

Northwest Deep Decarbonization Pathways Study



EVOLVED
ENERGY
RESEARCH

Prepared For:

Clean Energy Transition Institute

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Key Study Conclusions

Key Conclusions for Achieving a Low-Carbon Future in the Northwest

- **Pillars of Deep Decarbonization** to reach the Northwest's goals
 - Greater efficiency - the least cost means of reducing emissions
 - Decarbonize electricity – cost effectively offset fossil fuels with renewables
 - Electrify primary fuel end uses – utilize low cost renewable electricity production
 - Decarbonize fuels – use biomass and electric fuels for energy dense transportation applications
- **Aggressive decarbonization of electricity is key** to cost effective decarbonization
 - 96% decarbonization in our Central Case
- **Multiple strategies are possible** to reach decarbonization goals
 - Can be achieved with technology available today
 - Not dependent on any single technology breakthrough
 - Projected technology cost reductions will lower implementation costs
 - Future breakthroughs in technology could drive further cost reductions

Transformations needed in the demand side

- **Aggressive demand-side electrification essential** for cost effective decarbonization
- **Electrifying transportation is critical** to avoid using either constrained biofuel supplies or relatively expensive electric fuels
- Cost effective decarbonization **supports only a limited volume of fuel demand**
 - Either fuels are quantity constrained (biofuels) or
 - Fuels become increasingly expensive per unit of fuel produced (electric fuels)
- Biomass **most efficiently allocated to jet fuel and diesel** fuel rather than gas
 - Cost of avoided fuel is higher in liquids than gas so displacement of gas with biofuel is less cost effective

Transformations needed in electricity supply

- **Significant cost savings possible with expanded interties** between regions of the West
- **New technologies can play a key cross-sector role**
 - Synthetic fuel production and direct air capture create new flexible loads
 - Includes electrolysis, power-to-gas, power-to-liquids, steam production, and direct air capture
 - Use excess energy economically while balancing the system
 - Increases loads during times of excess renewable production, creating fuels or capturing carbon
 - Mitigates intra and inter-annual balancing challenges by reducing load at times of low renewable and/or hydro output
 - Important to capture these cross-sectoral solutions in optimal investment planning to reduce total costs of decarbonization
- **Thermal generation as a capacity resource** important for reliability in periods of low hydro and renewable output
- **Role for carbon capture** – either on biofuels facilities or direct air capture (DAC)
 - Provides direct sequestration of carbon or carbon feedstocks for fuels
 - Not significant in the Northwest at 80% decarbonization but more important with more stringent decarbonization targets

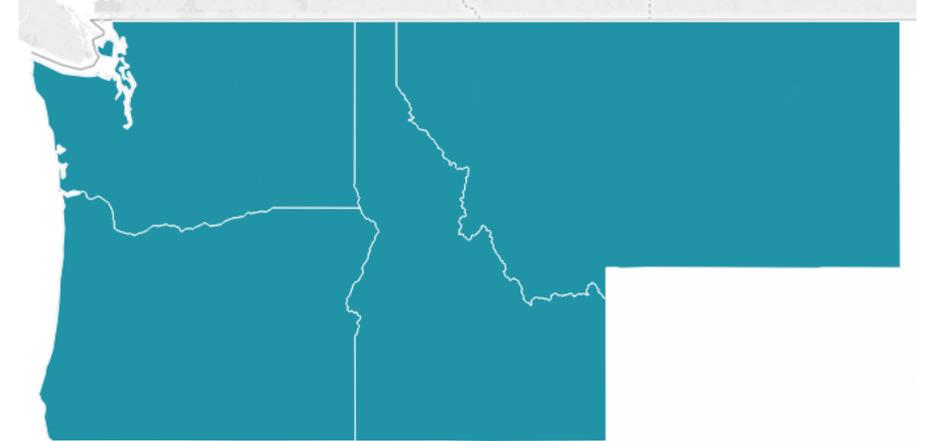


Background



Scope

- Geographic Scope
 - Includes Washington, Oregon, Idaho and Montana
- All sectors of each state's energy system are represented, including residential and commercial buildings, industry, transportation and electricity generation
- Evaluating only one source of emissions (e.g., electricity generation) at a time provides an incomplete assessment of decarbonization
 - For example: should biomass be used to produce biogas for gas-fired power plants or renewable jet fuel for aviation?
- Evaluating deep decarbonization holistically provides an understanding of cross-sectoral impacts and trade-offs



Scope: Comparison to Prior Decarbonization Studies

- This study contributes to an existing body of technical work related to decarbonization in the Northwest
- The first to optimize decisions across sectors, revealing new lower cost pathways to decarbonization

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

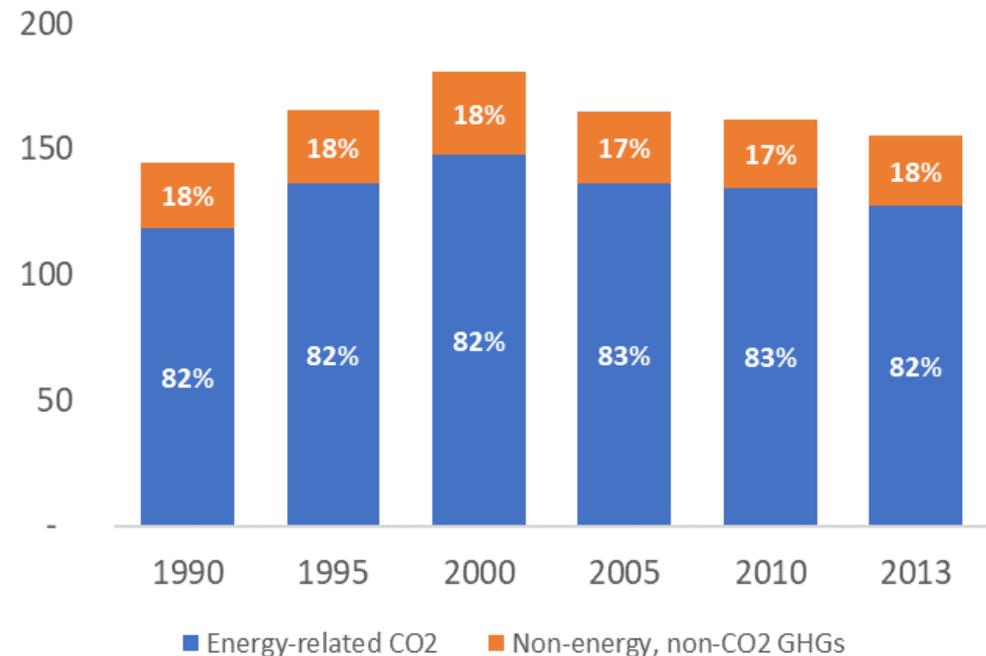
Background

- States in the Northwest have set goals and targets to significantly reduce greenhouse gas (GHG) emissions by mid-century
 - **Washington:** established limits on GHG emissions in 2008, including a 50% reduction below 1990 levels by 2050, and the Department of Ecology recommended strengthening that limit to 80%
 - **Oregon:** since 2007 has had a goal of reducing GHG emissions by 75% below 1990 levels by 2050, and recent legislative discussions have sought to reduce GHG emissions by 80% below 1990 levels by 2050
- Achieving mid-century GHG targets requires steep reductions in energy-related CO₂ emissions and a transformation of energy systems
 - **This transition is commonly referred to as deep decarbonization**

Greenhouse Gas Emissions Context

- Historically, GHG emissions in the Northwest are dominated by **energy-related CO₂** emissions
 - Includes CO₂ emissions from fossil fuel combustion in buildings, industry, transportation and electricity consumption
 - More than 80% of GHG emissions in Oregon and Washington
- Remaining emissions include **non-energy CO₂ and non-CO₂ GHGs**
 - Includes emissions from agriculture and industrial processes (e.g., hydrofluorocarbons or HFCs)

Oregon and Washington GHG Emissions
MMTCO₂e



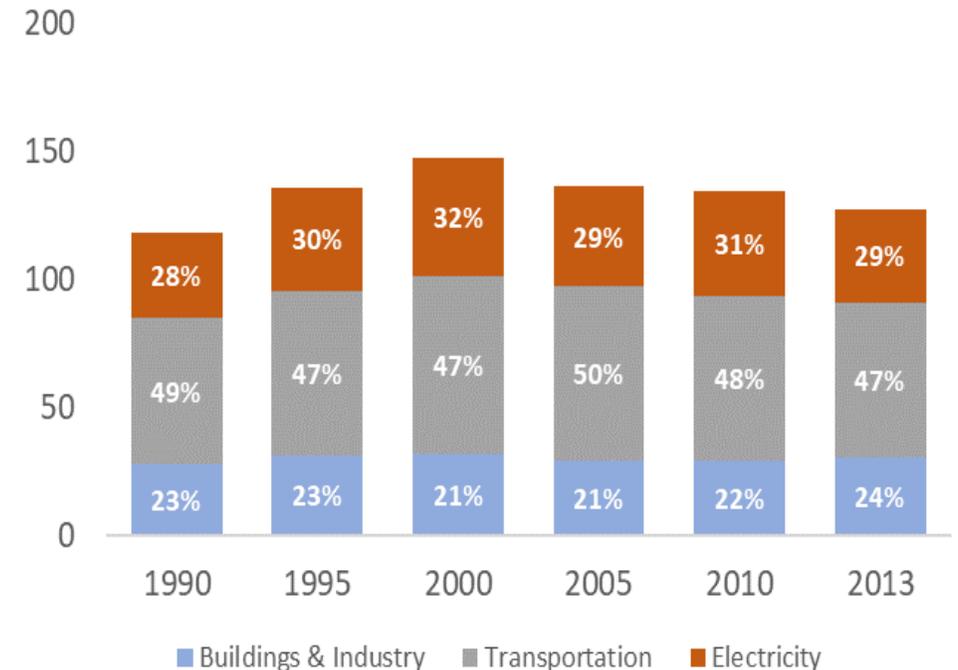
Source: data from Oregon DEQ and Washington Department of Ecology.

Sources of Energy-Related CO₂ Emissions

- CO₂ emissions from fossil fuel combustion are spread across three major sectors:
 - Electricity
 - Transportation
 - Buildings and Industry
- The transportation sector accounts for nearly half of all energy-related CO₂ emissions, primarily due to liquid fossil fuel consumption:
 - Gasoline fuel in passenger transportation
 - Diesel fuel in freight transportation
 - Residual fuel oil in marine vessels
 - Jet fuel in aviation

Oregon and Washington Energy CO₂ Emissions

MMTCO₂



Source: data from Oregon DEQ and Washington Department of Ecology.

Study Purpose

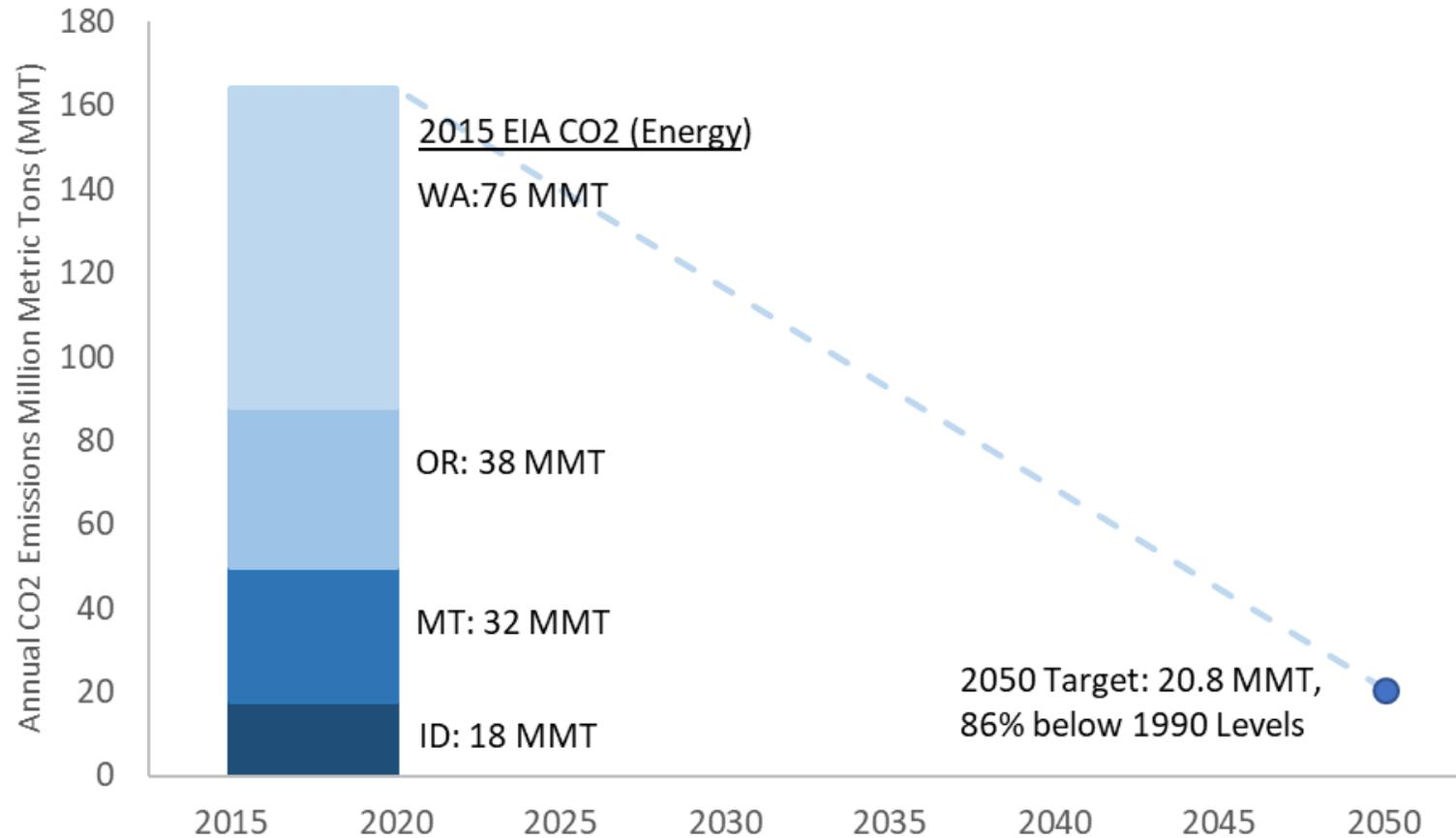
- Clean Energy Transition Institute commissioned Evolved Energy Research to explore pathways to deep decarbonization for states in the Northwest
- The purpose of this study is to provide an understanding of the practical implications of achieving mid-century climate targets
 - Explore how end-use sectors and energy supply need to transform
 - Examine the extent to which electricity generation needs to be decarbonized in order to achieve economy-wide carbon reduction goals
 - Estimate the cost-optimal allocation of biomass for decarbonizing fuels
 - Assess the impacts of alternative assumptions and constraints (e.g., biomass availability and the rate of electrification)

Study Emissions Target

- This study's emissions target is an 86 percent reduction in energy-related CO₂ emissions below 1990 levels by 2050
 - Energy CO₂ target is consistent with our [2016 Deep Decarbonization Pathways Analysis for Washington State](#) report
 - Target is applied to each Northwest state independently instead of regionally
- Target value for energy-related CO₂ emission reductions is consistent with an economy-wide GHG reduction target of 80 percent below 1990 levels by 2050
 - Allows for reductions below 80 percent for non-energy CO₂ and non-CO₂ GHG emissions, where mitigation feasibility is less understood relative to energy

Northwest Deep Decarbonization Target

Northwest Deep Decarbonization Target



Approach to Decarbonizing Energy Supply

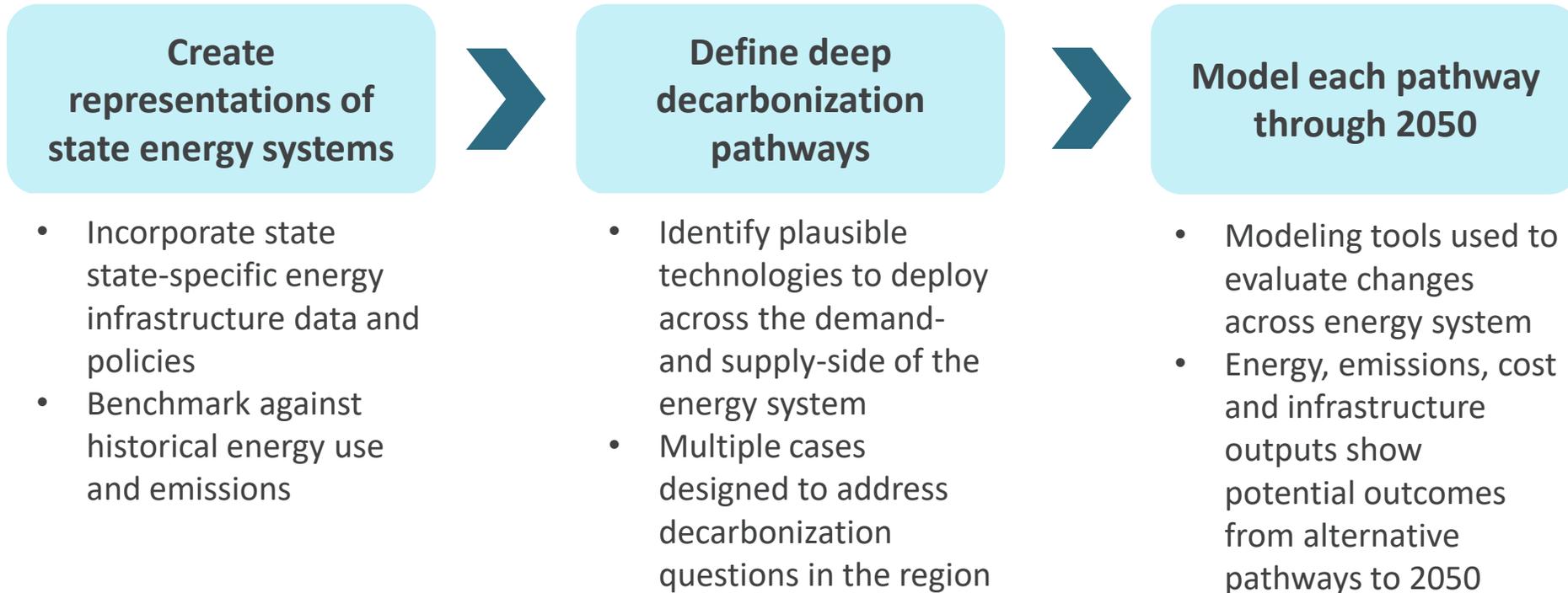
- Decarbonization of energy supply (electricity, pipeline gas, liquid fuels) in this study applies a least-cost, optimization framework to develop portfolios
 - This framework is already applied in certain industries, such as utility integrated resource planning, to plan for future energy needs
- Modeling determines optimal investment in resources to develop low-carbon energy supply portfolios
- Fuel and supply-side infrastructure decisions are determined simultaneously, while considering constraints such as electricity system reliability and biomass availability



Model Approach and Assumptions

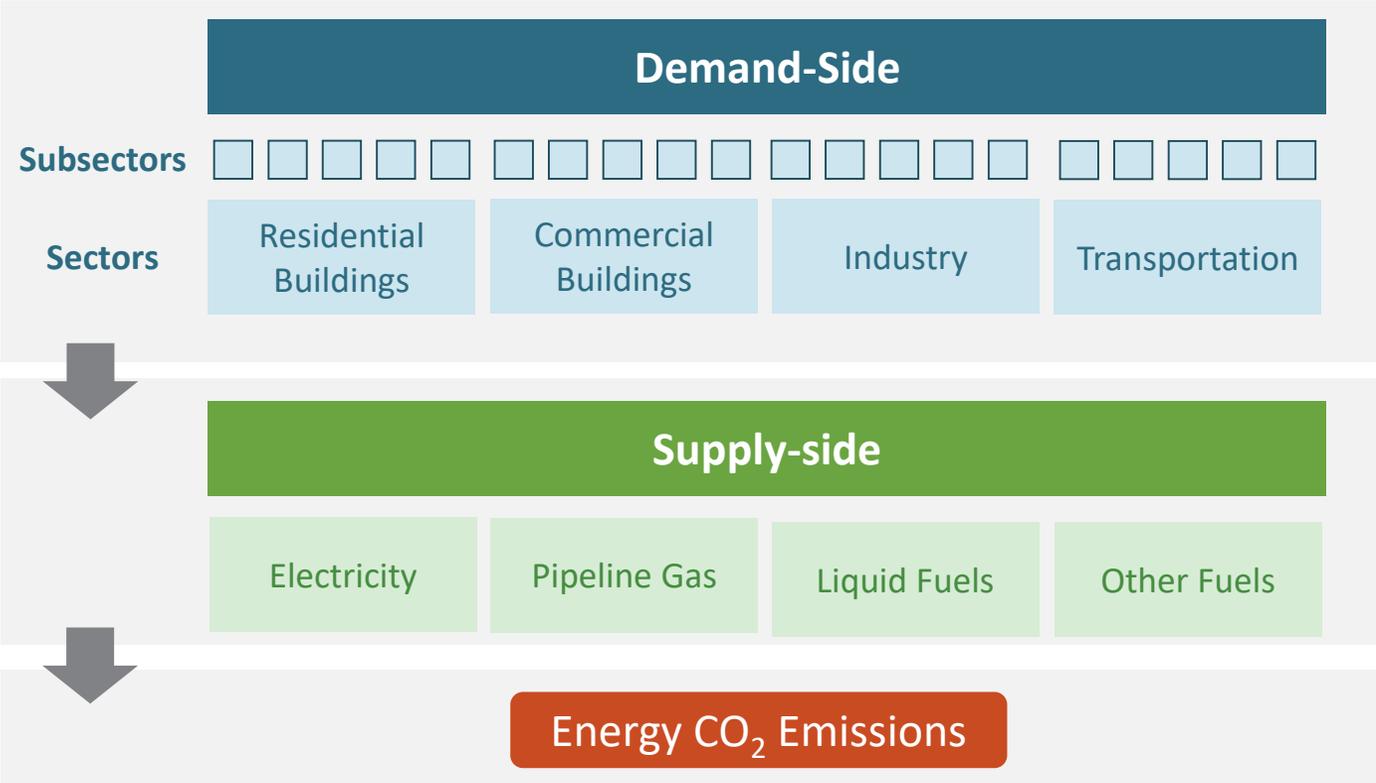
Overview of Approach

- Multiple pathways for Northwest states to achieve deep decarbonization are evaluated using the following approach



Transforming the Energy System

- We incorporate changes to both the demand- and supply-side of each state's energy system to achieve steep reductions in energy-related CO₂ emissions



Modeling Framework

Pairing EnergyPATHWAYS and RIO



ENERGY
PATHWAYS



Description

EnergyPATHWAYS (EP)

Scenario analysis tool used to develop demand-side scenarios across all end-use sectors

Regional Investment and Operations (RIO)

Tool to develop cost-optimal energy supply portfolios for all fuel types

Application

Scenario design allows for alternative electrification and efficiency measures, which produces:

- Annual final energy demand for all fuels (electricity, pipeline gas, diesel, etc.)
- Hourly electricity load shape

These energy demand parameters are used as parameters for RIO

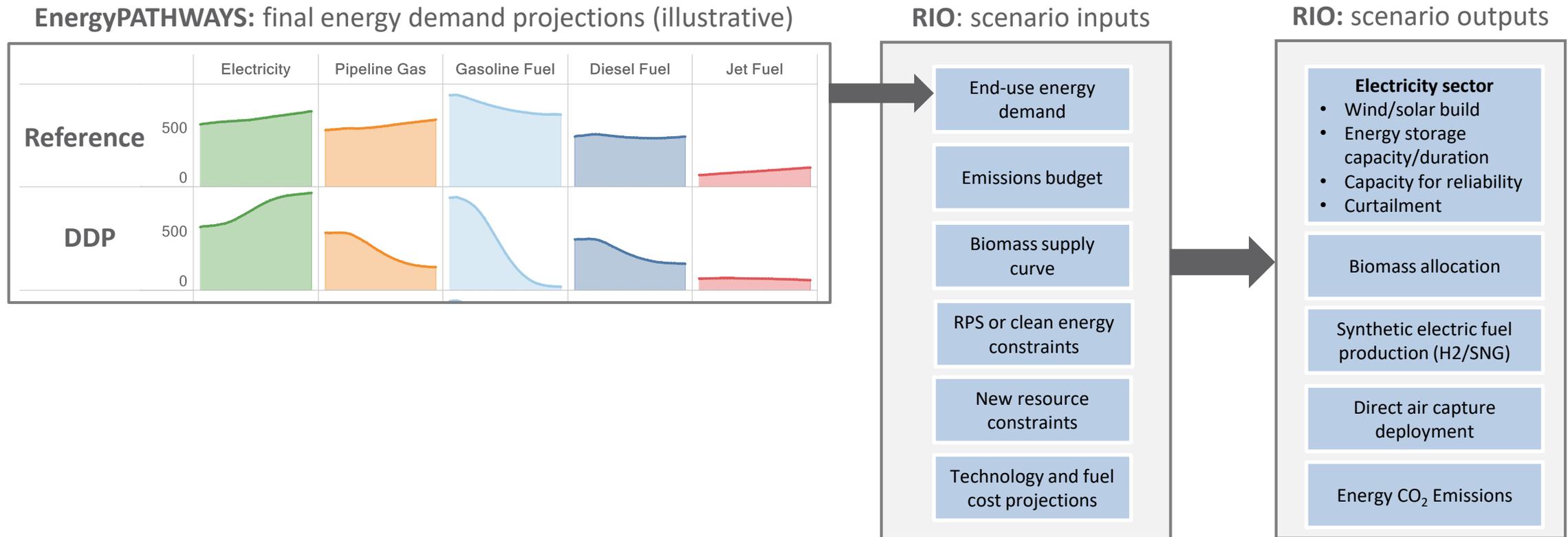
RIO uses demand projections from EP to produce cost-optimal energy supply portfolios:

- Electricity sector capacity expansion
- Biomass allocation across fuels
- Synthetic electric fuel production
- Direct air capture deployment



Modeling Framework

Pairing EnergyPATHWAYS and RIO



EnergyPATHWAYS

- EnergyPATHWAYS (EP) is a bottom-up energy system tool tracking energy infrastructure in each state, including stocks for buildings, industry and transportation
- Model has been applied in a number of jurisdictions to evaluate deep decarbonization, including Washington, Oregon, California and the Northeast
 - Additionally, we used the model to develop demand-side energy projections across the U.S. for NREL's *Electrification Futures Study*
- EP is a scenario tool, where user-defined measures specify new low-carbon and efficient technologies to replace energy infrastructure over time
 - We specify the scale and rate of adoption for new technologies in each demand sub-sector (e.g., the percent of light-duty car sales that are battery electric vehicle in each year)
- For this study, we used EP to develop demand-side projections by incorporating alternative electrification, other fuel switching and efficiency measures

EnergyPATHWAYS: Residential Water Heating Example

User-defined Input

Heat pump water heater (HPWH) sales are 50% of consumer adoption by 2035 and thereafter

Stock and Energy Consumption Results

HPWHs make up about half of the stock in residential homes by 2050

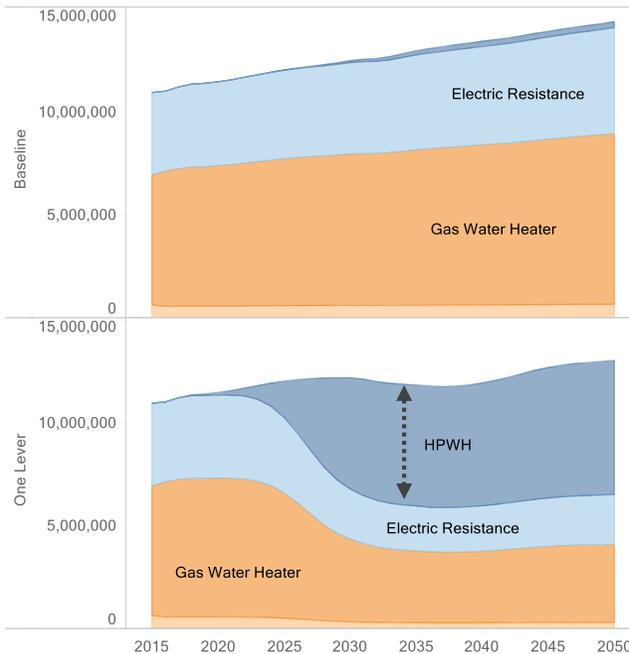
Overall energy demand decreases due to HPWH efficiency

Reference

Water Heating Electrification

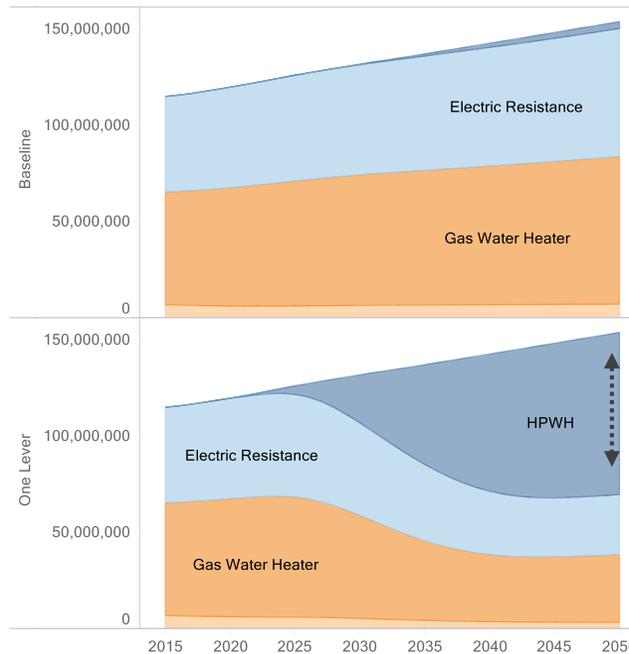
Sales

Water heaters sold per year



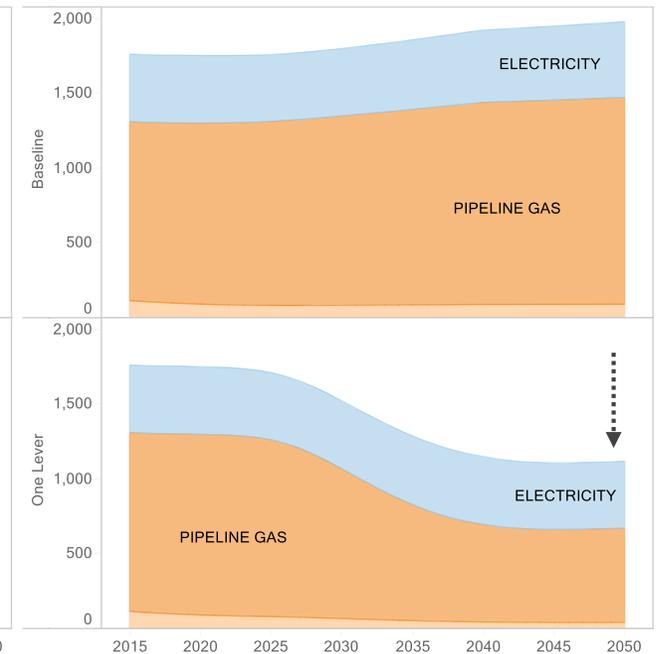
Stock

Water heaters in-service



Energy Demand

Trillion Btu



End-Use Sectors

- EnergyPATHWAYS represents approximately 80 demand sub-sectors
- The major energy consuming sub-sectors are listed below:

Residential Sector

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

Commercial Sector

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

Industrial Sector

- Boilers
- Process Heat
- Space Heating
- Curing
- Drying
- Machine Drives
- Additional subsectors (e.g., machinery; cement)

