A Transformative Climate Action Framework: Putting People at the Center of our Nation’s Clean Energy Transition

Union of Concerned Scientists
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Technical Appendix

Analysis conducted and prepared by Evolved Energy Research

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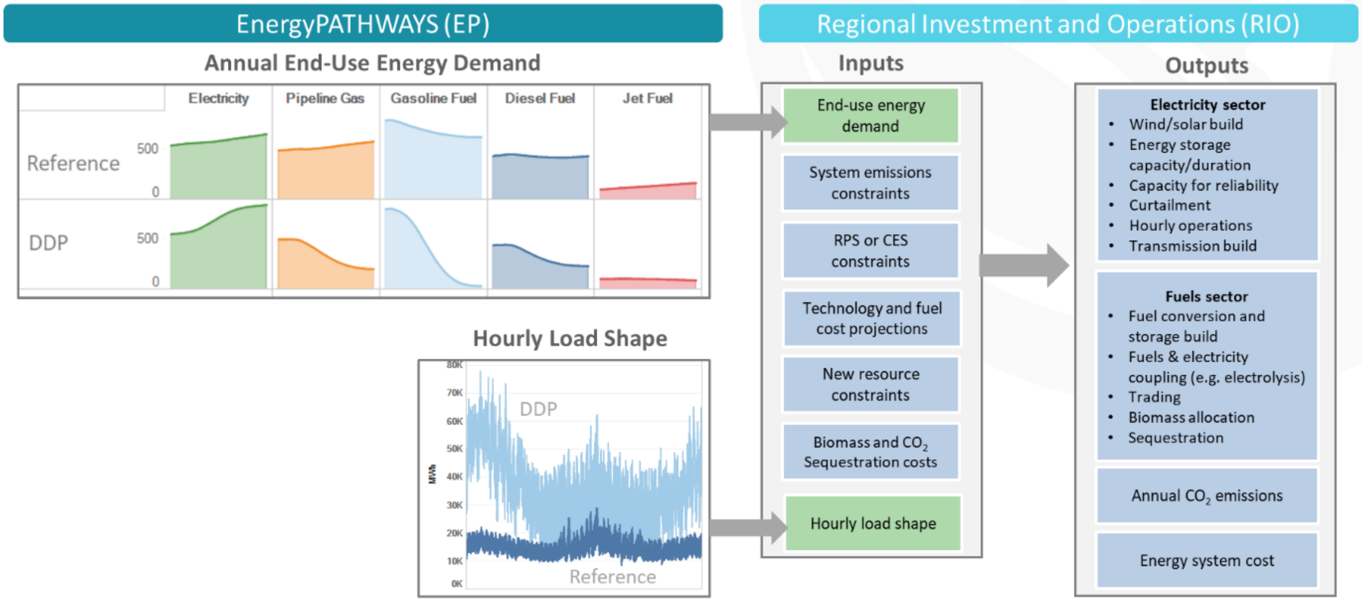
1. Methodology Overview

Modeling of the energy and industrial sectors in this study was performed using the Regional Investment and Operations (RIO) and EnergyPATHWAYS (EP), both of which are numerical models with high temporal, sectoral, and spatial resolution developed by Evolved Energy Research to study energy system transformation. EP is a bottom-up stock accounting model used to create final-energy demand across sixty-four demand subsectors and twenty-five final energy types. This final energy demand for fuels along with time-varying (8760 hour) electricity demand profiles are used as inputs to RIO, a linear programming model that combines capacity expansion and sequential hourly operations to find least-cost supply-side pathways. This pair of models produces energy, cost, and emissions data over the 30-year study period, 2020 – 2050. Interactions between EP and RIO are illustrated in Figure 1.

RIO has unique capabilities for this analysis because it models detailed interactions among electricity generation, fuel production, and carbon capture with high temporal granularity, allowing accurate evaluation of coupling between these sectors in the context of economy-wide emissions constraints. Additionally, RIO tracks fuels and energy storage state of charge over an entire year, making it possible to access electricity balancing in high variable generation systems; RIO also solves for all infrastructure decisions on a five-year time-step to optimize the energy system transition, not only the endpoint of the period. The following two sections provide a summary of the EP and RIO models with a full methodological description beginning on page 58.

Figure 1 EnergyPATHWAYS and RIO modeling flow-chart using illustrative data (study results are not pictured). EnergyPATHWAYS is used to create final energy demand and hourly electricity shapes that get passed into the RIO model. RIO optimizes the decisions to meet this final energy demand subject to user-defined constraints.



1.1 EnergyPATHWAYS (EP)

EnergyPATHWAYS (EP) is a bottom-up stock-rollover model of all energy-using technologies in the economy, employed to represent how energy is used today and in the future. It is a comprehensive accounting framework[1] designed specifically to examine large-scale energy system transformations. It accounts for the costs and emissions associated with producing, transforming, delivering, and consuming energy in the economy.

The model assumes decision-making stasis as a baseline. For example, when projecting energy demand for residential space heating, EP implicitly assumes that consumers will replace their current water heater with a water heater of a similar type. This baseline does, however, include efficiency gains and technology development that are either required by regulatory codes and standards or can be reasonably anticipated based on techno-economic projections. Departures from the baseline are made explicitly in scenarios through the

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[1] EnergyPATHWAYS is a scenario accounting tool that tracks user-defined decisions on the evolution of end-use energy. Unlike RIO, it does not optimize decisions based on cost or other criteria. The demand-side lends itself to scenario analysis because: (1) consumer decisions often do not reflect a cost minimization; (2) demand solutions between subsectors have fewer interactive effects than on the supply side; (3) the basic strategies of efficiency and fuel-switching (electrification) have few degrees of freedom when studying net-zero carbon targets (e.g. actions do not “trade-off” against one another as might happen when studying less aggressive carbon targets because all actions are required at a high degree).

application of *measures*. Measures can take the form of changes in sales shares (the adoption of a specific technology in a specific year) or in changes of stock (the total technology deployed in a specific year). Approximately 30 economic subsectors are represented by stock rollover, meaning changes in stock as new stock is added and old stock is retired. Other sectors that lack sufficiently granular data to create a stock representation are modeled with aggregate energy demands that trend over time or are exogenously specified from sources like the Energy Information Administration's (EIA) U.S. Annual Energy Outlook (e.g. aviation). These non-stock subsectors still have fuel switching and electrification measures applied at an assumed cost, but with less specificity in the underlying technology transition.

Inputs to determining final energy demand include:

1. Demand drivers – the characteristics of the energy economy that determine how people consume energy and in what quantity over time. Examples include population, square footage of commercial building types, and vehicle miles traveled. Demand drivers are the basis for forecasting future demand for energy services.

2. Service demand – Energy is not consumed for its own sake but to accomplish a service, such as heating homes, moving vehicles, and manufacturing goods.

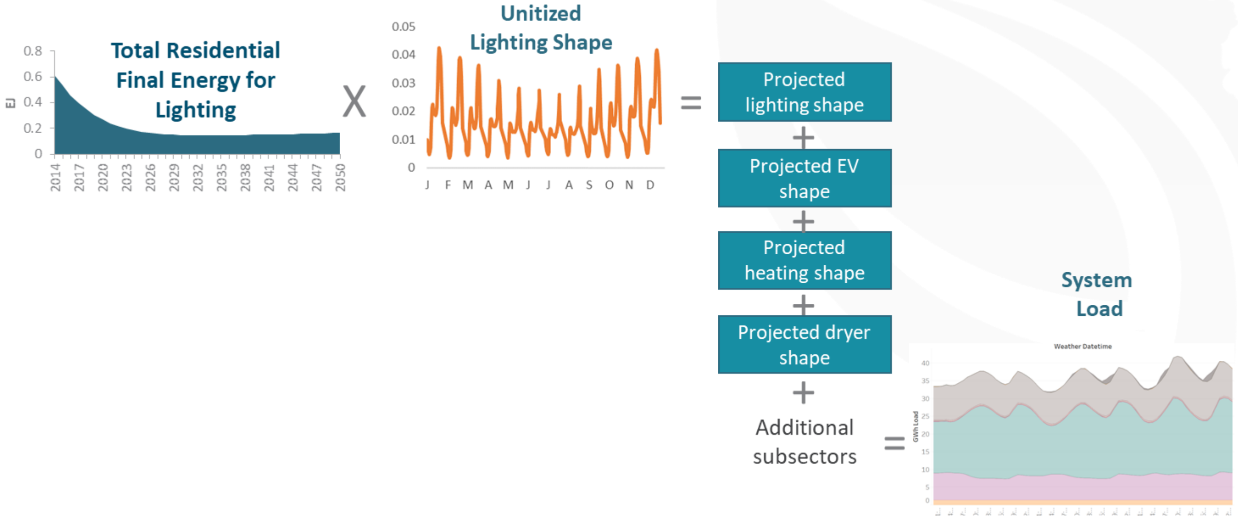
3. Technology efficiency – how efficiently technologies convert fuel or electricity into energy services. For example, how fuel efficient a vehicle is in converting gallons of gasoline into miles traveled.

4. Technology stock – what quantity of each type of technology is present in the population and how that stock changes over time. For example, how many gasoline, diesel, and electric cars are on the road in each year.

EP determines sectoral energy demand for every year over the model time horizon by dividing service demand by technology efficiency, considering the stock composition. Service demand and technology stocks are tracked separately for each zone (zones are shown in Figure 5) and the aggregate final energy demand must be met by supply-side energy production and delivery, modeled in RIO.

Due to the importance of hourly fluctuations in electricity demand when planning and operating the electricity system, a final step is taken in EP to build hourly load shapes bottom-up for future years, as illustrated in Figure 2. Each electricity-consuming sub-sector in the model has a normalized annual load shape with hourly time steps. Electrical final energy demand is multiplied by the load shape to obtain the hourly loads of each subsector. These are aggregated to obtain estimates of bulk system load. Benchmarking is done against historical system load shapes and correction factors are calculated and applied to correct for bias in the bottom-up estimates.

Figure 2 EP estimates system load shapes bottom-up by multiplying annual energy consumption by hourly allocation factors representing service demand patterns. Estimates for hourly allocation factors come from a *variety of sources, listed in Table 20. A benchmarking process is used to compare bottom-up estimates with 'known' historical bulk load that results in a series of correction factors, applied across future years.*



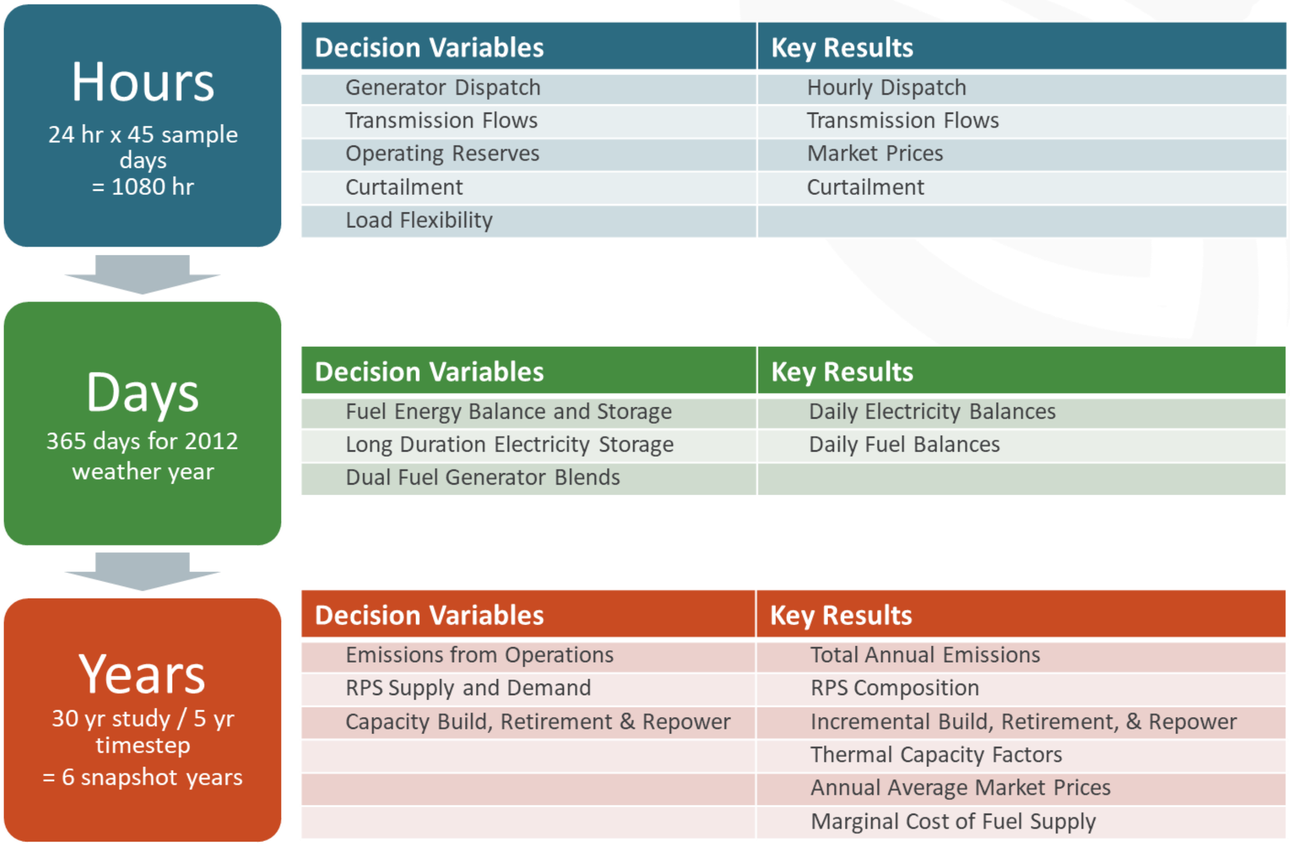
1.2 Regional Investment and Operations Model (RIO)

On the supply side, least-cost investments in electricity and fuel production to meet carbon and other constraints are determined using a capacity expansion model called the Regional Investment and Operations model (RIO). RIO is a linear program that optimizes investments and operations starting with current energy system infrastructure. It incorporates final energy demand in future years, the future technology and fuel options available (including their efficiency, operating, and cost characteristics), and clean energy goals (such as RPS, CES, and carbon intensity). Operational and capacity expansion decisions are co-optimized across all zones to minimize the present value cost of the energy system while still reaching emissions targets.

Multiple timescales are simultaneously relevant in energy system planning and operations, and the emerging importance of variable generation (wind and solar) in future power systems means that high temporal fidelity in electricity operations has increased in importance. RIO decision variables and temporal scales are shown in Figure 3.

The most important distinction between RIO and other capacity expansion models is the inclusion of the fuels system, making it possible to co-optimize across the entire supply-side of the energy system, while enforcing economy-wide emissions constraints within each zone. This is important for understanding critical factors like: coupling between the fuels and electricity sector; allocating scarce biomass resources across the economy; accounting for competition among low-cost geological storage sites; and exploring how the blending of clean drop-in fuels can help decarbonize existing electricity generators.

Figure 3 Relevant time scales in RIO along with the decision variables and key results for each. The model works to find a solution to each decision variable that minimizes total energy system cost while respecting all user-defined constraints, such as annual carbon emissions.



Hours

24 hr x 45 sample days
= 1080 hr

Decision Variables	Key Results
Generator Dispatch	Hourly Dispatch
Transmission Flows	Transmission Flows
Operating Reserves	Market Prices
Curtailment	Curtailment
Load Flexibility	

Days

365 days for 2012 weather year

Decision Variables	Key Results
Fuel Energy Balance and Storage	Daily Electricity Balances
Long Duration Electricity Storage	Daily Fuel Balances
Dual Fuel Generator Blends	

Years

30 yr study / 5 yr timestep
= 6 snapshot years

Decision Variables	Key Results
Emissions from Operations	Total Annual Emissions
RPS Supply and Demand	RPS Composition
Capacity Build, Retirement & Repower	Incremental Build, Retirement, & Repower
	Thermal Capacity Factors
	Annual Average Market Prices
	Marginal Cost of Fuel Supply

RIO utilizes the 8760 hourly profiles for electricity demand and generation from EnergyPATHWAYS and optimizes operations for a subset of representative days ("sample days") before mapping them back to the full year. Operations are performed over sequential hourly timesteps. Clustering of days using several dozen features or diurnal 'characteristics' is used with careful attention to ensure that the sampled days represent the full range of conditions encountered in the historical weather year. The clustering process is designed to identify days that represent a diverse set of potential system conditions, including different fixed generation profiles and load shapes. The number of sample days impacts the total runtime of the model and trades off with the ability to represent a range of historical conditions. Across the U.S. zones, 40 sample days was found to strike the right balance, giving both good day sampling statistics and reasonable model runtimes.

Figure 4 Operational framework for the RIO model. Forty sample days map back to 365 days over which fuels and long duration storage are tracked. The model represents years 2020 – 2050 with a 5-year timestep.

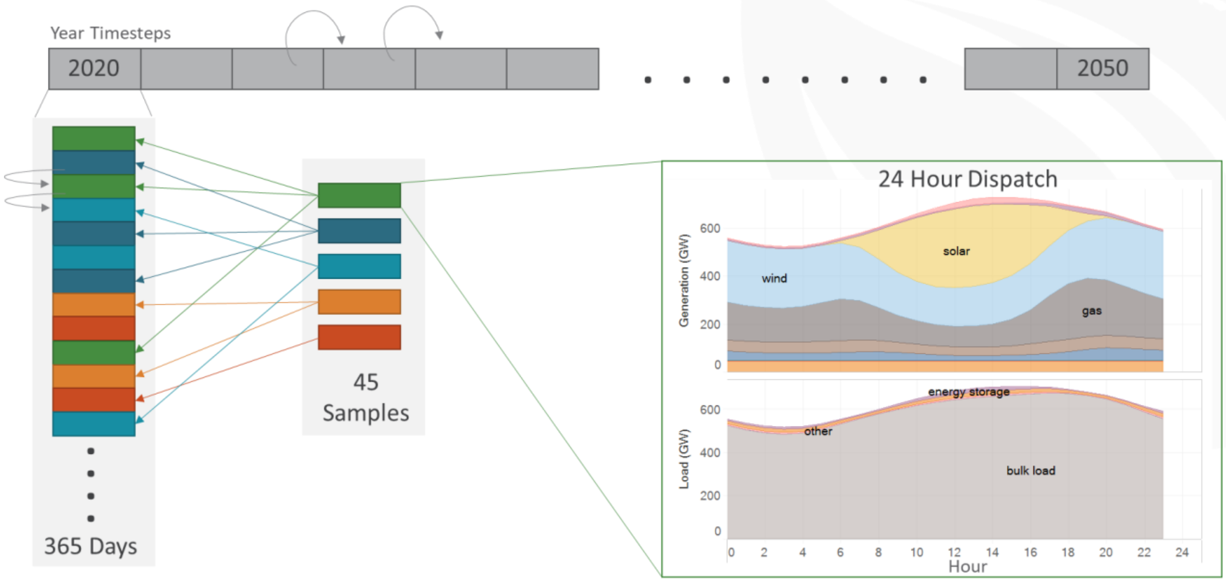


Table 1 provides a full list of RIO features along with the specific configurations used here. Additional detail on the RIO model is provided in Section 5.

Table 1 List of important RIO features and parameters

Feature	Settings used for the UCS Zero Carbon Pathways Analysis
Optimal generator selection	All generator types listed in Section 3.3.
Optimal energy storage selection	Optimal selection of energy & capacity, priced separately.
Long duration storage	Enabled with tracking of long duration state of charge across 365 days.
Optimal transmission selection	Enabled for all existing paths.
Optimal fuel technologies	Flexible framework allowing for selection and operations of any fuel conversion and supply infrastructure. Fuel conversions that consume electricity allowed to co-optimize operations with electricity generation.
Fuels storage	Optimal build and state-of-charge tracking over 365 days for hydrogen.
Dual fuel generators	All existing and new gas generators capable of burning a hythane mix of up to 60% hydrogen.
Flexible load	Traditional load shedding and a detailed framework with cumulative energy constraints for end-use flexible loads.
Number of zones	16 zones co-optimized in RIO
Number of resource bins	15 NREL TRG bins for wind and 6 bins for solar PV per zone.
Year timestep	Model run for the years 2020, 2025, 2030, 2035, 2040, 2045, 2050.
Hours modeled per year	40 sample days

Weather years	Weather year 2011
Day sample dependency on year	No dependency. Future years sample different calendar days because electrification and increasing penetrations of renewables will change the days that are most critical to represent.
Perfect foresight	RIO has perfect foresight because all model time periods are simultaneously solved.
Electricity reliability	Determined endogenously with hourly tracking of planning reserve margins and resource derates to account for weather-related risk.
Renewable capacity value	Determined endogenously as pre-computed values can have little utility with increasing electrification and changes in system load shape.
Load shapes	Built bottom-up in EnergyPATHWAYS
Generator retirements	Announced retirements are enforced. Otherwise, retirement of generators before the end of their physical lifetimes is optimized with the benefit being savings in O&M.
Generator repower/extension	Solved endogenously. At the end of their physical lifetimes, generators can be repowered at (typically) lower cost than new construction.
Annual carbon emissions constraints	Straight-line path to a 46.5% reduction below 2005 levels in 2030 and zero CO2 emissions in 2050 provided in *Other assumptions included in scenarios 2-9: 1) Rooftop and distributed PV increases to 111 GW by 2030 and 500 GW by 2050, assuming 45% of the technical potential from NREL's 2016 Rooftop Solar Photovoltaic Technical Potential in the United States report, and 2) offshore wind increases to at least 30 GW by 2030, 45 GW in 2035, and 55 GW in 2040, based on current and projected state commitments. Table 9. Total U.S. heat-trapping emissions are 50% below 2005 levels by 2005 and net zero (with the land sink) by 2050. Non-CO2 gases and the land sink are exogenous to the modeling.
Cumulative carbon emission constraints	None applied
Carbon taxes	None applied
RPS/CES	Existing state policy (2019)
RPS/CES qualification	Existing state resource qualifications
Annual resource build constraints	Annual maximum builds by resource group defined with compound growth rates to represent supply-chain constraints
Cumulative resource build constraints	Potential constraints enforced for all renewables with data derived from the NREL ReEDS model.
Fuel prices	Specified exogenously for fossil and with supply curves for biomass and carbon sequestration.
Biomass allocation	Determined endogenously between electricity and fuels
Carbon sequestration/use allocation	Determined endogenously between electricity, fuels, and industry

1.3 Cost Methodology

The cost estimates for the decarbonization pathways are derived using a suite of methodologies that cover the whole energy system. Table 2 provides a list of the cost calculation methods for each component of the energy system, along with examples.

These costs are presented two different ways. First shown are gross system cost. This includes capital and operating costs for anything that produces or delivers energy along with incremental costs above the baseline for demand-side technologies. Second is net system cost, which focuses on differences between gross system costs between two pathways. The 'reference' scenario without any carbon constraints serves as the comparison point for all net cost calculations. Not included in the cost estimates presented here are any macroeconomic feedbacks, benefits from avoided climate change, benefits from improved air quality, policy & implementation costs, and employment impacts.

All costs are assessed on a societal basis. This means, for example, that the cost of biomass is summed for each price tier of the biomass supply curve, as opposed to being calculated based on the marginal price of the final tier, as might happen in a market for biomass. Using the societal method is appropriate from a public policy perspective because, in this example, the market profits from biomass growers are not a true cost, but rather a cost transfer. The same dynamic exists in electricity markets, where a societal cost approach is also taken. The societal cost here does not include explicit assessments of the different costs across members of society.

Table 2 List of energy system costs included in this analysis and the basic methods used for each.

Supply/Demand	Fixed/Variable	Method	Costs	Examples
Demand	Fixed	Technology Stock	Levelized equipment costs of all energy-consuming equipment in the economy represented at the technology level	Electric Vehicles
Demand	Fixed	Generic cost per unit of energy saved	Incremental energy efficiency measure costs. Represents demand-side costs where technology-level data is not available to support bottom-up calculation.	Industrial energy efficiency measures
Supply	Fixed	Technology Stock	Levelized equipment costs of all energy producing, converting, delivering, and storing infrastructure in the economy represented at the technology level	Solar Power Plants; Wind Power Plants; Battery Storage; Hydrogen Electrolysis Facilities
Supply	Fixed/Variable	Revenue Requirement	Projected revenue requirements based on current revenue requirements, anticipated growth levels consistent with scenarios (i.e. growing peak demand) and type of	Electricity T&D Costs; Gas T&D Costs

			costs (i.e. the costs can be fixed investments or variable costs that can decline with lower demand).	
Supply	Variable	Commodity Costs	Costs based on exogenous unit cost assumptions	Biomass, Fossil Gasoline, Fossil Diesel, Natural Gas, etc.

1.4 Model topology

Many regions of the US are highly interconnected to surrounding regions through electricity transmission and fuels supply. RIO represents transmission zones and the constraints in shifting energy between them. The modeled regional topology of the US is shown in Figure 5 below. Constraints between regions start from present day electricity transmission capacity and include the planned transmission expansion. Transmission of electricity is also allowed to expand between regions. Expanding transmission has an associated cost per additional MW of transmission that is specific to each modeled transmission corridor.

