Energy Decarbonization Pathways

Washington Utilities
and Transportation Commission

Appendix A

Data, Methods, and Assumptions (DMA) Manual

SSG

UTC
Washington Utilities
and Transportation
Commission

Purpose of this Document

This Data, Methods, and Assumptions (DMA) manual presents the modeling approach used to provide energy and emission benchmarks and projections, as well as a summary of the data and assumptions used in scenario modeling. The DMA makes the modeling elements fully transparent and illustrates the scope of data required for future modeling efforts using the same methodology.

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Glossary

Balancing Authority (BA): an entity responsible for integrating resource plans, maintaining load-interchange-generation balances within a metered boundary (the Balancing Authority Area), and supporting interconnection frequency in real time.

Base Year: the starting year for energy or emissions projections.

Business-As-Usual (BAU): a scenario illustrating energy use and GHG emissions if no additional plans, policies, programs, or projects are implemented.

Business-As-Planned (BAP): a scenario illustrating energy use and GHG emissions if additional plans, policies, programs, and projects which have already been passed or are currently underway continue to be implemented.

Carbon sequestration: The process of storing carbon in a carbon pool.

Clean Energy Transformation Act (CETA): Passed by the Washington State Legislature in 2019, the Engrossed Second Substitute Senate Bill 5116 or CETA requires Washington's electric utilities to fully transition to clean, renewable and non-emitting resources by 2045.

Commercial Buildings Energy Consumption Survey (CBECS): Developed by the EIA, the CBECS provides information on the estimated 5.9 million commercial buildings in the U.S., including the number of workers, ownership and occupancy, structural characteristics, energy sources and uses, and other energy-related features (2018 data at the time of writing).

Combined heat and power (CHP): the simultaneous production of two or more useful forms of energy, typically electricity and heat, by a single device (also known as co-generation).

Electrolysis: The process of using electricity to split water into hydrogen and oxygen, a reaction which takes place in an electrolyzer.

Energy Demand and Supply Simulator for the U.S. (EDSSUS): A model and data dictionary developed by SSG and whatIf? Technologies that can be used to simulate energy demand and supply for states, regions, and municipalities within the United States.

Energy Information Administration (EIA): An agency of the U.S. Federal Government that collects, analyzes, and disseminates information on energy and its interaction with the economy and the environment, including production, stocks, demand, imports, exports, and prices.

Environmental Protection Agency (EPA): An agency of the U.S. Federal Government that studies environmental issues, develops and enforces regulations to protect the environment, and provides grants to various entities to promote environmental conservation and human health.

Greenhouse gases (GHG): gases that trap heat in the atmosphere by absorbing and emitting solar radiation, causing a greenhouse effect. The main GHGs are water vapor, carbon dioxide, methane, nitrous oxide, and ozone.

Geographic information system (GIS): a type of a computer program or system that analyzes and displays geographically referenced data.

Heating Degree Day (HDD): a measurement designed to quantify the demand for energy needed to heat a building, consisting of the number of degrees that a given day's average temperature is below 18^{o}C, thus requiring heating.

National Renewable Energy Laboratory (NREL): The National Renewable Energy Laboratory is a federally funded research and development center sponsored by the Department of Energy and operated by the Alliance for Sustainable Energy, specializing in the research and development of renewable energy, energy efficiency, energy systems integration, and sustainable transportation.

Marginal abatement cost curves (MACC): MACCs show the relative economic costs or savings of emission abatement actions, in units of US\$/tCO_2e over time.

REPLICA: a proprietary provider of modeled and observed building and transportation data. https://replicahq.com/

Residential Energy Consumption Survey (RECS): Developed by the EIA, the RECS provides an estimate of residential energy costs and usage for heating, cooling, appliances, and other end uses, developed using a nationally representative sample of housing units and their energy characteristics combined with data from energy suppliers.

State Energy Data System (SEDS): Developed by the EIA, it provides comprehensive statistics regarding the consumption, production, prices, and expenditures of energy for each state and for the country as a whole.

Intergovernmental Panel on Climate Change (IPCC): a United Nations body that assesses the science related to climate change via regular reports and analyses about the state of scientific, technical and socio-economic knowledge on climate change, its impacts and future risks, and options for reducing the rate at which climate change is taking place.

Scenario: A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships. Note that scenarios are neither predictions nor forecasts, but are used to provide a view of the implications of developments and actions.

Vehicle Miles Traveled (VMT): distance traveled by vehicles within a defined region over a specified time period.

Washington Department of Commerce (WDOC): A department of the State of Washington that is the lead agency responsible for enhancing and promoting sustainable communities and economic vitality in Washington, through programming and via state boards and commissions.

Washington Department of Ecology (WDOE): A department of the State of Washington with a mission to restore, maintain, and enhance the quality of Washington's air, land, and water resources.

Washington State Department of Transportation (WSDOT): A department of the State of Washington that develops programs related to Washington's systems of transportation, including highways, roads, bridges, railways, and public transit, as well as services related to transportation safety programs, driver and vehicle licensing, and motor carrier regulation.

Washington Utilities and Transportation Commission (UTC): a three-member commission appointed by the governor of Washington and confirmed by the state senate that regulates electric, telecommunications, natural gas, water, and transportation providers.

Western Electricity Coordinating Council (WECC): a non-profit corporation that exists to assure a reliable Bulk Electric System in the geographic area known as the Western Interconnection, which has a footprint extending to 2 Canadian provinces, 14 Western states, and Northern Baja Mexico.

Accounting and Reporting Principles

SSG's greenhouse gas inventory development and scenario modeling approach correlate with IPCC-derived accounting methods for developing fair and true accounts of national and state-level emissions. The GHG inventory includes detailed calculations of emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) in detail, and high-level calculations of perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3) for each of the following sectors: transportation, energy, residential, commercial, industry.

The GHG emission and removal estimates contained in Washington's GHG inventory are developed using methodologies consistent with guidelines for National Greenhouse Gas Inventories developed by the Intergovernmental Panel on Climate Change (IPCC) in the Fifth Assessment Report, which incorporates carbon feedback into its Global Warming Potential (GWP) values. For this reason, SSG's GHG inventory results are similar to but not exactly the same as reported in Washington State Greenhouse Gas Emissions Inventory: 1990-2018, published by the Department of Ecology in January 2021.

SSG has developed the following principles for GHG accounting and reporting, based on decades of research and experience working with municipal, state, and national government clients:

- **Relevance:** The reported GHG emissions appropriately reflect emissions occurring as a result of activities and consumption within the state. The inventory is meant to serve the decision-making needs of the State's Agencies, Commissions, and Offices, taking into consideration relevant local, state, and national regulations. Relevance applies when selecting data sources and determining and prioritizing data collection improvements.
- **Completeness:** All emission sources within the inventory boundary are accounted for, and any exclusions of sources (for example electricity generation destined for export) are justified and explained.
- **Consistency:** Emissions calculations are consistent in their approach, boundaries, and methodology.

- **Transparency:** Activity data, emissions sources, emissions factors and accounting methodologies require adequate documentation and disclosure to enable verification.
- **Accuracy:** The calculation of GHG emissions should not systematically overstate or understate actual GHG emissions, and should be accurate enough to give decision makers and the public reasonable assurance regarding the integrity of the reported information. Uncertainties in the quantification process should be reduced to the extent possible and practical.

Scope

Scope of this Manual

The Data, Methods, and Assumptions (DMA) Manual contains methods and assumptions for model calibration as well as the business-as-usual, business-as-planned, and decarbonization scenarios.

Project Scope

The purpose of this study is to identify and describe the various potential pathways for investor-owned electric and natural gas utilities to contribute to achieving Washington's overall GHG emission reduction goals.

RCW 70A.45.020 states that Washington shall limit anthropogenic emissions of greenhouse gases (GHGs) as follows:

i. By 2020, reduce GHGs to 1990 levels, or 90.5 million metric tons;
ii. By 2030, reduce GHGs to 50 million metric tons, or 45% below 1990 levels;
iii. By 2040, reduce GHGs to 27 million metric tons, or 70% below 1990 levels;
iv. By 2050, reduce GHGs to 5 million metric tons, or 95% below 1990 levels.

Senate Bill 5092, section 143 (Chapter 334, Laws of 2021), provided funding to the Washington Utilities and Transportation Commission for the study, which must identify and consider:

i. How natural gas utilities can decarbonize;
ii. The impacts of increased electrification on the ability of electric utilities to deliver services to current natural gas customers reliably and affordably;
iii. The ability of electric utilities to procure and deliver electric power to reliably meet that load;
iv. The impact on regional electric system resource adequacy, and the transmission and distribution infrastructure requirements for such a transition;
v. The costs and benefits to residential and commercial customers, including environmental, health, and economic benefits;

vi. Equity considerations and impacts to low-income customers and highly impacted communities; and

vii. Potential regulatory policy changes to facilitate decarbonization of the services that gas companies provide while ensuring customer rates are fair, just, reasonable, and sufficient.

This project is about identifying and describing the various pathways to achieve a certain level of natural gas emissions reduction. This project is not about choosing one pathway.

The Washington Utilities and Transportation Commission will use the Energy Decarbonization Pathways Examination to report to the legislature on feasible and practical pathways for investor-owned electric and natural gas utilities to decarbonize, and the impacts of energy decarbonization on customers and utilities. The State legislature will use the findings of the study to discuss and develop policies related to investor-owned utility decarbonization.

Geographic Boundary

The geographic scope of this project is the state of Washington. SSG completed energy and emissions inventories for the state as a whole, as well as sub-zones that correspond to Washington's 39 counties.

Annual and hourly energy demand is simulated at the county level and also by balancing authority (BA) for electricity demand.

Annual and hourly electricity generation within the state of Washington is simulated by county and BA. Electricity that is generated outside of Washington but consumed within the state is represented by the state and BA of generation. Emissions resulting from the out-of-state generation of electricity that is consumed in Washington are included in the modeled emissions. Transmission of electricity is modeled as trade among BAs.

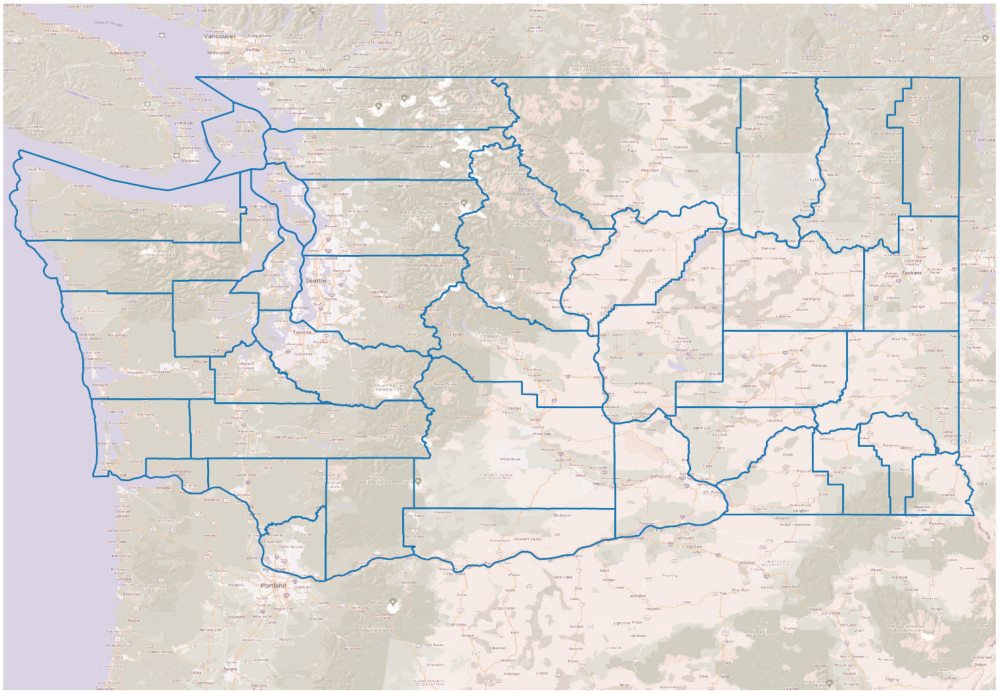

Figure 1. Geographic scope and sub-scopes (counties, in purple) of this study.

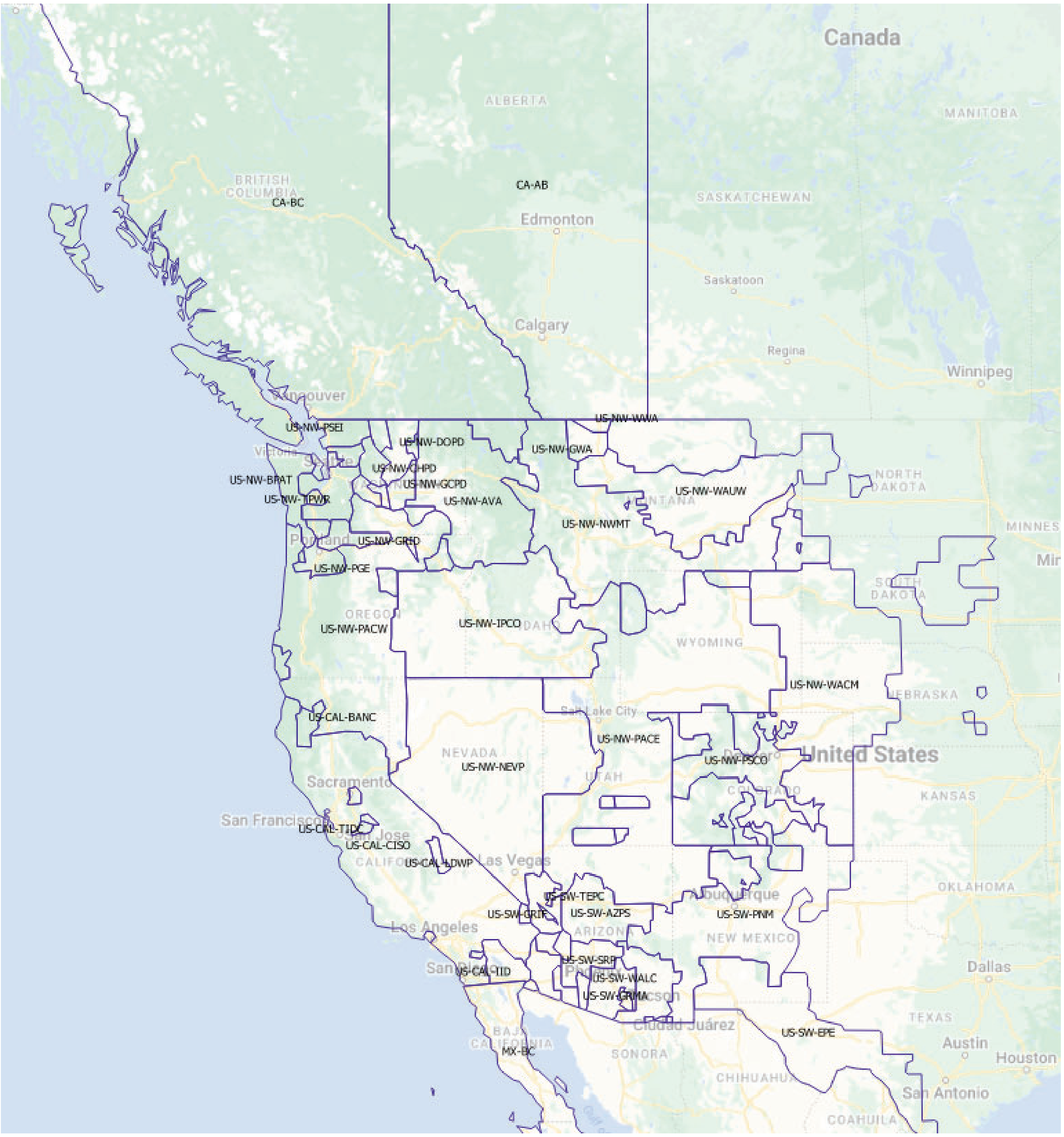

Figure 2. Map of the balancing authorities within the Western Electricity Coordinating Council (WECC) used for electricity supply modeling.

Time Frame of Assessment

The modeling time frame includes years 2019-2050. The year 2019 was used as the base year because it is the year for which the most current and complete data is available for calibration and modeling. Data from the 2019 American Community Survey (5-year) and the 2020 U.S. Census was also used.

As set by RCW 70A.45.020, the relevant target years are 2030, 2040, and 2050. The goals are for Washington to achieve a 45% reduction below 1990 GHG emissions levels by 2030, a 70% reduction by 2040, and a 95% reduction by 2050. Model calibration for the base year uses as much locally observed data as possible, supplemented by data collected at the federal levels.

The modeling for this project simulates energy supply and demand in both annual and hourly time steps.

Energy and Emissions Structure

Energy

The total energy consumption for the State is defined as the sum of the following aspects:

$$Energy_{State} = Energy_{transport} + Energy_{buildings} + Energy_{localEnergyProduction}$$

Where:

$Energy_{transport}$ is the movement of goods and people on foot, in vehicles, and using trucks, planes, and trains, etc.

$Energy_{buildings}$ is the use of energy to provide services such as heating and cooling, and other stationary energy use in buildings such as appliances and plugs.

$Energy_{LocalEnergyProduction}$ is energy used within the state of Washington to generate other energy currencies such as steam, electricity, etc.

GHG Emissions

GHG emissions from anthropogenic activities within the state are defined as the sum of all in-scope emissions sources:

$$GHG_{State} = GHG_{transport} + GHG_{buildings} + GHG_{energyGen} + GHG_{fugitive} + GHG_{CarbonCapture} + GHG_{process}$$

Where:

$GHG_{transport}$ are emissions generated by the movement of goods and people (for example, from the use of on-road vehicles (cars, buses, trucks), rail, marine, aviation, and non-road vehicles (construction vehicles, tractors, ATVs, logging trucks).

$GHG_{buildings}$ are emissions generated by energy use (lighting, appliances, heating, cooling, etc.) in buildings (both residential and commercial), including industrial facilities such as refineries.

$GHG_{energyGen}$ are emissions generated by the in-state generation of heat and electricity, the transmission of natural gas through pipelines within the state, and in-state alternative fuel production.

$GHG_{fugitive}$ are emissions caused by leaks from distribution pipelines, regulating equipment, and transfer stations in the state's pipeline network.

$GHG_{CarbonCapture}$ are emissions gathered and stored using carbon capture and storage technologies installed at power generation facilities or elsewhere.

$GHG_{process}$ are emissions generated from industrial processes that emit GHGs (such as cement manufacturing or iron and steel production) or the decomposition of materials in landfills.

Refer to Appendix 1 for a detailed list of included GHG emissions sources by scope.

Models

The modeling for this project integrates the following three component models which are used to analyze different temporal scales and sectors:

- Energy Systems Simulator (Annual and Hourly Energy and Electricity Demand)
- Calliope (Hourly Electricity Supply and Dispatch)[1]

Each component model is described in the following sections.

Energy Systems Simulator

The Energy Systems Simulator (ESS) is an energy, emissions, and finance accounting tool developed by Sustainability Solutions Group. The model integrates fuels, sectors, and land-use in order to enable bottom-up accounting for energy supply and demand, including:

- renewable resources (hydro, solar, wind, geothermal, renewable natural gas, biofuels, etc.),
- fossil fuels (gasoline, diesel, fossil natural gas, coal, etc.),
- energy-consuming technology stocks (e.g. vehicles, appliances, dwellings, buildings), and
- all intermediate energy flows (e.g. electricity and heat).

