How to Use this Report and Information

• At the request of the Montana Department of Environmental Quality, the Clean Energy Transition Institute and Evolved Energy Research have provided this summary of analysis relevant to Montana from the Institute’s June 2019 report: *Meeting the Challenge of Our Time: Pathways to a Clean Energy Future for the Northwest*, which describes the results of the Northwest Deep Decarbonization Pathways Study (NWDDP) conducted in the winter 2018.

• Data specific to Montana is shared here to help members of the public understand some of the emissions reductions pathways and tradeoffs facing Montana, as well as the ways in which Montana’s energy system and unique assets may be able to serve regional needs in the future.

• Caution should be used in interpreting and applying the specific results presented here. As the Montana Climate Solutions Council report highlights, there is a need for a stakeholder process to support future study and investigation that tailors assumptions to Montana’s specific state objectives and context, and more fully considers the implications of proposed projects, policies, and the timing of resource retirements.
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  – Final energy demand
  – Electrification assumptions
• The Supply Side
  – Electricity sector
  – Fuels supply
• Summary
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• Planning Framework for Decarbonization
  – Designing a state driven process to achieve climate goals most effectively
• Planning Process
  – Steps to follow through a stakeholder process
• Appendices
  – A: NWDDP Scenario Definitions
  – B: Model Overview
Executive Summary

• To meet future energy needs at least cost, the study finds that decarbonization can be achieved through a combination of five key strategies (energy efficiency, decarbonized electricity, decarbonized fuels, electrification, and carbon capture) along with the continued use of very limited natural gas resources to address peaking capacity needs.

• The study finds that Montana utilizes its geographic strengths on the supply side to meet these shifting demands across the NW region:
  – A large wind sector is established, supplying clean energy to Montana and surrounding regions
  – Carbon is sequestered in saline aquifers in the production of liquid fuels from biomass, offsetting emissions from other sources
  – Policy actions taken in the rest of the West could impact Montana’s investments in significant ways, with opportunities to play a major export role in a decarbonized Western system

• The NWDDP assumptions drive decreased total energy demand as a result of efficiency gains, much of which comes from electrification in transportation and buildings. As a result, electricity demand grows by approximately 70%.
Executive Summary -2-

- Decarbonization costs are 1 to 1.5% of Montana GDP in the NWDDP using 2018 technology price forecasts, though likely a net benefit to the state when factoring in externalities.
  - Fossil fuel and electric vehicle price uncertainties have a major impact on total costs. Price declines in electric vehicle forecasts since 2018 may make decarbonization a net benefit to the state before factoring in externalities.
- Stakeholder-driven, energy system planning specific to Montana can help further determine investments necessary to minimize total cost of achieving targets for different future scenarios and can inform subsequent policy analysis of how best to achieve those investments and allocate costs.
- Background on a modeling approach for the state is included to inform next steps.
Background
Introduction

Supporting Montana: Summarizing Pathways Analysis for Future Decarbonization

• The following report shows Montana-specific results generated from analysis done for the Northwest Deep Decarbonization Pathways Study (NWDDP) released in June 2019

• Results include:
  – The demand side transformation – what types of investments were assumed across energy-consuming sectors of the economy over the next 30 years?
  – Supply side optimization – how best can we serve the energy needs of the economy while adhering to limits on total emissions?
  – Summary of high-level findings – what do they mean for Montana?
  – Caveats to the results – what has changed since this study took place?

• The report concludes with a high-level approach to studying Montana’s specific decarbonization needs, incorporating the interests of stakeholders in the state
The Northwest Deep Decarbonization Pathways (NW DDP) analysis was conducted using state-level granularity to determine least-cost pathways.

The study released in June 2019 summarized results for the region, including Idaho, Montana, Oregon, and Washington.

This report presents results and insights specific to the state of Montana.

- The exception is the electricity sector, where operations and planning are already integrated regionally, and investments in resources benefit multiple states.
- We show resource decisions in Montana as part of the larger regional system.

Our analytical approach, assumptions and scenario design are not described in this document since they are extensively detailed in our technical report and do not vary by state.
Historical Montana Energy-Related CO₂ Emissions

• Half of the emissions from within Montana’s borders come from electric power
  – Montana’s 2007 emissions inventory shows that ~50% of those emissions were from electricity exported to other states in 2005 (next slide)
  – Montana has remained a large net exporter of power through 2020
• The transportation sector accounts for a quarter of all energy-related CO₂ emissions, primarily due to liquid fossil fuel consumption:
  – Gasoline fuel in passenger transportation
  – Diesel fuel in freight transportation
  – Jet fuel in aviation

Montana GHG Inventory

• Net emissions from exports to other states, Montana emitted 19.2 MMT CO2 from energy in 1990
• 12.9 MMT came from non-energy sources
• While there is a clear technological path to reducing energy-related emissions, measures for non-energy emissions reductions are less well developed

Table ES-1. Montana Historical and Reference Case GHG Emissions, Consumption-based, by Sector

<table>
<thead>
<tr>
<th>Million Metric Tons CO2e</th>
<th>Historic</th>
<th>Projection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Sector</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>8.9</td>
<td>9.5</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Petroleum Coke</td>
<td>0</td>
<td>0.8</td>
</tr>
<tr>
<td>Net Exported Electricity</td>
<td>-7</td>
<td>-7.8</td>
</tr>
<tr>
<td>Res/Comm/Non-Fossil Ind (RCI)</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Coal</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>2.1</td>
<td>3.1</td>
</tr>
<tr>
<td>Oil</td>
<td>1.9</td>
<td>1.1</td>
</tr>
<tr>
<td>Wood (CH4 and N2O)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Transportation</td>
<td>5.9</td>
<td>7.3</td>
</tr>
<tr>
<td>Motor Gasoline</td>
<td>3.8</td>
<td>4.4</td>
</tr>
<tr>
<td>Dieselb</td>
<td>1.7</td>
<td>2.5</td>
</tr>
<tr>
<td>Natural Gas, LPG, other</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Jet Fuel, Aviation Gasoline</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Fossil Fuel Industry</td>
<td>3.5</td>
<td>4.1</td>
</tr>
<tr>
<td>Natural Gas Industry</td>
<td>1.4</td>
<td>1.7</td>
</tr>
<tr>
<td>Oil Industry</td>
<td>2</td>
<td>2.2</td>
</tr>
<tr>
<td>Coal Mining (Methane)</td>
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<td>0.2</td>
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<tr>
<td>Coal to Liquids</td>
<td></td>
<td></td>
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<tr>
<td>Industrial Processes</td>
<td>1.2</td>
<td>1</td>
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<tr>
<td>ODS Substitutes</td>
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<td>0.2</td>
</tr>
<tr>
<td>SF6 from Electric Utilities</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Cement &amp; Other Industry</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Aluminum Industry</td>
<td>0.7</td>
<td>0.3</td>
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<tr>
<td>Waste Management</td>
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<td>0.2</td>
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<tr>
<td>Solid Waste Management</td>
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<td>0.2</td>
</tr>
<tr>
<td>Wastewater Management</td>
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<td>0.1</td>
</tr>
<tr>
<td>Agriculture</td>
<td>7.9</td>
<td>9.5</td>
</tr>
<tr>
<td>Livestock Management</td>
<td>3.2</td>
<td>3.7</td>
</tr>
<tr>
<td>Ag. Soils and Residue Burning</td>
<td>4.7</td>
<td>5.8</td>
</tr>
<tr>
<td>Total Gross Emissions</td>
<td>32.2</td>
<td>36.1</td>
</tr>
<tr>
<td>Forestry and Land Use</td>
<td>-23.1</td>
<td>-23.1</td>
</tr>
<tr>
<td>Agricultural Soils Sink</td>
<td>-2.3</td>
<td>-2.3</td>
</tr>
<tr>
<td>Net Emissions (including sinks)</td>
<td>6.8</td>
<td>10.7</td>
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<tr>
<td>Energy-related CO2 emissions</td>
<td>19.2</td>
<td>21.2</td>
</tr>
<tr>
<td>Non-energy GHG emissions</td>
<td>12.9</td>
<td>14.9</td>
</tr>
<tr>
<td>Total Gross emissions</td>
<td>32.1</td>
<td>36.1</td>
</tr>
</tbody>
</table>