Figure 5: Model topology for RIO and EnergyPATHWAYS

2. Scenario Descriptions

Scenarios consist of combinations of energy demand assumptions as well as emissions targets and other constraints applied to the entire energy economy on the supply-side. In this framework, we have nine different scenarios, summarized in Table 3. Additional details on the inputs for each scenario are contained within the following sections.

Table 3 Summary of scenarios

	Scenario	Description
1.	Reference	No new policies or emission constraints, using assumptions primarily from EIA's Annual Energy Outlook 2019 and 2020 and NREL's Annual Technology Baseline 2019.
2.	Zero CO2 2050	US achieves CO_2 reductions of 46.5% below 2005 levels by 2030 declining to zero CO_2 emissions by 2050, resulting in a cumulative CO_2 budget of 77 GT for 2020-2050. Total net U.S. heat-trapping emissions are more than 50% below 2005 levels by 2030 and net zero by 2050 with the land sink fixed at current levels. Non-CO_2 gases and the land sink are exogenous to model (see Table 9). Transportation sector uses core case vehicle electrification assumptions (see scenario 6).
Sensitivities to Zero CO_2 2050 case		
3.	Low energy demand	Assumes additional 20% reduction in demand in buildings and 33% reduction in industry based on ACEEE study. For transportation, assumes 40% reduction in driving, 100% increase in transit/school buses and rail, and a 20% reduction in flying and other goods movement. Coal phased out by 2030 in the power sector.
4.	50% biomass supply	Assumes half the biomass supply from DOE billion-ton study.
5.	Renewable build limits	Limit onshore wind builds to 25 GW/yr and utility-scale solar PV builds to 30 GW/yr in 2030 and 40 GW/yr 2040-2050. Assumes PV will have more siting flexibility and fewer transmission constraints.
Vehicle electrification scenarios (combined with the Zero CO_2 2050 carbon cap)		
6.	Core EV	100% ZEV sales share from LDV by 2035 and MDV/HDV by 2040 based on House Select Committee proposal.
7.	5 year+ EV delay	100% ZEV sales share from LDV by 2040, MDV by 2045, and HDV by 2050
8.	10 year+ EV delay	100% ZEV sales share from LDV by 2045, MDV by 2050 and 97% HDV by 2050
9.	Accelerated EV	100% ZEV sales share from LDV, MDV, and HDV by 2035

2.1 Demand-side cases

Across the nine scenarios, the demand-side cases can be defined by applied measures to service demand, energy efficiency, and fuel-switching. Table 4 breaks each down into the further sub-categories of buildings, transportation, and industry. Aside from the listed assumptions, all other demand-side inputs remain constant across scenarios, including technology cost and performance. The full set of data inputs can be found in Section 3 on data sources.

High efficiency trajectories are defined for many technologies. The high efficiency trajectories are adopted in all the decarbonization scenarios in this analysis. For aviation and industrial subsector where individual technologies are not tracked, percent per year efficiency improvements are used from literature.

In most cases, fuel switching means switching from fossil combustion to electricity, but the broader term also encompasses the use of hydrogen in end-uses and shifts in industrial processes, such as switching to direct reduced iron.

Table 4 Summary of demand-side assumptions for each unique demand-side case

		Reference	**Zero CO2 2050/Core EV***	**5 year+ EV delay**	**10 year+ EV delay**	**Accelerated EV**	**Low demand**
Service demand	**Buildings**	Annual Energy Outlook (AEO) 2019					20% service reductions in HVAC, lighting, and plug loads
	Transport	Annual Energy Outlook (AEO) 2019					40% service reductions in LDV and 20% service reductions in other subsectors. 100% increase in passenger rail and buses (school, intercity and transit)
	Industry	Annual Energy Outlook (AEO) 2019					33% service reductions across all subsectors
Efficiency	**Buildings**	AEO embedded efficiency	Adoption of high efficiency lighting, appliances, and residential building shell (100% sales by 2030)				
	Transport	Existing CAFE standards	1.43% per year improvement for heavy-duty trucks; 1.39% per year for medium-duty trucks; 2.7% per year for light-duty autos; 2.61% for light-duty trucks; and 1.5% per year aviation efficiency improvement				
	Industry	AEO embedded efficiency	1% per year incremental efficiency improvements across most of industry above AEO reference				

Fuel Switching	**Buildings**	NREL Electrification Futures Study Reference Adoption	Rapid heat pump adoption with 100% sales by 2040, depending on climate zone	Delayed heat pump adoption by 10 years depending on climate zone	Rapid heat pump adoption with 100% sales by 2040, depending on climate zone		
	Transport	~10% EV adoption in LDV	100% ZEV sales by 2035 for light duty autos; 100% ZEV sales by 2040 for medium and heavy duty.	100% ZEV sales share from LDV by 2040, MDV by 2045, and HDV by 2050	100% ZEV sales share from LDV by 2045, MDV by 2050 and 97% HDV by 2050	100% ZEV sales share from LDV, MDV, and HDV by 2035	Matches Zero CO_2 2050 scenario
	Industry	No electrification	Fuel switching for some process heat and other fuel use, DRI in iron and steel, carbon capture on cement	Fuel switching delayed by 15-20 years	Fuel switching for some process heat and other fuel use, DRI in iron and steel, carbon capture on cement		

* Demand-side assumptions are shared between the Zero CO_2 2050 scenario and the following scenarios not listed in the table: Renewable build limits and 50% biomass supply.

Table 4 provides an overview of demand-side assumptions. Detailed Sales shares, stock shares, and final energy demand can be found in Tables Table 5 - Table 7.

Table 5 Sales shares by scenario for each decade

Subsector	Demand Technology (group)	Scenario	2020	2030	2040	2050
commercial air conditioning	High Efficiency	Reference	3%	13%	16%	16%
commercial air conditioning	High Efficiency	Zero CO2 2050	3%	85%	94%	93%
commercial air conditioning	High Efficiency	5 year+ EV delay	3%	83%	93%	93%
commercial air conditioning	High Efficiency	Accelerated EV	3%	85%	94%	93%
commercial air conditioning	High Efficiency	Core EV	3%	85%	94%	93%
commercial air conditioning	High Efficiency	Low demand	3%	85%	94%	93%
commercial air conditioning	Reference	Reference	97%	87%	84%	84%
commercial air conditioning	Reference	Zero CO2 2050	97%	15%	6%	7%
commercial air conditioning	Reference	5 year+ EV delay	97%	17%	7%	7%
commercial air conditioning	Reference	Accelerated EV	97%	15%	6%	7%
commercial air conditioning	Reference	Core EV	97%	15%	6%	7%
commercial air conditioning	Reference	Low demand	97%	15%	6%	7%
commercial cooking	Electric	Reference	33%	35%	35%	35%
commercial cooking	Electric	Zero CO2 2050	33%	69%	96%	97%

commercial cooking	Electric	5 year+ EV delay	33%	46%	88%	96%
commercial cooking	Electric	Accelerated EV	33%	69%	96%	97%
commercial cooking	Electric	Core EV	33%	69%	96%	97%
commercial cooking	Electric	Low demand	33%	69%	96%	97%
commercial cooking	Reference	Reference	67%	65%	65%	65%
commercial cooking	Reference	Zero CO2 2050	67%	31%	4%	3%
commercial cooking	Reference	5 year+ EV delay	67%	54%	12%	4%
commercial cooking	Reference	Accelerated EV	67%	31%	4%	3%
commercial cooking	Reference	Core EV	67%	31%	4%	3%
commercial cooking	Reference	Low demand	67%	31%	4%	3%
commercial lighting	High Efficiency	Reference	52%	86%	88%	88%
commercial lighting	High Efficiency	Zero CO2 2050	49%	99%	100%	100%
commercial lighting	High Efficiency	5 year+ EV delay	49%	99%	100%	100%
commercial lighting	High Efficiency	Accelerated EV	49%	99%	100%	100%
commercial lighting	High Efficiency	Core EV	49%	99%	100%	100%
commercial lighting	High Efficiency	Low demand	49%	99%	100%	100%
commercial lighting	Reference	Reference	48%	14%	12%	12%
commercial lighting	Reference	Zero CO2 2050	51%	1%	0%	0%
commercial lighting	Reference	5 year+ EV delay	51%	1%	0%	0%
commercial lighting	Reference	Accelerated EV	51%	1%	0%	0%
commercial lighting	Reference	Core EV	51%	1%	0%	0%
commercial lighting	Reference	Low demand	51%	1%	0%	0%
commercial refrigeration	High Efficiency	Reference	0%	12%	15%	17%
commercial refrigeration	High Efficiency	Zero CO2 2050	0%	88%	100%	100%
commercial refrigeration	High Efficiency	5 year+ EV delay	0%	88%	100%	100%
commercial refrigeration	High Efficiency	Accelerated EV	0%	88%	100%	100%
commercial refrigeration	High Efficiency	Core EV	0%	88%	100%	100%
commercial refrigeration	High Efficiency	Low demand	0%	88%	100%	100%
commercial refrigeration	Reference	Reference	100%	88%	85%	83%
commercial refrigeration	Reference	Zero CO2 2050	100%	12%	0%	0%
commercial refrigeration	Reference	5 year+ EV delay	100%	12%	0%	0%
commercial refrigeration	Reference	Accelerated EV	100%	12%	0%	0%
commercial refrigeration	Reference	Core EV	100%	12%	0%	0%
commercial refrigeration	Reference	Low demand	100%	12%	0%	0%
commercial space heating	Electric	Reference	10%	18%	19%	19%
commercial space heating	Electric	Zero CO2 2050	10%	46%	95%	99%
commercial space heating	Electric	5 year+ EV delay	10%	23%	75%	97%
commercial space heating	Electric	Accelerated EV	10%	46%	95%	99%
commercial space heating	Electric	Core EV	10%	46%	95%	99%

commercial space heating	Electric	Low demand	10%	46%	95%	99%
commercial space heating	High Efficiency	Reference	0%	0%	0%	0%
commercial space heating	High Efficiency	Zero CO2 2050	0%	0%	0%	0%
commercial space heating	High Efficiency	5 year+ EV delay	0%	0%	0%	0%
commercial space heating	High Efficiency	Accelerated EV	0%	0%	0%	0%
commercial space heating	High Efficiency	Core EV	0%	0%	0%	0%
commercial space heating	High Efficiency	Low demand	0%	0%	0%	0%
commercial space heating	Reference	Reference	90%	82%	81%	81%
commercial space heating	Reference	Zero CO2 2050	90%	54%	5%	1%
commercial space heating	Reference	5 year+ EV delay	90%	77%	25%	3%
commercial space heating	Reference	Accelerated EV	90%	54%	5%	1%
commercial space heating	Reference	Core EV	90%	54%	5%	1%
commercial space heating	Reference	Low demand	90%	54%	5%	1%
commercial ventilation	High Efficiency	Zero CO2 2050	0%	87%	100%	100%
commercial ventilation	High Efficiency	5 year+ EV delay	0%	87%	100%	100%
commercial ventilation	High Efficiency	Accelerated EV	0%	87%	100%	100%
commercial ventilation	High Efficiency	Core EV	0%	87%	100%	100%
commercial ventilation	High Efficiency	Low demand	0%	87%	100%	100%
commercial ventilation	Reference	Reference	100%	100%	100%	100%
commercial ventilation	Reference	Zero CO2 2050	100%	13%	0%	0%
commercial ventilation	Reference	5 year+ EV delay	100%	13%	0%	0%
commercial ventilation	Reference	Accelerated EV	100%	13%	0%	0%
commercial ventilation	Reference	Core EV	100%	13%	0%	0%
commercial ventilation	Reference	Low demand	100%	13%	0%	0%
commercial water heating	Electric	Reference	5%	6%	6%	6%
commercial water heating	Electric	Zero CO2 2050	5%	41%	94%	100%
commercial water heating	Electric	5 year+ EV delay	5%	19%	72%	97%
commercial water heating	Electric	Accelerated EV	5%	41%	94%	100%
commercial water heating	Electric	Core EV	5%	41%	94%	100%
commercial water heating	Electric	Low demand	5%	41%	94%	100%
commercial water heating	High Efficiency	Reference	0%	0%	0%	0%
commercial water heating	High Efficiency	Zero CO2 2050	0%	0%	0%	0%
commercial water heating	High Efficiency	5 year+ EV delay	0%	0%	0%	0%
commercial water heating	High Efficiency	Accelerated EV	0%	0%	0%	0%
commercial water heating	High Efficiency	Core EV	0%	0%	0%	0%
commercial water heating	High Efficiency	Low demand	0%	0%	0%	0%
commercial water heating	Reference	Reference	95%	94%	94%	94%
commercial water heating	Reference	Zero CO2 2050	95%	59%	6%	0%
commercial water heating	Reference	5 year+ EV delay	95%	81%	28%	3%

commercial water heating	Reference	Accelerated EV	95%	59%	6%	0%
commercial water heating	Reference	Core EV	95%	59%	6%	0%
commercial water heating	Reference	Low demand	95%	59%	6%	0%
residential air conditioning	High Efficiency	Reference	10%	23%	26%	26%
residential air conditioning	High Efficiency	Zero CO2 2050	10%	90%	97%	97%
residential air conditioning	High Efficiency	5 year+ EV delay	10%	88%	97%	97%
residential air conditioning	High Efficiency	Accelerated EV	10%	90%	97%	97%
residential air conditioning	High Efficiency	Core EV	10%	90%	97%	97%
residential air conditioning	High Efficiency	Low demand	10%	90%	97%	97%
residential air conditioning	Reference	Reference	90%	77%	74%	74%
residential air conditioning	Reference	Zero CO2 2050	90%	10%	3%	3%
residential air conditioning	Reference	5 year+ EV delay	90%	12%	3%	3%
residential air conditioning	Reference	Accelerated EV	90%	10%	3%	3%
residential air conditioning	Reference	Core EV	90%	10%	3%	3%
residential air conditioning	Reference	Low demand	90%	10%	3%	3%
residential building shell	High Efficiency	Zero CO2 2050	5%	52%	100%	100%
residential building shell	High Efficiency	5 year+ EV delay	5%	52%	100%	100%
residential building shell	High Efficiency	Accelerated EV	5%	52%	100%	100%
residential building shell	High Efficiency	Core EV	5%	52%	100%	100%
residential building shell	High Efficiency	Low demand	5%	52%	100%	100%
residential building shell	Reference	Reference	100%	100%	100%	100%
residential building shell	Reference	Zero CO2 2050	95%	48%	0%	0%
residential building shell	Reference	5 year+ EV delay	95%	48%	0%	0%
residential building shell	Reference	Accelerated EV	95%	48%	0%	0%
residential building shell	Reference	Core EV	95%	48%	0%	0%
residential building shell	Reference	Low demand	95%	48%	0%	0%
residential clothes drying	High Efficiency	Reference	0%	0%	0%	0%
residential clothes drying	High Efficiency	Zero CO2 2050	1%	87%	100%	100%
residential clothes drying	High Efficiency	5 year+ EV delay	1%	76%	99%	100%
residential clothes drying	High Efficiency	Accelerated EV	1%	87%	100%	100%
residential clothes drying	High Efficiency	Core EV	1%	87%	100%	100%
residential clothes drying	High Efficiency	Low demand	1%	87%	100%	100%
residential clothes drying	Reference	Reference	100%	100%	100%	100%
residential clothes drying	Reference	Zero CO2 2050	99%	13%	0%	0%
residential clothes drying	Reference	5 year+ EV delay	99%	24%	1%	0%
residential clothes drying	Reference	Accelerated EV	99%	13%	0%	0%
residential clothes drying	Reference	Core EV	99%	13%	0%	0%
residential clothes drying	Reference	Low demand	99%	13%	0%	0%
residential clothes washing	High Efficiency	Reference	0%	0%	0%	0%

residential clothes washing	High Efficiency	Zero CO2 2050	1%	87%	100%	100%
residential clothes washing	High Efficiency	5 year+ EV delay	1%	87%	100%	100%
residential clothes washing	High Efficiency	Accelerated EV	1%	87%	100%	100%
residential clothes washing	High Efficiency	Core EV	1%	87%	100%	100%
residential clothes washing	High Efficiency	Low demand	1%	87%	100%	100%
residential clothes washing	Reference	Reference	100%	100%	100%	100%
residential clothes washing	Reference	Zero CO2 2050	99%	13%	0%	0%
residential clothes washing	Reference	5 year+ EV delay	99%	13%	0%	0%
residential clothes washing	Reference	Accelerated EV	99%	13%	0%	0%
residential clothes washing	Reference	Core EV	99%	13%	0%	0%
residential clothes washing	Reference	Low demand	99%	13%	0%	0%
residential cooking	Electric	Reference	62%	62%	62%	62%
residential cooking	Electric	Zero CO2 2050	62%	83%	100%	100%
residential cooking	Electric	5 year+ EV delay	62%	69%	95%	100%
residential cooking	Electric	Accelerated EV	62%	83%	100%	100%
residential cooking	Electric	Core EV	62%	83%	100%	100%
residential cooking	Electric	Low demand	62%	83%	100%	100%
residential cooking	Reference	Reference	38%	38%	38%	38%
residential cooking	Reference	Zero CO2 2050	38%	17%	0%	0%
residential cooking	Reference	5 year+ EV delay	38%	31%	5%	0%
residential cooking	Reference	Accelerated EV	38%	17%	0%	0%
residential cooking	Reference	Core EV	38%	17%	0%	0%
residential cooking	Reference	Low demand	38%	17%	0%	0%
residential dishwashing	High Efficiency	Zero CO2 2050	1%	87%	100%	100%
residential dishwashing	High Efficiency	5 year+ EV delay	1%	87%	100%	100%
residential dishwashing	High Efficiency	Accelerated EV	1%	87%	100%	100%
residential dishwashing	High Efficiency	Core EV	1%	87%	100%	100%
residential dishwashing	High Efficiency	Low demand	1%	87%	100%	100%
residential dishwashing	Reference	Reference	100%	100%	100%	100%
residential dishwashing	Reference	Zero CO2 2050	99%	13%	0%	0%
residential dishwashing	Reference	5 year+ EV delay	99%	13%	0%	0%
residential dishwashing	Reference	Accelerated EV	99%	13%	0%	0%
residential dishwashing	Reference	Core EV	99%	13%	0%	0%
residential dishwashing	Reference	Low demand	99%	13%	0%	0%
residential freezing	High Efficiency	Zero CO2 2050	1%	87%	100%	100%
residential freezing	High Efficiency	5 year+ EV delay	1%	87%	100%	100%
residential freezing	High Efficiency	Accelerated EV	1%	87%	100%	100%
residential freezing	High Efficiency	Core EV	1%	87%	100%	100%
residential freezing	High Efficiency	Low demand	1%	87%	100%	100%

residential freezing	Reference	Reference	100%	100%	100%	100%
residential freezing	Reference	Zero CO2 2050	99%	13%	0%	0%
residential freezing	Reference	5 year+ EV delay	99%	13%	0%	0%
residential freezing	Reference	Accelerated EV	99%	13%	0%	0%
residential freezing	Reference	Core EV	99%	13%	0%	0%
residential freezing	Reference	Low demand	99%	13%	0%	0%
residential lighting	High Efficiency	Reference	49%	80%	83%	81%
residential lighting	High Efficiency	Zero CO2 2050	48%	100%	100%	100%
residential lighting	High Efficiency	5 year+ EV delay	48%	100%	100%	100%
residential lighting	High Efficiency	Accelerated EV	48%	100%	100%	100%
residential lighting	High Efficiency	Core EV	48%	100%	100%	100%
residential lighting	High Efficiency	Low demand	48%	100%	100%	100%
residential lighting	Reference	Reference	51%	20%	17%	19%
residential lighting	Reference	Zero CO2 2050	52%	0%	0%	0%
residential lighting	Reference	5 year+ EV delay	52%	0%	0%	0%
residential lighting	Reference	Accelerated EV	52%	0%	0%	0%
residential lighting	Reference	Core EV	52%	0%	0%	0%
residential lighting	Reference	Low demand	52%	0%	0%	0%
residential refrigeration	High Efficiency	Reference	0%	0%	0%	0%
residential refrigeration	High Efficiency	Zero CO2 2050	1%	87%	100%	100%
residential refrigeration	High Efficiency	5 year+ EV delay	1%	87%	100%	100%
residential refrigeration	High Efficiency	Accelerated EV	1%	87%	100%	100%
residential refrigeration	High Efficiency	Core EV	1%	87%	100%	100%
residential refrigeration	High Efficiency	Low demand	1%	87%	100%	100%
residential refrigeration	Reference	Reference	100%	100%	100%	100%
residential refrigeration	Reference	Zero CO2 2050	99%	13%	0%	0%
residential refrigeration	Reference	5 year+ EV delay	99%	13%	0%	0%
residential refrigeration	Reference	Accelerated EV	99%	13%	0%	0%
residential refrigeration	Reference	Core EV	99%	13%	0%	0%
residential refrigeration	Reference	Low demand	99%	13%	0%	0%
residential space heating	Electric	Reference	35%	53%	55%	55%
residential space heating	Electric	Zero CO2 2050	35%	71%	94%	96%
residential space heating	Electric	5 year+ EV delay	35%	56%	86%	95%
residential space heating	Electric	Accelerated EV	35%	71%	94%	96%
residential space heating	Electric	Core EV	35%	71%	94%	96%
residential space heating	Electric	Low demand	35%	71%	94%	96%
residential space heating	High Efficiency	Reference	0%	0%	0%	0%
residential space heating	High Efficiency	Zero CO2 2050	0%	0%	0%	0%
residential space heating	High Efficiency	5 year+ EV delay	0%	0%	0%	0%

residential space heating	High Efficiency	Accelerated EV	0%	0%	0%	0%
residential space heating	High Efficiency	Core EV	0%	0%	0%	0%
residential space heating	High Efficiency	Low demand	0%	0%	0%	0%
residential space heating	Reference	Reference	65%	47%	45%	45%
residential space heating	Reference	Zero CO2 2050	65%	29%	6%	4%
residential space heating	Reference	5 year+ EV delay	65%	44%	14%	5%
residential space heating	Reference	Accelerated EV	65%	29%	6%	4%
residential space heating	Reference	Core EV	65%	29%	6%	4%
residential space heating	Reference	Low demand	65%	29%	6%	4%
residential water heating	Electric	Reference	40%	54%	54%	54%
residential water heating	Electric	Zero CO2 2050	40%	73%	98%	100%
residential water heating	Electric	5 year+ EV delay	40%	61%	88%	99%
residential water heating	Electric	Accelerated EV	40%	73%	98%	100%
residential water heating	Electric	Core EV	40%	73%	98%	100%
residential water heating	Electric	Low demand	40%	73%	98%	100%
residential water heating	High Efficiency	Reference	0%	0%	0%	0%
residential water heating	High Efficiency	Zero CO2 2050	0%	0%	0%	0%
residential water heating	High Efficiency	5 year+ EV delay	0%	0%	0%	0%
residential water heating	High Efficiency	Accelerated EV	0%	0%	0%	0%
residential water heating	High Efficiency	Core EV	0%	0%	0%	0%
residential water heating	High Efficiency	Low demand	0%	0%	0%	0%
residential water heating	Reference	Reference	60%	46%	46%	46%
residential water heating	Reference	Zero CO2 2050	60%	27%	2%	0%
residential water heating	Reference	5 year+ EV delay	60%	39%	12%	1%
residential water heating	Reference	Accelerated EV	60%	27%	2%	0%
residential water heating	Reference	Core EV	60%	27%	2%	0%
residential water heating	Reference	Low demand	60%	27%	2%	0%
heavy duty trucks	Electric	Reference	0%	0%	0%	0%
heavy duty trucks	Electric	Zero CO2 2050	0%	11%	50%	62%
heavy duty trucks	Electric	5 year+ EV delay	0%	5%	31%	60%
heavy duty trucks	Electric	Accelerated EV	0%	47%	62%	62%
heavy duty trucks	Electric	Core EV	0%	19%	62%	62%
heavy duty trucks	Electric	Low demand	0%	11%	50%	62%
heavy duty trucks	High Efficiency	Reference	0%	0%	0%	0%
heavy duty trucks	High Efficiency	Zero CO2 2050	0%	0%	0%	0%
heavy duty trucks	High Efficiency	5 year+ EV delay	0%	0%	0%	0%
heavy duty trucks	High Efficiency	Accelerated EV	0%	0%	0%	0%
heavy duty trucks	High Efficiency	Core EV	0%	0%	0%	0%
heavy duty trucks	High Efficiency	Low demand	0%	0%	0%	0%