Transportation Sector

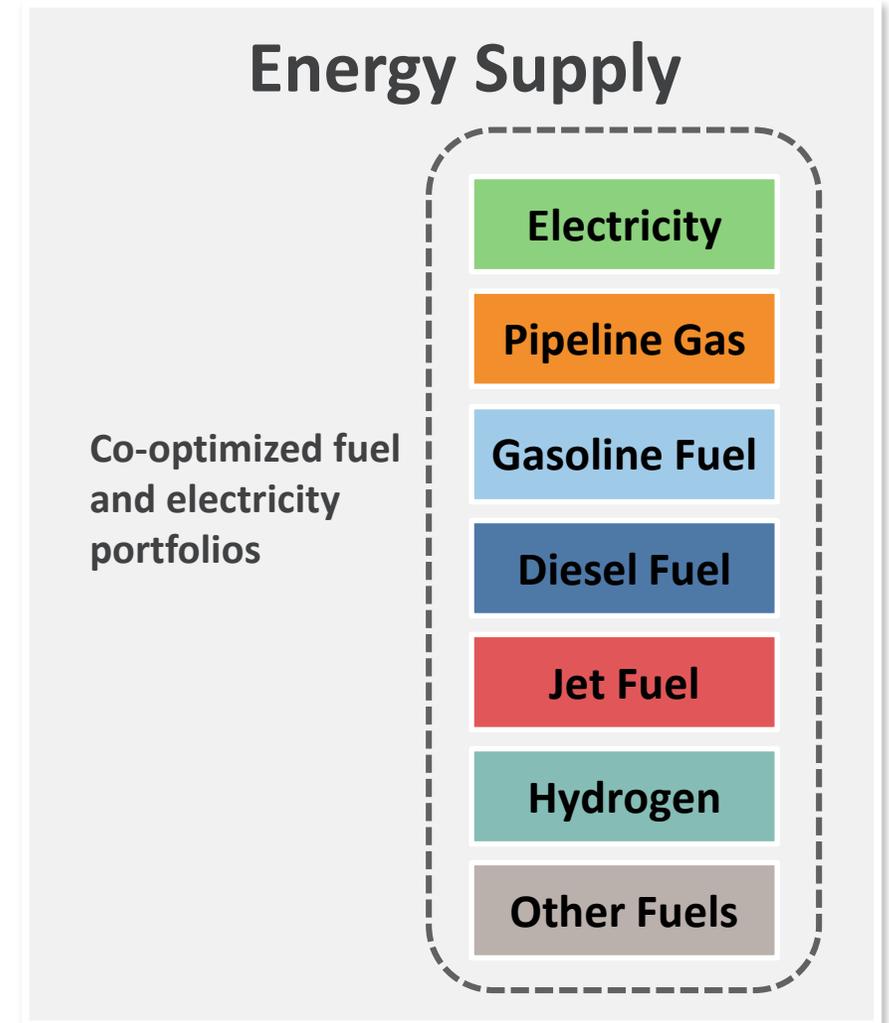
- Light-duty autos
- Light-duty trucks
- Medium-duty vehicles
- Heavy-duty vehicles
- Transit buses
- Aviation
- Marine vessels

End-Use Stocks and Technologies

- Northwest Energy Efficiency Alliance (NEEA) regional building stock assessments were used to characterize the existing building stocks in each state
- Cost and performance for new end-use technologies is primarily derived from:
 - NREL’s Electrification Futures Study, which includes projections for:
 - **Buildings Sector:** Air-source heat pumps and heat pump water heaters
 - **Transportation Sector:** Battery electric vehicles for light-duty cars and trucks; medium-duty battery electric trucks; heavy-duty battery electric trucks; and battery electric buses
 - **Industrial Sector:** Air-source heat pumps; electric machine drives; industrial heat pumps; electric boilers; and electric process heating
 - Input data for EIA’s National Energy Modeling System used to produce the Annual Energy Outlook
 - Includes baseline and projected cost and performance for residential and commercial equipment, such as residential clothes dryers and commercial ventilation systems

Regional Investment and Operations (RIO)

- RIO is a capacity expansion tool that produces cost-optimal resource portfolios
- Includes electric sector capacity expansion and the optimization of all energy supply options
 - Optimization allows for trade-offs of limited resources across energy system, such as biomass, to be determined simultaneously
- Model decides the suite of technologies to deploy over time to meet annual emissions and other constraints



RIO: Electricity Sector

- Simulates sequential hourly system operations for each year
 - Hourly dispatch ensures sustained peaking capability of energy-limited resources such as hydro is captured
- Incorporates long-duration energy storage resources
 - 365 day chronology represented in the model, allowing long-duration storage to shift energy from periods of excess energy to those, such as during storms, where additional energy is needed
 - Necessary at high renewable penetrations: without long-term storage, daily energy needs would require uneconomic overbuild of renewables and cause excessive curtailment
- Optimizes economic additions and retirement of resources
- Operations and investment are simulated while accounting for dynamics across the energy system, such as:
 - Electric fuel production competes with other forms of energy storage to balance the system
 - Bioenergy allocation to pipeline gas for power plants or diesel fuel, depending on economics
 - Changing dynamics in neighboring regions (e.g., California and its 100% clean electricity requirement)

Load, Hydro and Renewables

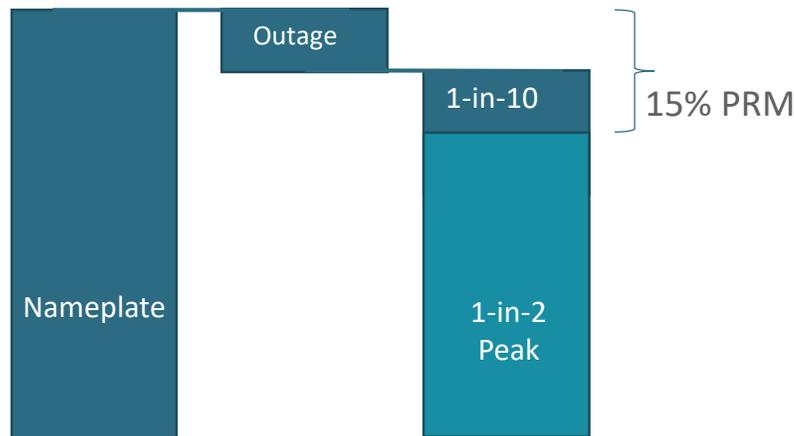
- In order to capture a range of electricity system operating conditions in RIO, we incorporate load, wind, solar and hydro profiles from multiple weather years
 - Weather-driven or seasonal trends in load, hydro availability and renewable production cause operational challenges that can persist over long periods
- **Load, wind and solar**
 - Hourly profiles are from three weather years: 2010, 2011 and 2012
 - Load shapes further account for scenarios-specific electrification and energy efficiency impacts over time
- **Hydro**
 - Hourly hydro generation from three historical years is used to derive operational constraints, including energy budgets, minimum and maximum capabilities and ramp rates
 - Dry, normal and wet hydro conditions based on data from WECC for 2001, 2005 and 2011, respectively

Conventional Reserve Margin Process

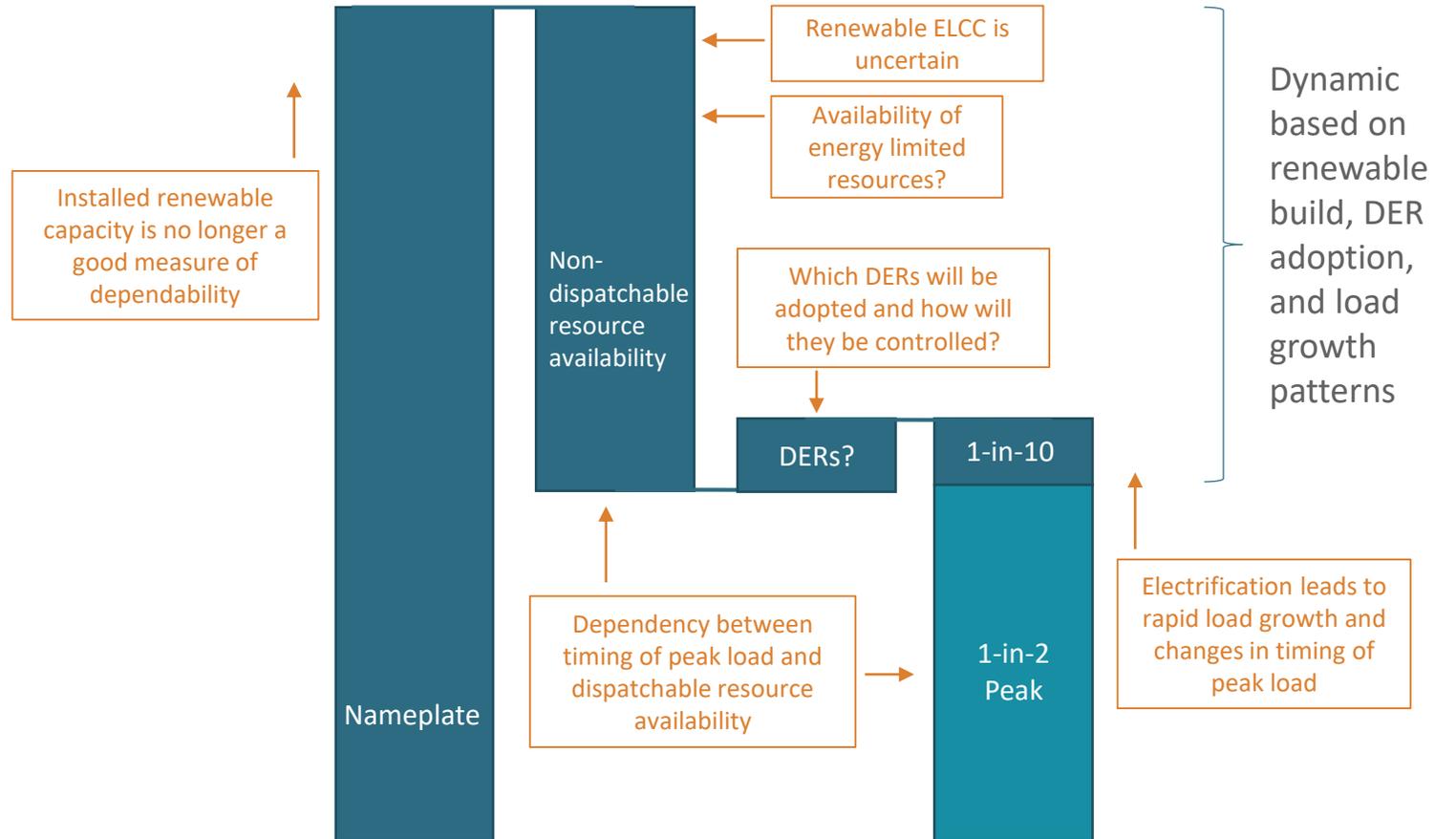
- Reserve margins are used as a proxy for meeting system reliability standards in-between detailed loss-of-load studies
 - Defined as $[\text{sum}(\text{resources})/\text{median peak load} - 1]$
 - Typical industry margins vary from 10-15%
- This process works well as long as resources are dispatchable and nameplate roughly equals the contribution of that resource to reliability
- This benchmark breaks down when resources are:
 - Energy limited (hydro; energy storage);
 - Non-dispatchable (wind; solar); or
 - Non-conventional (flexible load)
- Alternatively, RTO enforces a capacity reserve constraint across all model hours that accounts for the contributions of these resource types

Assessing Reliability Becomes Challenging in Low-Carbon Electricity Systems

Traditional Reserve Margin



Future System Reliability Assessment



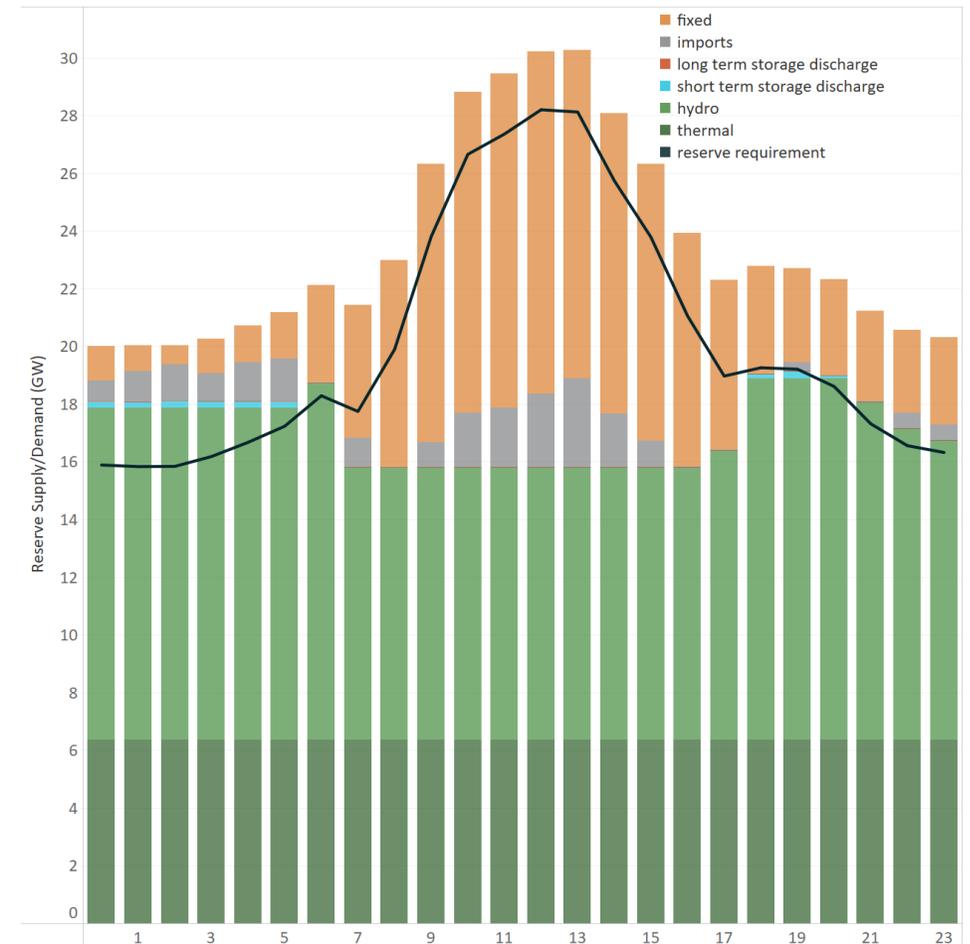
Hourly Planning Reserve Constraints by Zone

Accounting for non-dispatchable and energy-limited resources

- Reserve requirement = 107% of gross load representing weather-related risk of load exceeding that sampled
- Reserve supply must exceed the reserve requirement across all hours in all years with:
 - Thermal: Derated* nameplate
 - Hydro: Derated hourly output
 - Renewables: Derated hourly output
 - Energy storage: Derated hourly discharge minus charge
 - Imports: Derated net flows
 - Flexible loads: Net from load (not pictured)

*All resources are given a resource specific derate representing forced outage rates, energy limited risk, and weather related risk

Illustrative Hourly Reserve Requirement and Supply



Electric Topology

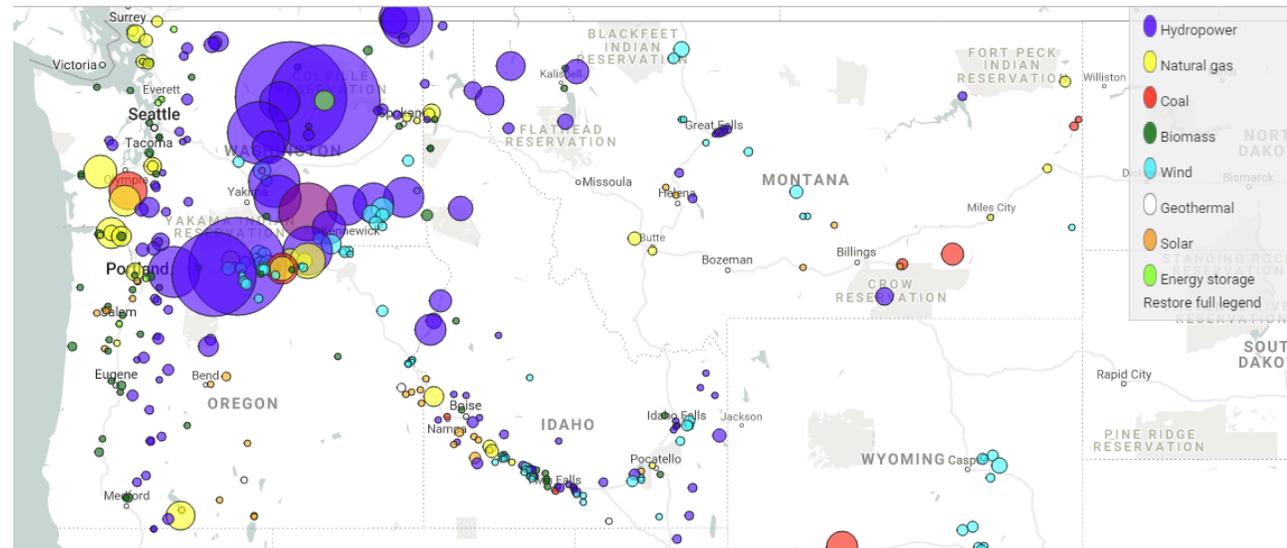
- Electricity sector operations and investment modeled across
 - Northwest states
 - California
 - Rest of the Western Electric Coordination Council (WECC)
- Transfer capability between zones is based on major WECC paths and their line ratings
- Capacity of major remote generation resources (e.g., Colstrip) is allocated to states based on utility ownership



Existing Generation Resources

- Installed capacity of generation resources in each state is derived from the U.S. Energy Information Administration's Form EIA-860
- Capacity from the existing hydroelectric system is assumed to remain constant through 2050

Map of Existing Power Supply



Source: image from [NWPPCC](#)

Existing Coal Resources

- Study incorporates planned retirement of coal-fired resources
- Plants without a planned retirement year are assumed to retire at the end of their economic lifetimes

Washington and Oregon Coal Resources

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

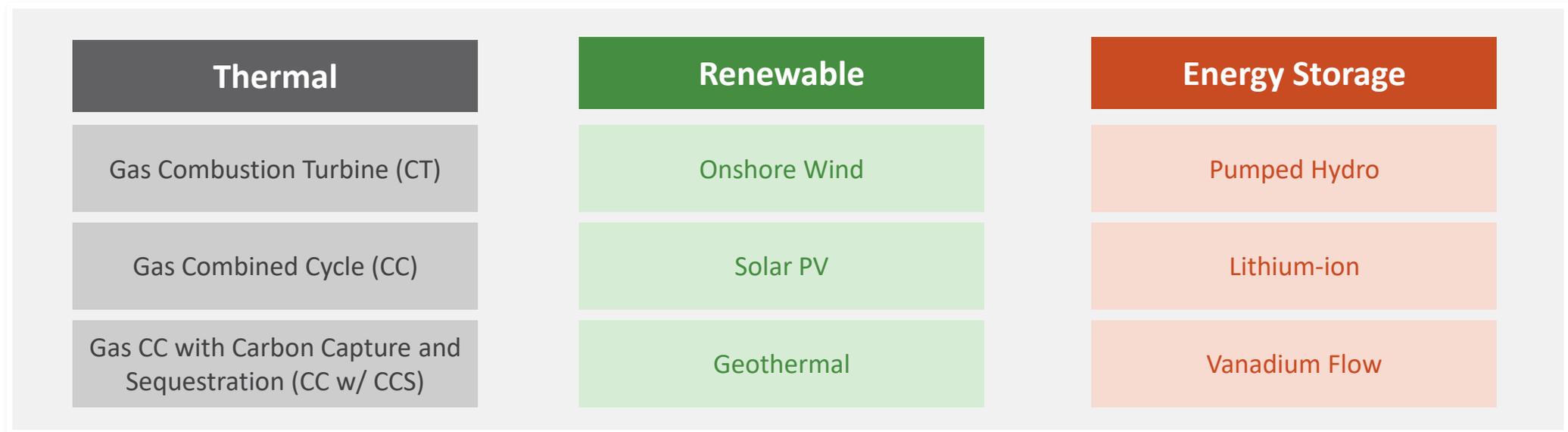
Existing Nuclear

- Columbia Generating Station (CGS) is the only operating nuclear power plant in the Northwest and its current license expires at the end of 2043
- RIO allows CGS to retire or continue operations after 2043 to maintain dependable capacity and carbon-free energy
- The going-forward fixed costs of maintaining CGS are derived from Energy Northwest's Fiscal Year 2019 Long Range Plan
 - Fixed capital costs are assumed to equal \$85/kW-yr
 - Fixed operations and maintenance costs are assumed to equal \$238/kW-yr
 - Total going-forward fixed costs are equal to \$323/kW-yr

New Electric Sector Resource Options

Overview

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



New Electric Sector Resource Options

Thermal

- RIO can select from three gas-fired resource alternatives
 - Combustion Turbine
 - Combined Cycle
 - Combined Cycle with Carbon Capture and Sequestration
- Capital, fixed operations and maintenance (O&M), variable O&M and heat rate characteristics are from NREL's 2018 Annual Technology Baseline (ATB)
- Fuel costs vary depending on the pipeline gas composition
 - Natural gas fuel costs are from the Annual Energy Outlook 2017
 - Cost of decarbonized pipeline gas is solved for endogenously in RIO
- New coal and advanced nuclear resources were not considered

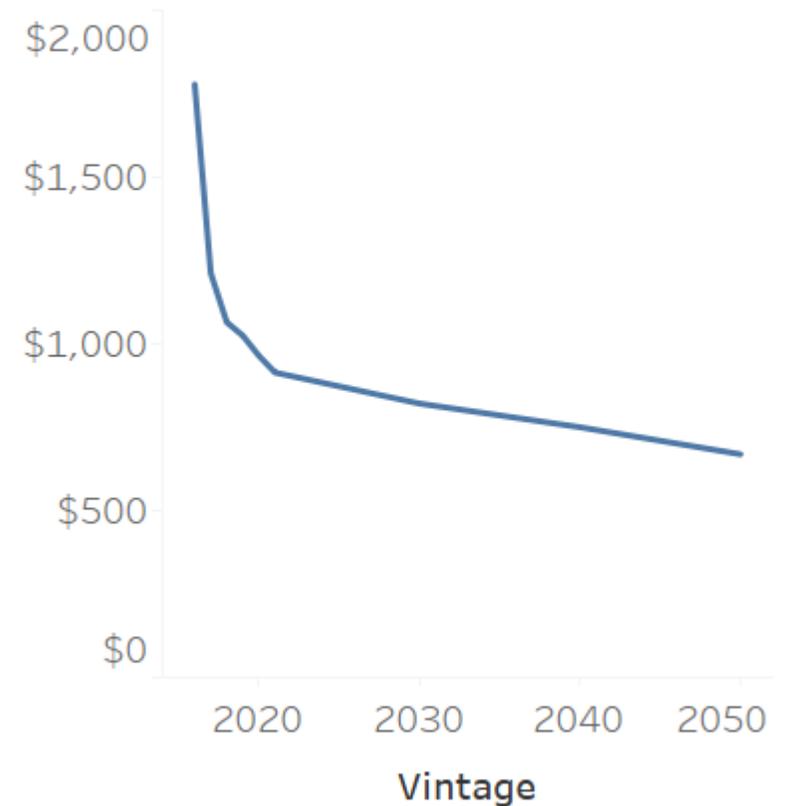
New Electric Sector Resource Options

Renewable

- Various state-level inputs characterizing renewable resources are derived from NREL's Regional Energy Deployment System (ReEDS)
 - Potential
 - Performance (capacity factor)
 - Transmission costs
- Capital cost projections for wind, solar and geothermal resources are from NREL's 2018 ATB
- See Appendix for more cost information

Utility-scale Solar PV Installed Cost

2016\$/kW-dc



New Electric Sector Resource Options

Energy Storage

- Cost and efficiency inputs are derived from the International Renewable Energy Agency (IRENA) *Electricity Storage and Renewables: Costs and Markets to 2030* report
- Costs are portioned into capacity (\$/kW) and energy (\$/kWh) components, where RIO selects the optimal duration of new resources over time
- New pumped hydro storage potential is limited to 2,000 MW in the Northwest based on a review of existing projects under development
 - Reflects the Gordon Butte, Goldendale and Swan Lake pumped storage projects
- See Appendix for more cost information

Conversion Technology Options

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

Biomass-based

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

Electric-based

- **Power-to-X** processes convert carbon-free electricity into synthetic fuels (e.g., power-to-gas; power-to-liquids)
- Processes rely on:
 - Electrolysis to produce hydrogen; and
 - Carbon feedstocks either from CO₂ embodied in biomass or direct air capture

Supply-Side Resource Options

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

Acronyms

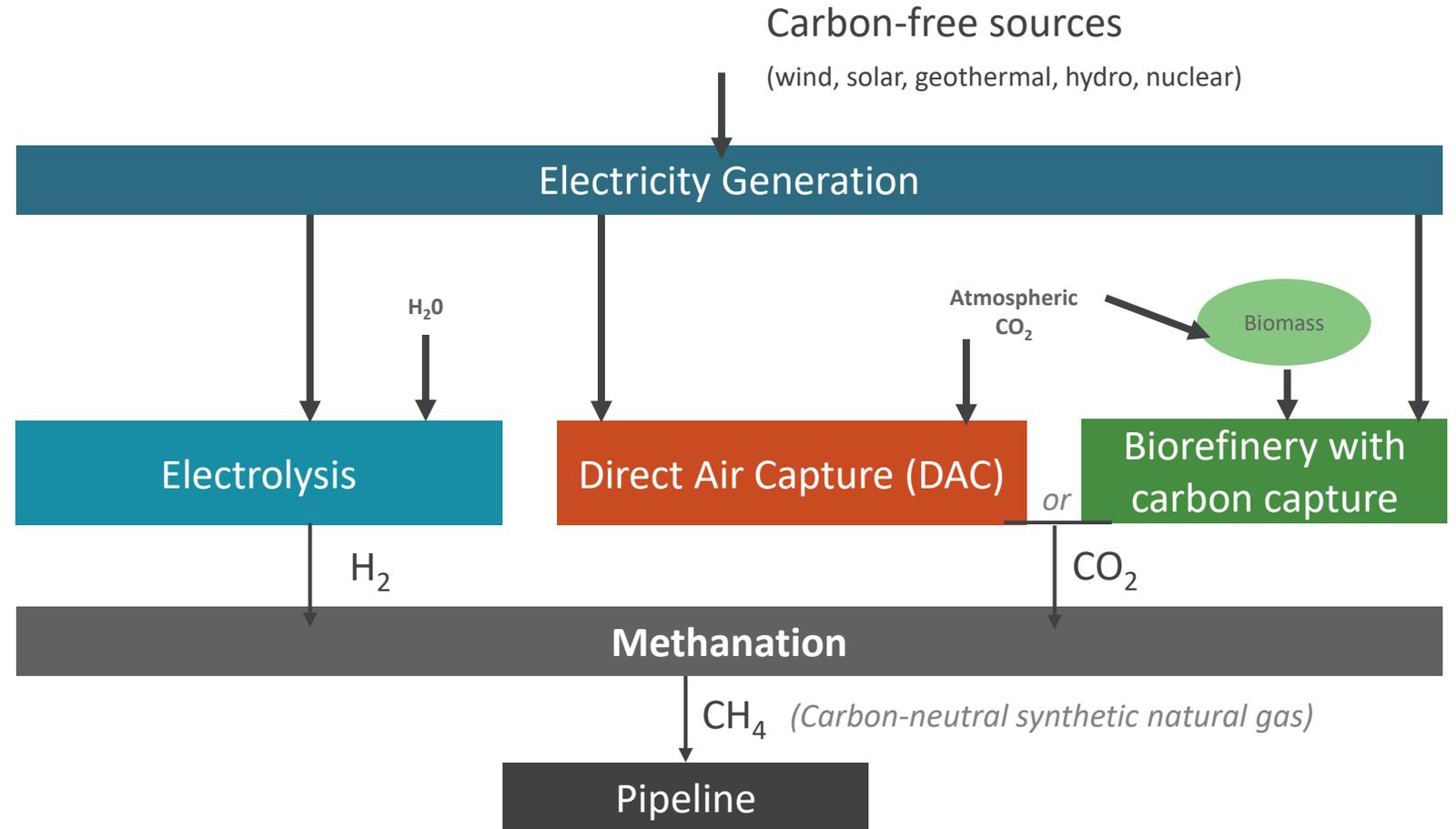
CHP: combined heat and power
 CCS: carbon capture and sequestration
 CCU: carbon capture and utilization
 DAC: direct air capture
 FT: Fischer-Tropsch

Illustration of Power-to-Gas

[1] Hydrogen (H₂) is produced from **electrolysis** using **carbon-free electricity** and water

[2] CO₂ is captured either through **direct air capture** or from **biorefineries**, which both use **carbon-free electricity**

[3] H₂ and CO₂ are combined via **methanation** to produce carbon-neutral synthetic natural gas, which is directly injected into the pipeline



Biomass Availability and Costs

- Prior deep decarbonization pathways studies have relied on the Department of Energy (DOE) Billion-Ton Study for estimates of biomass availability and costs
 - Study includes feedstock potential by U.S. county at different price points for agricultural residues, forest residues, purpose-grown energy crops and waste streams
- Sub-national studies (e.g., Washington State and Portland General Electric) assumed an allocation of biomass to the jurisdiction that is equal to its population-weighted share of national supply
- This study follows the same approach as earlier work, where each state in the Northwest is allocated a share of national supply based on its relative population
 - We evaluate the tradeoffs of assuming lower biomass availability in one DDP case
- RIO determines the application of biomass for the energy system by allocating limited supply to the most cost-optimal fuel type

Key References and Data Sources

- Deep decarbonization analyses require a wide variety of inputs and data sources to characterize current and future energy systems
- We rely on state and regional data sources (e.g., Northwest Energy Efficiency Alliance) where available, and leverage public sources primarily from federal government reports, including the U.S. Energy Information Administration (EIA), U.S. Department of Energy (DOE) and National Renewable Energy Laboratory (NREL)
 - A list of key references and data sources is provided in the Appendix
- These sources tend to be conservative about the projected cost and performance of low-carbon technologies



Scenarios

Overview

- This study explores multiple pathways for decarbonizing the Northwest energy system, while addressing policy questions and potential implementation challenges in the context of economy-wide carbon limits
- We constructed a **Central Case** that represents our core deep decarbonization pathway (DDP)
- Additional DDP cases were developed *as sensitivities to* the Central Case to draw out insights from alternative assumptions and policies
 - A **Reference Case** was also developed to compare the DDP cases against
- This approach allows for a better understanding of the trade-offs across the energy system when we assume:
 - Alternative levels of electrification
 - Mandates to use 100% clean electricity generation or prohibit new gas power plants
 - Constraints on the use of biomass
 - Further electricity sector integration between the Northwest and California

Scenario Overview

Case	Description
Reference	<ul style="list-style-type: none"> A continuation of current and planned policy Provides a benchmark against the deep decarbonization pathways
Central	<ul style="list-style-type: none"> Represents the core pathway to achieve deep decarbonization Flexible pathway to achieve emissions reductions (e.g., technology-agnostic in the electricity sector)
100% Clean Electricity	<ul style="list-style-type: none"> 100% of electricity generation in the Northwest must come from zero-carbon sources Allows gas-fired generation to burn biogas and synthetic electric fuels
Limited Demand Transformation	<ul style="list-style-type: none"> Aggressive electrification fails to materialize Adoption of electrification is half of the Central Case
No New Gas Plants	<ul style="list-style-type: none"> Pathway prohibits any new gas-fired power plants across the region throughout the study horizon Existing gas plants retire at the end of their natural life, which effectively results in zero gas plants by 2050
Increased NW-CA Transmission	<ul style="list-style-type: none"> NW and CA power systems are currently connected by approximately 8,000 MW of interties Pathway allows for transmission interties to be expanded as both regions strive to achieve decarbonization
Constrained Biomass	<ul style="list-style-type: none"> Each state's bioenergy potential is limited to waste and wood feedstocks without access to energy crops or resources outside of the region Biomass supply is ~60% less than Central Case
Increased Gas in Transportation	<ul style="list-style-type: none"> Freight vehicle fleet has a large composition of compressed and liquefied pipeline gas trucks Increased pipeline gas use in freight transportation supplants diesel fuel demand in the Central Case

Central Case: Overview

- **Demand-side**: Incorporates significant levels of efficiency and electrification across all end-use sectors
 - Similar levels to the Electrification Case from the 2016 Washington State DDP Report
- **Supply-side**: Allows for cost-optimal decarbonization of energy supply without explicit constraints on which fuels are decarbonized
 - No explicit 100% clean electricity requirement or constraints on new gas plants
- **Key questions addressed:**
 - How clean must electricity generation be to realize economy-wide goals?
 - What is the cost-optimal allocation of biomass?