NWDDP Deep Decarbonization Target

- **Target**: 86 percent reduction in energy-related $\text{CO}_2$ emissions below 1990 levels by 2050
- Energy target 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 $\text{CO}_2$ and non-$\text{CO}_2$ GHG emissions, where mitigation feasibility is less understood
The Demand Side

How was Montana forecast to consume energy in the NWDDP?
Montana Energy Demand: End-Use Consumption

• End-use consumption or final energy demand represents 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 one-third below today
  – Electricity consumption increases by more than 70% and comprises one-half of all end-use consumption by 2050
  – Gasoline and diesel decrease from one-half of demand today to one-fifth by 2050 as on-road vehicles transition to electricity
Montana Energy Demand: Retail Electricity Sales by End-Use

• Net increase in end-use electricity consumption is primarily related to electrifying passenger and freight transportation

• By 2050, all passenger vehicles on the road are electric, whereas about half of freight trucks are
  – Freight trucks that continue to use liquid fuels primarily consume renewable diesel in the 2050 timeframe

![Retail Electricity Sales Chart]

- Transportation
- Buildings
- Productive

2018 - 2050
Montana Transportation Electrification

- Vehicles on the road rapidly transition from liquid fuels to electric
  - Aggressive adoption over the next three decades is necessary
- This results in an overall decrease in final energy demand due to the efficiency of an electric powertrain relative to an internal combustion engine
Montana Building Electrification

Example: Residential Buildings

- Energy consumption from buildings decreases significantly over time despite the growth of households and floorspace.
- Electrification of space and water heating translates into deep energy use reductions due to the efficiency of heat pump technology relative to the best in-class combustion equipment.
- This same trend is observed in commercial building stocks, as well as other end uses such as cooling and water heating.
The Supply Side

Electricity Sector and Fuel Supply
Capacity Expansion
Northwest-Wide

- 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
Electricity Generation
Northwest-Wide

- 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.
- Columbia Generating Station is extended after 2043 and operates through the study horizon (2050).
Hourly Operations

Northwest-Wide

- 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

Flexible demand consumes high output from hydro, wind and solar in the Spring
Energy Demand: Transmission-Level Electric Load

Montana

- Transmission-level load increases by 90 percent between 2020 and 2050
- A large portion of the net increase is from higher “fixed” loads (e.g., end-use retail sales)
- However, another significant portion of load growth in the state is from electrolysis facilities, which produce hydrogen primarily for synthetic fuels
New Sources of Electric Load

Montana

- Large, flexible sources of electric load help Montana manage electricity imbalances across the year
- Most of the new loads produce inputs for synthetic natural gas production, while electric boilers produce steam for commercial and industrial activity
Montana’s Electricity Export Market

Montana

• In all cases, Montana is a significant net exporter of electricity to other states by 2050

• Total exports are limited by the available transmission
  - 2.2 GW to Washington
  - 0.34 GW to Idaho
  - 0.6 GW to the rest of the West

• Expanding transmission to surrounding regions would increase the export market potential for Montana
  - Key opportunity to investigate in future state planning efforts
Exports Increase with Development of Montana Wind Sector

Montana Net Exports in the Central Case

• A close to doubling of wind from 2035 to 2040 supplies out of state demand for clean energy
  – Washington State is the main export market, driven by larger transmission ties to the state

• Montana energy is majority wind by 2050

• New, tighter emissions targets proposed in Washington and other Western states since the NWDDP was conducted will drive further demand for low cost and clean Montana wind exports
Biofuels with CCS are the primary source of diesel and jet fuel in 2050.

While other states decarbonize a fraction of pipeline gas with synthetic electric fuels, Montana retains fossil gas, choosing instead to offset emissions with CCS.

### Liquid and Gaseous Fuel Supply Mix

<table>
<thead>
<tr>
<th></th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
<th>2035</th>
<th>2040</th>
<th>2045</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Diesel Fuel</strong></td>
<td>100%</td>
<td>50%</td>
<td>0%</td>
<td>50%</td>
<td>0%</td>
<td>100%</td>
<td>50%</td>
</tr>
<tr>
<td><strong>Jet Fuel</strong></td>
<td>100%</td>
<td>50%</td>
<td>0%</td>
<td>50%</td>
<td>0%</td>
<td>100%</td>
<td>50%</td>
</tr>
<tr>
<td><strong>Pipeline Gas</strong></td>
<td>100%</td>
<td>50%</td>
<td>0%</td>
<td>50%</td>
<td>0%</td>
<td>100%</td>
<td>50%</td>
</tr>
</tbody>
</table>

- **Fossil Fuels**
- **Biofuels**
- **Biofuels w/ CCS**
- **Hydrogen**
- **Power-to-X**
Caveats
Caveats

There are several ways in which the NWDDP analysis cannot be directly applied to Montana

- Scenario definitions and assumptions are not tailored to Montana interests or to represent the Montana policies and uncertainties most valuable to investigate to inform policy development
  - Tailored analysis supporting State and stakeholder driven questions will best serve State climate policy action
- Targets have since been proposed for Montana
  - Carbon neutral electricity by 2035 and net zero emissions by 2050
  - These will drive more clean energy investment in the state than in the NWDDP
- Targets have changed for other Western states
  - Since the NWDDP was conducted, Western states including Washington, Colorado, and Nevada have set more stringent emissions and clean energy standards
  - These will drive more clean energy investment, and potentially greater demand for Montana resources
- Prices are out of date
  - Forecasted prices have been lowered for many clean energy technologies, in some cases substantially, since the NWDDP analysis was conducted in 2018. This includes for electric vehicles – one of the largest drivers of decarbonization cost reductions
- Covid-19 has impacted demand and fuel prices
  - Short-term market price impacts, and longer term demand impacts and structural changes may revise the outlook for demand and prices over the coming years
Caveats

Continued

• No transmission expansion and limited interstate representation
  – The NWDDP did not simulate the opportunity of expanding transmission and thus expanding the market for Montana clean energy to other regions
  – Investigating this becomes more important with the move of other states towards stringent clean energy and emissions goals

• Lack of detailed consideration of Montana’s coal generators
  – Policy options surrounding Montana’s coal industry, including retirement schedules, were not investigated in the NWDDP

• Fuels trading limitations
  – The NWDDP did not allow states to trade clean fuels and build supply routes for clean fuel exports. This is an important pathway towards more realistic and lower cost regional decarbonization solutions

• Outdated assumptions about vehicle stock rollover
  – Assumed levels of electrification and remaining internal combustion energy stocks in the economy may not be appropriate for Montana
  – Options for trucking using fuel cells have become more viable since the NWDDP analysis was conducted. Fuel cells may play an important role in the future, particularly in long-distance trucking
Summary
## What Are the Least Cost Strategies that Policy Should Target?