heavy duty trucks	Reference	Reference	100%	100%	100%	100%
heavy duty trucks	Reference	Zero CO2 2050	100%	83%	20%	0%
heavy duty trucks	Reference	5 year+ EV delay	100%	92%	50%	3%
heavy duty trucks	Reference	Accelerated EV	100%	25%	0%	0%
heavy duty trucks	Reference	Core EV	100%	70%	0%	0%
heavy duty trucks	Reference	Low demand	100%	83%	20%	0%
heavy duty trucks	Hydrogen	Reference	0%	0%	0%	0%
heavy duty trucks	Hydrogen	Zero CO2 2050	0%	6%	30%	38%
heavy duty trucks	Hydrogen	5 year+ EV delay	0%	3%	19%	37%
heavy duty trucks	Hydrogen	Accelerated EV	0%	28%	38%	38%
heavy duty trucks	Hydrogen	Core EV	0%	11%	38%	38%
heavy duty trucks	Hydrogen	Low demand	0%	6%	30%	38%
light duty autos	Electric	Reference	6%	9%	15%	18%
light duty autos	Electric	Zero CO2 2050	6%	40%	96%	95%
light duty autos	Electric	5 year+ EV delay	6%	20%	77%	95%
light duty autos	Electric	Accelerated EV	6%	73%	95%	95%
light duty autos	Electric	Core EV	6%	45%	96%	95%
light duty autos	Electric	Low demand	6%	40%	96%	95%
light duty autos	High Efficiency	Reference	6%	10%	11%	11%
light duty autos	High Efficiency	Zero CO2 2050	7%	7%	0%	0%
light duty autos	High Efficiency	5 year+ EV delay	7%	9%	3%	0%
light duty autos	High Efficiency	Accelerated EV	7%	3%	0%	0%
light duty autos	High Efficiency	Core EV	7%	6%	0%	0%
light duty autos	High Efficiency	Low demand	7%	7%	0%	0%
light duty autos	Reference	Reference	88%	80%	74%	71%
light duty autos	Reference	Zero CO2 2050	87%	53%	0%	0%
light duty autos	Reference	5 year+ EV delay	87%	71%	17%	0%
light duty autos	Reference	Accelerated EV	87%	22%	0%	0%
light duty autos	Reference	Core EV	87%	49%	0%	0%
light duty autos	Reference	Low demand	87%	53%	0%	0%
light duty autos	Hydrogen	Reference	0%	0%	0%	0%
light duty autos	Hydrogen	Zero CO2 2050	0%	0%	4%	5%
light duty autos	Hydrogen	5 year+ EV delay	0%	0%	3%	5%
light duty autos	Hydrogen	Accelerated EV	0%	2%	5%	5%
light duty autos	Hydrogen	Core EV	0%	0%	4%	5%
light duty autos	Hydrogen	Low demand	0%	0%	4%	5%
light duty trucks	Electric	Reference	1%	1%	2%	3%
light duty trucks	Electric	Zero CO2 2050	1%	29%	92%	91%
light duty trucks	Electric	5 year+ EV delay	1%	17%	64%	91%

light duty trucks	Electric	Accelerated EV	1%	71%	90%	90%
light duty trucks	Electric	Core EV	1%	34%	92%	91%
light duty trucks	Electric	Low demand	1%	29%	92%	91%
light duty trucks	High Efficiency	Reference	1%	3%	4%	7%
light duty trucks	High Efficiency	Zero CO2 2050	1%	2%	0%	0%
light duty trucks	High Efficiency	5 year+ EV delay	1%	3%	1%	0%
light duty trucks	High Efficiency	Accelerated EV	1%	1%	0%	0%
light duty trucks	High Efficiency	Core EV	1%	2%	0%	0%
light duty trucks	High Efficiency	Low demand	1%	2%	0%	0%
light duty trucks	Reference	Reference	98%	95%	93%	90%
light duty trucks	Reference	Zero CO2 2050	98%	68%	0%	0%
light duty trucks	Reference	5 year+ EV delay	98%	80%	29%	0%
light duty trucks	Reference	Accelerated EV	98%	24%	0%	0%
light duty trucks	Reference	Core EV	98%	63%	0%	0%
light duty trucks	Reference	Low demand	98%	68%	0%	0%
light duty trucks	Hydrogen	Reference	0%	0%	0%	0%
light duty trucks	Hydrogen	Zero CO2 2050	0%	1%	8%	9%
light duty trucks	Hydrogen	5 year+ EV delay	0%	0%	6%	9%
light duty trucks	Hydrogen	Accelerated EV	0%	5%	10%	10%
light duty trucks	Hydrogen	Core EV	0%	1%	8%	9%
light duty trucks	Hydrogen	Low demand	0%	1%	8%	9%
medium duty trucks	Electric	Reference	0%	0%	1%	1%
medium duty trucks	Electric	Zero CO2 2050	0%	19%	64%	70%
medium duty trucks	Electric	5 year+ EV delay	0%	9%	41%	70%
medium duty trucks	Electric	Accelerated EV	0%	62%	70%	70%
medium duty trucks	Electric	Core EV	0%	28%	75%	70%
medium duty trucks	Electric	Low demand	0%	19%	64%	70%
medium duty trucks	High Efficiency	Reference	0%	0%	0%	1%
medium duty trucks	High Efficiency	Zero CO2 2050	0%	0%	0%	0%
medium duty trucks	High Efficiency	5 year+ EV delay	0%	0%	0%	0%
medium duty trucks	High Efficiency	Accelerated EV	0%	0%	0%	0%
medium duty trucks	High Efficiency	Core EV	0%	0%	0%	0%
medium duty trucks	High Efficiency	Low demand	0%	0%	0%	0%
medium duty trucks	Reference	Reference	100%	99%	98%	98%
medium duty trucks	Reference	Zero CO2 2050	100%	80%	15%	0%
medium duty trucks	Reference	5 year+ EV delay	100%	90%	45%	0%
medium duty trucks	Reference	Accelerated EV	100%	25%	0%	0%
medium duty trucks	Reference	Core EV	100%	70%	0%	0%
medium duty trucks	Reference	Low demand	100%	80%	15%	0%

medium duty trucks	Hydrogen	Reference	0%	0%	0%	0%
medium duty trucks	Hydrogen	Zero CO2 2050	0%	1%	21%	30%
medium duty trucks	Hydrogen	5 year+ EV delay	0%	1%	14%	30%
medium duty trucks	Hydrogen	Accelerated EV	0%	14%	30%	30%
medium duty trucks	Hydrogen	Core EV	0%	2%	25%	30%
medium duty trucks	Hydrogen	Low demand	0%	1%	21%	30%
transit buses	Electric	Reference	1%	1%	1%	1%
transit buses	Electric	Zero CO2 2050	1%	27%	95%	100%
transit buses	Electric	5 year+ EV delay	1%	11%	67%	97%
transit buses	Electric	Accelerated EV	1%	27%	95%	100%
transit buses	Electric	Core EV	1%	27%	95%	100%
transit buses	Electric	Low demand	1%	27%	95%	100%
transit buses	High Efficiency	Reference	19%	19%	19%	19%
transit buses	High Efficiency	Zero CO2 2050	17%	13%	1%	0%
transit buses	High Efficiency	5 year+ EV delay	17%	15%	6%	0%
transit buses	High Efficiency	Accelerated EV	17%	13%	1%	0%
transit buses	High Efficiency	Core EV	17%	13%	1%	0%
transit buses	High Efficiency	Low demand	17%	13%	1%	0%
transit buses	Reference	Reference	80%	80%	80%	80%
transit buses	Reference	Zero CO2 2050	82%	60%	4%	0%
transit buses	Reference	5 year+ EV delay	82%	74%	27%	2%
transit buses	Reference	Accelerated EV	82%	60%	4%	0%
transit buses	Reference	Core EV	82%	60%	4%	0%
transit buses	Reference	Low demand	82%	60%	4%	0%

Table 6 Stock-shares for each scenario by decade

Subsector	Demand Technology (group)	Scenario	2020	2030	2040	2050
commercial air conditioning	High Efficiency	Reference	5%	10%	13%	14%
commercial air conditioning	High Efficiency	Zero CO2 2050	5%	27%	72%	89%
commercial air conditioning	High Efficiency	5 year+ EV delay	5%	26%	69%	88%
commercial air conditioning	High Efficiency	Accelerated EV	5%	27%	72%	89%
commercial air conditioning	High Efficiency	Core EV	5%	27%	72%	89%
commercial air conditioning	High Efficiency	Low demand	5%	27%	72%	89%
commercial air conditioning	Reference	Reference	95%	90%	87%	86%
commercial air conditioning	Reference	Zero CO2 2050	95%	73%	28%	11%
commercial air conditioning	Reference	5 year+ EV delay	95%	74%	31%	12%
commercial air conditioning	Reference	Accelerated EV	95%	73%	28%	11%
commercial air conditioning	Reference	Core EV	95%	73%	28%	11%

commercial air conditioning	Reference	Low demand	95%	73%	28%	11%
commercial cooking	Electric	Reference	35%	34%	35%	35%
commercial cooking	Electric	Zero CO2 2050	35%	46%	88%	97%
commercial cooking	Electric	5 year+ EV delay	35%	39%	68%	93%
commercial cooking	Electric	Accelerated EV	35%	46%	88%	97%
commercial cooking	Electric	Core EV	35%	46%	88%	97%
commercial cooking	Electric	Low demand	35%	46%	88%	97%
commercial cooking	Reference	Reference	65%	66%	65%	65%
commercial cooking	Reference	Zero CO2 2050	65%	54%	12%	3%
commercial cooking	Reference	5 year+ EV delay	65%	61%	32%	7%
commercial cooking	Reference	Accelerated EV	65%	54%	12%	3%
commercial cooking	Reference	Core EV	65%	54%	12%	3%
commercial cooking	Reference	Low demand	65%	54%	12%	3%
commercial lighting	High Efficiency	Reference	39%	85%	93%	94%
commercial lighting	High Efficiency	Zero CO2 2050	39%	92%	100%	100%
commercial lighting	High Efficiency	5 year+ EV delay	39%	92%	100%	100%
commercial lighting	High Efficiency	Accelerated EV	39%	92%	100%	100%
commercial lighting	High Efficiency	Core EV	39%	92%	100%	100%
commercial lighting	High Efficiency	Low demand	39%	92%	100%	100%
commercial lighting	Reference	Reference	61%	15%	7%	6%
commercial lighting	Reference	Zero CO2 2050	61%	8%	0%	0%
commercial lighting	Reference	5 year+ EV delay	61%	8%	0%	0%
commercial lighting	Reference	Accelerated EV	61%	8%	0%	0%
commercial lighting	Reference	Core EV	61%	8%	0%	0%
commercial lighting	Reference	Low demand	61%	8%	0%	0%
commercial refrigeration	High Efficiency	Reference	0%	9%	14%	17%
commercial refrigeration	High Efficiency	Zero CO2 2050	0%	36%	90%	100%
commercial refrigeration	High Efficiency	5 year+ EV delay	0%	36%	90%	100%
commercial refrigeration	High Efficiency	Accelerated EV	0%	36%	90%	100%
commercial refrigeration	High Efficiency	Core EV	0%	36%	90%	100%
commercial refrigeration	High Efficiency	Low demand	0%	36%	90%	100%
commercial refrigeration	Reference	Reference	100%	91%	86%	83%
commercial refrigeration	Reference	Zero CO2 2050	100%	64%	10%	0%
commercial refrigeration	Reference	5 year+ EV delay	100%	64%	10%	0%
commercial refrigeration	Reference	Accelerated EV	100%	64%	10%	0%
commercial refrigeration	Reference	Core EV	100%	64%	10%	0%
commercial refrigeration	Reference	Low demand	100%	64%	10%	0%
commercial space heating	Electric	Reference	14%	17%	20%	20%
commercial space heating	Electric	Zero CO2 2050	14%	20%	59%	88%

commercial space heating	Electric	5 year+ EV delay	14%	15%	39%	75%
commercial space heating	Electric	Accelerated EV	14%	20%	59%	88%
commercial space heating	Electric	Core EV	14%	20%	59%	88%
commercial space heating	Electric	Low demand	14%	20%	59%	88%
commercial space heating	High Efficiency	Reference	0%	0%	0%	0%
commercial space heating	High Efficiency	Zero CO2 2050	0%	0%	0%	0%
commercial space heating	High Efficiency	5 year+ EV delay	0%	0%	0%	0%
commercial space heating	High Efficiency	Accelerated EV	0%	0%	0%	0%
commercial space heating	High Efficiency	Core EV	0%	0%	0%	0%
commercial space heating	High Efficiency	Low demand	0%	0%	0%	0%
commercial space heating	Reference	Reference	86%	83%	80%	80%
commercial space heating	Reference	Zero CO2 2050	86%	80%	41%	12%
commercial space heating	Reference	5 year+ EV delay	86%	85%	61%	25%
commercial space heating	Reference	Accelerated EV	86%	80%	41%	12%
commercial space heating	Reference	Core EV	86%	80%	41%	12%
commercial space heating	Reference	Low demand	86%	80%	41%	12%
commercial ventilation	High Efficiency	Zero CO2 2050	0%	19%	67%	96%
commercial ventilation	High Efficiency	5 year+ EV delay	0%	19%	67%	96%
commercial ventilation	High Efficiency	Accelerated EV	0%	19%	67%	96%
commercial ventilation	High Efficiency	Core EV	0%	19%	67%	96%
commercial ventilation	High Efficiency	Low demand	0%	19%	67%	96%
commercial ventilation	Reference	Reference	100%	100%	100%	100%
commercial ventilation	Reference	Zero CO2 2050	100%	81%	33%	4%
commercial ventilation	Reference	5 year+ EV delay	100%	81%	33%	4%
commercial ventilation	Reference	Accelerated EV	100%	81%	33%	4%
commercial ventilation	Reference	Core EV	100%	81%	33%	4%
commercial ventilation	Reference	Low demand	100%	81%	33%	4%
commercial water heating	Electric	Reference	6%	6%	6%	6%
commercial water heating	Electric	Zero CO2 2050	6%	16%	64%	95%
commercial water heating	Electric	5 year+ EV delay	6%	10%	39%	81%
commercial water heating	Electric	Accelerated EV	6%	16%	64%	95%
commercial water heating	Electric	Core EV	6%	16%	64%	95%
commercial water heating	Electric	Low demand	6%	16%	64%	95%
commercial water heating	High Efficiency	Reference	0%	0%	0%	0%
commercial water heating	High Efficiency	Zero CO2 2050	0%	0%	0%	0%
commercial water heating	High Efficiency	5 year+ EV delay	0%	0%	0%	0%
commercial water heating	High Efficiency	Accelerated EV	0%	0%	0%	0%
commercial water heating	High Efficiency	Core EV	0%	0%	0%	0%
commercial water heating	High Efficiency	Low demand	0%	0%	0%	0%

commercial water heating	Reference	Reference	94%	94%	94%	94%
commercial water heating	Reference	Zero CO2 2050	94%	84%	36%	5%
commercial water heating	Reference	5 year+ EV delay	94%	90%	61%	19%
commercial water heating	Reference	Accelerated EV	94%	84%	36%	5%
commercial water heating	Reference	Core EV	94%	84%	36%	5%
commercial water heating	Reference	Low demand	94%	84%	36%	5%
residential air conditioning	High Efficiency	Reference	10%	19%	24%	25%
residential air conditioning	High Efficiency	Zero CO2 2050	10%	36%	83%	97%
residential air conditioning	High Efficiency	5 year+ EV delay	10%	34%	82%	97%
residential air conditioning	High Efficiency	Accelerated EV	10%	36%	83%	97%
residential air conditioning	High Efficiency	Core EV	10%	36%	83%	97%
residential air conditioning	High Efficiency	Low demand	10%	36%	83%	97%
residential air conditioning	Reference	Reference	90%	81%	76%	75%
residential air conditioning	Reference	Zero CO2 2050	90%	64%	17%	3%
residential air conditioning	Reference	5 year+ EV delay	90%	66%	18%	3%
residential air conditioning	Reference	Accelerated EV	90%	64%	17%	3%
residential air conditioning	Reference	Core EV	90%	64%	17%	3%
residential air conditioning	Reference	Low demand	90%	64%	17%	3%
residential space heating	Electric	Reference	36%	45%	52%	54%
residential space heating	Electric	Zero CO2 2050	36%	47%	72%	89%
residential space heating	Electric	5 year+ EV delay	36%	43%	61%	81%
residential space heating	Electric	Accelerated EV	36%	47%	72%	89%
residential space heating	Electric	Core EV	36%	47%	72%	89%
residential space heating	Electric	Low demand	36%	47%	72%	89%
residential space heating	High Efficiency	Reference	0%	0%	0%	0%
residential space heating	High Efficiency	Zero CO2 2050	0%	0%	0%	0%
residential space heating	High Efficiency	5 year+ EV delay	0%	0%	0%	0%
residential space heating	High Efficiency	Accelerated EV	0%	0%	0%	0%
residential space heating	High Efficiency	Core EV	0%	0%	0%	0%
residential space heating	High Efficiency	Low demand	0%	0%	0%	0%
residential space heating	Reference	Reference	64%	55%	48%	46%
residential space heating	Reference	Zero CO2 2050	64%	53%	28%	11%
residential space heating	Reference	5 year+ EV delay	64%	57%	39%	19%
residential space heating	Reference	Accelerated EV	64%	53%	28%	11%
residential space heating	Reference	Core EV	64%	53%	28%	11%
residential space heating	Reference	Low demand	64%	53%	28%	11%
residential building shell	High Efficiency	Zero CO2 2050	0%	8%	24%	44%
residential building shell	High Efficiency	5 year+ EV delay	0%	8%	24%	44%
residential building shell	High Efficiency	Accelerated EV	0%	8%	24%	44%

residential building shell	High Efficiency	Core EV	0%	8%	24%	44%
residential building shell	High Efficiency	Low demand	0%	8%	24%	44%
residential building shell	Reference	Reference	100%	100%	100%	100%
residential building shell	Reference	Zero CO2 2050	100%	92%	76%	56%
residential building shell	Reference	5 year+ EV delay	100%	92%	76%	56%
residential building shell	Reference	Accelerated EV	100%	92%	76%	56%
residential building shell	Reference	Core EV	100%	92%	76%	56%
residential building shell	Reference	Low demand	100%	92%	76%	56%
residential clothes drying	High Efficiency	Reference	0%	0%	0%	0%
residential clothes drying	High Efficiency	Zero CO2 2050	0%	24%	82%	100%
residential clothes drying	High Efficiency	5 year+ EV delay	0%	21%	76%	99%
residential clothes drying	High Efficiency	Accelerated EV	0%	24%	82%	100%
residential clothes drying	High Efficiency	Core EV	0%	24%	82%	100%
residential clothes drying	High Efficiency	Low demand	0%	24%	82%	100%
residential clothes drying	Reference	Reference	100%	100%	100%	100%
residential clothes drying	Reference	Zero CO2 2050	100%	76%	18%	0%
residential clothes drying	Reference	5 year+ EV delay	100%	79%	24%	1%
residential clothes drying	Reference	Accelerated EV	100%	76%	18%	0%
residential clothes drying	Reference	Core EV	100%	76%	18%	0%
residential clothes drying	Reference	Low demand	100%	76%	18%	0%
residential clothes washing	High Efficiency	Reference	0%	0%	0%	0%
residential clothes washing	High Efficiency	Zero CO2 2050	0%	26%	85%	100%
residential clothes washing	High Efficiency	5 year+ EV delay	0%	26%	85%	100%
residential clothes washing	High Efficiency	Accelerated EV	0%	26%	85%	100%
residential clothes washing	High Efficiency	Core EV	0%	26%	85%	100%
residential clothes washing	High Efficiency	Low demand	0%	26%	85%	100%
residential clothes washing	Reference	Reference	100%	100%	100%	100%
residential clothes washing	Reference	Zero CO2 2050	100%	74%	15%	0%
residential clothes washing	Reference	5 year+ EV delay	100%	74%	15%	0%
residential clothes washing	Reference	Accelerated EV	100%	74%	15%	0%
residential clothes washing	Reference	Core EV	100%	74%	15%	0%
residential clothes washing	Reference	Low demand	100%	74%	15%	0%
residential cooking	Electric	Reference	61%	62%	62%	62%
residential cooking	Electric	Zero CO2 2050	61%	66%	84%	99%
residential cooking	Electric	5 year+ EV delay	61%	63%	75%	92%
residential cooking	Electric	Accelerated EV	61%	66%	84%	99%
residential cooking	Electric	Core EV	61%	66%	84%	99%
residential cooking	Electric	Low demand	61%	66%	84%	99%
residential cooking	Reference	Reference	39%	38%	38%	38%

residential cooking	Reference	Zero CO2 2050	39%	34%	16%	1%
residential cooking	Reference	5 year+ EV delay	39%	37%	25%	8%
residential cooking	Reference	Accelerated EV	39%	34%	16%	1%
residential cooking	Reference	Core EV	39%	34%	16%	1%
residential cooking	Reference	Low demand	39%	34%	16%	1%
residential dishwashing	High Efficiency	Zero CO2 2050	0%	26%	86%	100%
residential dishwashing	High Efficiency	5 year+ EV delay	0%	26%	86%	100%
residential dishwashing	High Efficiency	Accelerated EV	0%	26%	86%	100%
residential dishwashing	High Efficiency	Core EV	0%	26%	86%	100%
residential dishwashing	High Efficiency	Low demand	0%	26%	86%	100%
residential dishwashing	Reference	Reference	100%	100%	100%	100%
residential dishwashing	Reference	Zero CO2 2050	100%	74%	14%	0%
residential dishwashing	Reference	5 year+ EV delay	100%	74%	14%	0%
residential dishwashing	Reference	Accelerated EV	100%	74%	14%	0%
residential dishwashing	Reference	Core EV	100%	74%	14%	0%
residential dishwashing	Reference	Low demand	100%	74%	14%	0%
residential freezing	High Efficiency	Zero CO2 2050	0%	18%	63%	94%
residential freezing	High Efficiency	5 year+ EV delay	0%	18%	63%	94%
residential freezing	High Efficiency	Accelerated EV	0%	18%	63%	94%
residential freezing	High Efficiency	Core EV	0%	18%	63%	94%
residential freezing	High Efficiency	Low demand	0%	18%	63%	94%
residential freezing	Reference	Reference	100%	100%	100%	100%
residential freezing	Reference	Zero CO2 2050	100%	82%	37%	6%
residential freezing	Reference	5 year+ EV delay	100%	82%	37%	6%
residential freezing	Reference	Accelerated EV	100%	82%	37%	6%
residential freezing	Reference	Core EV	100%	82%	37%	6%
residential freezing	Reference	Low demand	100%	82%	37%	6%
residential lighting	High Efficiency	Reference	68%	83%	81%	81%
residential lighting	High Efficiency	Zero CO2 2050	68%	89%	92%	95%
residential lighting	High Efficiency	5 year+ EV delay	68%	89%	92%	95%
residential lighting	High Efficiency	Accelerated EV	68%	89%	92%	95%
residential lighting	High Efficiency	Core EV	68%	89%	92%	95%
residential lighting	High Efficiency	Low demand	68%	89%	92%	95%
residential lighting	Reference	Reference	32%	17%	19%	19%
residential lighting	Reference	Zero CO2 2050	32%	11%	8%	5%
residential lighting	Reference	5 year+ EV delay	32%	11%	8%	5%
residential lighting	Reference	Accelerated EV	32%	11%	8%	5%
residential lighting	Reference	Core EV	32%	11%	8%	5%
residential lighting	Reference	Low demand	32%	11%	8%	5%

residential refrigeration	High Efficiency	Reference	0%	0%	0%	0%
residential refrigeration	High Efficiency	Zero CO2 2050	0%	22%	75%	98%
residential refrigeration	High Efficiency	5 year+ EV delay	0%	22%	75%	98%
residential refrigeration	High Efficiency	Accelerated EV	0%	22%	75%	98%
residential refrigeration	High Efficiency	Core EV	0%	22%	75%	98%
residential refrigeration	High Efficiency	Low demand	0%	22%	75%	98%
residential refrigeration	Reference	Reference	100%	100%	100%	100%
residential refrigeration	Reference	Zero CO2 2050	100%	78%	25%	2%
residential refrigeration	Reference	5 year+ EV delay	100%	78%	25%	2%
residential refrigeration	Reference	Accelerated EV	100%	78%	25%	2%
residential refrigeration	Reference	Core EV	100%	78%	25%	2%
residential refrigeration	Reference	Low demand	100%	78%	25%	2%
residential water heating	Electric	Reference	47%	60%	63%	63%
residential water heating	Electric	Zero CO2 2050	47%	66%	91%	99%
residential water heating	Electric	5 year+ EV delay	47%	62%	80%	96%
residential water heating	Electric	Accelerated EV	47%	66%	91%	99%
residential water heating	Electric	Core EV	47%	66%	91%	99%
residential water heating	Electric	Low demand	47%	66%	91%	99%
residential water heating	High Efficiency	Reference	0%	0%	0%	0%
residential water heating	High Efficiency	Zero CO2 2050	0%	0%	0%	0%
residential water heating	High Efficiency	5 year+ EV delay	0%	0%	0%	0%
residential water heating	High Efficiency	Accelerated EV	0%	0%	0%	0%
residential water heating	High Efficiency	Core EV	0%	0%	0%	0%
residential water heating	High Efficiency	Low demand	0%	0%	0%	0%
residential water heating	Reference	Reference	53%	40%	37%	37%
residential water heating	Reference	Zero CO2 2050	53%	34%	9%	1%
residential water heating	Reference	5 year+ EV delay	53%	38%	20%	4%
residential water heating	Reference	Accelerated EV	53%	34%	9%	1%
residential water heating	Reference	Core EV	53%	34%	9%	1%
residential water heating	Reference	Low demand	53%	34%	9%	1%
heavy duty trucks	Electric	Reference	0%	0%	0%	0%
heavy duty trucks	Electric	Zero CO2 2050	0%	3%	22%	50%
heavy duty trucks	Electric	5 year+ EV delay	0%	2%	11%	38%
heavy duty trucks	Electric	Accelerated EV	0%	14%	46%	61%
heavy duty trucks	Electric	Core EV	0%	4%	28%	55%
heavy duty trucks	Electric	Low demand	0%	3%	22%	50%
heavy duty trucks	High Efficiency	Reference	0%	0%	0%	0%
heavy duty trucks	High Efficiency	Zero CO2 2050	0%	0%	0%	0%
heavy duty trucks	High Efficiency	5 year+ EV delay	0%	0%	0%	0%