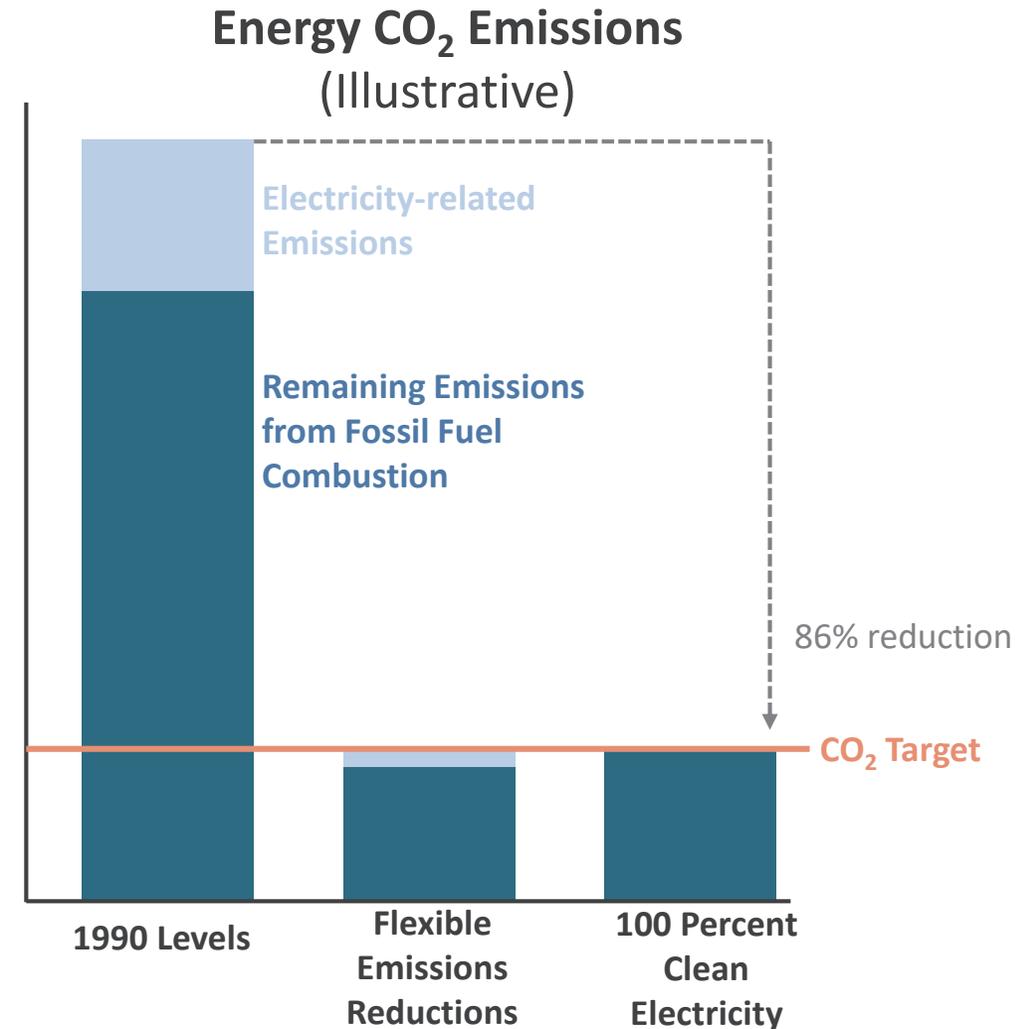
Central Case: Demand-Side Assumptions

Primary Equipment Types or Approach by 2050

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

100 Percent Clean Electricity Case

- Description. Northwest states achieve economy-wide deep decarbonization while mandating that electricity generation is 100% clean by 2050
 - Case provides for an understanding of 100% clean electricity in the context of the energy system
- Implementation. RIO does not allow fossil fuel combustion in electricity generation by 2045
 - Allows for higher emissions from other forms of energy supply while maintaining the same overall energy CO₂ target
 - Thermal power plants can continue to operate, but their pipeline gas consumption must be 100% decarbonized (e.g., biogas/synthetic natural gas)



Limited Demand-Side Transformation Case

- Description. Pathway where aggressive electrification on the demand-side fails to materialize
 - Explores the mitigation burden placed on energy supply when consumers are less active in adopting low-carbon and efficient technologies
- Implementation. Adoption of electrification measures in EnergyPATHWAYS is one-half of the Central Case assumptions
 - Lower electrification is realized across all demand-subsectors

Comparison of Electrification Sales Shares

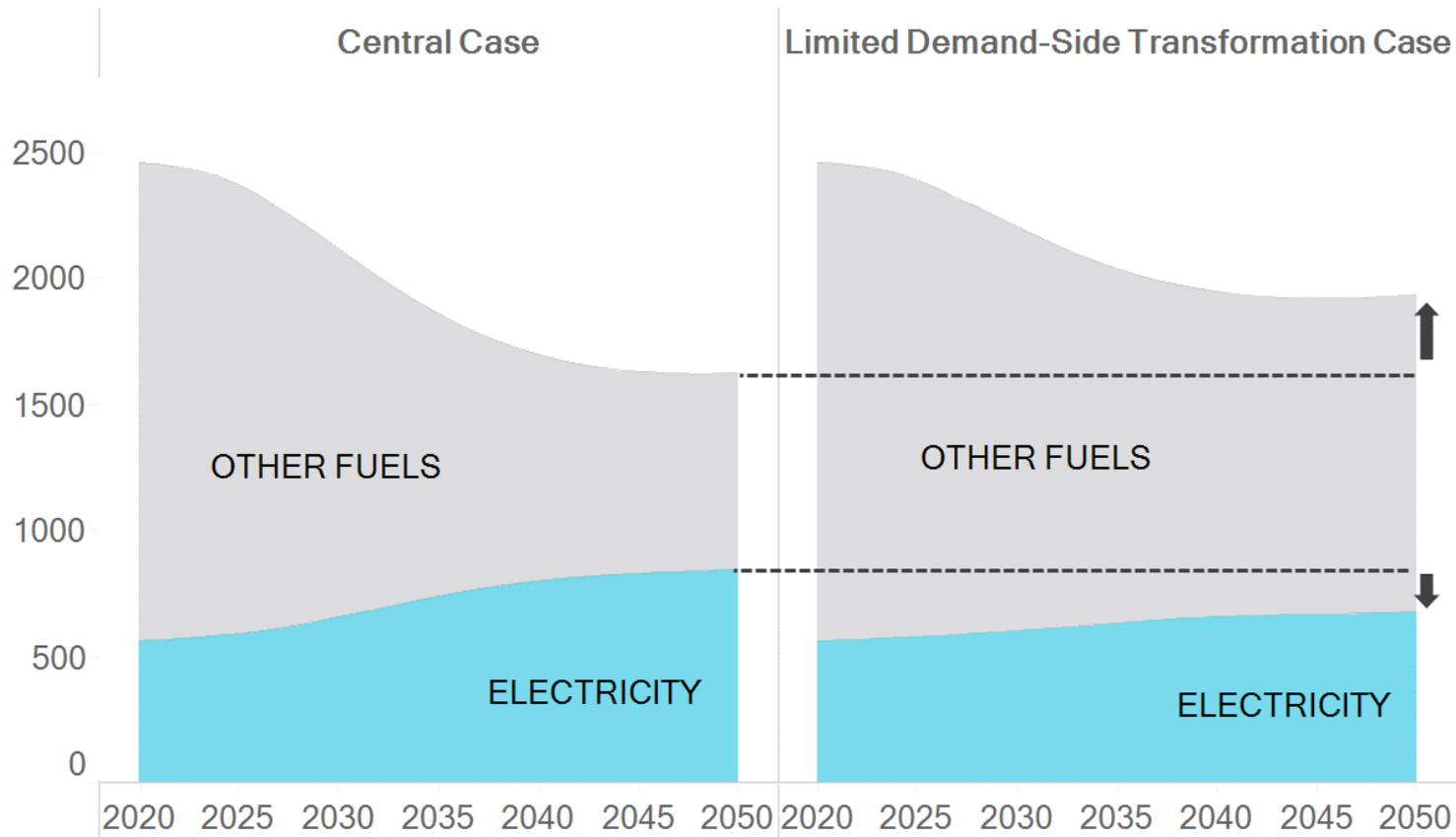
Sector	Subsector	Central Case	Limited Demand-Side Transformation Case
Transportation	Light-duty vehicles	90% battery electric 10% plug-in hybrid electric	45% battery electric 5% plug-in hybrid electric
	Medium-duty trucks	60% battery electric	30% battery electric
	Heavy-duty trucks	40% battery electric	20% battery electric
Buildings	Space Conditioning	Primarily air source heat pump	One-half of the Central Case
	Water Heating	Primarily heat pump water heater	One-half of the Central Case
Industry	Various	Electrification adoption similar to NREL EFS 'High scenario'	One-half of the Central Case

Limited Demand-Side Transformation Case

Alternative demand side assumptions lower electrification versus the Central Case

Northwest Final Energy Demand

Trillion Btu



Change in Model Input
Assumptions: Lower levels of electrification translates into higher overall final energy demand

No New Gas Case

- Description. Pathway prohibits the development of any new gas-fired resources across the region throughout the study horizon (2020 to 2050)
- Implementation.
 - RIO cannot select any gas-fired combustion turbine, combined cycle or combined cycle with CCS resources
 - Existing gas resources retire at the end of their natural life and cannot be extended or replaced, which effectively results in zero gas-fired resources online in 2050
 - Outside of the electricity sector, there are no constraints on pipeline gas use

Increased Northwest-California Transmission Case

- Northwest and California's electricity systems are currently connected by approximately 8,000 MW of interties
 - Includes California-Oregon Intertie (COI) and Pacific Direct Current Intertie (PDCI)
- Description. This pathway explores how increased transmission between the two regions could allow both to achieve deep decarbonization at potentially lower costs
 - Hypothesis: same emissions reductions are achieved at lower cost due to lower balancing-related infrastructure needs

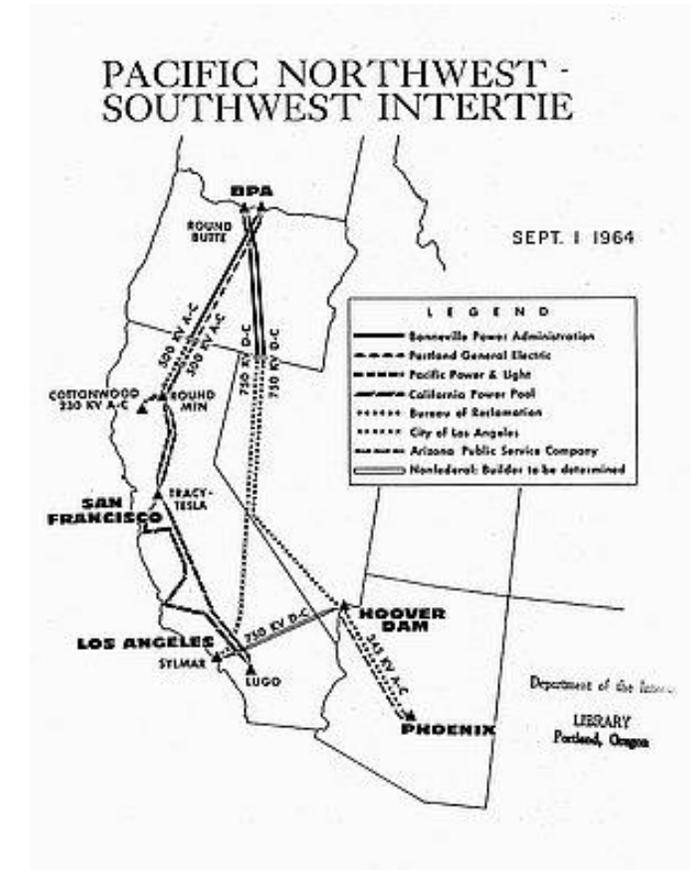


Image source: [BPA](#)

Increased Northwest-California Transmission Case

- Implementation.

- Allow RIO to economically expand transmission between the regions
 - Proxy cost to expand transmission is \$1,383/kW
 - Based on inputs from the California Public Utilities Commission (CPUC) RPS Calculator v6.2
- CAISO’s net export limit, which is enforced in planning studies, is relaxed over time
- Hurdle rates between the two regions are removed starting in 2030

NW-CA Transmission Assumptions

Category	Central Case	Increased NW-CA Transmission Case
Allow Economic Build of New Transmission Between NW and CA	No	Yes
California Net Export Limit	2020: 2,000 MW 2030: 5,000 MW 2050: 5,000 MW	2020: 2,000 MW 2030: 8,000 MW 2050: None (up to physical)
Hurdle Rates	Maintain through study horizon	Eliminate hurdle rates starting in 2030
RPS Eligibility	Resources in both regions are eligible	Resources in both regions are eligible

Constrained Biomass Case

- Description. The supply of biomass available to be converted into net-zero carbon biofuels is limited relative to the Central Case
 - Case addresses concerns about biomass availability, particularly purpose-grown energy crops
- Implementation. Each state's bioenergy potential is limited to: (1) in-state waste; and (2) population-weighted share of regional wood feedstocks
 - No access to purpose-grown energy crops or resources outside of the Northwest
 - Overall biomass supply is more than 60 percent less than the Central Case assumptions

Feedstock	Central Case	Constrained Biomass Case
Waste	State supply	State supply
Wood	Population-weighted share of national supply	Population-weighted share of regional supply
Energy Crops	Population-weighted share of national supply	None

Increased Gas in Transportation Case

- Description. Freight vehicle fleet has a large composition of compressed and liquefied pipeline gas trucks
- Implementation. Adoption of compressed natural gas and liquefied natural gas trucks in place of diesel trucks

Comparison of Freight Truck Sales Shares in 2035

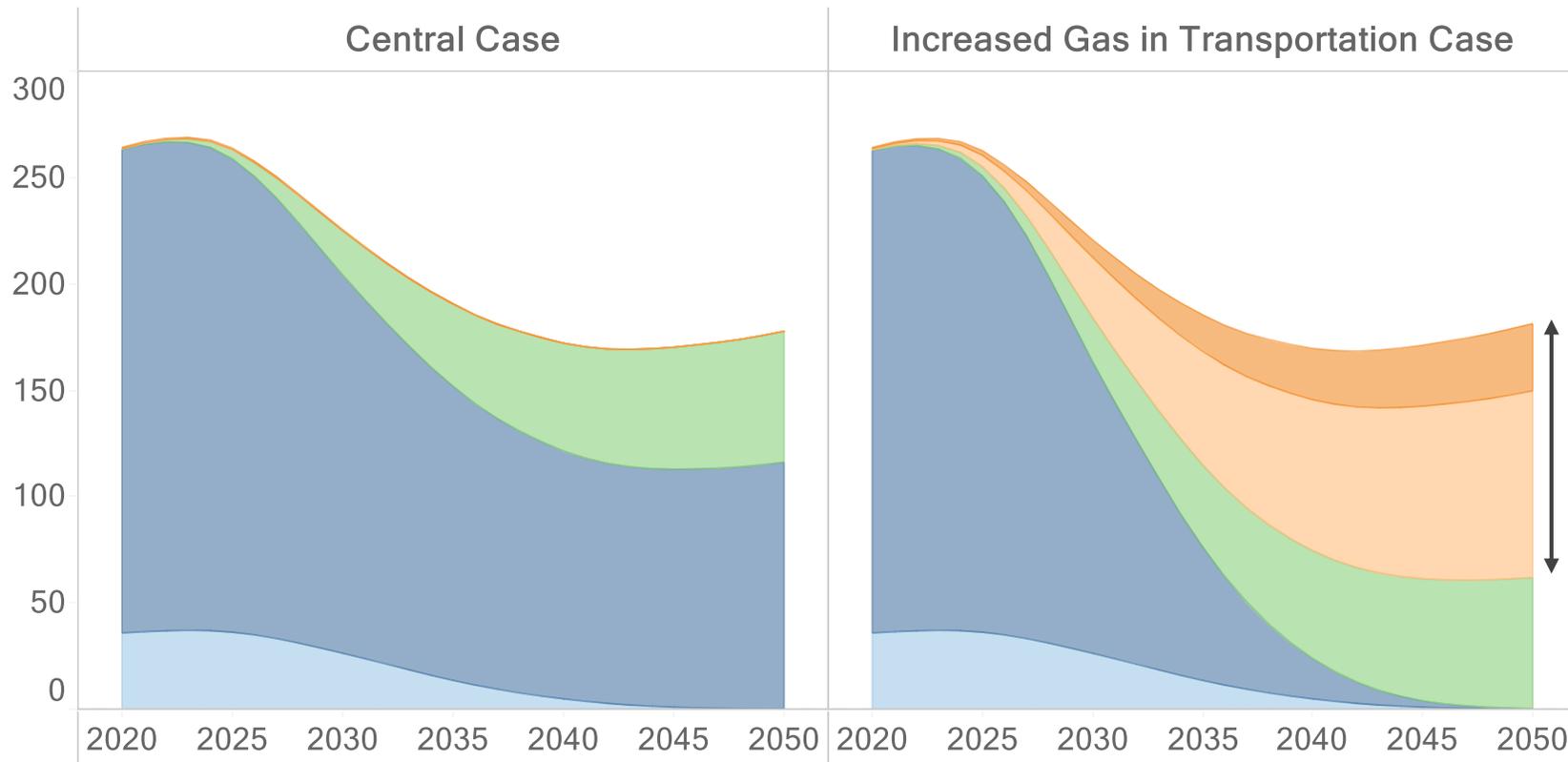
Sub-sector	Technology	Central Case	Increased Gas in Transportation Case
Medium-duty Vehicles	Battery Electric	60%	60%
	Hybrid Diesel	40%	0%
	Hybrid CNG	0%	40%
Heavy-duty Vehicles	Battery Electric	40%	40%
	Hybrid Diesel	60%	0%
	Hybrid LNG	0%	60%

Increased Gas in Transportation Case

Alternative demand side assumptions on gas in transportation versus the Central Case

Final Energy Demand: MDV and HDV

Trillion Btu



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



Results

Structure of Results

- The results in this section are structured as follows:
 - The Reference and Central cases are first presented with a focus on how the Central Case achieves deep decarbonization
 - Next, the remaining six DDP cases are presented in the context of how the results differ from the Central Case
 - Next, metrics from all of the cases are summarized
 - Finally, energy system costs are presented
- All results presented here are for the Northwest region as a whole unless specified otherwise
- Costs are expressed in 2016 dollars



Overview of the Reference and Central Case

Energy CO₂ Emissions

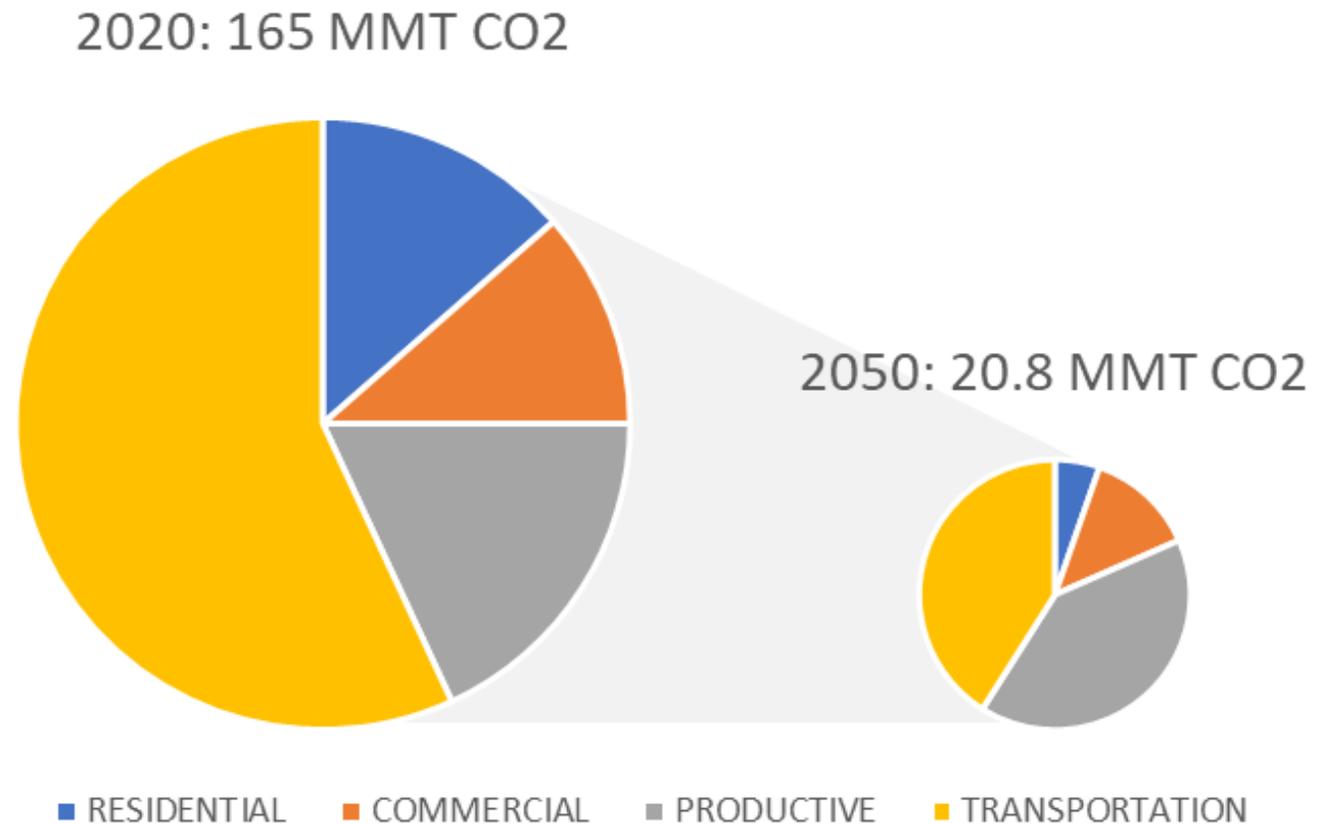
- **Reference Case** emissions trajectory fall significantly short of the 2050 energy CO₂ target
- Electrification, energy efficiency and decarbonization of energy supply in the **Central Case** enable all Northwest states to meet the mid-century energy CO₂ target

Energy CO₂ Emissions
MMT



Northwest CO₂ Emissions Decrease by Sector in the Central Case

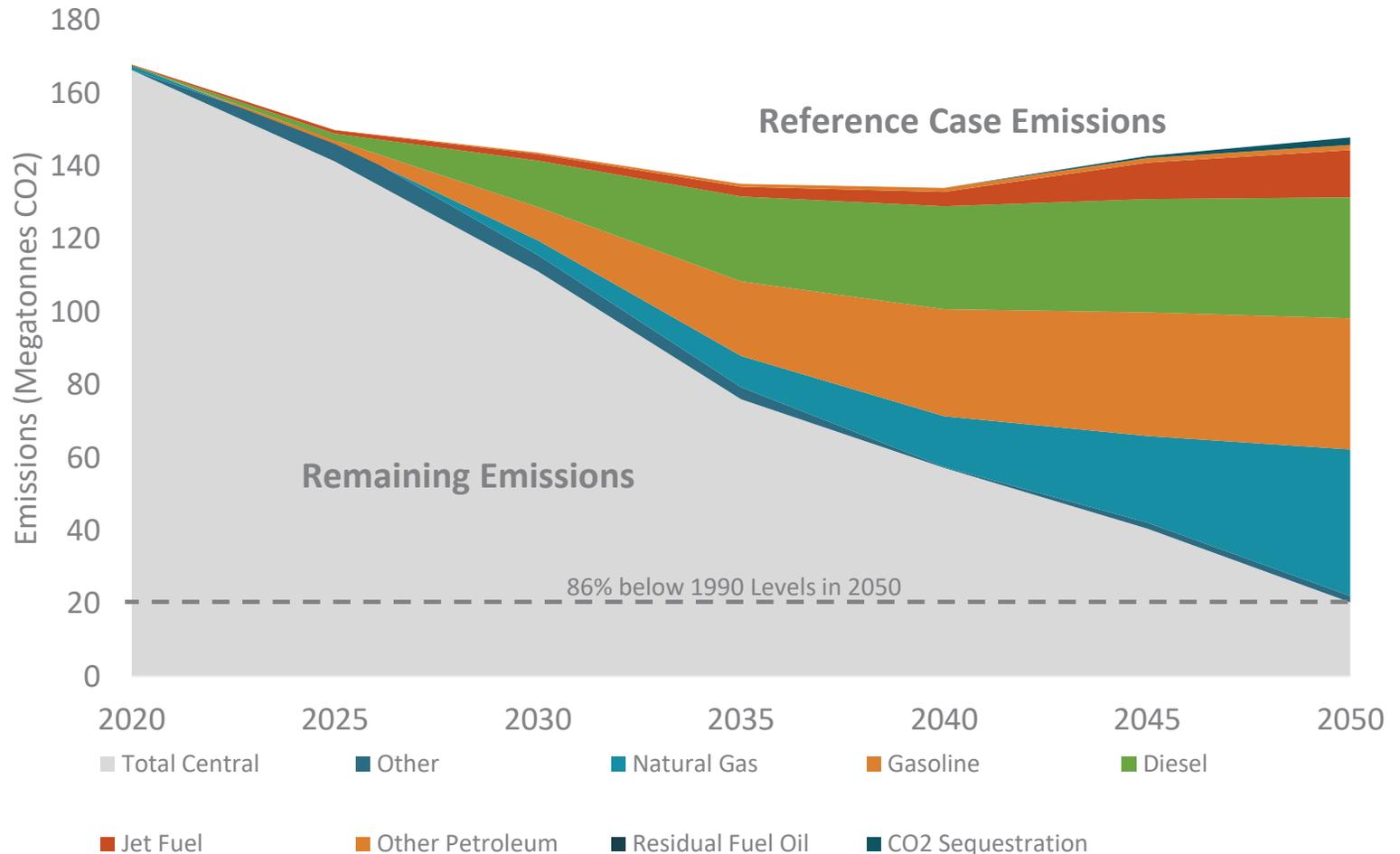
- Central Case CO₂ emissions decrease in the Central Case from 165 MMT in 2020 to 20.8 MMT in 2050
- Percentage of total emissions by sector:
 - Decrease in residential and transportation emissions due to relatively inexpensive abatement measures
 - Increase in the productive sector due to the difficulty and expense of decarbonizing some industrial end uses



Central Case Emissions Trajectory from 2020-2050

- Emissions from fossil fuel sources are reduced in the central case through:
 - Energy efficiency
 - Decarbonizing electricity
 - Decarbonizing gas and liquid fuels
 - Fuel switching in industry, transportation and buildings
 - Carbon capture
- The cost of achieving these reductions is offset by avoided fossil fuel purchases

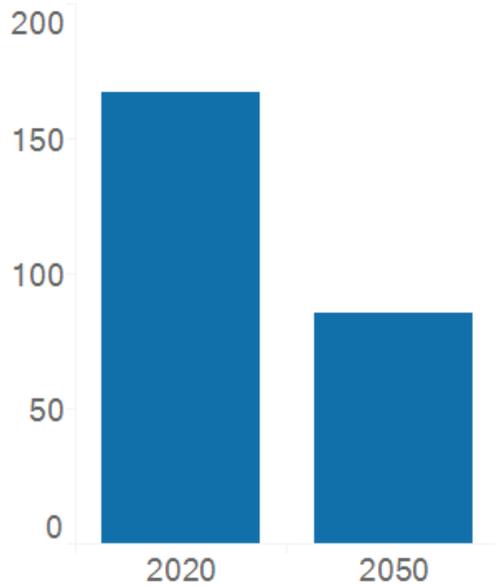
Central Case Emissions Reductions vs Reference



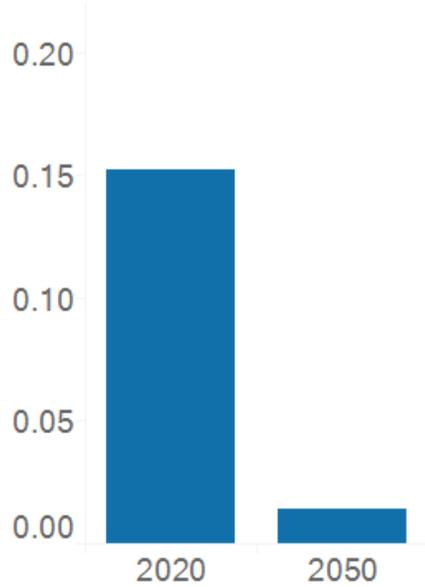
Deep Decarbonization Strategies



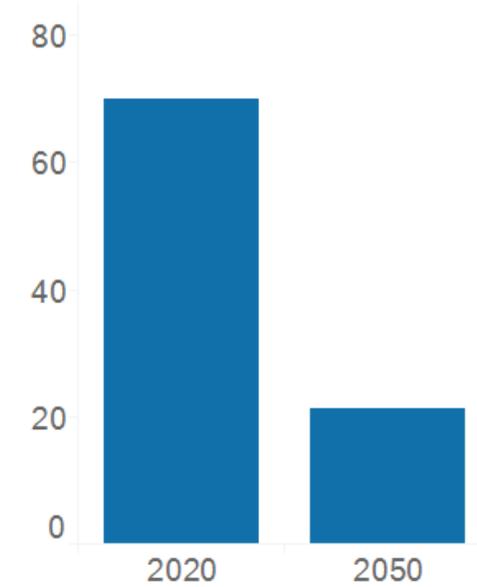
Energy Efficiency
MMBtu per person



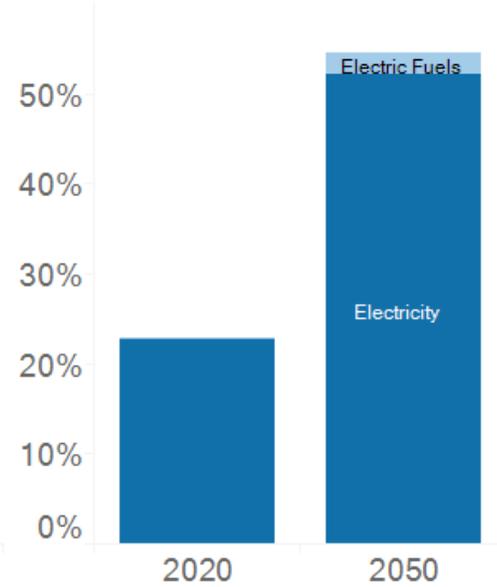
Decarbonize Electricity
tonnes CO2 per MWh