**Northwest-wide**

<table>
<thead>
<tr>
<th>Energy Efficiency</th>
<th>Decarbonized Electricity</th>
<th>Decarbonized Fuels</th>
<th>Electrification</th>
<th>Carbon Capture</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMBtu per person</td>
<td>tonnes CO₂ per MWh</td>
<td>kg CO₂ per MMBtu</td>
<td>Share of Total Final Energy, %</td>
<td>MMT CO₂ Capture</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td></td>
<td>0.20</td>
<td>80</td>
<td>5</td>
</tr>
<tr>
<td>150</td>
<td></td>
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<td></td>
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<tr>
<td>100</td>
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<td>0</td>
<td></td>
<td>0.00</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

Source: Northwest Deep Decarbonization Pathways Study, June 2019, Evolved Energy Research

Figure for illustration purposes only
• The five decarbonization strategies reduce Montana’s emissions over the next three decades

• The largest remaining source of emissions is natural gas
  – Natural gas is the cheapest fossil fuel, therefore it is the last to be decarbonized

• Montana offsets remaining emissions with carbon sequestration in saline aquifers to reach the 2050 target
Montana Energy CO₂ Emissions By Sector

- Overall emissions decrease across all sectors of the state’s economy
- Transportation emissions decline significantly with on-road (LDV, MDV, and HDV) significantly reduced
  - In 2050, biofuels with CCS are the dominant source of diesel and jet fuel, resulting in negative emissions
- Building emissions are reduced to ~1MMT by 2050 as heating services are electrified
Load

Northwest-Wide

- 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 CO$_2$ and using electric boilers to produce steam

### Load: Central Case

<table>
<thead>
<tr>
<th>Year</th>
<th>GWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td></td>
</tr>
<tr>
<td>2050</td>
<td></td>
</tr>
</tbody>
</table>

- Increased in fixed load, which represents end-use demand from buildings, transportation, etc.
- Additional electric load to produce hydrogen, capture CO$_2$, store energy, etc.
State-level Energy CO₂ Emissions in 2050

Northwest Wide

- 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.
  - The NWDDP did not include options for decarbonizing this sector. Future studies will impact regional investments.
- Montana has geological CO₂ sequestration potential, which allows for the capture of CO₂ and storage in saline aquifers.
Montana Net Costs

Estimated as the difference between the Central Case and Reference Case

- Net costs for the state primarily represent incremental:
  - Biofuel feedstocks and infrastructure;
  - Demand-side electrification and efficiency investments; and
  - Renewable power plants and supporting electricity infrastructure

- These incremental costs are mitigated by savings from avoided fossil fuel expenditures

- Net costs peak around 2040 as costs of key decarbonization technologies are still declining and the alternative cost of fossil fuels continues an upward trajectory
Net Costs Relative to Montana’s Economy

Share of GDP

- Magnitude of net costs are small relative to the size of the state’s economy
  - Montana’s gross domestic product in 2019 was $52.2 billion
- Between 2030 and 2050, incremental net costs of the Central Case are between 1% and 1.5% of today’s economy for Montana
- Since this study was conducted, the forecasts for renewables and electric vehicle prices have dropped so decarbonization costs are lower
- These costs would be even smaller if future economic growth and benefits from avoided climate change and pollution were considered
  - Factoring in carbon and health externalities in other studies resulted in a net benefit from decarbonization
  - An example of these net benefits are shown on the next slide from the New Jersey Energy Master Plan
Example: New Jersey Energy Master Plan

Costs and benefits of decarbonizing in 2050

- New Jersey targeted an 80% emissions reduction and 100% clean electricity by 2050
- The chart opposite shows annual costs and benefits in 2050 of achieving that target relative to a reference case
- While decarbonization is a net cost when considering incremental costs and avoided costs, factoring in externalities would drive New Jersey to net benefits
- A future decarbonization study for Montana may find that net costs are close to zero, or a net benefit, while considering only incremental energy and avoided costs given price declines since the NWDDP
  - Adding additional accounting for externalities including health and climate change impacts is highly likely to result in a net benefit to the state

Source: New Jersey Energy Master Plan, analysis conducted by Evolved Energy Research and Rocky Mountain Institute
New Jersey Example

- While Montana’s incremental spending to decarbonize the economy is 1 to 1.5% of today’s economy in the NWDDP, this is worth thinking about in context.
- Energy spending in general across the US is set to decrease as economic growth is further decoupled from energy consumption.
- Contextualizing spending in a future study of Montana decarbonization is likely to show the decreasing percentage spending in GDP terms, and lower spending compared to historical precedent.

**Sources and notes:** New Jersey, Energy Master Plan. Historical state GDP from the U.S. Bureau of Economy Analysis; historical energy spending from U.S. Energy Information Administration.
Uncertainty in Cost Inputs

New Jersey Example: Sensitivity to fuel prices in 2050

- Decarbonization costs are uncertain, and this uncertainty increases with time
- Uncertainty is illustrated through ranges in net cost for the New Jersey example, with alternative fossil fuel prices and battery electric vehicle costs
  - Range of fossil fuel price projections are from EIA’s AEO 2019
    - Oil price +/-10% in 2050
    - Gas price +70%/-30% in 2050
  - Range of BEV cost projections is +/-10% of the baseline assumption
- Deep decarbonization will reduce Montana’s exposure to uncertain and volatile fossil fuel prices
  - Hedge against fuel prices dictated by international markets, increasing energy security
- Electric vehicle price forecasts have been trending downwards. They are an important driver of total decarbonization costs, with a 10% decrease in forecasted prices resulting in net benefits of decarbonization for New Jersey

![Chart showing fossil fuel and BEV cost uncertainty](chart.png)
Key Takeaways

• The NWDDP assumptions drive final energy demand to fall by 35% through greater efficiency, much of which comes from a transition to electrified transportation and electrified end uses in buildings
  – As a result electricity demand rises 71%. Whether this result is best for Montana was not investigated in the NWDDP, and any future decarbonization study should include weighing the costs and benefits of electrification policy with assumptions tailored to Montana

• Montana utilizes its geographic strengths on the supply side in the NWDDP
  – A large wind sector is established, supplying clean energy to Montana and surrounding regions
  – Carbon is sequestered in saline aquifers in the production of liquid fuels from biomass, offsetting emissions from other sources