heavy duty trucks	High Efficiency	Accelerated EV	0%	0%	0%	0%
heavy duty trucks	High Efficiency	Core EV	0%	0%	0%	0%
heavy duty trucks	High Efficiency	Low demand	0%	0%	0%	0%
heavy duty trucks	Hydrogen	Reference	0%	0%	0%	0%
heavy duty trucks	Hydrogen	Zero CO2 2050	0%	2%	14%	30%
heavy duty trucks	Hydrogen	5 year+ EV delay	0%	1%	7%	23%
heavy duty trucks	Hydrogen	Accelerated EV	0%	8%	28%	37%
heavy duty trucks	Hydrogen	Core EV	0%	3%	17%	33%
heavy duty trucks	Hydrogen	Low demand	0%	2%	14%	30%
heavy duty trucks	Reference	Reference	100%	100%	100%	100%
heavy duty trucks	Reference	Zero CO2 2050	100%	96%	64%	20%
heavy duty trucks	Reference	5 year+ EV delay	100%	97%	82%	39%
heavy duty trucks	Reference	Accelerated EV	100%	78%	26%	2%
heavy duty trucks	Reference	Core EV	100%	93%	55%	12%
heavy duty trucks	Reference	Low demand	100%	96%	64%	20%
light duty autos	Electric	Reference	1%	6%	11%	15%
light duty autos	Electric	Zero CO2 2050	1%	14%	58%	89%
light duty autos	Electric	5 year+ EV delay	1%	8%	36%	77%
light duty autos	Electric	Accelerated EV	1%	24%	73%	93%
light duty autos	Electric	Core EV	1%	16%	66%	92%
light duty autos	Electric	Low demand	1%	14%	58%	89%
light duty autos	High Efficiency	Reference	4%	8%	10%	11%
light duty autos	High Efficiency	Zero CO2 2050	4%	7%	4%	1%
light duty autos	High Efficiency	5 year+ EV delay	4%	8%	7%	2%
light duty autos	High Efficiency	Accelerated EV	4%	6%	2%	0%
light duty autos	High Efficiency	Core EV	4%	7%	3%	0%
light duty autos	High Efficiency	Low demand	4%	7%	4%	1%
light duty autos	Hydrogen	Reference	0%	0%	0%	0%
light duty autos	Hydrogen	Zero CO2 2050	0%	0%	2%	4%
light duty autos	Hydrogen	5 year+ EV delay	0%	0%	1%	3%
light duty autos	Hydrogen	Accelerated EV	0%	1%	3%	5%
light duty autos	Hydrogen	Core EV	0%	0%	2%	4%
light duty autos	Hydrogen	Low demand	0%	0%	2%	4%
light duty autos	Reference	Reference	95%	86%	79%	74%
light duty autos	Reference	Zero CO2 2050	95%	78%	36%	6%
light duty autos	Reference	5 year+ EV delay	95%	83%	56%	17%
light duty autos	Reference	Accelerated EV	95%	69%	21%	2%
light duty autos	Reference	Core EV	95%	77%	29%	3%
light duty autos	Reference	Low demand	95%	78%	36%	6%

light duty trucks	Electric	Reference	0%	1%	2%	2%
light duty trucks	Electric	Zero CO2 2050	0%	8%	47%	82%
light duty trucks	Electric	5 year+ EV delay	0%	6%	26%	68%
light duty trucks	Electric	Accelerated EV	0%	21%	67%	88%
light duty trucks	Electric	Core EV	0%	10%	57%	87%
light duty trucks	Electric	Low demand	0%	8%	47%	82%
light duty trucks	High Efficiency	Reference	1%	2%	3%	5%
light duty trucks	High Efficiency	Zero CO2 2050	1%	2%	2%	0%
light duty trucks	High Efficiency	5 year+ EV delay	1%	2%	2%	1%
light duty trucks	High Efficiency	Accelerated EV	1%	1%	1%	0%
light duty trucks	High Efficiency	Core EV	1%	2%	1%	0%
light duty trucks	High Efficiency	Low demand	1%	2%	2%	0%
light duty trucks	Hydrogen	Reference	0%	0%	0%	0%
light duty trucks	Hydrogen	Zero CO2 2050	0%	0%	3%	7%
light duty trucks	Hydrogen	5 year+ EV delay	0%	0%	2%	6%
light duty trucks	Hydrogen	Accelerated EV	0%	1%	6%	10%
light duty trucks	Hydrogen	Core EV	0%	0%	3%	8%
light duty trucks	Hydrogen	Low demand	0%	0%	3%	7%
light duty trucks	Reference	Reference	99%	97%	95%	92%
light duty trucks	Reference	Zero CO2 2050	99%	90%	49%	10%
light duty trucks	Reference	5 year+ EV delay	99%	92%	70%	25%
light duty trucks	Reference	Accelerated EV	99%	76%	26%	2%
light duty trucks	Reference	Core EV	99%	88%	39%	5%
light duty trucks	Reference	Low demand	99%	90%	49%	10%
medium duty trucks	Electric	Reference	0%	0%	0%	1%
medium duty trucks	Electric	Zero CO2 2050	0%	4%	31%	61%
medium duty trucks	Electric	5 year+ EV delay	0%	3%	16%	45%
medium duty trucks	Electric	Accelerated EV	0%	18%	53%	69%
medium duty trucks	Electric	Core EV	0%	6%	36%	65%
medium duty trucks	Electric	Low demand	0%	4%	31%	61%
medium duty trucks	High Efficiency	Reference	0%	0%	0%	0%
medium duty trucks	High Efficiency	Zero CO2 2050	0%	0%	0%	0%
medium duty trucks	High Efficiency	5 year+ EV delay	0%	0%	0%	0%
medium duty trucks	High Efficiency	Accelerated EV	0%	0%	0%	0%
medium duty trucks	High Efficiency	Core EV	0%	0%	0%	0%
medium duty trucks	High Efficiency	Low demand	0%	0%	0%	0%
medium duty trucks	Hydrogen	Reference	0%	0%	0%	0%
medium duty trucks	Hydrogen	Zero CO2 2050	0%	0%	6%	21%
medium duty trucks	Hydrogen	5 year+ EV delay	0%	0%	4%	17%

medium duty trucks	Hydrogen	Accelerated EV	0%	3%	18%	29%
medium duty trucks	Hydrogen	Core EV	0%	0%	7%	22%
medium duty trucks	Hydrogen	Low demand	0%	0%	6%	21%
medium duty trucks	Reference	Reference	100%	100%	99%	98%
medium duty trucks	Reference	Zero CO2 2050	100%	95%	63%	18%
medium duty trucks	Reference	5 year+ EV delay	100%	97%	81%	38%
medium duty trucks	Reference	Accelerated EV	100%	79%	29%	2%
medium duty trucks	Reference	Core EV	100%	93%	56%	12%
medium duty trucks	Reference	Low demand	100%	95%	63%	18%
transit buses	Electric	Reference	0%	1%	1%	1%
transit buses	Electric	Zero CO2 2050	0%	9%	70%	99%
transit buses	Electric	5 year+ EV delay	0%	4%	37%	87%
transit buses	Electric	Accelerated EV	0%	9%	70%	99%
transit buses	Electric	Core EV	0%	9%	70%	99%
transit buses	Electric	Low demand	0%	9%	70%	99%
transit buses	High Efficiency	Reference	17%	19%	19%	19%
transit buses	High Efficiency	Zero CO2 2050	17%	16%	5%	0%
transit buses	High Efficiency	5 year+ EV delay	17%	17%	11%	2%
transit buses	High Efficiency	Accelerated EV	17%	16%	5%	0%
transit buses	High Efficiency	Core EV	17%	16%	5%	0%
transit buses	High Efficiency	Low demand	17%	16%	5%	0%
transit buses	Reference	Reference	82%	80%	80%	80%
transit buses	Reference	Zero CO2 2050	83%	75%	25%	1%
transit buses	Reference	5 year+ EV delay	83%	79%	52%	10%
transit buses	Reference	Accelerated EV	83%	75%	25%	1%
transit buses	Reference	Core EV	83%	75%	25%	1%
transit buses	Reference	Low demand	83%	75%	25%	1%

Table 7 Final energy demand by scenario in 2020 and 2050 (TBtu)

Subsector	Final Energy (group)	Reference 2020	Reference 2050	Zero CO2 2050	5 year+ EV delay 2050	Accelerate EV 2050	Core EV 2050	Low demand 2050
commercial air conditioning	electricity	511	422	380	376	380	380	304
commercial air conditioning	other	22	31	21	23	21	21	17
commercial cooking	electricity	84	111	278	269	278	278	278
commercial cooking	other	236	312	16	32	16	16	16
commercial lighting	electricity	471	304	277	277	277	277	222
commercial other	electricity	1,562	2,214	1,889	1,793	1,889	1,889	1,266
commercial other	other	729	773	72	265	72	72	39

commercial refrigeration	electricity	616	766	715	715	715	715	715
commercial space heating	electricity	106	127	519	428	519	519	415
commercial space heating	other	1,523	1,445	223	480	223	223	178
commercial ventilation	electricity	513	590	517	517	517	517	414
commercial water heating	electricity	25	29	358	305	358	358	358
commercial water heating	other	597	771	39	153	39	39	39
commercial water heating	biomass	2	5	5	5	5	5	5
district services	electricity	3	4	4	4	4	4	2
district services	steam	100	133	186	169	186	186	125
district services	other	49	62	14	30	14	14	10
office equipment (non-p.c.)	electricity	240	408	408	408	408	408	408
office equipment (p.c.)	electricity	321	250	250	250	250	250	250
residential air conditioning	electricity	682	818	620	618	620	620	497
residential air conditioning	other	20	18	26	26	26	26	21
residential clothes drying	electricity	190	188	125	124	125	125	125
residential clothes drying	other	46	45	0	2	0	0	0
residential clothes washing	electricity	26	15	11	11	11	11	11
residential computers and related	electricity	85	38	38	38	38	38	38
residential cooking	electricity	54	62	130	114	130	130	130
residential cooking	other	119	126	7	34	7	7	7
residential dishwashing	electricity	105	126	77	77	77	77	77
residential freezing	electricity	71	66	66	66	66	66	66
residential furnace fans	electricity	79	62	62	62	62	62	50
residential lighting	electricity	365	254	107	107	107	107	86
residential other uses	electricity	1,715	2,182	1,736	1,692	1,736	1,736	1,163
residential other uses	other	305	322	63	129	63	63	42
residential refrigeration	electricity	298	292	254	254	254	254	254
residential secondary heating	electricity	122	95	146	129	146	146	116
residential secondary heating	other	81	71	4	26	4	4	3
residential secondary heating	biomass	321	289	289	289	289	289	231
residential space heating	electricity	624	680	1,008	920	1,008	1,008	808
residential space heating	other	3,951	2,638	309	731	309	309	247
residential space heating	biomass	117	160	152	148	152	152	122
residential televisions and related	electricity	205	265	265	265	265	265	212
residential water heating	electricity	595	889	595	606	595	595	595
residential water heating	other	1,097	883	15	85	15	15	15
residential water heating	biomass	3	7	6	6	6	6	6
aviation	other	2,615	3,586	2,295	2,295	2,295	2,295	1,836
domestic shipping	hydrogen			20	12	20	20	14

domestic shipping	other	89	47	24	34	24	24	16
freight rail	hydrogen			127	64	127	127	85
freight rail	other	509	507	366	437	366	366	245
heavy duty trucks	electricity	0	0	576	419	692	639	461
heavy duty trucks	hydrogen	0	5	1,509	1,101	1,796	1,669	1,207
heavy duty trucks	other	4,132	4,085	664	1,534	31	317	531
international shipping	hydrogen			258	129	258	258	173
international shipping	other	861	907	621	764	621	621	416
light duty autos	electricity	24	268	1,443	1,265	1,496	1,488	866
light duty autos	hydrogen	0	4	69	62	86	71	42
light duty autos	other	5,346	4,654	230	693	63	114	138
light duty trucks	electricity	6	114	2,381	2,005	2,501	2,501	1,428
light duty trucks	hydrogen	0	10	189	166	248	194	113
light duty trucks	other	10,709	7,385	494	1,324	110	230	296
lubricants	other	133	129	129	129	129	129	86
medium duty trucks	electricity	0	10	750	555	843	802	600
medium duty trucks	hydrogen	0	5	269	213	369	284	215
medium duty trucks	other	1,480	1,961	306	691	24	204	244
military use	other	590	559	559	559	559	559	447
motorcycles	electricity			4	4	4	4	3
motorcycles	other	19	16	5	5	5	5	4
passenger rail	electricity	25	31	43	38	43	43	86
passenger rail	other	24	34	10	19	10	10	20
recreational boats	electricity			30	15	30	30	24
recreational boats	other	244	236	160	198	160	160	128
school and intercity buses	electricity			95	59	95	95	189
school and intercity buses	other	140	162	18	72	18	18	37
transit buses	electricity	0	0	20	18	20	20	40
transit buses	other	104	90	1	11	1	1	2
agriculture-crops	electricity	86	113	379	276	379	379	254
agriculture-crops	steam	25	31	31	31	31	31	21
agriculture-crops	other	548	670	253	414	253	253	170
agriculture-other	electricity	72	91	250	190	250	250	168
agriculture-other	steam	6	8	8	8	8	8	5
agriculture-other	other	350	436	184	279	184	184	123
aluminum industry	electricity	98	121	93	92	93	93	62
aluminum industry	steam	0	0	0	0	0	0	0
aluminum industry	other	117	137	96	96	96	96	64
balance of manufacturing other	electricity	397	525	626	590	626	626	419

balance of manufacturing other	hydrogen			113	79	113	113	75
balance of manufacturing other	steam	285	294	218	218	218	218	146
balance of manufacturing other	other	634	734	139	217	139	139	93
bulk chemicals	electricity	612	778	1,322	1,239	1,322	1,322	886
bulk chemicals	hydrogen	848	864	1,011	967	1,011	1,011	677
bulk chemicals	steam	1,918	1,901	1,901	1,901	1,901	1,901	1,274
bulk chemicals	other	4,721	6,992	6,226	6,364	6,226	6,226	4,171
cement	electricity	52	66	53	53	53	53	36
cement	steam	0	0	0	0	0	0	0
cement	other	260	377	271	272	271	271	181
Cement and Lime CO2 Capture	electricity	0	0	110	110	110	110	74
computer and electronic products	electricity	93	151	125	123	125	125	84
computer and electronic products	hydrogen			2	2	2	2	2
computer and electronic products	steam	15	24	18	18	18	18	12
computer and electronic products	other	37	50	13	17	13	13	9
construction	electricity	186	257	444	338	444	444	297
construction	other	1,514	2,339	1,789	1,946	1,789	1,789	914
electrical equip., appliances, and components	electricity	40	73	67	65	67	67	45
electrical equip., appliances, and components	hydrogen			6	4	6	6	4
electrical equip., appliances, and components	steam	5	7	5	5	5	5	3
electrical equip., appliances, and components	other	33	52	16	20	16	16	11
fabricated metal products	electricity	136	201	211	201	211	211	141
fabricated metal products	hydrogen			22	15	22	22	14
fabricated metal products	steam	12	19	14	14	14	14	9
fabricated metal products	other	176	202	40	60	40	40	27
food and kindred products	electricity	268	427	422	406	422	422	283
food and kindred products	hydrogen			75	53	75	75	51
food and kindred products	steam	414	641	476	476	476	476	319
food and kindred products	other	336	529	112	165	112	112	75
glass and glass products	electricity	19	25	22	21	22	22	14
glass and glass products	steam	0	0	0	0	0	0	0
glass and glass products	other	147	151	106	107	106	106	71
iron and steel	electricity	209	225	283	283	283	283	190
iron and steel	hydrogen			410	410	410	410	275
iron and steel	steam	0	0	0	0	0	0	0
iron and steel	other	919	832	414	416	414	414	277
lime	electricity	2	3	3	3	3	3	2
lime	steam	0	0	0	0	0	0	0

lime	other	84	174	127	127	127	127	85
machinery	electricity	73	125	114	111	114	114	76
machinery	hydrogen			3	2	3	3	2
machinery	steam	14	21	16	16	16	16	10
machinery	other	66	76	17	24	17	17	12
metal and other non-metallic mining	electricity	169	180	233	218	233	233	156
metal and other non-metallic mining	steam	18	21	16	16	16	16	10
metal and other non-metallic mining	other	245	312	121	138	121	121	81
paper and allied products	electricity	316	381	291	289	291	291	195
paper and allied products	steam	1,158	1,453	1,078	1,078	1,078	1,078	722
paper and allied products	other	130	151	96	98	96	96	64
plastic and rubber products	electricity	157	243	203	200	203	203	136
plastic and rubber products	hydrogen			6	5	6	6	4
plastic and rubber products	steam	33	39	29	29	29	29	19
plastic and rubber products	other	64	74	14	21	14	14	9
transportation equipment	electricity	142	230	228	220	228	228	153
transportation equipment	hydrogen			19	14	19	19	13
transportation equipment	steam	28	40	30	30	30	30	20
transportation equipment	other	146	198	44	62	44	44	29
wood products	electricity	68	99	92	89	92	92	62
wood products	hydrogen			6	4	6	6	4
wood products	steam	198	149	111	111	111	111	74
wood products	other	60	61	12	18	12	12	8

2.2 Supply-side inputs

Energy supply portfolios are selected using the RIO optimization in order to meet economy-wide emissions constraints at least cost. Each scenario is composed of a combination of a demand-side case and one or more additional supply-side constraints. As outlined in section 0, many of the scenarios share the “core net-zero” demand-side case assumptions, but with different supply-side assumptions. The term sector coupling refers to the pairing together of the electricity and fuels systems in flexible ways not seen in our current energy system. When sector coupling was disallowed, the electrolysis and dual-fuel electric boiler technologies were unavailable to the model.

*Table 8 Supply-side differences between scenarios**

	Scenario	Demand case	Emissions constraint	CES/RPS Policy	Wind & solar build constraints	Available biomass supply
1	Reference Case	Reference	None	Current policy	10% growth rate	Billion-ton study
2	Zero CO2 2050	Zero CO2 2050	**net-zero (*Other** assumptions included in scenarios 2-9: 1) Rooftop and distributed PV increases to 111 GW by 2030 and 500 GW by 2050, assuming 45% of the technical potential from NREL’s 2016 Rooftop Solar Photovoltaic Technical Potential in the United States report, and 2) offshore wind increases to at least 30 GW by	Current policy	10% growth rate	Billion-ton study

			2030, 45 GW in 2035, and 55 GW in 2040, based on current and projected state commitments. Table 9**)**			
3	Low energy demand	Zero CO2 2050	**net-zero (*Other** assumptions included in scenarios 2-9: 1) Rooftop and distributed PV increases to 111 GW by 2030 and 500 GW by 2050, assuming 45% of the technical potential from NREL's 2016 Rooftop Solar Photovoltaic Technical Potential in the United States report, and 2) offshore wind increases to at least 30 GW by 2030, 45 GW in 2035, and 55 GW in 2040, based on current and	Current policy	10% growth rate	Billion-ton study

			projected state commitments. Table 9**)**			
4	50% biomass supply	Zero CO2 2050	**net-zero (*Other** assumptions included in scenarios 2-9: 1) Rooftop and distributed PV increases to 111 GW by 2030 and 500 GW by 2050, assuming 45% of the technical potential from NREL's 2016 Rooftop Solar Photovoltaic Technical Potential in the United States report, and 2) offshore wind increases to at least 30 GW by 2030, 45 GW in 2035, and 55 GW in 2040, based on current and projected state commitments. Table 9**)**	Current policy	10% growth rate	**50% of Billion-ton study**

5	Renewable build limits	Zero CO2 2050	**net-zero (*Other** assumptions included in scenarios 2-9: 1) Rooftop and distributed PV increases to 111 GW by 2030 and 500 GW by 2050, assuming 45% of the technical potential from NREL's 2016 Rooftop Solar Photovoltaic Technical Potential in the United States report, and 2) offshore wind increases to at least 30 GW by 2030, 45 GW in 2035, and 55 GW in 2040, based on current and projected state commitments. Table 9**)**	Current policy	**Onshore wind 25 GW/year, Solar 30 GW/year in 2030 and 40 GW/year 2040-2050**	Billion-ton study
6	Core EV	Core EV	**net-zero (*Other** assumptions included in scenarios 2-9: 1)	Current policy	10% growth rate	Billion-ton study

			Rooftop and distributed PV increases to 111 GW by 2030 and 500 GW by 2050, assuming 45% of the technical potential from NREL's 2016 Rooftop Solar Photovoltaic Technical Potential in the United States report, and 2) offshore wind increases to at least 30 GW by 2030, 45 GW in 2035, and 55 GW in 2040, based on current and projected state commitments. Table 9**)**			
7	5 year+ EV delay	5 year+ EV delay	**net-zero (*Other** assumptions included in scenarios 2-9: 1) Rooftop and distributed PV increases to 111 GW by 2030 and 500 GW by	Current policy	10% growth rate	Billion-ton study

			2050, assuming 45% of the technical potential from NREL's 2016 Rooftop Solar Photovoltaic Technical Potential in the United States report, and 2) offshore wind increases to at least 30 GW by 2030, 45 GW in 2035, and 55 GW in 2040, based on current and projected state commitments. Table 9**)**			
8	10 year+ EV delay	10 year+ EV delay	**net-zero (*Other** assumptions included in scenarios 2-9: 1) Rooftop and distributed PV increases to 111 GW by 2030 and 500 GW by 2050, assuming 45% of the technical potential from NREL's	Current policy	10% growth rate	Billion-ton study

			2016 Rooftop Solar Photovoltaic Technical Potential in the United States report, and 2) offshore wind increases to at least 30 GW by 2030, 45 GW in 2035, and 55 GW in 2040, based on current and projected state commitments. Table 9**)**			
9	Accelerated EV	Accelerated EV	**net-zero (*Other** assumptions included in scenarios 2-9: 1) Rooftop and distributed PV increases to 111 GW by 2030 and 500 GW by 2050, assuming 45% of the technical potential from NREL's 2016 Rooftop Solar Photovoltaic Technical Potential in	Current policy	10% growth rate	Billion-ton study

			the United States report, and 2) offshore wind increases to at least 30 GW by 2030, 45 GW in 2035, and 55 GW in 2040, based on current and projected state commitments. Table 9**)**			

*Other assumptions included in scenarios 2-9: 1) Rooftop and distributed PV increases to 111 GW by 2030 and 500 GW by 2050, assuming 45% of the technical potential from NREL's 2016 Rooftop Solar Photovoltaic Technical Potential in the United States report, and 2) offshore wind increases to at least 30 GW by 2030, 45 GW in 2035, and 55 GW in 2040, based on current and projected state commitments.

Table 9 US CO_2 and Greenhouse Gas Emission Budget for Zero 2050 CO2 case

Year	Energy & Industry CO2 (Gt CO2)[1]	Total non-CO2 gases (Gt CO2e)[2, 3]	Land Sink (Gt CO2e)[2,4]	Total Net CO2e (Gt CO2e)[2]	Total Net CO2e (% below 2005)
2005[5]	6.14	1.29	-0.79	6.64	n/a
2020[5]	5.02	1.30	-0.79	5.54	17%
2025	4.15	1.08	-0.79	4.49	33%
2030	3.28	0.83	-0.79	3.32	50%
2035	2.46	0.77	-0.79	2.44	63%
2040	1.64	0.76	-0.79	1.61	76%
2045	0.82	0.76	-0.79	0.79	88%
2050	0	0.76	-0.79	-0.03	100%

Notes: [1]Annual emissions constraints in RIO including all energy and industrial process CO_2 in the U.S. not directly related to energy exports. [2]Exogenous to model. [3]Non-CO2 gases include methane, nitrous oxide, and fluorinated gases. Reductions in non-CO2 gases are based on a range of studies (Abhyankar, Mohanty, and Phadke 2021; EDF 2021; EPA 2021; Fargione et al. 2018; Hultman et al. 2021; NAS 2018; NRDC 2021; Larsen, Larsen, and Pitt 2020.) [4]Land sink assumed to stay constant at current levels. [5]2005 and 2020 levels based on 2021 EPA U.S. Greenhouse Gas Inventory with 2019 levels assumed for 2020; 2020 CO2 emissions based on EIA Short-term Energy Outlook.