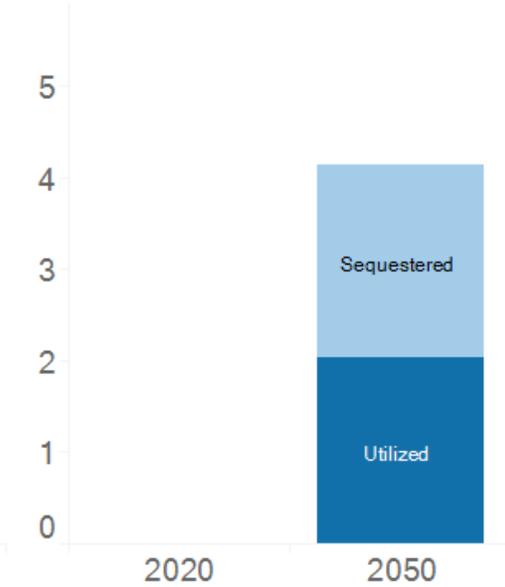
Decarbonize Fuels
kg CO2 per MMBtu



Electrification
Share of Total Final Energy, %

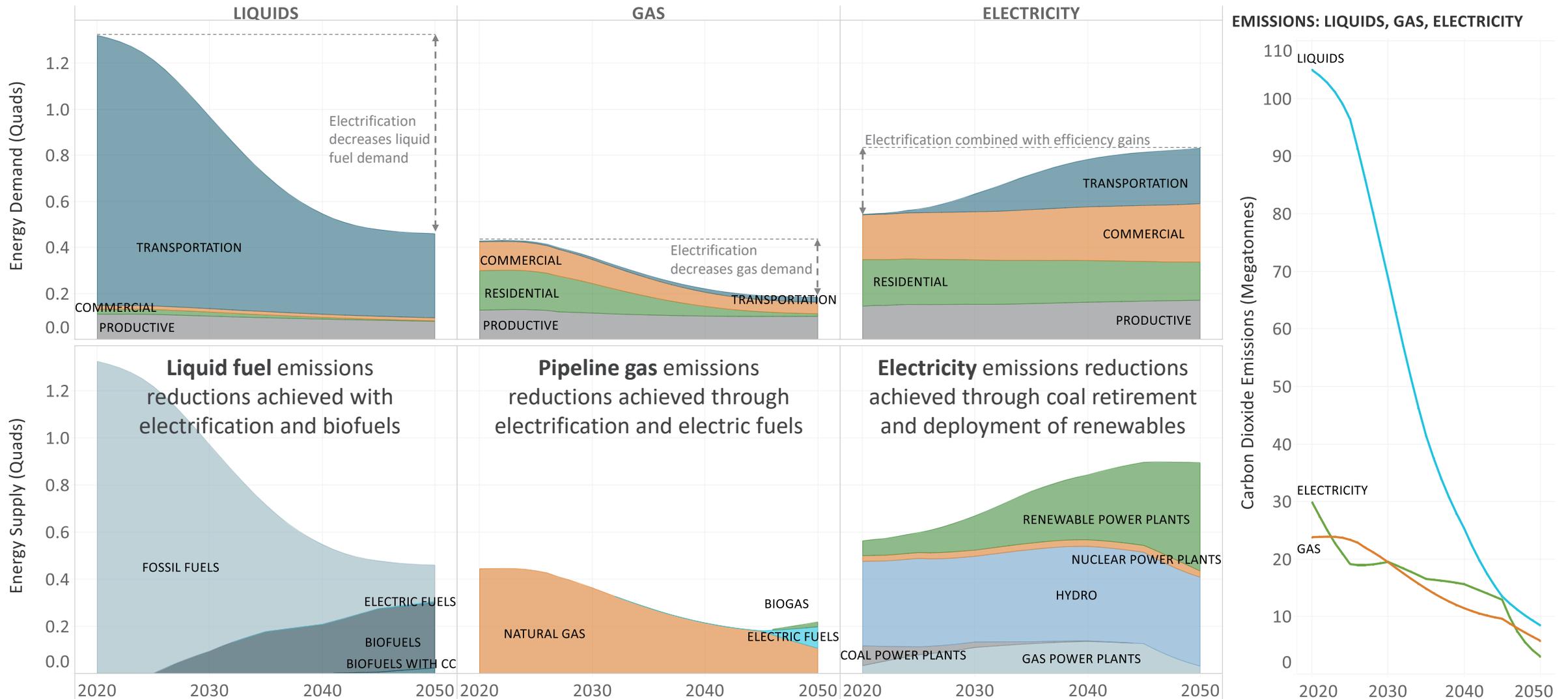


Carbon Capture
MMT CO2 Capture



Emissions Reductions from Liquid Fuels, Gaseous Fuels, and Electricity

Central Case – Liquid, Gas, and Electricity Demand by Sector and Supply by Fuel Type

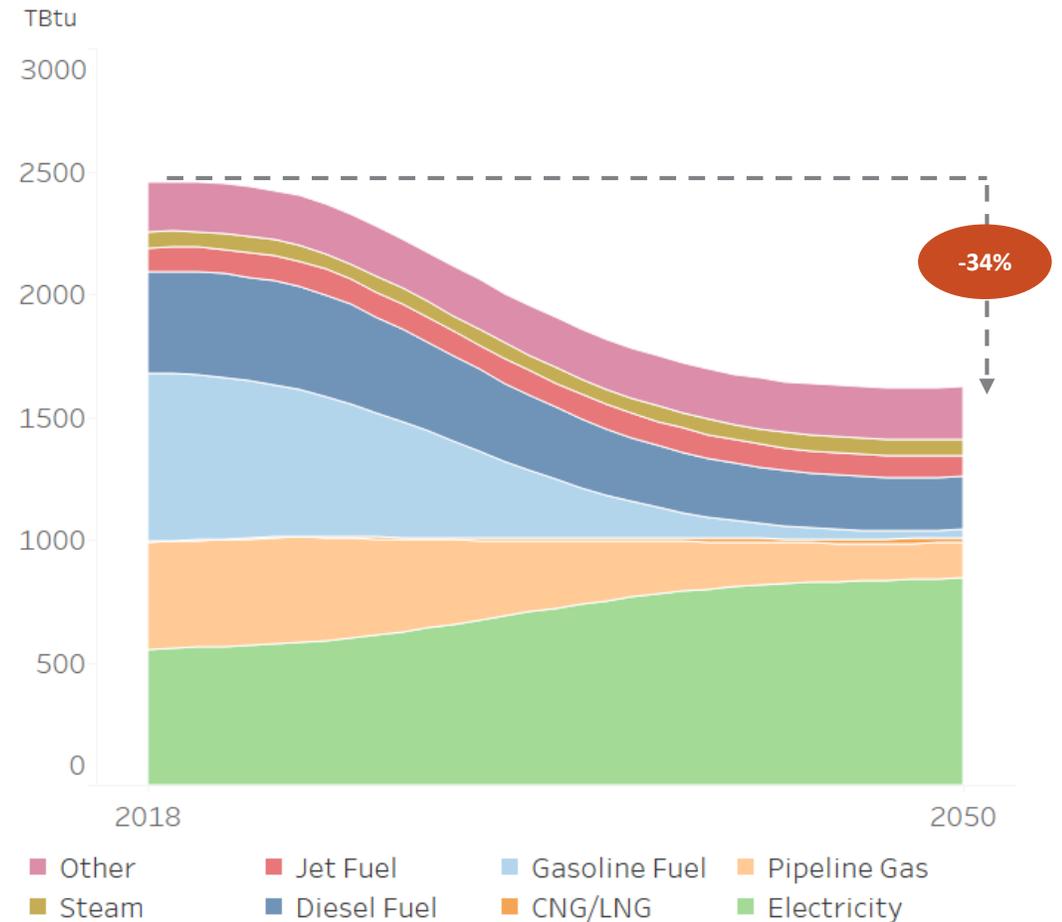


Final Energy Demand

Central Case

- Final energy demand defined:
 - Energy used in the delivery of services such as heating or transportation
 - Excludes energy consumed in converting to other forms of energy (e.g., pipeline gas consumed by power plants)
- Overall end-use demand in 2050 is more than one-third below today
- Electricity consumption increases by more than 50% and comprises one-half of all end-use demand by 2050
- Liquid fuels decrease from one-half of demand today to one-fifth by 2050 as on-road vehicles transition to electricity

Final Energy Demand: Central Case



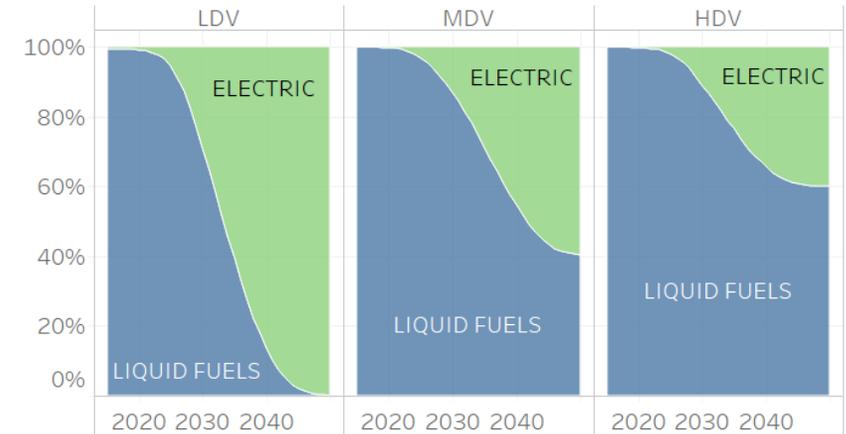
Transportation Electrification

Central Case

- The net increase in electricity consumption is primarily related to electrifying light-duty vehicles (LDV), medium-duty vehicles (MDV) and heavy-duty vehicles (HDV)
- By 2050, all LDVs on the road are electric, whereas about half of freight trucks are
 - The freight trucks that continue to use liquid fuels primarily consume renewable diesel in the 2050 timeframe

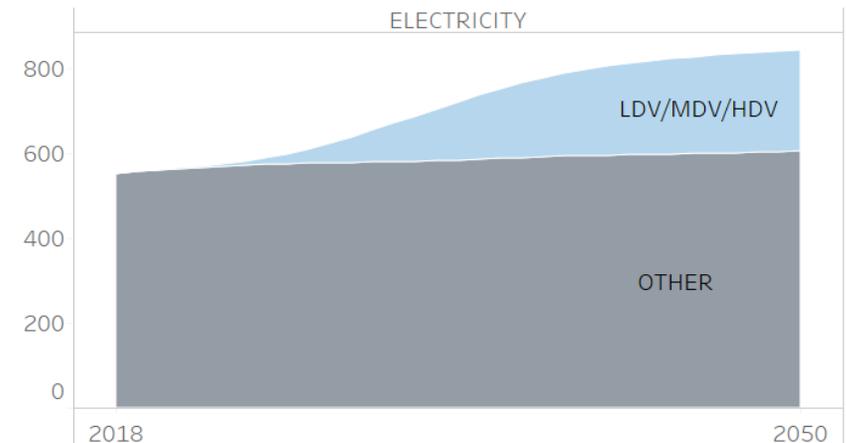
Vehicles on the Road

% of Total



Final Energy Demand

TBtu

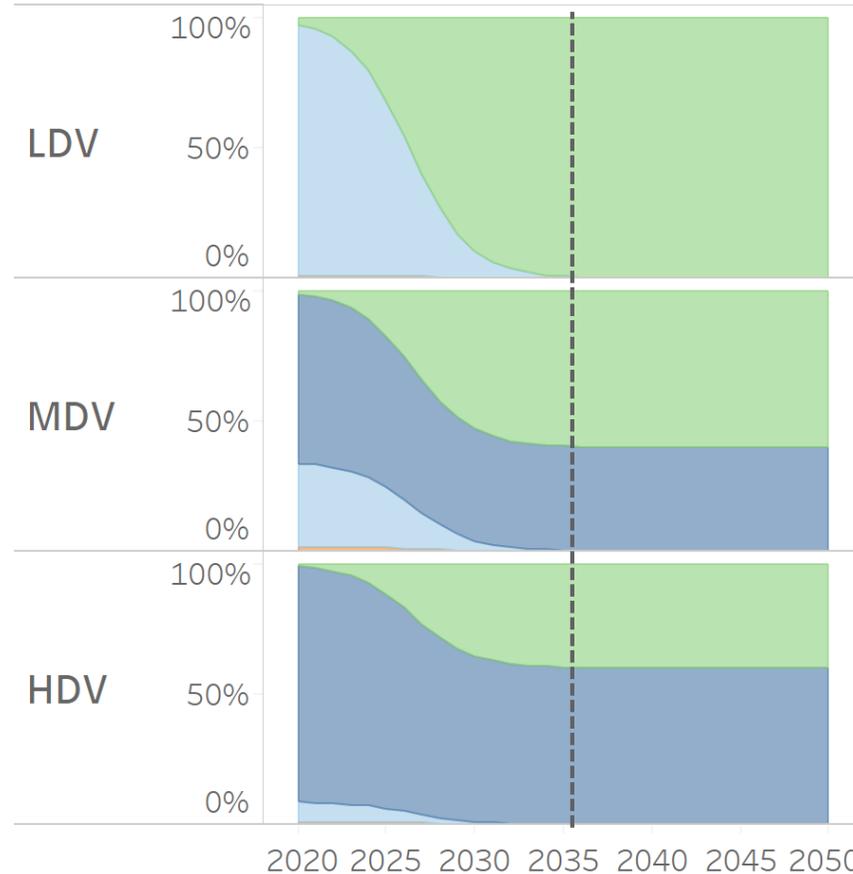


Transportation: Rate of Adoption and Fuel Mix

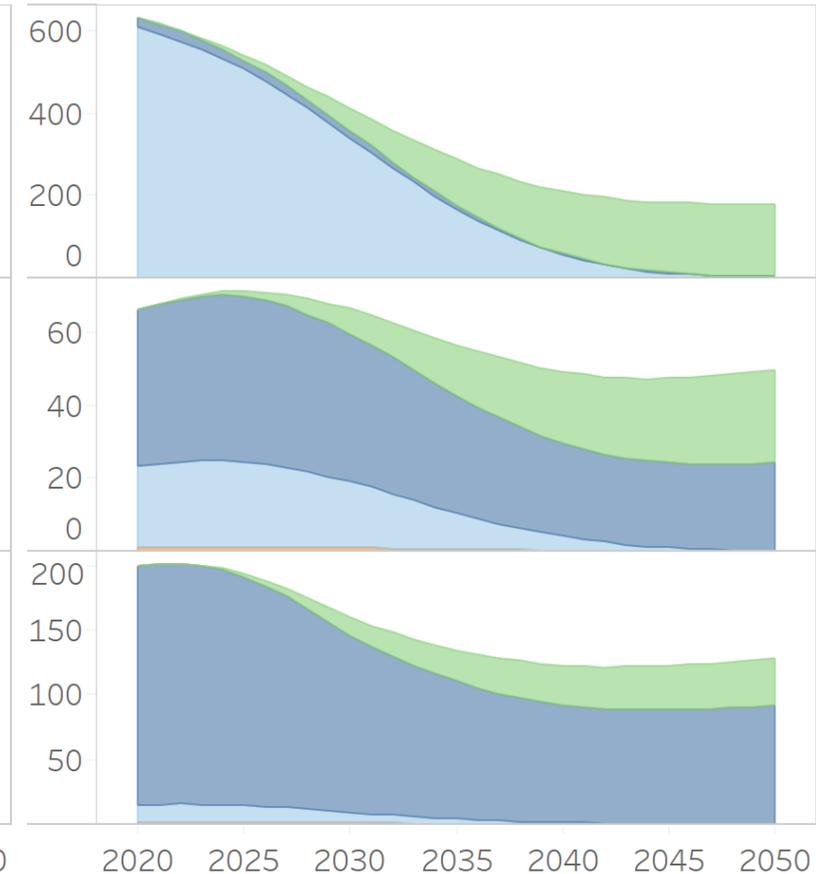
Central Case

- Aggressive adoption over the coming decades is necessary to transform the passenger and freight transportation fleets
 - All new LDV sales are electric by 2035
- Freight truck fleet uses a combination of electricity and diesel by 2050

Vehicle Adoption
% of Annual Sales



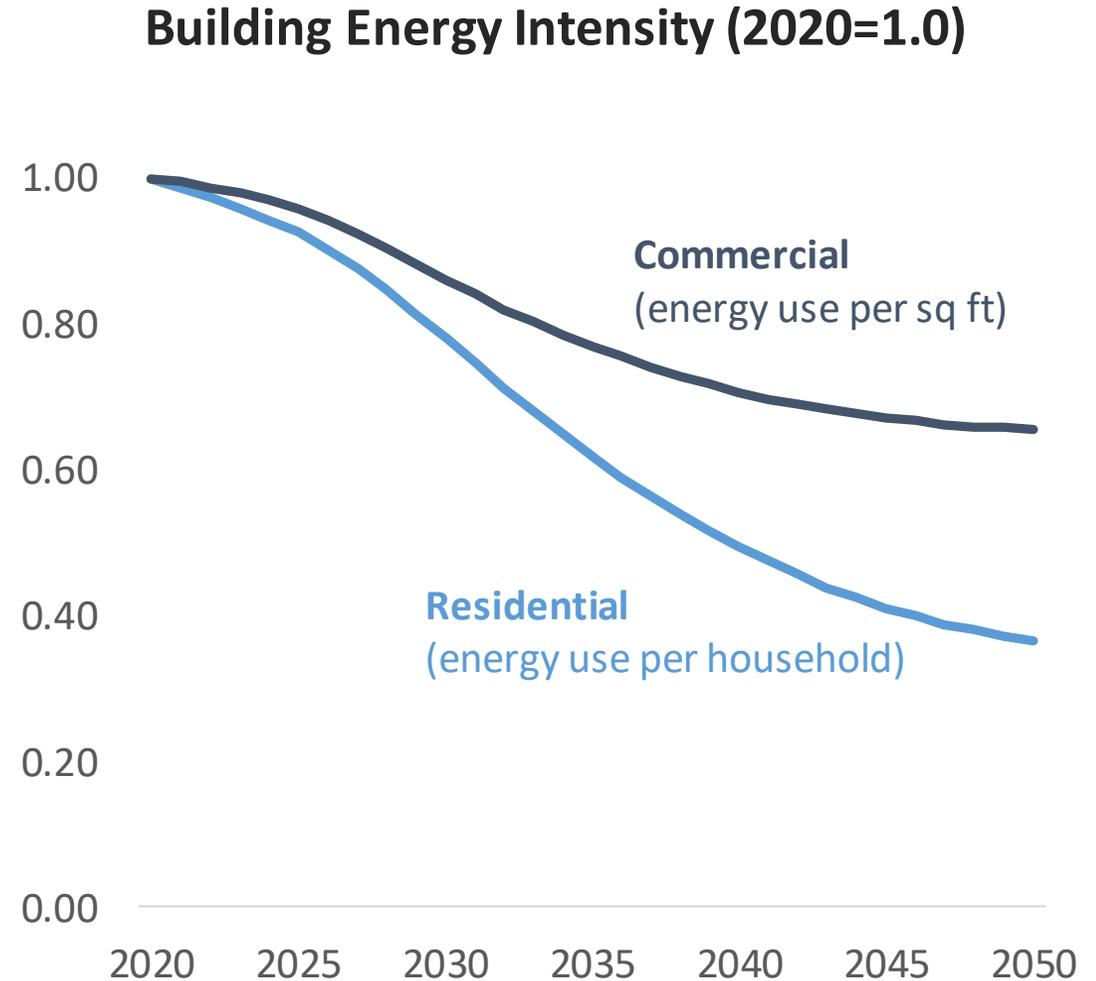
Final Energy Demand
TBtu



Electricity Diesel Gasoline Other

Buildings: Energy Efficiency and Electrification Impacts

- Residential and commercial energy intensity drops significantly over time despite the growth of households and commercial square footage
- Declines are due to:
 - ✓ Aggressive efficiency in electric end-uses, such as lighting, clothes washers and ventilation
 - ✓ Electrification of space and water heating, where the efficiency of heat pump technology relative to the best-in-class combustion equipment translates into deep energy use reductions

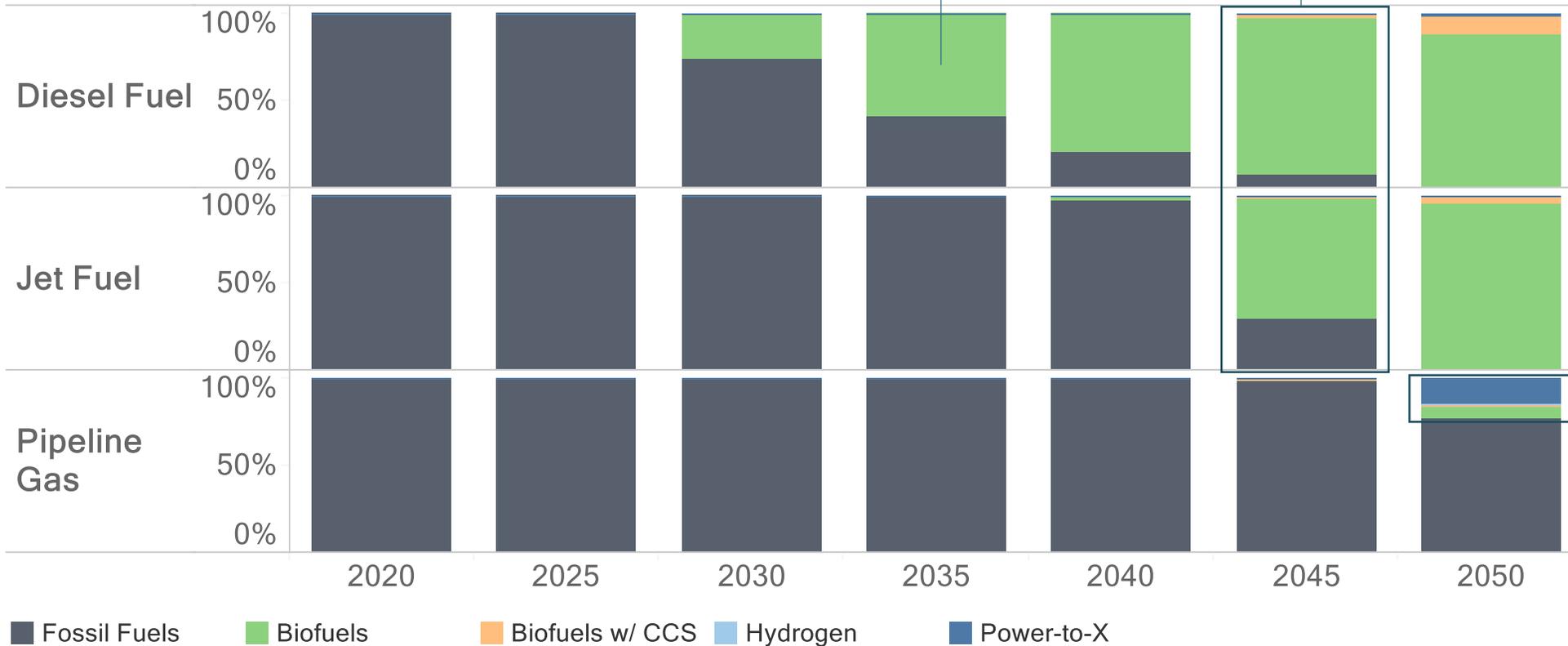


Energy Supply: Liquid and Gaseous Fuel Composition Over Time

Central Case

Liquid and Gaseous Fuel Supply Mix

% of Total



More than half of **diesel fuel** is decarbonized by 2035

Nearly all **diesel and jet fuel** is biofuels by 2045

25 percent of **pipeline gas** is decarbonized

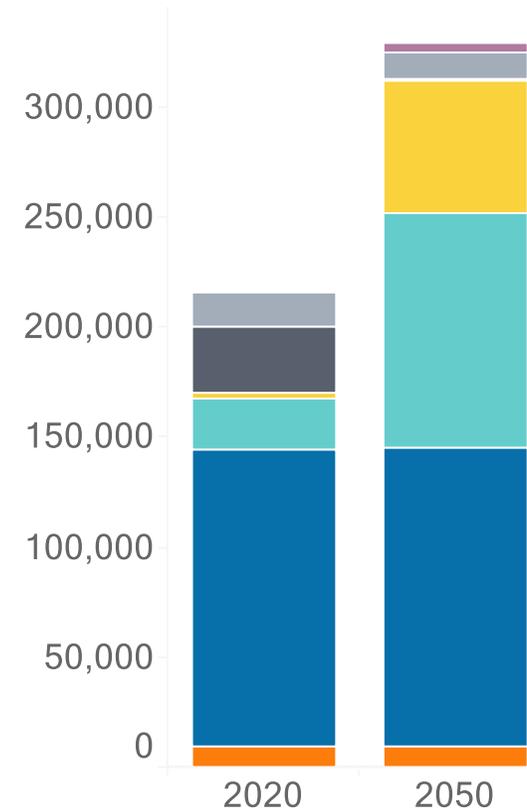
Key takeaways:
 Biomass is largely allocated to liquid fuels
 Synthetic electric fuels make up more than 10% of pipeline gas in 2050

Energy Supply: Electricity Generation

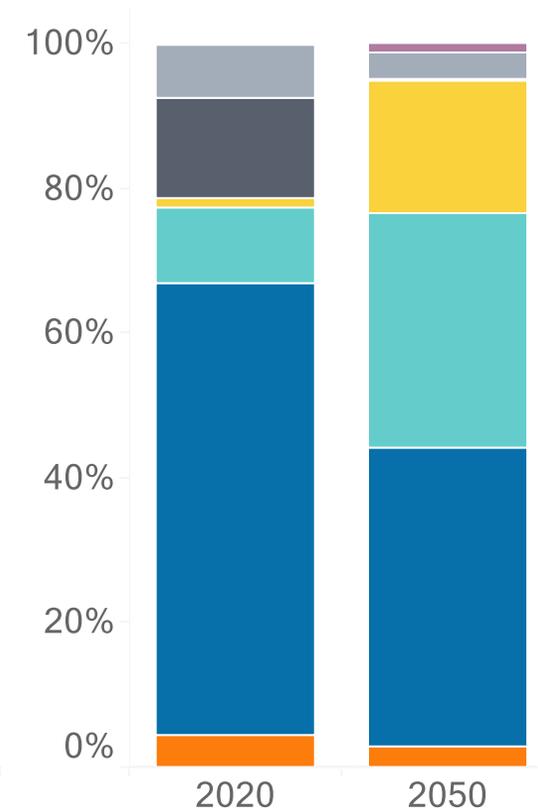
Central Case

- Incremental wind and solar PV are the principal sources of supply to both decarbonize electricity generation and meet growing electricity consumption
 - Wind generation is nearly the same size as hydro generation by 2050
- Gas-fired generation share is 4% in 2050, while coal-fired generation is eliminated
- CGS is extended after 2043 and operates through the study horizon (2050)

Electricity Generation
GWh



Generation Mix
% Total Generation

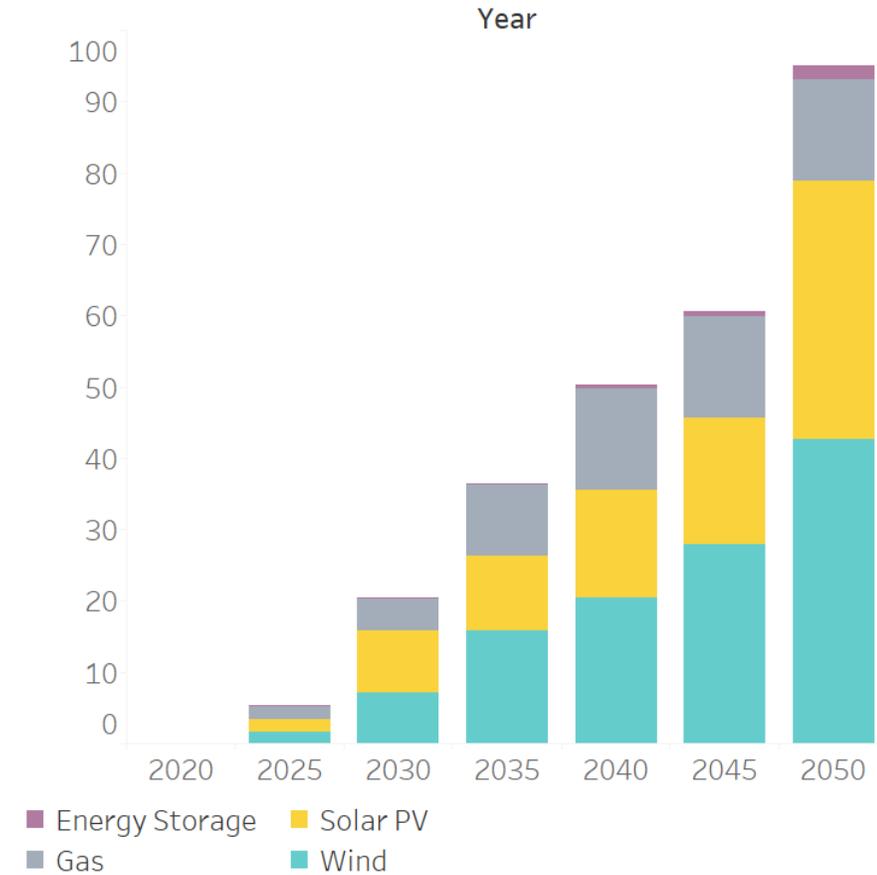


Electricity Sector: New Generation Resource Build

Central Case

- Northwest electricity sector adds nearly 100 GW of new electricity supply resources by 2050
- Renewable resources dominate capacity additions, with more than 40 GW of new onshore wind developed and 35 GW of solar PV
- Gas and storage resources are added primarily to provide resource adequacy and balancing
 - The capacity factor (utilization) of the gas-fired fleet is below 10% in 2050

Cumulative New Resource Build
GW



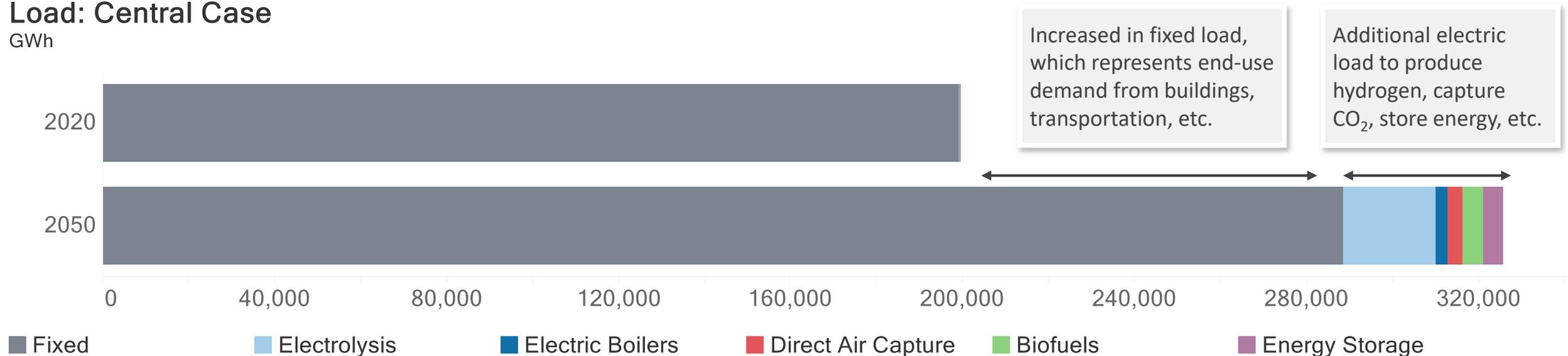
Electricity Sector: Load

Central Case

- Load increases by more than 60 percent between 2020 and 2050
- A large portion of the net increase is from higher “fixed” loads, such as transportation electrification
- However, a significant portion is from other demand sources, including the production of hydrogen, capturing CO₂ and using electric boilers to produce steam

