes the types of resources that can supply each final energy type, and the supply mix determines the emissions intensity of fuels. For example, electricity can be supplied by a variety of fossil and carbon-free

⁹ Additional final energy types are modeled, but these represent the vast majority of final energy demand.

resources, and Section III.B.1 details electricity supply assumptions for PGE’s service territory. Pipeline gas can be supplied with a mix of natural gas, renewable natural gas (RNG) produced from bioenergy, hydrogen (H2) produced through electrolysis, and synthetic natural gas (SNG) produced through power-to-gas (P2G). Liquid fuels are supplied by refined fossil sources, as well as fuels developed using bioenergy (i.e., renewable diesel and jet fuel).

Table 3 Final Energy Types and Supply Sources

Category	Final Energy Type	Supply Sources
Electricity	Electricity	Coal and natural gas (fossil); hydro; wind; solar PV; geothermal
Pipeline Gas	Pipeline Gas	Natural gas (fossil); RNG (biomethane); H2; SNG
	Compressed Pipeline Gas (CNG)	
	Liquefied Pipeline Gas (LNG)	
Liquid Fuels	Gasoline	Fossil gasoline; ethanol
	Diesel	Fossil diesel; renewable diesel
	Jet Fuel	Fossil jet fuel; renewable jet fuel

D. Biomass

Biomass is key resource for decarbonizing energy systems due to its versatility, which allows for biofuels to directly replace both liquid and gaseous fossil fuels. Examples of conversion routes include renewable natural gas (RNG) that replaces natural gas and renewable diesel that replaces diesel. However, the supply of sustainable or net-zero carbon bioenergy resources is limited, and, in prior analyses, scarce bioenergy resources are allocated to fuels and sectors that are challenging to electrify, such as jet fuel for aviation.

In this study, we use the U.S. Department of Energy’s *2016 Billion-Ton Report* as the primary source for the availability and cost of bioenergy resources. Given that the supply curve is for the U.S., we make the following assumptions. First, the PGE service territory’s allocation of the national supply is its population-weighted share, which is equal to 7.3 million dry tons (MDT), as shown below:

$$PGE's\ share = \frac{PGE\ population}{U.S.\ population} \times U.S.\ supply\ of\ sustainable\ biomass\ feedstocks$$

$$7.3\ MDT = \frac{1.8\ million}{320.9\ million} \times 1,300\ MDT$$

Second, we assume that other jurisdictions pursue similar bioenergy-related actions, which means that the cost of producing and consuming biofuels reflects movement up the national supply curve. This assumption addresses two considerations: (1) for sub-national (e.g., state or utility service territory) deep decarbonization analyses, it would be unrealistic to assume individual jurisdictions all consume the same (low-cost) portion of the bioenergy supply curve; and (2) given the high cost of transporting biomass across long distances, it’s likely that biofuels would be developed close to their source and transported across the country via the same networks that currently transport fossil fuels. Finally, we assume that the biomass feedstock is net-zero carbon, which results in biofuels with very low emissions rates due to some emissions from non-bioenergy use in conversion and refining processes.

E. Key Data Sources

Table 4 summarizes the key data sources used in our energy system modeling. We use data from PGE’s 2016 IRP to characterize the cost and performance of electricity supply technologies and rely on the 2013 PGE RASS study to characterize the existing stock of residential appliances, as described above. This is supplemented by state and regional data sources, such as Oregon’s Office of Economic Analysis (OEA) and the Northwest Energy Efficiency Alliance (NEEA). Most of the remaining sources are publicly-available reports produced by national laboratories, such as the U.S. Department of Energy (DOE).

Table 4 Overview of Key Data Sources

Category	Sources
Energy Supply Technology Cost and Performance	<ul style="list-style-type: none"> • PGE 2016 Integrated Resource Plan • NREL Annual Technology Baseline 2017 • EIA Form 923 • DOE Hydrogen Analysis (H2A) Project • ENEA Consulting (2016)
End-Use Technology Cost and Performance	<ul style="list-style-type: none"> • Input data for EIA’s National Energy Modeling System (NEMS) used to produce the Annual Energy Outlook • NREL Electrification Futures Study: End-Use Electric Technology Cost and Performance Projections
Building Stock Characteristics	<ul style="list-style-type: none"> • PGE 2013 Residential Appliance Saturation Study • NEEA Building Stock Assessment reports
Fossil Fuel Prices	<ul style="list-style-type: none"> • EIA Annual Energy Outlook 2017
Miscellaneous	<ul style="list-style-type: none"> • DOE 2017 Billion-Ton Report • FERC Form 714 • 2017 Oregon Highway Cost Allocation Study • OEA Forecasts of Oregon's County Populations and Components of Change, 2010 – 2050

Note: DOE is the U.S. Department of Energy; EIA is the U.S. Energy Information Administration; FERC is the Federal Energy Regulatory Commission; NEEA is the Northwest Energy Efficiency Alliance; NREL is National Renewable Energy Laboratory; and OEA is Oregon’s Office of Economic Analysis.

III. Scenarios

A. Overview

Table 5 provides an overview of the three pathways included in this study, which each incorporate alternative emissions reduction strategies and technologies. One of the primary objectives of our scenario design was to reflect a broad range of outcomes for the electricity sector.

The **High Electrification** pathway relies on electrifying space and water heating in buildings and deploying bulk energy storage to balance high levels of renewable generation. Passenger transportation is characterized by high levels of battery electric vehicles (BEV), while freight transportation includes both battery electric and hybrid diesel trucks. The **Low Electrification** pathway decarbonizes energy supply with a variety of renewable fuels, and electrolysis and power-to-gas facilities provide both electricity balancing services and decarbonized pipeline gas. Passenger transportation is primarily BEV, while compressed and liquefied natural gas trucks are incorporated in the freight transportation sector. The **High DER** pathway is highly electrified and distributed, with increased rooftop solar PV and distributed energy storage in buildings and industry.

To provide a benchmark to compare the pathways against, we developed a **Reference Case** that projects business-as-usual conditions. This includes compliance with state-level policy such as the OCEP and CFP, as well as major federal policy such as improvements in corporate average fuel economy standards. The scenario is not designed to achieve an emissions target.

Table 5 Overview of Scenarios

Scenario	Description
High Electrification	Fossil fuel consumption is reduced by electrifying end-uses to the extent possible and increasing renewable electricity generation
Low Electrification	Greater use of renewable fuels, notably biofuels and synthetic electric fuels, to satisfy energy demand and reduce emissions
High DER	Distributed energy resources proliferate in homes and businesses, which also realize higher levels of electrification
Reference	A continuation of current and planned policy, and provides a benchmark against the deep decarbonization pathways

Although the future energy scenarios are characterized by alternative mitigation strategies, they are all constrained by a set of common scenario design principles. This conservative approach allays a broad range of concerns surrounding the technical feasibility and economic affordability of realizing a deeply decarbonized energy system, such as the need for revolutionary technological improvements or disruptive lifestyle changes. The scenario design principles in this analysis include: (a) applying the same demand for energy services; (b) replacing energy infrastructure at the end of its natural life (i.e., there are no early retirements); (c) using commercial or near-commercial technologies; (d) limiting the supply of sustainable bioenergy use; and (e) ensuring there are sufficient electricity resources to serve load in all hours. The sections below describe the energy supply and demand assumptions for each pathway.

B. Energy Supply

1. Electricity Resources

Table 6 summarizes our electricity supply assumptions for each pathway. Coal-fired resource assumptions are consistent with PGE’s 2016 IRP and OCEP, where Boardman ceases operations by the end of 2020 and Colstrip units 3 and 4 are out of the resource mix by 2035. We assume the capacity of PGE’s existing gas-fired resource fleet is online through 2050, while the amount of energy generated from these resources is a function of our electricity dispatch.

Hydroelectric resources include Pelton-Round Butte, run-of-river (ROR) hydro, Mid-C hydro and other contracts. We assume projected hydro resources and contracts are extended through 2050 (a total of 933 MW), and an additional 23 MW of small hydro is placed on-line in 2035. We assume new geothermal resources of 100 MW in 2035 and growing to 500 MW by 2050. Prior studies have identified 832 MW of conventional geothermal potential in Oregon with a further undiscovered enhanced geothermal system potential of 1,800 MW.¹⁰

The High DER pathway includes approximately 2,500 MW of behind-the-meter (BTM) solar PV resources across buildings and industry by 2050. We developed this target based on the technical potential of distributed solar PV across PGE’s service territory identified in the 2016 IRP.¹¹ The High and Low Electrification pathways assume approximately 400 MW of BTM solar PV, which is two times the highest level of adoption from the same study.

Pathways rely on high levels of transmission-connected wind and solar PV to decarbonize electricity generation, including: (a) onshore wind located in the Pacific Northwest (PNW); (b) onshore wind located in central Montana; and (c) solar PV located in central Oregon. Approximately 75 percent of electricity generation comes from these resources in the High and Low Electrification pathways, and this level is lower in the High DER pathway due to the quantity of BTM solar PV resources. The installed capacity of these resources depends on the level of transmission-connected load.

Our Reference Case reflects current RPS policy (i.e., 50% in 2040) and any gap between the RPS obligation and generation from existing/projected qualifying resources is met with an equal amount of energy from PNW onshore wind and central Oregon utility-scale solar PV resources. Our analysis did not consider low-carbon generation from new carbon capture and storage (CCS) or nuclear resources.

¹⁰ See Pletka and Finn (2009).

¹¹ See Table 1-3 of Black and Veatch (2015). Technical potential of 2,810 MW_{dc} translated to 2,555 MW_{ac} assuming an inverter loading ratio of 1.1.

Table 6 Electricity Supply

	High Electrification	Low Electrification	High DER
Coal	Boardman ceases operations by the end of 2020 Colstrip 3 and 4 out of the resource mix by 2035		
Gas	Maintain current fleet		
Hydro	Extend projected hydro contracts through 2050 (933 MW) Additional 23 MW of small hydro		
Geothermal	500 MW additional		
Behind-the-meter Solar PV	405 MW _{ac}		2,555 MW _{ac}
Utility-scale Wind and Solar PV	75% of electricity generation		67% of electricity generation

Note: values for 2050 unless specified otherwise.

The high levels of variable renewable generation included in the pathways necessitate balancing resources to ensure renewables are sufficiently integrated. Table 7 summarizes the flexible resource assumptions for each pathway, all of which include 36 MW/160 MWh of energy storage that comes online in 2021 to approximate PGE’s proposed energy storage projects. Balancing in the High Electrification pathway is accomplished through 1,000 MW of bulk 8-hour energy storage, whereas the High DER pathway relies on 2,555 MW of distributed 6-hour storage, which is sized to the same capacity of distributed solar PV. No additional energy storage is developed in the Low Electrification pathway, which alternatively relies on flexible electrolysis and P2G loads. The size of these facilities depends on demand for hydrogen and synthetic natural gas, respectively.

All pathways incorporate flexible demand from select end-use sectors where: (a) load automatically shifts with changing electricity grid conditions; and (b) total electricity consumption does not change.¹² For example, the owner of an EV may wish to charge his or her vehicle when they arrive home, but they’re willing to delay charging to later in the evening without affecting the ability to take future trips. Two promising electric loads to operate flexibility include: (1) loads that have a thermal storage medium (i.e., hot water heater) that can operate within a range and allow for flexible operation without service degradation; and (2) transportation loads that require battery storage, which can allow for flexible charging and state-of-charge management without degrading service.

We assume 75 percent of load from light-duty vehicles and water heaters in buildings is flexible by 2050, and 50 percent is flexible in residential space conditioning, residential clothes washing and drying, and commercial space heating subsectors. The amount of flexible load in each pathway depends on the level of electrification, and the higher quantity of electric appliances (e.g., heat pump water heaters) in the High Electrification and High DER pathways provides higher end-use demand flexibility relative to the Low Electrification pathway.

¹² Flexible load is further constrained by the number of hours load can be delayed and advanced in time.

Table 7 Balancing Resources

	High Electrification	Low Electrification	High DER
Energy storage	Proposed energy storage resources (36 MW / 160 MWh)		
	1,000 MW bulk 8-hour storage	No additional	2,555 MW distributed 6-hour storage
Flexible Electric Fuel Loads	Excluded	H2 electrolysis and P2G facilities	Excluded
Flexible End-Use Loads	Percent of electric load that is flexible by 2050: <ul style="list-style-type: none"> • Light duty vehicles = 75% • Residential and commercial water heating = 75% • Residential space conditioning = 50% • Residential clothes washing and drying = 50% • Commercial space heating = 50% 		

2. Liquid and Pipeline Gas Fuel Blends

Table 8 summarizes our assumptions about the composition of pipeline gas, diesel and jet fuel in 2050. The Low Electrification pathway is characterized by several renewable fuels to decarbonize energy supply. Pipeline gas for buildings and industry is assumed to contain 15 percent renewable natural gas (RNG) and 15 percent synthetic electric fuels (H2 and SNG). The share of RNG is 85 percent in pipeline gas that is further liquefied or compressed for transportation vehicles, while the share of H2 and SNG is the same. Biomass is further used to produce liquid transportation fuels (e.g., renewable diesel). The High Electrification and High DER pathways assume no change to the supply of pipeline gas, with all biomass resources allocated to liquid transportation fuels.

Table 8 Liquid and Pipeline Gas Fuel Blend Assumptions in 2050

Type	Blend	High Electrification and High DER	Low Electrification	
		All Sectors	Res/Com/Ind	Transportation
Pipeline Gas	Natural Gas	100%	70%	0%
	RNG	0%	15%	85%
	SNG	0%	8%	8%
	H2	0%	7%	7%
Diesel	Fossil Diesel	0%	0%	0%
	Renewable Diesel	100%	100%	100%
Jet Fuel	Fossil Jet Fuel	0%	0%	0%
	Renewable Jet Fuel	100%	100%	100%

C. Energy Demand

1. Buildings and Industry

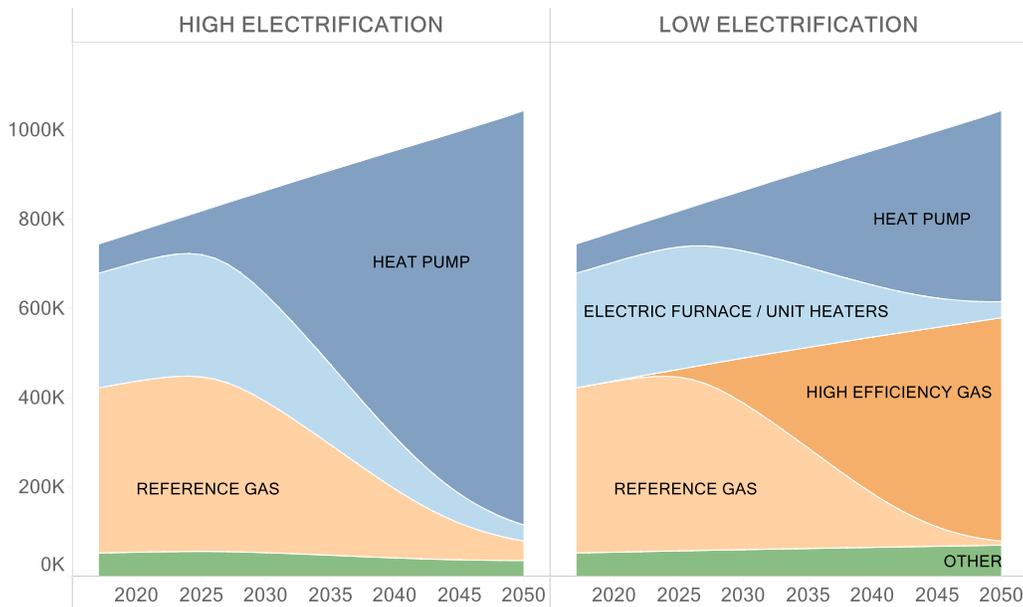
Table 9 summarizes the major low-carbon and efficient technologies in residential and commercial buildings. The High Electrification and High DER pathways are characterized by high levels of air source heat pump (ASHP) adoption for space heating and cooling needs, as well as efficient heat pump water heaters. The Low Electrification pathway relies on high efficiency gas-fired equipment to service space and water heating loads. In both pathways, lighting is provided by LEDs and the best available technology is adopted for other appliances, such as clothes washers, clothes dryers, refrigerators, etc.

Table 9 Predominant End-use Technologies in Buildings

	High Electrification and High DER	Low Electrification
Space Conditioning	Air source heat pump	High efficiency gas furnace High efficiency air conditioner
Water Heating	Heat pump water heater	High efficiency gas water heater
Lighting	LED	
Other Appliances	Best available technology	

We illustrate the change in today’s building equipment by showing the evolution of the residential space heating stock through 2050 in Figure 9. Heat in the High Electrification and High DER pathways is largely provided by heat pumps, which includes both standard systems and ductless, mini-split heat pumps. In contrast, heat in the Low Electrification pathway is met by adopting high-efficiency natural gas furnaces, as well as pursuing electric energy efficiency by replacing electric furnaces and heaters with heat pumps.