• Policy actions taken in the rest of the West could impact Montana’s investments in significant ways, with opportunities to play a major export role in a decarbonized Western system
  – Low cost and complementary wind resource
    • Coastal states have a relatively poor wind resource and import significant quantities of wind from Montana and Wyoming. Transmission between Montana and Washington was fully utilized to export clean energy in the NWDDP
  – Transmission expansion
    • The NWDDP did not allow transmission expansion between Montana and neighbors. However, transmission expansion is likely cost effective and would open up greater opportunity for exports for Montana. This would be a valuable avenue of investigation for a future decarbonization study
  – Decarbonized fuels
    • Decarbonized fuels from biomass and hydrogen play a major role in Montana’s transportation sector by 2050. Other Western states also rely on decarbonized fuels to reach their own targets. Montana has low cost resources to produce fuels and could export fuels to other states – another opportunity to investigate
    • Fuels export can also take the pressure off expansion of transmission lines, by exporting clean energy through pipelines or other forms of transport instead

• Decarbonization costs are 1 to 1.5% of Montana GDP in the NWDDP. This estimate will have decreased with falling price forecasts for clean energy technology
  – Decarbonization is likely to be a net benefit to the state when factoring in externalities
  – Fossil fuel and electric vehicle price uncertainties have a major impact on total costs. Further price forecast declines in electric vehicles could result in net benefits for Montana
Planning Framework for Decarbonization

Designing a state-driven process to achieve climate goals most effectively
What is Success when Planning State Climate Policy?

- Policy and near-term action development that:
  - Achieve “best” balance of state objectives – what outcomes would best satisfy Montana’s many, sometimes competing, objectives?
  - Are actually implemented through collective action across state agencies, utilities, and other participants

- Multiple objectives including reaching climate targets, but also labor, productivity, equity, environmental, environmental justice, etc.

- Effective planning includes:
  - Representative stakeholder participation for all interests in the state
  - Providing as much information to policymakers as possible, economic and otherwise, to weigh the options
Tailored Analytical Approach

• Least-cost energy system planning, and policy/action design complement one another
  – Process to determine Montana’s best path forward
  – Least cost energy system planning determines investments necessary to minimize total cost of achieving targets for different future scenarios
  – Policy and action design determine how best to achieve those investments and allocate those costs

• The best path is a balance of different, often competing objectives
  – Not all objectives can be quantified in economic terms
  – Analysis provides more information to allow decisionmakers to weigh one option against another

• Stakeholder input essential to define the options and evaluate policies and actions
Three Framing Questions

• Where are we now?
  – What is the current state of Montana’s energy system?

• Where do we want to go?
  – What are Montana’s most desirable pathways to meeting emissions goals?

• How should we get there?
  – What policies and actions get us to where we want to go?
Where Are We Now?

• Present day
  – What do Montana’s energy technologies/systems and consumption patterns look like on the demand and supply side?
    • e.g., what types of appliances are homes and businesses currently using? What are transportation energy consumption patterns? How does the state generate electricity? What do imports and exports look like? What are industrial process emissions?
  – What policies presently drive investments and behavior?
  – What behaviors are markets incentivizing?
  – What do technologies and fuels presently cost?
• Building the full picture of what Montana’s energy consumption and emissions profile looks like today
Where Do We Want to Go?

• What is the best future we can envision for the state?
  – Balance of different, often competing objectives
  – Alternative least cost pathways examining different priorities

• Understanding the tradeoffs
  – How much does one pathway cost versus another?
    • Counterpoint for policymakers and stakeholders
  – Provides a target for near-term policy and action design to hit

• Understanding the uncertainties
  – How does an uncertain future impact our decisions?
How Should We Get There?

• By targeting favorable future pathways we can **develop and prioritize near-term policies and actions**

• Targets are not prescriptive, but provide the best guidance given current information and uncertainties
  – Common elements deployed 2020-2030: “no regrets”
  – Replace or avoid long-lived resources
  – Early action on long lead-time or hard to achieve energy transformations

• Policy development that favors Montana’s goals
  – Balance competing objectives in the state
  – Detailed sectoral analysis to evaluate distributional/equity/workforce etc. impacts and develop targeted policy guided by integrated economy wide planning efforts
Near-Term Focus on Long-Lived Assets

Early action needed to avoid carbon lock-in or stranded assets

Stock replacement count before mid-century

- Bulb
- Appliances
- AC & Furnace
- Vehicles
- Commercial boilers
- Power plant
- Pipelines

U.S. Energy-related CO₂ Emissions

Reference

Dead-end pathway

2050 Target
Planning Process

Steps followed through stakeholder process
Scenario Development: Investigate State Objectives

- Translate State objectives and potential policy pathways into constrained scenarios
  - What are state and stakeholder policy goals?
  - How hard should the state prioritize particular actions or strategies?

- Understanding the tradeoffs
  - How much does one pathway cost versus another?
    - Counterpoint for policymakers and stakeholders
    - Provides a target for near-term policy and action design to hit

- Understanding the uncertainties
  - How does an uncertain future impact State decisions?
Components of a Scenario

- Many assumptions go into projecting a decarbonization pathway
- Sets the parameters for the world within which the planning model optimizes decisions
  - Assumptions on how uncertainties now manifest in the future
  - Assumptions on how policies/actions/customer behavior manifest in driving energy needs and how they can be served

<table>
<thead>
<tr>
<th>Component</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDV Electrification</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RE Resource Potential</td>
<td></td>
<td></td>
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<tr>
<td>Heat Pump Adoption</td>
<td></td>
<td></td>
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<tr>
<td>Gas Price Trajectory</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Import clean fuels</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extension of existing nuclear</td>
<td></td>
<td></td>
</tr>
<tr>
<td>New gas build</td>
<td></td>
<td></td>
</tr>
<tr>
<td>New transmission</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regional Clean Energy Policy</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Example scenario components
Connect Scenarios to Important Outcomes for the State

• Develop with the feedback from the State and stakeholder process
• Provides valuable information for the policy development process
  - What outcomes should be targeted through near-term policy and action development?
What Happens after Scenario Development?

Least Regrets

Where do we want to go?
Cost effective outcomes from modeling to inform policy

Policy Development

How should we get there?
Creation of a state policy and action implementation plan

Figure for methodology illustration only

Near term policies/actions that support long term goals

Rate reform?  Level playing field?  New business models?

Transformational policy?  Infrastructure development?  Public/private partnerships?

2020  2025  2030  2035  2040  2045  2050
THANK YOU

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San Francisco, CA, 94115

(415) 580-1804
info@evolved.energy
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Appendix A

Deep Decarbonization Scenario Definitions from Northwest Deep Decarbonization Pathways Study
## Summary of Alternative Deep Decarbonization Pathways

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
</tr>
</thead>
</table>
| Limited Demand Transformation | • Increased fuel demand from lower electrification requires significant volumes of synthetic fuel production  
• Raises net costs by $15 billion in 2050                                                                                                           |
| Constrained Biomass           | • Similar impacts as the “Limited Demand Transformation”, where additional synthetic fuels are needed to meet the carbon constraint  
• Raises net costs by $3 billion in 2050                                                                                                           |
| Increased Gas in Transportation| • Biofuels are primarily allocated to pipeline gas rather than liquid fuels                                                                                                                                 |
| 100% Clean Electricity        | • State can achieve a 100% clean electricity standard with a small increase in synthetic natural gas production for gas-fired power plants                                                                                  |
| No New Gas Plants             | • Additional energy storage and renewables are required across the region for balancing  
• This incentivizes additional synthetic fuels and avoids some biofuels consumption                                                                                                 |
| Increased NW-CA Transmission  | • 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 which is exported to the Northwest |

Model Overview
High level description of our approach
Model calculates the energy needed to power the Montana economy, and the least-cost way to provide that energy under clean energy goals.
1. The model calculates energy demand by assuming population growth, economic growth, and adoption of new technologies.