Energy and GHG emissions values are derived from a series of connected stock and flow models, evolving based on current and future geographic and technology decisions/assumptions (e.g. electric vehicle (EV) uptake rates). The model accounts for physical flows (e.g. energy use, new vehicles by technology, vehicle miles traveled (VMT)) as determined by stocks (buildings, vehicles, heating equipment, etc.).

The model incorporates and adapts concepts from the system dynamics approach to complex systems analysis. For any given year, the model traces the flows and transformations of energy from sources through energy currencies (e.g. gasoline, electricity, hydrogen) and end uses (e.g. personal vehicle use, space heating) to energy costs and GHG emissions. An energy balance is achieved by accounting for efficiencies, technology conversion, and trading losses at each stage of the journey from source to end use.

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[1] The production of green hydrogen via electrolysis was also included in the model. Details may be found in the section of the DMA on decarbonization scenario assumptions.

Table 1. Model characteristics.

Characteristic	Rationale
Integrated	The tool models and accounts for all energy and emissions in relevant sectors and captures relationships between sectors. The demand for energy services is modeled independently of the fuels and technologies that provide the energy services. This decoupling enables exploration of fuel-switching scenarios. Viable scenarios are established when energy demand and supply are balanced.
Scenario-based	Once calibrated with historical data, the model enables the creation of dozens of scenarios to explore different possible futures. Each scenario can consist of either one or a combination of policies, actions, and strategies. Historical calibration ensures that scenario projections are rooted in observed data.
Spatial	The model includes spatial dimensions that can include as many zones (the smallest areas of geographic analysis) as deemed appropriate; in this case, they are Washington counties. The spatial components can be integrated with Geographic Information Systems (GIS) and land-use projections.
Sector-based	The model is designed to report emissions according to categories based on sectors (residential, industry, etc.).
Economic impacts	The model incorporates a high-level financial analysis of costs related to energy (expenditures on energy) and emissions (carbon pricing, social cost of carbon), as well as operating and capital costs for policies, strategies, and actions. This allows for the generation of marginal abatement costs.

ESS Model Structure

The major components of the ESS model and the first level of their modeled relationships (or influences) are represented by the blue arrows in Figure 2. Additional relationships may be modeled by modifying inputs and assumptions—specified either directly by users, or in an automated fashion by code or scripts running “on top of” the base model structure. Integrated modeling generates a total picture of the overall impact of inputs and assumptions, including the emissions or sequestration intensity of other inputs within the model.

The model is also spatially explicit. All buildings, transportation, and land-use data are tracked within the model through a GIS platform, and by varying degrees of spatial resolution. To divide the State into smaller configurations, we use data at the level of Washington's 39 counties. This enables more accurate modeling of energy use for each of the counties, as there are significant differences between, for example, marine climate counties to the West of the Cascades and cold climate counties to the East.

In any given year, various factors shape the picture of energy and emissions flows, including: the population and the energy services it requires; commercial floorspace; energy production and trade; technologies deployed to deliver energy services (service technologies) and to transform energy sources to currencies (harvesting technologies). The model is based on an explicit mathematical relationship between these factors—some contextual and some being part of the energy consuming or producing infrastructure—and the energy flow picture.

Some factors are modeled as stocks—counts of similar things, classified by various properties. For example, population is modeled as a stock of people classified by age and gender. Population change over time is projected by accounting for: the natural aging process, inflows (births, immigration), and outflows (deaths, emigration). The fleet of personal use vehicles—an example of a service technology—is modeled as a stock of vehicles classified by size, engine type and model year, with a similarly classified fuel consumption intensity. As with population, projecting change in the vehicle stock involves aging vehicles and accounting for major inflows (new vehicle sales) and outflows (vehicle discards). This stock-turnover approach is applied to other service technologies (e.g. furnaces, water heaters) and harvesting technologies (e.g. electricity generating capacity).

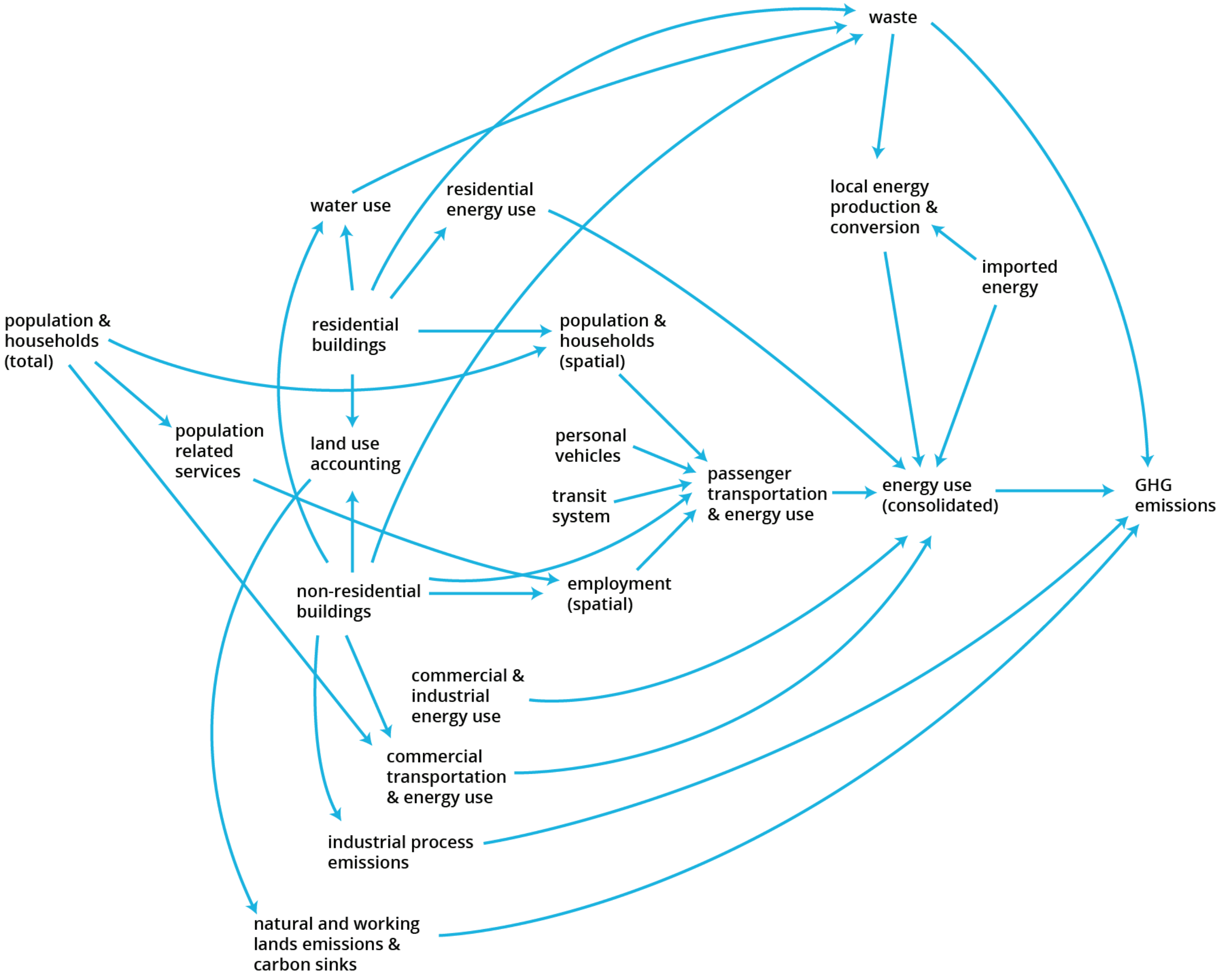

Figure 3. Representation of the ESS model structure.

Sub-Models and Local Context Calibration

The overall model operates based on the interactions within and between factors of various sub-models, as described in this section. To develop the business-as-usual, business-as-planned, and decarbonization scenarios, we calibrate the model with local data, building the model from the ground up.

Data Request and Collection

The data we used to calibrate the model was supplied by Washington state agencies, such as the Washington Department of Commerce, Washington State Office of Financial Management, and the Washington State Department of Transportation (WSDOT), supplemented by data from federal and regional sources such as the Northwest Energy Efficiency Alliance (NEEA) . The complete list of data and sources is provided in Appendix 4. To supplement any gaps in the observed data, we developed assumptions which are described below. We applied the data and assumptions using the modeling processes described below.

Zone System

The model is spatially explicit: population, employment, residential, and non-residential floorspace are allocated and tracked spatially for each of Washington's 39 counties (see Figure 3). These elements drive stationary energy demand. The passenger transportation sub-model, which contributes to transportation energy demand, also operates within the same zone system.

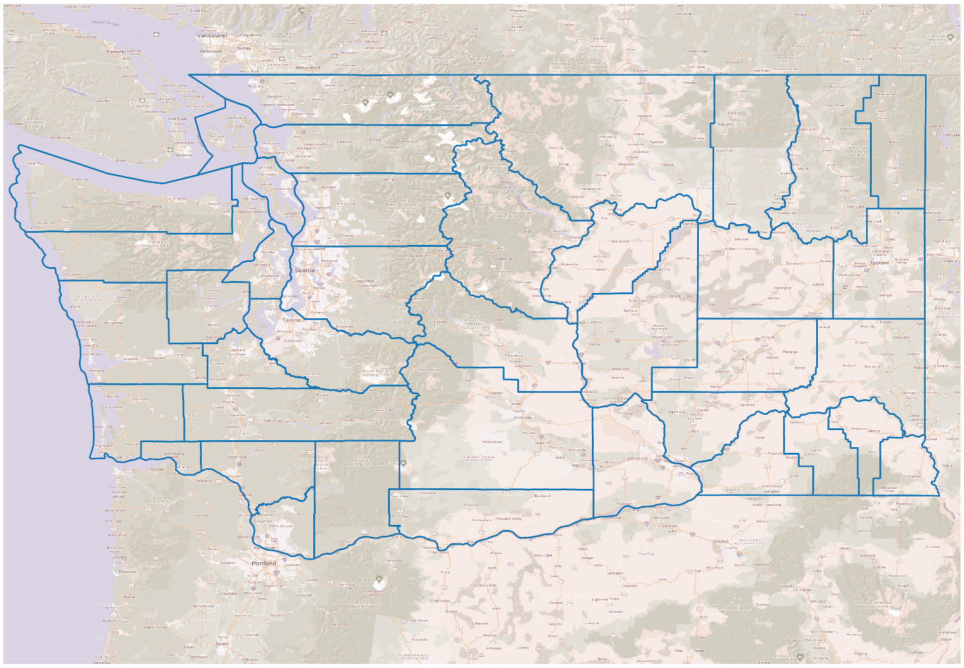

Figure 4. Zone system (Washington counties) used in ESS modeling.

Population and Employment

How the Sub-model Works

State-wide population is modeled using the standard population cohort-survival method, disaggregated by single year of age and gender. It accounts for typical components of change: births, deaths, immigration, and emigration. The age-structured population is important for analysis of demographic trends, generational differences and implications for shifting energy use patterns. These numbers are calibrated against base year data and existing projections. a

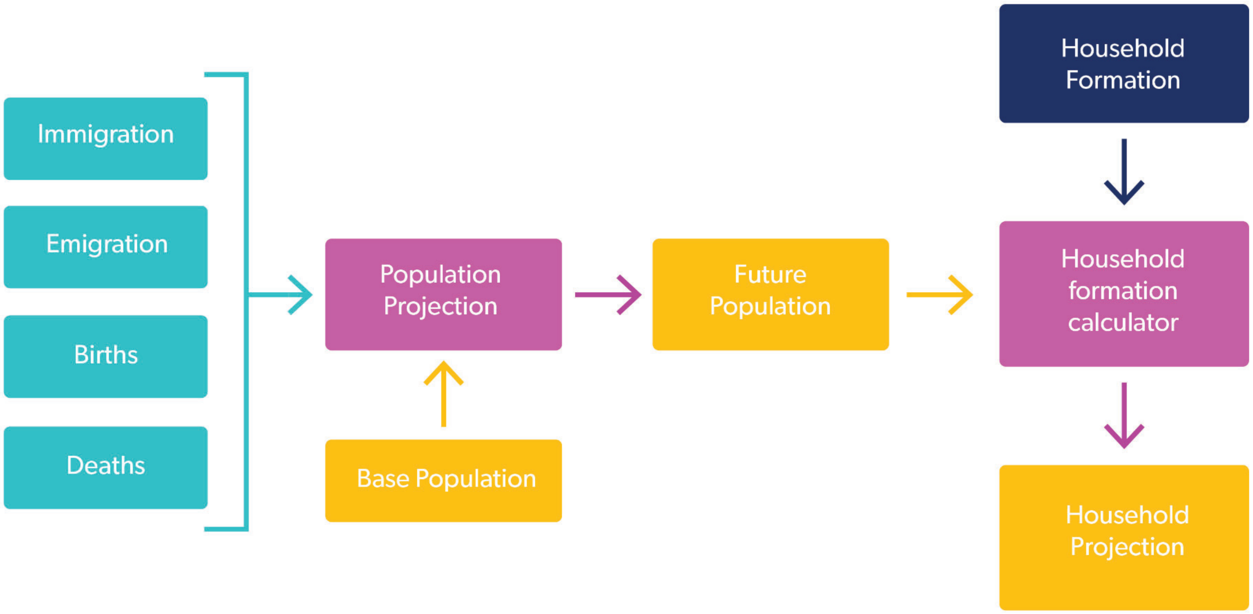

Figure 5. Population and employment submodel design flow. Light blue rectangles represent flows, fuchsia rectangles represent model calculations, yellow rectangles represent stocks, and dark blue rectangle represent model parameters.av

US Census population and employment data is spatially allocated to the residential (population) and non-residential (employment) buildings. This enables indicators to be derived from the model, such as emissions per household, and drives the business-as-usual (BAU) energy and emissions projections for buildings and transportation.

An additional layer of model logic (not shown explicitly in Figure 4) captures energy-related financial flows and employment impacts. Calculated financial flows include the capital, operating, and maintenance costs of energy-consuming and energy-producing stocks, as well as fuel costs. We also model employment related to the construction of new buildings, retrofit activities and energy infrastructure; assess the financial impact on businesses and households of implementing the strategies, and apply various local economic multipliers (depending on the geographic and economic variability of the calculation and anticipated output) to investments.

How We Calibrate the Sub-model

We distributed the 2019 population to residential buildings in space, using initial assumptions about persons-per-unit (PPU) by dwelling type, and adjusting them so that the total population in the model (which is driven by the number of residential units by type multiplied by PPU by type) matches the total population from census/regional data.

Employment in 2019 is spatially allocated to non-residential buildings, using intensities (e.g. square feet per retail employees). As with population, the model adjusts these initial ratios so that the derived total employment matches total employment from the census and regional data.

Buildings

How the Sub-model Works

Residential buildings are spatially located and classified using a detailed set of 12 building archetypes (see Appendix 2) capturing footprint, height, and type (single-family, duplex, semi-attached, row-housing, apartment high-rise, apartment low-rise, etc.) and year of construction. The archetypes are used to generate a “box” model that helps to estimate the floor area and energy use, and then is used to simulate the impact of energy efficiency measures.

Using assumptions on thermal envelope performance and heating and cooling degree days, the model calculates space-conditioning energy demand independent of space heating or cooling technologies. First, the model multiplies the residential building floorspace area by an estimated thermal conductance (heat flow per unit of surface area per degree day) and the number of degree days (heating and cooling) to derive the energy transferred out of the building during winter months and into the building during summer months. The energy transferred through the building envelope, the solar gain through the building windows, and the heat gains from equipment inside the building constitute the net space-conditioning load required to be provided by the heating and air-conditioning systems (as shown in Figure 5).

This space conditioning demand is satisfied by stocks of energy service technologies, including heating systems, air conditioners, and water heaters. These stocks are modeled with a stock-turnover approach, capturing equipment age, retirements, and additions—exposing opportunities for efficiency gains and fuel-switching, but also constraining the rate of technology adoption.

Residential building archetypes are also characterized by the number of dwelling units they contain, allowing the model to not only capture the energy effects of shared walls, but also the urban form and transportation implications of population density.

Non-residential buildings, commercial and otherwise (see Appendix 2) are located in space and mapped to a set of 40+ archetypes. The floorspace of these archetypes varies by location. Non-residential floorspace generates demand for energy and water, and provides an anchor point for locating employment of various types.

The model calculates the space-conditioning load for non-residential buildings as it does for residential buildings, with two distinctions: the thermal conductance parameter for non-residential buildings is based on floor area instead of surface area, and incorporates data from REPLICA, a proprietary provider of modeled and observed building and transportation data. Using assumptions for thermal envelope performance for each building type, the model calculates total energy demand for all buildings, independent of any space heating or cooling technology and fuel.

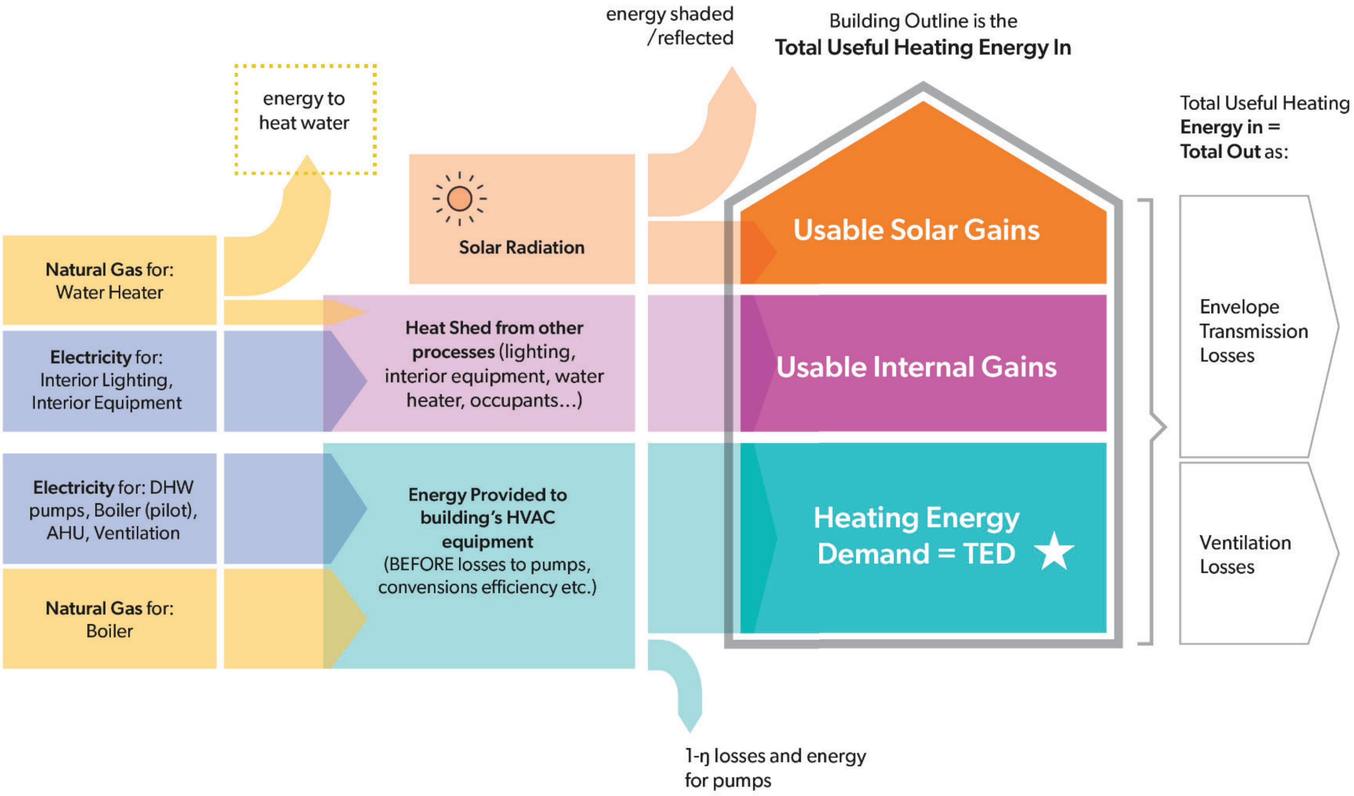

Figure 6. A diagram showing the considerations in the model for energy and emissions related to buildings.