3. Data Sources

3.1 United States EnergyPATHWAYS Database

The database of the United States energy economy used in this analysis has high geographical resolution on technology stocks; technology cost and performance; built infrastructure and resource potential as well as high temporal resolution on electricity loads by end-use as well as renewable generation profiles. EnergyPATHWAYS leverages many of the same input files used to populate the National Energy Modeling System (NEMS) used by the United States Energy Information Administration (EIA) to forecast their Annual Energy Outlook.

The model of the U.S. energy economy is separated into 64 energy-using demand subsectors. Subsectors, like residential space heating, represent energy-use associated with the performance of an energy-service. A description of the methods EnergyPATHWAYS use to project energy-service demands, energy demands, and ultimately cost and emissions associated with the performance of that service is found in Demand. On the supply side, the model is separated into interconnected nodes, which are associated with the production, transformation, and delivery of energy to demand subsectors.

The numbered sources throughout this section refer to citation numbers in the bibliography. The bibliography is located at the end of the document in Section 6.

3.2 Demand-side Data Description

Table 10 lists all the subsectors in the US Database grouped by demand sector. It also specifies the methodology used to calculate energy demand in each subsector.

Table 10 Sectors, subsectors, and method of demand energy projection

Sector	Subsector	Method
residential	residential water heating	B
residential	residential furnace fans	D
residential	residential clothes drying	A
residential	residential dishwashing	A
residential	residential refrigeration	A
residential	residential freezing	A
residential	residential cooking	B
residential	residential secondary heating	D
residential	residential other appliances	D
residential	residential clothes washing	A
residential	residential lighting	A
residential	residential other - electric	D
residential	residential air conditioning	B
residential	residential space heating	B
commercial	commercial water heating	A
commercial	commercial ventilation	A
commercial	office equipment (p.c.)	D

commercial	office equipment (non-p.c.)	D
commercial	commercial space heating	A
commercial	commercial air conditioning	A
commercial	commercial lighting	A
commercial	district services	D
commercial	commercial refrigeration	A
commercial	commercial cooking	A
commercial	commercial other	D
transportation	heavy duty trucks	A
transportation	international shipping	D
transportation	recreational boats	D
transportation	transit buses	A
transportation	military use	D
transportation	lubricants	D
transportation	medium duty trucks	A
transportation	aviation	D
transportation	motorcycles	D
transportation	domestic shipping	D
transportation	passenger rail	D
transportation	school and intercity buses	A
transportation	freight rail	D
transportation	light duty trucks	A
transportation	light duty autos	A
industry	metal and other non-metallic mining	D
industry	aluminum industry	D
industry	balance of manufacturing other	D
industry	plastic and rubber products	D
industry	wood products	D
industry	bulk chemicals	D
industry	glass and glass products	D
industry	cement	D
industry	agriculture-other	D
industry	agriculture-crops	D
industry	fabricated metal products	D
industry	machinery	D
industry	computer and electronic products	D
industry	transportation equipment	D
industry	construction	D
industry	iron and steel	D
industry	food and kindred products	D
industry	paper and allied products	D

industry	electrical equip., appliances, and components	D
Productive	iron & steel co2 capture	C
Productive	cement co2 capture	C

The methods for representing demand-side subsectors are described in section 59. *Table 11* describes the input data used to populate stock representations in the subsectors that employ Method A. and Table 12 describes the energy service demand inputs.

Table 11 Demand stock data

Subsector	Unit	Service Demand Dependent	Driver	Input Data: Geography	Input Data: Year(s)	Additional Detail	Bibliography Source
Residential Lighting	Bulbs	No	Total square footage	Census division	2009-2050	Housing types; Lighting category	(33)
Residential Clothes Washing	Clothes washer	No	Households	Census division	2009	Housing types	(30)
Residential Clothes Drying	Clothes dryer	No	Households	Census division	2009	Housing types	(30)
Residential Dishwashing	Dishwashers per household	No	Households	Census division	2009	Housing types	(30)
Residential Refrigeration	Cubic feet	No	Households	Census division	2009	Housing types	(30)
Residential Freezing	Cubic feet	No	Households	Census division	2009	Housing types	(30)
Commercial Water Heating	Capacity factor	Yes	Commercial square feet	Census division	2012	Building types	(29)
Commercial Space Heating	Capacity factor	Yes	Commercial square feet	Census division	2012	Building types	(29)
Commercial Air Conditioning	Capacity factor	Yes	Commercial square feet	Census division	2012	Building types	(29)
Commercial Lighting	Capacity factor	Yes	n/a	Census division	2012	Building types	(29)
Commercial Refrigeration	Capacity factor	Yes	Commercial square feet	Census division	2012	Building types	(29)
Commercial Cooking	Capacity factor	Yes	Commercial square feet	Census division	2012	Building types	(29)
Commercial Ventilation	Capacity factor	Yes	Commercial square feet	Census division	2012	Building types	(29)
Light Duty Autos	Cars	No	n/a	US	2015-2050	n/a	(33)
Light Duty Trucks	Trucks	No	n/a	US	2015-2050	Light truck class	(33)
Medium Duty Trucks	Truck	No	n/a	US	2015-2050	n/a	(33)

Heavy Duty Trucks	Truck	No	n/a	US	2015-2050	n/a	(33)
Transit Buses	Bus	Yes	n/a	US	2014	n/a	(3)

Table 12 Service demand inputs

Subsector	Unit	Stock Dependent	Driver	Input Data: Geography	Input Data: Year(s)	Additional Detail	Bibliography Source
Residential Lighting	klm-hr per housing unit	No	Total square feet	US	2012	Lighting category	(1)
Residential Clothes Washing	Cu. Ft. Cycle	Yes	n/a	Census division	2009	Housing types	(30)
Residential Clothes Drying	Pound	Yes	n/a	Census division	2009	Housing types	(30)
Residential Dishwashing	Cycle	Yes	n/a	Census division	2009	Housing types	(30)
Residential Refrigeration	Cu. Ft.	Yes	n/a	Census division	2009	Housing types	(30)
Residential Freezing	Cu. Ft.	Yes	n/a	Census division	2009	Housing types	(30)
Commercial Water Heating	Terabtu	No	Commercial square feet	Census division	2012 - 2050	Building types	(33)
Commercial Space Heating	Terabtu	No	Commercial square feet	Census division	2012 - 2050	Building types	(31, 33)
Commercial Air Conditioning	Terabtu	No	Commercial square feet	Census division	2012 - 2050	Building types	(33)
Commercial Lighting	gigalumen_year	No	Commercial square feet	Census division	2012 - 2050	Building types	(33)
Commercial Refrigeration	Terabtu	No	Commercial square feet	Census division	2012 - 2050	Building types	(33)
Commercial Cooking	Terabtu	No	Commercial square feet	Census division	2012 - 2050	Building types	(33)
Commercial Ventilation	gigacubic_foot	No	Commercial square feet	Census division	2012 - 2050	Building types	((33)
Light Duty Autos	Gigamile	No	n/a	US	2015-2050		(33)
Light Duty Trucks	Gigamile	No		US	2015-2050	Light truck class	(33)
Medium Duty Trucks	Mile	No		US	2015-2050		(33)
Heavy Duty Trucks	Mile	No	N/A	US	2015-2050		(33)
Transit Buses	Mile	No	Population	Census division	1995-2008		(31)

Table 13 describes stock input data sources for subsectors that uses Method B. *Table 14* describes energy demand input sources.

Table 13 Equipment stock data sources for Method B subsectors

Subsector	Unit	Service Demand Dependent	Driver	Input Data: Geography	Input Data: Year(s)	Additional Detail	Source
Residential Water Heating	Water heater	No	Households; Residential Heating Energy Share	Census division	2015-2050	Housing types	(33)
Residential Space Heating	Space heater	No	Households; Residential Heating Energy Share; Heating Degree Days	Census division	2015-2050	Housing types	(33)
Residential Air Conditioning	Air conditioner	No	Households; Cooling Degree Days; House Age Index	Census division	2015-2050	Housing types	(33)
Residential Cooking	Cooktop	No	Households; Residential Heating Energy Share	Census division	2015-2050	Housing types	(33)

Table 14 Energy demand data sources for Method B subsectors

Subsector	Unit	Driver	Input Data: Geography	Input Data: Year(s)	Additional Detail	Source
Residential Water Heating	MMBTU	Households; Residential Heating Energy Share	Census division	2015-2050	Housing types	(33)
Residential Space Heating	MMBTU	Households; Residential Heating Energy Share; Heating Degree Days	Census division	2015-2050	Housing types	(33)
Residential Air Conditioning	MMBTU	Households; Cooling Degree Days; House Age Index	Census division	2015-2050	Housing types	(33)
Residential Cooking	MMBTU	Households; Residential Heating Energy Share	Census division	2015-2050	Housing types	(33)

Demand subsectors with technology stock also require technology-specific parameters for cost and performance. These input sources by subsector and technology-type are show below in Table 15.

Table 15 Demand technology inputs

Subsector	Technologies	Source
Residential Space Heating and Air Conditioning	Air source heat pump (ducted)	Cost: (13) Efficiency: NREL building simulations in support of (13)
	Ductless mini-split heat pump	Cost: (5) Efficiency: NREL building simulations in support of (13)
	Remainder	(21)
Residential Water Heating	Heat pump water heater	(13)
	Remainder	(21)
Residential Remaining Subsectors	All	(21)
Commercial Space Heating and Air Conditioning	Air source heat pump	(13)
	Remainder	(21)
Commercial Water Heating	Heat pump water heater	(13)

	Remainder	(21)
Commercial Lighting	All	(31)
Commercial Building Shell	All	(31)
Light-duty Vehicles	Battery electric vehicle and plug-in hybrid electric vehicle	Cost: (6, 18, 13) Efficiency: (13)
	Remainder	Efficiency: (33) Cost: (33)
Medium Duty Vehicles	Battery electric	(13)
	Hydrogen fuel cell	(2)
	Remainder (CNG, diesel, etc.)	(24)
Heavy Duty Vehicles	Battery electric	(13)
	Hydrogen fuel cell	(9)
	Reference diesel, gasoline and propane	(24)
	Diesel hybrid and liquefied pipeline gas	(24)
Transit Buses	All	(13, 3)

Table 16 includes the service demand projections for subsectors represented with Method C (4.3.1.6). Table 17 includes the service efficiency for Method C subsectors.

Table 16 Service demand data sources for Method C subsectors

Subsector	Unit	Stock Dependent	Driver	Input Data: Geography	Input Data: Year(s)	Additional Detail	Source
Iron and Steel CO2 Capture	Tonnes of Captured CO2	No	n/a	Census Division	2020-2050	n/a	Analysis of production facilities
Cement CO2 Capture	Tonnes of Captured CO2	No	n/a	Census Division	2020-2050	n/a	Analysis of production facilities

Table 17 Service efficiency data sources

Subsector	Unit	Stock Dependent	Driver	Input Data: Geography	Input Data: Year(s)	Additional Detail	Source
Iron and Steel CO2 Capture	MMBTU/Tonne of CO2	No	n/a	US	2018	n/a	(16)
Cement CO2 Capture	MMBTU/Tonne of CO2	No	n/a	US	2018	n/a	(16)

Table 18 shows baseline energy demand projection input data sources for subsectors employing Method D (4.3.1.7).

Table 18 Energy demand data sources for Method D subsectors

Subsector	Unit	Driver	Input Data: Geography	Other Downscaling method	Input Data: Year(s)	Additional Detail	Source
Residential computers and related	MMBTU	Households	Census division		2015-2050	Housing types; Computer equipment types	(33)
Residential televisions and related	MMBTU	Households	Census division		2015-2050	Housing types; Television equipment types	(33)
Residential Secondary Heating	MMBTU per household	Households; HDD	Census division		2015-2050	Housing types	(33)
Residential other uses	MMBTU	Households	Census division		2015-2050	Housing types; Other equipment types	(33)
Residential Furnace Fans	MMBTU	Households	Census division		2015-2050	Housing types	(33)
Office Equipment (P.C.)	Quads	Commercial square footage	US		2015-2050		(33)
Office Equipment (Non-P.C.)	Quads	Commercial square footage	US	Employment in all industries (NAICS, no code) 2007	2015-2050		(33)
Commercial Other	Quads	Commercial square footage	Census Division	Employment in all industries (NAICS, no code) 2007	2015-2050	Building Types	(33)
Non-CHP District Services	kilobtu per square feet	Commercial square footage	Census division	Households 2010	2012	Building Types	(31)
CHP District Services	Terabtu	Commercial square footage	Census Division	Households 2010	2015-2050	Building types	(33)
Domestic Shipping	Terabtu	Vessel Bunkering Sales	US		2015-2050		(33)
Military Use	Terabtu	Military Air Bases (Count)	US		2015-2050		(33)
Motorcycles	Terabtu	Motorcycle VMT	US		2015-2050		(33)
Lubricants	Terabtu	Population	US		2015-2050		(33)
International Shipping	Terabtu	Vessel Bunkering Sales	US		2015-2050		(33)
Recreational Boats	Terabtu	n/a	US	Households 2010	2015-2050		(33)

School and intercity buses	Terabtu	Passenger miles, population	US		2015-2050		(33)
Passenger rail	Terabtu	Rail passenger miles	Census division	Rail Fuel Use	2015-2050	Passenger rail mode (commuter, intercity, transit)	(33)
Freight rail	Terabtu	Historical non-coal freight miles	Census division	Rail Fuel Use	2015-2050	Industrial end-use category	(33)
Aviation	Terabtu	Passenger-mile departures	US		2015-2050	Industrial end-use category	(33)
Agriculture – Crops	Terabtu	GDP by Industry	Census region		2015 – 2050	Industrial end-use category	(33)
Agriculture – Other	Terabtu	GDP by Industry	Census region		2015-2050	Industrial end-use category	(33)
Aluminum Industry	Terabtu	Aluminum Production	Census region		2015-2050	Industrial end-use category	(33)
Balance of Manufacturing Other	Terabtu	Value of Shipments by Industry	Census region		2015-2050	Industrial end-use category	(33)
Bulk Chemicals	Terabtu	Facility Emissions by Industry	Census region		2015-2050	Industrial end-use category	(33)
Cement	Terabtu	Facility Emissions by Industry	Census region		2015-2050	Industrial end-use category	(33)
Computer and Electronic Products	Terabtu	Value of Shipments by Industry	Census region		2015-2050	Industrial end-use category	(33)
Construction	Terabtu	GDP by Industry	Census region		2015-2050	Industrial end-use category	(33)
Electrical Equip., Appliances, and Components	Terabtu	Value of Shipments by Industry	Census region		2015-2050	Industrial end-use category	(33)
Fabricated Metal Products	Terabtu	Value of Shipments by Industry	Census region		2015-2050	Industrial end-use category	(33)
Food and Kindred Products	Terabtu	Facility Emissions by Industry	Census region		2015-2050	Industrial end-use category	(33)
Glass and Glass Products	Terabtu	Facility Emissions by Industry	Census region		2015-2050	Industrial end-use category	(33)
Iron and Steel	Terabtu	Facility Emissions by Industry	Census region		2015-2050	Industrial end-use category	(33)
Lime	Terabtu	Facility Emissions by Industry	Census region		2015-2050	Industrial end-use category	(33)

Machinery	Terabtu	Value of Shipments by Industry	Census region		2015-2050	Industrial end-use category	(33)
Metal and Other Non-metallic Mining	Terabtu	GDP by Industry	Census region		2015-2050	Industrial end-use category	(33)
Paper and Allied products	Terabtu	Facility Emissions by Industry	Census region		2015-2050	Industrial end-use category	(33)
Plastic and Rubber Products	Terabtu	Value of Shipments by Industry	Census region		2015-2050	Industrial end-use category	(33)
Transportation Equipment	Terabtu	Value of Shipments by Industry	Census region		2015-2050	Industrial end-use category	(33)
Wood products	Terabtu	Value of Shipments by Industry	Census region		2015-2050	Industrial end-use category	(33)

Demand drivers are data that allow us to downscale and project other linked data that may not have the geographic granularity we require. Table 19 describes data we use for this purpose in its original form. This is then mapped to the model's chosen granularity for use.

Table 19 Demand Drivers

Driver	Geographic Granularity	Data Year (s)	Additional Detail	Source
Commercial Square Footage	Census Division	2015-2050	Building Types	(33)
GDP by Industry	State	1997-2018		(25)
VOS by Industry	State	2012		(27)
Facility Emissions by Industry	State	2017	Industrial Subcategory	(25)
Aluminum Production	State	2017		(35)
Household Heating Fuel Share	State	2017	Housing Type	(26)
House Age Index Share	State	2017		(26)
Heating Degree Days	State	2000; 2017		(20)
Cooling Degree Days	State	2000; 2017		(20)
Households	State	2017	Building Types	(26)
LDV VMT	State	2017		(8)
LDA Registrations	State	2017		(8)
LDT Registration	State	2017		(8)
HDT Registrations	State	2017		(8)
HDV VMT	State	2017		(8)
MDV VMT	State	2017		(8)
Motorcycle VMT	State	2017		(8)

Table 20 Load shape sources

Shape Name	Used By	Input Data Geography	Input Temporal Resolution	Source
Bulk System Load	Initial electricity reconciliation, all subsectors not otherwise given a shape	Emissions and Generation Resource Integrated Database (EGRID) with additional granularity in the Western Interconnection	Hourly, 2012	(37)
Light-Duty Vehicles (LDVs)	All LDVs	United States	Month-hour-weekday/weekend average, separated by home vs work charging	Evolved Energy Research analysis of 2016 National Household Travel Survey
Water Heating (Gas Shape)	Residential hot water			Northwest Energy Efficiency Alliance Residential Building Stock Assessment Metering Study (Northwest)
Other Appliances	Residential TV & computers			
Lighting	Residential lighting			
Clothes Washing	Residential clothes washing			
Clothes Drying	Residential clothes drying			
Dishwashing	Residential dish washing			
Residential Refrigeration	Residential refrigeration			
Residential Freezing	Residential freezing			
Residential Cooking	Residential cooking			
Industrial Other	All other industrial loads			California Load Research Data
Agriculture	Industry agriculture			
Commercial Cooking	Commercial cooking			
Commercial Water Heating	Commercial water heating	North American Electric reliability Corporation (NERC) region		EPRI Load Shape Library 5.0
Commercial Lighting Internal	Commercial lighting			
Commercial Refrigeration	Commercial refrigeration			
Commercial Ventilation	Commercial ventilation			
Commercial Office Equipment	Commercial office equipment			
Industrial Machine Drives	Machine drives			
Industrial Process Heating	Process heating			

Electric_furnace_res	Electric resistance heating technologies	IECC Climate Zone by state (114 total geographical regions)	Hourly, 2012 weather	Evolve 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 2102 from the National Oceanic and Atmospheric Administration (NOAA)
Reference_central_ac_res	Central air conditioning technologies			
High_efficiency_central_ac_res	High-efficiency central air conditioning technologies			
Reference_room_ac_res	Room air conditioning technologies			
High_efficiency_room_ac_res	High-efficiency room air conditioning technologies			
Reference_heat_pump_heating_res	ASHPs			
High_efficiency_heat_pump_heating_res	High-efficiency ASHPs			
Reference_heat_pump_cooling_res	ASHPs			
High_efficiency_heat_pump_cooling_res	High-efficiency ASHPs			
Chiller_com	Commercial chiller technologies			
Dx_ac_com	Direct expansion air conditioning technologies			
Boiler_com	Commercial boiler technologies			
Furnace_com	Commercial electric furnaces			
Flat shape	MDV and HDV charging	United States	n/a	n/a

*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.

3.3 Supply-side Data Description

Table 21 Supply-side data sources

Data Category	Data Description	Supply Node	Source
Resource Potential	Binned resource potential (GWh) by state with associated resource performance (capacity factors) and transmission costs to reach load.	Transmission – sited Solar PV (3 resource bins); Onshore Wind (10 resource bins); Offshore Wind – Fixed (5 resource bins); Offshore Wind – Floating (10 resource bins); Geothermal	(7)

	Binned resource potential of biomass resources by state with associated costs	Biomass Primary – Herbaceous; Biomass Primary – Wood; Biomass Primary – Waste; Biomass Primary – Corn	(17)
	Binned annual carbon sequestration injection potential by state with associated costs	Carbon Sequestration	(28)
	Domestic production potential of natural gas	Natural Gas Primary – Domestic	(31)
	Domestic production potential of oil	Oil Primary – Domestic	(31)
Product Costs	Commodity cost of natural gas at Henry Hub	Natural Gas Primary – Domestic	(33)
	Undelivered costs of refined fossil products	Refined Fossil Diesel; Refined Fossil Jet Fuel; Refined Fossil Kerosene; Refined Fossil Gasoline; Refined Fossil LPG	(33)
	Commodity cost of Brent oil	Oil Primary – Domestic; Oil Primary - International	(33)
Delivery Infrastructure Costs	AEO transmission and delivery costs by EMM region	Electricity Transmission Grid; Electricity Distribution Grid	(33)
	AEO transmission and delivery costs by census division and sector	Gas Transmission Pipeline; Gas Distribution Pipeline	(33)
	AEO delivery costs by fuel product	Gasoline Delivery; Diesel Delivery; Jet Fuel; LPG Fuel Delivery; Kerosene Delivery	(33)
Technology Cost and Performance	Renewable and conventional electric technology installed cost projections	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	(19)
		Transmission – Sited Solar PV Power Plant capital cost	(Union of Concerned Scientists, 2020)
	Electric fuel cost projections including electrolysis and fuel synthesis facilities	Central Hydrogen Grid Electrolysis; Power-To-Liquids; Power to Gas	(36)
	Hydrogen Gas Reformation costs with and without carbon capture	H2 Natural Gas Reformation; H2 Natural Gas Reformation w/CCS	(12)
	Nth plant Direct air capture costs for sequestration and utilization	Direct Air Capture with Sequestration; Direct Air Capture with Utilization	(15)

	Gasification cost and efficiency of conversion including gas upgrading.	Biomass Gasification; Biomass Gasification with CCS	(10)
	Cost and efficiency of renewable Fischer-Tropsch diesel production.	Renewable Diesel; Renewable Diesel with CCS	(10)
	Cost and efficiency of industrial boilers	Electric Boilers; Other Boilers	(36)
	Cost and efficiency of other, existing power plant types	Fossil Steam Turbines; Coal Power Plants	(14)

4. EnergyPATHWAYS Methodology

4.1 Model Structure

The EnergyPATHWAYS model is a comprehensive energy accounting and analysis framework specifically designed to examine large-scale energy system transformations. It accounts for the costs and emissions associated with producing, transforming, delivering, and consuming energy in an economy. It has strengths in infrastructure accounting and electricity operations that separate it from models of similar types. It is used, as it has been in this analysis, to calculate the effects of energy system decisions on future infrastructure, emissions, and costs to energy consumers and the economy more broadly.

Figure 6 shows the basic calculation steps for EnergyPATHWAYS and the outputs from each step.

EnergyPATHWAYS projects energy demand and costs in subsectors based on explicit user-decisions about technology adoption (e.g., electric vehicle adoption) and activity levels (e.g., reduced VMTs). These projections of energy demand across energy carriers are then sent to the supply-side of the model. In combination with

RIO, the supply-side of the model calculates upstream energy flows, primary energy usage, infrastructure requirements, emissions, and costs of supplying energy. These supply-side outputs are then combined with the demand-side outputs to calculate the total costs of the modeled energy system.

The sections below describe the EnergyPATHWAYS demand-side, supply-side, infrastructure, emissions, and cost calculation methods in detail.