Example: Water heaters

- Model estimates how many water heaters of each type are purchased each year.
- Model calculates the changing stock of hot water heaters by year.
- Model calculates the gas and electricity required for water heaters.

This ‘stock rollover’ analysis is repeated for ~30 end-uses across the economy.
2. The model optimizes investments in energy infrastructure to meet energy demands and satisfy emissions constraints.

**Example: Electricity**

- **Reliability:** Model requires supply is met during rare, severe weather events, while maintaining reserve margin.
- Fuel and electricity supply are optimized together.
- Model uses best available public data.
End-Use Sectors Modeled

• Approximately 70 demand sub-sectors represented
• The major energy consuming sub-sectors are listed below:

Key energy-consuming subsectors.

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

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

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

Transportation Sector
- Light-duty autos
- Light-duty trucks
- Medium-duty vehicles
- Heavy-duty vehicles
- Transit buses
- Aviation
- Marine vessels
New Electric Sector Resource Options

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

<table>
<thead>
<tr>
<th>Thermal</th>
<th>Renewable</th>
<th>Energy Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Combustion Turbine (CT)</td>
<td>Onshore/Offshore Wind</td>
<td>Pumped Hydro</td>
</tr>
<tr>
<td>Gas Combined Cycle (CC)</td>
<td>Solar PV</td>
<td>Lithium-ion</td>
</tr>
<tr>
<td>Gas CC with Carbon Capture and Sequestration (CC w/ CCS)</td>
<td>Geothermal</td>
<td>Vanadium Flow</td>
</tr>
</tbody>
</table>
### Supply-Side Fuel Options

<table>
<thead>
<tr>
<th>Diesel Fuel</th>
<th>Jet Fuel</th>
<th>Pipeline Gas</th>
<th>Liquid Hydrogen</th>
<th>Gasoline Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power-to-Diesel</td>
<td>Power-to-Jet Fuel</td>
<td>Power-to-Gas</td>
<td>Electrolysis</td>
<td>Corn Ethanol</td>
</tr>
<tr>
<td>FT Diesel</td>
<td>FT Jet Fuel</td>
<td>Hydrogen</td>
<td>Natural Gas Reformation</td>
<td>Cellulosic Ethanol</td>
</tr>
<tr>
<td>FT Diesel with CCS</td>
<td>FT Jet Fuel with CCS</td>
<td>Biomass Gasification</td>
<td>Natural Gas Reformation with CCS</td>
<td>Steam</td>
</tr>
<tr>
<td>FT Diesel with CCU</td>
<td>FT Jet Fuel with CCU</td>
<td>Biomass Gasification with CCU</td>
<td>Natural Gas Reformation with CCU</td>
<td>Fuel Boilers</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CHP</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Electric Boilers</td>
</tr>
</tbody>
</table>

#### Acronyms
- CHP: combined heat and power
- CCS: carbon capture and sequestration
- CCU: carbon capture and utilization
- DAC: direct air capture
- FT: Fischer-Tropsch
Model Structure and Operations
EnergyPATHWAYS and RIO

**Description**

Scenario analysis tool that is used to develop economy-wide energy demand scenarios

**Application**

EnergyPATHWAYS (EP) scenario design produces parameters for RIO’s supply-side optimization:
- Demand for fuels (electricity, pipeline gas, diesel, etc.) over time
- Hourly electricity load shape
- Demand-side equipment cost

RIO returns optimized supply-side decisions to EP:
- Electricity sector portfolios, including renewable mix, energy storage capacity & duration, capacity for reliability, transmission investments, etc.
- Biomass allocation across fuels

Optimization tool to develop portfolios of low-carbon technology deployment for electricity generation and balancing, alternative fuel production, and direct air capture
RIO & EP Data and Methods have Improved across many Past Studies

<table>
<thead>
<tr>
<th>Project</th>
<th>Geography</th>
<th>EP</th>
<th>RIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risky Business Project From Risk to Return</td>
<td>National</td>
<td>U.S./Census Division</td>
<td>✓</td>
</tr>
<tr>
<td>National Renewable Energy Laboratory Electrification Futures Study</td>
<td>National</td>
<td>U.S./50 states</td>
<td>✓</td>
</tr>
<tr>
<td>National Renewable Energy Laboratory North American Renewable Integration Study</td>
<td>National</td>
<td>Canada/Mexico</td>
<td>✓</td>
</tr>
<tr>
<td>Our Children’s Trust 350 PPM Pathways for the United States</td>
<td>National</td>
<td>U.S./12 regions</td>
<td>✓</td>
</tr>
<tr>
<td>Hydro Québec Deep Decarbonization in the Northeastern U.S.</td>
<td>Regional</td>
<td>Northeast</td>
<td>✓</td>
</tr>
<tr>
<td>State of Washington: Office of the Governor Deep Decarbonization Pathways Analysis</td>
<td>State</td>
<td>WA</td>
<td>✓</td>
</tr>
<tr>
<td>Confidential California utility Economy-wide GHG policy analysis</td>
<td>State/Utility Service Territory</td>
<td>CA</td>
<td>✓</td>
</tr>
<tr>
<td>Clean Energy Transition Institute Northwest DDP Study</td>
<td>Regional</td>
<td>ID, MT, OR, WA</td>
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<tr>
<td>New Jersey Board of Public Utilities Integrated Energy Plan</td>
<td>State</td>
<td>NJ</td>
<td>✓</td>
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<tr>
<td>Portland General Electric Deep Decarbonization Pathways Analysis</td>
<td>Utility territory</td>
<td>PGE</td>
<td>✓</td>
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<td>Inter-American Development Bank Deep Decarbonization of Mexico</td>
<td>National</td>
<td>Mexico/5 Regions</td>
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<tr>
<td>Confidential Client Zero Carbon European Power Grid</td>
<td>Regional</td>
<td>EU/8 Regions</td>
<td>✓</td>
</tr>
<tr>
<td>Confidential Client Low Carbon Electricity in Japan</td>
<td>National</td>
<td>Japan/5 Regions</td>
<td>✓</td>
</tr>
<tr>
<td>Princeton University Low-Carbon Infrastructure Project (ongoing)</td>
<td>National</td>
<td>US/16 Regions</td>
<td>✓</td>
</tr>
<tr>
<td>Pathways for Florida (ongoing)</td>
<td>State</td>
<td>U.S./16 regions</td>
<td>✓</td>
</tr>
<tr>
<td>Massachusetts State Energy Plan (ongoing)</td>
<td>State</td>
<td>Northeast &amp; Canada (11 states and provinces)</td>
<td>✓</td>
</tr>
<tr>
<td>State of Washington: State Energy Strategy (ongoing)</td>
<td>Regional</td>
<td>U.S. West (11 states)</td>
<td>✓</td>
</tr>
</tbody>
</table>
### RIO Decisions Variables and Outputs