Figure 9 Residential Space Heating Stock



We incorporated electrification measures in the High Electrification and High DER pathways for a limited number of industrial end-uses, including process heat and boilers. This was informed by NREL’s Electrification Futures Study and includes adoption of electrotechnologies such as industrial heat pumps, resistance heating, induction furnaces and electric boilers.¹³ These measures translate into electricity representing slightly less than 10 percent of final energy demand for industrial boilers and process heat by 2050.

2. Transportation

Table 10 summarizes our assumptions for vehicle sales shares in 2035 for passenger transportation and freight trucks. In all pathways, battery electric vehicles (BEV) are 90 percent of light-duty vehicle sales, while the remaining 10 percent is: (a) plug-in hybrid electric vehicles (PHEV) in the High Electrification and Higher DER pathways; and (b) hydrogen fuel cell vehicles (HFCV) in the Low Electrification pathway. We assume battery electric trucks account for half of freight truck sales, while the remaining 50 percent is: (a) hybrid diesel trucks consuming renewable diesel fuel in the High Electrification and High DER pathways; and (b) CNG and LNG trucks consuming decarbonized gas in the Low Electrification pathway.

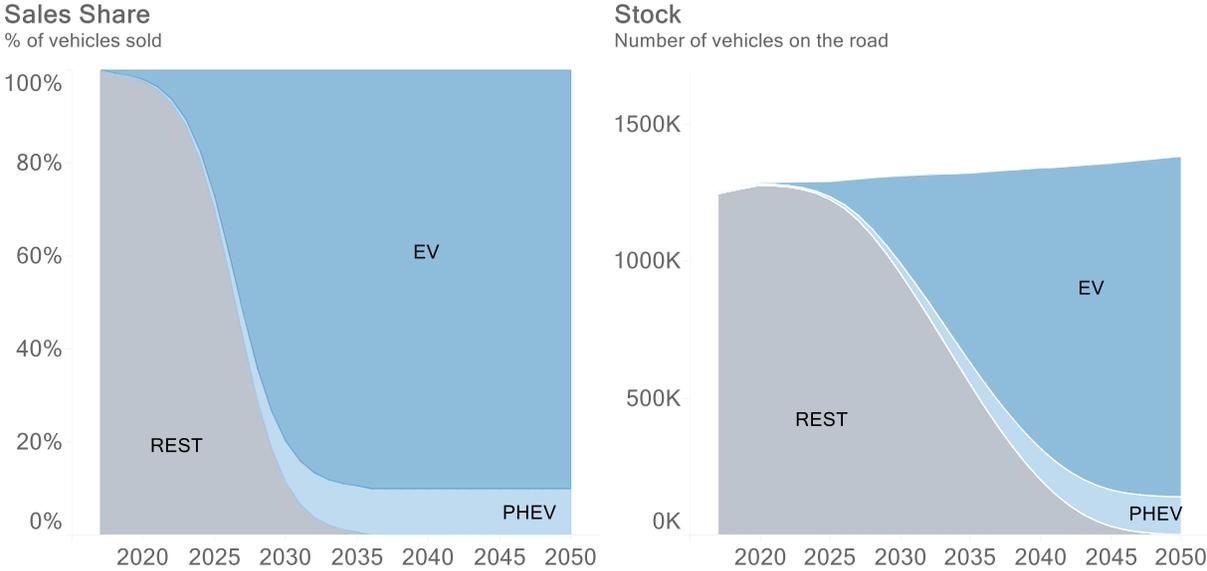
Table 10 On-Road Transportation Vehicle Sales Shares in 2035

Subsector	Technology Type	High Electrification and High DER	Low Electrification
Light-Duty Vehicles	Battery Electric	90%	90%
	Plug-in Hybrid Electric	10%	0%
	Hydrogen Fuel Cell	0%	10%
Medium-Duty Vehicles	Battery Electric	50%	50%
	Hybrid Diesel	50%	0%
	Hybrid CNG	0%	50%
Heavy-Duty Vehicles	Battery Electric	50%	50%
	Hybrid Diesel	50%	0%
	Hybrid LNG	0%	50%

Figure 10 shows how the assumptions in Table 10 change the stock of infrastructure over time, with light-duty vehicle sales shown on the left-hand side and the light-duty stock shown on the right-hand side. In the near-term, EV and PHEV light-duty autos and trucks make up a small portion of sales, but then increase to all vehicle sales in 2035. By the early 2030s, there are more than half a million EVs and PHEVs on the road, but the stock of vehicles does not completely turn-over to ZEVs until the mid-century.

¹³ See Section 4 of P. Jadun, et al. (2017).

Figure 10 Light-Duty Vehicle Stock-Rollover: High Electrification Pathway

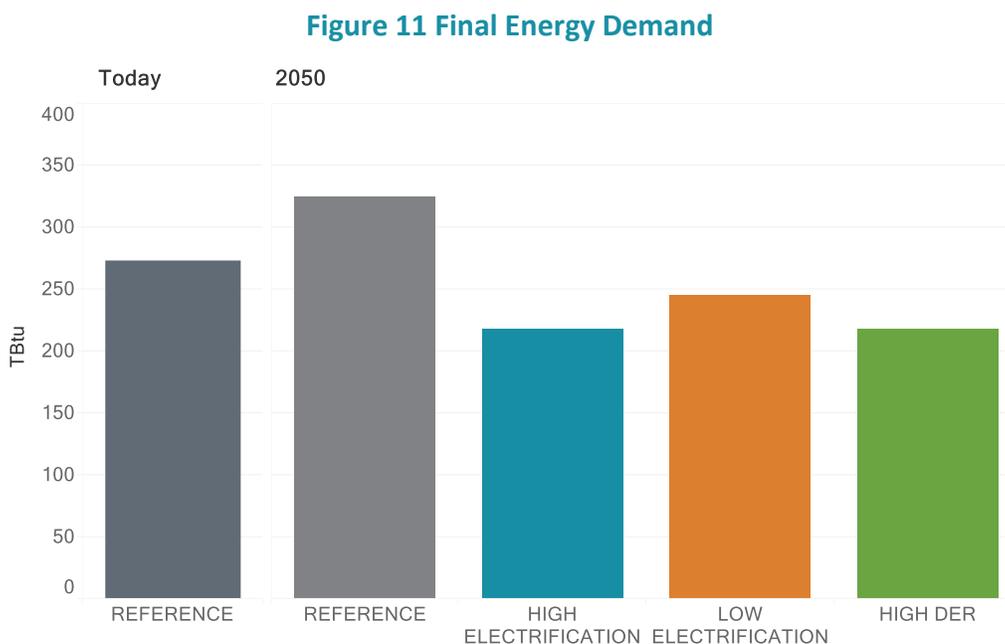


IV. Results: Energy System

In this section, we summarize the changes in the energy system for our future energy scenarios. We report several metrics for the energy system, including final energy demand, energy supply, energy related CO₂ emissions, and incremental energy system costs.

A. High-Level Summary

Reference Case final energy demand is projected to increase from 272 TBtu today to 325 TBtu, approximately a 20 percent increase, as shown in Figure 11 below. End-use demand is projected to increase as the drivers of energy use, such as population and economic activity, all grow through 2050. Final energy is used more efficiently in the pathways scenarios with a range of 218 to 245 TBtu by 2050, which represents a decrease of 25 to 33 percent below the Reference Case in 2050, and 11 to 19 percent below today's level.



Energy-related CO₂ emissions are projected to slightly decrease (-4%) in the Reference Case between 2017 and 2050, as shown in Figure 12. This is largely due to existing policies decarbonizing electricity generation and transportation fuels being offset by growth in overall electricity consumption and vehicle miles traveled. Emissions for all three pathways are below the study's 2050 GHG target of 4.3 MMTCO₂. Emissions per capita decrease from 10.9 tCO₂ per person in 2017 to 1.6 tCO₂ per person in 2050, an 85 percent decrease.

Figure 12 Energy-related CO₂ Emissions

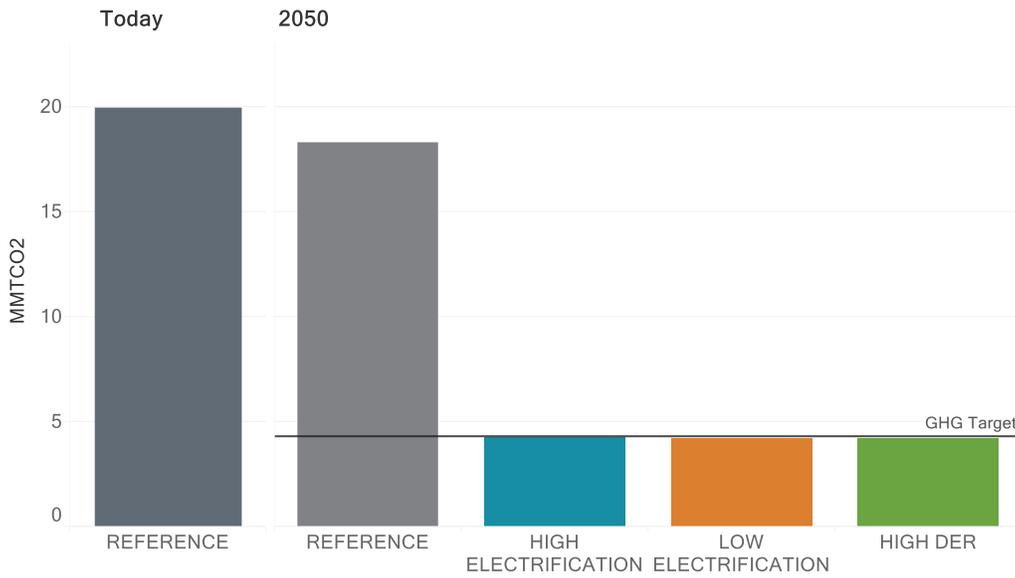
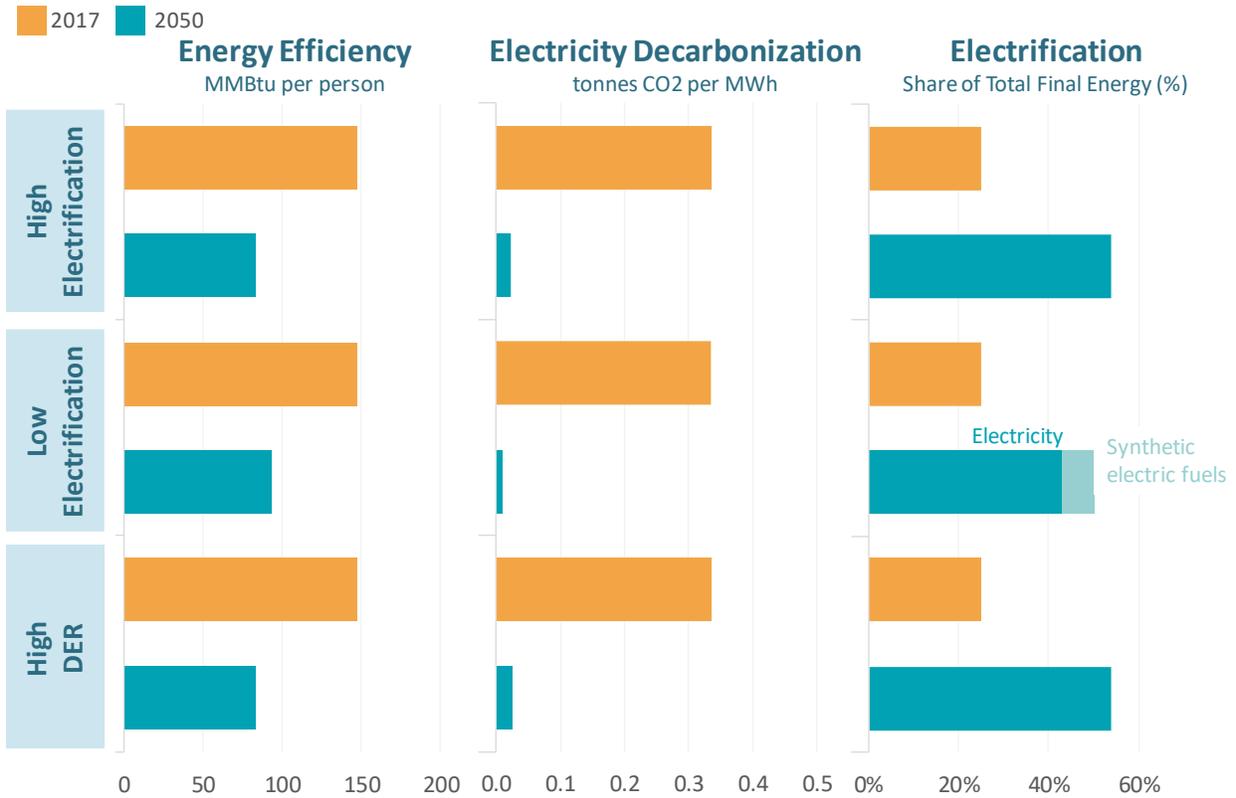


Figure 13 shows three metrics for decarbonization strategies (“three pillars”): (1) energy efficiency, which is estimated as final energy consumed per person; (2) electricity decarbonization, which is measured in tCO₂ emitted per MWh of generation; and (3) electrification, which is expressed as the share of total final energy that is electricity and electric fuels. Per capita energy consumption decreases from approximately 150 MMBtu per person today to between 83 and 93 MMBtu per person, a 37 to 44 percent decrease. This is accomplished without explicit reductions from baseline (Reference Case) energy service demand (e.g., vehicle miles traveled). The carbon intensity of electricity generation decreases by more than 90 percent and is below 0.03 tCO₂/MWh (300 kg CO₂/MWh) in all pathways. The percentage of electricity and electric fuels in total final energy increases from one-quarter today to at least half by 2050. In the Low Electrification pathway, the share of electricity is 43 percent (11 percentage points below the High Electrification pathway), but electric fuels make up 7 percent of total final energy, resulting in a total of 50 percent.

Figure 13 Three Pillars of Decarbonization



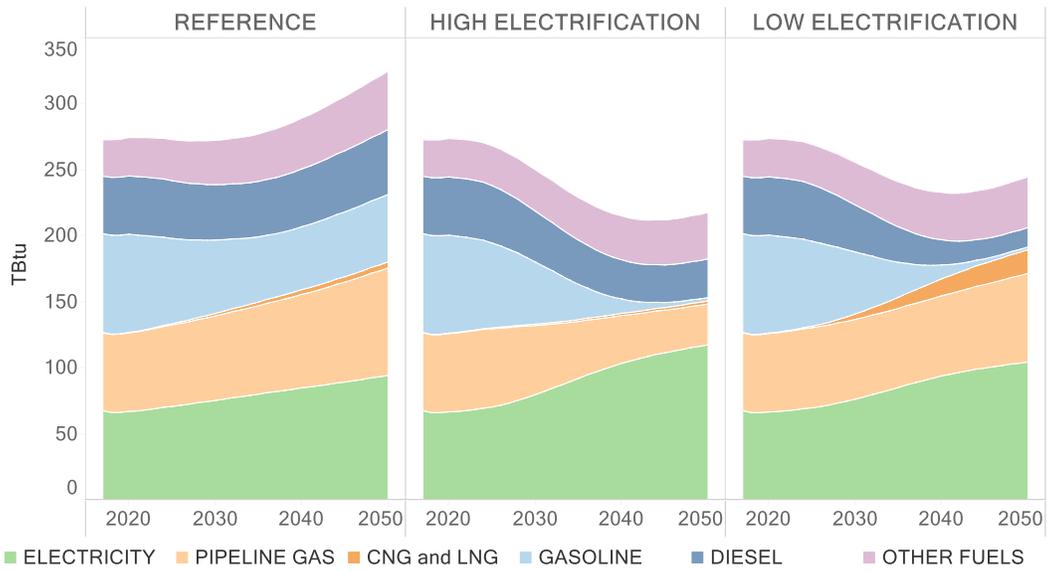
B. Energy Demand

Figure 14 shows end-use demand disaggregated by final energy type for each energy future.¹⁴ The role of electricity expands across all pathways and increases from 25 percent of total end-use demand to 43 to 54 percent in 2050.¹⁵ For comparison, the share of electricity only increases to 29 percent by 2050 in the Reference Case. Demand for liquid transportation fuels, such as gasoline and diesel, sharply decrease in all pathways. This decrease is compensated by higher demand for electricity, as well as CNG and LNG demand in freight transportation in the Low Electrification pathway.

¹⁴ In this section, results for the High DER scenario are not shown, because final energy demand is equivalent to the High Electrification scenario. The impact of increased rooftop solar PV is accounted for when we show retail energy deliveries, which is discussed in Section V.A.

¹⁵ This excludes synthetic electric fuels, which are categorized as “intermediate energy carriers”.

Figure 14 Final Energy Demand by Type



Note: "Other Fuels" includes final energy types such as jet fuel, liquefied petroleum gas, biomass, and steam.