Load: Central Case

GWh

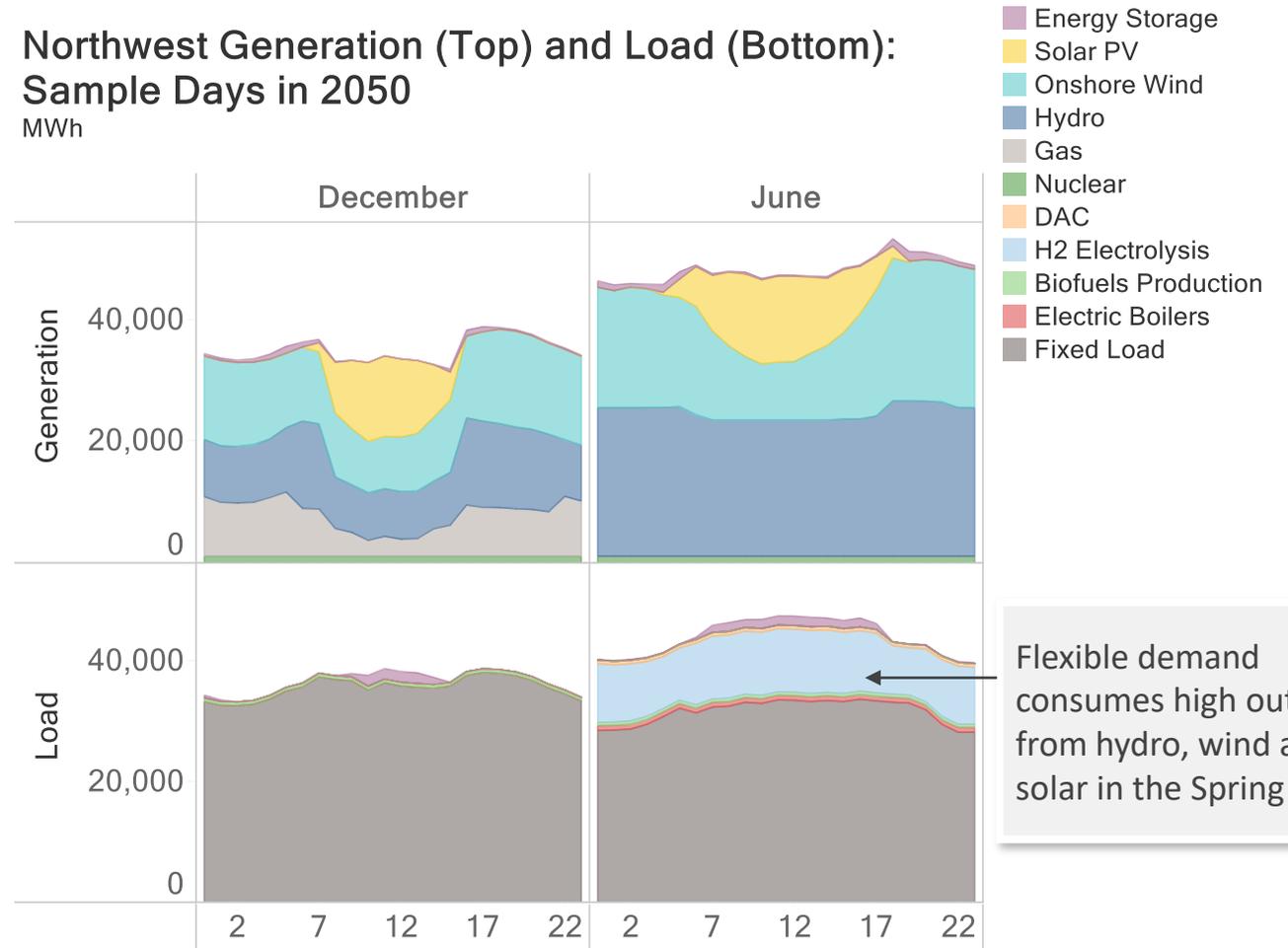


Electricity Sector: Hourly Operations

Central Case

- Electricity balancing is one of the principal technical and economic challenges of a decarbonized energy system
- The energy systems in this study have a large percentage of non-dispatchable generation resources (e.g., wind and solar)
- In many studies of low-carbon electricity systems, balancing is limited to thermal and energy storage resources
- However, this is an incomplete toolkit, specifically when dealing with imbalances that can persist over days and weeks
- This study expands the portfolio of options available to address balancing challenges, employing solutions such as flexible electric fuel production (e.g., electrolysis) in addition to energy storage, thermal generation and transmission

Northwest Generation (Top) and Load (Bottom):
Sample Days in 2050
MWh

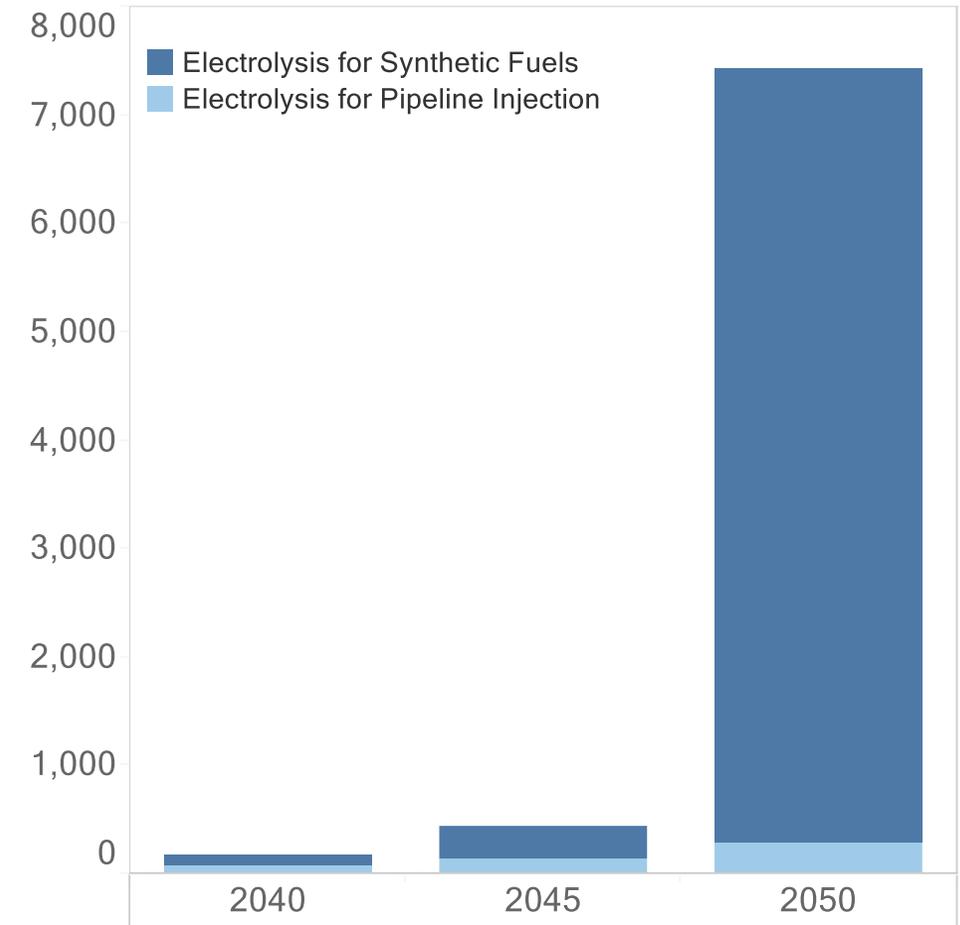


Hydrogen Electrolysis

Central Case

- Flexible load from hydrogen electrolysis plays a key role in balancing the electricity system while producing hydrogen that can be used:
 - As a feedstock for synthetic electric fuels; or
 - Directly injected into pipeline (7% by energy)
- 7,500 MW of electrolysis capacity is added in the Northwest by 2050, most of which is used to produce synthetic gas
 - Hydrogen production in this case uses existing delivery mechanisms, which avoids new infrastructure challenges

Electrolysis Capacity
MW

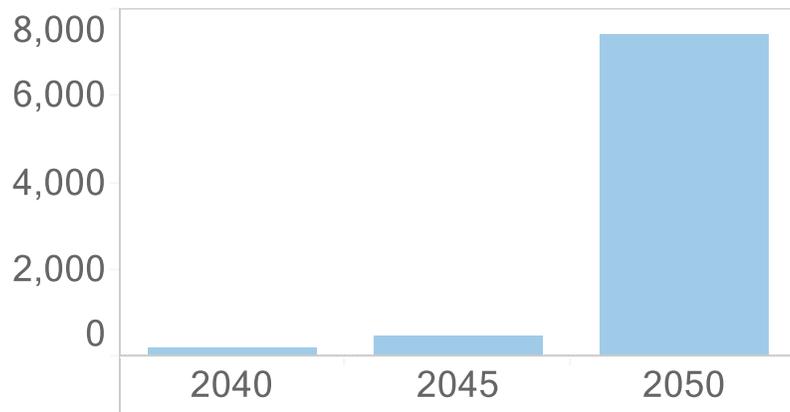


New Sources of Electric Load

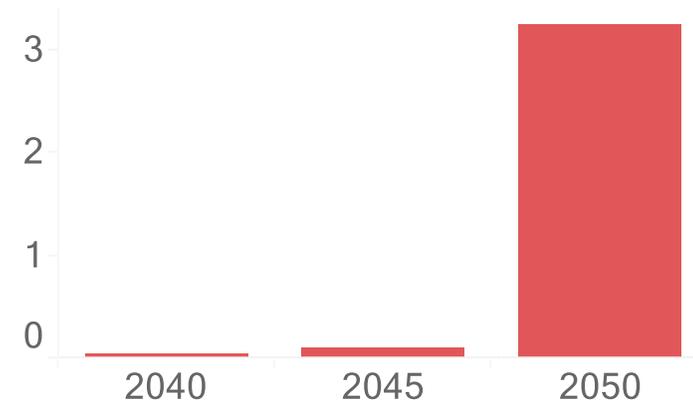
Central Case

- In the long-run (2040s), new sources of electric load play essential roles for both the electricity system and energy system as a whole
- First, new loads are flexible, which manages electricity imbalances across the year; and
- Second, they produce co-products that are useful for energy system-wide decarbonization
 - H₂ from electrolysis and CO₂ from DAC produces synthetic natural gas
 - Electric boilers produce steam for commercial and industrial activity

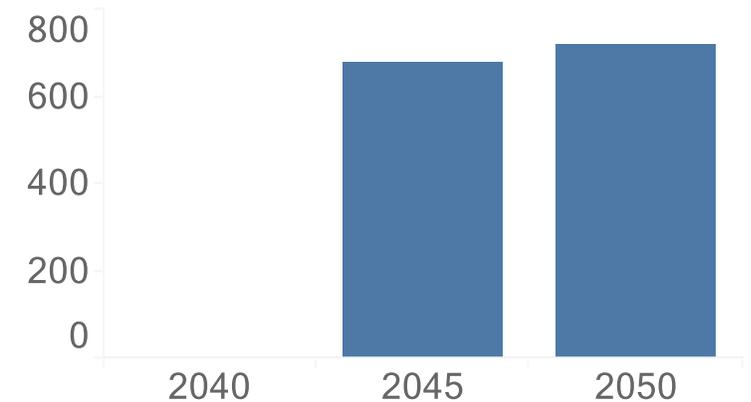
Electrolysis Capacity
MW



DAC Total Capture Capacity
MMT per year



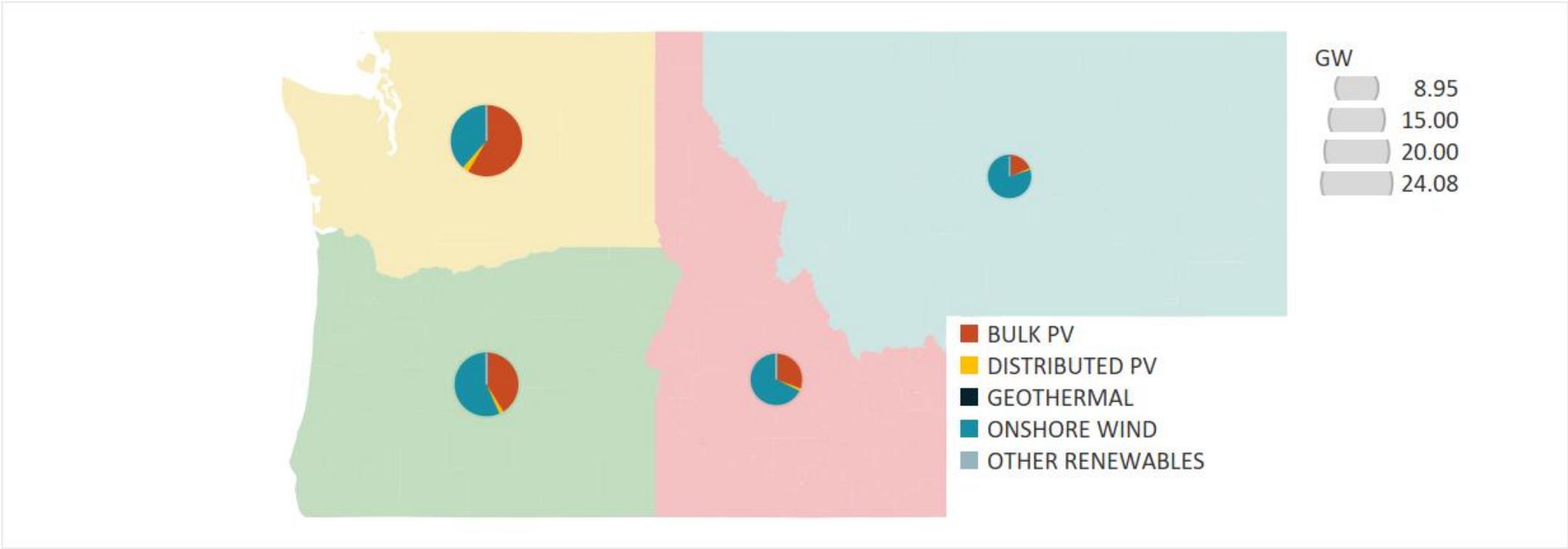
Electric Boiler Capacity
MW



Renewable Generation Mix in 2050

Central Case

RENEWABLE GENERATION

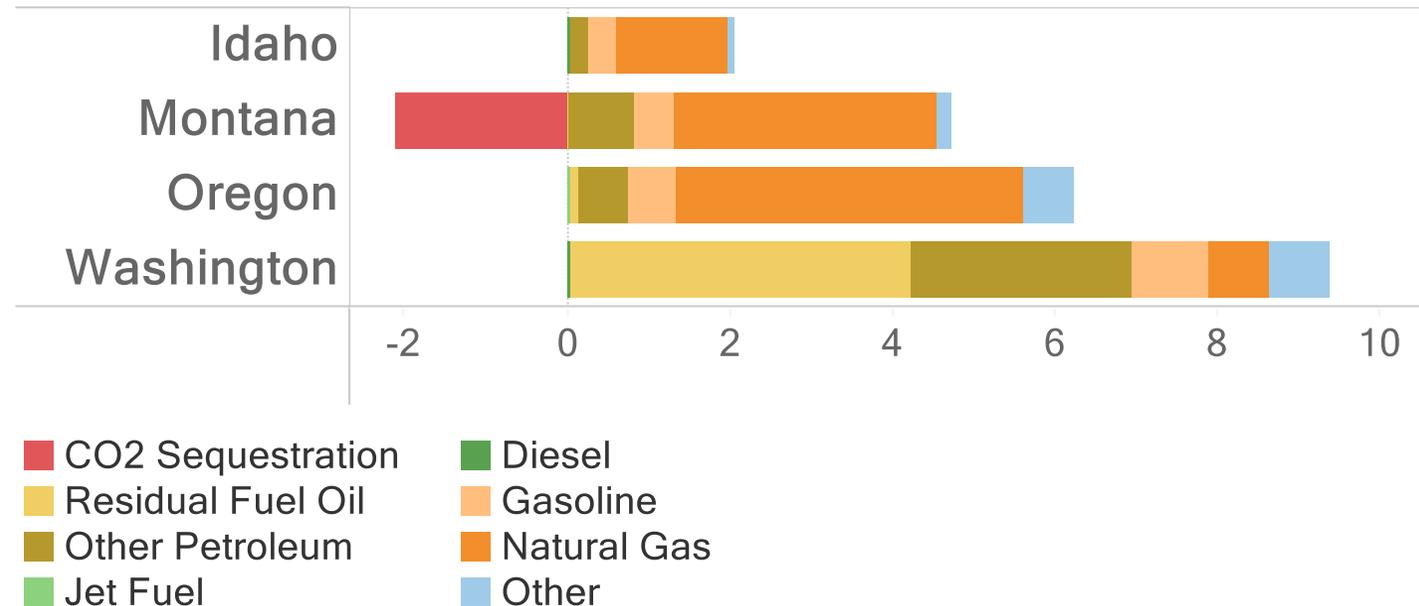


State-Level Energy CO₂ Emissions in 2050

Central Case

- In most states, the majority of remaining emissions are from natural gas combustion
- The exception is Washington State, where residual fuel oil used in shipping is the largest remaining source of emissions
- Montana has geological CO₂ sequestration potential, which allows for the capture of CO₂ and storage in saline aquifers

Energy CO₂ Emissions, 2050
MMT





Additional DDP Cases

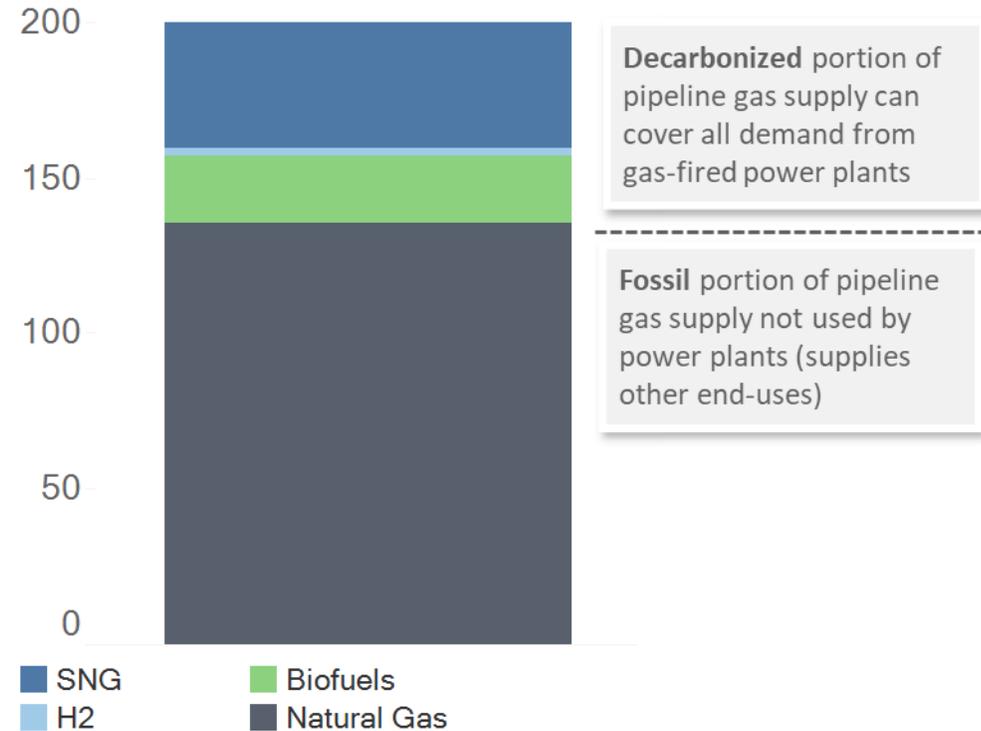
100% Clean Electricity Generation Case

Energy System Impacts

- Requiring 100% of electricity generation in the Northwest to come from zero-carbon sources produces marginally different results from the Central Case
 - Share of gas-fired generation decreases from 3.7% to 1.7% due to incremental renewables and energy storage deployment
 - Decarbonized pipeline gas supply (biofuels, hydrogen and synthetic natural gas) covers all demand from power generation
 - The majority of the incremental decarbonized pipeline gas is from synthetic natural gas

Pipeline Gas Supply (2050)

TBtu



100% Clean Electricity Generation Case

Takeaways

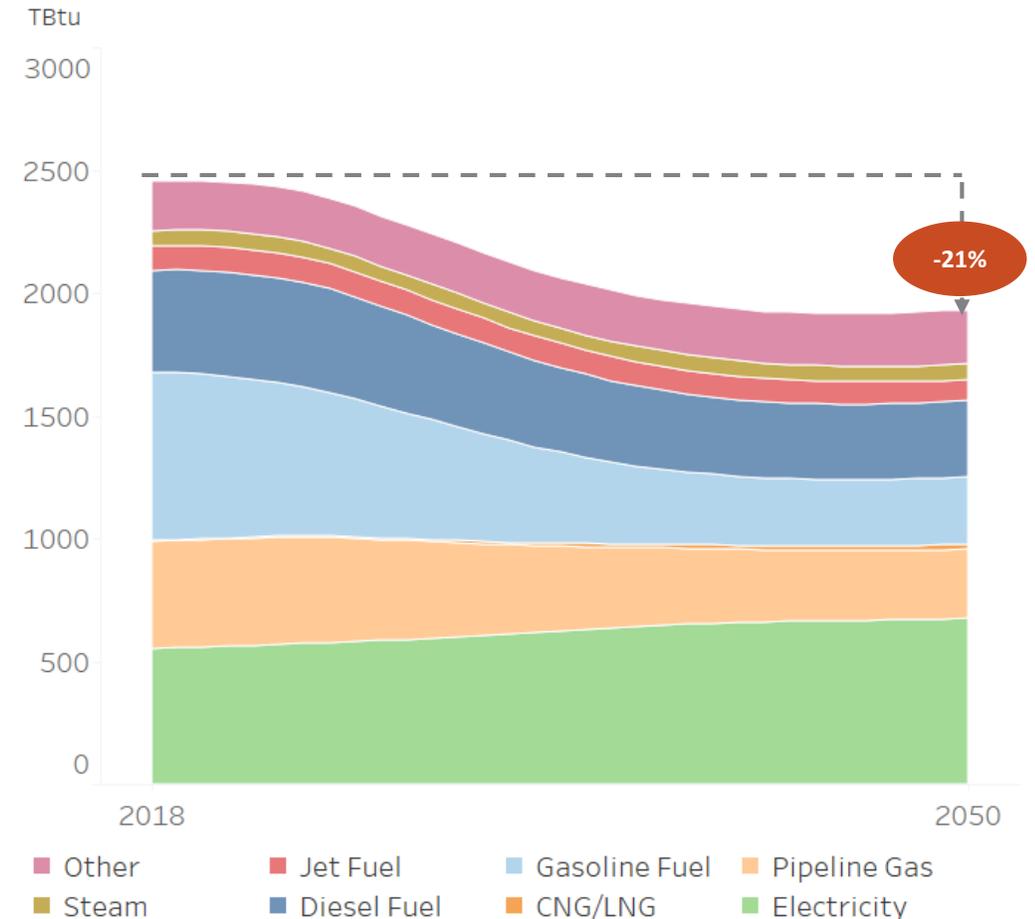
- In order to achieve deep decarbonization of the energy system, the Central Case is nearly 100% clean without a specific mandate (e.g., 96% clean by 2050)
- A relatively small quantity of additional synthetic fuels and biofuels is needed to bridge the gap between 96% and 100% clean electricity in the Northwest
- 100% clean electricity is likely easier to obtain in the context of economy-wide decarbonization, because energy technologies that have co-products across the energy system (e.g., hydrogen) are considered as part of the solution set
- In addition, California's 100% clean electricity requirement allows the Northwest to export to California with fewer requirements for balancing

Limited Demand Transformation (LDT) Case

Final Energy Demand

- Overall end-use demand declines relative to today, but to a lesser extent than the Central Case
 - 21% decrease for the LDT Case versus 34% decrease in the Central Case
- Lack of progress in realizing fuel switching translates into large volumes of liquid fuels remaining in the energy system during the next three decades
- Weak demand-side progress places higher importance on the supply-side to achieve emissions reduction outcomes

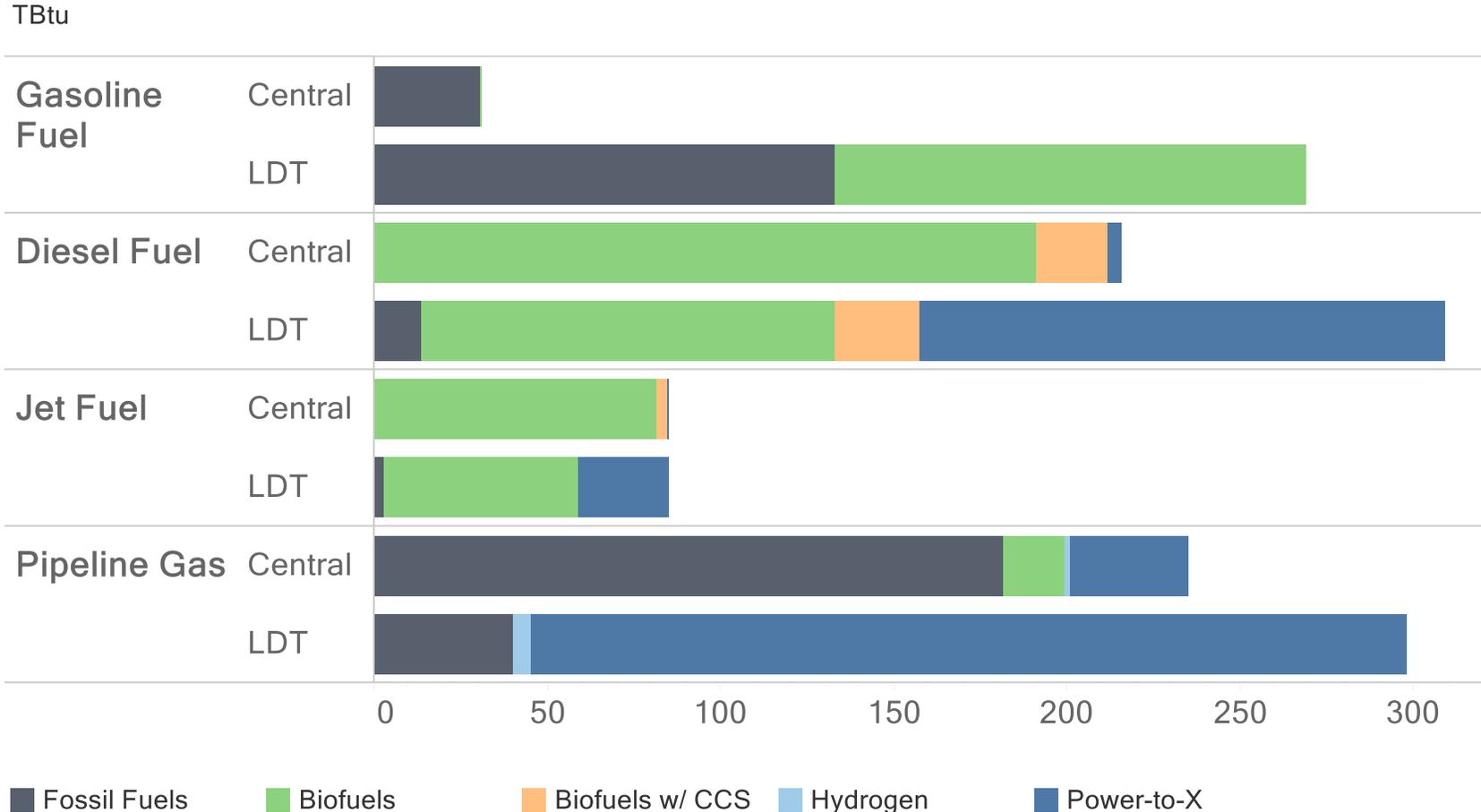
Final Energy Demand



Limited Demand Transformation (LDT) Case

Changes to Fuel Supply and Biomass Allocation

Liquid and Gaseous Fuel Supply Mix (2050)



Biomass is allocated to **gasoline fuel** as cellulosic ethanol, but fossil fuels still account for a large quantity of supply

As a result of the biomass re-allocation, power-to-fuels is needed for liquid and gaseous fuels to decarbonize supply

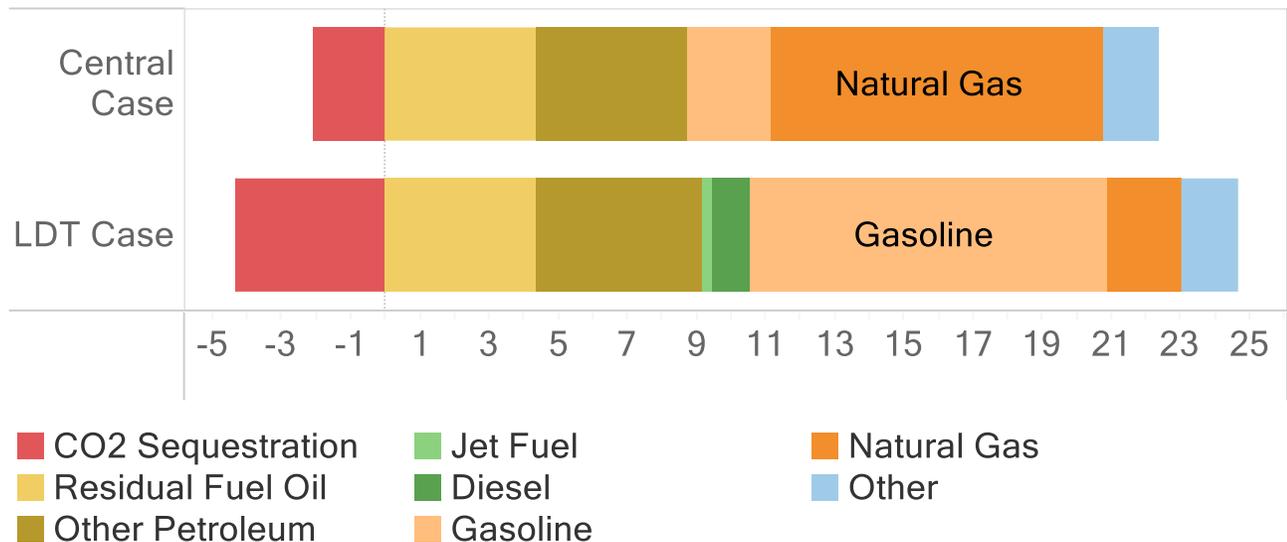
Pipeline gas contains less natural gas to offset higher refined fossil gasoline emissions

Limited Demand Transformation (LDT) Case

Energy CO₂ Emissions

- Lower levels of end-use electrification, particularly in transportation, leave large volumes of residual liquid fuel demand (diesel fuel, jet fuel and gasoline) which:
 - Limits availability of biofuels for pipeline gas; or
 - Uses up remaining emissions budget
- Both factors squeeze the use of gas-fired resources out of electricity generation

Energy CO₂ Emissions, 2050
MMT

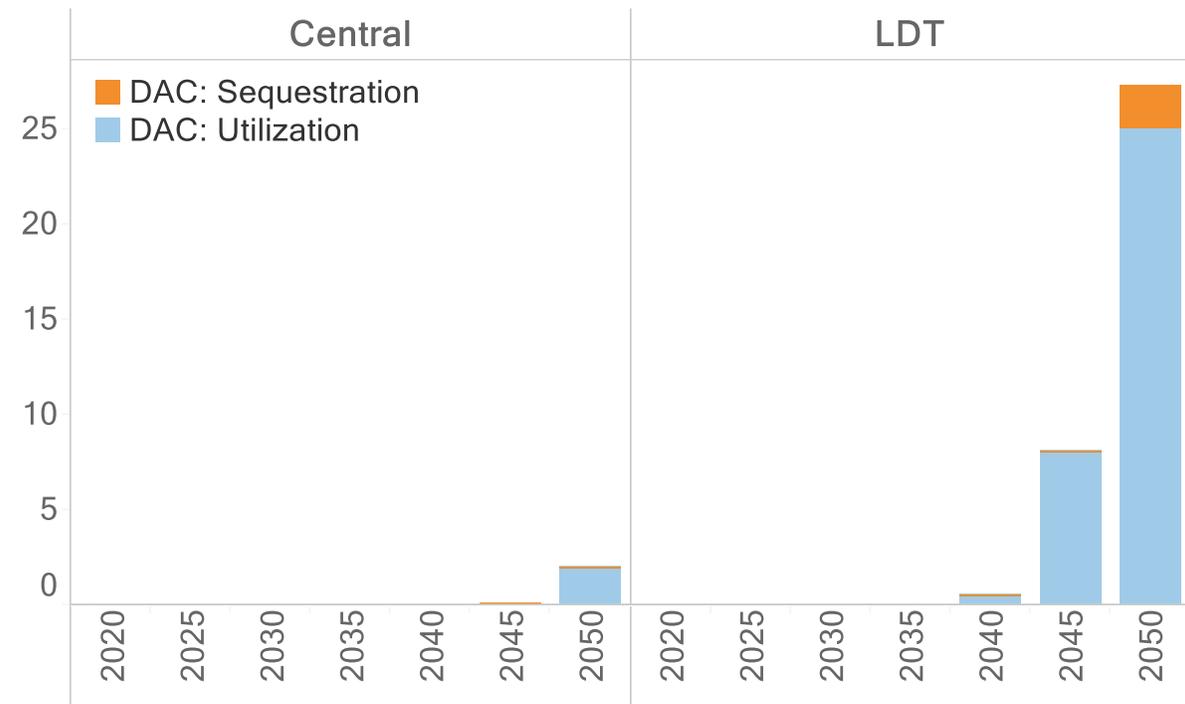


Limited Demand Transformation (LDT) Case

Direct Air Capture Deployment

- Direct air capture (DAC) deployment substantially increases in the Northwest when end-use electrification fails to materialize
 - Central Case: ~2 million metric tons (MMT) captured in 2050
 - LDT Case: ~ 27 MMT captured in 2050
- Most captured carbon is used to produce synthetic fuels (“DAC: Utilization”), while a relatively small portion is sequestered in Montana (“DAC: Sequestration”)