**Hours**
- 24 hr * 40 – 60 sample days = 960 – 1440 hr

**Days**
- 365 days * 1-3 weather years = 365 – 1095 days

**Years**
- 30 yr study / 2 – 5 yr timestep = 6 – 15 years

### Decision Variables and Key Results

<table>
<thead>
<tr>
<th>Decision Variables</th>
<th>Key Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator Dispatch</td>
<td>Hourly Dispatch</td>
</tr>
<tr>
<td>Transmission Flows</td>
<td>Transmission Flows</td>
</tr>
<tr>
<td>Operating Reserves</td>
<td>Market Prices</td>
</tr>
<tr>
<td>Curtailment</td>
<td>Curtailment</td>
</tr>
<tr>
<td>Load Flexibility</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Decision Variables</th>
<th>Key Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Energy Balance and Storage</td>
<td>Daily Electricity Balances</td>
</tr>
<tr>
<td>Long Duration Electricity Storage</td>
<td>Daily Fuel Balances</td>
</tr>
<tr>
<td>Dual Fuel Generator Blends</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Decision Variables</th>
<th>Key Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissions from Operations</td>
<td>Total Annual Emissions</td>
</tr>
<tr>
<td>RPS Supply and Demand</td>
<td>RPS Composition</td>
</tr>
<tr>
<td>Capacity Build, Retirement &amp; Repower</td>
<td>Incremental Build, Retirement, &amp; Repower</td>
</tr>
<tr>
<td></td>
<td>Thermal Capacity Factors</td>
</tr>
<tr>
<td></td>
<td>Annual Average Market Prices</td>
</tr>
<tr>
<td></td>
<td>Marginal Cost of Fuel Supply</td>
</tr>
</tbody>
</table>
RIO Optimizes across Time-Scales

Solution Constraints

- Carbon constraints
- RPS constraints
- CES constraints
- Build-rate constraints
- Renewable potential
- Geologic sequestration
- Biomass

Capacity build decisions

Daily fuels tracking

24 hr sequential dispatch

2010

365+ days

40-60 daily snapshots

5-year timestep

2050

2010-2050: 24 hr sequential dispatch

Daily H2 Production
RIO optimizes across Geographic Constraints

- Transmission constraints and potential between states
  - Model can optimally expand interties and fuels delivery infrastructure

- Loads, resources, and new resource potentials by state
  - Captures unique geographic advantages and local conditions by state
Flexible Load Operations

Flexible Load Shapes

Cumulative Energy Constraints

Figure for methodology illustration only

- delay
- native
- advance
Economic Generator Lifecycles

RIO optimizes plant investment decisions including life extensions, repowering, and retirements based on system value and ongoing costs.

Figure for methodology illustration only.
Electricity and Fuels Sector Integration

- Traditional capacity expansion approaches have narrowly defined their problem in terms of the electric sector.
- Decarbonization and pushes towards 100% renewables has revealed the inadequacy of that approach as both will require sectoral integration.
- A key opportunity for sectoral integration is in the fuel-supply sector, as it may be counted on to provide low-carbon fuels for thermal generation/primary end uses and provide electricity balancing services to the grid.
- Endogenizing decisions in both allows us to explore opportunities for sectoral integration that have escaped other modeling frameworks.
Daily Energy Imbalances

- Renewable energy produced when the sun shines and the wind blows
- Inconvenient because it does not match production exactly with load
- Already happening in regions with significant renewable penetration
- Need to disconnect instantaneous load and supply
  - Overgeneration conditions
  - Diurnal energy storage opportunities
Energy Imbalances beyond a Day to Seasonal to Annual

- Storms or other weather events will cause multi-day energy deficits
- Seasonal energy imbalances become the dominant challenge for achieving deep decarbonization in electricity in many climates

U.S. Eastern Interconnect 2015 Load with simulated 40% Solar & 60% Onshore Wind by Energy
Balancing Load and Supply in a Decarbonized System?
RIO Fuels Structure

- Endogenous demand from electric generators
- Endogenous demand from fuel conversion processes
- Exogenous demand

Product Fuels

Conversion Fuels

Blend Fuel
Integrated Supply Side: Electricity and Fuels

- Conventional means of “balancing” may not be the most economic or meet clean energy goals
- New opportunities: Storage and flexible loads
- Fuels are another form of energy storage
- Large flexible loads from producing decarbonized fuels:
  - Electrolysis, synthetic fuels production

Source: CETI, NWDDP, 2019
Reliability

Reliable operations in a rapidly changing electricity system
Hourly Reserve Margin Constraints by Zone

Assessing Reliability Becomes Challenging in Low-Carbon Electricity Systems

### Traditional Reserve Margin

- **Nameplate**
  - Outage
  - 1-in-10
  - 1-in-2 Peak

- **15% PRM**

### Future System Reliability Assessment

- **Nameplate**
- **Non-dispatchable resource availability**
- **Renewable ELCC is uncertain**
- **Availability of energy limited resources?**
- **Which DERs will be adopted and how will they be controlled?**

- **DERs?**
- **1-in-10**
- **1-in-2 Peak**

- **Dependency between timing of peak load and dispatchable resource availability**

- **Electrification leads to rapid load growth and changes in timing of peak load**

- **Dynamic based on renewable build, DER adoption, and load growth patterns**

- **Installed renewable capacity is no longer a good measure of dependability**
How Does RIO Approach Reliability?

- Reliability is assessed across all modeled hours with explicit accounting for:
  - Demand side variations – higher gross load than sampled
  - Supply side availability – outage rates, renewable resource availability, energy availability risk, single largest contingencies
- Multiple years used in day sampling adds robustness
- Advantage over pre-computed reliability assessments because it accommodates changing load shapes and growing flexible load
  - Any pre-computed reliability assessment implicitly assumes a static load shape, which is not a realistic assumption
- No economic capacity expansion model can substitute fully for a LOLP study, but different models offer different levels of rigor
## Example Derates for Resources

<table>
<thead>
<tr>
<th>Load/Resource</th>
<th>Reliability contribution</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loads</td>
<td>106%</td>
<td>Represents weather related risk of load exceeding that sampled</td>
</tr>
<tr>
<td>Thermal resources</td>
<td>80-95%</td>
<td>Derated by generator forced outage rates</td>
</tr>
<tr>
<td>Renewable resources</td>
<td>70-90% of hourly production</td>
<td>Additional 10-30% derate from hourly profiles comes from weather related risk and is informed by statistical analysis of multiple weather years</td>
</tr>
<tr>
<td>Hydro</td>
<td>95% of hourly production</td>
<td>For energy limited resources, hourly production is used to ensure sustained peaking capability</td>
</tr>
<tr>
<td>Energy storage</td>
<td>95% of hourly production</td>
<td>Similar to hydro, energy storage must demonstrate reliability through dispatch</td>
</tr>
<tr>
<td>Imports/Exports</td>
<td>0-100% of hourly interchange</td>
<td>Depends on contractual arrangements and N-1 contingencies. By dispatching neighboring regions we ensure external resources will be available and still maintain reliability regionally.</td>
</tr>
</tbody>
</table>
Sourcing the data
EnergyPATHWAYS database includes 67 subsectors