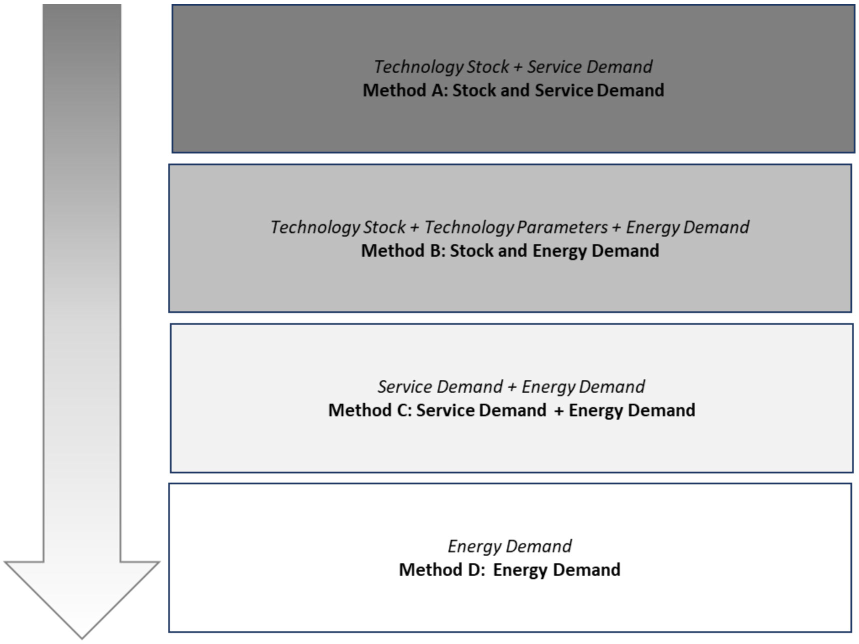
4.2 Subsectors

Subsectors represent separately modeled units of demand for energy services. These are often referred to as end-uses in other modeling frameworks. EnergyPATHWAYS is flexible in the configuration of subsectors, and methods used in each subsector depending on data availability. The high level of detail in subsectors in the EnergyPATHWAYS U.S. database is enabled by the availability of numerous high-quality data sources for the U.S. energy economy. Below we describe the calculations used for individual subsectors on the demand-side. Total demand is simply the summation of these calculations for all subsectors.

4.3 Energy Demand Projection

Data availability determines subsector granularity and informs the methods used in each subsector. The flow diagram below represents the decision matrix used to determine the methods – named A, B, C, D – used to model an individual energy demand subsector (Figure 64). The arrow downward indicates a progression from most-preferred (A) to least-preferred (D) methodology for modeling a subsector. The preferred methods allow for more explicit measures and better accounting of costs and energy impacts. Each method for projecting energy demand is described below.

Figure 7 Methods for projecting energy demand



4.3.1 Method A: Stock and Service Demand

This method is the most explicit representation of energy demand possible in the EnergyPATHWAYS framework. It has a high data requirement; many end-uses are not homogenous enough to represent with technology stocks and others do not have measurements of energy service demand. When the data requirements are met, EnergyPATHWAYS uses the following formula to calculate energy demand from a subsector.

Equation 1

$$E_{ycr} = \sum_{v \in V} \sum_{t=T} U_{yvtcr} * f_{vtc} * d_{yr} * (1 - R_{yrc})$$

Where:

E = Energy demand in year y of energy carrier c in region r

U_{yvtcr} = Normalized share of service demand in year y of vintage v of technology t for energy carrier c in region r

f_{vtc} = Efficiency (energy/service) of vintage v of technology t using energy carrier c

d_{yr} = Total service demand input aggregated for year y in region r

R_{yrc} = Unitized service demand reductions for year y in region r for energy carrier c. Service demand reductions are calculated from input service demand measures, which change the baseline energy service demand levels.

4.3.1.1 Service Demand Share (U)

The normalized share of service demand (U) is calculated as a function of the technology stock (S), service demand modifiers (M), and energy carrier utility factors (C). Below is the decomposition of *U* into its component parts of *S* and *M and C.*

Equation 2

$$U_{yvtr} = \frac{S_{yvtr} * M_{yvtr} * C_{tc}}{\sum_{v \in V} \sum_{t \in T} S_{yvtr} * M_{yvtr}}$$

Where:

S_{yvtr} = Technology stock in year y of vintage v of technology t in region r

M_{yvtr} = Service demand modifier in year y for vintage v for vintage t in region r

C_{tc} = Utility factor for energy carrier c for technology t

The calculation of these factors is detailed in the sections below.

4.3.1.2 Technology Stock (S)

The composition of the technology stock is governed by stock-rollover mechanics in the model, technology inputs (lifetime parameters, the distribution and pattern of technology retirements), initial technology stock states, and the application of sales share or stock measures. The section below describes the ways in which these model variables can affect the eventual calculation of technology share.

4.3.1.3 Initial Stock

The model uses an initial representation of the technology stock to project forward. This usually represents a single-year stock representation based on customer survey data (e.g. the U.S. Commercial Building Energy Consumption Survey data informs 2012 technology stock estimates) but can also be "specified" into the future, where the composition of the stock is determined exogenously. At the end of this initial stock specification, the model uses technology parameters and rollover mechanics to determine stock compositions by year.

Stock Decay and Replacement

EnergyPATHWAYS allows for technology stocks to decay using linear representations or Weibull distributions, which are typical functions used to represent technology reliability and failure rates. These parameters are governed by a combination of technology lifetime parameters. Technology lifetimes can be entered as minimum and maximum lifetimes or as an average lifetime with a variance.

After the conclusion of the initial stock specification period, the model decays existing stock based on the age of the stock, technology lifetimes, and specified decay functions. This stock decay in a year (y) must be replaced with technologies of vintage (v) $v = y$. The share of replacements in vintage v is equal to the share of replacements unless this default is overridden with exogenously specified sales share or stock measures. This share of sales is also used to inform the share of technologies deployed to meet any stock growth.

Sales Share Measures

Sales share measures override the pattern of technologies replacing themselves in the stock rollover.

An example of a sales share measure is shown below for two technologies – A and B - that are represented equally in the initial stock and have the same decay parameters. EnergyPATHWAYS applies a sales share measure in the year 2020 that requires 80% of new sales in 2020 to be technology A and 20% to be technology B. The first equation shows the calculation in the absence of this sales share measure. The second shows the stock rollover governed with the new sales share measure.

S = Stock
D = Stock decay
G = Year on year stock growth
R = Stock decay replacement
H = User specified share of sales for each technology
N = New Sales
a = Technology A
b = Technology B

<u>Before Measure (i.e., Baseline)</u>

S_{2019} = 100
S_{a2019} = 50

$S_{b2019} = 50$
$D_{2020} = 10$
$D_{a2020} = 5$
$D_{b2020} = 5$
$S_{2020} = 110$
$G_{2020} = S_{2020} - S_{2019} = 110 - 100 = 10$
$R_{a2020} = D_{a2020} = 5$
$R_{b2020} = D_{b2020} = 5$
$G_{a2020} = \frac{D_{a2020}}{D_{2020}} * G_{2020} = 5/10 * 10 = 5$
$G_{b2020} = \frac{D_{b2020}}{D_{2020}} * G_{2020} = 5/10 * 10 = 5$
$N_{a2020} = R_{a2020} + G_{a2020} = 5 + 5 = 10$
$N_{b2020} = R_{b2020} + G_{b2020} = 5 + 5 = 10$
$S_{a2020} = S_{a2019} + D_{a2020} + N_{a2020} = 50 - 5 + 10 = 55$
$S_{b2020} = S_{b2019} + D_{b2020} + N_{b2020} = 50 - 5 + 10 = 55$

After Sales Share Measure
$S_{2019} = 100$
$S_{a2019} = 50$
$S_{b2019} = 50$
$D_{2020} = 10$
$D_{a2020} = 5$
$D_{b2020} = 5$
$S_{2020} = 110$
$G_{2020} = S_{2020} - S_{2019} = 110 - 100 = 10$
$R_{a2020} = D_{2020} * H_{a2020} = 10 * .8 = 8$
$R_{b2020} = D_{2020} * H_{b2020} = 10 * .2 = 2$
$G_{a2020} = G_{2020} * H_{a2020} = 10 * .8 = 8$
$G_{b2020} = G_{2020} * H_{b2020} = 10 * .2 = 2$
$N_{a2020} = R_{a2020} + G_{a2020} = 8 + 8 = 16$
$N_{b2020} = R_{b2020} + G_{b2020} = 2 + 2 = 4$
$S_{a2020} = S_{a2019} + D_{a2020} + N_{a2020} = 50 - 5 + 16 = 61$
$S_{b2020} = S_{b2019} + D_{b2020} + N_{b2020} = 50 - 5 + 4 = 49$

This shows a very basic example of the role that sales share measures play to influence the stock of technology. In the context of energy demand, these technologies can use different energy carriers (i.e. gasoline internal combustion engine vehicles to electric vehicles) and/or have different efficiency characteristics.

Though not shown in the above example, the stock is tracked on a vintaged basis, so decay of technology A in 2020 in the above example would be decay in 2020 of all vintages before 2020. In the years immediately following the deployment of vintage cohort, there is very little technology retirement given the shape of the decay functions. As a vintage approaches the end of its anticipated useful life, however, retirement accelerates.

4.3.1.4 Service Demand Modifier (M)

Many energy models use stock technology share as a proxy for service demand share. This makes the implicit assumption that all technologies of all vintage in a stock are used equally. This assumption obfuscates some key dynamics that influence the pace and nature of energy system transformation. For example, new heavy-duty vehicles are used heavily at the beginning of their useful life but are sold to owners who operate them for reduced duty-cycles later in their lifecycles. This means that electrification of this fleet would accelerate the rollover of electrified miles faster than it would accelerate the rollover of the trucks themselves. Similar dynamics are at play in other vehicle subsectors. In subsectors like residential space heating, the distribution of current technology stock is correlated with its utilization. Even within the same region, with the same climactic conditions, the choice of heating technology informs its usage. Homes that have baseboard electric heating, for example, are often seasonal homes with limited heating loads.

EnergyPATHWAYS has two methods for determining the discrepancy between stock shares and service demand shares. First, technologies can have the input of a *service demand modifier*. This is used as an adjustment between stock share and service demand share.

Using the example stock of Technology, A and B, the formula below shows the impact of service demand modifier on the service demand share.

S = Stock
x = Stock ratio
M = service demand modifier
U = service demand allocator
$S_{2019} = 100$
$S_{a2019} = 50$
$S_{a2020} = 50$
$x_{a2019} = \frac{S_{a2019}}{S_{2019}} = \frac{50}{100} = .5$
$x_{b2019} = \frac{S_{b2019}}{S_{2019}} = \frac{50}{100} = .5$
$M_{a2019} = 2$
$M_{b2019} = 1$
$U_{a2019} = \frac{S_{a2019} * M_{a2019}}{\sum_{t=a..b} S_{t2019} * M_{t2019}} = \frac{50*2}{150} = .667$
$U_{b2019} = \frac{S_{b2019} * M_{b2019}}{\sum_{t=T} S_{t2019} * M_{t2019}} = \frac{50*1}{150} = .333$

When service demand modifiers aren't entered for individual technologies, they can potentially still be calculated using input data. For example, if the service demand input data is entered with the index of t, the model calculates service demand modifiers by dividing stock and service demand inputs.

Equation 3

$M_{tyr} = \frac{s_{tyr}}{d_{ty}r}$
Where
M_{ty} = Service demand modifier for technology t in year y in region r
s_{tyr} = Stock input data for technology t in year y in region r
d_{tyr} = Energy demand input data for technology t in year y in region r

Energy Carrier Utility Factors (C)

Energy carrier utility factors are technology inputs that allocate a share of the technology's service demand to energy carriers. The model currently supports up to two energy carriers per technology. This allows EnergyPATHWAYS to support analysis of dual-fuel technologies, like plug-in-hybrid electric vehicles. The input structure is defined as a primary energy carrier with a utility factor (0 – 1) and a secondary energy carrier that has a utility factor of 1 – the primary utility factor.

4.3.1.5 Method B: Stock and Energy Demand

Method B is like Method A in almost all its components except for the calculation of service demand. In Method A, service demand is an input. In Method B, the energy demand of a subsector is used as a substitute input for service demand. From this input, EnergyPATHWAYS takes the additional step of deriving service demand, based on stock and technology inputs.

Equation 4

$$E_{ycr} = \sum_{v \in V} \sum_{t=T} U_{yvtcr} * f_{vtc} * D_{yr} * (1 - R_{yrc})$$

Where

E = Energy demand in year y of energy carrier c in region r

U = Normalized share of service demand in year y of vintage v of technology t for energy carrier c in region r

f = Efficiency (energy/service) of vintage v of technology t using energy carrier c

D = Total service demand calculated for year y in region r

R_{yrc} = Unitized service demand reductions for year y in region r for energy carrier c

Total Service Demand (D)

Total service demand is calculated using stock shares, technology efficiency inputs, and energy demand inputs. The intent of this step is to derive a service demand term (D) that allows us to use the same calculation framework as Method A.

Equation 5

$$D_{yr} = \sum_{v \in V} \sum_{c \in C} \sum_{t=T} U_{yvtcr} * f_{vtc} * e_{ycr}$$

Where

D_{yr} = Total service demand in year y in region r

f_{vtc} = Efficiency (energy/service) of vintage v of technology t using energy carrier c

e_{ycr} = Input energy data in year y of carrier c in region r

4.3.1.6 Method C: Service and Service Efficiency

Method C is used when EnergyPATHWAYS does not have sufficient input data, either at the technology level or the stock level, to parameterize a stock rollover. Instead EnergyPATHWAYS replaces the stock terms in the energy demand calculation with a service efficiency term (j). This is an exogenous input that substitutes for the stock rollover dynamics and outputs in the model. Within this study, no subsectors use Method C, but the description is included here for completeness.

Equation 6

$E_{ycr} = j_{ycr} * d_{yr} * R_{yrc} - O_{yrc}$

where

E_{ycr} = Energy demand in year y for energy carrier c in region r

j_{ycr} = Service efficiency (energy/service) of subsector in year y for energy carrier c in region r

d_{yr} = Input service demand for year y in region r

R_{yrc} = Unitized service demand multiplier for year y in region r for energy carrier c

O_{yrc} = Energy efficiency savings in year y in region r for energy carrier c

Energy Efficiency Savings (O)

Energy efficiency savings are a result of exogenously specified energy efficiency measures in the model. These take the form of prescribed levels of energy savings that are netted off the baseline projection of energy usage.

4.3.1.7 Method D: Energy Demand

The final method is simply the use of an exogenous specification of energy demand. This is used for subsectors where there is neither the data necessary to populate a stock rollover nor any data available to decompose energy use from its underlying service demand.

Equation 7

$E_{ycr} = e_{ycr} - O_{yrc}$

Where

E_{ycr} = Energy demand in year y for energy carrier c in region r

e_{ycr} = Input baseline energy demand in year y for energy carrier c in region r

O_{yrc} = Energy efficiency savings in year y in region r for energy carrier c

4.3.1.8 Demand-Side Costs

Cost calculations for the demand-side are separable into technology stock costs and measure costs (energy efficiency and service demand measures).

4.3.1.9 Technology Stock Costs

EnergyPATHWAYS uses vintaged technology cost characteristics as well as the calculated stock rollover to calculate the total costs associated with technology used to provide energy services.[2]

$C_{yr}^{stk} = C_{yr}^{cap} + C_{yr}^{ins} + C_{yr}^{fs} + C_{yr}^{fom}$

Where

C_{yr}^{stk} = Total levelized stock costs in year y in region r

C_{yr}^{cap} = Total levelized capital costs in year y in region r

C_{yr}^{ins} = Total levelized installation costs in year y in region r

C_{yr}^{fs} = Total levelized fuel switching costs in year y in region r

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[2] Levelized costs are the principal cost metric reported, but the model also calculates annual costs (i.e. the cost in 2020 of all technology sold). Supply-side technology costs are included in the accompanying Excel workbook to this technical appendix.

C_{yr}^{fom} = Total fixed operations and maintenance costs in year y in region r

Technology Stock Capital Costs

The model uses information from the physical stock rollover used to project energy demand, with a few modifications. First, the model uses a different estimate of technology life. The financial equivalent of the physical "decay" of the technology stock is the depreciation of the asset. The asset is depreciated over the "book life," which doesn't change, regardless of whether the physical asset has retired.

To provide a concrete example of this, a 2020 technology vintage with a book life of 15 years is maintained in the financial stock in its entirety for the 15 years before it is financially "retired" in 2035. This financial stock estimate, in addition to being used in the capital costs calculation, is used for calculating installation costs and fuel switching costs.

Equation 8

$$C_{yr}^{cap} = \sum_{v \in V} \sum_{t \in T} S_{tvyr}^{fin} * W_{tvr}^{cap}$$

Where

C_{yr}^{cap} = Total levelized technology costs in year y in region r

W_{tvr}^{cap} = Levelized capital costs for technology t for vintage v in region r

S_{tvyr}^{fin} = Financial stock of technology t and vintage v in year y in region r

EnergyPATHWAYS primarily uses this separate financial accounting so that EnergyPATHWAYS accurately account for the costs of early-retirement of technology. There is no way to financially early-retire an asset, so physical early retirement increases overall costs (by increasing the overall financial stock).

Levelized Capital Costs (W)

EnergyPATHWAYS levelizes technology costs over the mean of their projected useful lives (referred to as book life). This is either the input mean lifetime parameter or the arithmetic mean of the technology's max and min lifetimes. EnergyPATHWAYS additionally assesses a cost of capital on this levelization of the technology's upfront costs. While this may seem an unsuitable assumption for technologies that could be considered "out-of-pocket" purchases, EnergyPATHWAYS assumes that all consumer purchases are made using backstop financing options. This is the implicit assumption that if "out-of-pocket" purchases were reduced, the amount needed to be financed on larger purchases like vehicles and homes could be reduced in-kind.

$$W_{tvr}^{cap} = \frac{d_t * z_{tvr}^{cap} * (1 + d_t)^{l_t^{book}}}{(1 + d_t)^{l^{book}} - 1}$$

Where

W_{tvr}^{cap} = Levelized capital costs for technology t for vintage v in region r

d_t = Discount rate of technology t

z_{tvr}^{cap} = Capital costs of technology t in vintage v in region r

l_t^{book}= Book life of technology t

Technology Stock Installation Costs

Installation costs represent costs incurred when putting a technology into service. The methodology for calculating these is the same as that used to calculate capital costs. These are levelized in a similar manner.

Technology Stock Fuel Switching Costs

Fuel switching costs represent costs incurred for a technology only when switching from a technology with a different primary energy carrier. This input is used for technologies like gas furnaces that may need additional gas piping if they are being placed in service in a household that had a diesel furnace. Calculating these costs requires the additional step of determining the number of equipment sales in a given year associated with switching fuels.

4.3.1.10 Technology Stock Fixed Operations and Maintenance Costs

Fixed operations and maintenance (O&M) costs are the only stock costs that utilize physical and not financial representations of technology stock. This is because O&M costs are assessed annually and are only incurred on technologies that remain in service. If equipment has been retired, then it no longer has ongoing O&M costs.

$$C_{yr}^{fom} = \sum_{v\in V} \sum_{t\in T} S_{tyvr} * W_{tvr}^{fom}$$

Where

S_{tyvr}= Technology stock of technology t in year y of vintage v in region r

W_{tvr}^{fom} = Fixed O&M costs for technology t for vintage v in region r

4.3.1.11 Measure Costs

Measure costs are assessed for interventions either at the service demand (service demand measures) or energy demand levels (energy efficiency measures). While these measures are abstracted from technology-level inputs, EnergyPATHWAYS uses a similar methodology for these measures as for technology stock costs. EnergyPATHWAYS uses measure savings to create “stocks” of energy efficiency or service demand savings. These measure stocks are vintaged like technology stocks and EnergyPATHWAYS use analogous inputs like capital costs and useful lives to calculate measure costs.

4.3.1.12 Energy Efficiency Measure Costs

Energy efficiency costs are costs associated the reduction of energy demand. These are representative of incremental equipment costs or costs associated with non-technology interventions like behavioral energy efficiency.

Equation 9

$$C_{yr}^{ee} = \sum_{v\in V} \sum_{m\in M} S_{mvyr}^{ee} * W_{mvr}^{ee}$$

Where

C_{yr}^{ee} = Total energy efficiency measure costs

S_{mvyr}^{sd} = Financial stock of energy demand reductions from measure m of vintage v in year y in region r

W_{mvr}^{ee} = Levelized per-unit energy efficiency costs

4.4 EnergyPATHWAYS supply-side

4.4.1 Supply Nodes

Supply nodes represent the fundamental unit of analysis on the supply-side and are analogous to subsectors on the demand-side. We will primarily describe the calculations for individual supply nodes in this document, but assessing the total costs and emissions from the supply-side is just the summation of all supply nodes for a year and region.

4.4.2 I/O Matrix

There is one principal difference between supply nodes and subsectors that explains the divergent approaches taken for calculating them; energy flows through supply nodes must be solved concurrently due to several dependencies between nodes. As an example, it is not possible to know the flows through the gas transmission pipeline node without knowing the energy flow through gas power plant nodes. This tenet requires a fundamentally different supply-side structure. To solve the supply-side, EnergyPATHWAYS leverages techniques from economic modeling by arranging supply nodes in an input-output matrix, where coefficients of a node represent units of other supply nodes required to produce the output product of that node.

Consider a simplified representation of upstream energy supply with four supply nodes:

a. Electric Grid

b. Gas Power Plant

c. Gas Transmission Pipeline

d. Primary Natural Gas

This is a system that only delivers final energy to the demand-side in the form of electricity from the electric grid. It also has the following characteristics:

1. The gas transmission pipeline has a loss factor of 2% from leakage. It also uses grid electricity to power compressor stations and requires .05 units of grid electricity for every unit of delivered gas.
2. The gas power plant has a heat rate of 8530 Btu/kWh, which means that it requires 2.5 (8530 Btu/kWh/3412 Btu/kWh) units of gas from the transmission pipeline for every unit of electricity generation.
3. The electricity grid has a loss factor of 5%, so it needs 1.05 units of electricity generation to deliver 1 unit of electricity to its terminus.

The I/O matrix for this system is shown in tabular form in Table 20 as well as in matrix form in the equation below.

Table 22. Tabular I/O Matrix

	Natural Gas	Gas Transmission Pipeline	Gas Power Plant	Electric Grid
Natural Gas		1.02		
Gas Transmission Pipeline			2.5	
Gas Power Plant				1.05

Electric Grid		.05		

Equation 10

$$A = \begin{pmatrix} & 1.05 & & \\ & & 2.5 & \\ & & & 1.05 \\ & .05 & & \end{pmatrix}$$

With this I/O matrix, if we know the demand for energy from a node (supplied from the demand-side of the EnergyPATHWAYS model), we can calculate energy flows through every upstream supply node. To continue the example, if 100 units of electricity are demanded:

$$d = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 100 \end{pmatrix}$$

We can calculate the energy flow through each node using the equation, which represents the inverted matrix multiplied by the demand term.

$$x = (I - A)^{-1} * d$$

This gives us the following result:

$$x = \begin{pmatrix} 308 \\ 302 \\ 121 \\ 115 \end{pmatrix}$$

Applied in EnergyPATHWAYS the I/O structure is much more complex than this simple example. Most of the supply-side calculations are focused on populating I/O coefficients and solving throughput through each node, which allows us to calculate infrastructure needs, costs, resource usage, and greenhouse gas emissions associated with energy supply.

There are six distinct types of nodes that represent different components of the energy supply system. These will be examined individually in all of the supply-side calculation descriptions. The list below details some of their basic functionality.

1. **Conversion Nodes –** Conversion nodes represent units of infrastructure specified at the technology level (i.e. gas combined cycle power plant) that have a primary purpose of converting the outputs of one supply node to the inputs of another supply node. Gas power plants in the above example are a conversion node, converting the output of the gas transmission pipeline to the inputs of the electric grid.

2. **Delivery Nodes –** Delivery nodes represent infrastructure specified at a non-technology level. The gas transmission pipeline is an example of a delivery node. A transmission pipeline system is the aggregation of miles of pipeline, hundreds of compressor stations, and storage facilities. We represent it as an aggregation of these components. The role of delivery nodes is to deliver the outputs of one supply node to a different physical location in the system required so that they can be used as inputs to another supply node. In the above example, gas transmission pipelines deliver natural gas from gas fields to gas power plants, which are not co-located with the resource. A full list of the delivery nodes in EnergyPATHWAYS is given in Table 21.

3. **Primary Nodes –** Primary nodes are used for energy accounting, but they generally represent the start of the energy supply chain. That is, absent some exceptions, their coefficients are generally zero.

4. **Product Nodes –** Product nodes are used to represent energy products where it is not possible to endogenously build up the costs and emissions back through to their primary energy source.

5. **Blend Nodes –** Blend nodes are non-physical control nodes in the energy supply chain. These are the locations in the energy system that we apply measures to change the relative inputs to other supply nodes. There are no blend nodes in the simplified example above, but an alternative energy supply system may add a biogas product node and place a blend node between the gas transmission pipeline and the primary natural gas node. This blend node would be used to control the relative inputs to the gas transmission pipeline (between natural gas and biogas).

6. **Electric Storage Nodes –** Electric storage nodes are nodes that provide a unique role in the electricity dispatch functionality of EnergyPATHWAYS, as discussed further below.