DAC: Captured Carbon
MMT

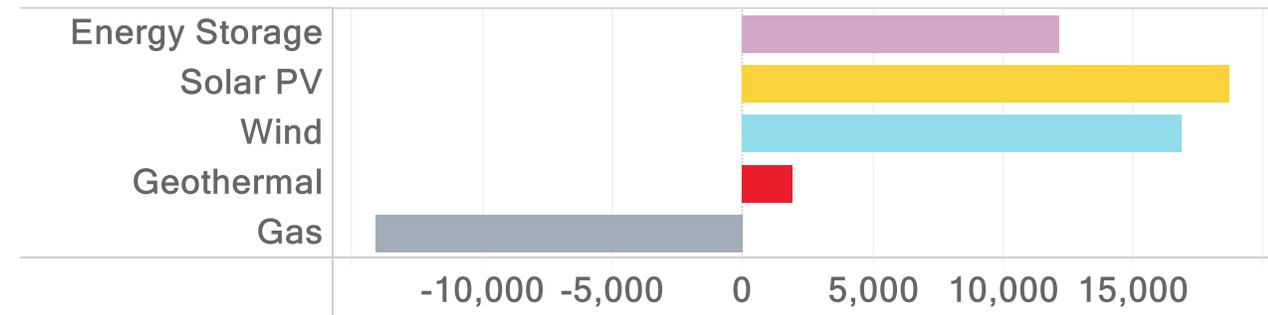


No New Gas Case

Changes in the Electricity Sector

- Prohibiting the development of new gas-fired generating resources in the electricity sector results in:
 - Higher levels of energy storage resources to maintain resource adequacy (+12,000 MW)
 - More than 35,000 MW of additional wind, solar and geothermal resources to provide carbon-free electricity for energy storage to utilize for charging as well as to provide marginal resource adequacy

Change in Installed Capacity Relative to Central Case (2050)
MW



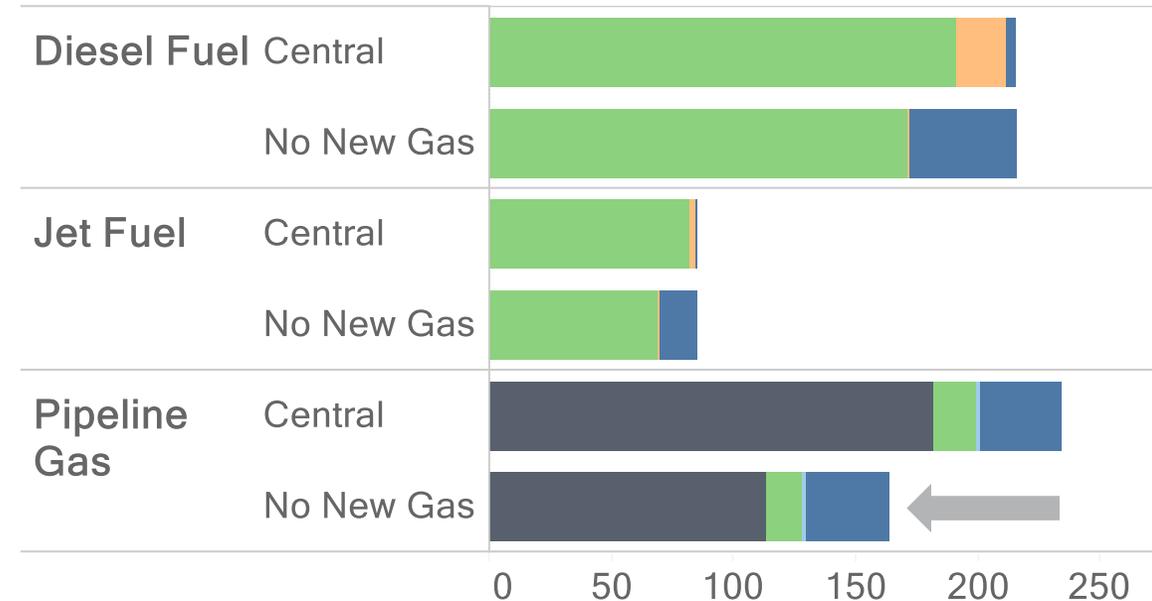
No New Gas Case

Changes Across the Energy System

- The constraint on gas-fired resources in the electricity sector also has spillover effects on the rest of the energy system
- Higher penetrations of renewables incentivizes the production of additional electric fuels, notably **power-to-diesel** and **power-to-jet fuel**
- As a result, fewer **biofuels** are utilized and this is the only DDP case that does not fully utilize available biomass
 - Biomass use is 30% below the Central Case

Liquid and Gaseous Fuel Supply Mix (2050)

TBtu

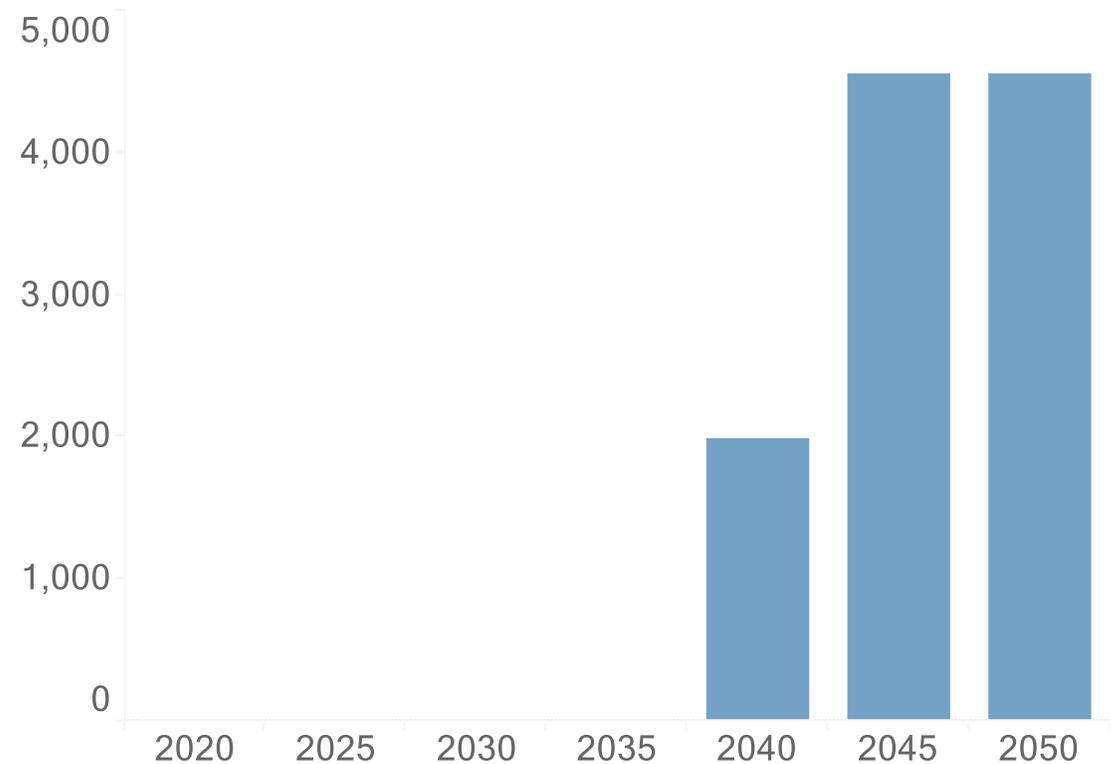


Increased Northwest-California Transmission Case

Transmission

- Approximately 4,500 MW of incremental transmission capacity is developed between the Northwest and California's power systems
- Increased exports from California to the Northwest during daylight hours, while the Northwest increases exports to California during traditionally off-peak hours
 - Next exports from the Northwest increase by approximately 7,000 GWh in 2050

Incremental NW-CA Transmission Capacity
MW



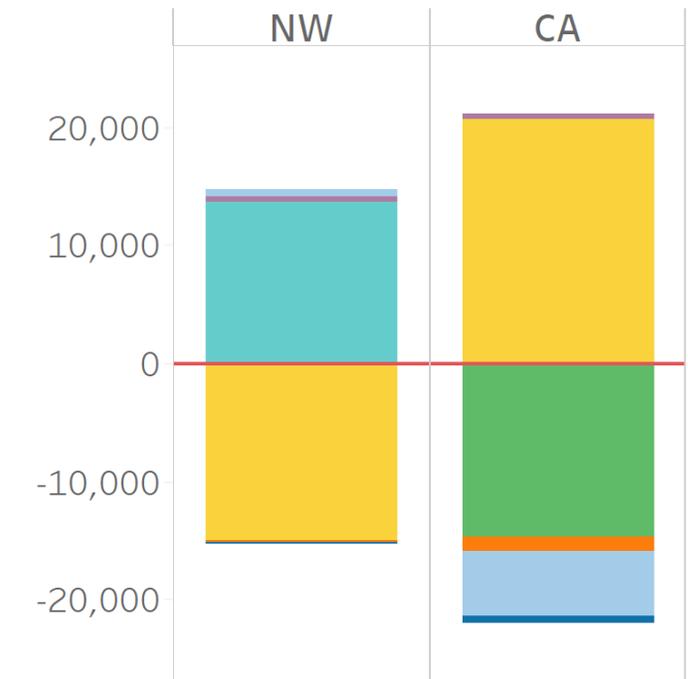
Increased Northwest-California Transmission Case

Electricity Supply Resources

- Expanded interties changes the optimal electricity supply mix, with each region avoiding the development of local, low-quality renewables and expanding the development of high-quality resources that are more efficiently shared across both areas
 - Northwest avoids developing low-quality solar and increases wind development
 - California avoids procurement of remote wind generation from other Western states (NM and WY) and develops additional high-quality solar
- The net present value of savings across the study period is \$11.1B, with higher transmission investment costs offset by resource cost savings
 - Allocation of benefits and costs is beyond the scope of this study

Change in New Resource Build

MW



- Electric Boiler
- H2 Electrolysis
- Power-to-X
- Energy Storage
- Solar PV
- Wind
- Wind (Remote)

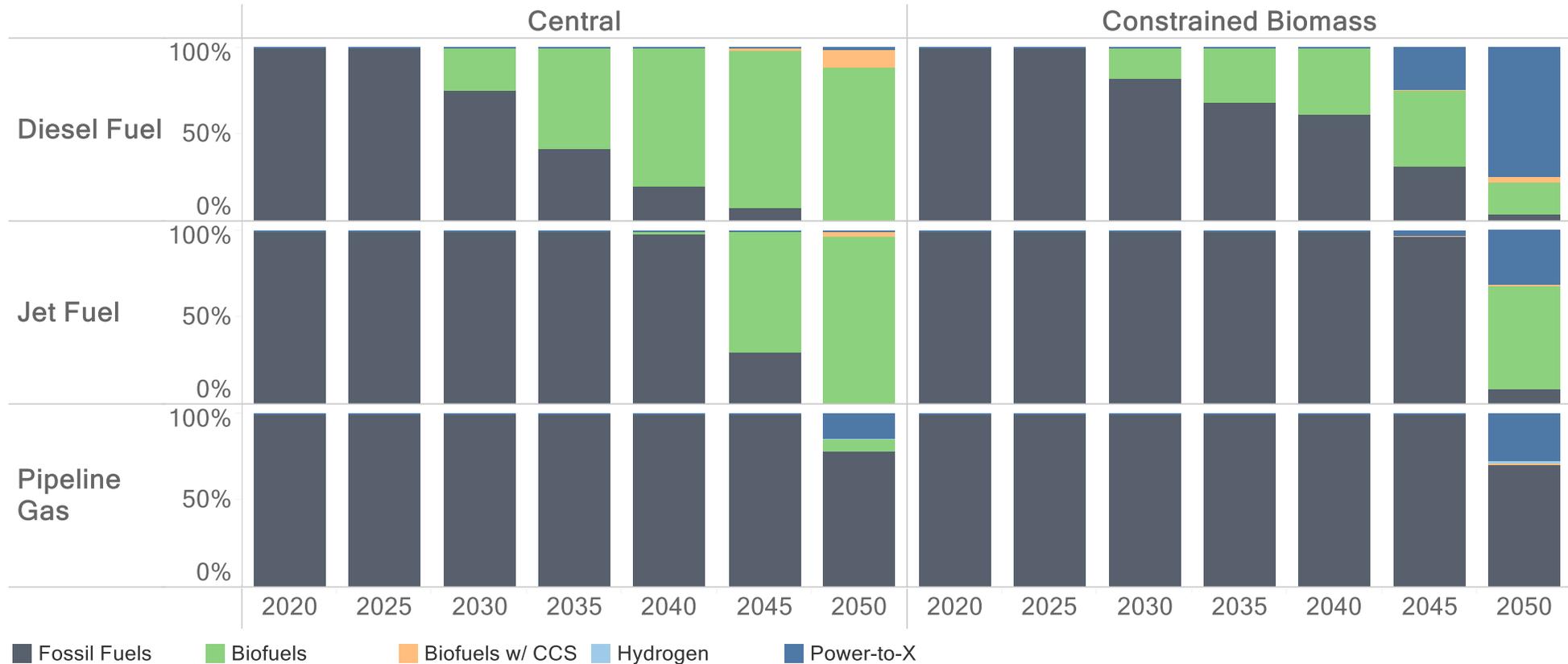
Constrained Biomass Case

Fuel Supply Mix

Constrained Biomass Case relies on **synthetic fuels** to replace decreased **biofuels** availability

Liquid and Gaseous Fuel Supply Mix

% of Total



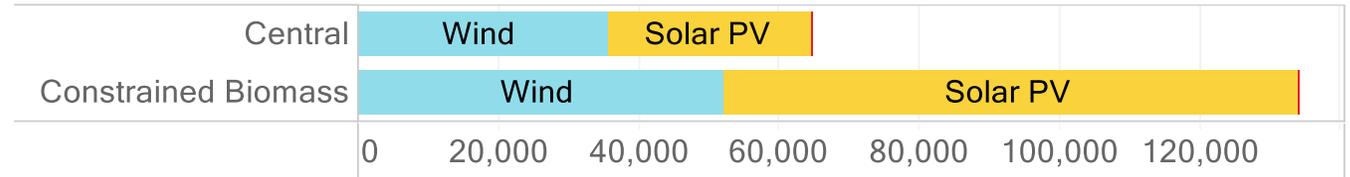
Constrained Biomass Case

Infrastructure Implications

- Producing high volumes of synthetic electric fuels to replace biofuels has considerable infrastructure implications, including:
 - 2x installed capacity of wind and solar resources
 - 5x electrolysis capacity
 - 6x direct air capture capacity

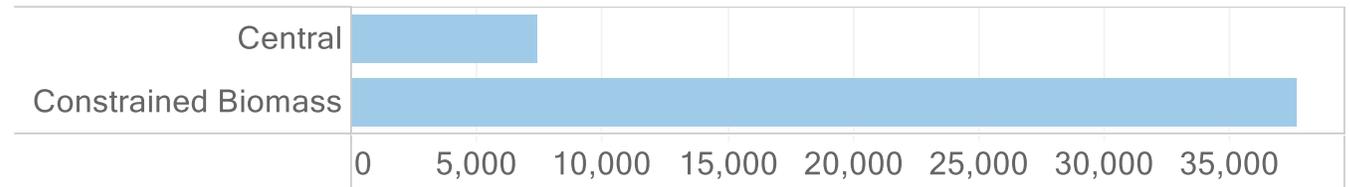
Renewables: Installed Capacity (2050)

MW



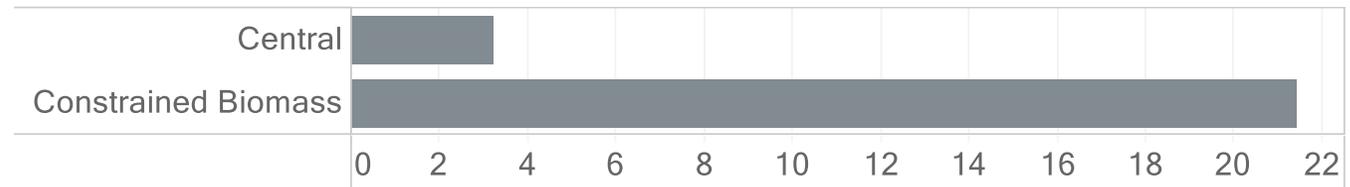
Hydrogen Electrolysis (2050)

MW



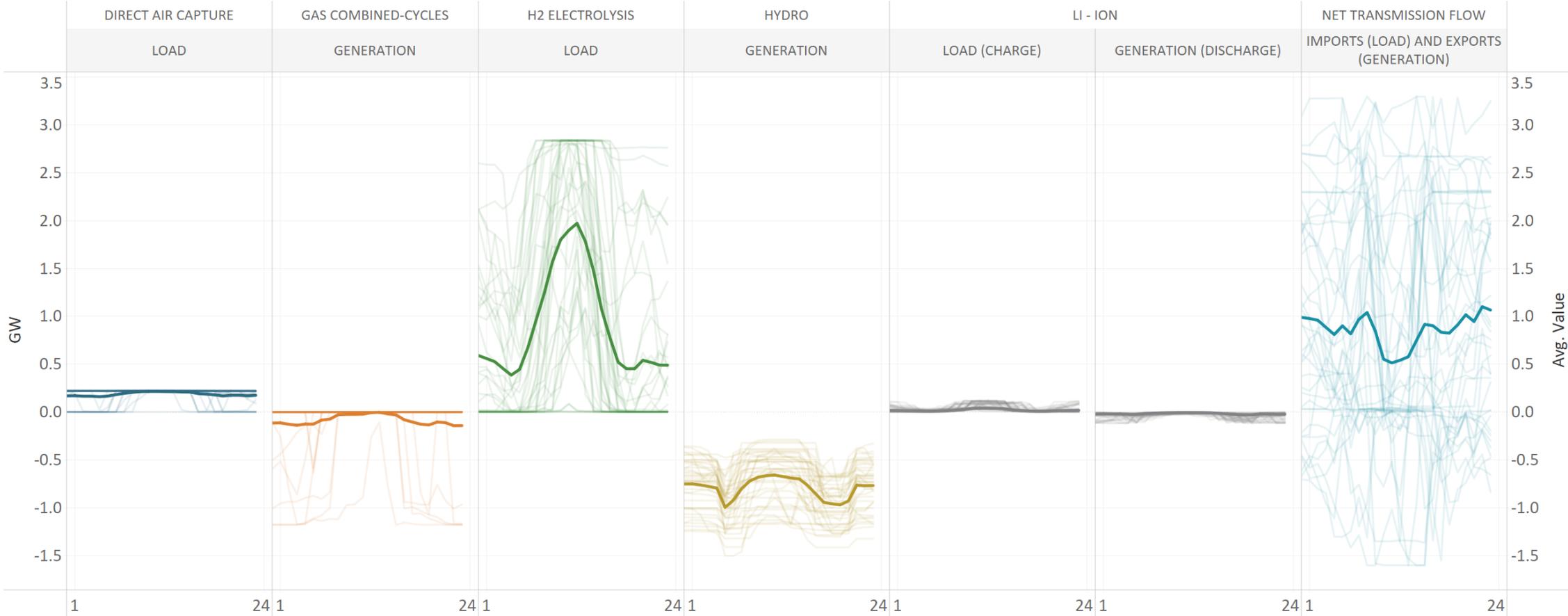
Direct Air Capture: Total Capacity (2050)

MMT per year



Constrained Biomass Case

Example: Electricity Balancing Behavior in Montana in 2050

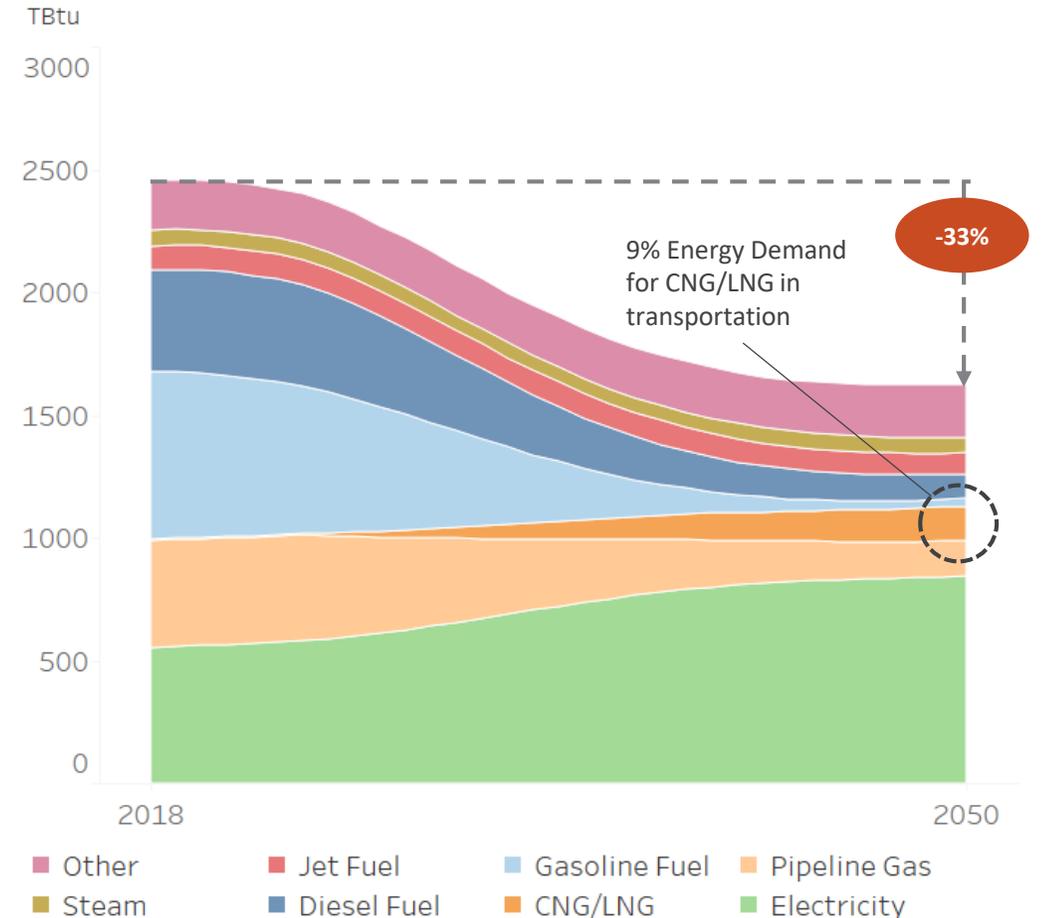


Increased Gas in Transportation (IGT) Case

Final Energy Demand

- Compressed and liquefied pipeline gas demand constitute nearly 10 percent of end-use demand by 2050
- Half of freight trucks consume compressed or liquefied pipeline gas by 2050
- Diesel fuel demand is further reduced relative to the Central Case

Final Energy Demand



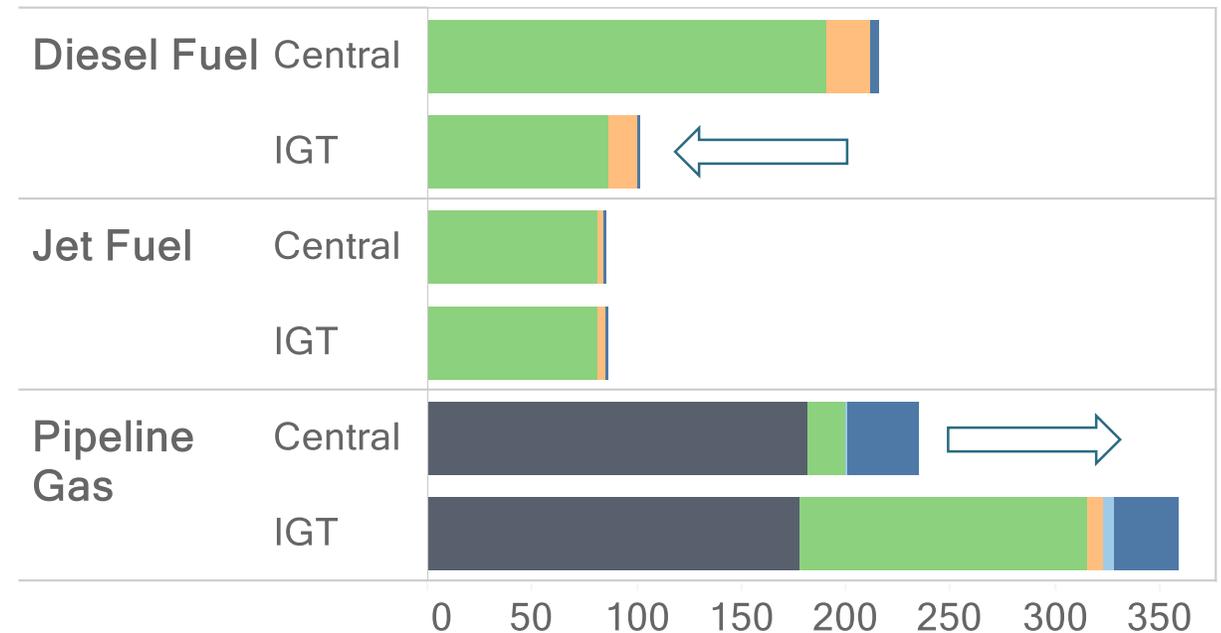
Increased Gas in Transportation (IGT) Case

Fuel Supply

- Higher pipeline gas consumption from freight trucks in the IGT Case is supplied by:
 - Increasing biofuels to pipeline gas
 - Decreasing biofuels to diesel fuel
- Minimal impacts across the energy system other than a re-allocation from liquid biofuels to gaseous biofuels

Liquid and Gaseous Fuel Supply Mix (2050)

TBtu





Summary of the Cases

Scenario comparison to Central Case

- **100% Clean Energy. Limited impact.** Produces marginally different results from the Central Case
 - Share of gas-fired generation decreases from 3.7% to 1.7% due to incremental renewables and energy storage deployment
 - Decarbonized pipeline gas supply (biofuels, hydrogen and synthetic natural gas) covers all demand from power generation
 - The majority of the incremental decarbonized pipeline gas is from synthetic natural gas
- **Limited Demand Side Transformation. Significant impact.** Large volumes of residual liquid fuel demand (diesel fuel, jet fuel and gasoline) which:
 - Limits availability of biofuels for pipeline gas or uses up remaining emissions budget
 - Both factors squeeze the use of gas-fired resources out of electricity generation
 - Direct air capture (DAC) deployment substantially increases in the Northwest when end-use electrification fails to materialize
 - Central Case: ~2 million metric tons (MMT) captured in 2050
 - LDT Case: ~ 27 MMT captured in 2050
- **No New Gas Plants. Significant impact.**
 - Higher levels of energy storage resources to maintain resource adequacy (+12,000 MW)
 - More than 35,000 MW of additional wind, solar and geothermal resources to provide carbon-free electricity for energy storage to utilize for charging as well as provide marginal resource adequacy
 - Higher penetrations of renewables incentivizes the production of additional electric fuels, notably **power-to-diesel** and **power-to-jet fuel**

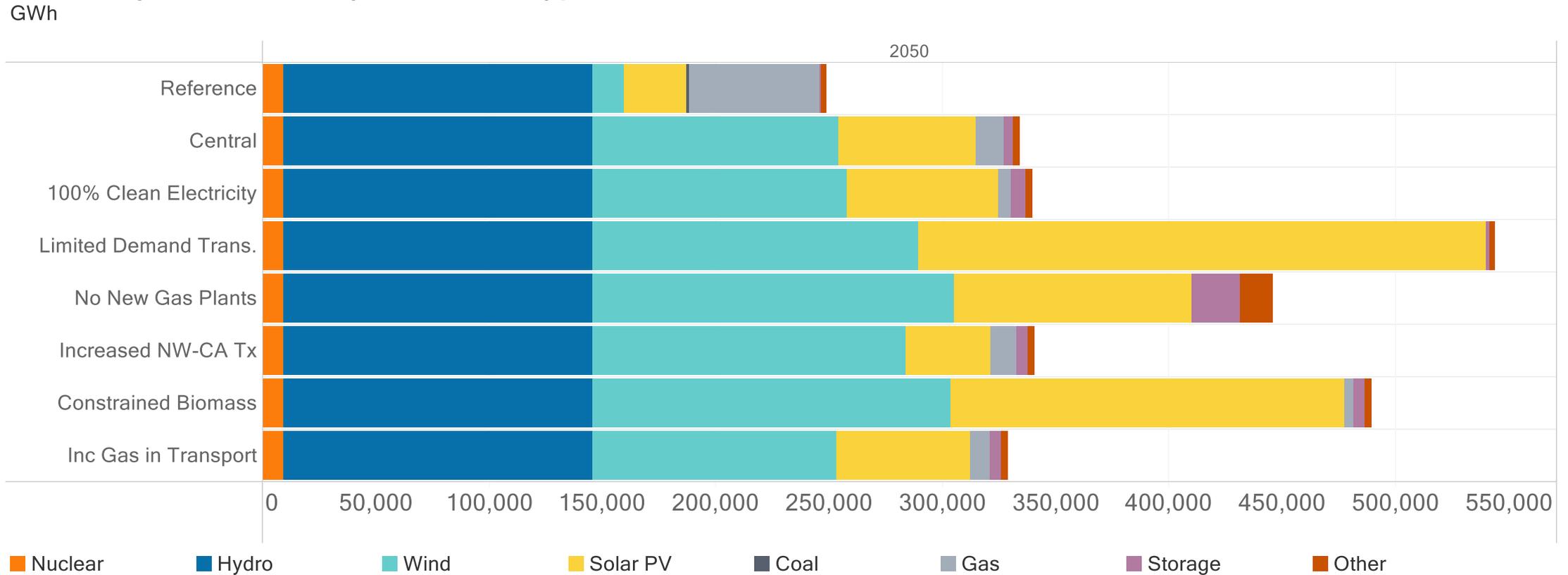
Scenario comparison to Central Case

- **Increased NW-CA Transmission. Significant benefit.** Expanded interties changes the optimal electricity supply mix, with each region avoiding the development of local, low-quality renewables and expanding the development of high-quality resources that are more efficiently shared across both areas
 - Northwest avoids developing low-quality solar and increases wind development
 - California avoids procurement of remote wind generation from other Western states (NM and WY) and develops additional high-quality solar
- **Constrained Biomass. Significant impact.** Producing high volumes of synthetic electric fuels to replace biofuels has considerable infrastructure implications, including:
 - 2x installed capacity of wind and solar resources
 - 5x electrolysis capacity
 - 6x direct air capture capacity
- **Increased Gas in Transportation. Limited impact.** Higher pipeline gas consumption from freight trucks in the IGT Case is supplied by:
 - Increasing biofuels to pipeline gas
 - Decreasing biofuels to diesel fuel
 - Minimal impacts across the energy system other than a re-allocation from liquid biofuels to gaseous biofuels
 - **Caveat:** Only includes direct CO₂ combustion emissions, not any changes to methane leakage