How We Calibrate the Sub-model: Residential Buildings

For each Washington county, building data (including building type, number of stories, number of units, and year built) was sourced from the 2019 U.S. Census for residential buildings, and from REPLICA Places Land Use data for commercial and industrial buildings. Total floorspace area for each building type was calculated referencing building archetypes that are typical in Washington.

The initial estimates for thermal conductance and output energy use intensity by end use and equipment efficiency assumptions are regional averages by dwelling type from a North American energy systems simulator, calibrated for the Pacific Northwest. The assumed distribution of residential heat system types comes from the Northwest Energy Efficiency Alliances' Residential Building Stock Assessment database. The initial thermal conductance and output energy use intensity estimates are adjusted through the calibration process until natural gas use in residential buildings tracks on natural gas deliveries to the residential sector, as reported by Washington state natural gas utilities, and until residential electricity use tracks on Washington state electricity sales to the residential sector, as reported in the EIA Annual Electric Power Industry Report (Form 861).

How We Calibrate the Sub-model: Non-residential Buildings

Starting values for output energy intensities and equipment efficiencies for non-residential end uses are taken from the 2018 Commercial Buildings Energy Consumption Survey (CBECS) complemented by the EPA's Portfolio Manager Technical Reference that provides Energy Use Intensity by Property Type for some additional building types. All parameter estimates are further adjusted during the calibration process. The calibration target for non-residential building energy use is the observed commercial and industrial fuel consumption in the base year, as reported by Washington state natural gas utilities, and in the EIA Annual Electric Power Industry Report (Form 861).

Passenger Transportation

How the Sub-model Works

The model captures personal transportation energy use by modeling household travel. Families make trips for various purposes (work, school, socializing, errands, drop-offs, shopping), and these trips are shared out over the various modes of transportation (walk, bike, auto, transit). The energy use and emissions associated with various types of personal vehicles are calculated by assigning VMT to a stock-turnover personal vehicle model. The induced approach is used to track emissions.

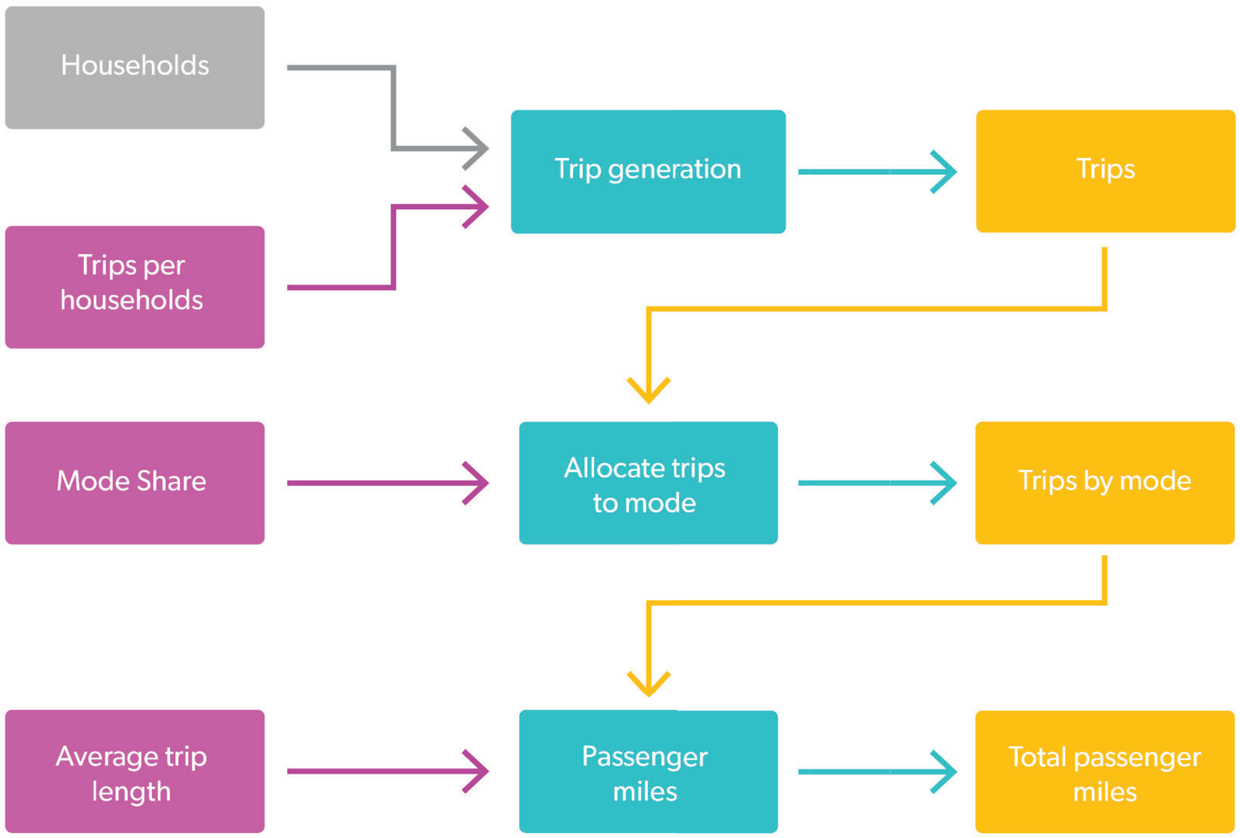

Figure 7. Conceptual diagram of how the model generates trips, trips by mode, and total miles traveled, per a given year. Gray rectangles represent stocks, fuchsia rectangles represent model parameters, light blue rectangles represent calculations made in the model, and yellow rectangles represent model outputs. All the outputs in this case represent flows.

How We Calibrate the Sub-model

The model is calibrated with data from the Washington State Department of Transportation's Annual mileage and travel information by county, which is collected by agencies throughout the state to support federal reporting requirements via the Highway Performance Monitoring System (HPMS). A stock of personal use vehicles is coupled with the VMT data to calculate energy consumption for personal vehicle use. This category is supplemented by transit fuel use (calculated on the basis of bus VMT), recreational marine fuel use, and off-road fuel use. The remaining commercial vehicle energy use is then calibrated so that total energy use by the transportation sector is aligned with SEDS.

The modeled stock of personal vehicles by size, fuel type, efficiency, and vintage was informed by the regional vehicle registration statistics. The total number of personal-use vehicles is proportional to the projected number of households in the BAU. Transit VMT and fuel consumption were modeled based on bus VMT data provided by ODOT.

Local Electricity Production

How the Sub-model Works

The model simulates in-state production of electricity and combined heat and power (CHP). Production capacity is represented as a stock while generation is modeled as a flow resulting from the use of that capacity. Energy produced from primary sources (e.g. solar, wind) is modeled alongside energy converted from imported fuels (e.g. electricity generation, combined heat and power (CHP)). The model applies a conversion efficiency to calculate fuel use.

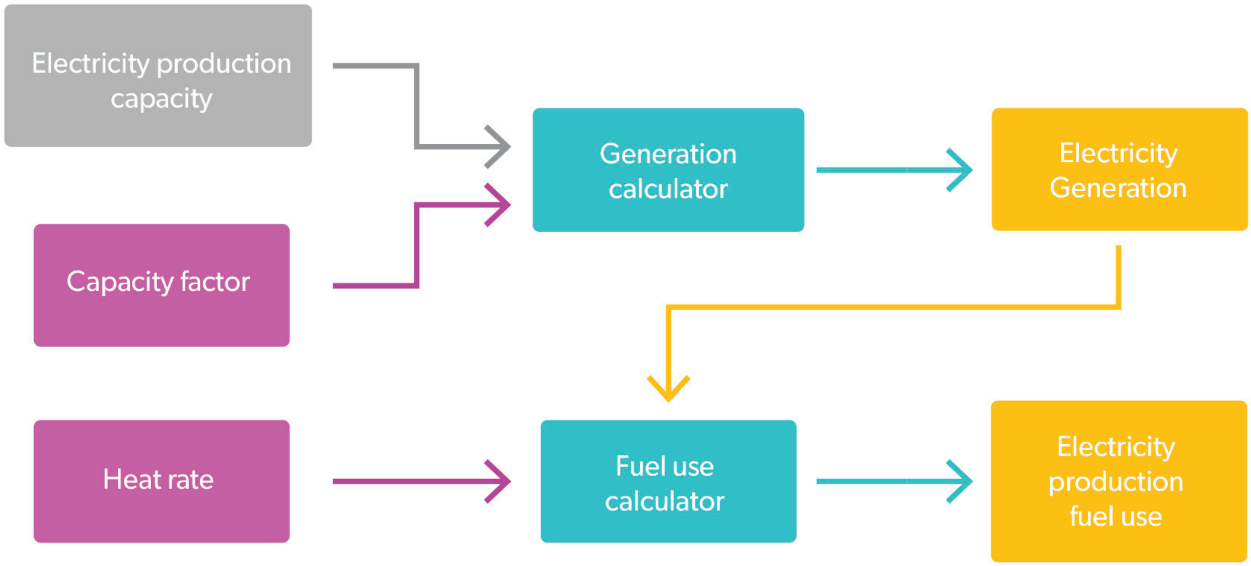

Figure 8: Conceptual diagram of how the model derives electricity production generation and fuel use.

How We Calibrate the Sub-model

The allocation of grid generation to demand in each county is based on utility data reported through the Washington Department of Commerce's fuel mix program. Through this program, utilities disclose the generating resources used to provide the electricity sold within Washington state. The data includes the name and characteristics of the generating plant, including plants outside of Washington, as well as the amount of generation claimed by the utility.

Demand by county is calculated based on building electricity use as described in the Buildings section. Service territory data from EIA Form 861 indicates which counties each utility serves. The model uses these two data sources to estimate the amount of electricity each utility provides to each county and in turn the fuel source used to generate the electricity used in each county.

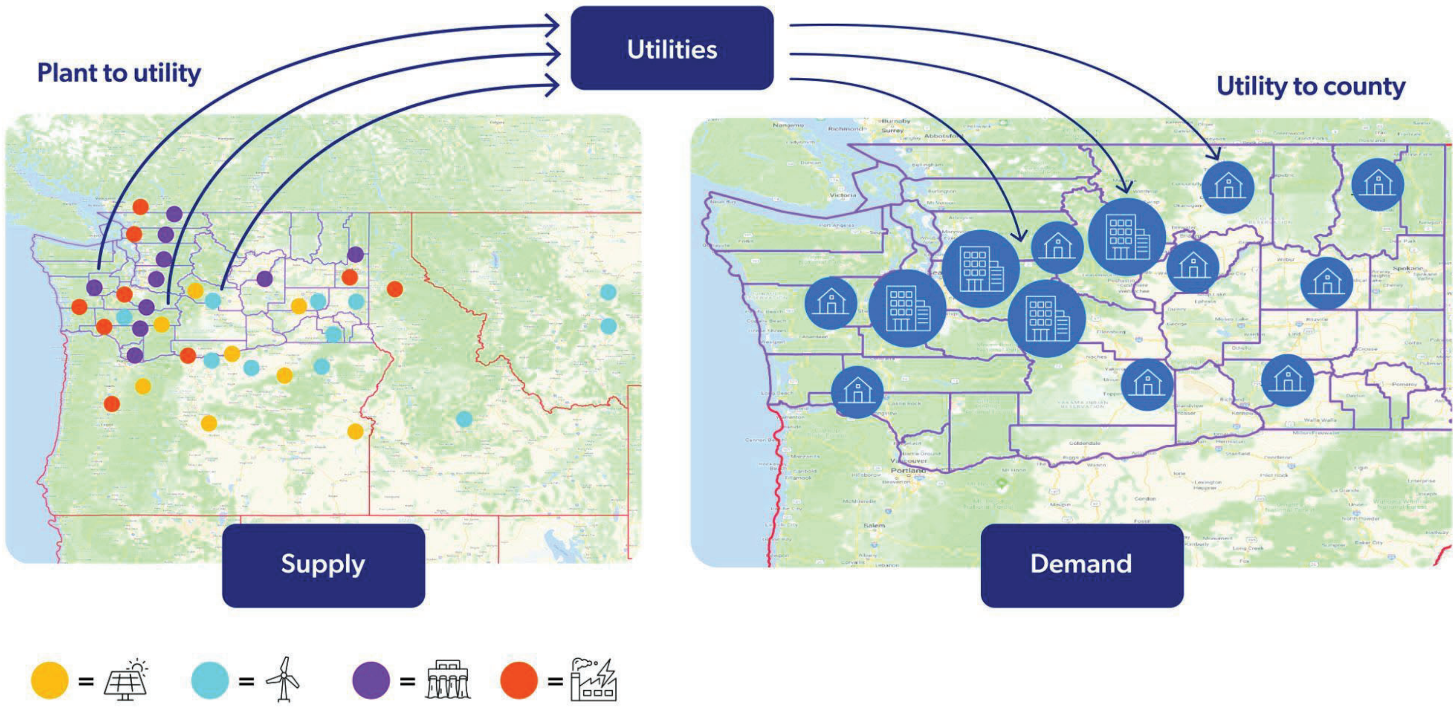

Figure 9: Allocation of grid electricity supply to demand by county. The plant to utility mapping is derived from the fuel mix disclosure program data. The utility to county mapping is derived from service territory data from EIA Form 861 and modeled electricity demand by county.

Fugitive Emissions

How the Sub-model Works

Fugitive emissions from natural gas pipelines are modeled as an emissions rate applied to total natural gas sales within Washington state.

How We Calibrate the Sub-model

The fugitive emissions rate is calibrated so that the modeled fugitive emissions match the emissions caused by leaks from distribution pipelines reported by local natural gas distribution companies under Subpart W of the EPA Greenhouse Gas Reporting Program (GHGRP).

Hourly Demand

An hourly electricity demand model was integrated with the ESS model developed for Washington.

The outputs from the ESS include annual electricity consumption by county, sector, and end use for the calibrated base year of 2019 and projected through 2050 for the scenarios. The hourly model spreads this annual consumption across the 8,760 hours in a year for the years 2019, 2030, 2040, and 2050 using hourly load shapes specific to each sector and end use.

Figure 10 (next page) summarizes this process:

1. Each load shape is multiplied by the corresponding annual consumption for that load shape's sector and end use.
2. The resulting hourly demand by county is aggregated to corresponding balancing authorities (BAs)
3. The resulting hourly demand by BA is adjusted to better align with observed hourly demand by BA from the EIA Hourly and Daily Balancing Authority Operations Report (EIA-930) for 2019.

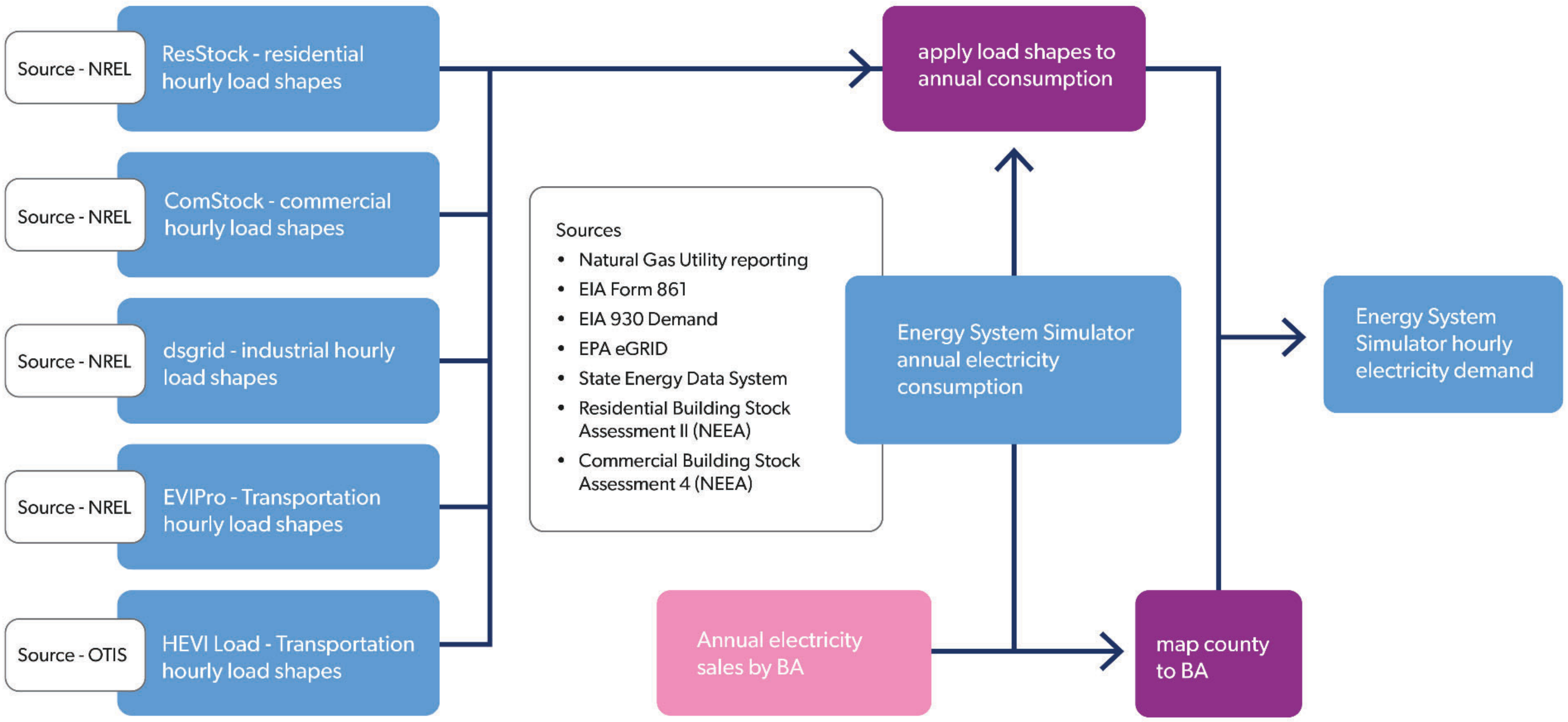

Figure 10: Annual electricity consumption to hourly demand process. Purple boxes represent calculations within the hourly model given inputs from various sources.

Residential and Commercial

County-level hourly shapes for electricity consumption in residential and commercial buildings in Washington were derived from end-use load profiles for U.S. building stock developed by the National Renewable Energy Laboratory (NREL) and its research partners.[2] These end-use load profiles were developed using NREL's ResStock and ComStock building energy models with validation against observed data such as whole-building interval meter data, submetering studies, and other data sources. The ResStock and ComStock simulation models represent the energy use and energy saving potential of residential and commercial building stocks with high granularity at national, regional, and local scales. The derived load shapes used in the hourly electricity demand model therefore capture the sub-regional climatic variation in heating and cooling hourly demand.

Industrial

The industrial load shapes were derived from industrial electricity load datasets created by NREL's demand-side grid (dsgrid) toolkit.[3] For the industrial sector in dsgrid, NREL partnered with Oak Ridge National Laboratory and the Electric Power Research Institute to model industrial energy use with the Industrial Geospatial Analysis Tool for Energy Evaluation (IGATE-E).[4] The resulting datasets provide hourly industrial loads by county and end use. The dsgrid industrial load profiles were normalized to create the default hourly industrial load shapes. Weeklong load shapes for motive and process heat end uses are shown in Figure 11.