Figure 15 summarizes final energy demand for the residential, commercial, productive and transportation sectors. The figure shows Reference Case final energy demand growing over time, with decreases in the transportation sector (primarily due to fuel economy standards) offset by increases in buildings and industry. Total end-use demand decreases by 2050 for all pathways largely due to the efficiency improvements in passenger transportation related to adopting battery electric vehicles. As a result, the transportation sector's share of end-use demand decreases from approximately 46 percent today to 30 percent in 2050. Energy is used more efficiently in residential and commercial buildings, but the level of change varies across pathways based on technology adoption, which we discuss in more detail below.

Figure 15 Final Energy Demand by Sector

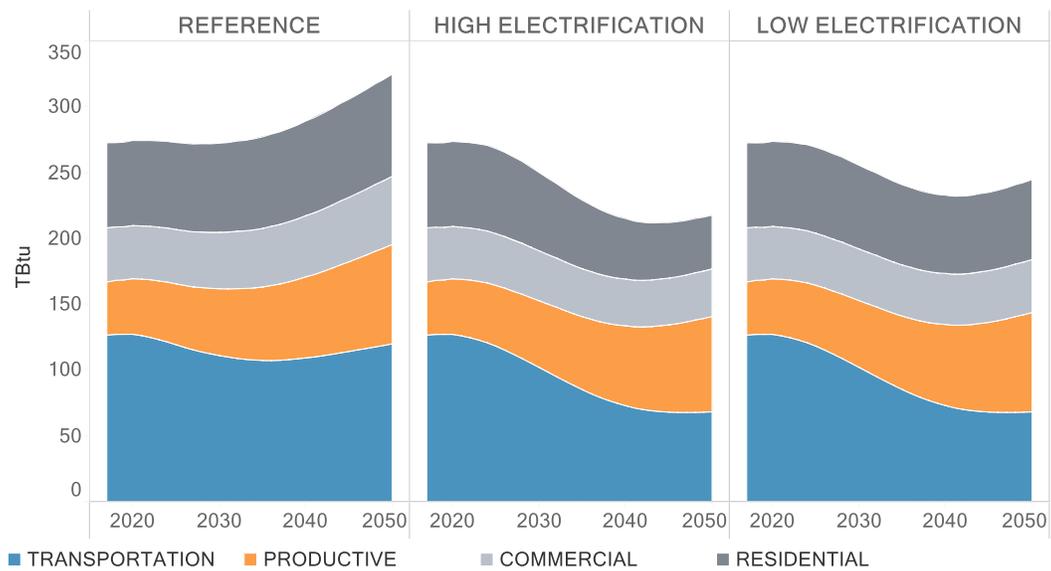
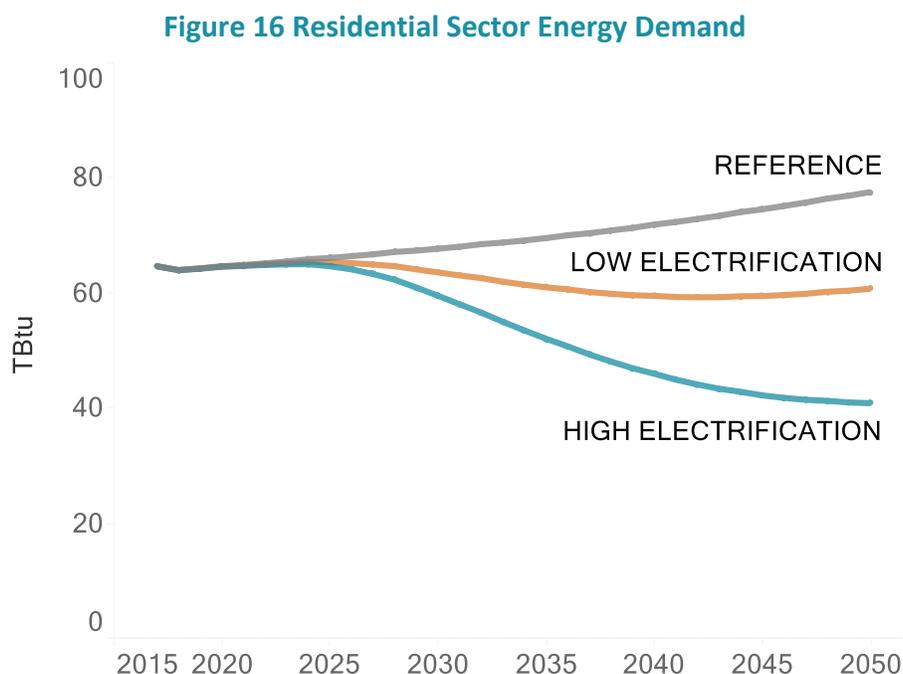


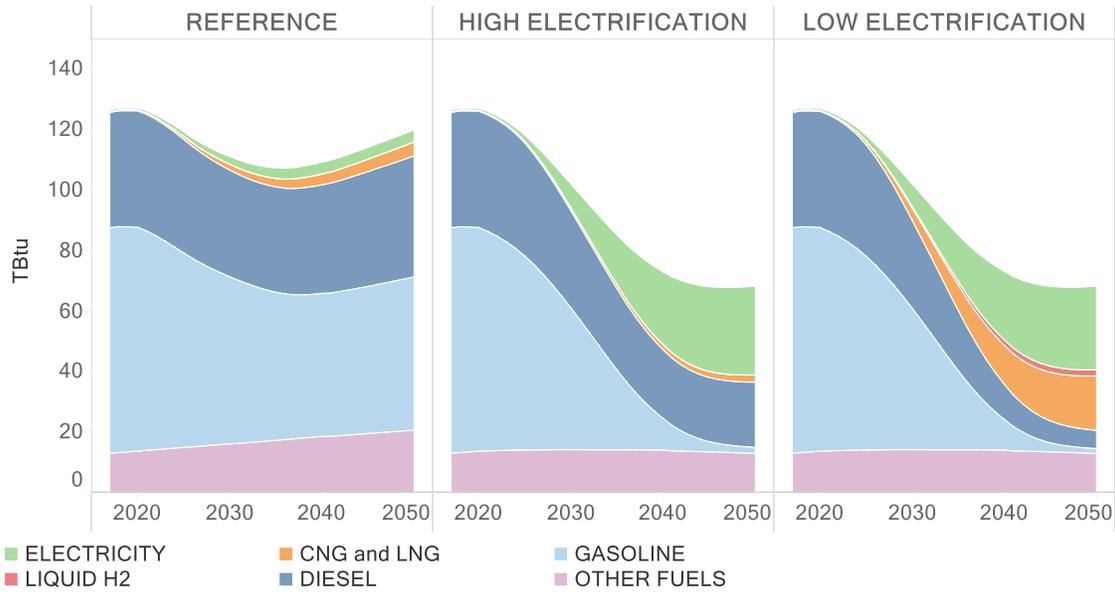
Figure 16 compares projections of residential energy demand and illustrates the improved use of energy in homes in the pathways scenarios relative to the Reference Case. All pathways include several electric energy efficiency measures, such as more efficient clothes washers and dryers, refrigerators, dishwashers and LED lighting. However, the large difference in final energy demand by 2050 between the High and Low Electrification scenarios is due to choices in space and water heating. The High Electrification pathway represents a world where households replace combustion-based furnaces and water heaters with air source heat pumps and heat pump water heaters, respectively. In the Low Electrification pathway, households adopt the most efficient gas furnaces and gas water heaters. However, the efficiency of heat pump technology relative to the best-in-class combustion equipment translates into deeper energy demand reductions.¹⁶



The projections of energy demand for the transportation sector shown in Figure 17 reflect the changing composition of vehicles on the road. By 2050, the light-duty vehicle fleet is almost entirely electric vehicles, which results in significant decreases in gasoline fuel consumption and only modest increases in electricity consumption, because battery electric powertrains are more efficient than internal combustion engines. In all pathways, half of all freight trucks are electric by 2050, resulting in electricity becoming the largest transportation fuel type. The High Electrification pathway continues to use diesel fuel for the remainder of its freight trucks, but the supply is increasingly renewable diesel (100 percent by 2050). The Low Electrification pathway alternatively relies on hybrid CNG medium-duty trucks and LNG hybrid heavy-duty trucks. By 2050, demand from the CNG and LNG trucks in the Low Electrification pathway accounts for over 20 percent of total pipeline gas demand.

¹⁶ For example, a high efficiency gas furnace has an annual fuel utilization efficiency (AFUE) of 0.98, whereas a standard air source heat pump installed in 2015 in the U.S. has a seasonal coefficient of performance (COP) of 2.45 and this is projected to increase to 3.75 by 2030. See Navigant Consulting (2014) and Jadun, et al. (2017).

Figure 17 Transportation Sector Energy Demand by Final Energy Type



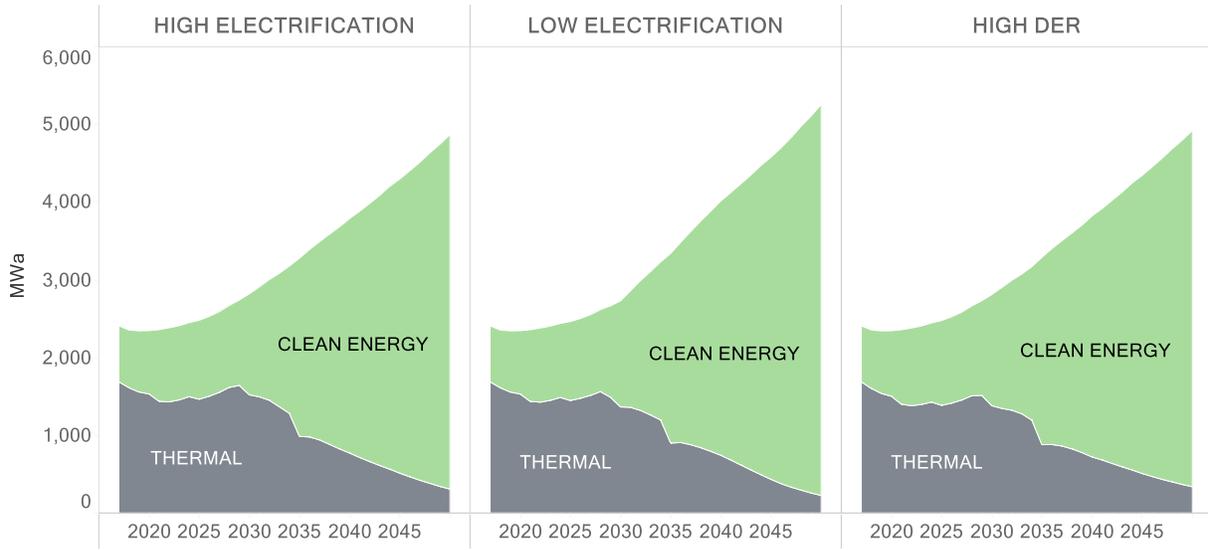
C. Energy Supply

1. Electricity

Figure 18 summarizes electricity supply through 2050, with generation from various resource types categorized as: (a) thermal, which includes generation from coal- and gas-fired resources, generic capacity and market purchases; and (b) clean energy, which includes generation from wind, solar, hydro and geothermal resources.¹⁷ The figure shows that total electricity generation across all pathways grows rapidly, and total generation requirements in 2050 are more than double today's level. In all pathways, generation from non-emitting resources is more than 90 percent of the total and increases by 165 to 190 MWa per year between 2030 and 2050. Generation from thermal resources decreases significantly after 2035, and annual generation falls between 300 and 400 MWa by 2050.

¹⁷ Our generation projections are not directly comparable to PGE's most recent IRP dispatch modeling due to the vintage of the load forecast provided for this study and the inclusion of direct access loads.

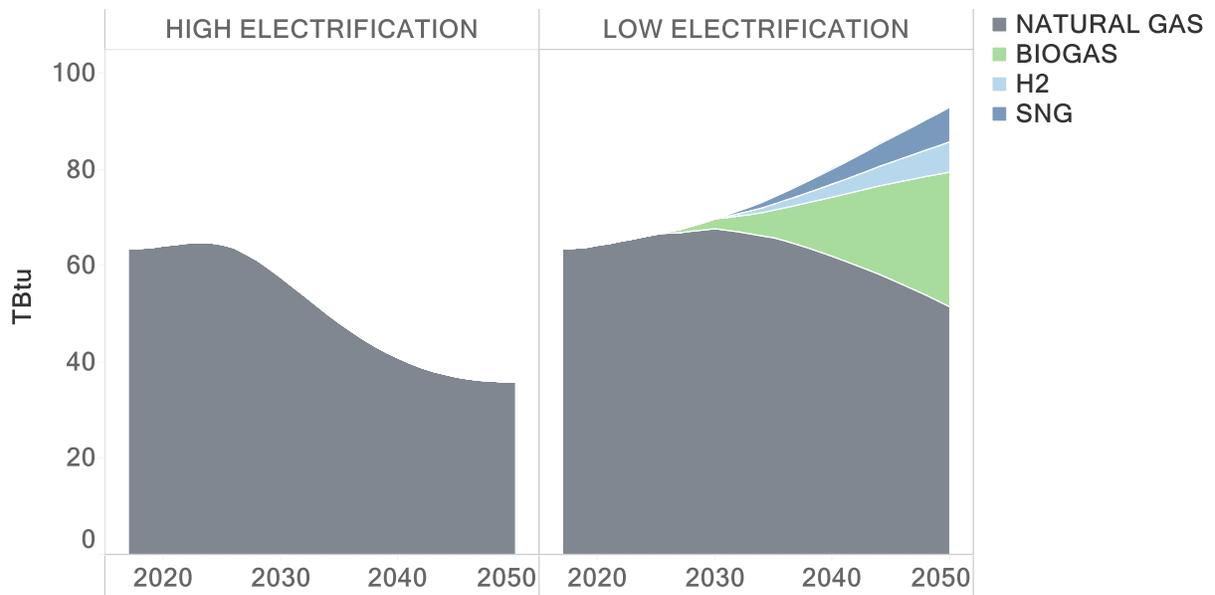
Figure 18 Electricity Supply



2. Pipeline Gas

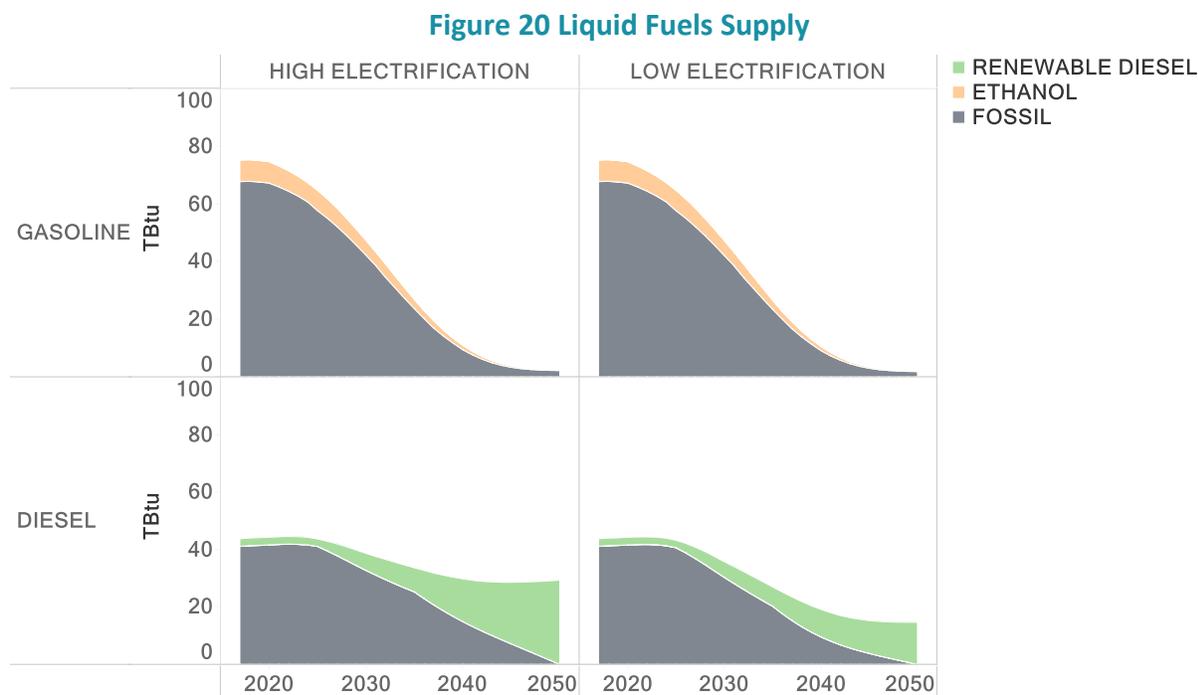
Figure 19 compares pipeline gas supply for the High Electrification and Low Electrification pathways. In the High Electrification pathway, the pipeline gas supply remains entirely natural gas and total supply decreases by more than 40 percent relative to today due to electrification in buildings. Pipeline gas is decarbonized in the Low Electrification pathway with a combination of biogas and synthetic electric fuels, which reduces the share of natural gas to approximately 55 percent by 2050. Total gas supply increases by approximately 40 percent relative to today largely due to incremental gas demand from freight trucks with only a portion offset by more efficient use of pipeline gas in buildings.