- Primary data-sources include:
  - Annual Energy Outlook 2020 inputs/outputs (AEO; EIA)
  - Residential/Commercial Buildings/Manufacturing Energy Consumption Surveys (RECS/CBECS/MECS; EIA)
  - State Energy Data System (SEDS; DOE)
  - NREL

- 8 industrial process categories, 11 commercial building types, 3 residential building types

- 363 demand-side technologies w/ projections of cost (capital, installation, fuel-switching, O&M) and service efficiency

- commercial air conditioning
- commercial cooking
- commercial lighting
- commercial other
- commercial refrigeration
- commercial space heating
- commercial ventilation
- commercial water heating
- district services
- office equipment (non-p.c.)
- office equipment (p.c.)
- aviation
- domestic shipping
- freight rail
- heavy duty trucks
- international shipping
- light duty autos
- light duty trucks
- lubricants
- medium duty trucks
- military use
- motorcycles

- residential clothes washing
- residential computers and related
- residential cooking
- residential dishwashing
- residential freezing
- residential furnace fans
- residential lighting
- residential other uses
- residential refrigeration
- residential secondary heating
- residential space heating
- residential televisions and related
- residential water heating
- Cement and Lime CO2 Capture
- Cement and Lime Non-Energy CO2
- Iron and Steel CO2 Capture
- Other Non-Energy CO2
- Petrochemical CO2 Capture
- agriculture-crops
- agriculture-other
- aluminum industry
- balance of manufacturing other

- food and kindred products
- glass and glass products
- iron and steel
- machinery
- metal and other non-metallic mining
- paper and allied products
- plastic and rubber products
- transportation equipment
- wood products
- bulk chemicals
- cement
- computer and electronic products
- construction
- electrical equip., appliances, and components
- passenger rail
- recreational boats
- school and intercity buses
- transit buses
- residential air conditioning
- residential building shell
- residential clothes drying
## Load Shape Sources

<table>
<thead>
<tr>
<th>Shape Name</th>
<th>Used By</th>
<th>Input Data Geography</th>
<th>Input Temporal Resolution</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk System Load</td>
<td>initial electricity reconciliation, all subsectors not otherwise given a shape</td>
<td>Emissions and Generation Resource Integrated Database (EGRID) with additional granularity in the western interconnection</td>
<td>hourly, 2012</td>
<td>FERC Form No. 714</td>
</tr>
<tr>
<td>Light-Duty Vehicles (LDVs)</td>
<td>all LDVs</td>
<td></td>
<td></td>
<td>Evolved Energy Research analysis of 2016 National Household Travel Survey</td>
</tr>
<tr>
<td>Water Heating (Gas Shape)²</td>
<td>residential hot water</td>
<td></td>
<td></td>
<td>Northwest Energy Efficiency Alliance Residential Building Stock Assessment Metering Study (Northwest)</td>
</tr>
<tr>
<td>Other Appliances</td>
<td>residential TV &amp; computers</td>
<td></td>
<td></td>
<td>California Load Research Data</td>
</tr>
<tr>
<td>Lighting</td>
<td>residential lighting</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clothes Washing</td>
<td>residential clothes washing</td>
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<tr>
<td>Clothes Drying</td>
<td>residential clothes drying</td>
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<td>Dishwashing</td>
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<tr>
<td>Residential Refrigeration</td>
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<td>Residential Freezing</td>
<td>residential freezing</td>
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<td>Residential Cooking</td>
<td>residential cooking</td>
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<tr>
<td>Industrial Other</td>
<td>all other industrial loads</td>
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<td>Agriculture</td>
<td>industry agriculture</td>
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<td>Commercial Cooking</td>
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<td>Commercial Water Heating</td>
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<tr>
<td>Commercial Lighting Internal</td>
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<td>Commercial Refrigeration</td>
<td>commercial refrigeration</td>
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</table>

² Gas heating includes central heating and forced air heating.
### Load Shape Sources, Continued

<table>
<thead>
<tr>
<th>Shape Name</th>
<th>Used By</th>
<th>Input Data Geography</th>
<th>Input Temporal Resolution</th>
<th>Source</th>
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<tbody>
<tr>
<td>Commercial Ventilation</td>
<td>commercial ventilation</td>
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<td>Evolved Energy Research Regressions trained on NREL building simulations in select U.S. cities for a typical meteorological year and then run on county level HDD and CDD for 2012 from the National Oceanic and Atmospheric Administration (NOAA)</td>
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<td>Commercial Office Equipment</td>
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<td>Industrial Machine Drives</td>
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<td>Industrial Process Heating</td>
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<td>commercial electric furnaces</td>
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<td>Flat shape</td>
<td>MDV and HDV charging</td>
<td>United States</td>
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</table>

*natural gas shape is used as a proxy for the service demand shape for electric hot water due to the lack of electric water heater data.*
## Supply-Side Data