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[2] Lawrence Berkeley National Laboratory and Argonne National Laboratory

[3] "Dsgrid: Demand-Side Grid Toolkit." NREL.gov. Accessed May 19, 2023. https://www.nrel.gov/analysis/dsgrid.html.

[4] "Industrial Geospatial Analysis Tool for Energy Evaluation- IGATE-E | ORNL." Accessed May 19, 2023. https://www.ornl.gov/technology/201303062.

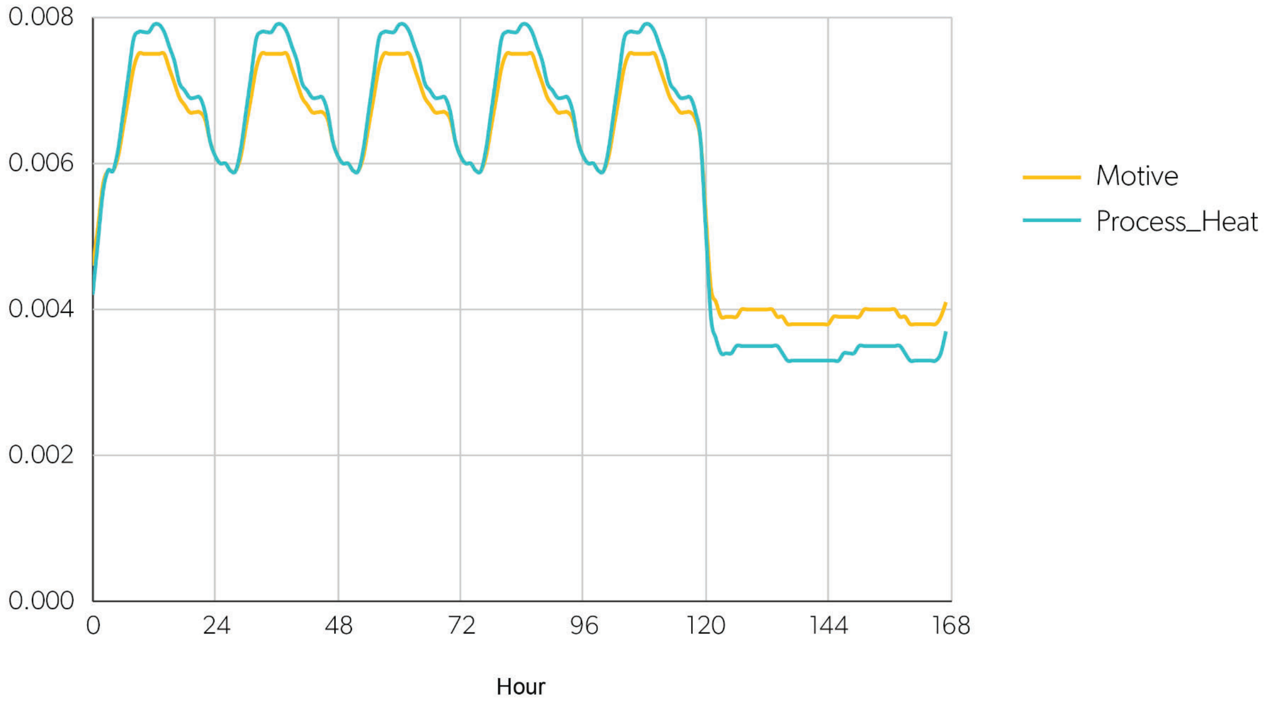

Figure 11. Weeklong load shapes for selected industrial sector end uses.

Transportation

Personal Use Vehicles

The personal use vehicle charging load shapes come from the U.S. Department of Energy's Electric Vehicle Infrastructure Projection Tool (EVI-Pro) Lite. EVI-Pro Lite was used to construct weekday and weekend electricity load profiles for Seattle, Washington in which electric vehicles are charged at home as quickly as possible. The specific assumptions are listed in Table 2. The EVI-Pro Lite load profiles were normalized to create the default hourly load shapes shown in Figure 12.

Table 2. Personal use vehicle charging assumptions.

Assumption	***Value/Description***
Average Daily Miles Traveled per Vehicle	35 miles
Average Ambient Temperature	50°F
Plug-in Vehicles that are All-Electric	50% – Equal Shares of EVs and PHEVs The fleet has about the same number of EVs as PHEVs with this breakdown: 15% PHEVs that can drive 20 electric miles 35% PHEVs that can drive 50 electric miles 15% EVs that can drive 100 miles 35% EVs that can drive 250 miles
Home Charging Infrastructure	50% Level 1 and 50% Level 2
Preference for Home Charging	100% prefer primarily charging at home
Home Charging Strategy	Immediate – as fast as possible This option assumes vehicles begin charging as soon as possible upon arriving at a charging location and charge at full power/speed until fully charged or the vehicle departs.

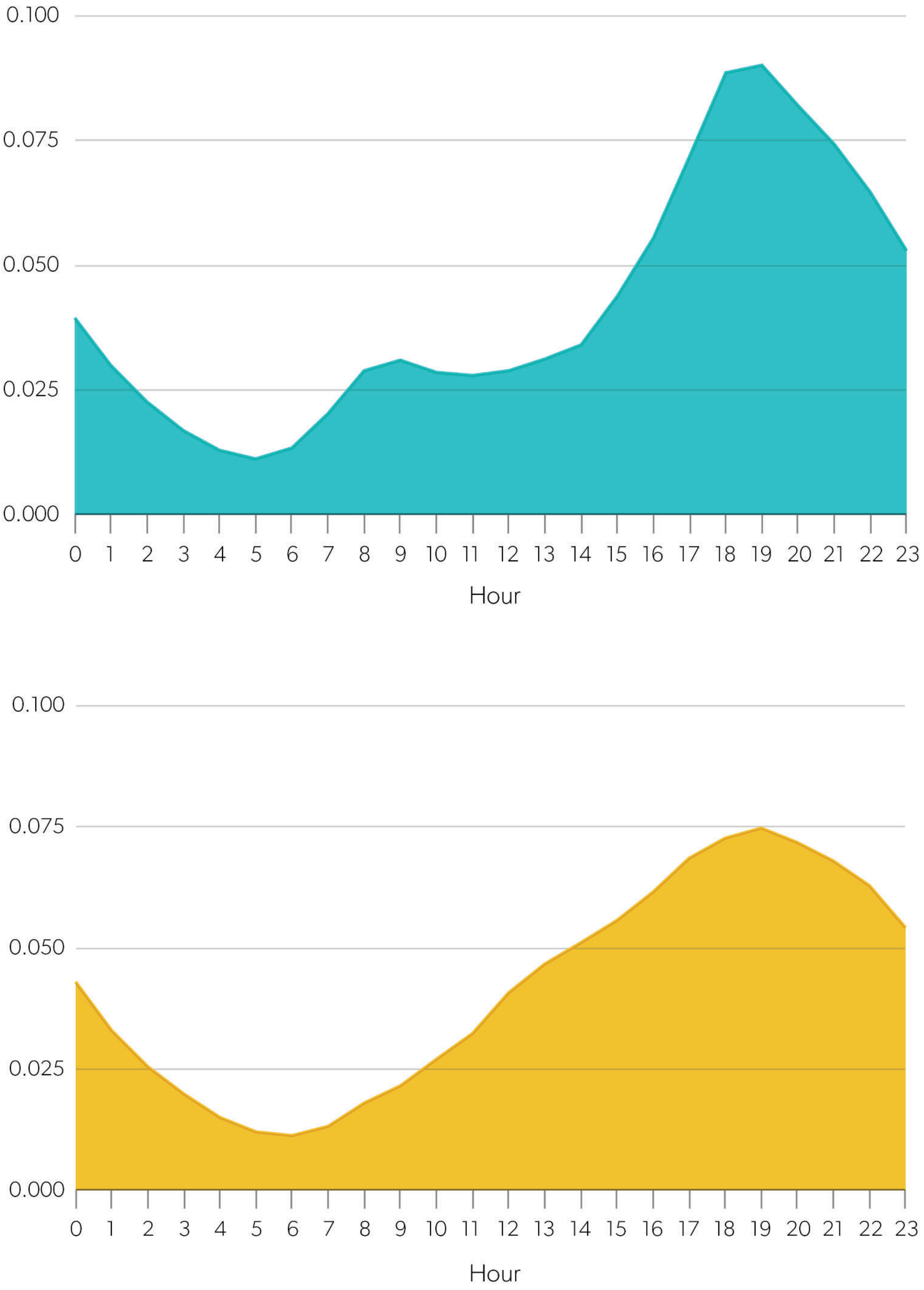

Figure 12. Weekday (top) and weekend (bottom) personal vehicle charging load shapes.

Commercial Use Vehicles

The hourly load shape for commercial vehicle charging is derived from data accompanying the inaugural Electric Vehicle Charging Infrastructure Assessment by the California Energy Commission (CEC),[5] a biannual report on the charging needs of 5 million zero emission vehicles (ZEVs) that is required by California Assembly Bill (AB) 2127. The modeling analysis in the CEC report used Medium- and Heavy-Duty Electric Vehicle Infrastructure Load, Operations, and Deployment (HEVI-LOAD) to explore charging patterns of 180,000 medium- and heavy-duty ZEVs. HEVI-LOAD simulates patterns of trip generation based on the vehicle type and payload for nine vehicle categories to estimate when vehicles need to recharge. The total projected medium duty and heavy duty vehicle charging load from the HEVI-LOAD analysis in the CEC report was normalized to create the aggregate hourly load shape shown in Figure 13.

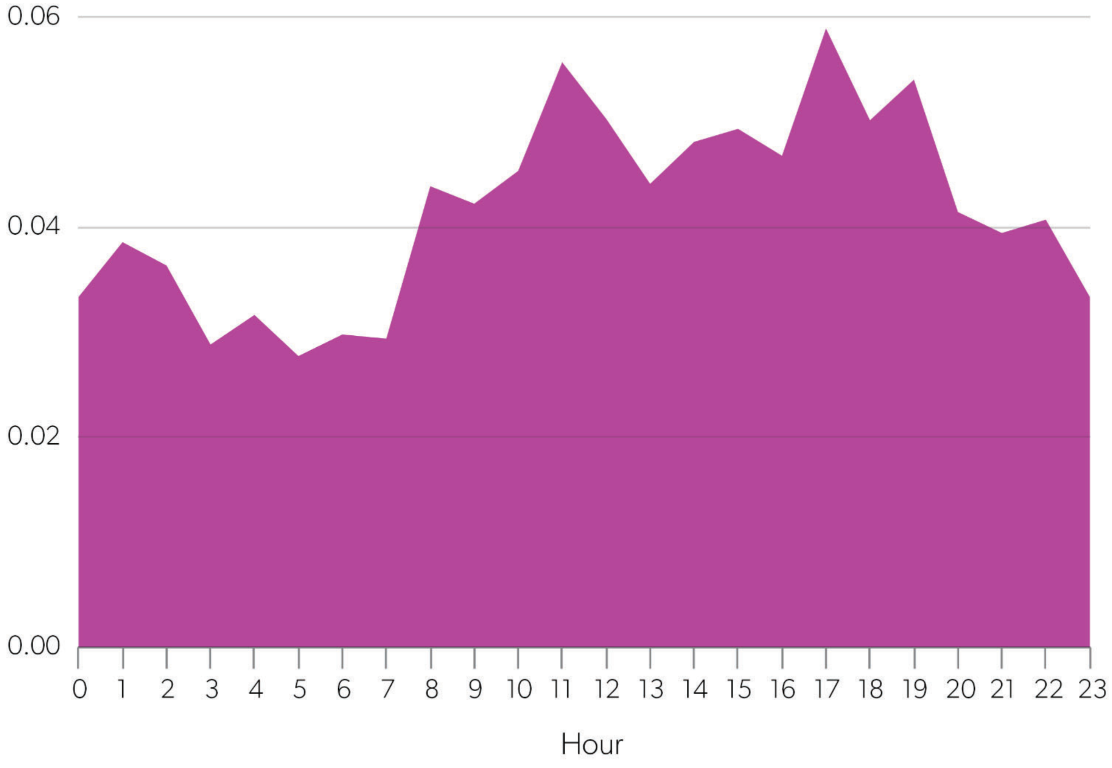

Figure 13: Commercial vehicle charging load shape.

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[5] Alexander, Matt, Noel Crisostomo, Wendell Krell, Jeffrey Lu, and Raja Ramesh. July 2021. Assembly Bill 2127 Electric Vehicle Charging Infrastructure Assessment: Analyzing Charging Needs to Support Zero-Emission Vehicles in 2030 – Commission Report. California Energy Commission. Publication Number: CEC-600-2021-001-CMR.

Hourly Dispatch

An hourly dispatch model was used to match electricity supply consisting of generation from various resources to electricity demand from the hourly demand model. This dispatch model was developed using Calliope, a Python library for energy system analysis described below.

Calliope

Calliope is a free and open-source Python library that provides a framework for building and analyzing energy system models. The library allows users to create and explore complex models of energy systems, including their physical components, interactions, and constraints.[6]

Through Calliope's high-level Python interface, users can specify the components of the system, including generators, renewable energy sources, storage devices (i.e. batteries), and transmission lines, and the relationships between them.

Once a model is defined, users can use Calliope's built-in tools to analyze its behavior under different scenarios and constraints. The library supports various optimization techniques, including linear and nonlinear programming, and provides interfaces to optimization solvers. Calliope also includes tools for visualizing model outputs, such as energy flows, system costs, and emissions.

Calliope is built on the Pyomo optimization framework, which provides a powerful and flexible platform for modeling and solving optimization problems. Pyomo supports a wide range of optimization techniques, including mixed-integer linear and nonlinear programming, and can be used to solve large-scale optimization problems efficiently.

Overall, Calliope is an energy system modeling and analysis tool that provides a flexible and intuitive interface for building complex models and analyzing their behavior under different scenarios and constraints. The library is widely used in academic research, industry, and government applications and continues to evolve and improve as new features and optimizations are added.

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[6] "A Multi-Scale Energy Systems Modelling Framework." Calliope. Accessed May 18, 2023. https://calliope.readthedocs.io/en/stable/index.html.

Model

A Calliope energy system model is a complex framework composed of several key components that simulate and optimize energy production and consumption within a given system.[7] These components include:

1. **Locations (nodes):** These are the fundamental building blocks of a Calliope model and represent individual points within the energy system, such as power plants, substations, and consumer locations. Nodes can be connected by links to allow energy to flow between them.
2. **Links:** These represent the physical connections between nodes that allow energy to be transmitted from one location to another. Links can be defined to include various transmission technologies, such as high-voltage power lines,
3. **Technologies:** These are the various types of energy generation and storage technologies that can be deployed within the system, such as solar panels, wind turbines, batteries, and hydro generation. Each technology is associated with specific parameters that determine its cost, efficiency, and operational constraints.
4. **Constraints:** These rules and limitations restrict how energy can be produced, stored, and transmitted within the system. Constraints can include capacity limits on technologies, minimum and maximum generation levels, and reserve capacity requirements. Constraints can be implemented at various levels, such as node-level constraints that restrict the capacity of individual energy technologies or system-level constraints that dictate the overall balance of supply and demand.
5. **Objective function:** This is a mathematical expression that defines the optimization goal of the model. The objective function can be designed to minimize the cost of energy production and transmission, minimize carbon emissions, or achieve other goals. The objective function is typically defined as a set of decision variables, such as the capacity of different energy technologies or the flow of energy between different nodes.
6. **Time resolution:** This specifies the time intervals at which the model operates. The model can be solved at various time resolutions, from hourly to annual. The choice of time resolution can significantly impact the accuracy and computational complexity of the model.

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[7] "A Multi-Scale Energy Systems Modelling Framework." Calliope. Accessed May 18, 2023. https://calliope.readthedocs.io/en/stable/index.html.

7. **Data inputs:** These include information about energy demand, the availability and cost of different technologies, and other data needed to run the model. Data inputs can be obtained from a variety of sources, such as historical energy consumption data, market data on energy prices and technology costs, and weather data used to model renewable energy resources.

The seven main components of the model designed for Washington State are explained in the following sections.

Locations

In the model, there are a total of nine locations, each of which represents a Balancing Authority (BA) within the state of Washington. For each location, referential coordinates were assigned to ensure accuracy in the representation of the geographic area. The specific locations and the approximate corresponding geographical coordinates of the centroids of each BA are presented in Table 3. A map of the BA areas is shown in Figure 2.

Table 3. Referential coordinates of each balancing authority.

Balancing Authority	***Code***	***Latitude***	***Longitude***
Avista Corporation	AVA	47.6239	-117.8910
Bonneville Power Administration	BPAT	47.0339	-120.1883
Public Utility District No. 1 of Chelan County	CHPD	47.8580	-120.6262
Public Utility District No. 1 of Douglas County	DOPD	48.1750	-119.5673
Public Utility District No. 2 of Grant County, Washington	GCPD	47.1976	-119.4470
PacifiCorp - West	PACW	46.2924	-119.9424
Puget Sound Energy, Inc.	PSEI	47.9519	-122.1392
Seattle City Light	SCL	47.9130	-122.7539
City of Tacoma, Department of Public Utility, Light Division	TPWR	46.9788	-122.0389

Links

The links refer to the physical alternating current (AC) transmission power lines linking two BAs. Table 4 shows the existing links between BAs and the initial capacity in MW. The model used existing connections based on data from the NPWCC. For the transmission capacity, two-way transmission is considered. For example, the transmission capacity from BPAT to AVA is 4,300 MW and the transmission capacity from AVA to BPAT is also 4,300 MW. The total initial transmission capacity (year 2030) in the state of Washington is 70,800 MW. Within the assumptions section, the changes in transmission capacity are shown throughout the scenarios and years analyzed.

Table 4. AC transmission power lines between BA, including initial capacity in MW.

	AVA	*BPAT*	*CHPD*	*DOPD*	*GCPD*	*PACW*	*PSEI*	*SCL*	*TPWR*	*TOTAL*
AVA		4,300	600		600	1,000				6,500
BPAT	4,300		2,500	1,700	6,500		6,100			21,100
CHPD	600	2,500		1,000			1,400			5,500
DOPD		1,700	1,000							2,700
GCPD	600	6,500				600				7,700
PACW	1,000				600					1,600
PSEI		6,100	1,400					5,000	4,100	16,600
SCL							5,000			5,000
TPWR							4,100			4,100
TOTAL	6,500	21,100	5,500	2,700	7,700	1,600	16,600	5,000	4,100	70,800

Technologies

The technologies incorporated in the model can be classified into two categories based on their characteristics and origins. The first category is the existing generation, which encompasses several types of power generation sources such as hydro reservoir, hydro run of river, fossil gas, nuclear, ground mounted photovoltaic (PV), onshore and offshore wind, and rooftop PV. The presence of these technologies is verified through Table 5, which provides a detailed overview of the existing technologies across the various Balancing Authorities.

The second category of technologies is the new technologies that are introduced over time to meet electricity demand in line with the constraints on emissions from electricity generation required by the Clean Energy Transformation Act (CETA). These new technologies consist of PV and wind power generation, which will be available across all the BAs. Additionally, battery storage is added in each BA. In order to identify the hours when imports from outside of Washington are needed, a technology named “unspecified supply” is available in each BA. The incorporation of these new technologies is expected to enhance the power supply capacity of the BAs, as well as enable the system to efficiently accommodate the demand for electricity.