Figure 19 Pipeline Gas Supply



3. Liquid Fuels

Figure 20 summarizes the supply of today's two largest liquid fuels: gasoline and diesel. The supply of gasoline decreases by more than 95 percent by 2050 due to adoption of BEV, PHEV and HFCV vehicles in passenger transportation. Diesel remains a major fuel type in the High Electrification pathway, where half of freight trucks are hybrid diesel trucks. However, diesel supply transitions to 100 percent renewable diesel by 2050. The same supply transition occurs in the Low Electrification pathway, but total demand decreases by two-thirds by 2050 relative to today due to a shift from diesel trucks towards LNG and CNG freight trucks.



D. Energy-related CO₂ Emissions

Figure 21 and Figure 22 summarize energy-related CO₂ emissions by sector and energy type, respectively. The transportation sector's emissions, which is the largest source of emissions today, decrease by more than 90 percent across all pathways. This is the largest reduction by sector and total transportation emissions are less than the combined emissions from residential and commercial buildings by 2050. The transportation sector is primarily decarbonized through the following strategies: (1) electrification of passenger vehicles and freight trucks paired with very low-carbon electricity generation; and (2) decarbonization of liquid and gaseous fuels supplying the remaining fleet of freight trucks with bioenergy. The productive sector contains the largest remaining CO₂ emissions by 2050, and these are primarily from the direct combustion of fossil fuels, as opposed to emissions associated with electricity consumption. Most of the residual emissions in buildings are from combusting pipeline gas, and these are 50 percent higher in the Low Electrification pathway relative to the other pathways.

Figure 21 CO₂ Emissions by Sector

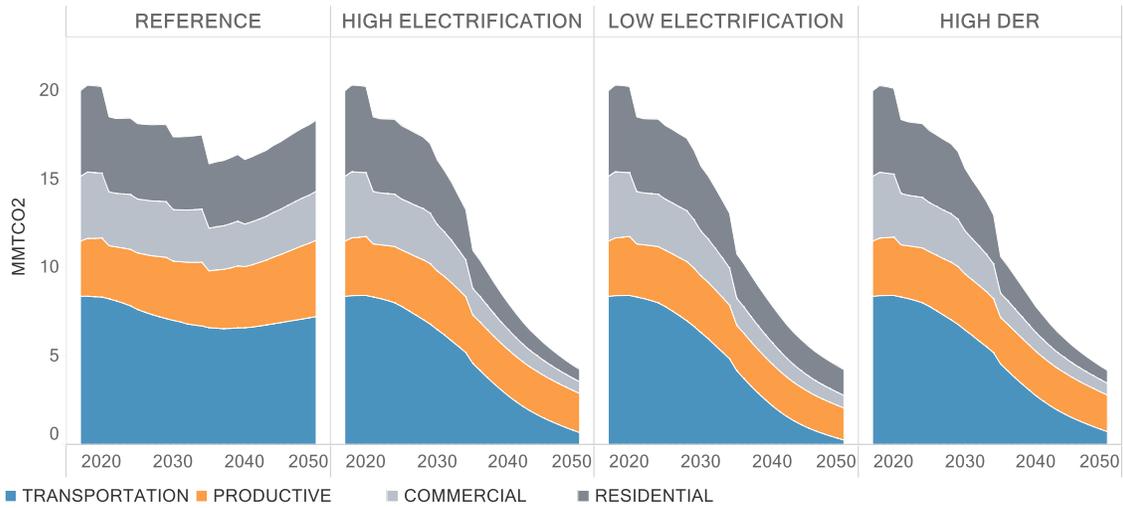


Figure 22 CO₂ Emissions by Energy Type

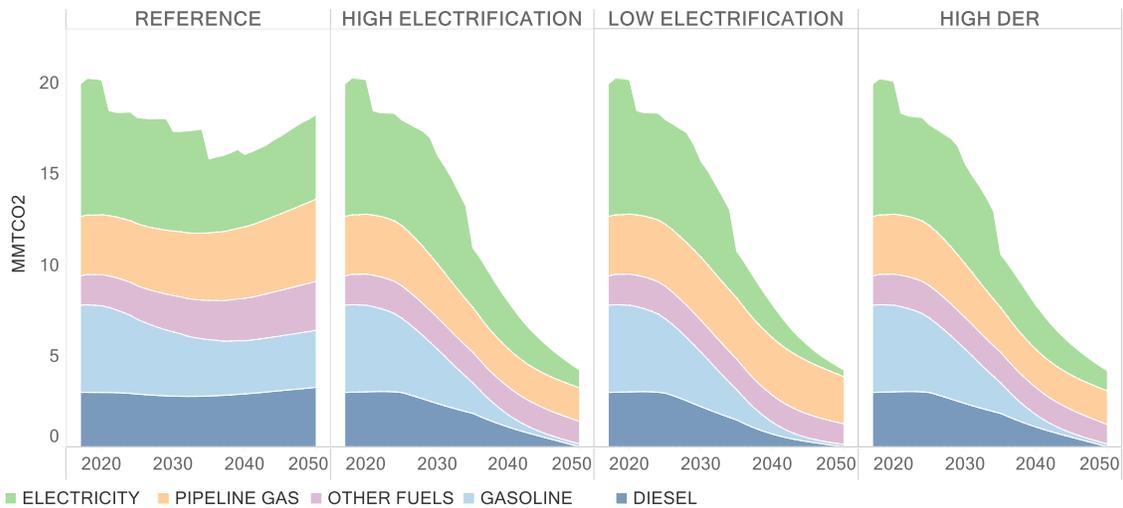
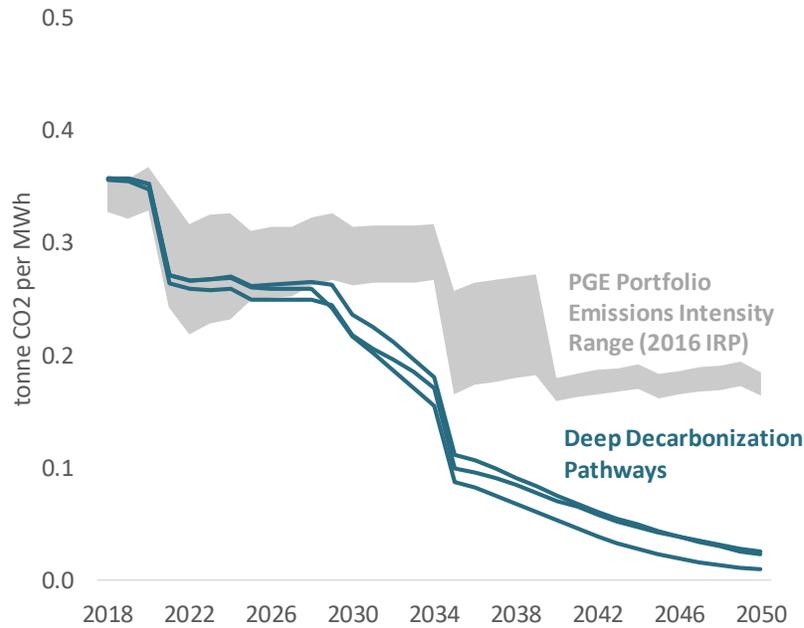


Figure 23 compares the emissions intensity of electricity generation from the three pathways against the range of PGE’s portfolio from the 2016 IRP. Both projections decrease over time, with noticeable drops in 2020 and 2035 due to the assumed phase out of coal-fired electricity supply. The emissions intensity in the pathways scenarios begins to aggressively decrease beginning in the mid-2020s, and, relative to the minimum of the range, is at least 33 percent lower in 2035 and more than 85 percent lower by 2050. In 2050, the emissions intensity is below 0.03 tCO₂/MWh for all pathways, while the 2016 IRP ranges from 0.16 to 0.19 tCO₂/MWh.

Figure 23 Emissions Intensity of Electricity Generation



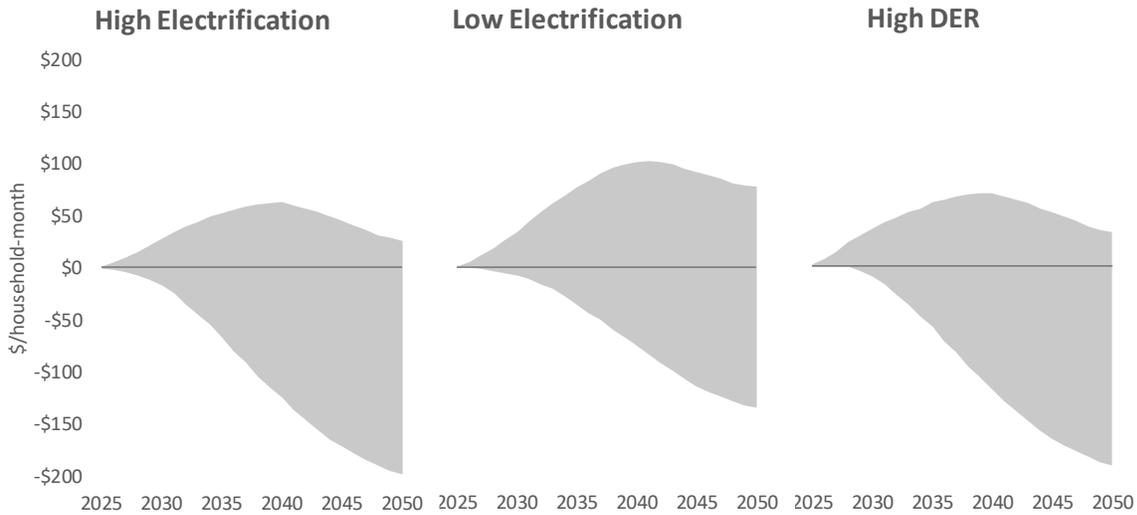
E. Energy System Costs

We measure the cost of transitioning towards a low-carbon energy economy by comparing the incremental cost of investment in low-carbon and efficient equipment and infrastructure against the savings from avoiding fossil fuel purchases. This is calculated by taking the difference in energy system-related costs between a pathway scenario and the Reference Case. We exclude costs outside of the energy system, as well as benefits from avoiding climate change and air pollution.

The annual, incremental cost for households is shown in Figure 24, which includes: (a) the annualized cost of appliances (e.g., high efficiency dishwasher); (b) the annualized cost associated with passenger transportation (e.g., electric vehicle); and (c) energy costs associated with using the equipment (e.g., gasoline for a vehicle and electricity for lighting). Given the challenge of projecting relative costs through a long study horizon (i.e., 2050), we show the results across a range of alternative fossil fuel price and end-use electric technology cost projections.¹⁸ Year-to-year variations are due to: (a) the timing of investment needs; and (b) the assumed projections of technology costs and fuel prices. The range of uncertainties encompass both net cost increases and net cost decreases (savings) by 2050.

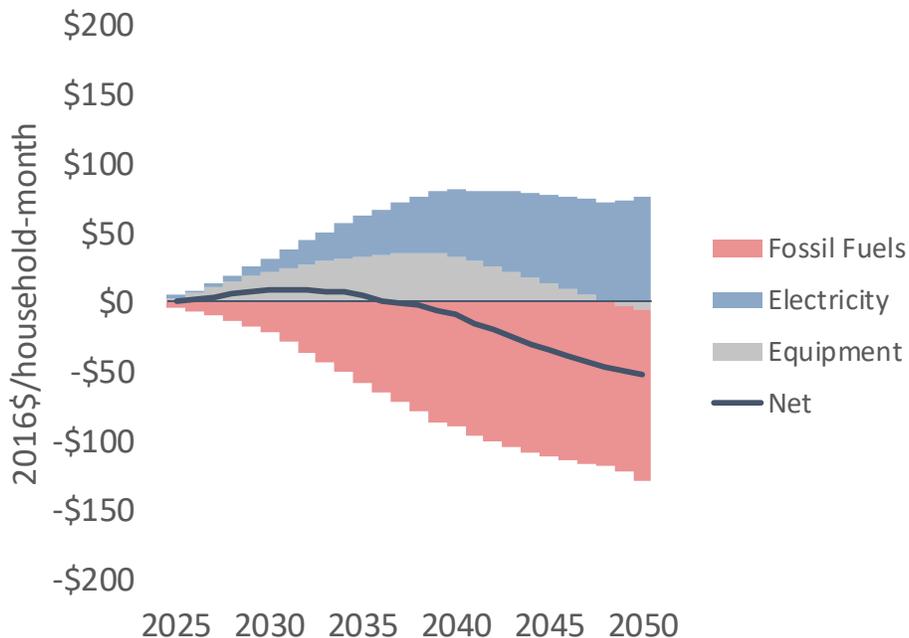
¹⁸ Range of fossil fuel price projections are from the EIA's *Annual Energy Outlook 2017* and end-use electric technology cost projections are from NREL's *Electrification Futures Study*.

Figure 24 Range of Incremental Household Costs



Incremental household costs reflect the underlying changes in the energy system, such as: (a) increased spending on efficient end-use equipment (fixed costs); (b) increased spending on clean electricity infrastructure (fixed costs); and (c) decreased spending on fossil fuel costs (variable costs). Figure 25 illustrates how the structure of incremental household costs evolve over time for the High Electrification pathway under base fossil fuel price and end-use electric technology cost assumptions. Between 2025 and 2050, the average household spends additional money on equipment, such as an electric vehicle, air source heat pump and heat pump hot water heater, as well as additional money to power their equipment with clean electricity, including renewable power plants and transmission/distribution network upgrades. Meanwhile, households spend less money on fossil fuels, such as: (1) gasoline and diesel for their cars and trucks; and (2) natural gas for space and water heating.

Figure 25 Incremental Household Costs by Component: High Electrification Pathway

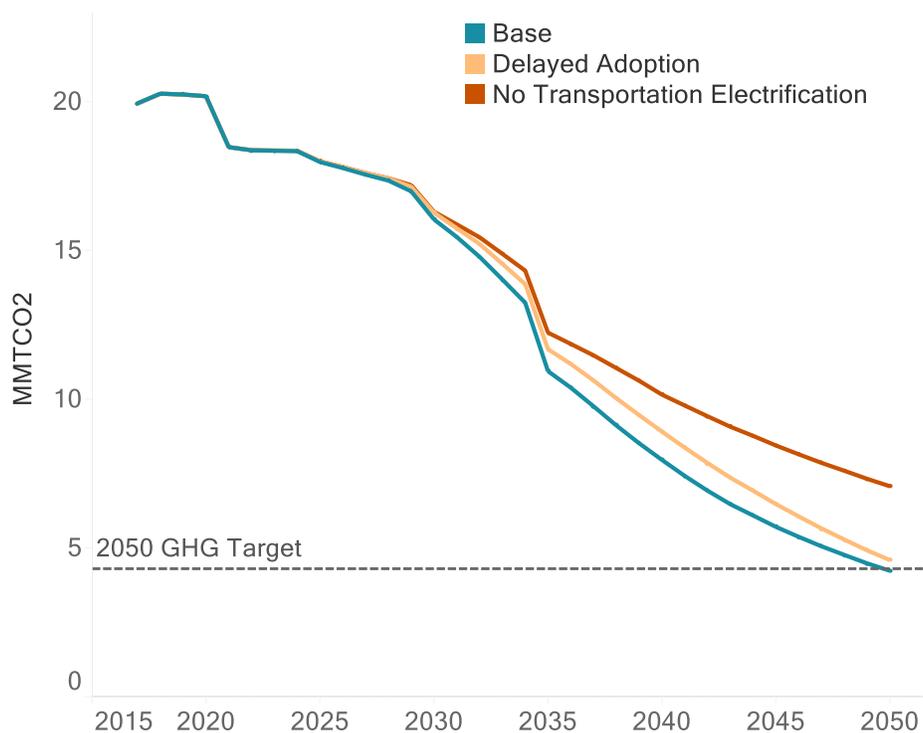


F. Transportation Electrification Sensitivity Analysis

Decarbonizing the transportation sector is essential to realizing economy-wide GHG reduction goals, and the pathways outlined above rely on passenger and freight transportation electrification. This requires aggressive consumer adoption by the mid-2030s for the fleet of vehicles on the road in 2050 to have the necessary low-carbon attributes. In the High Electrification pathway, 100 percent of light-duty vehicle sales are BEV or PHEV by 2035 and 50 percent of medium- and heavy-duty vehicle sales are BEV by 2035. To assess the importance of these aggressive transportation electrification strategies, we tested two sensitivities: (1) delay the assumed year of 100 percent BEV/PHEV adoption for light-duty vehicles from 2035 to 2050 (“Delayed Adoption”); and (2) remove all passenger and freight transportation electrification measures (“No Transportation Electrification”).