Table 23 EnergyPATHWAYS supply-side delivery nodes

EnergyPATHWAYS Delivery Nodes
Coal - Rail Delivery
Coal - End-Use Delivery
Diesel End-Use Delivery
Electricity Distribution Grid
Electricity Transmission Grid
Gas Distribution Pipeline
Gas Transmission Pipeline
Hydrogen Fueling Stations

Liquid Hydrogen Truck Delivery
LPG Feedstock Delivery
Lubricants Delivery
Motor Gasoline End-Use Delivery
Petrochemical Feedstock Delivery
Pipeline Gas Feedstock Delivery
Residual Fuel-Oil End-Use Delivery

4.4.3 Energy Flows

4.4.3.1 Coefficient Determination (A – Matrix)

The determination of coefficients is unique to supply-node types. For primary, product, and delivery nodes, these efficiencies are exogenously specified by year and region.

4.4.3.2 Conversion Nodes

Conversion node efficiencies are calculated as the weighted averages of the online technology stocks. We use both stock and capacity factor terms because we want the energy-weighted efficiency, not capacity-weighted.

Equation 11

$$X_{ynr} = \sum_{t\in T}\sum_{v\in V}\frac{S_{tvyr} * u_{tvyr}}{\sum_{t\in T}\sum_{v\in V} S_{tvyr} * u_{tvyr}} * f_{tvnr}$$

Where

X_{ynr} = Input coefficients in year y of node n in region r

S_{tvyr} = Technology stock of technology t in year of vintage v in year y in region r

u_{tvyr} = Utilization rate, or capacity factor, of technology t of vintage v in year y in region r

f_{vntr} = Input requirements (efficiency) of technology t of vintage v using node n in region r

4.4.3.3 Energy Demands

Demand Mapping

To help develop the (d) term in the matrix calculations described in section 9.1.4.2, EnergyPATHWAYS must map the demand for energy carriers calculated on the demand-side to specific supply-nodes. In the simplified energy system example, electricity as a final energy carrier, for example, maps to the Electric Grid supply node.

Energy Export Specifications

In addition to demand-side energy requirements, the energy supply system must also meet export demands, that is demand for energy products that aren't used to satisfy domestic energy service demands, but instead are sent to other countries. These products aren't ultimately consumed in the model, but their upstream impacts must still be accounted for. Within the Net-Zero America Study, these fossil fuel exports are gradually trended down along with petroleum consumption, which reduces up-stream emissions in the decarbonization scenarios.

Total Demand

Total demand is the sum of domestic energy demands from the demand-side of EnergyPATHWAYS as well as any specified energy exports.

Equation 12

$$D_{yrn} = D_{yrn}^{end} + D_{yrn}^{exp}$$

Where

D_{yrn} = Total energy demand in year y in region r for supply node n

D_{yrn}^{end} = Endogenous energy demand in year y in region r for supply node n

D_{yrn}^{exp} = Export energy demand in year y in region r for supply node n

This total demand term is then multiplied by the inverted coefficient matrix to determine energy flows through each node.

4.5 Infrastructure Requirements

Infrastructure is represented by delivery and conversion supply nodes. Infrastructure here refers to physical assets that produce or move energy to end-use applications. In delivery nodes, this infrastructure is represented at the aggregate node-level. In conversion nodes, infrastructure is represented in technology stocks similarly to stocks on the demand-side. The sections below detail the basic calculations used to determine the infrastructure capacity needs associated with energy flows through the supply node.

4.5.1 Delivery Nodes

The infrastructure capacity required is determined by Equation 13 below:

Equation 13

$$I_{yr} = \frac{E_{yr}}{u_{yr} * 8760}$$

Where

u_{yr}[3] = Utilization (capacity) factor in year y in region r

E_{yr} = Energy flow through node in year y in region r

h = Hours in a year, or 8760

---

[3] Capacity factors of delivery nodes are exogenous inputs to the model except in the special cases of the Electricity Transmission Grid Node and the Electricity Distribution Grid node, where capacity factors are determined in the electricity dispatch.

4.5.2 Conversion Nodes

Conversion nodes are specified on a technology-basis, and a conversion node can contain multiple technologies to produce the energy flow required by the supply system. The operations of these nodes are analogous to the demand-side in terms of stock rollover mechanics, with sales shares and specified stock measures determining the makeup of the total stock. The only difference is that the size of the total stock is determined by the demand for energy production for the supply node, which is different than on the demand-side, where the size of the total stock is an exogenous input.

The formula to determine the size of the total stock remains essentially the same as the one used to determine the size of the total delivery stock. However, the average capacity factor of the node is a calculated term determined by the weighted average capacity factor of the stock in the previous year:

Equation 14

$$U_{yr} = \frac{\sum_{t\in T}\sum_{v\in V} S_{tvy-1r} * u_{tvyr}}{\sum_{t\in T}\sum_{v\in V} S_{tvy-1r}}$$

Where

U_{yr} = Utilization (capacity) factor in year y in region r

S_{tvy-1r} = Technology stock of technology t in year of vintage v in year y-1 in region r

u_{tvyr} = Utilization rate, or capacity factor, of technology t of vintage v in year y in region r

4.6 Emissions

There are two categories of greenhouse gas emissions in the model. First, there are physical emissions. These are traditional emissions associated with the combustion of fuels, and they represent the greenhouse gas emissions embodied in a unit of energy. For example, natural gas has an emissions rate of 53.06 kG/MMBTU of consumption while coal has an emissions rate of 95.52 kG/MMBTU.[4]. Physical emissions are accounted for on the supply-side in the supply nodes where fuels are consumed, which can occur in primary, product, delivery, and conversion nodes. Emissions, or consumption, coefficients, that is the units of fuel consumed can be a subset of energy coefficients. While the gas transmission pipeline may require 1.03 units of natural gas, it only consumes 0.03 units. Gas power plants, however, consume all 2.5 units of gas required. Equation 15 shows the calculation of physical emissions in a node:

Equation 15

$$G_{yr}^{phy} = \sum_{n\in N} X_{yrn}^{con} * E_{yr} * B_{yrn}^{phy}$$

Where

G_{yr}^{phy} = Physical greenhouse gas emissions in year y in region r

X_{yrn}^{con} = Consumption coefficients in year y in region r of node n

E_{yr}= Energy flow through node in year y in region r

B_{yrn}^{phy} = Emissions rates (emissions/energy) in year y in region r of input nodes n.

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[4] The full list of emissions factors are found in the Excel sheet that accompanies this appendix.

Emissions rates are either a function of a direct connection in the I/O matrix to a node with an emissions coefficient or they are “passed through” delivery nodes, which don’t consume them. Gas powerplants in the supplied example take the emission rates from the Natural Gas Node, despite being linked in the I/O matrix only through the delivery node of Gas Transmission Pipeline.

The second type of emissions are accounting emissions. These are not associated with the consumption of energy products elsewhere in the energy system. Instead, these are a function of energy production in a node[5]. Accounting emissions rates are commonly associated with carbon capture and sequestration supply nodes or with biomass. Accounting emissions are calculated using:

Equation 16

$$G_{yr}^{acc} = E_{yr} * B_{yrn}^{acc}$$

Where

G_{yr}^{acc} = Accounting greenhouse gas emissions in the node in year y in region r

E_{yr} = Energy flow through the node in year y in region r

B_{yr}^{acc} = Node accounting emissions rate

For primary, product, and delivery nodes, the accounting emissions rate in year y in region r is exogenously specified. For conversion nodes, this is an energy-weighted stock average.

$$B_{yr}^{acc} = \frac{\sum_{t\in T}\sum_{v\in V} S_{tvyr} * b_{tvyr}^{acc}}{\sum_{t\in T}\sum_{v\in V} S_{tvyr}}$$

Where

B_{yr}^{acc} = Energy weighted average of node accounting emissions factor in year y in region r

S_{tvyr} = Stock of technology t of vintage v in year y in region r

b_{tvyr}^{acc} = Exogenous inputs of accounting emissions rate for technology t of vintage v in year y in region r

4.7 Costs

Costs are calculated using different methodologies for those nodes with infrastructure (delivery, conversion, and electric storage) and those without represented infrastructure (primary and product).

4.7.1 Primary and Product Nodes

Primary and product nodes are calculated as the multiplication of the energy flow through a node and an exogenously specified cost for that energy.

$$C_{yr} = E_{yr} * w_{yr}$$

Where

C_{yr} = total costs of supplying energy from node in year y in region r

---

[5] For example, biomass may have a positive physical emissions rate, but biomass is considered to be zero-carbon for the Princeton study, so positive physical emissions rate is offset by a negative accounting emissions rate. For accounting purposes, this would result in the Biomass Node showing negative greenhouse gas emissions and the supply nodes that use biomass, for example Biomass Power Plants, recording positive greenhouse gas emissions.

E_{yr}= Energy flow through node in year y in region r
w_{yr}= Exogenous cost input for node in year y in region r

4.7.2 Delivery Nodes

Delivery node cost inputs are entered as per-energy unit tariffs. We use and adjust for any changes for the ratio of on-the-books capital assets and node throughput. This is done to account for dramatic changes in the utilization rate of capital assets in these nodes. This allows EnergyPATHWAYS to calculate and demonstrate potential death spirals for energy delivery systems[6], where the demand for energy from a node declines faster than the capital assets can depreciate. This pegs the tariff of the delivery node to the existing utilization rates of capital assets and increases them when that relationship diverges.

Equation 17

$$C_{yr} = \left(\frac{\frac{S_{yr}}{S_{yr}^{fin}}}{\sum_{y\in 1} \frac{S_{yr}}{S_{yr}^{fin}}} * \frac{\sum_{y\in 1} u_{yr}}{u_{yr}} * q * w_{yr} + (1-q) * w_{yr} \right) * E_{yr}$$

Where
C_{yr} = Total costs of delivery node in year y in region r
S_{yr}= Physical stock of delivery node in year y in region r
S_{yr}^{fin} = Financial stock of delivery node in year y in region r
u_{yr} = Exogenously specified utilization rate of delivery node in year y in region r
q = Share of tariff related to throughput-related capital assets, which are the only share of the tariff subjected to this adjustment.
w_{yr} = Exogenous tariff input for delivery node in year y in region r
E_{yr} = Energy flow through node in year y in region r

4.7.3 Conversion Nodes

Conversion node cost accounting is similar to the cost accounting of stocks on the demand-side with terms for capital, installation, and fixed O&M cost components. Instead of fuel switching costs, however the equation substitutes a variable O&M term.

Equation 18

$$C_{yr}^{stk} = C_{yr}^{cap} + C_{yr}^{ins} + C_{yr}^{fom} + C_{yr}^{vom}$$

Where
C_{yr}^{stk} = Total levelized stock costs in year y in region r

---

[6] For example, if delivered energy declines by 50% while the delivery assets are only depreciated 25%, the delivery costs seen by remaining customers will increase by 50% ((1-0.25) / (1-0.5)), this creates a further incentive for customers to exit the system, whereby remaining costs are spread over an even smaller number of customers.

C_{yr}^{cap} = Total levelized capital costs in year y in region r
C_{yr}^{ins} = Total levelized installation costs in year y in region r
C_{yr}^{fom} = Total fixed operations and maintenance costs in year y in region r
C_{yr}^{vom} = Total levelized variable operations and maintenance costs in year y in region r

There is no difference in the calculation of the capital, installation, and fixed O&M terms from the demand-side, so reference calculation for calculating those components of technology stocks in section 9.1.3.1.9.

4.7.3.1 Variable O&M Costs

Variable O&M costs are calculated as the energy weighted average of technology stock variable O&M costs.

$$C_{yr}^{vom} = \sum_{t\in T}\sum_{v\in V}\frac{S_{tvyr} * u_{tvyr}}{\sum_{t\in T}\sum_{v\in V} S_{tvyr} * u_{tvyr}} * w_{tvry}^{vom} * E_{yr}$$

Where
C_{yr}^{vom} = Total levelized variable operations and maintenance costs in year y in region r
S_{tvyr} = Technology stock of technology t in year of vintage v in year y in region r
U_{tvyr} = Utilization rate, or capacity factor, of technology t of vintage v in year y in region r
w_{tvry}^{vom} = Exogenous input of variable operations and maintenance costs for technology t of vintage v in region r in year y
E_{yr} = Energy flow through node in year y in region r

4.7.4 Electric Storage Nodes

Electric storage nodes are a special case of node used in the electricity dispatch. They add an additional term, which is a capital energy cost, to the equation used to calculate the costs for conversion nodes. This is the cost for the storage energy capacity, which is additive with the storage power capacity.

$$C_{yr}^{stk} = C_{yr}^{cap} + C_{yr}^{ecap}\ C_{yr}^{ins} + C_{yr}^{fom} + C_{yr}^{vom}$$

Where
C_{yr}^{stk} = Total levelized stock costs in year y in region r
C_{yr}^{cap} = Total levelized capital costs in year y in region r
C_{yr}^{ecap} = Total levelized energy capital costs in year y in region r
C_{yr}^{ins} = Total levelized installation costs in year y in region r
C_{yr}^{fom} = Total fixed operations and maintenance costs in year y in region r
C_{yr}^{vom} = Total levelized variable operations and maintenance costs in year y in region r

4.7.4.1 Electricity Capacity Costs

Energy storage nodes have specified durations, defined as the ability to discharge at maximum power capacity over a specified period of time, and also have an input of energy capital costs, which are levelized like all capital investments.

Equation 19

$$C_{yr}^{ecap} = \sum_{v\in V}\sum_{t\in T} S_{tvyr}^{fin} * d_t * W_{tvr}^{ecap}$$

Where

C_{yr}^{ecap} = Total levelized energy capacity capital costs in year y in region r

W_{tvr}^{ecap} = Levelized energy capacity capital costs for technology t for vintage v in region r

d_t = Exogenously specified discharge duration of technology t

S_{tvyr}^{fin} = Financial stock of technology t and vintage v in year y in region r

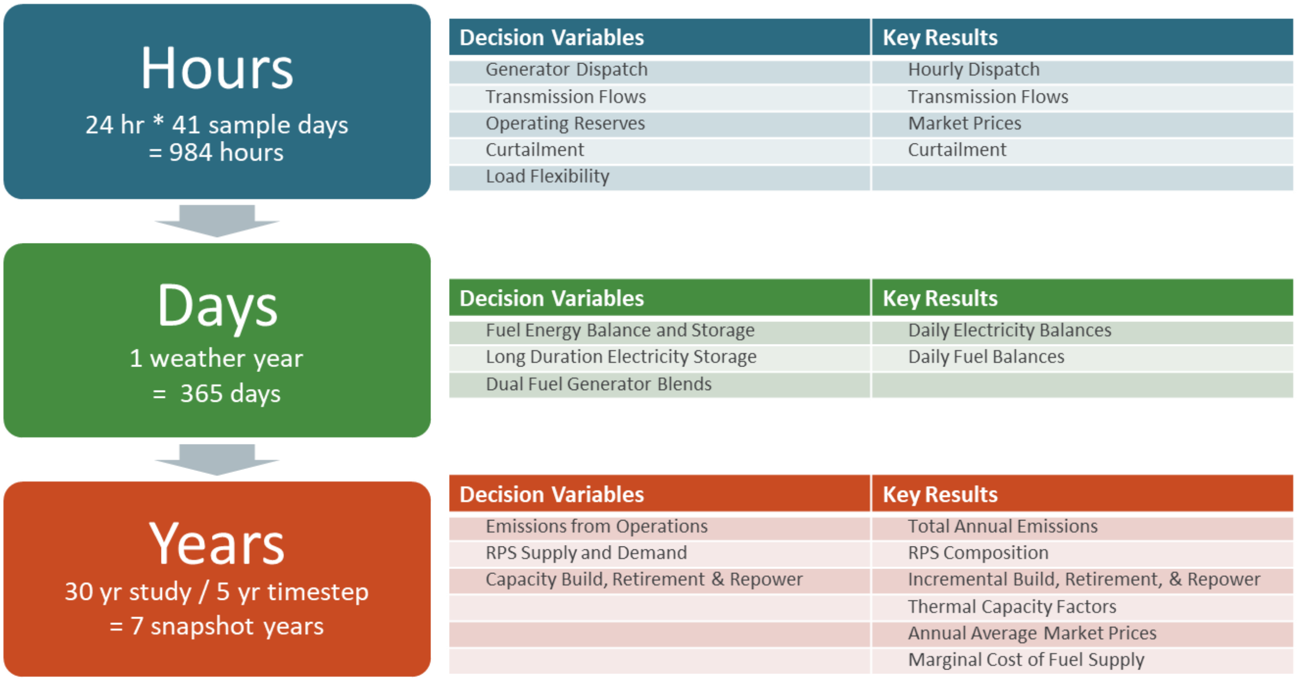
5. RIO Methodology

5.1 Overview

RIO is a model that sets up a linear optimization problem with the decision variables relating to capacity build and operational decisions on the supply-side of the energy system. RIO minimizes a representation of all future avoided costs in the energy system, discounted to present day using a 2% societal time preference. Operational and capacity expansion decisions are co-optimized with perfect foresight in a single optimization problem with approximately 15 million decision variables. This problem formulation means that multiple timescales are simultaneously relevant, as shown in Figure 4.

The formulation for RIO is proprietary; however, the methodology descriptions below provide the reader with a conceptual understanding of how RIO works and what advantages this approach has for the Net Zero America study. The most important distinction between RIO and other capacity expansion models for this study was the inclusion of the fuels system, making it possible to co-optimize across the entire supply-side of the energy system, while enforcing economy-wide emissions constraints, and still maintaining very high temporal fidelity in the electric power system.

Figure 8 RIO decision variables and results for each of the represented timescales



Hours

24 hr * 41 sample days
= 984 hours

Decision Variables	Key Results
Generator Dispatch	Hourly Dispatch
Transmission Flows	Transmission Flows
Operating Reserves	Market Prices
Curtailment	Curtailment
Load Flexibility	

Days

1 weather year
= 365 days

Decision Variables	Key Results
Fuel Energy Balance and Storage	Daily Electricity Balances
Long Duration Electricity Storage	Daily Fuel Balances
Dual Fuel Generator Blends	

Years

30 yr study / 5 yr timestep
= 7 snapshot years

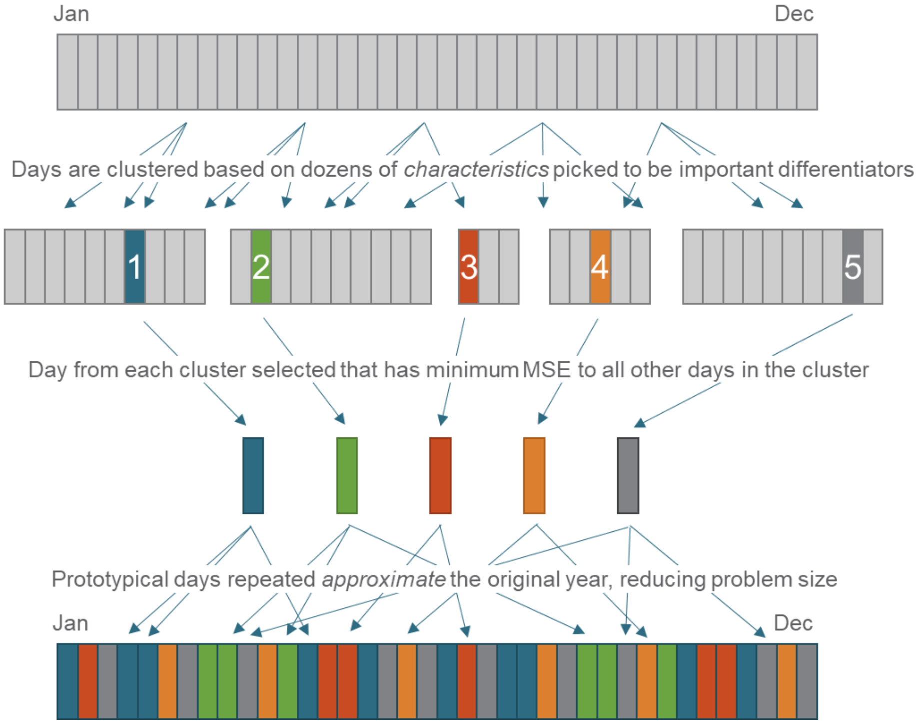
Decision Variables	Key Results
Emissions from Operations	Total Annual Emissions
RPS Supply and Demand	RPS Composition
Capacity Build, Retirement & Repower	Incremental Build, Retirement, & Repower
	Thermal Capacity Factors
	Annual Average Market Prices
	Marginal Cost of Fuel Supply

5.2 Day Sampling

RIO utilizes the 8760 hourly profiles for electricity demand and generation from EnergyPATHWAYS and optimizes operations for a subset of representative days (sample days) and maps them to the rest of the year. Operations are performed over sequential hourly timesteps. To ensure that the sample days can reasonably represent the full set of days over the year, RIO uses clustering algorithms on the initial 8760 data sets. The clustering process is designed to identify days that represent a diverse set of potential system conditions, including different fixed generation profiles and load shapes. The number of sample days impacts the total runtime of the model. A balance is struck in the day selection process between representation of system conditions through number of sample days, and model runtime. Clustering and sample day selection occurs for each model year in the time horizon. This process is shown in Figure 1. The starting dataset is the EnergyPATHWAYS load and generation shapes, scaled to system conditions for the model year being sampled and mapped. Load shapes come directly from EnergyPATWHAYS accounting runs. The coincidence of fixed generation profiles (i.e., renewables) and load determine when important events for investment decision making occur during the year. For example, annual peak load and low load events may be the coincident occurrence of relatively high loads and relatively low renewables, and the inverse, respectively. However, renewable build is determined by RIO decision making. To ensure that the sample days in each model year are representative of the events that define investment decisions, renewable scaling happens for expected levels of renewables in future years as well as a range of renewables proportional builds (for example, predominantly wind, predominantly solar). The sample days are then selected to be representative of system conditions under all possible renewable build decisions by RIO.

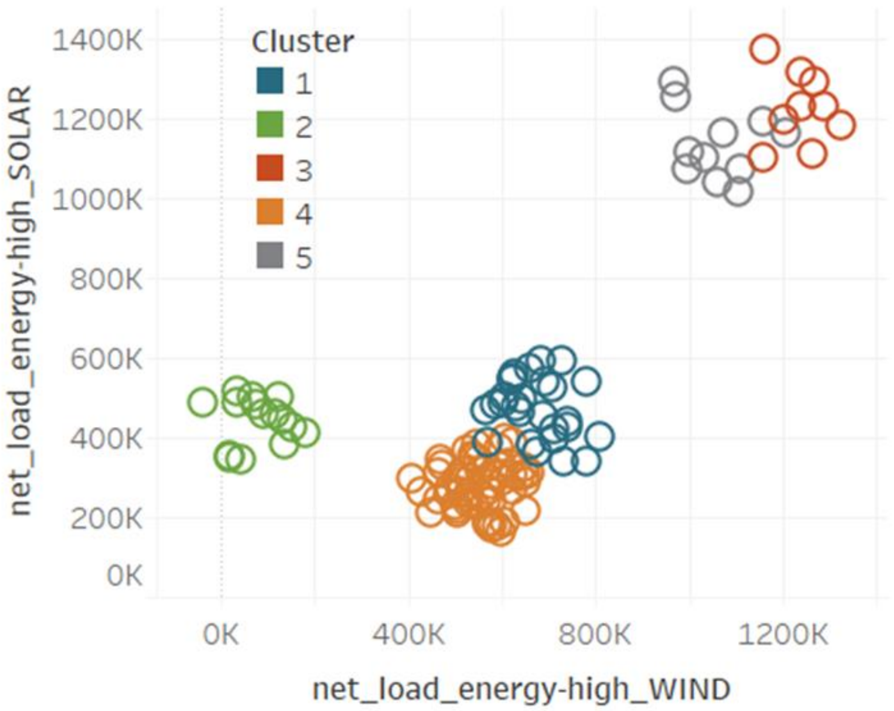
As Figure 1 shows, the scaled historical days are clustered based on a number of characteristics. These include different metrics describing every day in the data set. Examples include peak daily load, peak daily net load, lowest daily solar output, largest daily ramping event etc. The result is a set of clusters of days with similar characteristics. One day within each cluster is selected to represent the rest by minimizing mean square error (MSE). As described in the previous section, RIO determines short-term operations for each of these representative days. For long-term operations, each representative day is mapped back to the chronological historical data series, with the representative day in place of every other day from its cluster.