<table>
<thead>
<tr>
<th>Data Category</th>
<th>Data Description</th>
<th>Supply Node</th>
<th>Source</th>
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</thead>
<tbody>
<tr>
<td>Resource Potential</td>
<td>Binned resource potential (GWh) by state with associated resource performance</td>
<td>Transmission – sited Solar PV; Onshore Wind; Offshore Wind; Geothermal</td>
<td>(Eurek et al. 2017)</td>
</tr>
<tr>
<td></td>
<td>(capacity factors) and transmission costs to reach load</td>
<td></td>
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</tr>
<tr>
<td>Resource Potential</td>
<td>Binned resource potential of biomass resources by state with associated costs</td>
<td>Biomass Primary – Herbaceous; Biomass Primary – Wood; Biomass Primary –</td>
<td>(Langholtz, Stokes, and Eaton 2016)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Waste; Biomass Primary – Corn</td>
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<tr>
<td></td>
<td>costs</td>
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</tr>
<tr>
<td>Resource Potential</td>
<td>Domestic production potential of oil</td>
<td>Oil Primary – Domestic</td>
<td>(U.S. Energy Information Administration 2020)</td>
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<tr>
<td>Product Costs</td>
<td>Commodity cost of natural gas at Henry Hub</td>
<td>Natural Gas Primary – Domestic</td>
<td>(U.S. Energy Information Administration 2020)</td>
</tr>
<tr>
<td>Product Costs</td>
<td>Undelivered costs of refined fossil products</td>
<td>Refined Fossil Diesel; Refined Fossil Jet Fuel; Refined Fossil Kerosene;</td>
<td>(U.S. Energy Information Administration 2020)</td>
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<tr>
<td></td>
<td></td>
<td>Refined Fossil Gasoline; Refined Fossil LPG</td>
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<tr>
<td>Product Costs</td>
<td>Commodity cost of Brent oil</td>
<td>Oil Primary – Domestic; Oil Primary - International</td>
<td>(U.S. Energy Information Administration 2020)</td>
</tr>
<tr>
<td>Delivery Infrastructure Costs</td>
<td>AEO transmission and delivery costs by EMM region</td>
<td>Electricity Transmission Grid; Electricity Distribution Grid</td>
<td>(U.S. Energy Information Administration 2020)</td>
</tr>
<tr>
<td>Delivery Infrastructure Costs</td>
<td>AEO transmission and delivery costs by census division and sector</td>
<td>Gas Transmission Pipeline; Gas Distribution Pipeline</td>
<td>(U.S. Energy Information Administration 2020)</td>
</tr>
<tr>
<td>Delivery Infrastructure</td>
<td>AEO delivery costs by fuel product</td>
<td>Gasoline Delivery; Diesel Delivery; Jet Fuel; LPG Fuel Delivery; Kerosene Delivery</td>
<td>(U.S. Energy Information Administration 2020)</td>
</tr>
<tr>
<td>Data Category</td>
<td>Data Description</td>
<td>Supply Node</td>
<td>Source</td>
</tr>
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<tr>
<td>Technology Cost and Performance</td>
<td>Renewable and conventional electric technology installed cost projections</td>
<td>Nuclear Power Plants; Onshore Wind Power Plants; Offshore Wind Power Plants; Transmission – Sited Solar PV Power Plants; Distribution – Sited Solar PV Power Plants; Rooftop PV Solar Power Plants; Combined – Cycle Gas Turbines; Coal Power Plants; Combined – Cycle Gas Power Plants with CCS; Coal Power Plants with CCS; Gas Combustion Turbines</td>
<td>(National Renewable Energy Laboratory 2020)</td>
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<tr>
<td>Technology Cost and Performance</td>
<td>Nth plant Direct air capture costs for sequestration and utilization</td>
<td>Direct Air Capture with Sequestration; Direct Air Capture with Utilization</td>
<td>(Keith et al. 2018)</td>
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<tr>
<td>Technology Cost and Performance</td>
<td>Gasification cost and efficiency of conversion including gas upgrading.</td>
<td>Biomass Gasification; Biomass Gasification with CCS</td>
<td>(G. del Alamo et al. 2015)</td>
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<tr>
<td>Technology Cost and Performance</td>
<td>Cost and efficiency of renewable Fischer-Tropsch diesel production.</td>
<td>Renewable Diesel; Renewable Diesel with CCS</td>
<td>(G. del Alamo et al. 2015)</td>
</tr>
<tr>
<td>Technology Cost and Performance</td>
<td>Cost and efficiency of industrial boilers</td>
<td>Electric Boilers; Other Boilers</td>
<td>(Capros et al. 2015)</td>
</tr>
<tr>
<td>Technology Cost and Performance</td>
<td>Cost and efficiency of other, existing power plant types</td>
<td>Fossil Steam Turbines; Coal Power Plants</td>
<td>(Johnson et al. 2006)</td>
</tr>
</tbody>
</table>
Impact of Covid-19

- None of the long-term forecasts include Covid impacts
- Long-term versus short-term
- Changes to near-term adoption rates of new technologies
  - Impacts on consumer spending for new appliances, vehicles etc.?
  - Accelerated action later? Delayed electrification?
  - Opportunity for economic development in post-Covid environment?
- Impact on fuel prices
  - Supply and demand imbalance
Key Results

Examples of how results are presented
A reference scenario is needed because business-as-usual is not zero-cost.

Total cost to meet clean energy goals are offset by avoided BAU costs such as fossil fuels
  - Actual Montana avoided costs, not social cost of carbon

Annual costs compare clean energy policy versus the alternative
Net Energy System Costs by Scenario

Figure for illustration purposes only

Source: Northwest Deep Decarbonization Pathways Study, June 2019, Evolved Energy Research
What Are the Least Cost Strategies that Policy Should Target?

<table>
<thead>
<tr>
<th>Energy Efficiency</th>
<th>Decarbonized Electricity</th>
<th>Decarbonized Fuels</th>
<th>Electrification</th>
<th>Carbon Capture</th>
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</thead>
<tbody>
<tr>
<td>MMBtu per person</td>
<td>tonnes CO₂ per MWh</td>
<td>kg CO₂ per MMBtu</td>
<td>Share of Total Final Energy, %</td>
<td>MMT CO₂ Capture</td>
</tr>
</tbody>
</table>

Figure for illustration purposes only

Source: Northwest Deep Decarbonization Pathways Study, June 2019, Evolved Energy Research
Final Energy Demand

Figure for illustration purposes only

Source: Northwest Deep Decarbonization Pathways Study, June 2019
Energy Supply: Electricity Generation

Electricity Generation by Resource Type (GWh) 2050

- Business as Usual
- Central
- 100% Clean Electricity Grid
- Limited Electrification and Efficiency Achieved
- No New Gas Plants for Electricity
- Increased Northwest-California Transmission
- Limited Biomass Available for Liquid Fuels

Figure for illustration purposes only

Source: Northwest Deep Decarbonization Pathways Study, June 2019
Energy Supply: Liquid and Gaseous Fuel Composition Over Time

The chart shows the composition of liquid and gaseous fuel supply mix from 2020 to 2050, with a focus on the decarbonization of diesel and jet fuel by 2035 and pipeline gas by 2045.

- **Diesel Fuel**
  - 2020: 100% Fossil Fuels
  - 2025: 50% Biofuels, 50% Fossil Fuels
  - 2030: 50% Biofuels, 50% Fossil Fuels
  - 2035: 50% Biofuels, 50% Fossil Fuels
  - 2040: 50% Biofuels, 50% Fossil Fuels
  - 2045: 50% Biofuels, 50% Fossil Fuels
  - 2050: 50% Biofuels, 50% Fossil Fuels

- **Jet Fuel**
  - 2020: 100% Fossil Fuels
  - 2025: 50% Biofuels, 50% Fossil Fuels
  - 2030: 50% Biofuels, 50% Fossil Fuels
  - 2035: 50% Biofuels, 50% Fossil Fuels
  - 2040: 50% Biofuels, 50% Fossil Fuels
  - 2045: 50% Biofuels, 50% Fossil Fuels
  - 2050: 50% Biofuels, 50% Fossil Fuels

- **Pipeline Gas**
  - 2020: 100% Fossil Fuels
  - 2025: 50% Biofuels w/CCS, 50% Fossil Fuels
  - 2030: 50% Biofuels w/CCS, 50% Fossil Fuels
  - 2035: 50% Biofuels w/CCS, 50% Fossil Fuels
  - 2040: 50% Biofuels w/CCS, 50% Fossil Fuels
  - 2045: 25% Pipeline Gas is decarbonized
  - 2050: Nearly all diesel and jet fuel are biofuels by 2045

**Source:** Northwest Deep Decarbonization Pathways Study, June 2019
Emissions Reductions from Liquid/Gaseous Fuels, and Electricity

Liquid, Gas, and Electricity Demand by Sector and Supply by Fuel Type

Figure for illustration purposes only

Source: Northwest Deep Decarbonization Pathways Study, June 2019, Evolved Energy Research