Figure 26 shows the difference in CO₂ emissions between the High Electrification pathway (“Base”) and the two sensitivities. The figure shows that delaying adoption of EVs in passenger transportation increases emissions in 2050 by 8 percent or 0.36 MMTCO₂, which results in the pathway no longer complying with the study’s 2050 GHG target. This is because more than 10 percent of cars and trucks on the road in 2050 still consume petroleum rather than clean electricity as their fuel. CO₂ emissions increase by two-thirds without any transportation electrification (above 7 MMTCO₂) and the sensitivity does not achieve the emissions reductions necessary to meet the 2050 GHG target. We also note that the increase in emissions is partially mitigated through increased renewable diesel consumption by freight trucks (i.e., diesel freight trucks that transition to electric freight trucks in the base case now consume renewable diesel). However, the amount of bioenergy in this sensitivity exceeds the limit described in Section II.D, and, if strictly enforced, then emissions would be higher than shown here.

Figure 26 Energy-related CO₂ Emissions: Transportation Electrification Sensitivities



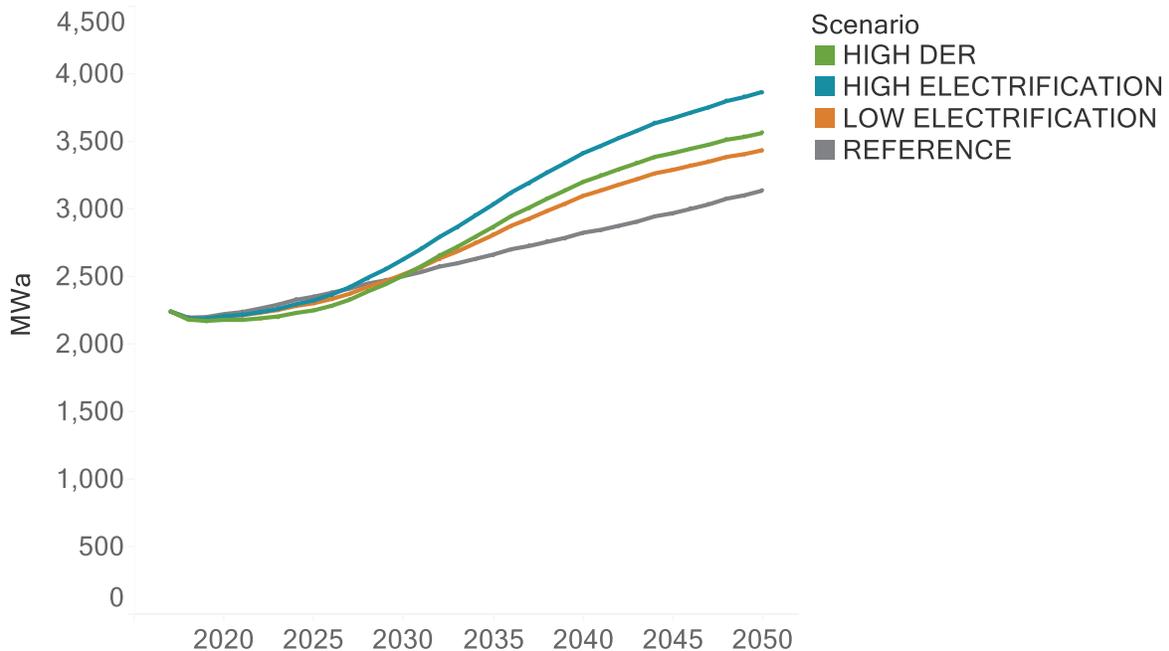
V. Results: Electricity System

This section summarizes results for the electricity system, including load, resources and hourly system operations. We also report the sensitivity of the results to variations in flexible end-use load, flexible electric fuel production, battery energy storage and pumped hydro storage assumptions.

A. Load

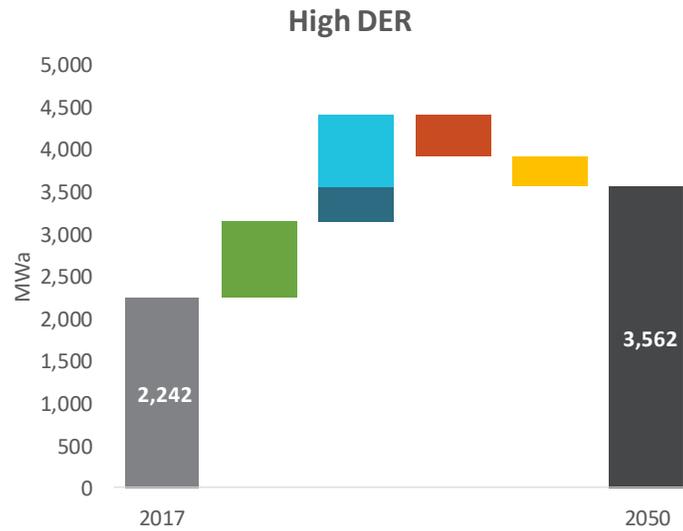
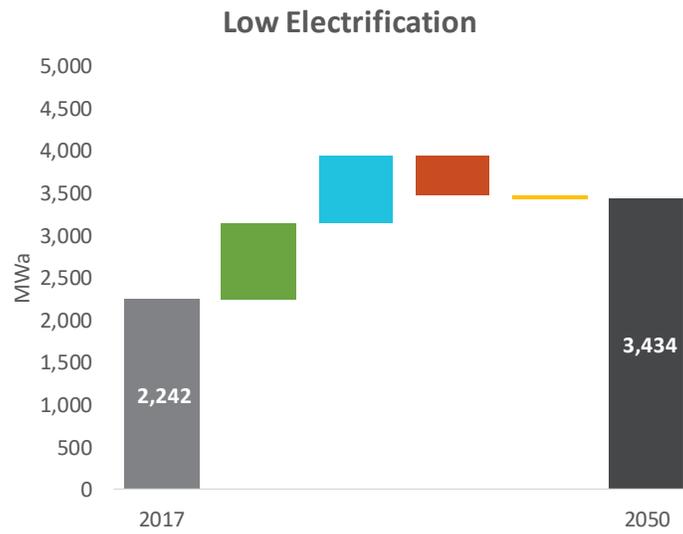
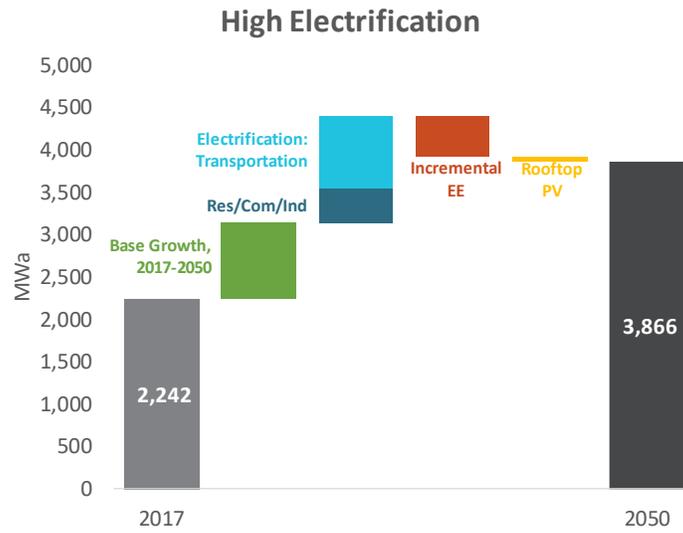
Figure 27 shows the trajectory of retail electricity sales for each scenario through 2050. In the long-run, retail sales in all pathways are higher than the Reference Case, and, as expected, the High Electrification pathway is the highest. Deployment of rooftop solar PV resources in the High DER pathway partially offsets end-use electrification measures, resulting in retail sales that are slightly above the Low Electrification pathway in 2050. Relative to today, retail sales increase by 50 to 70 percent by 2050.

Figure 27 Retail Electricity Sales



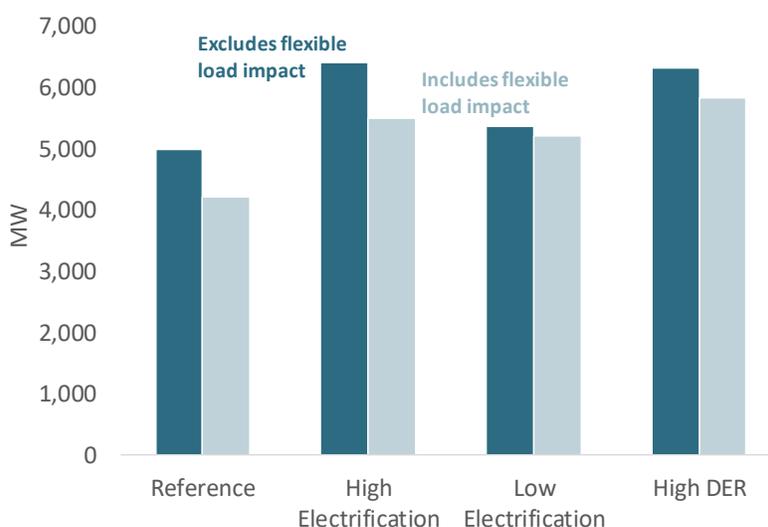
The components of the change in retail sales between 2017 and 2050 are shown in Figure 28, which separates: (a) baseline growth (i.e., growth that is embedded in the Reference Case); (b) electrification of buildings and industry; (c) transportation electrification; (d) incremental energy efficiency (EE measures beyond what's embedded in the Reference Case); and (e) rooftop solar PV generation. This figure highlights two key insights. First, transportation electrification is responsible for 50 to 65 percent of the net increase, as liquid fuels are replaced by electricity. Second, generation from rooftop solar PV has a smaller than expected *net* impact on retail sales. This is most apparent in the High DER scenario, where rooftop solar PV exceeds 2,500 MW (larger than today's average load). In this pathway, incremental electricity demand from end-use electrification still outweighs the directionally opposite impact from rooftop solar. This is a result of the lower-quality solar resource (i.e., low capacity factor) in PGE's service territory, and we would not expect similar conclusions to be drawn in geographies such as California or Arizona.

Figure 28 Evolution of Retail Electricity Sales, 2017-2050



We estimate the system peak load as the highest hourly load value from our simulations. As discussed in Section II.B, our hourly load (and resource) shapes reflect 2011 weather conditions, which means that the results we report here will not exactly match a 1-in-2 (weather-normalized) peak demand. Figure 29 plots the system peak load in 2050 in two ways. The first metric (in dark blue) represents “fixed demand” and excludes any impacts from load shifting, storage charge/discharge and flexible electric fuel production. The chart illustrates how widespread end-use electrification in the High Electrification and Higher DER pathways results in a system peak load of approximately 6,400 MW, which is about 1,400 MW higher than the Reference Case. Despite the proliferation of rooftop solar PV in the High DER pathway, the system peak load is nearly equivalent to the High Electrification pathway since it occurs during a winter morning before meaningful insolation. The second system peak load metric (in light blue) accounts for impacts from flexible end-use loads during the same hour, which moderates the impacts of electrification on peak loads.

Figure 29 2050 System Peak Load



B. Resources

1. Installed Capacity

Figure 30 shows the projection of installed capacity for thermal, generic capacity and renewable resources. Decarbonization of electricity generation and electrification requires renewable resource additions that far exceeds additions included in the Reference Case. The installed capacity of wind, solar, geothermal and hydro resources in the pathways is more than 2x the Reference Case quantity by 2050 and includes: (a) 5,100 to 5,900 MW of onshore wind in the Pacific Northwest; (b) 1,700 to 1,900 MW of onshore wind in Montana; and (c) 3,600 to 5,200 MW of utility-scale solar PV in central Oregon.¹⁹ Rooftop solar PV in the High DER scenario reduces the amount of transmission-connected renewable generation, but its generation portfolio still requires utility-scale additions to reduce the carbon

¹⁹ For context, NREL estimates technical potential of onshore wind resources in Oregon and Washington of approximately 45,480 MW and Black & Veatch estimates approximately 56,150 MW of utility-scale solar PV in Oregon alone. See Lopez et al. (2012) and Black & Veatch (2015).

intensity of electricity generation to levels consistent with the study’s carbon budget. The Low Electrification pathway contains the highest installed capacity due to the amount of electricity required to serve synthetic electric fuel production loads.

Figure 30 Installed Generating Capacity

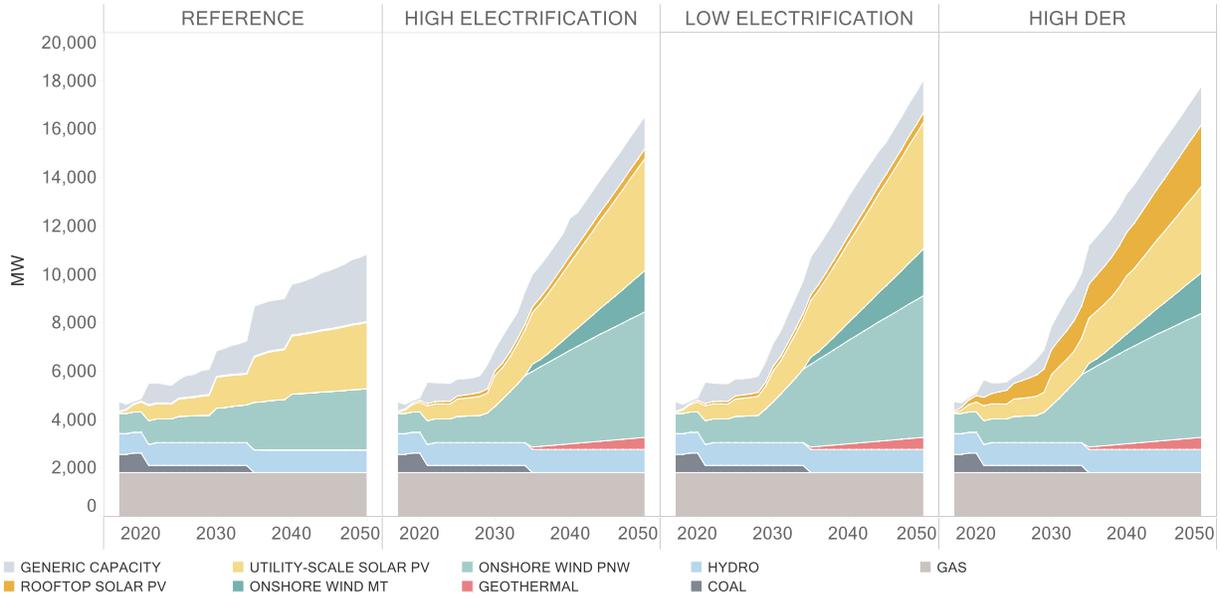
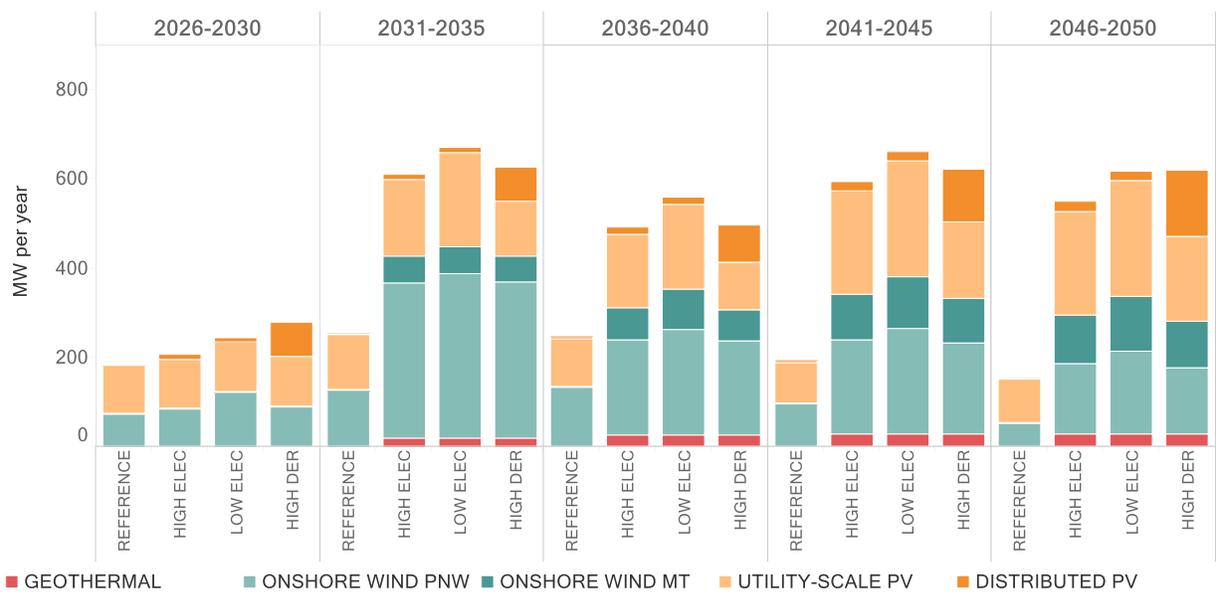


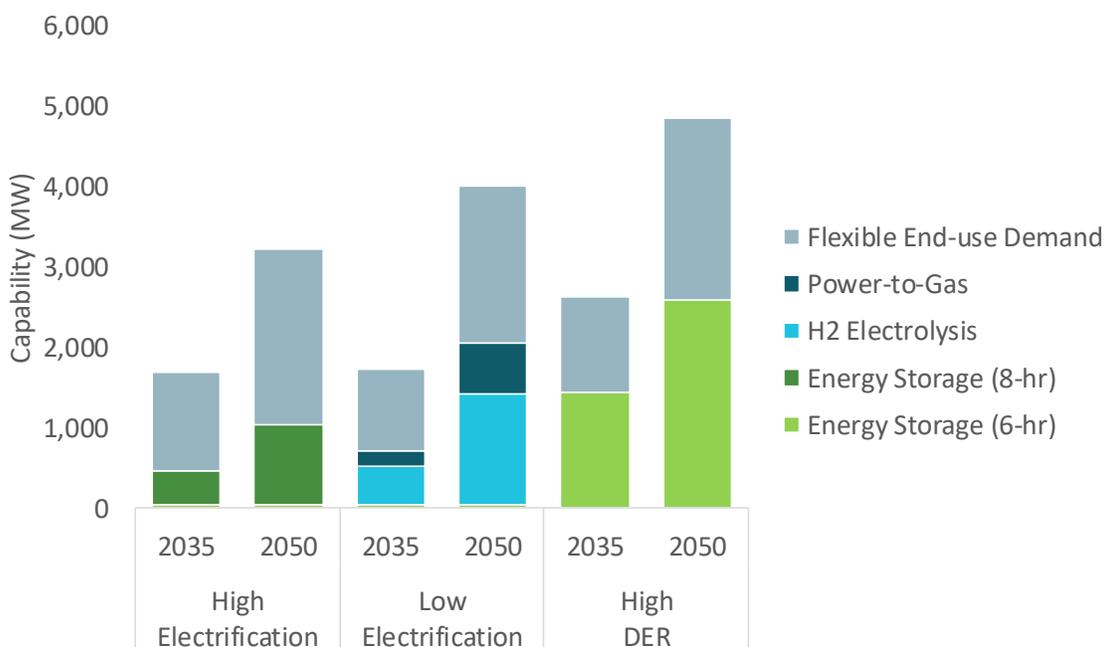
Figure 31 shows the annual average capacity additions of renewable resources, which are approximately 600 MW per year between 2030 and 2050 for the pathways scenarios. Annual renewable additions for the pathways scenarios are more than 2.0x Reference Case levels during the 2030s and more than 3.0x during the 2040s. For context, the amount of new onshore wind capacity beginning in 2030 is the equivalent to one to two Tucannon River (267 MW) wind power plants installed each year.