Impacts to Electricity Generation in 2050 by Case

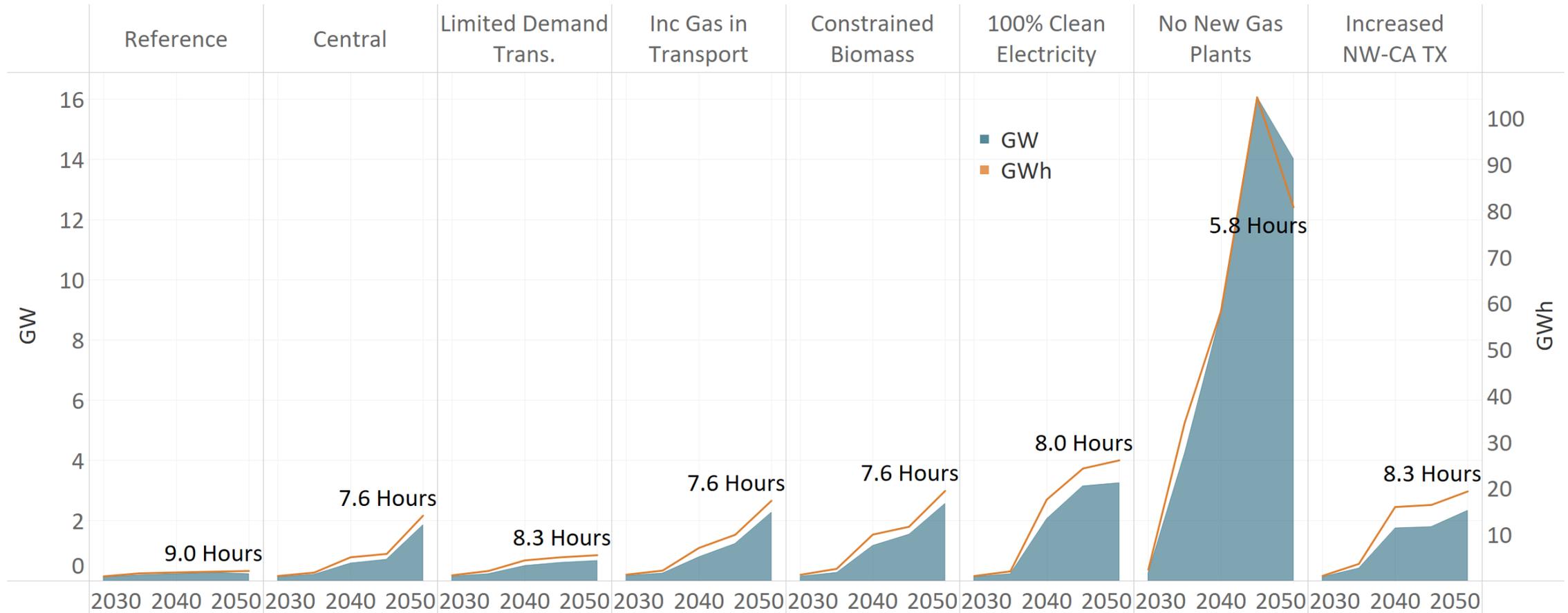
Significant impacts of Limited Demand Side transformation, Constrained Biomass, and No New Gas Plants cases on total electricity generation

Electricity Generation by Resource Type

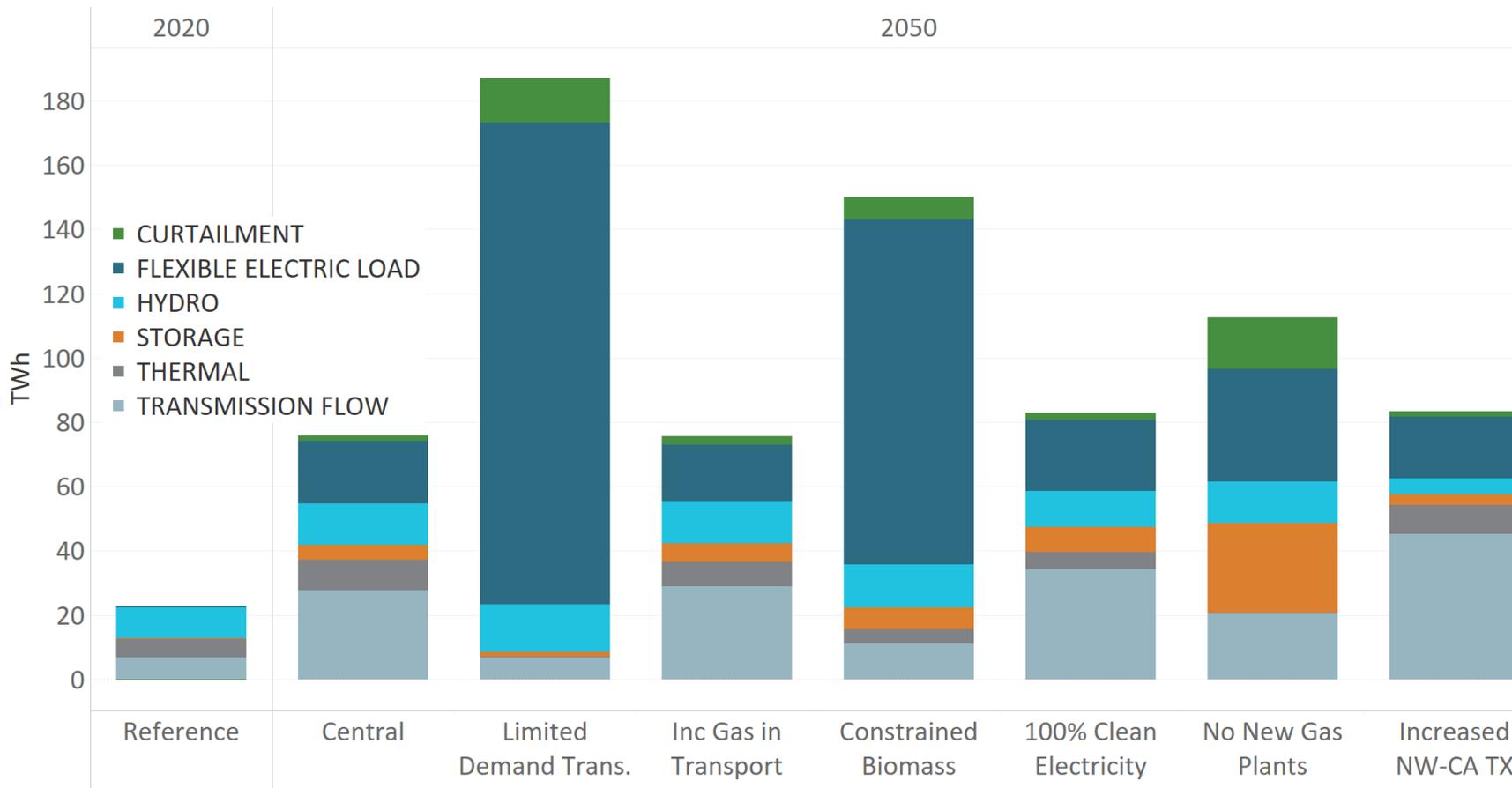


New Energy Storage Build

Capacity, Energy and Average Duration



Contribution to Electricity Balancing



Increase in non-dispatchable generation drastically increases balancing needs on the system

Flexible electric loads from fuel production, boilers, and direct-air capture facilities become primary balancers of supply/demand imbalances

Storage plays the largest role when new gas is not allowed

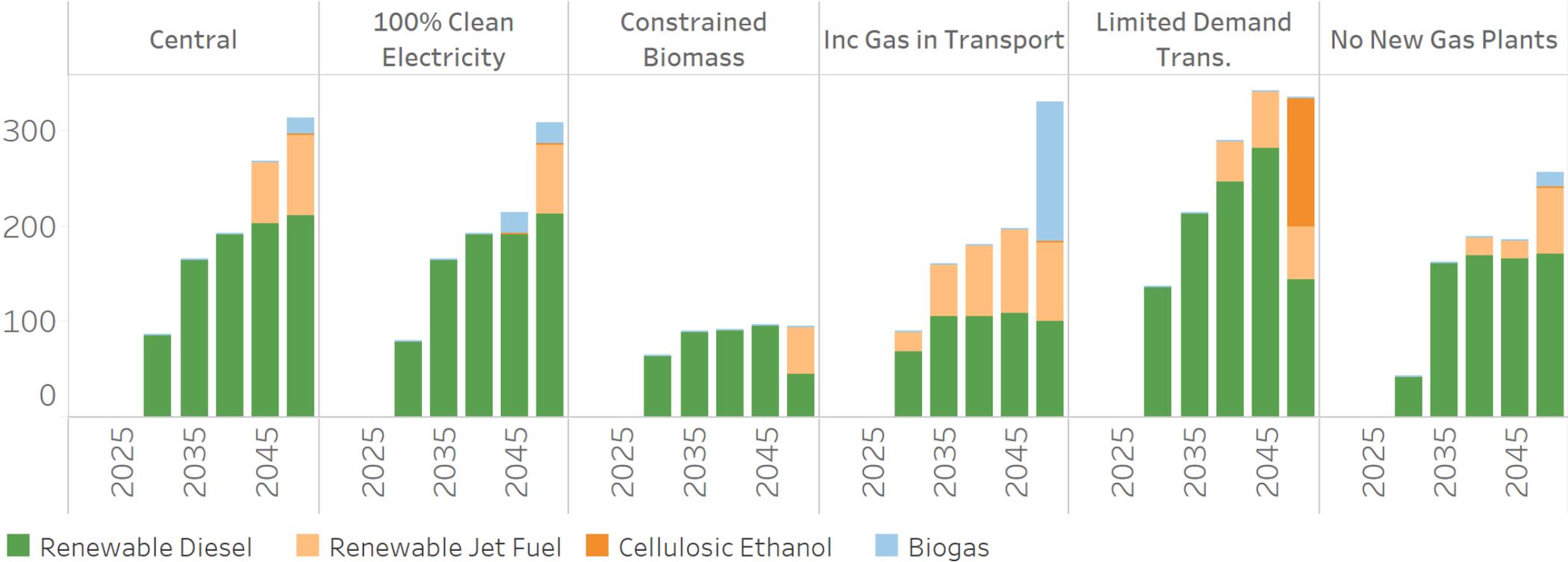
Additional transmission resources in the transmission expansion case expands the role of inerties in balancing

Summary of Biomass Allocation

-Across the DDP cases, biomass is overwhelmingly allocated to liquid transportation fuels rather than biogas
 -The exception is if the freight transportation fleet contains significant penetration of CNG and LNG trucks

Biofuels

TBtu

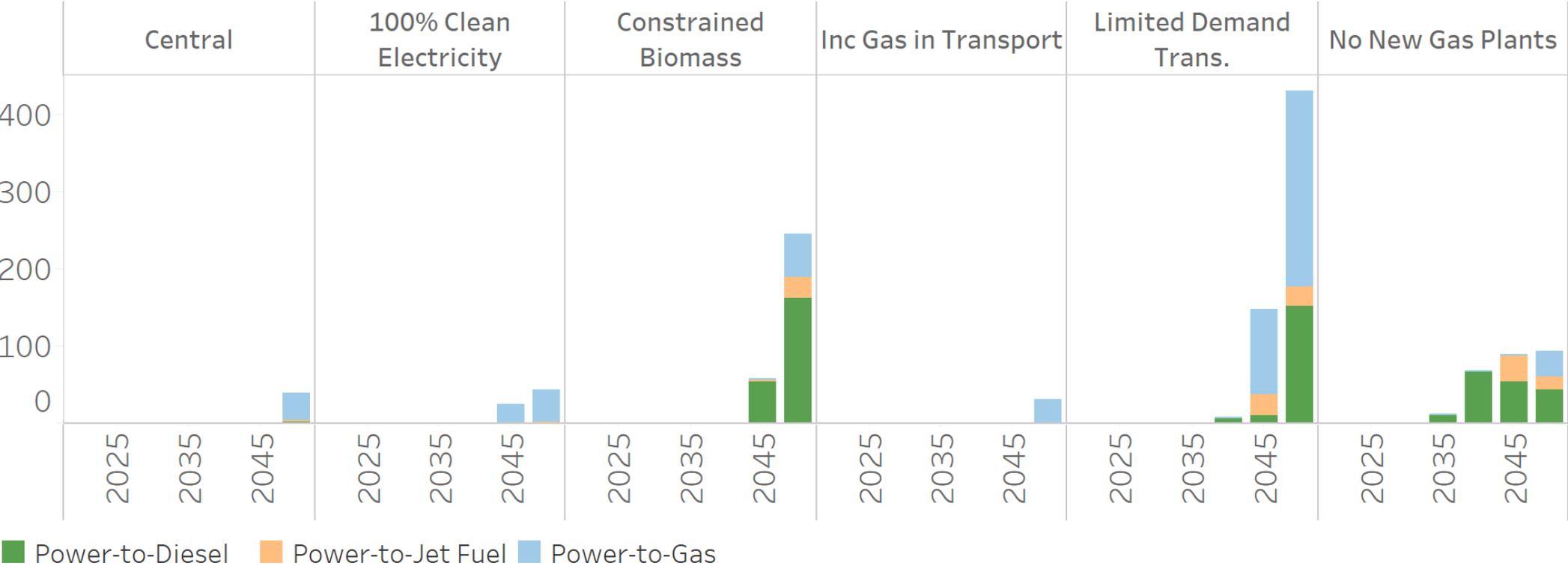


Summary of Synthetic Fuels

- Synthetic fuels become a key decarbonized fuel source in the 2040s
- Potential implementation constraints (e.g., biomass; lack of electrification) affect the magnitude

Synthetic Electric Fuels

TBtu





Energy System Costs

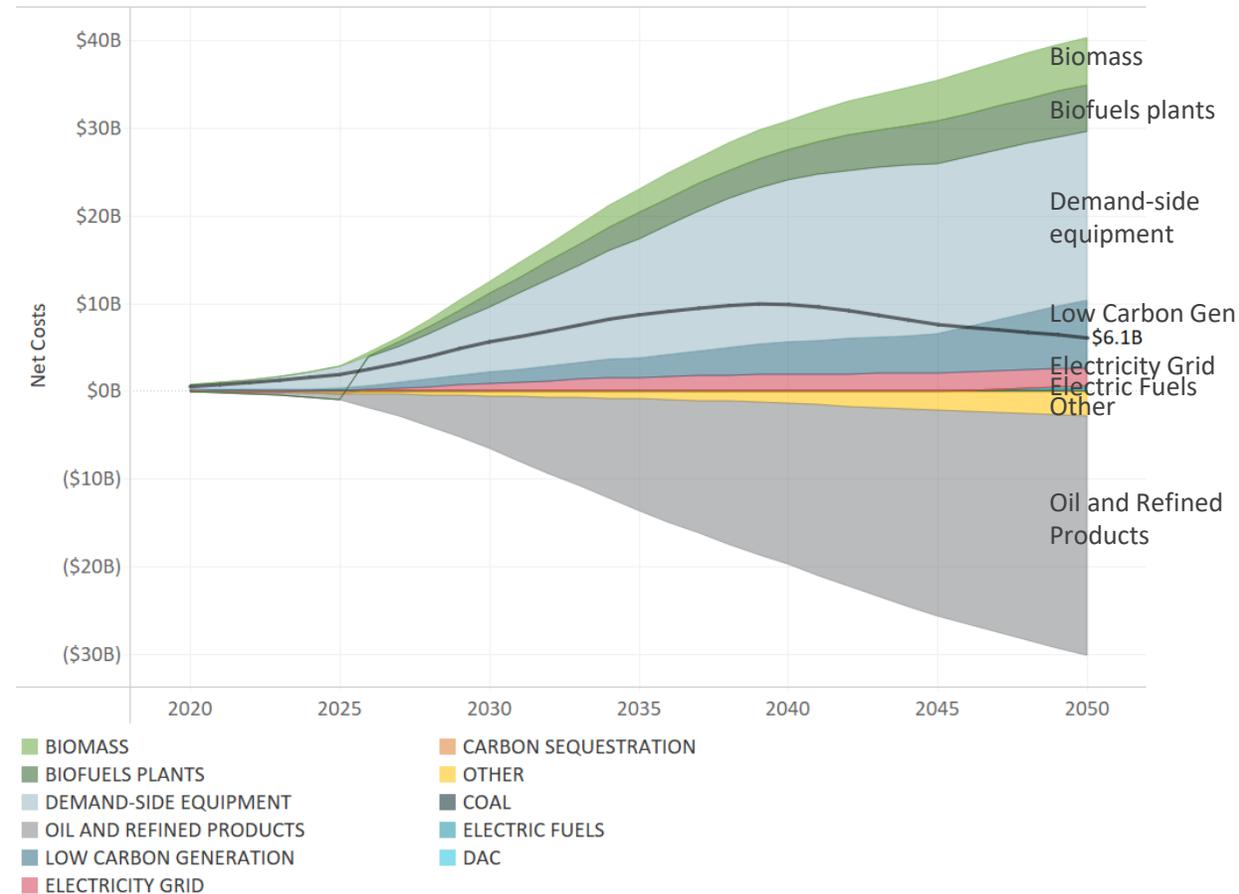
Overview

- Scope of costs in this study is limited to energy system costs, which includes:
 - Annualized capital costs of equipment (both supply and demand)
 - Fixed and variable O&M costs
 - Variable fuel costs
- Energy system costs represent the annual cost of producing, distributing and consuming energy
- Study **excludes** costs outside of the energy system or benefits from avoiding climate change and air pollution

Summary of Net Energy System Costs: Central Case

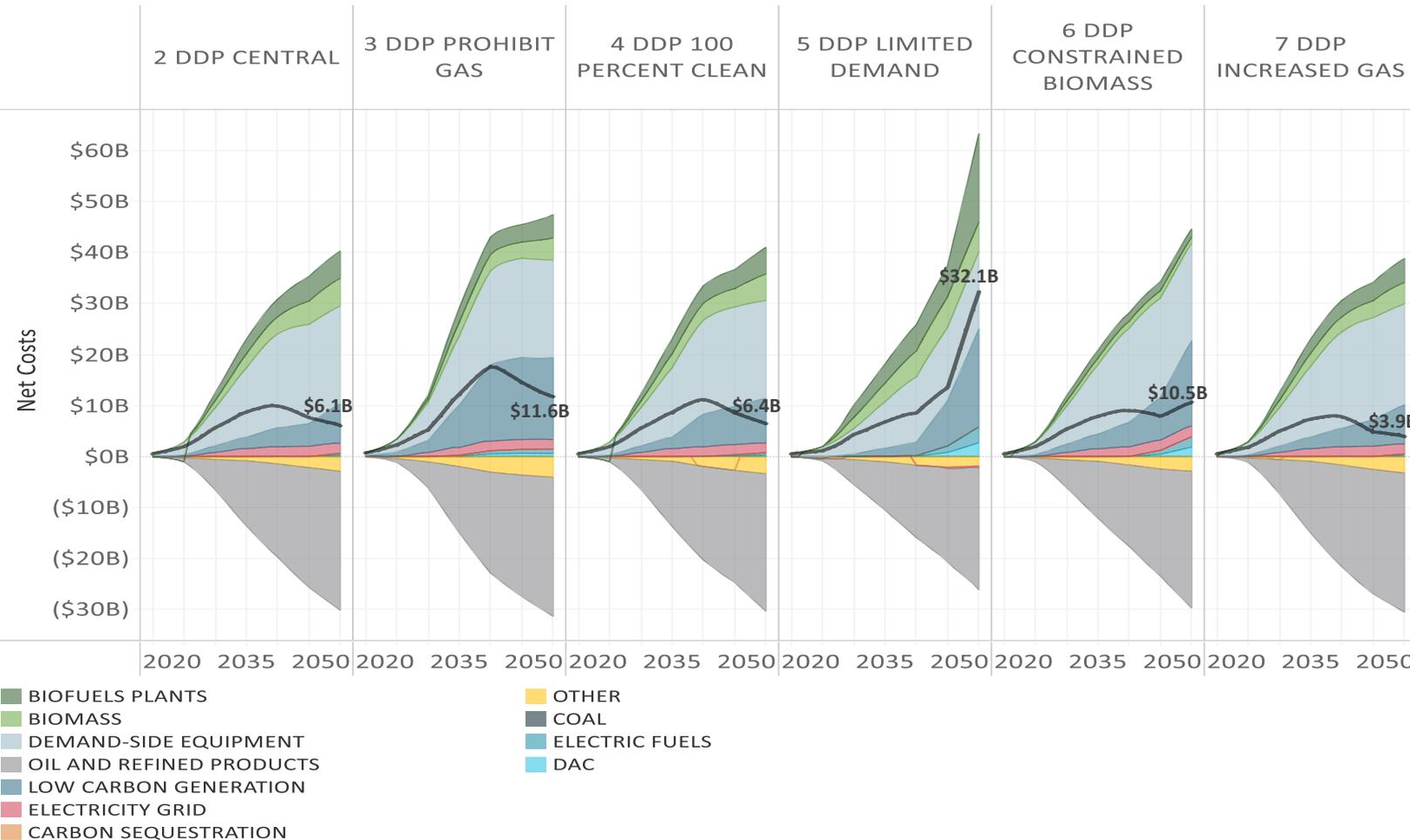
- **Net energy system cost** is estimated as the difference between the Central Case and Reference Case
- Net costs peak in the 2035-2040 timeframe as costs of key decarbonization technologies are still declining and the alternative cost of fossil fuels continues on an upward trajectory
- Increased costs in a decarbonized system consist primarily of:
 - Biofuel feedstocks and infrastructure;
 - Demand-side electrification and efficiency investments; and
 - Renewable power plants and supporting electricity infrastructure
- These increased costs are mitigated by the savings from fossil fuels, primarily expensive liquid petroleum products

Annual Net Energy System Costs
(relative to Reference Case)



Net Energy System Costs: DDP Case Sensitivities

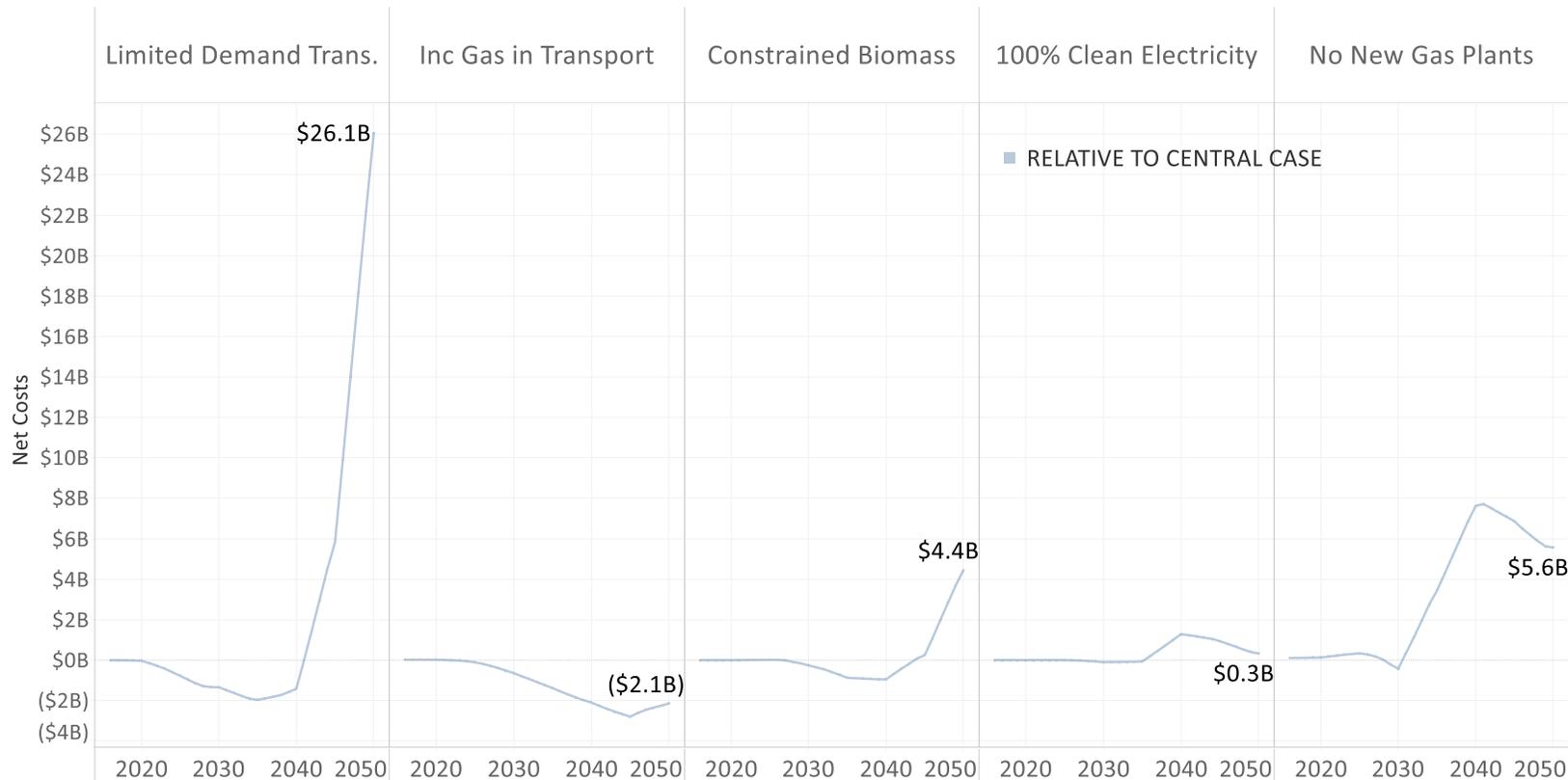
Annual Net Energy System Costs



- Net annual energy system costs are the difference in cost between each of the cases and the reference case (shown by the black line)
- Differences in investments by category between each case and the reference case are shown by the stacked area
- In comparison to the reference case, investments in additional clean energy measures (positive cost differences) are offset by the avoided fuel purchases (negative cost differences)

Net Energy System Costs: DDP Case Sensitivities

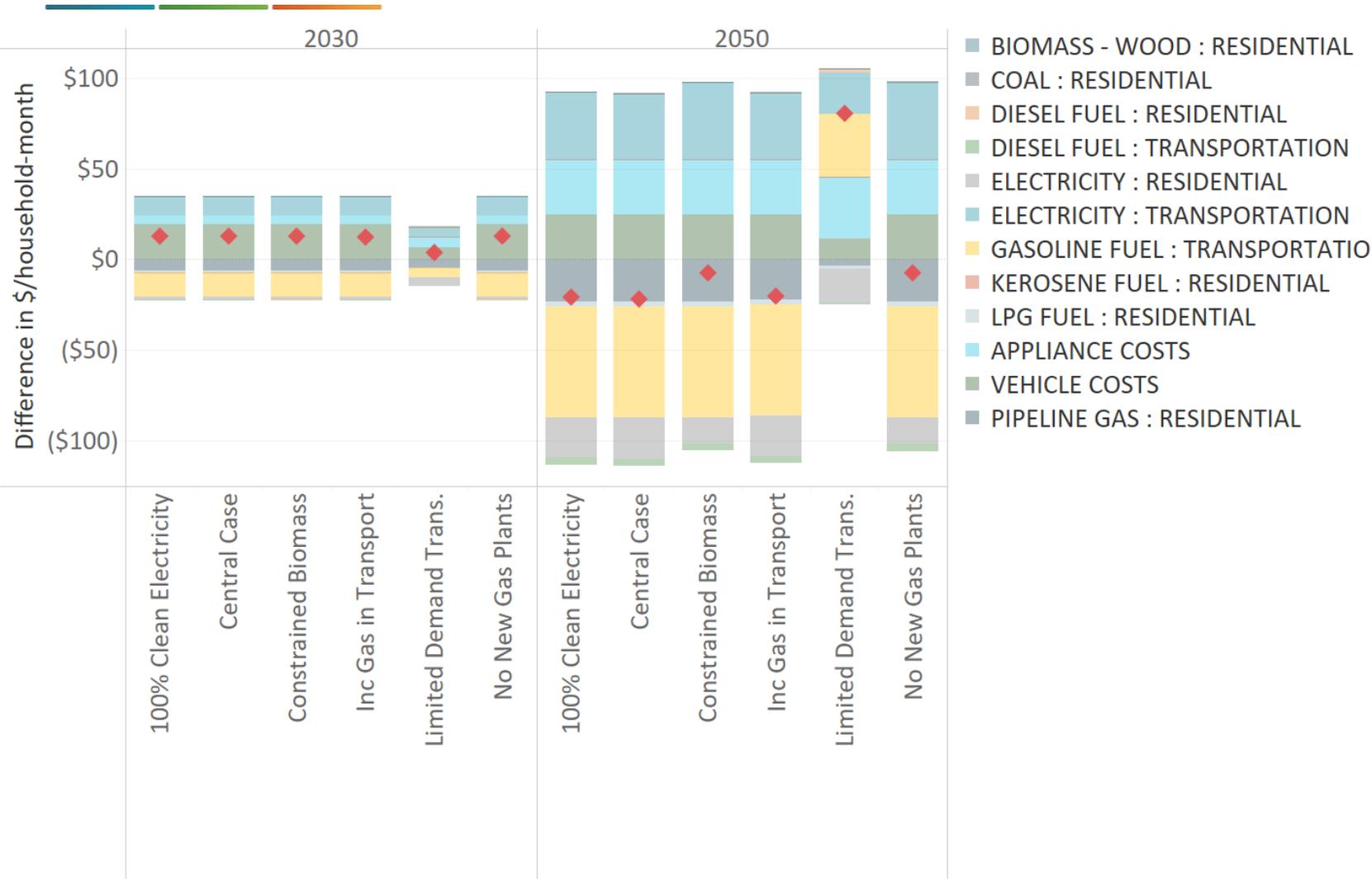
Annual Net Energy System Costs (relative to Central Case Case)



- The most impactful sensitivities in terms of net system costs include prohibition of new gas assets; limited demand-side transformation achievement; and constrained biomass
- 100% clean electricity is only a marginal change from the Central Case, and so it has a minimal impact on costs
- Increased gas in transportation allows access to a lower emissions/lower cost fossil fuel
 - However, this case may have higher methane emissions that are not accounted for in the study