The use of these existing and new technologies is instrumental in shaping the operational dynamics of the power system, facilitating efficient generation, and managing the variability and uncertainty of the system's power supply.

Table 5. Existing generation technologies by BA, including installed capacity in MW.

	AVA	BPAT	CHPD	DOPD	GCPD	PACW	PSEI	SCL	TPWR
Hydro reservoir	160	11000	1800	770	1700		900	1800	
Hydro run of river	20	60					220	60	
Gas	97.6	3001					1450.2	5	
Nuclear		1207							
PV	20						0.5		
Wind	105.3	2556				304.8	366.9		
PV rooftop	10.0	38.0	1.5	2.2	13.2	13.4	67.8	15.8	7.8
TOTAL	252.9	17862	1801.5	772.2	1713.2	318.2	3005.4	1880.8	7.8

Constraints

This section highlights the primary restrictions that have been incorporated into the model to help simulate various power system scenarios.

Firstly, the existing installed capacity of each BA by the source must be considered. This data provides insight into the current state of the power system and helps the model ensure that it remains within the existing power generation capacity limits.

Secondly, the maximum potential installed capacity of new PV and wind power generation by BA must be factored into the model. These constraints reflect the available renewable energy potential of each BA, and help to guide decisions regarding the most cost-effective and sustainable energy sources that can be incorporated into the power system.

Thirdly, the installation, operational, and capital costs associated with each generation source are essential inputs into the model. These cost constraints help ensure that the power system's operations are sustainable and efficient, by considering the financial implications of various decisions and trade-offs.

Finally, the transmission capacity for each link is a constraint that has been incorporated into the model. This data helps to ensure that the power system can reliably and efficiently transmit electricity from one BA to another, while minimizing transmission losses and ensuring that the system operates within the transmission infrastructure's capacity limits.

Objective Function

In the context of power system modeling, the objective function serves as a critical component that guides decision-making processes. In the case of the model being implemented, the objective function is designed to minimize the monetary cost associated with power system operations. This cost minimization approach ensures that the power system operates efficiently and cost-effectively, while still meeting the electricity demand of consumers.

The cost function of the model encompasses various components, including installation costs, operational and maintenance costs associated with each generation resource, transmission costs, and capital costs. These components reflect the comprehensive nature of the expenses that are involved in power system operations.

By minimizing total costs, the Calliope model aims to achieve a balance between the electricity supply and demand, while ensuring that the system operates efficiently and sustainably. The model seeks to ensure that the total demand for electricity is adequately covered, while at the same time minimizing the cost of meeting this demand.

Time Resolution

The time resolution of the model plays a significant role in evaluating its efficacy. The implemented model considers hourly generation and demand for a complete year, a total of 8,760 hours. This high temporal resolution enables the model to capture the temporal dynamics of power generation and demand, which is essential for making informed decisions in power system operations.

Furthermore, the model is designed to simulate power system operations in three different years: 2030, 2040, and 2050. These years have been chosen to provide insight into the long-term performance of the power system, given the expected changes in demand, new technological developments, and regulatory policies that are likely to influence the power system's operations in the future.

The use of hourly resolution, coupled with multi-year simulations, enables the model to capture the temporal and spatial variability of power generation and demand. The resultant outputs provide insights into the performance of the power system, facilitating informed decisions on operational planning, power system expansion, and infrastructure investments, among others.

Data Inputs

Table 6 provides a summary of the essential data inputs for the implemented model, which includes hourly demand by BA, hourly capacity factors by BA by source, existing installed capacity by BA by source, capacity transmission, maximum new PV installed capacity of each BA, maximum new wind installed capacity of each BA, and installation and operating cost by source.

The ESS model provides hourly demand data, while hourly capacity factors by BA by source are obtained from SAM developed by NREL. Existing installed capacity by BA and by generation source is sourced from NWPCC, while NWPCC also provides capacity transmission data.

Furthermore, the maximum new PV and wind installed capacity of each BA are determined using data from the Net-Zero America Project (NZA). Lastly, installation and operating cost data by source is obtained from SAM-NREL.

Table 6 provides critical information required to operationalize the model and generate meaningful insights into the power system's performance. By leveraging these data inputs, the model can simulate various scenarios and make informed decisions that can help optimize the power system's operations and achieve a balance between electricity supply and demand while minimizing costs.

Table 6. Data input by source of information

Data input	***Source of information***
Hourly Demand by BA	ESS
Hourly capacity factors for wind and solar by BA by resource	SAM - NREL[8,9]
Hourly capacity factor for hydro	NWPCC[10]
Existing installed capacity by BA by resource (all resources)	NWPCC[11]
Capacity transmission	NWPCC[12]
Maximum new PV installed capacity by BA	NZA
Maximum new wind installed capacity by BA	NZA
Installation and operating cost by resource	SAM - NREL[13]

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[8] Department of Energy National Renewable Energy Laboratory. "Wind Power - System Advisor Model - SAM." NREL System Advisor Model (SAM). Accessed April 28, 2023. https://sam.nrel.gov/wind.html.

[9] Department of Energy National Renewable Energy Laboratory. "SAM Photovoltaic Models - System Advisor Model - SAM." NREL System Advisor Model (SAM). Accessed April 28, 2023. https://sam.nrel.gov/photovoltaic.html.

[10] Northwest Power and Conservation Council. "Power Supply: Existing and New/Proposed Power Plants." Northwest Power and Conservation Council - Energy. Accessed May 19, 2023. https://www.nwcouncil.org/energy/power-supply/.

[11] Northwest Power and Conservation Council. "Power Supply: Existing and New/Proposed Power Plants." Northwest Power and Conservation Council - Energy. Accessed May 19, 2023. https://www.nwcouncil.org/energy/power-supply/.

[12] "Transmission | Northwest Power and Conservation Council." Accessed March 1, 2023. https://www.nwcouncil.org/energy/energy-topics/transmission/.

[13] National Renewable Energy Laboratory. "Financial Models - System Advisor Model - SAM." Accessed May 19, 2023. https://sam.nrel.gov/financial-models.html.

Data and Assumptions

Scenario Development

Scenarios are alternative descriptions of different possible futures that help interested parties consider the implications of these future possibilities for planning and decision-making today. Scenarios are not predictions or forecasts. Rather, they are stories about how the world could change over some specified time in the future.

A scenario is distinguishable from a vision and forecast in two ways:

- a scenario is a possible future – it need not be desirable to everyone, thus it is not a vision, and,
- it need not be likely, thus it is not a forecast; a scenario emphasizes a process of change, not just a point in the future.

Many people assume that the future will closely resemble the present; however, scenarios are not grounded principally in a continuation of past trends or data. Rather, they involve plausible visions of the ways that relevant uncertainties might evolve in the future.

Characteristics of Scenarios

- **Plausible:** The scenario must be believable.
- **Relevant to the key strategic issues and decisions at hand:** If the scenario would not cause a decision-maker to act differently compared to another scenario, there is little use in considering it.
- **Challenging today's conventional wisdom:** It should make one think about different possibilities and options.
- **Divergent from each other:** Together, the scenarios should “stretch” the thinking about the future environment, so that the decisions take account of a wider range of issues.
- **Balanced:** It is useful to ensure that a group of scenarios strike a good psychological balance between challenges and opportunities, and between risks and potential benefits.

Reference scenarios provide a baseline from which the impacts of the decarbonization actions can be explored. Two reference scenarios are used in the analysis: Business-as-Usual (BAU) and Business-as-Planned (BAP).

Business-As-Usual Scenario

The Business-As-Usual (BAU) scenario estimates energy use and emissions volumes from the base year (2019) to the target year (2050). Because it assumes the absence of policy measures that would differ substantially from those currently in place, it can be considered a projection of what would happen if nothing changes, except for the anticipated population and economic growth. This scenario provides a reference against which to assess the impacts of currently planned rules, bills and legislation. Detailed assumptions for the BAU scenario can be found in Table 7.

Methodology

1. Calibrate model and develop a 2019 base year data for the state using observed data and filling in gaps with assumptions where necessary.
2. Input existing projected quantitative data to 2050 where available, such as:
    - Population, employment, and housing projections by transport zone
    - Build out (buildings) projections by county
    - Transportation modeling from the State
    - Economic growth projections
    - Heating and cooling degree days projections
3. Where quantitative projections are not carried through to 2050, extrapolate what the projected trend would be to 2050.
4. Where specific quantitative projections are not available, develop projections through:
    - Analyzing current, on-the-ground action (reviewing action plans, engagement with staff, etc.), and where possible, quantifying the action.
    - Analyzing existing policy that has potential impact and, where possible, quantifying the potential impact.

Table 7. Business as usual assumptions.

Action	Details	Sources
Population Growth	7.61 million people in 2019 8.89 million people by 2035 (avg of 1.05% per year) 9.85 million people by 2050 (avg of 0.7% per year) Average rate of growth - 72,329 people per year	Office of Financial Management Projections of the state population by age, sex and race Growth Management Act population projections for counties: 2010 to 2040
Employment Growth	3.20 million jobs in 2019 3.87 million jobs by 2035 (avg of 0.5% per year) 4.32 million jobs by 2050 (avg of 0.7% per year) Average rate of growth - 36,162 jobs per year	Office of Financial Management Long-Term Economic Forecast
Transportation Fuel Standards	CAFE Fuel standards: Vehicle fuel consumption rates reflect the implementation of the U.S. Corporate Average Fuel Economy (CAFE) Fuel Standard for Light-Duty Vehicles, and Phase 1 and Phase 2 of EPA HDV Fuel Standards for Medium- and Heavy-Duty Vehicles.	(2012) (CAFE standards) retrieved from https://www3.epa.gov/otaq/climate/documents/420f12050.pdf http://www.nhtsa.gov/fuel-economy
Heating and Cooling Degree Days	Projections of Heating and Cooling degree days by county - Climate Explorer (nemac.org)	Climate Explorer (nemac.org) Statistically downscaled global climate models for county and county-equivalents
Energy Use by Buildings	Baseline building equipment types/stocks held from 2019-2050.	Residential Energy Consumption Survey (RECS) for baseline building equipment types State Energy Data System (SEDS) for building equipment efficiencies
New Building Growth	Residential buildings: Buildings are added alongside population growth; building types added based on building mix of county where population growth is happening. Non-residential buildings: Growth based on projected growth in employment; building types added based on building mix of county where job growth is happening.	

Business-As-Planned Scenario

The Business-As-Planned (BAP) scenario estimates energy use and emissions volumes from the base year (2019) to the target year (2050), incorporating assumptions about the likely effects of planned policies and programs.

Methodology

- Create BAU (see steps above)
- Create demand-side BAP
    - Add additional assumptions to the BAU to capture known policies and plans that are or will be implemented in the coming years. Key programs and pieces of legislation reflected in the BAP:
        - The Clean Energy Transformation Act (CETA),[14] which requires Washington's electric utilities to meet 100% of its retail electric load to Washington customers using non-emitting electric generation and electricity from renewable resources by 2045.
        - The Climate Commitment Act (CCA),[15] which creates an emissions cap and invest program that reduces GHG emissions (from approximately 75% of Washington's sources of GHG emissions) to net zero by 2050. Entities covered by the program include industrial facilities, certain fuel suppliers, in-state electricity generators, electricity importers, and natural gas. distributors with annual GHG emissions above 25,000 metric tons of CO_2e.

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[14] The CETA requires electric utilities to develop a four-year Clean Energy Implementation Plan (CEIP) for the GHG neutral and clean energy standards, and establish interim targets for meeting the standards. Since this study goes beyond 2026, we cannot accurately anticipate and describe a plan for investor-owned utilities (IOUs) to meet the requirements of CETA. An overall CETA emissions reduction, showing the impact of the CETA target, will be shown as part of the Business-As-Planned (BAP) scenario. Detailed CETA pathways will be modeled as part of the decarbonization scenarios to explore the different ways IOUs could comply with CETA.

[15] Since the CCA is a program based on allowances (compliance instruments) purchased via auction, and does not currently require covered entities to describe how they will reduce emissions in order to come into compliance and meet their purchased (or free) allowances, we cannot accurately anticipate and describe a plan for how these entities will reduce emissions. An overall CCA emissions reduction, showing the impact of the CCA emissions reduction target, is shown as part of the BAP scenario. Detailed CCA pathways will be modeled as part of the decarbonization scenarios to explore the different ways covered entities relevant to this study could comply with the CCA.

        - Move Ahead Washington, a set of transportation budget allocations that will accelerate active transit mode shifts, increase public transit ridership, and electrify some of WA State Ferries.
        - The Advancing Green Transportation Act, which encourages electric vehicle and alternative fuel vehicle adoption by providing tax credits, exemptions and grants for personal, public, and private use vehicles
        - The Clean Buildings for Washington Act and the Clean Buildings Performance Standard, which requires existing commercial buildings over 50,000 square feet to meet energy use performance standards by 2028
        - The 2018 Washington State Energy Code - Commercial, which requires new commercial buildings to use heat pumps for space heating and at least half of water heating needs (with exceptions)
        - Legislation in the cities of Seattle, Shoreline, and Bellingham banning the use of natural gas for space heating in commercial buildings and multifamily buildings over 4 stories tall.
        -
    - In all cases: Where quantitative projections are not carried through to 2050, historical trends are extrapolated to 2050.
- Where specific quantitative projections are not available, assumptions are identified by:
    - Analyzing current, on-the-ground action (reviewing action plans, engagement with staff, etc.), and where possible, quantifying the action.
    - Analyzing existing policy that has potential impact and, where possible, quantifying the potential impact.

Table 8. Business as planned scenario assumptions.

Action	Details	Sources
Clean Energy Transformation Act (CETA)	Requires Washington's electric utilities to achieve 100% coal-free electricity generation by 2025; 100% carbon neutral electricity generation by 2030 (80% actually generated; 20% can be offsets, RECs, etc.); 100% clean electricity generation by 2045.	SB 5116 (CETA) Final Bill Report

Action	Details	Sources
Climate Commitment Act	**45%** reduction by **2030**, **70%** by **2040** and **95%** by **2050** in greenhouse gas emissions. Starting on Jan. 1, 2023, the cap-and-invest program will cover industrial facilities, certain fuel suppliers, in-state electricity generators, electricity importers, and natural gas distributors with annual greenhouse gas emissions above 25,000 metric tons of carbon dioxide equivalent.	SB 5125 Climate Commitment Act
Washington State Energy Code (WSEC)	New commercial (includes multifamily 4 stories and higher) construction required to use 100% electric heat pumps for heating and 50% electric heat pumps for water heating.	Washington State Energy Code Washington State Energy Code Roadmap
Clean Buildings for Washington Act and Washington Clean Buildings Performance Standard	Between 2013 and 2032, building code must reduce energy use of newly constructed buildings by 70% Tier 1 - Existing buildings more than **50,000** sqft need to meet energy targets, starting in **2026**. Tier 2 - Existing buildings **22,000** sqft or larger and multifamily buildings will need to meet (as yet undefined) energy targets starting in **2027.**	Washington State Clean Buildings Performance Standard
Move Ahead Washington	A $16.8 billion comprehensive transportation funding and appropriations package which leverages anticipated funds from the Climate Commitment Act's cap-and-invest allowance auctions to preserve and maintain existing transportation infrastructure, expand transit, cycling, and walking infrastructure, replace diesel ferries with hybrid electric ones, and support hydrogen and electric vehicle infrastructure deployment across the state. Approx $10 billion from CCA and $6 billion from other sources. The impact of this funding was modeled as a 5% increase in cycling, walking, and transit ridership between 2022 and 2050 in urban counties and 2% in rural counties.	House 2022 Supplemental Transportation Budget Proposals Legislative Evaluation & Accountability Program Committee Transportation Document

Action	Details	Sources
Advancing Green Transportation	HB 2042 encourages electric vehicle and alternative vehicle adoption by providing tax credits, exemptions, grants, and technical support for electric and alternative vehicles purchases HB 5811 directs the Department of Ecology to adopt the motor vehicle emissions standards of California, including its Zero Emissions Vehicles program; also requires labels to be affixed that disclose the comparative GHGs for new vehicles, including passenger cars, light duty trucks, and medium duty passenger vehicles. Modeled as share of new personal use and light duty commercial vehicle sales that are EVs: **8%** in **2024** and **100%** in **2035.** By 2035, 55% of class 2b-3 trucks (vans, medium pick up trucks), 75% of class 4-8 trucks (delivery trucks, delivery/service vans, lighter truck tractors, bucket trucks) and 40% of class 8 (truck tractors, cement trucks, dump trucks, sleeper cab trucks) must meet the zero emission vehicle standards.	HB 2042 HB 5811 Department of Ecology - Zero Emission Vehicles
Washington Clean Fuel Standard	Requires fuel suppliers to gradually reduce the carbon intensity of transportation fuels to 20 percent below 2017 levels by 2038	Clean Fuel Standard

Decarbonization Pathways

Annual Demand

Common Actions

Demand

Action	Specification	Assumption
Buildings		
Deep retrofits in the building stock	Retrofit 95% of existing buildings by 2040 to achieve a 50% reduction in space heating/cooling and a 40% reduction other non heating energy use	All residential and commercial buildings constructed in 2019 and earlier are retrofitted by these measures: ● tighten building envelope ● replace electric tank water heaters with heat pump water heaters ● switch to high efficiency lighting and appliances
Increase density of development in urban zones	Reduce fraction of single new builds to 25% of new buildings in counties with high urban density by 2040, which results in a decrease in personal use vehicle miles traveled	New single dwelling units are replaced by rows and apartments for Benton, Clark, King, Kitsap, Pierce, Snohomish, Spokane, Thurston, and Whatcom counties. Personal use vehicles miles traveled decrease by 25% for those counties
Transportation		
Increase transit ridership	Triple transit ridership in urban centers by 2040	Transit mode shares are tripled by 2040 in Benton, Clark, King, Kitsap, Pierce, Snohomish, Spokane, Thurston, and Whatcom counties.
Decrease freight vehicle miles traveled	Decrease vehicle miles traveled by 15% by 2050	Average trip distance for commercial use vehicles decreases by 15% by 2050.

Action	Specification	Assumption
Mode Shift to cycling	Transfer 10% of personal use vehicle trips to electric micro-mobility (e.g., e-bike/e-scooter) in urban counties by 2035	Personal use vehicle shares decrease by 10% and micro-mobility shares increase by 145% in urban counties by 2035.
Marine passenger electrification	Electrify 100% of passenger ferries by 2040	Passenger ferries are 100% electric by 2040. Electric motors are assumed to be 2.5 times more efficient than diesel engines.
Industry		
Efficiency improvements in industry	Improve the energy efficiency of industrial facilities to achieve a 50% reduction in energy use by 2050	Efficiency of industrial process end uses increases by 50% by 2050

Electrification Scenario

Action	Specification	Assumption
Buildings		
Transition to heat pumps for residential space conditioning and water heating	95% of existing buildings are equipped with electric heat pumps for space and water heating by 2040. Heat pumps are installed when existing equipment needs to be replaced.	Electric air source heat pumps (ASHP) replace retired heat systems and electric heat pump water heaters (HPWH) replace retired water heaters in 95% of existing residential buildings by 2040. Electric ASHP coefficient of performance (COP) is 2.5. HPWH COP is 3.0.
Transition to heat pumps for commercial space conditioning and water heating	95% of existing commercial buildings are equipped with electric heat pumps for space and water heating by 2040. Heat pumps are installed when existing equipment needs to be replaced.	Electric air source heat pumps (ASHP) replace retired heat systems and HPWH replace retired water heaters in 95% of existing commercial buildings by 2040. Electric ASHP COP is 2.75 and season energy efficiency ratio (SEER) is 13. HPWH COP is 3.