Figure 31 Average Annual Renewable Installations



The high penetrations of must-run renewable resources added across the pathways necessitate resources to balance electricity supply and demand. In addition to traditional sources of flexibility, such as hydro and thermal, the pathways incorporate a variety of new balancing resources to mitigate curtailment of renewable generation. Figure 32 shows the type and quantity of balancing resources incorporated in each pathway, including: (a) energy storage, which is differentiated between 6- and 8-hr duration; (b) hydrogen electrolysis facilities; (c) power-to-gas facilities; and (d) flexible end-use demand, which is estimated as the maximum hourly load shift in each year. The High Electrification and High DER pathways rely on a combination of flexible end-use demand and energy storage, while the Low Electrification pathway incorporates more than 2,000 MW of hydrogen electrolysis and P2G facilities by 2050 to consume excess renewable electricity generation and produce decarbonized pipeline gas. The High Electrification pathway contains the lowest quantity of physical / central-station balancing resources (i.e., 1000 MW of 8-hr energy storage) and relies on end-use loads to shift energy. The ability of these balancing fleets to minimize curtailment is further discussed in Section C.4 below.

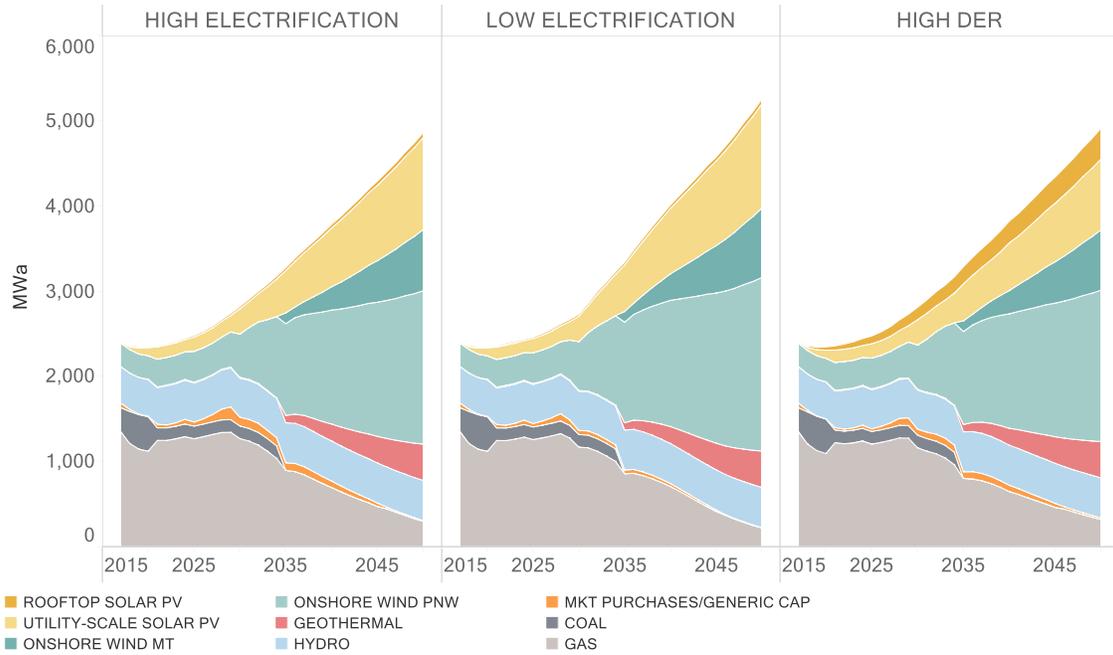
Figure 32 Balancing Resources



2. Generation

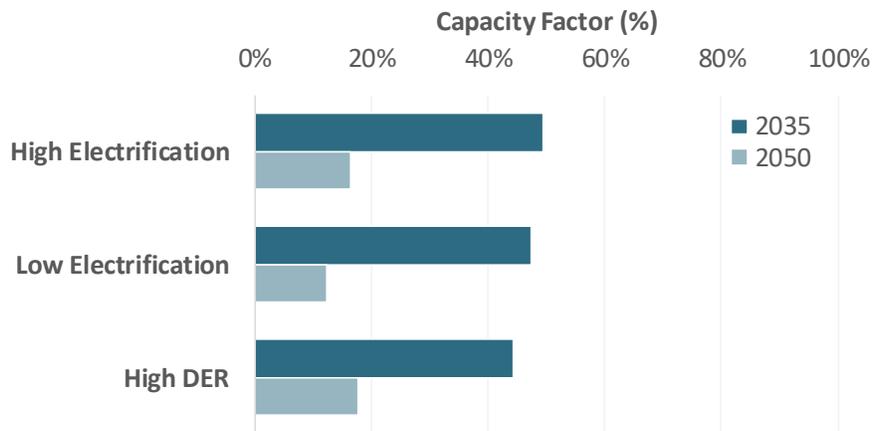
The overall generation mix by resource type for each pathway is shown in Figure 33. Annual generation more than doubles from approximately 2,400 MWh today to between 4,900 and 5,300 MWh by 2050. Carbon-free generation is more than 90 percent of the total by 2050, including an approximate mix of: (a) 50 percent onshore wind in the Pacific Northwest and Montana; (b) 25 percent solar PV, including both utility-scale in central Oregon and rooftop PV resources located within PGE’s service territory; (c) 9 percent hydro; and (d) 8 percent geothermal. Due to the increased penetrations of renewable resources, thermal generation decreases significantly over time and is between 4 to 7 percent of total generation by 2050.

Figure 33 Generation by Resource Type



The capacity factor of PGE’s existing gas-fired resource fleet is shown in Figure 34. The figure highlights how the growth in intermittent renewable generation between 2035 and 2050 decreases the utilization of these dispatchable resources from approximately 50 percent in 2035 to below 20 percent in 2050, a decrease of approximately 30 percentage points. The highly renewable power systems modeled in this study still require dispatchable resources to maintain reliability, and the gas-fired resource fleet, along with a variety of other balancing resources, have the characteristics to avoid unserved energy. The results here do indicate a shift in the role of these resources, particularly for combined cycle plants, from an energy to a capacity resource.

Figure 34 Gas-fired Resource Fleet Capacity Factor



C. System Operations

1. Load and Net Load

We compare the distribution of hourly load and net load in 2050 for each scenario as histograms in Figure 35, and report summary statistics in Table 11. These two metrics are estimated as follows: (a) load includes inflexible, transmission-level load less behind-the-meter generation (e.g., rooftop solar PV); and (b) net load is load minus non-dispatchable generation, including onshore wind, utility-scale solar PV, geothermal and run-of-river hydro resources. Both exclude the impact of flexible loads and resources.

The load distributions show the expected impacts of electrification, with the High Electrification and High DER distributions shifting towards the right. The net load distributions provide a more meaningful benchmark in terms of assessing the amount of dispatchable capacity needed to reliably meet demand and the flexibility required to avoid curtailment. The net load distribution for the Reference Case, which includes a 50% RPS in 2050, shows net load below zero for 5 percent of hours in the year. The pathways scenarios, which include at least twice as many non-dispatchable renewables, have net load distributions that are much flatter than the Reference Case and frequently below zero.

The High Electrification net load distribution is below zero in approximately 50 percent of hours per year, and the minimum net load experienced is approximately -8,000 MW. During these hours, flexible resources are needed to consume additional load (e.g., energy storage charge) to avoid curtailment. The maximum net load is approximately 5,000 MW, which is about 4 percent higher than the Reference Case's maximum net load. The High DER pathway shows similar net load distribution results due to comparable levels of electrification and renewables.

Relative to the other pathways, the Low Electrification pathway's net load is distributed further left (i.e., more hours with negative net load). Net load is below zero for 64 percent of hours in the year and nearly reaches -10,000 MW in a single hour. This shape is due to different load and resource characteristics, including: (a) lower levels of end-use electrification; and (b) higher levels of inflexible renewable generation. Flexible hydrogen electrolysis and power-to-gas facilities consume load during these negative net load hours to produce low-carbon electric fuels and avoid curtailment.

Figure 35 Distribution of Hourly Load and Net Load in 2050

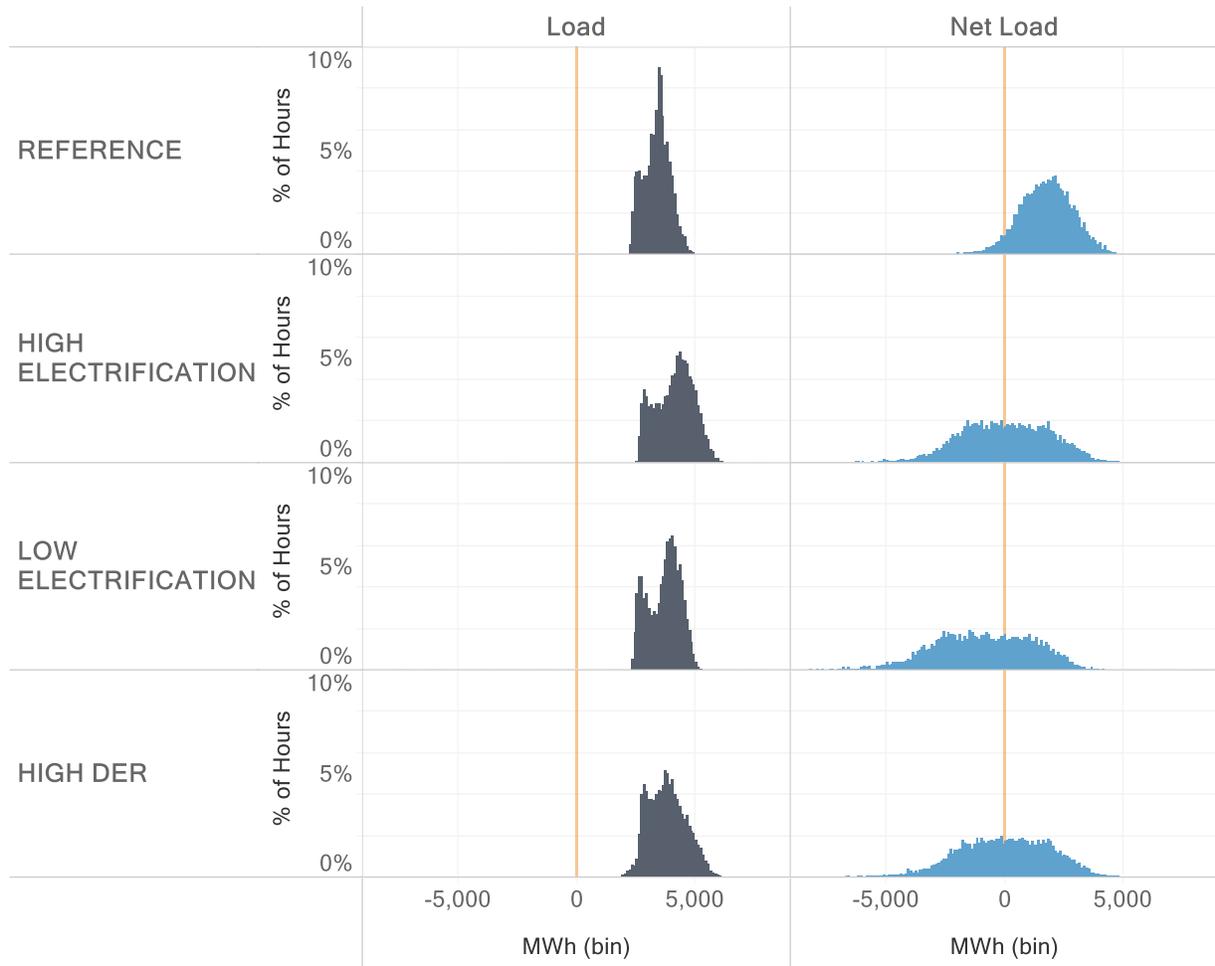


Table 11 Statistics for Hourly Load and Net Load in 2050

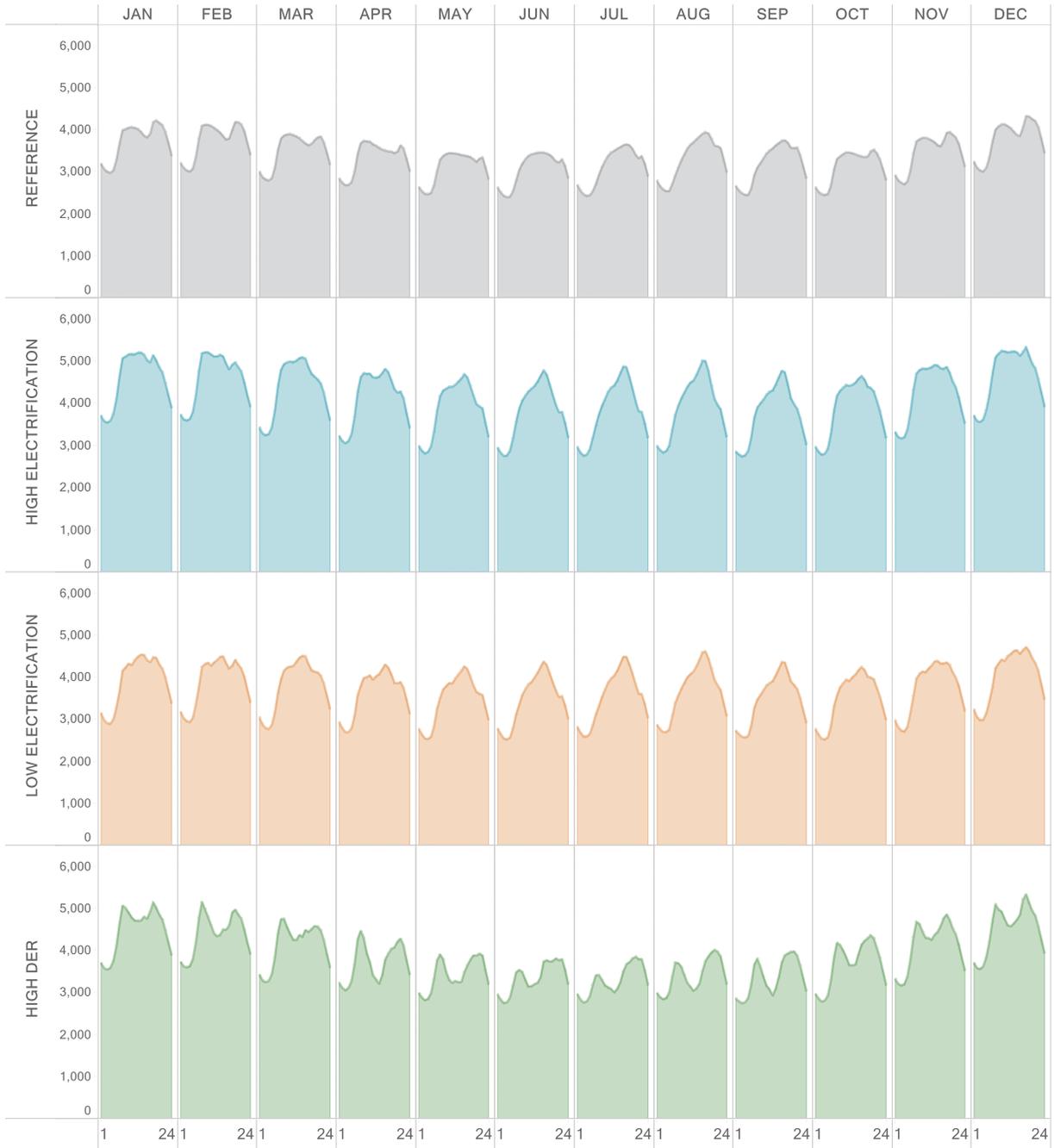
Scenario	Load		Net Load			
	Max	Min	Max	Min	Frequency below 0 MW	
	MW	MW	MW	MW	hrs	% of hrs
Reference	4,972	2,191	4,758	-2,392	457	5%
High Electrification	6,391	2,555	4,957	-7,942	4,346	50%
Low Electrification	5,351	2,273	4,261	-9,996	5,600	64%
High DER	6,310	1,920	4,961	-8,574	4,337	50%

2. Hourly System Load Shape

The average load by month and hour in 2050 for each scenario is summarized in Figure 36. The figure shows the system load shape prior to accounting for flexible loads and illustrates how the nature of electricity demand is affected by rooftop solar PV and varying levels of electrification.²⁰ The High Electrification pathway shows higher winter loads relative to the Reference Case primarily due to the electrification of space heating, but large new loads are also present in non-winter months largely due to transportation electrification. These non-heating related load increases are also present in the Low Electrification pathway and are most apparent in the early evening hours when most EV charging is assumed to take place. Although the High DER pathway contains the same electrification measures as the High Electrification pathway, the proliferation of rooftop solar PV changes both the daily and seasonal characteristics of electricity demand, including: (a) steep upward and downward ramps during the daylight hours across all months; and (b) large differences in daily energy requirements between winter and spring/summer months.