Residential Cost Impacts

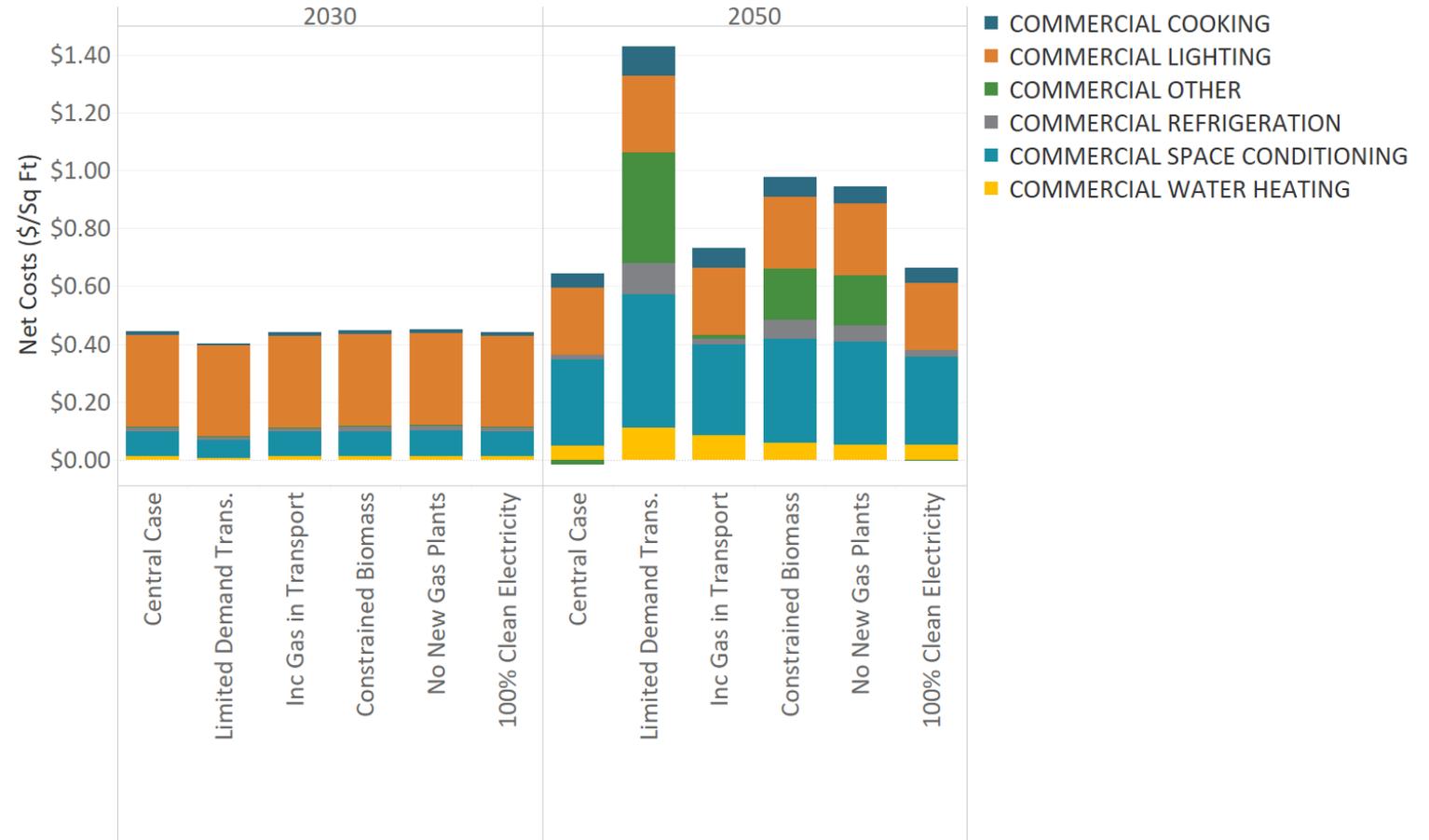
Relative to Reference Case



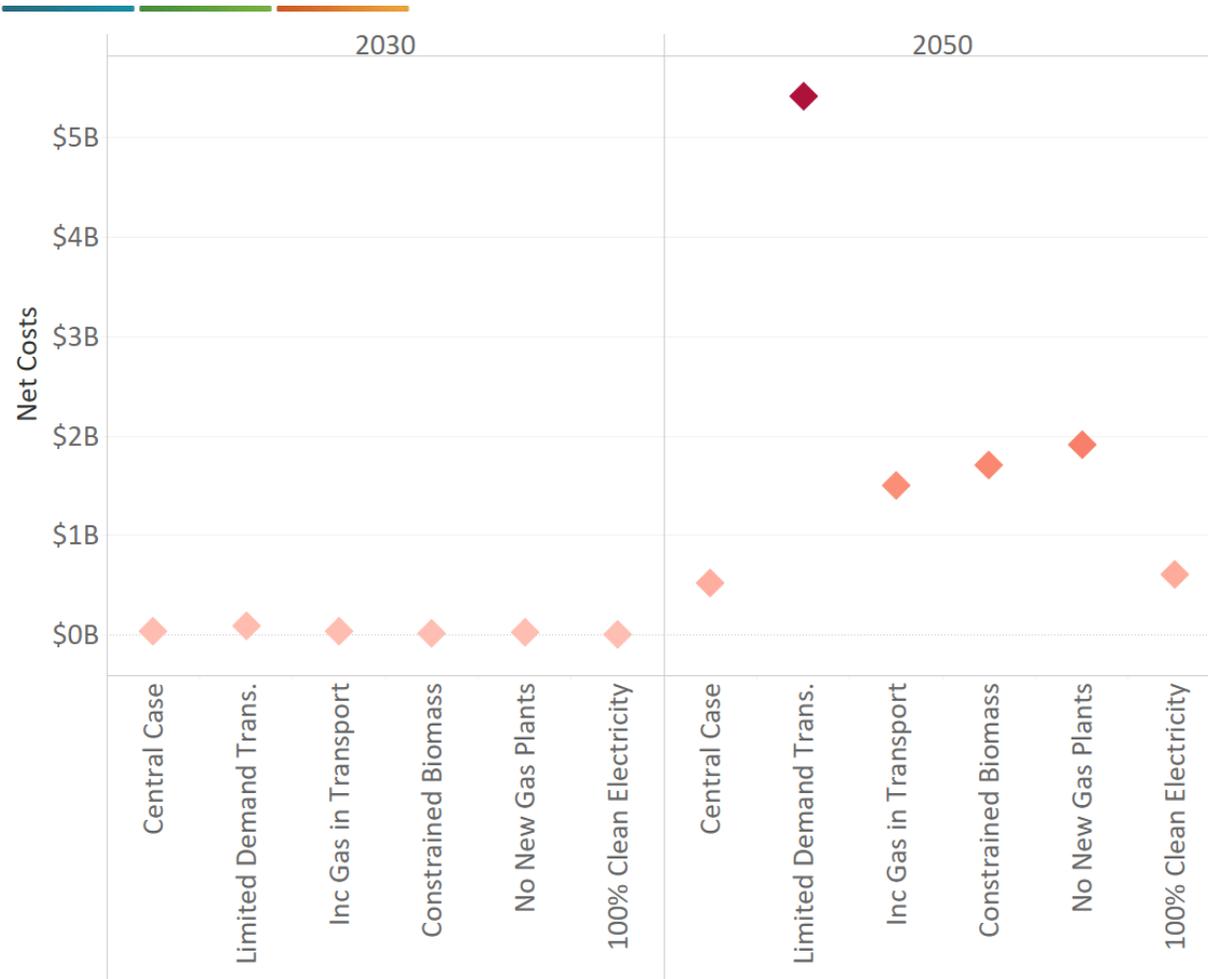
- Most cases show slightly positive monthly household expenditures in the 2030 timeframe, with slightly negative expenditures by 2050 (due to the increasing cost-effectiveness of EVs)
- The **Limited Demand Transformation** case is the lowest cost in the 2030 timeframe, as it doesn't have to incur as much in incremental costs for EVs and other electrified appliances. By 2050, however, limited electrification necessitates huge investments in electric and biofuels to offset the increased fuel usage, driving up costs

Commercial Cost Impacts

- Commercial cost impacts are consistent across cases in the 2030 timeframe with impacts around ~\$0.40/sq. ft.
- Impacts in 2050 are determined by energy supply costs (electricity and fuels)
- The highest supply costs are found in the **Limited Demand Transformation** case with its reliance on electric fuels to offset limited electrification

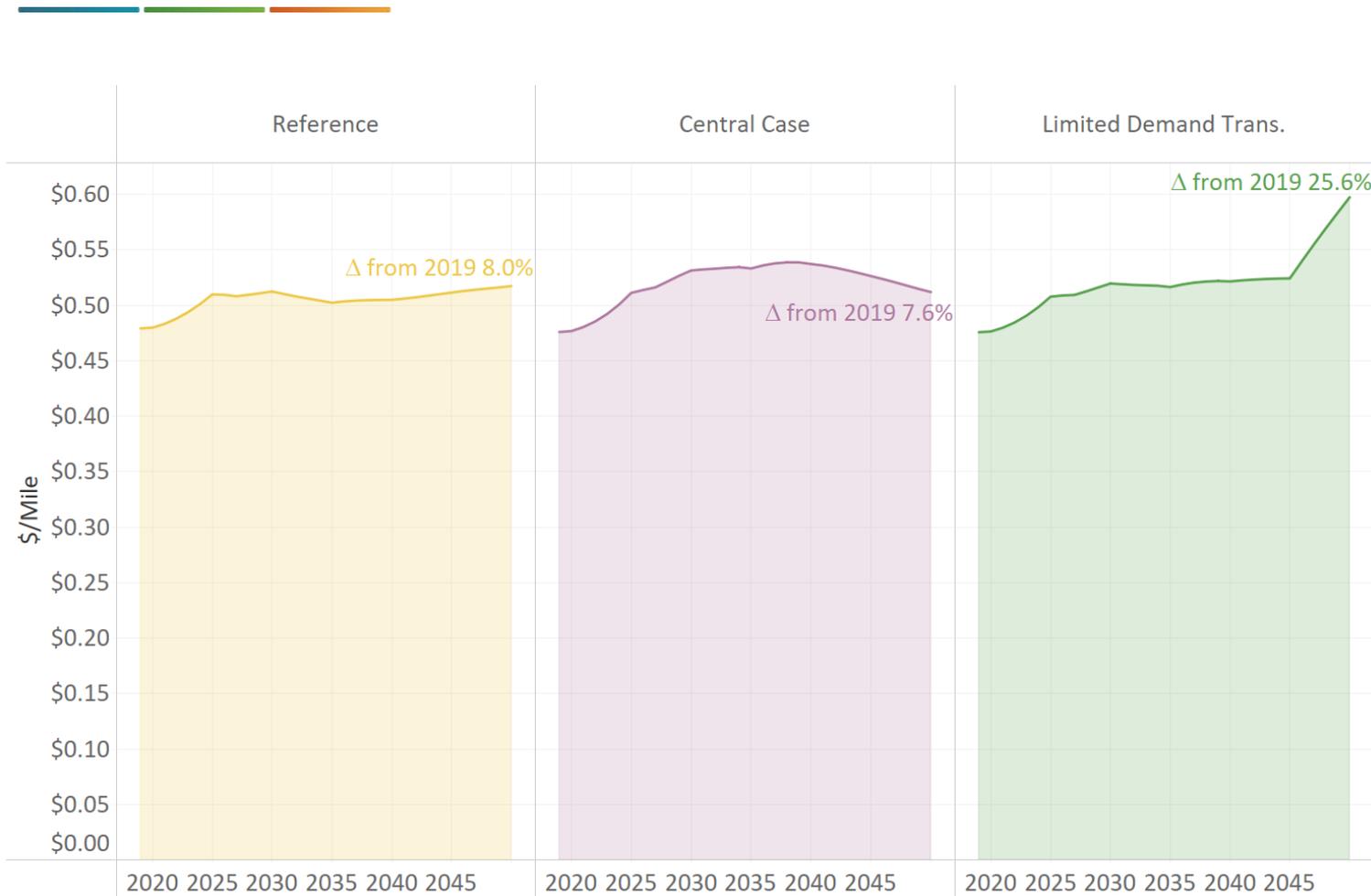


Industrial Cost Impacts



- Industrial cost impacts are not significant in the 2030 timeframe, with energy efficiency savings offsetting any increases in delivered energy costs
- By 2050, industry is one of the most impacted sectors due to its continued reliance on fuel
- This is especially significant in the **Limited Demand Transformation** case where fuel costs spike with such high penetrations of electric fuels

Light-Duty Vehicle Per-Mile Costs

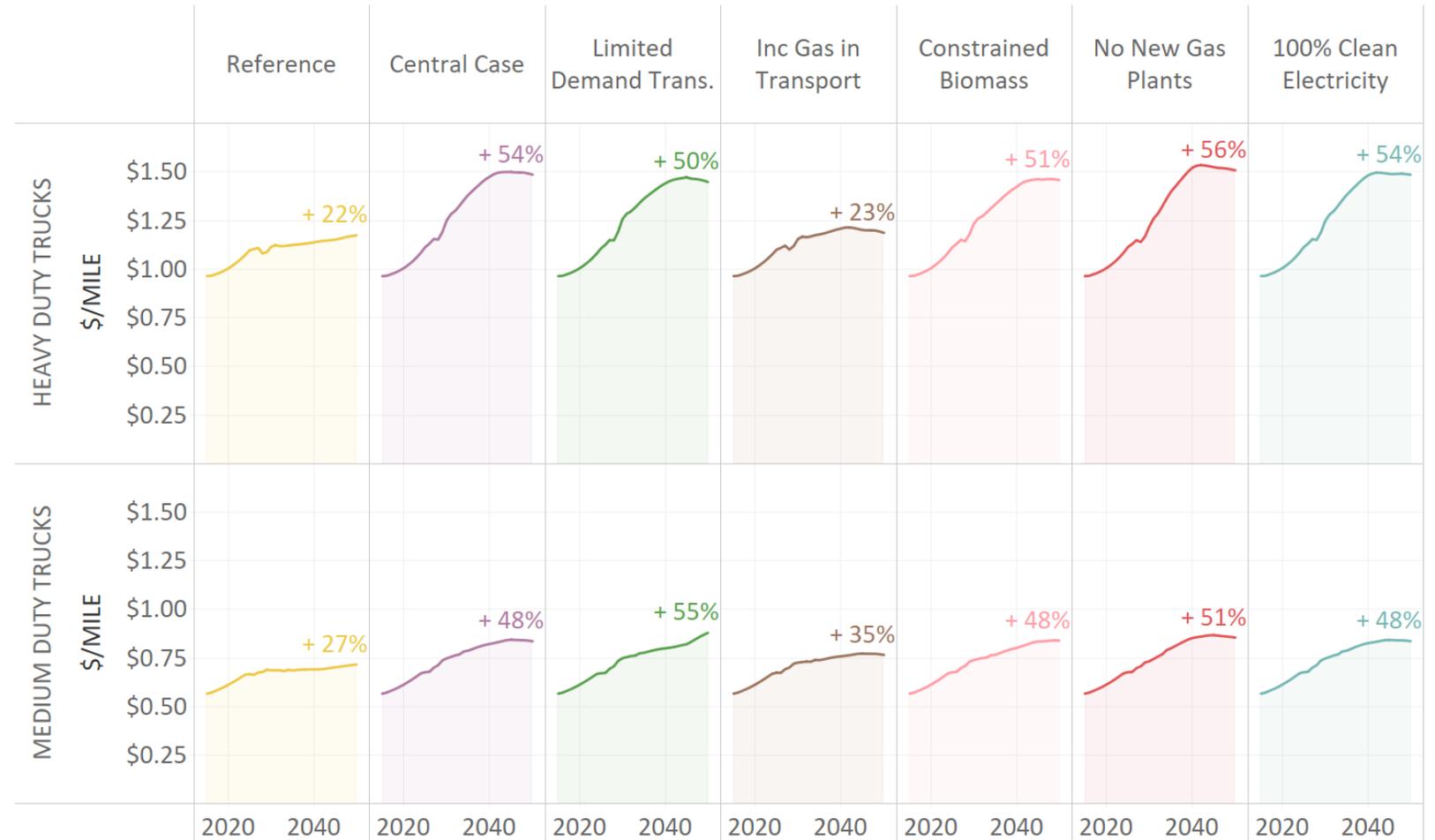


- The **Central Case** exceeds the Reference Case cost for LDV travel in most years before 2050, before becoming cheaper in 2050 due to the increasing fossil gasoline costs and decreasing costs of EVs
- The **Limited Demand Transformation** case is lower in intervening years due to lower vehicle electrification, but incomplete electrification in 2050 necessitates the use of expensive cellulosic ethanol to offset remaining fuel use, spiking costs

Medium- and Heavy-Duty Vehicle Per-Mile Costs

All Cases

- All cases except the **Increased Gas in Transportation Case** show significant cost increases relative to Reference Case levels
- Other cases show increases in per-mile costs of >50% from 2020 levels, making these one of the most impacted subsectors of deep decarbonization





Summary

Overview

- The results of the analysis demonstrate the feasibility of each state in the Northwest to achieve deep decarbonization
 - Mid-century climate targets can still be met despite a number of potential implementation challenges, such as lower levels of electrification and constraints on biomass availability
- This study incorporates a number of new and unique analytical approaches to assess deep decarbonization in the Northwest, including:
 - Developing cost-optimal energy supply portfolios
 - Incorporating new electric loads (direct air capture; fuel production; steam production)
 - Accounting for changing dynamics outside of the region (California energy policy)

Central Case

- The study's **Central Case** is a flexible pathway to achieve emissions reductions and highlighted a number of key findings:
 - Biomass is primarily allocated to jet fuel and diesel fuel even after partial electrification of freight trucks
 - Electricity generation approaches 100% clean without a specific mandate
 - Flexible electricity demand, notably from facilities that produce hydrogen and synthetic natural gas, play a large role in electricity balancing and energy system-wide carbon mitigation
- Aggressive electrification on the demand-side is also required, particularly in the transportation sector
 - All passenger transportation is electric by 2050

Demand-Side Electrification and Biomass

- Failure to electrify on the customer side has enormous implications for energy supply, as depicted in the **Limited Demand Transformation Case**
 - The scale of new wind, solar, direct air capture, electrolysis and power-to-X facilities could be considered prohibitive in implementation, and may ultimately require imports of electric fuels produced elsewhere
- Restricted availability of net-zero-carbon biomass (**Constrained Biomass Case**) results in similar energy system impacts
- If consumers don't electrify or biofuels are not available, then the “backstop” resource to decarbonize is synthetic electric fuels, which may face their own implementation challenges to develop at the necessary scale

Electricity Sector Insights

- The gap between the **100% Clean Electricity Case** and the Central Case is much smaller than anticipated, where a small quantity of additional synthetic fuels and biofuels is needed to bridge the gap
 - 100% clean electricity is likely easier to obtain in the context of economy-wide decarbonization, where resources that have co-products across the energy system (e.g., hydrogen) are considered
- Prohibiting new gas plants (**No New Gas Case**) results in additional energy storage and renewables that can provide reliable supply
 - The cost of implementing this strategy, which would otherwise involve a large amount of curtailment, is managed by electric fuels using excess renewables
 - Optimal expansion in the Central Case suggests a role for some low capacity factor gas resources
- Significant cost savings could be realized if interties between the Northwest and California were expanded (**Increased Northwest-California Transmission Case**)
 - The scale of benefits indicates deeper investigation is needed as both regions pursue decarbonization



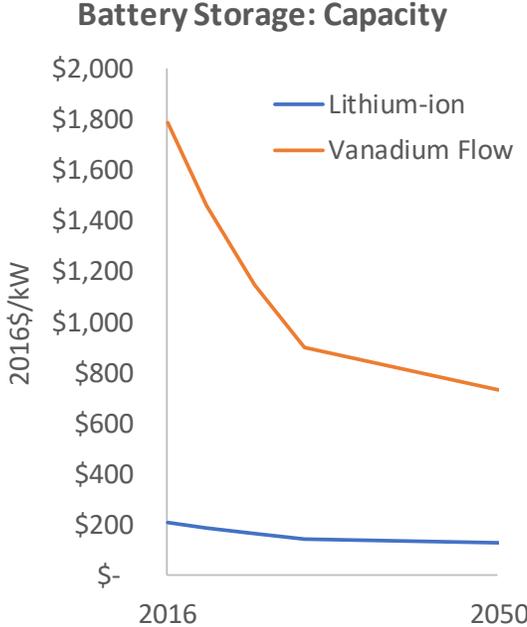
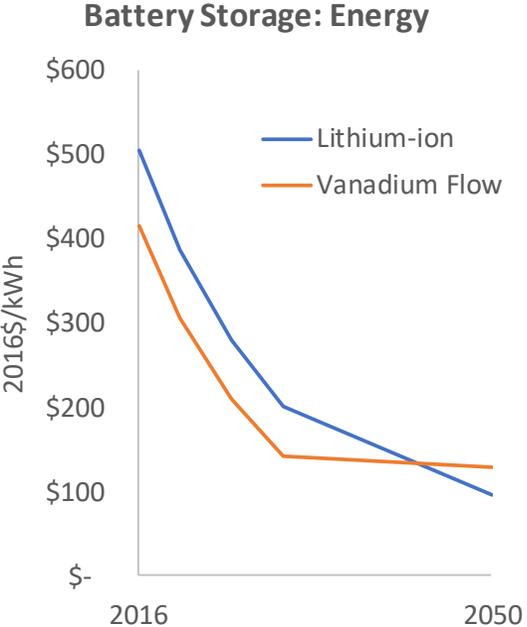
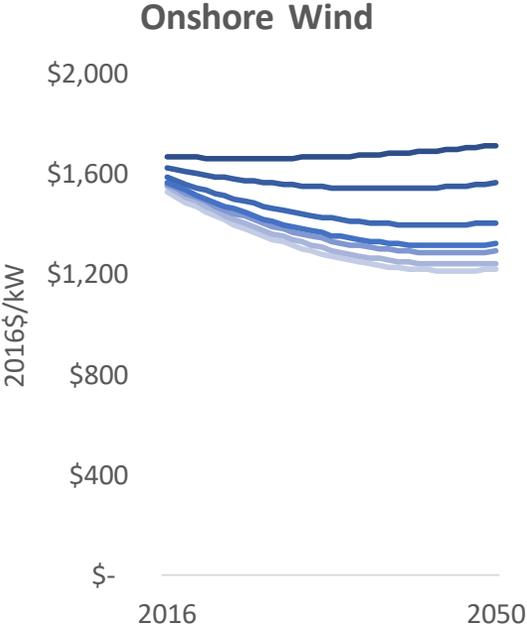
Thank You



Appendix

Technology Cost Projections

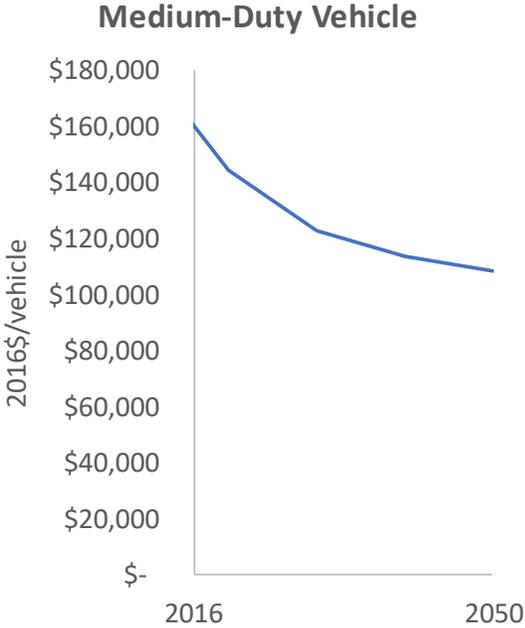
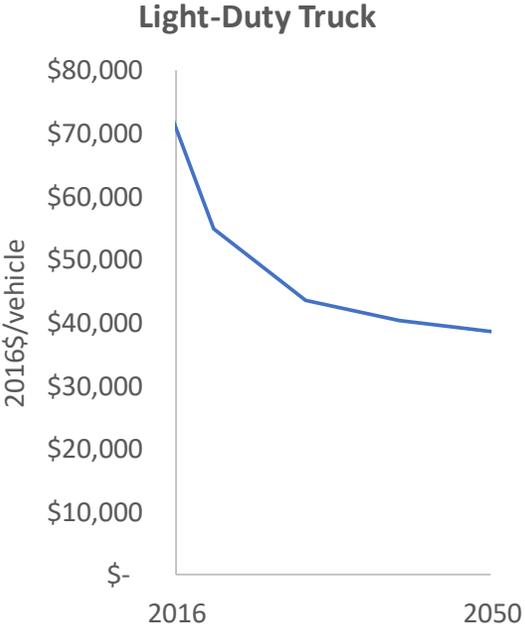
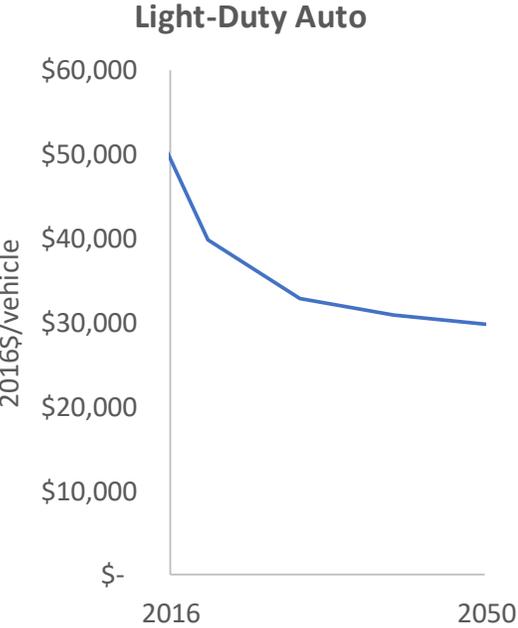
Electricity supply



Note: lines represent separate resource bins

Technology Cost Projections

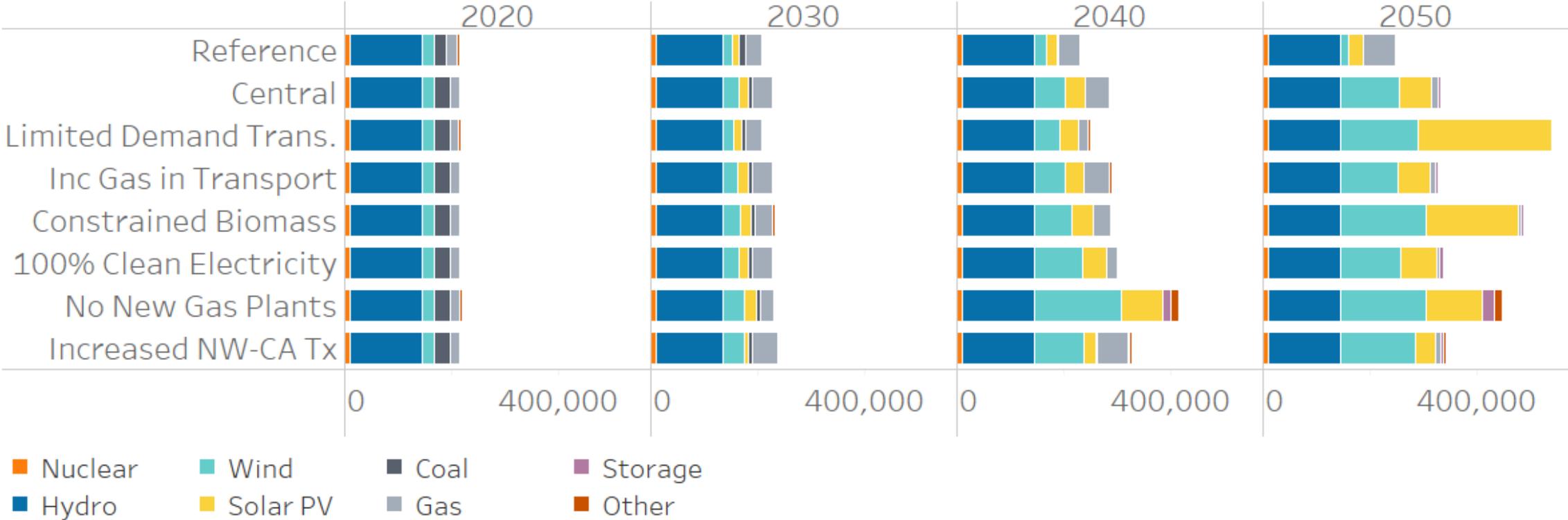
Battery Electric Vehicles



Annual Electricity Generation

Electricity Generation

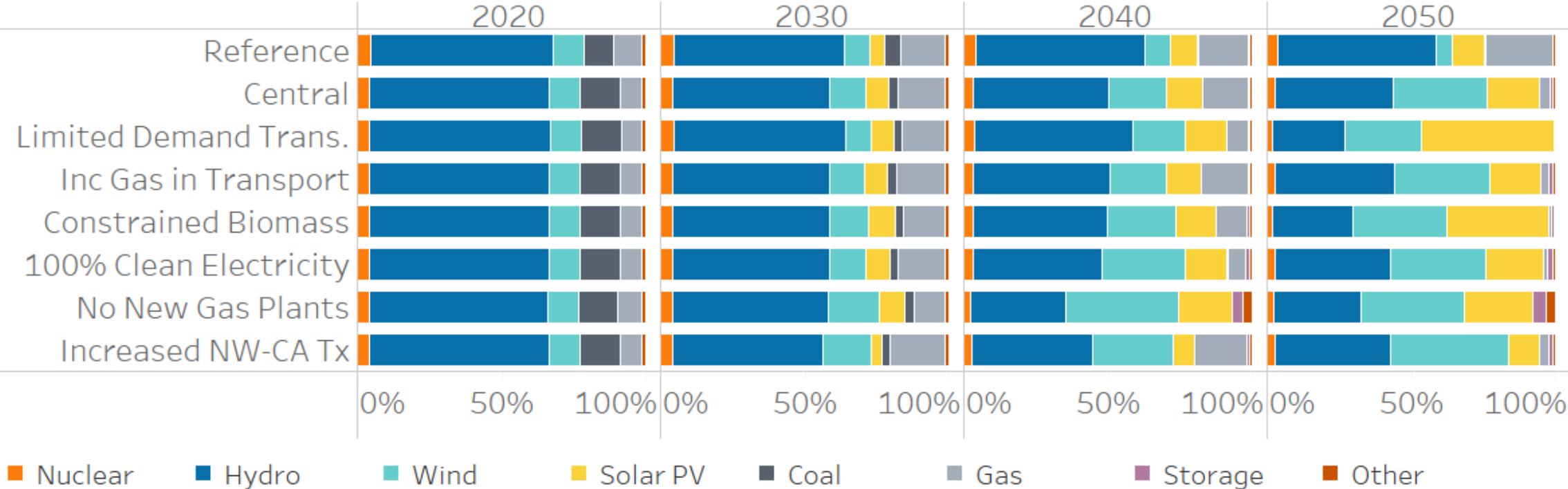
GWh



Annual Electricity Generation Share

Electricity Generation Share

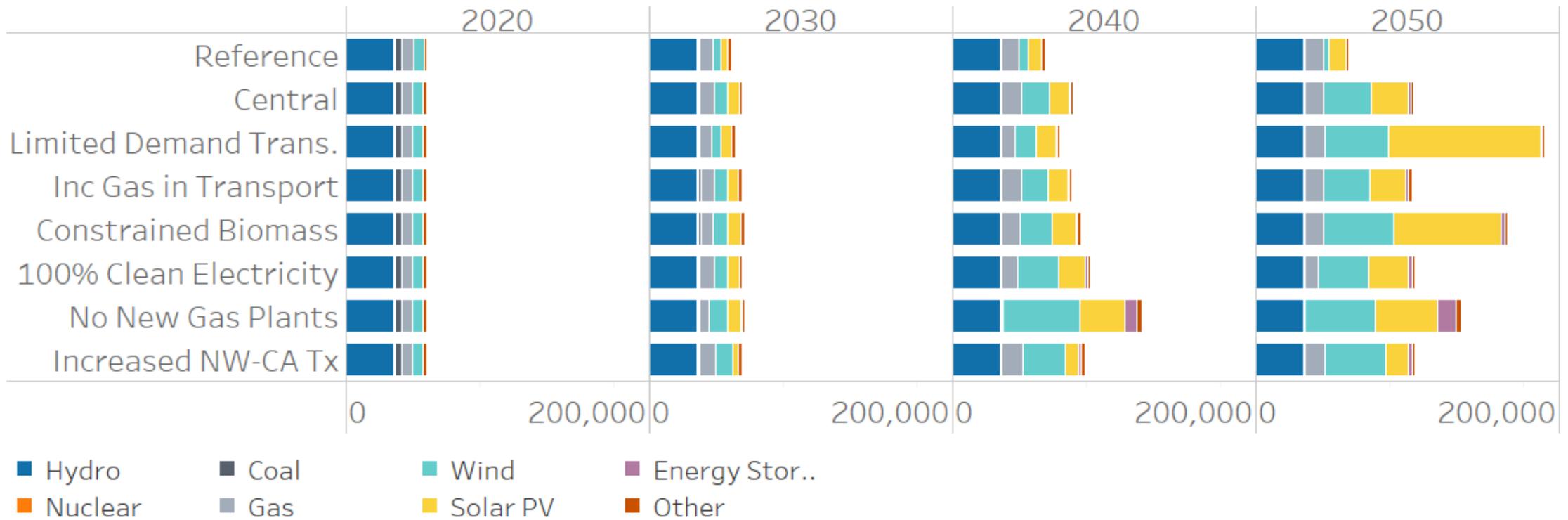
%



Installed Capacity

Installed Capacity

MW



Installed Capacity Share

Installed Capacity Share

%