Figure 1. Conceptual diagram of sampling and day matching process



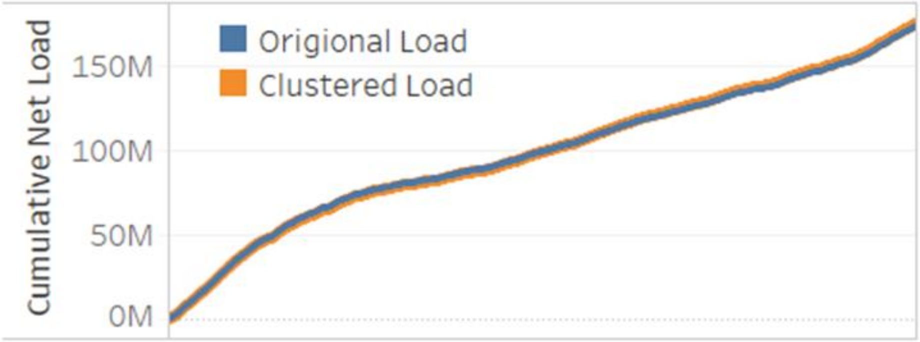
The clustering process depends on many characteristics of the coincident load and renewable shapes and uses statistical clustering algorithms to determine the best set of sample days. Figure 2 shows a simple, two characteristic, example of clustering. In this case the two characteristics are net load with high proportional solar build and net load with high proportional wind build. It is important to select sample days that both represent the full spectrum of potential net load, as well as be representative for both the solar and the wind case. The clustering algorithm has identified 5 clusters (a low number, but appropriate for the conceptual example) that ensure the sample days will represent the full range of net load differences among days and remain representative regardless of whether RIO chooses to build a high solar system or a high wind system. In the Net-Zero America Study, a total of 41 sample days were used.

Figure 2. Simple, two characteristic, example of clustering



Mapping the clustered days back to the chronological historical dataset, the newly created year of sample days can be validated by checking that metrics describing the original historical dataset match those of the new set. Cumulative net load in Figure 3 is one example. These are related to the characteristics used to select the sample days in the clustering process such as peak load, largest ramp etc. and the distribution of these over the whole year.

Figure 3. Comparison of original and clustered load



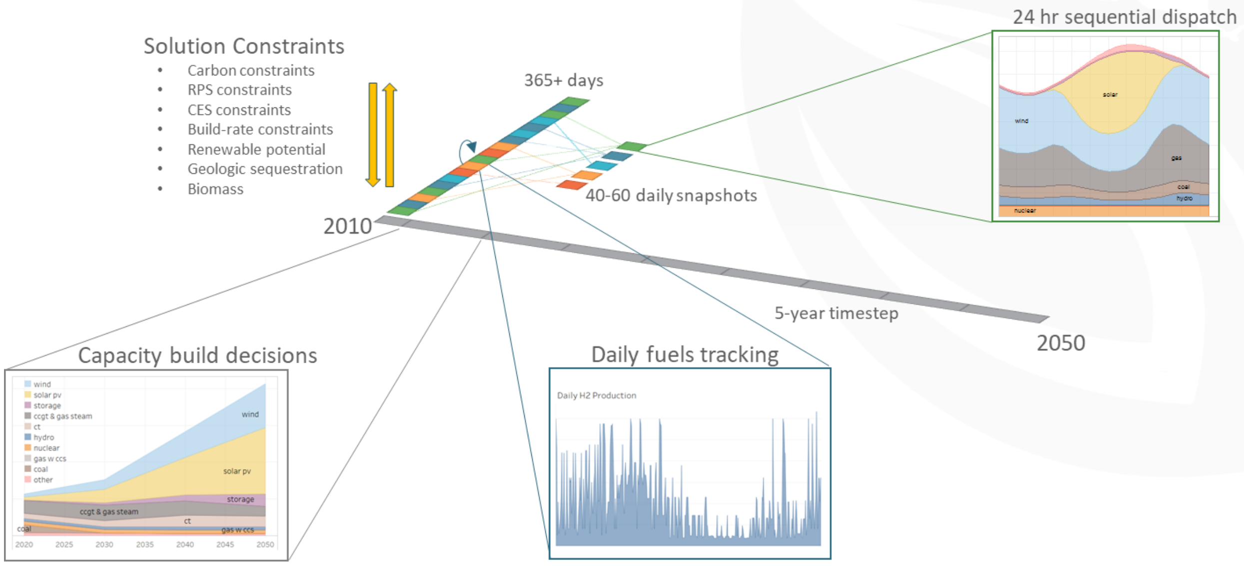
5.3 Operations

Time sequential operations are an important component of determining the value of a portfolio of resources. All resources have a set of attributes they can contribute to the grid, including, for example, energy, capacity, ancillary services, and flexibility. They work in complimentary fashion to serve the needs of the system. Whether a portfolio of resources is optimal or not depends on whether it can maintain system reliability, and whether it is cheaper than other portfolios. RIO determines the least cost dispatch for each one of the sample days to determine the least cost investments to make.

Operations are split into short-term and long-term operations in RIO. This is a division between those resources that do not have any multiday constraints on their operations, i.e. they can operate in the same way regardless of system conditions, and those resources that will operate differently depending on system condition trends that last longer than a day. An example of the former is a gas generator that can produce the same output regardless of system conditions over time, and an example of the latter is a long-duration storage system whose state of charge is drawn down over time when there is not enough energy to charge it. The long-term category includes all long-term storage mediums.

Operational decisions determine the value of one investment over another, so it is important to capture the detailed contributions and interactions of the many different types of resource that RIO can build. The overall RIO operational framework is shown in Figure 66.

Figure 9 RIO operations framework



5.3.1 Thermal Generator Operations

To reduce runtimes, generators are aggregated in RIO by common operating and cost attributes. These are by technology and vintage when the operating costs and characteristics vary significantly by installation year. Each modeled aggregation of generators contains a set of identical generators.

RIO can constrain operations based on constraints that are similar to those used in production simulation. Many of the plant-level operational constrains were ignored for the purpose of this study as they have secondary importance when modeling large regional zones and add significant computational complexity, which would have disallowed focus on other modeling aspects of higher importance in decarbonized energy systems (e.g. operation of electrolysis and hydrogen storage).

5.3.2 Hydro Operating Constraints

Hydro behavior is constrained by historical data on how fast the hydro system can ramp, the minimum and maximum discharge by hour, and the degree to which hydro energy can be shifted from one period to another. Summed daily hydro output over user defined periods of the year must fall within a cumulative energy envelope that allows up to 2 weeks of shift in the dispatch compared to historical levels.

Canadian imports to the Northeastern U.S. include a small amount of planned expansions but otherwise reflect the existing energy flow volume.

5.3.3 Storage Operating Constraints

Storage is constrained by maximum discharge rates dependent on built capacity. In addition, the model tracks storage state of charge hour to hour, including losses into and out of the storage medium. Storage, like all technologies, is dispatched with perfect foresight. Storage can operate through both short term and long-term operations. In short term operations, storage is dispatched on an hourly basis within each sample day, as with all other dispatchable technology types. Short term storage dispatch shifts energy stored within a sample day and discharges it within the same sample day, such that the short-term storage device is energy neutral across the day. In long term operations, storage can charge energy on one day and discharge it into another. This allows for optimal use of storage to address longer cycle reliability needs, such as providing energy on low renewable generation days, and participation in longer cycle energy arbitrage opportunities.

5.3.4 Transmission constraints

RIO uses a pipe-flow constraint formulation[7]. Transmission flows are constrained by the capacity of the line in every hour. When transmission is built by the model, additions are assumed to be symmetrical, meaning the capability of flow on the line is equal in both directions. However, not all existing transmission has equally sized paths in each direction. Transmission losses are specified by path and transmission hurdles[8] start from a benchmark against historical flows before converging at $5/MWh in 2040.

5.4 Reliability

The conditions that will stress electricity systems in the future and define reliability need will shift in nature compared to today, shown in Figure 67. Capacity is the principle need for reliable system operations when the dominant sources of energy are thermal. Peak load conditions set the requirement for capacity because generation can be controlled to meet the load and fuel supplies are not constrained. As the system transitions to high renewable output, the defining metric of reliability need is not peak load but net load (load net of renewables). Periods with the lowest renewable output may drive the most need for other types of reliable energy even if they do not align with peak gross load periods. In addition to that, resources will become increasingly energy constrained. Storage can only inject the energy it has in charge into the system. Reliability is therefore increasingly driven by energy need as well as capacity need.

In the future, the defining reliability periods may be when renewables have unusually low output, and when that low output is sustained for unusually long periods. To model a reliable system in the future, both capacity and energy needs driven by the impact of weather events and seasonal changes on renewable output and load need to be captured.

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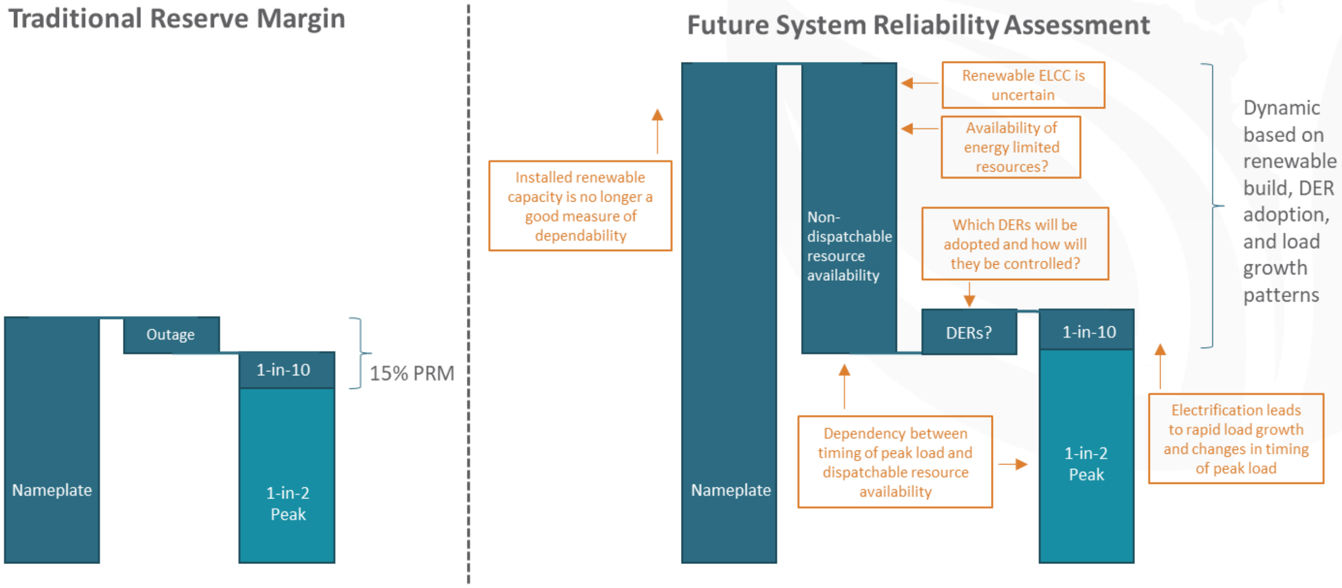
[7] See this NREL presentation for more information and contrast against DC power-flow constraint formulations: https://www.nrel.gov/docs/fy17osti/68929.pdf

[8] Hurdle rates are a common mechanism in power system models and represent friction between zones. These costs are not ‘true’ costs, but instead represent a penalty on transmission flows, which is added to the objective function.

Figure 10 Reliability framework in high renewable systems



To ensure we capture the impacts of these changing conditions on reliability, we enforce a planning reserve requirement on load in every modeled hour. This “planning demand” is found by scaling load up to account for the possibility that demand in each hour could be greater than expected. At the same time, we determine a dependable contribution of each resource to meeting the planning demand. Dependability is defined as the output of each resource that can be relied upon during reliability events. The planning demand must be met or exceeded by the summed dependable contributions of available resources in each hour.

5.4.1 Dependability

The dependable contribution from thermal resources is derated nameplate, reflecting forced outage rates. Renewable dependable contribution is the derated hourly output, reflecting that renewable output could be even lower than expected. For energy constrained resources such as hydro and storage, dependable contribution is derated hourly output. By using derated hourly output we can capture both the risk that it is not available because of forced outage, and the risk that it is not available because it has exhausted its stored energy supply. Dependability factors used for the Net Zero America study are shown in Table 22.

Table 24 Dependability factors used when enforcing RIO reliability constraints

Resource	Dependability
Existing Thermal Resources	93% applied to nameplate
New Thermal Resources	93% applied to nameplate
Transmission	90% applied to hourly flows
Energy storage	95% applied to hourly charge/discharge
Variable generation (wind & solar)	80% applied to hourly output
Electricity load	106% applied to hourly load

5.4.2 Resource build decisions

Concurrently with optimal operational decisions, the model makes resource build decisions that together produce the lowest total system cost. There are three modes for resource build decisions, specified by aggregate generator. In all modes, the addition of new capacity is limited by the rate at which capacity can be constructed year on year, and the total quantity of capacity that can be constructed by a future year. The model builds resources when needed and those resources remain through the end of their useful life when they are retired. Resources are not economically retired early, repowered, or extended. Generators using this mode are built on top of a predefined MW schedule of existing resources in every year.

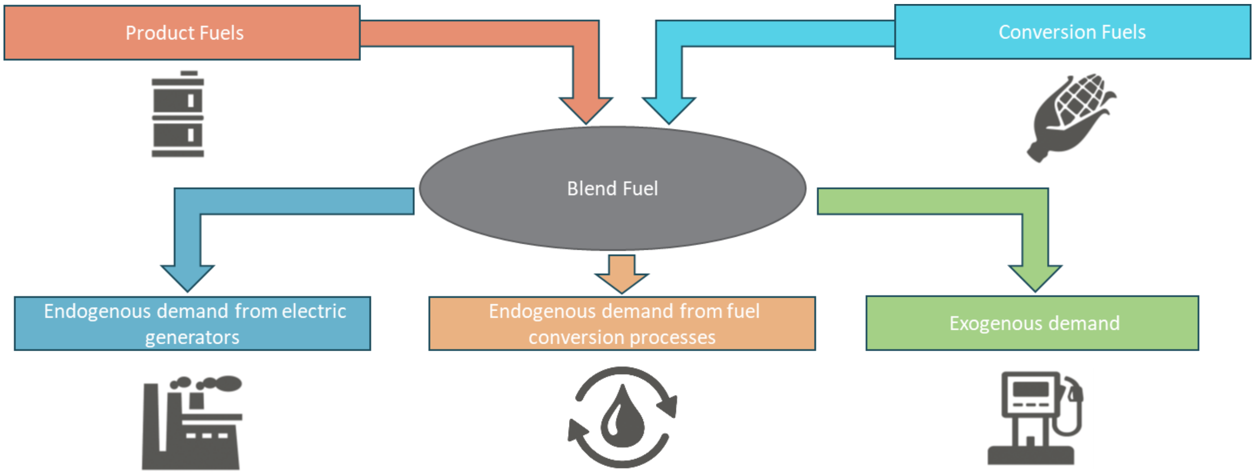
5.5 Fuels

In addition to electricity, RIO optimizes the composition of fuels that are used in electric generators and that go to satisfy final energy demands, calculated in EnergyPATHWAYS. RIO fuels operate around the concept of a 'blend fuel' shown in Figure 68. Each fuel blend may be supplied using 'product fuels', which are basically commodities (e.g. dry biomass, fossil diesel) that are specified at a price and quantity, or blends can be supplied with fuel conversions, which can convert one blend fuel into another or convert electricity into a fuel (e.g. electrolysis).

Fuel conversion technologies are included in the capacity expansion framework of RIO, thus decision variable cover both the build and operations of each conversion technology. The capital cost, O&M costs, and conversion efficiencies for all conversion technologies are given in the accompanying Excel workbook.

Fuel conversions that consume or produce electricity[9] can be specified as flexible or inflexible on an hourly basis. Electrolysis and electric boilers are assumed to operate flexibly, all other conversion technologies, including direct air capture, are not flexible hour-by-hour.

Figure 11 RIO fuels framework



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[9] Conversion technologies can have electricity as a co-product.

6. Bibliography

1. M. Ashe et al., “2010 U.S. Lighting Market Characterization” (U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, 2012).
2. E. den Boer et al., “Zero Emissions Trucks: An Overview of State-of-the-Art Technologies and Their Potential” (CE Delft, 2013).
3. A. Brooker et al., "ADOPT: A Historically Validated Light Duty Vehicle Consumer Choice Model," (SAE Technical Paper 2015-01-0974, 2015).
4. A. De Vita et al., "Technology pathways in decarbonisation scenarios" (Tractebel, Ecofys, E3-Modelling: Brussels, Belgium, 2018).
5. J. Dentz et al., “Mini-Split Heat Pumps Multifamily Retrofit Feasibility Study” (U.S. Department of Energy; Office of Energy Efficiency and Renewable Energy, 2014).
6. "Electric Vehicle Outlook" (Finance, Bloomberg New Energy, 2019; https://about.bnef.com/electric-vehicle-outlook/).
7. K. Eurek et al. “Regional Energy Deployment System (ReEDS) Model Documentation: Version 2016” (Publication TP-6A20-67067, NREL, 2017; www.nrel.gov/docs/fy17osti/67067.pdf).
8. Federal Highway Administration, “Highway Statistics” (Highway Statistics. U.S. Department of Transportation, 2018; https://www.fhwa.dot.gov/policyinformation/statistics.cfm).
9. L. Fulton, M. Miller, “Strategies for Transitioning to Low-Emissions Trucks” (UC Davis Institute of Transportation Studies, 2015; https://steps.ucdavis.edu/files/06-11-2015-STEPS-NCST-Low-carbon-Trucks-in-US-06-10-2015.pdf).
10. G. del Alamo et al., “Implementation of Bio-CCS in Biofuels Production” (Task 33 Special Project ISBN 978-1-910154-44-1, IEA Bioenergy, 2015; https://www.ieabioenergy.com/wp-content/uploads/2018/08/Implementation-of-bio-CCS-in-biofuels-production_final.pdf).
11. B. Haley et al., “350 PPM Pathways for the United States” (Evolved Energy Research, 2019; https://docs.wixstatic.com/ugd/294abc_95dfdf602afe4e11a184ee65ba565e60.pdf).
12. “Techno - Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS” (International Energy Agency GHG Programme, 2017; https://ieaghg.org/exco_docs/2017-02.pdf).
13. P. Jadun et al., “Electrification Futures Study: End-Use Electric Technology Cost and Performance Projections through 2050” (TP-6A20-70485, NREL, 2017; https://www.nrel.gov/docs/fy18osti/70485.pdf).
14. T. L. Johnson, “MARKAL Scenario Analyses of Technology Options for the Electric Sector: The Impact on Air Quality” (Publication 600/R-06/114, EPA, 20006; https://nepis.epa.gov/Exe/ZyPDF.cgi/P10089YQ.PDF?Dockey=P10089YQ.PDF).
15. Keith et al., A Process for Capturing CO_2 from the Atmosphere, *Joule* **2**, 1573–1594 (2018).
16. T. Kuramochi et al., Comparative Assessment of CO2 Capture Technologies for Carbon-Intensive Industrial Processes. *Progress in Energy and Combustion Science* **38**, 87–112 (2012).
17. M. H. Langholtz et al., “2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy” (Publication DOE/EE-1440, ORNL/TM-2016/160, Department of Energy, 2016; https://doi.org/10.2172/1271651).
18. N. Lutsey, M. Nicholas, “Update on Electric Vehicle Costs in the United States through 2030” (International Council on Clean Transportation, 2019; https://theicct.org/sites/default/files/publications/EV_cost_2020_2030_20190401.pdf).
19. “Annual Technology Baseline” (National Renewable Energy Laboratory, 2018; https://atb.nrel.gov/electricity/2019/).

20. "Degree Days Statistics" (National Weather Service: Climate Prediction Center, Accessed November 1, 2019; https://www.cpc.ncep.noaa.gov/products/analysis_monitoring/cdus/degree_days/).
21. Navigant Consulting, "Updated Buildings Sector Appliance and Equipment Costs and Efficiencies" (U.S. Energy Information Administration, 2014; https://www.eia.gov/analysis/studies/buildings/equipcosts/archive/2015/pdf/full.pdf).
22. C. le Quéré et al., Global Carbon Budget 2017. *Earth System Science Data* **10**, 405–48 (2018).
23. "From Risk To Return: Investing in a Clean Energy Economy" (Risky Business Project, 2016; https://riskybusiness.org/site/assets/uploads/sites/5/2016/10/RiskyBusiness_FromRiskToReturn.pdf).
24. TA Engineering Inc., "TRUCK5.1: Heavy Vehicle Market Penetration Model Documentation" (National Petroleum Council, 2012; https://www.npc.org/reports/HDV/TRUCK5.1_Model_Documentation-final.pdf).
25. "Regional Economic Accounts: Annual GDP by State" (U.S. Bureau of Economic Analysis, 2012; https://apps.bea.gov/regional/downloadzip.cfm.
26. "2017 American Community Survey" (U.S. Census Bureau, 2018; http://factfinder.census.gov.)
27. "Transportation—Commodity Flow Survey: United States: 2012" (Publication EC12TCF-US, U.S. Census Bureau & U.S. Bureau of Transportation Statistics. 2015.)
28. National Energy Technology Laboratory, "FE/NETL CO2 Saline Storage Cost Model" (U.S. Department of Energy, 2017; https://edx.netl.doe.gov/dataset/fe-netl-co2-saline-storage-cost-model-2017/resource/154e5905-e84b-4f80-8e6e-89e0228f28c5).
29. "Commercial Building Energy Consumption Survey" (U.S. Energy Information Administration, 2012; https://www.eia.gov/consumption/commercial/).
30. "Residential Energy Consumption Survey (RECS) 2009 Technical Documentation-Summary" U.S. Energy Information Administration, 2013; https://www.eia.gov/consumption/residential/methodology/2009/pdf/techdoc-summary010413.pdf).
31. "Annual Energy Outlook 2017" (U.S. Energy Information Administration, 2017; https://www.eia.gov/outlooks/aeo/pdf/0383(2017).pdf).
32. "State Electricity Profiles" (U.S. Energy Information Administration, 2018; https://www.eia.gov/electricity/state/).
33. "Annual Energy Outlook 2019" (U.S. Energy Information Administration, 2019; https://www.eia.gov/outlooks/aeo/pdf/aeo2019.pdf).
34. "Emissions & Generation Resource Integrated Database (EGRID)" (U.S. Environmental Protection Agency, 2018; https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid).
35. "2018 Greenhouse Gas Reporting Program." (U.S. Environmental Protection Agency, 2019; https://www.epa.gov/ghgreporting).
36. P. Capros et al., "Technology Pathways in Decarbonisation Scenarios" (Advanced System Studies for Energy Transition, 2018)
37. "Form No. 714 – Annual Electric Balancing Authority Area and Planning Area Report" (Federal Energy Regulatory Commission, Accessed 2019; https://www.ferc.gov/docs-filing/forms/form-714/data.asp
38. Grubler, A., Wilson, C., Bento, N. et al. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nat Energy 3, 515–527 (2018). https://doi.org/10.1038/s41560-018-0172-6
39. U.S. Greenhouse Gas Emissions and Sinks: 1990–2019 (published 2021), developed by the U.S. Government to meet annual U.S. commitments under the United Nations Framework Convention on Climate Change (UNFCCC). EPA
40. Lowell Ungar & Steven Nadel, "Halfway There: Energy Efficiency Can Cut Energy Use and Greenhouse Gas Emissions in Half by 2050" ACEEE, 2019.

41. EIA Short-Term Energy Outlook (STEO), https://www.eia.gov/outlooks/steo/

References for reductions in non-CO2 gases from table 9:

Abhyankar, N., P. Mohanty, and A. Phadke. 2021. *Illustrative Strategies for the United States to Achieve 50% Emission Reductions by 2030.* Berkeley, CA: Lawrence Berkeley National Laboratory, Energy Analysis and Environmental Impacts Division. https://eta-publications.lbl.gov/sites/default/files/us_50_percent_ndc_memo_finalap.pdf

EDF (Environment Defense Fund). 2021. *Recapturing US Leadership on Climate: Setting an Ambitious and Credible Nationally Determined Contribution.* Washington, DC. https://www.edf.org/sites/default/files/documents/Recapturing%20U.S.%20Leadership%20on%20Climate.pdf

EPA (Environmental Protection Agency). 2021. *Inventory of US Greenhouse Gas Emissions and Sinks: 1990–2019.* Washington, DC. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2019

Fargione, J. E., et al. 2018. "Natural Climate Solutions for the United States." *Science Advances* 4 (11): eeat1869. https://advances.sciencemag.org/content/4/11/eaat1869

Hultman, N., L. Clarke, H. McJeon, R. Cui, P. Hansel, E. McGlynn, K. O'Keefe, J. O'Neill, C. Wanner, and A. Zhao. 2021. *Charting an Ambitious US NDC of 51% Reductions by 2030*. College Park: University of Maryland School of Public Policy. https://cgs.umd.edu/research-impact/publications/working-paper-charting-ambitious-us-ndc-51-reductions-2030

Larsen, J., K. Larsen, and H. Pitt. 2020. *Climate Progress in the Year-End Stimulus*. New York: Rhodium Group. https://rhg.com/research/climate-progress-in-the-year-end-stimulus/

NAS (National Academies of Sciences, Engineering, and Medicine). 2021. *Accelerating Decarbonization of the US Energy System.* Washington, DC: National Academies Press. https://doi.org/10.17226/25932

NRDC (Natural Resources Defense Council). 2021. *The Biden Administration Must Swiftly Commit to Cutting Climate Pollution at Least 50 Percent by 2030.* New York. https://www.nrdc.org/sites/default/files/2030-biden-climate-pollution-ib.pdf