²⁰ The load shapes for the pathways also reflect high levels of electric energy efficiency.

Figure 36 System Load Shape: Month-Hour Average in 2050

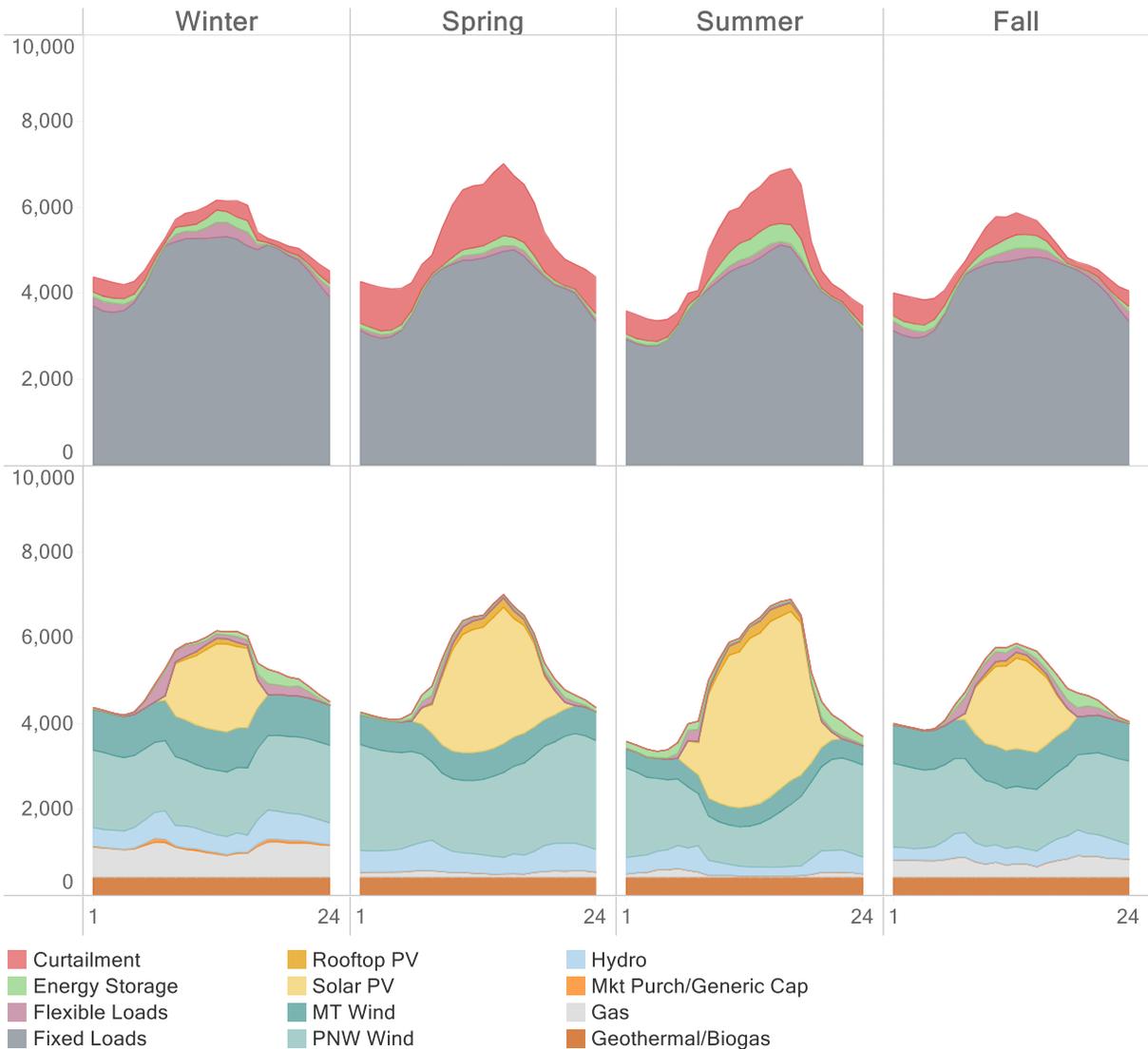


3. Month-Hour Electricity Dispatch

Figure 37 through Figure 39 show hourly average dispatch profiles by season for each pathway, where the top panel contains all sources of load and the bottom panel contains all sources of generation.²¹ The figures illustrate how electricity supply and demand technologies combine across hours and seasons, and the operating profiles of flexible balancing resources.

Figure 37 Electricity Dispatch: High Electrification Pathway, 2050

Load (Top) and Generation (Bottom)
MWh



²¹ Seasons defined as: (a) winter includes December through February; (b) spring includes March through June; (c) summer includes July through September; and (d) fall includes October through November.

Figure 38 Electricity Dispatch: Low Electrification Pathway, 2050

Load (Top) and Generation (Bottom)
MWh

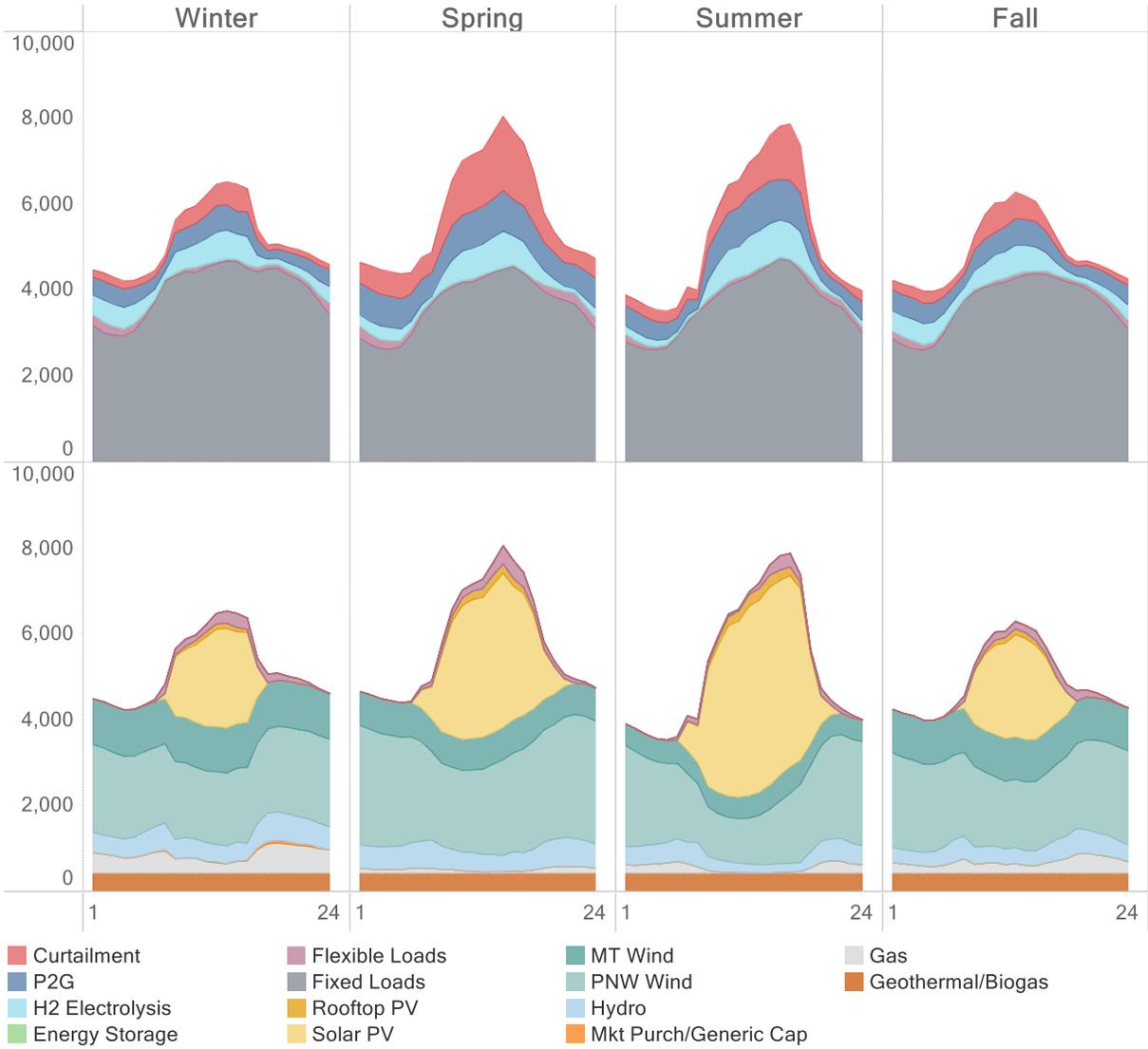
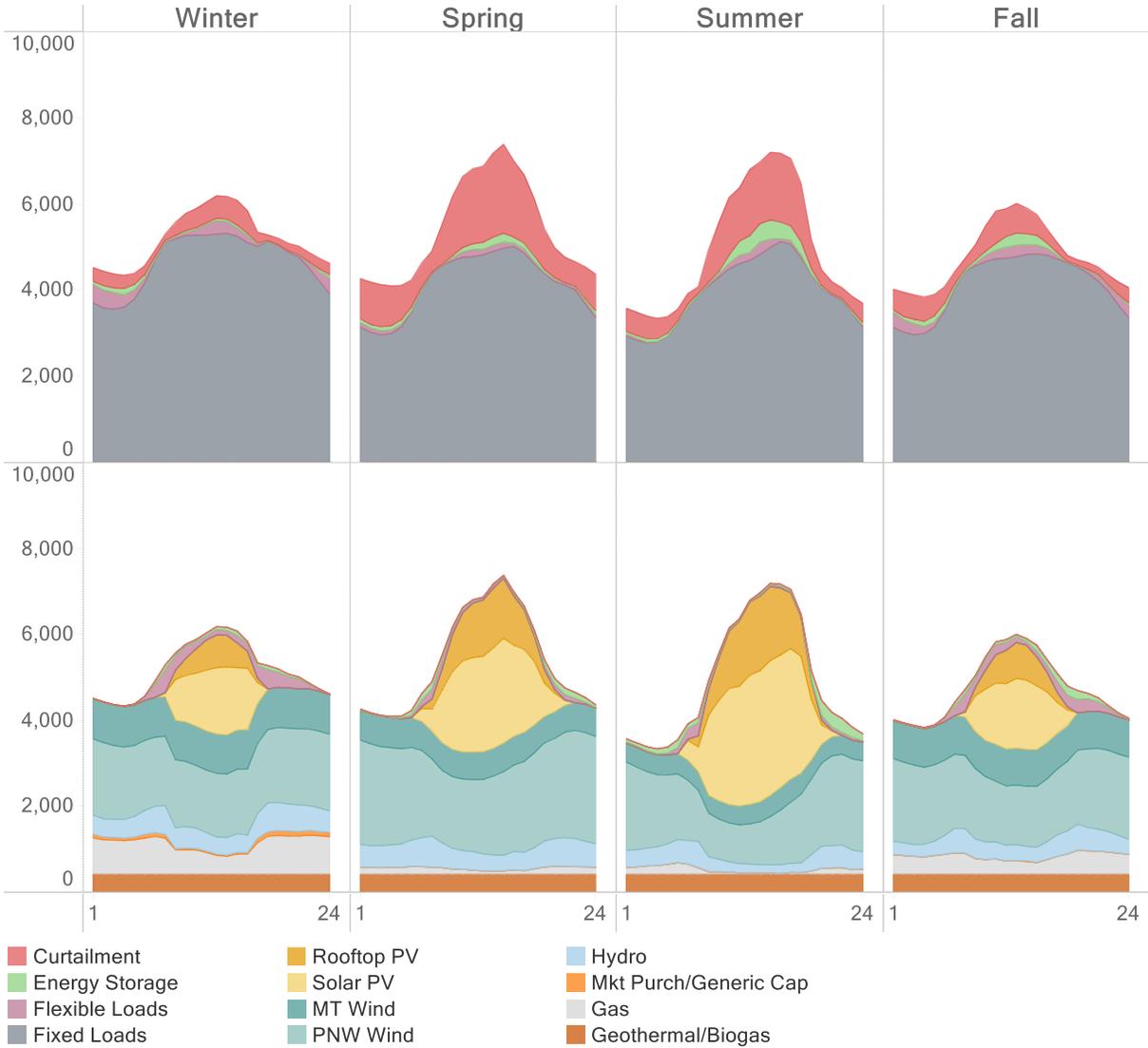


Figure 39 Electricity Dispatch: High Distributed Energy Resources Pathway, 2050

Load (Top) and Generation (Bottom)
MWa



4. Curtailment

Curtailment of renewable generation occurs during periods where: (1) must-run generation exceeds load, resulting in an initial negative net load signal; and (2) balancing resources are unable to shift surplus energy to hours with energy deficits (i.e., positive net load signal). Figure 40 plots annual curtailment for each scenario and shows that curtailment does not become prevalent until the 2035 timeframe. As the share of inflexible, renewable generation increases above 85 percent by 2050, curtailment increases exponentially even after the impacts of balancing resource are accounted for.

Figure 40 Annual Curtailment

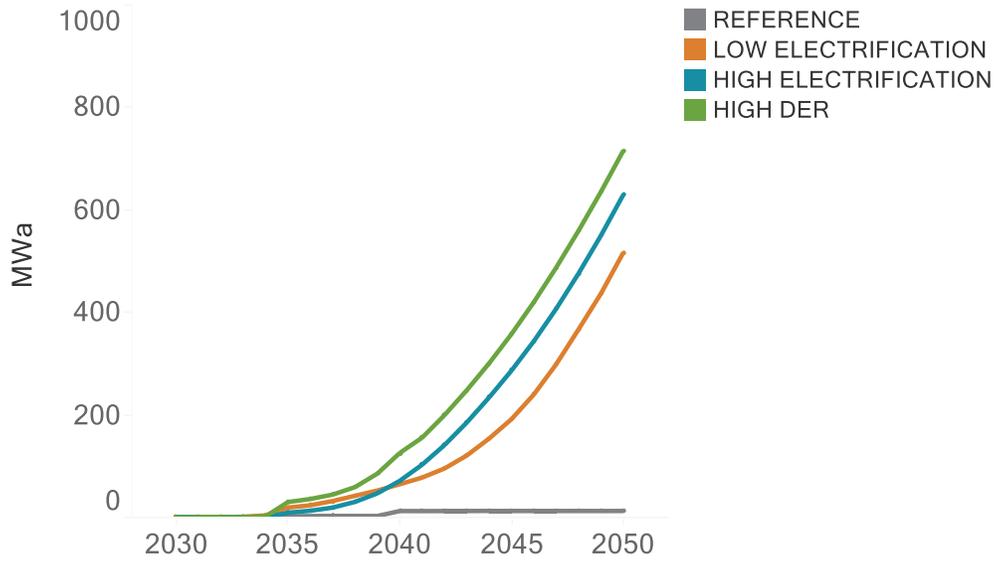


Table 12 summarizes several curtailment metrics for 2035 and 2050, including: (a) the amount of energy curtailed in average megawatts; (b) curtailment normalized as a percentage of available renewable energy; (c) maximum hourly observation; and (d) frequency, expressed in percentage of hours in a year. Curtailed generation is less than 2 percent of available renewable energy in 2035 across all pathways and increases to between 11 and 17 percent by 2050. Curtailment is experienced between 40 and 55 percent of hours in 2050, which is a decrease from the number of hours with negative net load (see Table 11) and reaches a maximum depth between 7,600 and 8,700 MW in a single hour. We explore the impact of alternative demand- and supply-side balancing resource assumptions on curtailment in the following section.