Action	Specification	Assumption
Transportation		
Electrify commercial use vehicles	Percentage of new vehicles (sales) that are electric by 2035: - Classes 2b–3 trucks (vans, medium pickup trucks): 100% - Classes 4–8 trucks (delivery trucks, delivery/service vans, lighter truck tractors, bucket trucks): 90% - Class 8 truck tractors: 80%	Energy efficiency ratio (EER) is 4 for battery electric trucks compared to diesel trucks
Industry		
Electrification of some industrial processes	Replace 55% of fossil fuel use in industry with electricity by 2050	55% of natural gas, diesel, and propane use is replaced by electricity for process heat and motive[16] end uses.
Energy		
Enable distributed energy resources with Enhanced Energy Storage	Add 18.5 GW of rooftop solar capacity to residential buildings by 2035. Add 3.45 GW of energy storage to residential buildings equipped with rooftop solar by 2035. Assume each energy storage unit is 14 kWh.	18.5 GW is slightly below the technical installed capacity potential of 22.8 GW for all buildings in Washington according to an assessment of rooftop solar PV potential by NREL[17]. Storage capability is added to 25% of residential non-apartment building stock by 2035. Total energy of each storage unit is 14 kWh.

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[16] The industrial "motive" end use comprises energy used for machine drive (pumps, fans, compressed air, material handling, material processing) and on-site transportation

[17] Gagnon et al., "Rooftop Solar Photovoltaic Technical Potential in the United States. A Detailed Assessment." January 2016. https://www.nrel.gov/docs/fy16osti/65298.pdf.

Action	Specification	Assumption
Blend RNG into the natural gas supply	Use Washington's full RNG potential of 87.5 tBTU by 2050.	87.5 tBTU represents Washington's population-based share of the potential US supply, excluding synthetic methane, according to a 2019 study from the American Gas Foundation[18]. RNG is assumed to be mixed into the existing natural gas supply.

Alternative Fuels Scenario

Action	Specification	Assumption
Buildings		
Transition to heat pumps for residential space conditioning and water heating	95% of existing buildings are equipped with electric and natural gas heat pumps for space and water heating by 2040. Heat pumps are installed when existing equipment needs to be replaced.	50% of the replacement heat pumps are electric ASHP and 50% are natural gas ASHP. Electric ASHP COP is 2.5. Natural gas ASHP COP is 1.4. HPWH COP is 3.0.
Transition to heat pumps for commercial space conditioning and water heating	95% of existing commercial buildings are equipped with electric and natural gas heat pumps for space and water heating by 2040. Heat pumps are installed when existing equipment needs to be replaced.	50% of the replacement heat pumps are electric ASHP and 50% are natural gas ASHP. Electric ASHP COP is 2.75. Natural gas ASHP COP is 1.4. HPWH COP is 3.0.
Deploy clean hydrogen fuel cells in residences for heating	5% of homes have hydrogen fuel cells by 2030	Residential fuel cells provide space and water heating via heat exchangers..

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[18] ICF. "Renewable Sources of Natural Gas." American Gas Foundation, December 19, 2019. https://gasfoundation.org/2019/12/18/renewable-sources-of-natural-gas/.

Action	Specification	Assumption
Transportation		
Transition nearly all commercial use vehicles to zero emission vehicles	Percentage of new vehicles (sales) by 2035: - 100% of Classes 2b–3 trucks (vans, medium pickup trucks) are zero emissions vehicles: 80% EV, 20% alternative fuels - 90% of Classes 4–8 trucks (delivery trucks, delivery/service vans, lighter truck tractors, bucket trucks): 30% EV, 70% alternative fuels - 80% of Class 8 truck tractors: 20% EV, 80% alternative fuels	Alternative fuels are hydrogen and RNG. For Class 4-8 trucks, 50% of new vehicles are hydrogen fuel cells and 20% are RNG. For Class 8 truck tractors, 70% of new vehicles are hydrogen fuel cells and 10% are RNG EER is 4 for battery electric, 2 for hydrogen fuel cells, and 1 for RNG compared to diesel trucks.
Industry		
Use hydrogen industrial processes	70% of industrial processes fueled by hydrogen by 2050	70% of fuel use from fossil fuels (diesel, natural gas, propane, heavy fuel oil) used for process heat and motive is shifted to hydrogen. Hydrogen is assumed to have the same end use efficiency as natural gas.
Energy		
Blend green hydrogen into the natural gas supply	Blend up to 15% hydrogen into the natural gas supply by 2035 and enacted a new round of standards for appliances and equipment beyond those codified in 2021 to support.	

Action	Specification	Assumption
Blend RNG into the natural gas supply	Use Washington's full RNG potential of 87.5 tBTU by 2050.	87.5 tBTU represents Washington's population-based share of the potential US supply, excluding synthetic methane, according to a 2019 study from the American Gas Foundation[19]. RNG is assumed to be mixed into the existing natural gas supply.
Produce RNG within Washington	Produce sufficient RNG to provide 6% of RNG demand within the state by 2050	Washington achieves medium term RNG production target described in a 2018 report on RNG to the Washington state legislature[20].
Provide hydrogen within Washington	Produce sufficient hydrogen to provide 50% of hydrogen demand within the state	The electrical energy needed to generate one kg of hydrogen is 51 kWh[21].

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[19] ICF. "Renewable Sources of Natural Gas." American Gas Foundation, December 19, 2019. https://gasfoundation.org/2019/12/18/renewable-sources-of-natural-gas/.

[20] Energy Program, Washington State University, and Department of Commerce Washington. Energy promoting RNG in Washington State, December 2018. https://www.commerce.wa.gov/wp-content/uploads/2019/01/Energy-Promoting-RNG-in-Washington-State.pdf.

[21] Florida Solar Energy Center. Hydrogen Basics - Solar Production, 2014. http://www.fsec.ucf.edu/en/consumer/hydrogen/basics/production-solar.htm.

Hybrid Scenario

Action	Specification	Assumption
Buildings		
Transition to heat pumps for residential space conditioning and water heating	95% of existing buildings are equipped with electric heat pumps for space and water heating by 2040. Heat pumps are installed when existing equipment needs to be replaced.	Electric ASHPs replace retired heat systems and electric HPWHs replace retired water heaters in 95% of existing residential buildings by 2040. Electric ASHP coefficient of performance (COP) is 2.5. HPWH COP is 3.0.
Transition to heat pumps for commercial space conditioning and water heating	95% of existing commercial buildings are equipped with electric heat pumps for space and water heating by 2040. Heat pumps are installed when existing equipment needs to be replaced.	Electric ASHPs replace retired heat systems and HPWHs replace retired water heaters in 95% of existing commercial buildings by 2040. Electric ASHP COP is 2.75 and season energy efficiency ratio (SEER) is 13. HPWH COP is 3.
Transportation		
Transition nearly all commercial use vehicles to zero emission vehicles	Percentage of new vehicles (sales) by 2035: - 100% of Classes 2b–3 trucks (vans, medium pickup trucks) are zero emissions vehicles: 80% EV, 20% alternative fuels - 90% of Classes 4–8 trucks (delivery trucks, delivery/service vans, lighter truck tractors, bucket trucks): 30% EV, 70% alternative fuels - 80% of Class 8 truck tractors: 20% EV, 80% alternative fuels	Alternative fuels are hydrogen and RNG. For Class 4-8 trucks, 50% of new vehicles are hydrogen fuel cells and 20% are RNG. For Class 8 truck tractors, 70% of new vehicles are hydrogen fuel cells and 10% are RNG EER is 4 for battery electric, 2 for hydrogen fuel cells, and 1 for RNG compared to diesel trucks.

Action	Specification	Assumption
Industry		
Use hydrogen for industrial processes	70% of industrial processes fueled by hydrogen by 2050	70% of fuel use from fossil fuels (diesel, natural gas, propane, heavy fuel oil) used for process heat and motive is shifted to hydrogen. Hydrogen is assumed to have the same end use efficiency as natural gas.
Energy		
Enable distributed energy resources with Enhanced Energy Storage	Add 18.5 GW of rooftop solar capacity to residential buildings by 2035. Add 3.45 GW of energy storage to residential buildings equipped with rooftop solar by 2035. Assume each energy storage unit is 14 kWh.	18.5 GW is slightly below the technical installed capacity potential of 22.8 GW for all buildings in Washington according to an assessment of rooftop solar PV potential by NREL. Storage capability is added to 25% of residential non-apartment building stock by 2035. Total energy of each storage unit is 14 kWh.
Blend green hydrogen into the natural gas supply	Blend up to 15% hydrogen into the natural gas supply by 2035 and enacted a new round of standards for appliances and equipment beyond those codified in 2021 to support.	
Blend RNG into the natural gas supply	Use Washington's full RNG potential of 87.5 tBTU by 2050.	87.5 tBTU represents Washington's population-based share of the potential US supply, excluding synthetic methane, according to a 2019 study from the American Gas Foundation[22]. RNG is assumed to be mixed into the existing natural gas supply.

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[22] ICF. "Renewable Sources of Natural Gas." American Gas Foundation, December 19, 2019. https://gasfoundation.org/2019/12/18/renewable-sources-of-natural-gas/.

Action	Specification	Assumption
Produce RNG within Washington	Produce sufficient RNG to provide 6% of RNG demand within the state by 2050	Washington achieves medium term RNG production target described in a 2018 report on RNG to the Washington state legislature[23].
Provide hydrogen within Washington	Produce sufficient hydrogen to provide 50% of hydrogen demand within the state	The electrical energy needed to generate one kg of hydrogen is 51 kWh.

Hourly Demand

Hourly load shapes for the years 2040 and 2050 in the Electrification, Alternative Fuels, and Hybrid scenarios were updated using End Use Savings Shapes from NREL to incorporate the expected impact of energy savings from building retrofits and the replacement of electric resistance heating and non-electric heat systems with heat pumps in the residential sector in those scenarios. Measures included in these end use savings shapes include attic insulation, duct sealing, wall insulation, and high efficiency home electrification. In the home electrification measure, high efficiency heat pumps with a COP of 3.9 for centrally ducted units and 4.2 for ductless units.[24] Heat pumps are assumed to use electric resistance as a backup heat source when the heat pump cannot meet the load in a given hour.

Demand Response

The demand response actions deployed in the three decarbonization scenarios targeted specific hours in which the demand exceeded supply by 6,500 MW or more in the output of the Calliope hourly dispatch model described in the Hourly Dispatch section above. The shortfall target of 6,500 MW is used because it represents the amount of demand that can be supplied

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[23] Energy Program, Washington State University, and Department of Commerce Washington. Energy promoting RNG in Washington State, December 2018. https://www.commerce.wa.gov/wp-content/uploads/2019/01/Energy-Promoting-RNG-in-Washington-State.pdf.

[24]" End-Use Savings Shapes, Residential Round 1, Technical Documentation and Measure Applicability Logic" [https://oedi-data-lake.s3.amazonaws.com/nrel-pds-building-stock/end-use-load-profiles-for-us-building-stock/2022/EUSS_ResRound1_Technical_Documentation.pdf]

by a combination of imports from outside of Washington and electricity produced from RNG or hydrogen within the state.

Table 9 summarizes the demand response actions deployed in the decarbonization scenarios.

Table 9. Demand response action summary.

Sector	***End Use***	***DR Action***	***Elec***	***Alt Fuels***	***Hybrid***
Residential	Space heating	Shift 50-100% to previous adjacent hours	x		
Commercial	Space heating	Shift 50-100% from afternoon to morning	x		
Industrial	Process Heat	Shed 50% of load	x		
	Motive	Shed 50% of load	x		
	Electrolysis	Shift 50-100% to hours with renewable curtailment		x	x
Transportation	Personal use vehicles	Apply load leveling profile for entire day to home and workplace charging to even spread over charging hours	x	x	x
	Commercial use vehicles	Shift 50-100% to other hours within same day	x		

Residential Space Heating

Residential space heating is a flexible load that can be shifted to adjacent time periods through the use of thermostat setpoints to preheat the space. This action is supported by deep building retrofits in the residential sector which enable for thermal heat to remain in the building for longer periods of time. Load shifting of residential space heating was applied only to the Electrification scenario for the hours in which demand exceeded the shortfall target in the hourly dispatch modeling results. Table 10 shows how load shifting was deployed as a demand response action for the days and hours in which it was required.

Table 10. Modeled residential space heating demand response

Year	Day	Hours shifted from	Hours shifted to	% of load shifted
2040	Feb 23	5-8pm	1-4pm	50
2050	Jan 23	5-8pm	12-3pm	50
	Feb 23	5-8pm	1-4pm	60
	Oct 09	5-8pm	1-4pm	50

Commercial Space Heating

Like residential space heating, commercial space heating loads can be shifted to adjacent time periods through the use of thermostat setpoints to preheat the space. Commercial spaces also have an increased capacity to "coast" or use the thermal mass of the building's structure, insulation, and other heat-absorbing materials to store and release heat gradually over time instead. Coasting allows commercial buildings to maintain a comfortable temperature for building occupants without additional energy consumption for space heating.

Load shifting of commercial space heating was applied only to the Electrification scenario for the hours in which demand exceeded the shortfall target in the hourly dispatch modeling results. Table 11 shows how load shifting was deployed as a demand response action for the days and hours in which it was required.

Table 11. Modeled commercial space heating demand response

Year	Day	Hours shifted from	Hours shifted to	% of load shifted
2030	Feb 27	6-7am	2-5am	50
2050	Jan 23	1-4pm	9am-12pm	100

Industrial

Process Heat and Motive

Demand response for the process heat and motive end uses were modeled as load shedding. It was assumed that industrial facilities develop on-site battery storage and/or power generation to support load shedding, and/or other arrangements might be made regarding interruptible service between utilities and industrial users. Load shedding of these industrial end uses was applied only to the Electrification scenario for the hours in which demand exceeded the shortfall target in the hourly dispatch modeling results. Table 12 shows how load shedding was deployed as a demand response action for the days and hours in which it was required.

Table 12. Modeled industrial process heat and motive demand response

Year	Start day/time	End day/time	% of load shed
2030	Feb 2 12am	Feb 2 11pm	50
2030	Feb 27 12am	Feb 27 11pm	50
	Oct 9 12 am	Oct 10 11pm	50
2040	Jan 1 12am	Jan 2 11pm	50
	Feb 20 9am	Feb 26 10pm	50
	Oct 9 12 am	Oct 10 11pm	50
2050	Jan 1 12am	Jan 2 11pm	50
	Feb 1 12am	Feb 28 11pm	50
	Sep 7 12am	Sep 7 11pm	50
	Oct 8 12am	Oct 10 11pm	50
	Oct 13 5pm	Oct 17 11pm	50
	Nov 1 12am	Nov 1 11pm	50

Electrolysis

Electrolysis in the industrial sector is used in the in-state production of green hydrogen in the Alternative Fuels and Hybrid scenarios. The hourly dispatch results for each of those scenarios include the time and magnitude of renewable electricity generation curtailment. The modeled demand response shifts the electrolysis load to the hours in which sufficient curtailed renewable electricity is available to serve that load. The hours to which the load is shifted are within the same month as the original load. Table 13 shows the number of hours in which the electrolysis load was shifted by year and month for each scenario.

Table 13. Modeled industrial electrolysis demand response

Year	**Month**	***# of hours shifted***	
		Alternative Fuels	***Hybrid***
2030	Jan	10	6
	Feb	65	65
	Mar	1	1
	Oct	49	49
	Dec	2	1
2040	Jan	0	24
	Feb	28	55
	Oct	47	47
	Dec	2	1
2050	Jan	6	24
	Feb	53	51
	Mar	0	1
	Sep	0	5
	Oct	47	51
	Dec	2	2

Transportation

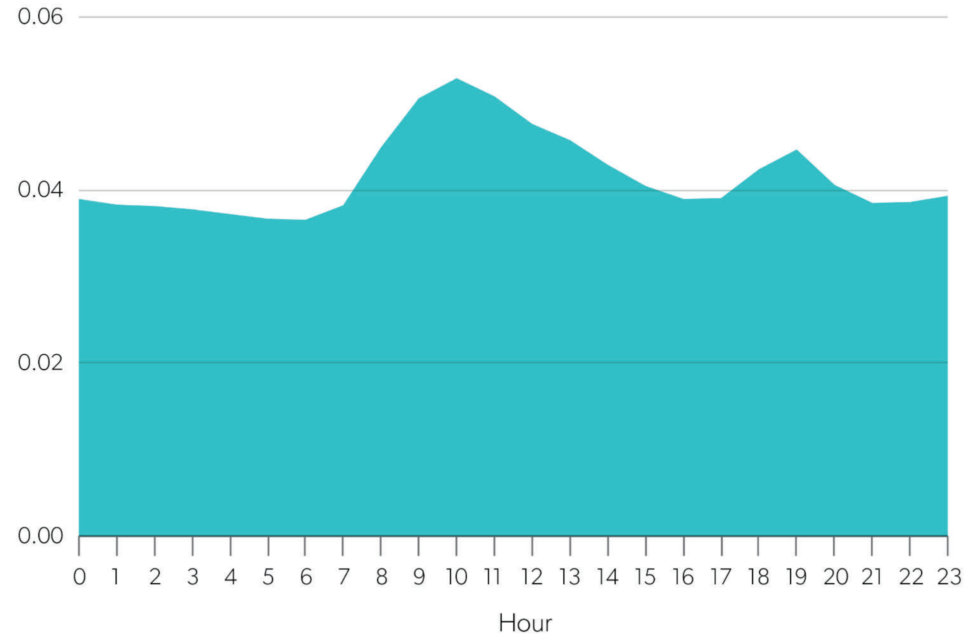
Personal Vehicle Charging

The default charging profile for personal use vehicles described in the "Hourly Demand" section above results in increased demand during weekday evening hours. When the shortfall target was exceeded during these hours, an alternative charging profile from EVI-Pro Lite was applied to reduce the peaks. These changes could be achieved via mechanisms such as time of use rates, grid-integrated vehicle chargers, or other price signals and/or technologies. This alternative profile starts home charging at midnight and introduces some workplace charging during the day. Table 14 lists the specific assumptions. Figure 14 shows the resulting personal use vehicle load shapes with the alternative charging profiles.

Table 14. Personal use vehicle charging assumptions with demand response.

Assumption	***Value/Description***
Average Daily Miles Traveled per Vehicle	35 miles
Average Ambient Temperature	50°F
Plug-in Vehicles that are All-Electric	75% – EV Dominant This fleet has more EVs than PHEVs with this breakdown: 10% PHEVs that can drive 20 electric miles 15% PHEVs that can drive 50 electric miles 25% EVs that can drive 100 miles 50% EVs that can drive 250 miles
Home Charging Infrastructure	50% Level 1 and 50% Level 2
Preference for Home Charging	80% prefer primarily charging at home
Home Charging Strategy	Delayed – start at midnight This option assumes vehicles begin home charging at midnight because some vehicle owners elect to program their vehicles to start charging at a specific time overnight, which is often midnight.
Workplace Charging Infrastructure	20% Level 1 and 80% Level 2

Assumption	***Value/Description***
Workplace Charging Strategy	Immediate – as slow as possible (even spread) This option assumes vehicles begin charging immediately upon arriving at a charging location, but the charging speed/power is controlled to be as slow/low as possible to spread the charge evenly over the time the vehicle is parked.