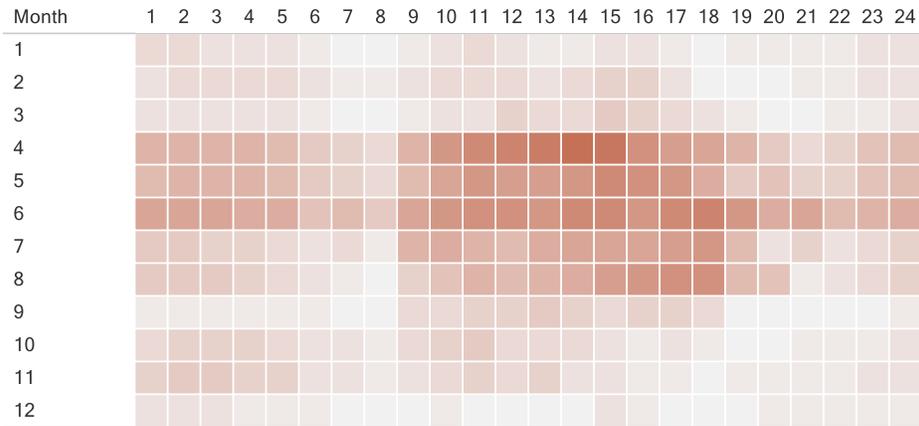
Table 12 Curtailment Metrics for 2035 and 2050

Scenario	Energy		Percent of Available RE		Hourly Maximum		Frequency	
	2035	2050	2035	2050	2035	2050	2035	2050
	MWa	MWa	%	%	MW	MW	% hours	% hours
Reference	2	13	0.2%	0.8%	966	2,048	1%	3%
High Electrification	9	630	0.5%	15.0%	2,146	8,032	2%	39%
Low Electrification	19	517	0.9%	11.1%	2,378	7,597	4%	53%
High DER	30	716	1.5%	16.9%	3,121	8,663	5%	46%

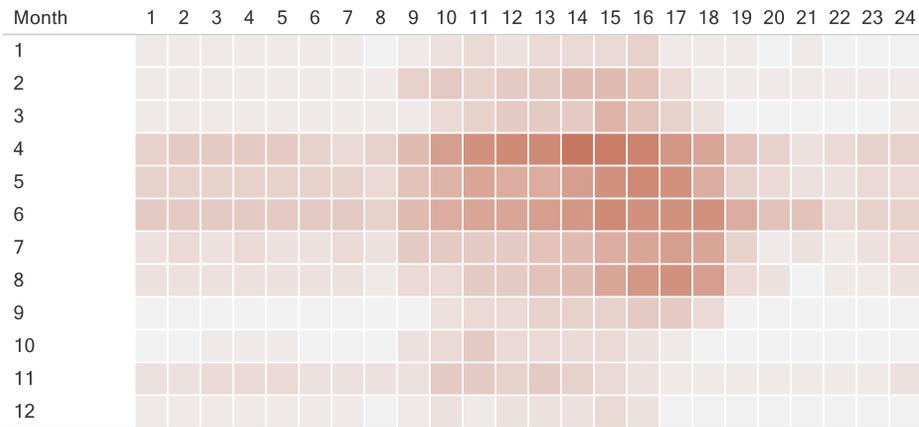
The average amount of curtailment for each month and hour in 2050 is depicted as a heat map in Figure 41, with a darker red highlighting more extreme curtailment. The heat maps show that curtailment is concentrated during spring months when loads are low and renewable generation is high. Curtailment experienced during April through June makes up approximately half of annual curtailment, while only 11 to 13 percent occurs between December through February. Although most curtailment is concentrated during day-light hours, it is still experienced during the night-time and is up to 30 percent of the total in the High Electrification pathway.

Figure 41 Curtailment Heat Map for 2050

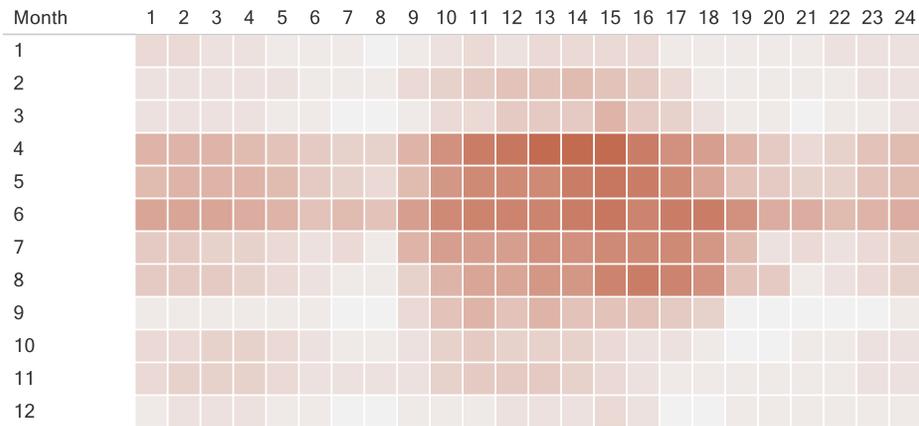
High Electrification



Low Electrification



High DER



D. Sensitivity Analyses

In this section, we evaluate the sensitivity of our modeling results to alternative assumptions about the availability of demand- and supply-side resource flexibility. These sensitivities explore the impacts of alternative assumptions from the High Electrification pathway, including: (a) varying the availability of flexible end-use load; (b) including flexible electric fuel production (i.e., electrolysis); and (c) varying the quantity and type of energy storage. These sensitivities are summarized below.

Flexible End-use Load. In the High Electrification pathway, we assume a percentage of electric load is flexible in key end-uses: (a) 75 percent of light-duty vehicle electric load is flexible by 2050; (b) 75 percent of residential and commercial water heating electric load is flexible by 2050; and (c) 50 percent of electric load is flexible for residential space conditioning, residential clothes washing and drying and commercial space heating. We tested three cases designed to assess the importance of end-use flexibility: (a) no flexible end-use load; (b) only flexibility from electric vehicles; and (c) only flexibility from water heaters.

Flexible Electric Fuel Production. The results presented in the prior section highlight the seasonal imbalance between electricity supply and demand in a highly renewable power system. The base assumption in the High Electrification pathway is that energy storage and flexible end-use loads are the principal balancing resources. To assess the impact of long-term or seasonal storage, we conducted a sensitivity analysis where hydrogen produced from electrolysis facilities provides 3.5 percent of pipeline gas supply, which translates into more than 300 MW of electrolysis facilities.

Variation in Energy Storage. Varying the quantity of energy storage affects the ability of a power system to successfully integrate inflexible renewable electricity generation. In the High Electrification pathway, the base assumption is that 1,000 MW of 8-hour energy storage is in-service by 2050. In this sensitivity, we assess the implications of: (a) increasing the quantity of 8-hour energy storage from 1,000 MW to 1,500 MW; and (b) assuming 500 MW of 24-hour pumped hydro storage (PHS) by 2050.

Table 13 summarizes the results of our sensitivity analyses for 2050, which are shown as differences relative to the High Electrification pathway. We report changes in: (a) curtailment, in terms of average megawatts and percent difference; and (b) energy system CO₂ emissions, in million metric tonnes and percent difference. Removing flexibility from end-use loads increases curtailment by nearly 10 percent and emissions increase by 5 percent due to higher thermal generation, which results in the sensitivity exceeding the study's 2050 carbon budget. Including flexibility from electric vehicles and hot water heaters dampens the effect of losing other end-use flexibility, with curtailment and emissions rising modestly. The sheer volume of electric load from electric vehicles (more than 15 percent of total load in 2050) relative to water heaters allows for better curtailment and emissions outcomes. Electrolysis facilities and pumped hydro, both long-duration storage, show similar outcomes with curtailment decreasing by more than 10 percent. In contrast, increasing the quantity of 8-hour storage produces less than half the reductions in curtailment. The results of these sensitivity analyses highlight the importance of flexible end-use loads for integrating renewable generation, as well as the effectiveness of long-duration energy storage to reduce curtailment and address seasonal energy imbalances that occur in highly renewable electricity systems.

Table 13 Flexibility Sensitivity Analysis Results (Relative to Base Assumptions)

Sensitivity	Curtailment (MWa)	Curtailment (%)	Emissions (MMTCO ₂)	Emissions (%)
Flexible End-Use Load				
None	+54	+9%	+0.21	+5%
Flexible EV Load Only	+14	+2%	+0.05	+1%
Flexible WH Load Only	+36	+6%	+0.14	+3%
Flexible Electric Fuel Production				
Add Electrolysis Facilities	-78	-12%	-0.08	-2%
Energy Storage				
Increase 8-hr energy storage	-31	-5%	-0.07	-2%
Add 24-hr PHS	-68	-11%	-0.15	-4%

Notes: values for 2050 and relative to High Electrification pathway base assumptions.

VI. Summary

We find that deep decarbonization of the PGE service territory's energy economy is possible and can be achieved using a variety of energy technologies and mitigation strategies. Our analysis of multiple pathways shows that they depend on a set of three pillars that are consistent with many studies examining deep decarbonization in the U.S. and abroad, including: (1) energy efficiency; (2) decarbonizing electricity generation; and (3) increasing the share of electricity and electric fuels. All three pillars are required and pursuing only one is insufficient.

The level of change to the energy system identified in this study is transformational and cannot be achieved with incremental improvements to energy supply and demand. In order to facilitate a pathway to 2050, both consumers and producers will need to participate to ensure that energy infrastructure is low-carbon and efficient. Although 2050 is more than three decades away, a successful transition to a low-carbon economy requires timely planning to account for: (a) the pace of consumer adoption; and (b) the fact that energy infrastructure is long-lasting and takes years to plan for. Despite the ambitious transformation of the energy system, the changes would not entail major lifestyle changes, but the structure of a household's energy bill will shift from fossil fuel expenditures to investments in technology.

Economy-wide decarbonization will profoundly change the way electricity systems are operated and planned for. In terms of power system operations, balancing electricity supply and demand becomes more challenging as inflexible, variable renewable generation becomes the principal source of supply. For example, the three pathways show renewable generation exceeding load in approximately half of all hours by 2050. This operational paradigm necessitates a transition to new forms of balancing resources to integrate renewables and avoid curtailment. New sources of flexibility, including energy storage and flexible demand, can complement traditional sources of flexibility, such as hydro and thermal resources. This also provides an opportunity for PGE's customers to facilitate renewable integration by playing a more active role through smart EV charging and water heating (among others), which expands upon traditional demand response programs.

Electricity system planning in the context of deep decarbonization will need to account for broad changes across the energy economy to ensure that infrastructure with the right attributes is available to come online in a timely fashion. For example, future resource adequacy analyses will need to address changes in: (a) overall load requirements; (b) the shape of hourly load; (c) the level of inflexible renewable resources; and (d) penetration of flexible demand. In addition, the scale of resource additions identified in this study exceeds historical levels due to: (1) reducing the carbon intensity of electricity generation to nearly zero; and (2) increased generation requirements from electrification and/or producing fuels from electricity (i.e., H2 and SNG). As a result, the installed capacity of renewables is substantially higher than what's anticipated in any current planning proceedings and is more than double the quantity we would expect under current RPS policy. If regulators pursue policies commensurate with the emissions reductions evaluated here, then the results of this study highlight a number of considerations that could be investigated in PGE's integrated resource planning efforts to ensure that near-term actions are consistent with a long-term decarbonized future.

VII. Bibliography

Black & Veatch (2015). *Solar Generation Market Research, Task 1: Solar Market Assessment and Cost Projections*. Available: <https://www.portlandgeneral.com/-/media/public/our-company/energy-strategy/documents/2015-08-13-solar-generation-market-research.pdf>

ENEA Consulting (2016). *The Potential of Power-to-Gas*. Available: <http://www.enea-consulting.com/wp-content/uploads/2016/01/ENEA-Consulting-The-potential-of-power-to-gas.pdf>

Federal Energy Regulatory Commission (2017). *Form No. 714 - Annual Electric Balancing Authority Area and Planning Area Report*. Available: <https://www.ferc.gov/docs-filing/forms/form-714/data.asp>

Haley, B., G. Kwok, R. Jones, and J. Williams (2016). *Deep Decarbonization Pathways Analysis for Washington State*. Available: <https://www.governor.wa.gov/issues/issues/energy-environment/deep-decarbonization>

Jadun, Paige, Colin McMillan, Daniel Steinberg, Matteo Muratori, Laura Vimmerstedt, and Trieu Mai (2017). *Electrification Futures Study: End-Use Electric Technology Cost and Performance Projections through 2050*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-70485. Available: <https://www.nrel.gov/docs/fy18osti/70485.pdf>

Lopez, A., B. Roberts, D. Heimiller, N. Blair and G. Porro (2012). *U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis*. Available: <https://www.nrel.gov/gis/re-potential.html>

National Renewable Energy Laboratory (2017). *2017 Annual Technology Baseline*. Available: <https://atb.nrel.gov/>

Navigant Consulting (2014). *EIA - Technology Forecast Updates – Residential and Commercial Building Technologies – Reference Case*. Available: <https://www.eia.gov/analysis/studies/buildings/equipcosts/pdf/appendix-a.pdf>

Northwest Energy Efficiency Alliance (2012). *Residential Building Stock Assessment*. Available: <http://neea.org/resource-center/regional-data-resources>

Northwest Energy Efficiency Alliance (2014). *Commercial Building Stock Assessment*. Available: <http://neea.org/resource-center/regional-data-resources>

Northwest Power and Conservation Council (2016). *Seventh Power Plan*. Available: <https://www.nwcouncil.org/energy/powerplan/7/plan/>

Pletka, R. and J. Finn (2009). *Western Renewable Energy Zones, Phase 1: QRA Identification Technical Report*. Available: <https://www.nrel.gov/docs/fy10osti/46877.pdf>

Portland General Electric (2014). *PGE 2013 Residential Appliance Saturation Study*.

Portland General Electric (2018). *2016 Integrated Resource Plan*. Available: <https://www.portlandgeneral.com/our-company/energy-strategy/resource-planning/integrated-resource-planning>

Risky Business Project (2016). *From Risk to Return: Investing in a Clean Energy Economy*. Available: <http://riskybusiness.org/fromrisktoreturn/>

State of Oregon Department of Environmental Quality (2016). *Oregon Greenhouse Gas In-boundary Inventory*. Available: <http://www.oregon.gov/deq/eq/programs/Pages/GHG-Inventory.aspx>

State of Oregon Office of Economic Analysis (2013). *Forecasts of Oregon's County Populations and Components of Change, 2010 - 2050*. Available:
<http://www.oregon.gov/das/OEA/Pages/forecastdemographic.aspx>

State of Oregon Office of Economic Analysis (2017). *2017 Highway Cost Allocation Study*. Available:
<http://www.oregon.gov/das/oea/pages/hcas.aspx>

U.S. Department of Energy (2015). *Hydrogen Analysis (H2A) Project*. Available:
https://www.hydrogen.energy.gov/h2a_analysis.html

U.S. Department of Energy (2016). *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks*. M. H. Langholtz, B. J. Stokes, and L. M. Eaton (Leads), ORNL/TM-2016/160. Oak Ridge National Laboratory, Oak Ridge, TN. 448p. doi: 10.2172/1271651. Available: <http://energy.gov/eere/bioenergy/2016-billion-ton-report>

U.S. Energy Information Administration (2013). *Residential Energy Consumption Survey*. Available:
<https://www.eia.gov/consumption/residential/index.php>

U.S. Energy Information Administration (2017a). *Annual Energy Outlook 2017*. Available:
<https://www.eia.gov/outlooks/archive/aeo17/>

U.S. Energy Information Administration (2017b). *Form EIA-923*. Available:
<https://www.eia.gov/electricity/data/eia923/>

U.S. Federal Highway Administration (FHWA) (2015). *Freight Analysis Framework*. Available:
https://ops.fhwa.dot.gov/freight/freight_analysis/faf/

Williams, J.H., B. Haley, F. Kahrl, J. Moore, A.D. Jones, M.S. Torn, H. McJeon (2014). *Pathways to deep decarbonization in the United States*. The U.S. report of the Deep Decarbonization Pathways Project of the Sustainable Development Solutions Network and the Institute for Sustainable Development and International Relations. Revision with technical supplement, Nov 16, 2015. Available:
<http://usddpp.org/downloads/2014-technical-report.pdf>