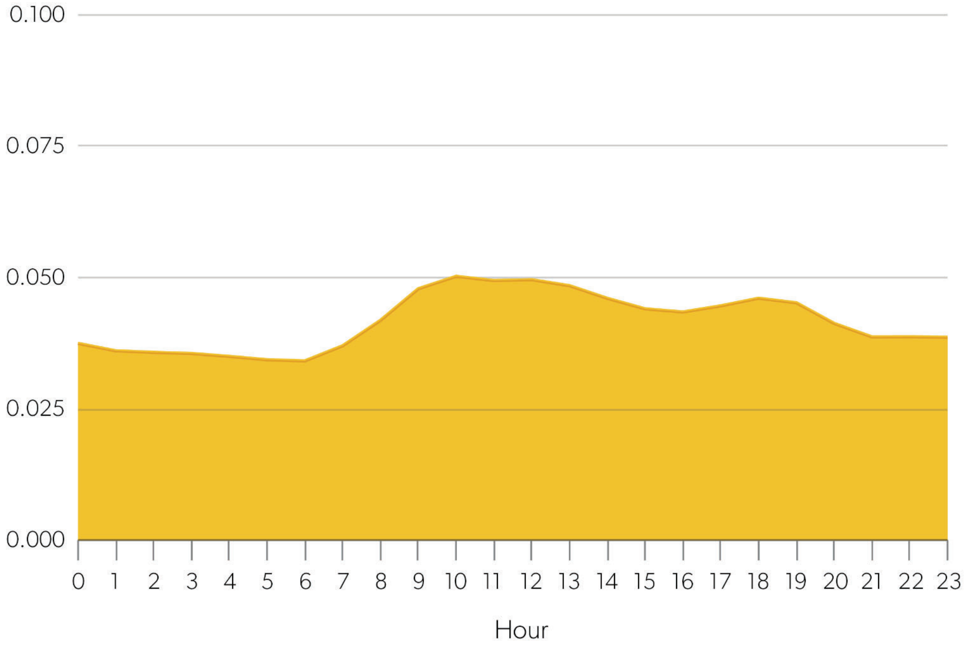


Figure 14. Weekday (top) and weekend (bottom) personal vehicle charging load shapes with demand response.

The 24-hour alternative charging profile was deployed as a demand response action in the Electrification and Hybrid scenarios for days with the hours in which demand exceeded the shortfall target in the hourly dispatch modeling results. Table 15 lists the number of days by year and month for each scenario.

Table 15. Modeled industrial electrolysis demand response. Applied in Electrification and Hybrid scenarios.

Year	**Month**	**# of days with alternative charging**	
		Electrification	**Hybrid**
2030	Feb	5	
	Mar	2	
	Oct	1	
	Dec	1	
2040	Jan	1	2
	Feb	3	5
	Sep	1	0
	Oct	5	2
	Dec	0	1
2050	Jan	4	4
	Feb	3	5
	Mar	0	1
	Aug	5	0
	Sep	3	2
	Oct	4	5
	Nov	2	1
	Dec	1	2

Commercial Vehicle Charging

Commercial vehicle charging is modeled as a flexible load that can be shifted to adjacent time periods within the same day, for example by using removable batteries that allow for offline charging at hours with lower demand. Load shifting of commercial vehicle charging was applied only to the Electrification scenario for the hours in which demand exceeded the shortfall target in the hourly dispatch modeling results. Table 16 shows the number of hours in which the commercial vehicle load was shifted by year and month.

Table 16. Modeled commercial vehicle charging demand response. Applied to Electrification scenario only.

Year	***Month***	***# of hours shifted***
2030	Feb	10
	Mar	2
	Oct	12
	Dec	2
2040	Feb	10
	Oct	10
2050	Jan	7
	Feb	9
	Aug	4
	Sep	7
	Oct	25
	Dec	2

Supply

Table 17 shows the main assumptions implemented in the Calliope model.

Table 17. Supply assumptions as implemented in the Calliope model.

Assumption	**Specification**
Comply with legislation	
Comply with Clean Energy Transformation Act	20% of annual demand can be met with GHG-emitting generating resources (excluding coal) if needed in 2030 and 2040
Focus on self-sufficiency	
Add additional generating capacity in-state first	States and provinces neighboring Washington state have similar clean energy goals and competition for new renewable resources in other states may be high. The ability to expand interstate transmission supplies may be constrained. There are currently no electricity trade agreements between states, although some are in development. This assumption assesses the capacity of Washington's utilities to achieve renewable electricity goals using in-state resources as much as possible.
Retain existing generating resources	
Retain existing natural gas power plant capacity through 2045	Current natural gas power plant capacity is available in 2030 and 2040, but is used only as needed to meet peak demands when no other resources are available.
Retain existing nuclear power plant capacity through 2050	The Columbia Generating Station is authorized to operate until at least 2043, or potentially 2063 with a license extension. It will operate through at least 2050.
Retain existing hydroelectric power plant capacity through 2050	Existing hydroelectric resources will continue to be operational through 2050 and that no new hydroelectric resources are added.[25] Hourly generation curves for a typical year were obtained from the Northwest Power and Conservation Council, reflecting supply, demand and environmental constraints. Generation was allowed to be shifted forward or backward by up to 5 days, while maintaining total, minimum and maximum generation for that 5-day period.

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[25] This includes four run-of-river dams and locks on the lower Snake River.

Assumption	Specification
Add additional renewable resources	
Use existing wind resources and incorporate additional wind capacity	Existing wind resources continue to be operational through 2050. Additional 80 meter-tall wind turbines can be added within each Balancing Authority (BA) area in quantities up to the technical potential as determined by NREL. Hourly capacity factor profiles (how much energy can be produced compared with the maximum output) for the wind turbines vary by BA, reflecting differences in terrain, weather patterns, and other variables relating to wind power output in different parts of the state. Profiles were informed by data from NREL.[26]
Use existing solar resources and incorporate additional utility-scale solar capacity	Existing solar resources continue to be operational through 2050. Additional utility-scale solar arrays could be added within each BA area in quantities up to the technical potential as determined by NREL. Hourly capacity factor profiles (how much energy can be produced compared with the maximum output) for the solar arrays vary by BA, reflecting differences in terrain, weather patterns, and other variables relating to solar power output in different parts of the state. Profiles were informed by data from NREL.[27]
Incorporate utility-scale energy storage	An unlimited quantity of 4-hour duration lithium ion batteries can be added by utilities to support meeting electricity demand. The batteries modeled have a 0.91 overall efficiency factor (for charging and discharging) and an energy storage loss fraction of 0.0000833 per hour.
Use demand response and industrial peak load shedding	During hours of peak demand, demand response methods such as time-of-use rates and interruptible service agreements are used to reduce demand by shifting it to other hours of the day. Up to half of industrial producers develop on-site battery storage and/or power generation by 2050 is able to contribute to load shedding as necessary to contribute to reducing peak demand.

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[26] Department of Energy National Renewable Energy Laboratory, “Wind Power - System Advisor Model - SAM.,” NREL System Advisor Model (SAM), accessed April 28, 2023, https://sam.nrel.gov/wind.html.

[27] Department of Energy National Renewable Energy Laboratory, “SAM Photovoltaic Models - System Advisor Model - SAM.,” NREL System Advisor Model (SAM), accessed April 28, 2023, https://sam.nrel.gov/photovoltaic.html.

Assumption	Specification
Transmission and imports	
Gradually increase transmission capacity between Washington's Balancing Authorities	● For the year 2030, existing transmission capacity between Washington's BAs was used. Data was obtained directly from the Northwest Power and Conservation Council. ● For the year 2040, transmission capacity between BAs increases by 25% compared to capacity in 2030. ● For the year 2050, transmission capacity between BAs increases 20% compared to capacity in 2040.
Meet remaining peak demand loads with imports, RNG or stored hydrogen	During hours of peak demand, after demand response and energy storage options have been used, the remaining load - up to 6,500 MW - can be supplied by imports from the rest of the WECC, or by either renewable natural gas (RNG) or stored hydrogen (made from surplus wind and solar generation) burned in combined-cycle generators.[28] The exact combination of imports, RNG and hydrogen was not specified, as this would have required modeling at least all of WECC, and possibly all of the North American electricity system. Instead, an allowance of $500/MWh was included in the cost estimate.
Use surplus supply to produce alternative fuels	The use of renewably produced electricity that would otherwise be curtailed is maximized to produce alternative fuels such as hydrogen.

Table 18 (next page) shows the details of the technical and economical assumptions for each type of generation implemented in the Calliope model.

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[28] While all wind, solar, RNG and hydro generation was assumed for modeling purposes to be located in-state, it may be more cost-effective to contract for out-of-state supply, and increase transmission capacity accordingly. Modeling indicated no significant cost difference between in-state and out-of-state generation after taking transmission costs into account.

Table 18. Technical and financial assumptions for generating resources in Calliope.

Technology	***Technical and economical assumptions***
Hydro reservoir	● Average capacity factor: ○ AVA: 0.50 ○ BPAT: 0.42 ○ CHPD: 0.56 ○ DOPD: 0.59 ○ GCPD: 0.59 ○ PSEI: 0.38 ○ SCL: 0.38 ● Operating and maintenance cost: $12.31 USD/MWh. ● Lifetime: 60 years.
Hydro run of river	● Average capacity factor: ○ AVA: 0.27 ○ BPAT: 0.57 ○ PSEI: 0.53 ○ SCL: 0.37 ● Operating and maintenance cost: $12.31 USD/MWh. ● Lifetime: 60 years.
Gas	● Energy efficiency: 0.87. ● Operating and maintenance cost: $400 USD/MWh (a high cost was assigned for gas to be the last energy resource to be assigned). ● Lifetime: 30.
Nuclear	● Operating and maintenance cost: $22.74 USD/MWh. ● Lifetime: 60
PV	● Average capacity factor: ○ AVA: 0.20 ○ BPAT: 0.20 ○ CHPD: 0.19 ○ DOPD: 0.20 ○ GCPD: 0.20 ○ PACW: 0.20 ○ PSEI: 0.15 ○ SCL: 0.19 ○ TPWR: 0.15 ● Maximum installed capacity in MW (restriction): ○ AVA: 157,733

Technology	***Technical and economical assumptions***
	○ BPAT: 98,572 ○ CHPD: 1,067 ○ DOPD: 43,815 ○ GCPD: 41,890 ○ PACW: 95,495 ○ PSEI: 15,339 ○ SCL: 2,178 ○ TPWR: 18,950 ● Installed capacity cost: $1,060,000 USD/MW. ● Operating and maintenance annual cost: $15,000USD/MW/year. ● Lifetime: 30 years.
Wind	● Average capacity factor: ○ AVA: 0.25 ○ BPAT: 0.34 ○ CHPD: 0.12 ○ DOPD: 0.18 ○ GCPD: 0.19 ○ PACW: 0.14 ○ PSEI: 0.14 ○ SCL: 0.18 ○ TPWR: 0319 ● Maximum installed capacity in MW (restriction): ○ AVA: 77,773 ○ BPAT: 51,065 ○ CHPD: 1,905 ○ DOPD: 23,283 ○ GCPD: 14,283 ○ PACW: 41,983 ○ PSEI: 10,569 ○ SCL: 1,543 ○ TPWR: 15,926 ● Installed capacity cost: $1,498,000 USD/MW. ● Operating and maintenance annual cost: $43,000USD/MW/year. ● Lifetime: 25 years.
PV rooftop	● Average capacity factor: ○ AVA: 0.20 ○ BPAT: 0.20 ○ CHPD: 0.19 ○ DOPD: 0.20

Technology	***Technical and economical assumptions***
	○ GCPD: 0.20 ○ PACW: 0.20 ○ PSEI: 0.15 ○ SCL: 0.19 ○ TPWR: 0.15 ● Battery storage efficiency (charging-discharging): 0.91 ● Cost[29]: ○ Residential: \$3,930/kw (2019), \$1,625/kw (2050) ○ Commercial: \$1,806/kw (2019), \$700/kw (2050) ● Lifetime: 25 years.
Battery storage	● Charge rate: 0.25 (4 hours duration). ● Efficiency (charging-discharging): 0.91. ● Storage loss fraction: 0.0000833 per hour. ● Maximum installed capacity in MW (restriction): Infiniti ● Installed energy capacity cost: \$269,000 USD/MW. ● Installed storage capacity cost: \$282000 USD/MWh. ● Operating and maintenance annual cost: \$15,000USD/MW/year. ● Lifetime: 15 years.
Unspecified supply	● Operating and maintenance cost: \$500 USD/MWh (a high cost was assigned for unspecified supply. This cost can be assigned to imports outside of Washington or another type of generation).

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[29] Data | Electricity | 2021 | ATB | NREL. (n.d.). https://atb.nrel.gov/electricity/2021/data

Energy Costs

Projected energy costs for electricity, natural gas and renewable natural gas through 2050 have been derived based on the 2021 Annual Company Reports submitted by regulated electricity and natural gas utilities to the Washington Utilities and Transportation Commission.[30] See Appendix 5 for detailed estimated average annual energy costs for electricity, natural gas, renewable natural gas, and hydrogen.

Natural gas/Renewable natural gas

Baseline average consumer natural gas rates for the residential, commercial and industrial sectors were calculated by dividing annual reported revenue for 2021 by observed natural gas consumption in each sector.

To develop future rate projections it was assumed that annual revenue requirements would increase 1% per year and that no significant decommissioning of infrastructure would occur.[31] Baseline rates were adjusted accordingly to meet these future revenue requirements based on the projected natural gas demand.

Renewable natural gas rate projections are based on the assumption that RNG is 1.5 times more expensive than natural gas.[32, 33]

Electricity

Baseline average consumer electricity rates for the residential, commercial, and industrial sectors were calculated by dividing the annual reported revenue for 2021 by the observed electricity consumption of each sector.

To project out future rates, utility revenue was broken out by production costs (reported power production expenses), transmission costs (reported transmission expenses), distribution costs (reported distribution expenses) and other costs (other expenses, depreciation expense, other and net income).

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[30] "Company Annual Reports" Washington Utilities and Transportation Commission. https://www.utc.wa.gov/regulated-industries/utilities/energy/company-annual-reports

[31] Anderson, Megan, Mark LeBel, and Max Dupuy. "Under Pressure: Gas Utility Regulation for a Time of Transition." Montpelier, VT: Regulatory Assistance Project, May 2021.

[32] "An Overview of Renewable Natural Gas from Biogas." *US Environmental Protection Agency*, July 2020.

[33] "How Do You Price RNG?" Natural Gas Intelligence, May 15, 2023. https://www.naturalgasintel.com/how-do-you-price-rng/.

Future production cost projections are based on the estimated unit cost per MWh and include both capital investment and operating expenses. Future production and transmission costs are projected out based on the estimated unit cost per MWh and transmission investment derived from the hourly dispatch model for the BAP, Electrification, Alternative Fuels and Hybrid scenarios. Production costs account for both capital investment and operating expenses per MW of capacity installed. Transmission capital investment is based on miles of new transmission line required and the operating expense is calculated based on a fraction of the capital investment. Distribution costs are assumed to increase by 30%[34] by 2050. All other costs are assumed to remain constant.

Addressing Uncertainty

There is extensive discussion of the uncertainty in models and modeling results. One reason is that the assumptions underlying a model can be adopted from other locations or large data sets and not reflect local conditions or behaviors. Even if the data does accurately reflect local conditions, it is exceptionally difficult to predict how those conditions and behaviors will respond to broader societal changes, and even what those changes will be.

The SSG modeling approach uses four strategies for managing uncertainty applicable to community energy and emissions modeling:

1. **Sensitivity analysis:** One of the most basic ways of studying complex models is sensitivity analysis, which helps quantify uncertainty in a model's output. To perform this assessment, each of the model's input parameters is drawn from a statistical distribution in order to capture the uncertainty in the parameter's true value (see "A review of urban energy system models: Approaches, challenges and opportunities," Keirstead, Jennings, & Sivakumar, 2012).

   Approach: Selected variables are modified by ±10-20% to illustrate the impact that an error of that magnitude has on the overall total.

2. **Calibration:** One way to challenge untested assumptions is the use of 'back-casting' to ensure that the model can 'forecast the past' accurately. The model can then be calibrated to generate historical outcomes, in order to better replicate observed data.

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[34] "Chapter 7. Distribution System Analysis: Final Report: LA100 - The Los Angeles 100% Renewable Energy Study", Los Angeles Department of Water & Power, National Renewable Energy Laboratory, March 2021, https://www.nrel.gov/docs/fy21osti/79444-7.pdf

Approach: Variables are calibrated in the model by using two independent sources of data. For example, the model calibrates building energy use (derived from building data) against actual electricity data from the electricity distributor.

3. **Scenario analysis:** Scenarios are used to demonstrate that a range of future outcomes is possible given the current conditions and that no one scenario is more likely than another.

   Approach: The model will develop a reference (BAU) scenario.

4. **Transparency:** The provision of detailed sources for all assumptions is critical to enabling policy-makers to understand the uncertainty intrinsic in a model.

   Approach: Modeling assumptions and inputs are presented in this document.

Weather Sensitivity

An additional scenario was created to evaluate the impacts on peak demand of an extreme cold event in February and an extreme heat event in August. This extreme event scenario was built on the Electrification scenario in the year 2050. Five day spans with the highest space heating demand during winter and the highest space cooling demand during summer were identified and adjusted upward to simulate an extreme weather event. The magnitude of the adjustment was based on findings in a memorandum prepared for the Northwest Power and Conservation Council (NWPCC).[35]

The objectives of the NWPCC memorandum were to define extreme weather, integrate extreme weather events into typical meteorological year (TMY) weather files and use those weather files to model the impact of hot and cold extreme events on efficiency, peak demand, and energy use. Extreme weather events were defined for three weather station locations (Seattle, WA, Elko, NV, and Miles City, MT) over four time periods (1-hour, 1-day, 3-day, 5-day) based on the coldest or hottest mean temperature observed over those time periods in the climatological record from 1991-2020. Comparable events occurred two to four times within the 30 years of data so the extreme weather events simulated for the NWPCC memorandum were considered to be one in ten year events. The extreme event temperatures were inserted into the TMY files for the three locations at the time periods that most closely matched when

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[35] Larson, Ben, and Justin Sharp. "Extreme Weather Events Findings." August 18, 2022. https://nwcouncil.app.box.com/v/082022-xtremeweatherevntsmemo.

the historical events occurred. Finally, model simulations explored the impact of extreme events with different heating and cooling equipment.

For the Washington decarbonization study, the impacts of a 5-day extreme weather to heat pump peak power reported in the NWPCC memorandum were used to adjust the residential hourly demand. Table 19 shows a summary of the power drawn over the hour with the highest consumption under typical and extreme conditions of different durations from the NWPCC memorandum for Seattle and Elko. As indicated in the table, the Seattle results were applied to the Washington counties in the Marine climate zone and the Elko results were applied to Cold climate zone counties. For the extreme cold events, the total peak power is the top value while the portion of the total power used for auxiliary (electric resistance) heating is the bottom value in italics.

Table 19. Heat pump peak power under typical and extreme conditions

Location (Climate Zone)	***Event Type***	***Event Duration***	***Typical (kW)***	***Extreme (kW)***	***% Change***
Seattle (Marine)	Extreme Cold	1-day	12.6 *9.4*	13.3 *10.2*	5.5
		3-day		14.8 *11.7*	17.5
		5-day		14.8 *11.7*	17.5
	Extreme Heat	1-day	3.8	4.0	5.26
		3-day		4.3	13.2
		5-day		4.3	13.2
Elko (Cold)	Extreme Cold	1-day	19.4 *16.5*	24.4 *21.8*	25.8
		3-day		25.4 *22.8*	30.9

Location (Climate Zone)	***Event Type***	***Event Duration***	***Typical (kW)***	***Extreme (kW)***	***% Change***
		5-day		25.4 *22.9*	30.9
	Extreme Heat	1-day	3.9	4.2	7.7
		3-day		4.2	7.7
		5-day		4.2	7.7

The extreme event impact to hourly demand was modeled as a concatenation of the 1-day, 3-day, and 5-day percent change between extreme and typical peak hour power demand. This concatenation captures the concept of “stacking” discussed in the NWPCC memorandum. The memorandum reported that power increases slightly over consecutive days of cold weather due to the fact that building and ground thermal masses cool or retain heat as the duration of extreme cold or heat events increases.

The percent changes were applied to the 5-day periods containing the hour with the highest demand for space heating and cooling in the modeled hourly demand, February 19-24 and August 5-10, respectively. The adjusted hourly demand was then processed as follows:

1. Adjusted hourly demand was compared to the Electrification scenario hourly dispatch results for the year 2050
2. Demand response was applied to hours with an excessive supply shortfall
3. Adjusted hourly demand with demand response was input into the hourly dispatch model to revise the supply-side results

The demand response actions were the same as what was used for the year 2050 in the Electrification scenario as described in the “Demand Response” section above with the addition of additional hours of shifted commercial vehicle charging lower during the extreme cold event.

The revised hourly dispatch results added more unspecified supply during the extreme weather events as shown in Table 20. The hourly dispatch model did not add capacity to meet the additional demand during the extreme events because that demand represents a small percentage of the total annual demand.

Table 20. Impacts of extreme weather to hourly dispatch results

	Unspecified Supply (MWh)		
Time Period	**Electrification 2050**	**Electrification + Extreme Weather 2050**	**% Change**
Feb 19-24	270,317	352,430	30
Aug 5-10	38,745	41,455	7
Annual	3,224,926	3,299,693	2

Appendix 1: Detailed Emissions Scope Table

Table 1-1. Detailed emissions scope.

GHG Emissions Sources & GHG Types			
Transportation	**CO_2**	**CH_4**	**N_2O**
On-road transportation, railways, water-borne navigation, aviation, off-road transportation	Motor gasoline, distillate fuel, natural gas, residual fuel, lubricants, aviation gasoline, liquefied petroleum gas (LPG), light rail electricity use, Naphtha		
Residential Buildings	**CO_2**	**CH_4**	**N_2O**
Emissions from fuel combustion and grid-supplied energy consumed by residential buildings	Residential electricity use, natural gas consumption, petroleum consumption, coal consumption		
Commercial Buildings	**CO_2**	**CH_4**	**N_2O**
Emissions from fuel combustion and grid-supplied energy consumed by commercial buildings	Commercial electricity use, natural gas combustion, petroleum combustion, and coal combustion		

GHG Emissions Sources & GHG Types			
Industrial Emissions	**CO_2**	**CH_4**	**N_2O**
Emissions from on-site stationary combustion and industrial processes that emit GHGs (such as cement manufacturing, semiconductor manufacturing, or aluminum production)	Industrial electricity use, natural gas combustion, petroleum combustion, cement manufacture, coal combustion, ammonia production, urea consumption, iron and steel production, soda ash production and consumption, limestone and dolomite use, lime manufacture		
Energy and Electricity Production	**CO_2**	**CH_4**	**N_2O**
Emissions from in-state electricity generation and distribution of fuels	Generation of steam, generation of electricity from non-renewables, natural gas pipeline transmission, fugitive emissions from pipelines		

Appendix 2: Building Types

Table 2-1. Building types in the model.

Residential Building Types	Non-residential Building Types	
Single_detached_small	school	surface_infrastructure
Single_detached_medium	hospital	water_pumping_or_treatment_station
Single_detached_large	hotel_motel_inn	industrial_generic
Double_detached_small	recreation	pulp_paper
Double_detached_large	community_centre	cement
Row_house_small	museums_art_gallery	chemicals
Row_house_large	retail	iron_steel_aluminum
Apt_1To3Storey	restaurant	mining
Apt_4To6Storey	commercial	agriculture
Apt_7To12Storey		pipelines
Apt_13AndUpStorey		
inMultiUseBldg		

Appendix 3: Emissions Factors

Table 3-1. Emissions factors used in the model.

Category	Value	Comment
Natural gas	CO_2: 53.06 kg/MMBtu CH_4: 0.001 kg/MMBtu N_2O: 0.0001kg/MMBtu	Sourced from the EPA Center for Corporate Climate Leadership's GHG Emission Factors Hub (Sept 15 2021)
Renewable natural gas	CH_4: 0.001 kg/MMBtu N_2O: 0.0001kg/MMBtu	Sourced from the EPA Center for Corporate Climate Leadership's GHG Emission Factors Hub (Sept 15 2021)
Electricity	State wide composite plant-specific emission rates (2019) CO_2e: 487 lbs CO_2e per MWh	eGRID2019 Data File (https://www.epa.gov/egrid/download-data)
Gasoline	CO_2: 69.55 kg/MMBtu CH_4: 4.22 g/MMBTU N_2O: 0.66 g/MMBTU	National inventory report 1990-2019 : Greenhouse Gas Sources and Sinks in Canada. Part 2. Table A6.1–14 This source was used because the units are compatible with SSG's model structure, which uses emission factors per energy unit instead of per mile.
Diesel	Light Duty Vehicles CO_2: 73.84 kg/MMBtu CH_4: 1.88 g/MMBTUmile N_2O: 6.06 g/MMBTU Medium/Heavy Duty Vehicles CO_2: 73.84 kg/MMBtu	National inventory report 1990-2019 : Greenhouse Gas Sources and Sinks in Canada. Part 2 Table A6.1–14 This source was used because the units are compatible with SSG's model structure, which uses emission factors per energy unit instead of per mile.

Category	Value	Comment
	CH_4: 3.03 g/MMBTU N_2O: 4.16 g/MMBTU	
Fuel oil	CO_2: 73.9 kg per MMBtu CH_4: 0.003 kg per MMBtu N_2O: 0.0006 kg per MMBtu	Environmental Protection Agency. "Emission factors for greenhouse gas inventories." *Stationary Combustion Emission Factors," US Environmental Protection Agency, available:* *https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf* (2014) Table 1 Stationary Combustion Emission Factor, Fuel Oil No. 2
Wood	CO_2: 93.80 kg per MMBtu CH_4: 0.0072 kg per MMBtu N_2O: 0.0036 kg per MMBtu	Environmental Protection Agency. "Emission factors for greenhouse gas inventories." *Stationary Combustion Emission Factors," US Environmental Protection Agency, available:* *https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf* (2014) Table 1 Stationary Combustion Emission Factor, Biomass fuels: Wood and Wood Residuals
Propane	CO_2: 62.87 kg per MMBtu CH_4 : 0.003 kg per MMBtu N_2O: 0.0006 kg per MMBtu For mobile combustion: CO_2: 5.7 kg per gallon	Environmental Protection Agency. "Emission factors for greenhouse gas inventories." *Stationary Combustion Emission Factors," US Environmental Protection Agency, available:* *https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf* (2014) Table 1 Stationary Combustion Emission Factor, Petroleum Products: Propane Table 2 Mobile Combustion CO_2 Emission Factors: Propane

GHGs	Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are included. GWP CO_2 = 1 CH_4 = 34 N_2O = 298	Global warming potential (GWP) assumptions are sourced from the Intergovernmental Panel on Climate Change (IPCC)’s Fifth Assessment Report.

Appendix 4:

Data Sources & Uses

Table 4-1. Input assumptions and calibration targets.

Data	Source	Use
Population by county, age, sex	US Census - 2019 ACS	Calibration target
Residential buildings by county, type, and year built	US Census - 2019 ACS	Input assumption
Residential floor space per unit by county and type	Replica land use data	Input assumption
Employment by county and sector	US Census - Longitudinal Employer-Household Dynamics Origin-Destination Employment Statistics (LODES)	Calibration target
Non-residential buildings by type and year built	NEEA CBSA 4	Input assumption
Non-residential floor space by county and type	Replica land use data	Input assumption
Non-residential floor space by type and year built	NEEA CBSA 4	Input assumption
Natural gas deliveries by sector and county	Utility data	Calibration target
Electricity sales by utility and customer sector	EIA Form 861	Calibration target
Gasoline and diesel fuel use	SEDS	Calibration target
End use equipment fuel shares	NEEA CBSA 4 NEEA RBSA II	Input assumption
Industrial emissions from large emitting facilities	EPA GHGRP	Calibration target

Data	Source	Use
Personal use vehicles	WSDOT - vehicle registration data	Calibration target
Transit miles and fuel use	WSDOT - Summary of Public Transportation	Input assumption
Electricity production capacity, generation, and fuel use	EPA eGRID	Input assumption
Net metering capacity and generation by utility, sector, and technology	EIA Form 861	Input assumption
Grid electricity allocation to county	WA Department of Commerce Fuel Mix Disclosure	Input assumption
Heating and cooling degree days by county	U.S. Climate Resilience Toolkit Climate Explore (Version 3.1)	Input assumption

Table 4-2. Business-As-Usual assumptions.

Data	Source
Population growth	State of Washington Office of Financial Management - State and County Population Projections (medium scenario)
Employment	State of Washington Office of Financial Management Long-term Economic Forecast Tables (Table 3-2: Washington Non-Agricultural Wage and Salary Employment by Industry (in thousands) 2020-2040)
Transportation	Corporate Average Fuel Economy (CAFE) Fuel Standard for light duty and heavy duty vehicles
Heating & cooling degree days (HDD and CDD)	Climate Explorer (nemac.org)
Energy use	Baseline building equipment types/stocks held from 2019-20250, using data from the Residential Energy Consumption Survey (RECS) for baseline building equipment types and State Energy Data System (SEDS) for building equipment efficiencies
Building growth	Residential buildings are added alongside population growth; building types added based on the building mix of counties where population growth is happening. Non-residential building growth is based on projected growth in employment; building types added (where job growth is happening), based on the current building mix of each county.

Table 4-3. Hourly demand assumptions.

Data	Source
Residential sector load shapes	NREL End-Use Load Profiles for the U.S. Building Stock Public datasets - 2021.1 Release Actual Meteorological Year 2018 https://resstock.nrel.gov/datasets
Residential sector load shapes with electrification and energy savings	NREL End-Use Load Profiles for the U.S. Building Stock Public datasets -2022.1 Release (End Use Savings Shapes) Actual Meteorological Year 2018 https://resstock.nrel.gov/datasets
Commercial sector load shapes	NREL End-Use Load Profiles for the U.S. Building Stock Published Datasets - 2021_1 Actual Meteorological Year 2018 https://nrel.github.io/ComStock.github.io/docs/data/published_datasets.html
Industrial sector load shapes	NREL dsgrid data produced for the Electrification Futures Study (EFS) Industrial data https://data.openei.org/submissions/4130
Personal use vehicle load shapes	NREL's Electric Vehicle Infrastructure – Projection (EVI-Pro) tool https://afdc.energy.gov/evi-pro-lite
Commercial use vehicle load shapes	California Energy Commission Electric Vehicle Charging Infrastructure Assessment - AB 2127 Spreadsheet of AB 2127 Commission Report Figure Results Figure 20 https://www.energy.ca.gov/programs-and-topics/programs/electric-vehicle-charging-infrastructure-assessment-ab-2127

Table 4-4. Calliope data sources.

Data input	***Source of information***
Hourly Demand by BA	ESS
Hourly capacity factors for wind and solar by BA by resource	SAM - NREL[36,37]
Hourly capacity factor for hydro	NWPCC[38]
Existing installed capacity by BA by resource (all resources)	NWPCC[39]
Capacity transmission	NWPCC[40]
Maximum new PV installed capacity by BA	NZA
Maximum new wind installed capacity by BA	NZA
Installation and operating cost by resource	SAM - NREL[41]

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[36] Department of Energy National Renewable Energy Laboratory. "Wind Power - System Advisor Model - SAM." NREL System Advisor Model (SAM). Accessed April 28, 2023. https://sam.nrel.gov/wind.html.

[37] Department of Energy National Renewable Energy Laboratory. "SAM Photovoltaic Models - System Advisor Model - SAM." NREL System Advisor Model (SAM). Accessed April 28, 2023. https://sam.nrel.gov/photovoltaic.html.

[38] Northwest Power and Conservation Council. "Power Supply: Existing and New/Proposed Power Plants." Northwest Power and Conservation Council - Energy. Accessed May 19, 2023. https://www.nwcouncil.org/energy/power-supply/.

[39] Northwest Power and Conservation Council. "Power Supply: Existing and New/Proposed Power Plants." Northwest Power and Conservation Council - Energy. Accessed May 19, 2023. https://www.nwcouncil.org/energy/power-supply/.

[40] "Transmission | Northwest Power and Conservation Council." Accessed March 1, 2023. https://www.nwcouncil.org/energy/energy-topics/transmission/.

[41] National Renewable Energy Laboratory. "Financial Models - System Advisor Model - SAM." Accessed May 19, 2023. https://sam.nrel.gov/financial-models.html.

Table 4-5. Energy cost data sources.

Data	**Source**
Electricity price forecasts	Derived from: Public Utility Company Annual Reports, Washington Utilities and Transportation Commission https://www.utc.wa.gov/regulated-industries/utilities/energy/company-annual-reports
Natural gas price forecasts	Derived from: Public Utility Company Annual Reports, Washington Utilities and Transportation Commission https://www.utc.wa.gov/regulated-industries/utilities/energy/company-annual-reports
Renewable natural gas price forecasts	Renewable natural gas prices escalator derived from: "An Overview of Renewable Natural Gas from Biogas." *US Environmental Protection Agency*, July 2020 and How Do You Price RNG?" Natural Gas Intelligence, May 15, 2023. https://www.naturalgasintel.com/how-do-you-price-rng/
Hydrogen price forecasts	2022-ODOE-Renewable-Hydrogen-Report.pdf (https://www.oregon.gov/energy/Data-and-Reports/Documents/2022-ODOE-Renewable-Hydrogen-Report.pdf) Bartlett, J. and Krupnick, A. Decarbonized Hydrogen in the US Power and Industrial Sectors: Identifying and Incentivizing Opportunities to Lower Emissions. 2020. Figure 9. Averages of renewable H2 production (https://www.rff.org/publications/reports/decarbonizing-hydrogen-us-power-and-industrial-sectors/).

Appendix 5: Average Annual Energy Costs

Table 5-1. Average Annual Energy Costs.

	Electrification	Alternative Fuels	Hybrid
			Average Natural Gas Cost, 2020-2050 (estimated), $/Therm
Residential	$2.80	$2.80	$2.80
Commercial	$1.21	$1.21	$1.21
Industrial	$0.01	$0.01	$0.01
			Average Renewable Natural Gas Cost, 2020-2050 (estimated), $/Therm
Residential	$3.19	$3.19	$3.19
Commercial	$1.59	$1.59	$1.59
Industrial	$0.48	$0.48	$0.48
			Average Electricity Cost, 2020-2050 (estimated), $/MWh
Residential	$95.59	$108.35	$85.57
Commercial	$79.16	$87.00	$68.70
Industrial	$79.16	$87.00	$68.70
			Average Hydrogen Cost, 2020-2050 (estimated), $/kgH2
Residential	$1.84	$1.84	$1.84
Commercial	$1.84	$1.84	$1.84
Industrial	$1.84	$1.84	$1.84

Appendix 6: Hourly Modeling Data Input Resources

System Advisor Model

System Advisor Model (SAM), is a powerful software tool developed by the National Renewable Energy Laboratory (NREL) for analyzing renewable energy systems. The software is designed to support the development, optimization, and analysis of a wide range of renewable energy technologies, including solar photovoltaic (PV) systems, wind turbines, concentrating solar power (CSP) systems, and biomass systems.[42]

SAM provides a comprehensive suite of tools for modeling and analyzing renewable energy systems. These tools include a graphical user interface for designing and configuring system components, a library of performance models for various renewable energy technologies, and a range of optimization and simulation tools for analyzing system performance under different conditions.

The software is built on a modular architecture, allowing users to easily configure and customize system components and performance models. SAM also provides a library of weather data for over 3,000 locations worldwide, enabling users to simulate system performance under various weather conditions.

One of SAM's key features is its ability to perform financial analysis of renewable energy systems. The software provides a variety of economic models for calculating the financial performance of renewable energy projects, including levelized cost of energy (LCOE), net present value (NPV), and internal rate of return (IRR). These tools enable users to evaluate the economic viability of renewable energy projects and compare different technology options.

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[42] National Renewable Energy Laboratory. “Home - System Advisor Model - SAM.” Accessed May 19, 2023. https://sam.nrel.gov/.

SAM is widely used in academic research, industry, and government applications and has become a standard tool for renewable energy analysis and optimization. The software is regularly updated to reflect the latest developments in renewable energy technology and policy and is supported by a large community of users and developers.

Overall, SAM is a powerful and versatile tool for renewable energy analysis, providing a comprehensive suite of tools for designing, analyzing, and optimizing renewable energy systems. Its ability to perform financial analysis and simulate system performance under different conditions makes it a valuable tool for evaluating renewable energy projects' economic and technical feasibility.

SAM was used in this project to determine the hourly capacity factors for solar and wind power generation in each region of the Balance Authority included in the study. In addition, SAM was used to provide data on installation costs and operating and maintenance costs for solar and wind generation; these details are discussed further in the model assumptions section.

Northwest Power and Conservation Council

The Northwest Power and Conservation Council (NWPCC) is a regional organization responsible for developing a long-term energy plan for the Pacific Northwest that balances the region's energy needs with environmental and economic considerations. The NWPCC supply forecast scenarios are a set of projections developed to estimate the future energy supply in the Pacific Northwest region of the United States.[43]

The supply forecast scenarios are developed using a range of inputs, including historical energy production data, current energy infrastructure, and technological advancements in the energy industry. The projections consider various factors that may impact future energy supply, including changes in energy policy, population growth, and economic development.

The supply forecast scenarios inform energy planning and decision-making in the Pacific Northwest region. They provide a basis for evaluating the potential impacts of different policy decisions and technological advancements on the region's energy supply and identifying potential areas of risk and opportunity.

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[43] https://www.nwcouncil.org/2021-power-plan-technical-information-and-data/

The scenarios are typically presented as a range of possible outcomes rather than a single prediction. This reflects the inherent uncertainty in energy supply forecasting and provides decision-makers with a range of potential outcomes to consider when making energy policy decisions.

Overall, the NWPCC supply forecast scenarios are important in energy planning and decision-making in the Pacific Northwest region. By providing a range of projections for future energy supply, they enable decision-makers to evaluate the potential impacts of different policy decisions and technological advancements on the region's energy supply and identify investment and improvement areas.

NWPCC data was used for this project to estimate hydroelectric generation in the state of Washington and as input to create hourly capacity factor by Balancing authorities. The scenario used as input was number 23 for the year 2027. Additionally, data from the NWPCC was used on existing projects and their installed capacity by the source of generation in the state of Washington.

Net Zero America

Net Zero America (NZA) is a proposed framework to achieve a net-zero carbon emissions target for the United States of America by 2050. The concept of net zero involves balancing the amount of greenhouse gas emissions released into the atmosphere with the amount that is removed through carbon sequestration or other means, effectively creating a neutral balance that can help mitigate the effects of climate change.[44]

To achieve this target, the NZA report produced by Princeton University researchers highlights the potential of renewable energy sources such as wind, solar, and hydropower. According to the report, the US has a vast potential for renewable energy generation, with enough wind and solar resources to meet the country's electricity demand several times over.

Data from the NZA was used in this project to estimate the PV and wind potential in each BA serving Washington.

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[44] Princeton University. “Net-Zero America Project.” Accessed May 19, 2023. https://netzeroamerica.princeton.edu/