Annual Decarbonization Perspective

2023

Technical Documentation

EVOLVED ENERGY RESEARCH

ABOUT THIS REPORT

This report provides supporting material to the 2023 Annual Decarbonization Perspective, an annual report investigating options for long-term deep decarbonization pathways for the United States. Supporting materials include documentation of modeling methodologies, scenario assumptions, and underlying databases.

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ABOUT EVOLVED ENERGY RESEARCH

Evolved Energy Research (EER) is a research and consulting firm focused on questions posed by transformation of the energy economy. Their consulting work and insight, supported by complex technical analyses of energy systems, are designed to support strategic decision-making for policymakers, stakeholders, utilities, investors, and technology companies.

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This documentation adopts a nested structure, which begins with a discussion of the specific analysis conducted (which includes specific scenario assumptions); a discussion of the underlying databases (which may be used across a variety of analyses that utilize the same underlying geographic representation); and a discussion of the models (RIO and EnergyPATHWAYS) which can be used across a variety of databases with different geographic representations.

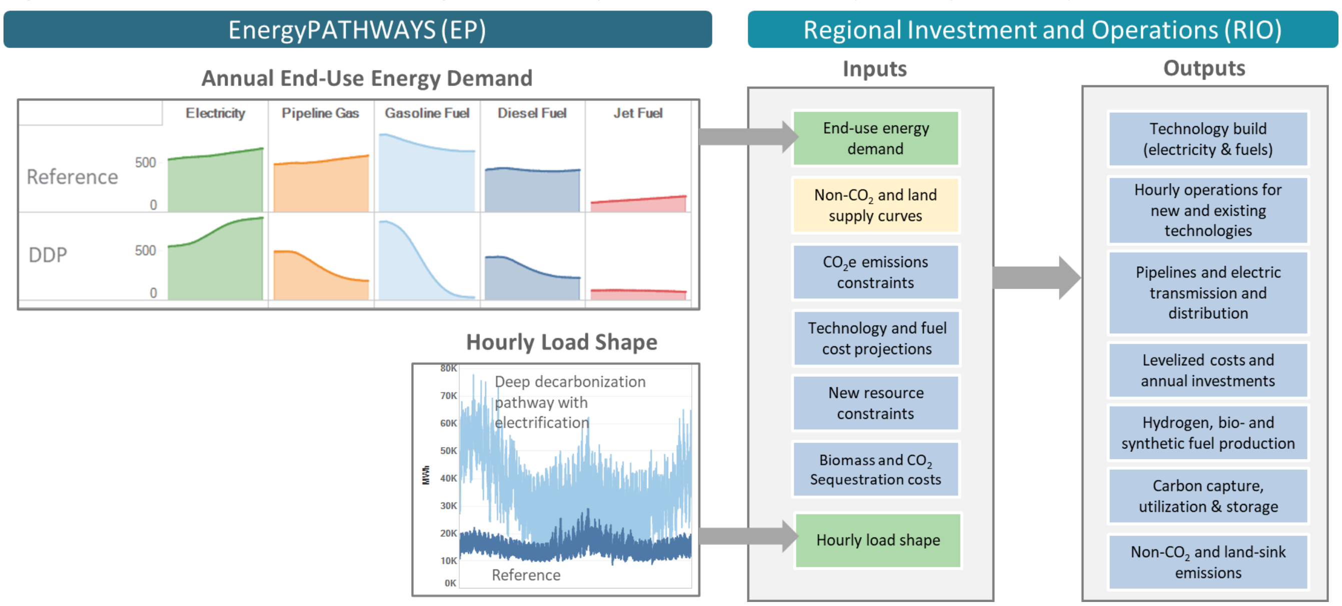
S1. Analysis

1.1. Description

This study employs a scenario modeling approach demonstrated in previous work (1,2,3,4,5). In this work, we develop low-carbon scenarios for the U.S. energy and industrial (E&I) system that meet the same demand for energy services as a business-as-usual reference case based on the *Annual Energy Outlook (AEO),* and use *AEO* assumptions for population, GDP, and industrial production (38). The scenarios are a detailed representation of E&I infrastructure as it changes over time, under reference conditions and under the constraint of reaching zero net emissions of CO_2 (or below) by 2050. The low-carbon scenarios include only technologies that are commercial or have been demonstrated at pilot scale, with performance and cost characteristics taken from well-vetted public sources (Section S2). This study expands the framework beyond the E&I system to include an assessment of emissions and mitigation opportunities in non-energy, non-CO_2 sectors and land sectors of the economy. This allows for a comprehensive accounting of all greenhouse gas emissions in the United States and the opportunity to compare tradeoffs between emissions reduction opportunities in different sectors under different scenarios.

The modeling work was performed using RIO (section 3.1) and EnergyPATHWAYS (EP) (section 3.3), numerical models with high temporal, sectoral, and spatial resolution developed by the authors for this purpose. Final-energy demand scenarios were developed in EP, a bottom-up stock accounting model with sixty-four demand subsectors. EP outputs, including time-varying electricity and fuel demand, were input into RIO, a linear programming model that combines capacity expansion and sequential hourly operations to find least-cost supply-side pathways. RIO has unique capabilities for this energy systems analysis: it models in detail interactions among electricity generation, fuel production, and CCUS, allowing accurate evaluation of the economics of coupling between these sectors; it tracks storage state of charge over an entire year, allowing accurate assessment of balancing requirements in electricity systems with very high levels of VRE; and it solves for all infrastructure decisions on a five year time-step to optimize the entire energy system transition, not only the endpoint. RIO finds technology configurations that minimize the net present value of the sum of all energy system costs over the 30-year modeling period, 2021 – 2050. The steps of the modeling analysis are framed at a high level by the flow chart in Figure 1.

Figure 1. Scenario stock-accounting tool (EP) paired with economy-wide partial equilibrium model (RIO)



1.1.1. EnergyPATHWAYS (EP)

On the energy demand side, we developed a model of US energy demand by sector across the economy**.** For this purpose, we created EnergyPATHWAYS (EP)—a bottom-up stock-rollover model of all energy-using technologies in the economy—to represent how energy is used today and in the future. The EP model is a comprehensive energy accounting and analysis framework designed specifically to examine large-scale energy system transformations.

1.1.2. Land Sink Baseline

Baseline land sink values were determined using regressions at a state level with 1990-2021 data taken from the EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks (78). This represents the decline in expected contributions from the U.S. land sink through 2050 without additional mitigation action. In scenarios with emissions constraints, this is augmented with other land sector mitigation measures selected by the RIO optimization from a supply curve derived from Fargione et. al (49). This derived supply results in a maximum potential annual contribution from the land sector (baseline (551 Mt) + mitigation (595 Mt)) of -1,146 Mt CO2 per year in 2050. The potential for land sink mitigation measures begins in 2028 and increases linearly through 2050.

1.1.3. Non – Energy, Non- CO_2

Non-Energy, Non-CO2 baseline emissions projections are taken from the report "Global Non-CO2 Greenhouse Gas Emissions Projections and Mitigation" by the U.S. Environmental Protection Agency (50). We include all non-CO_2 emissions that aren't scalable with energy usage. This baseline omits methane emissions from oil & gas systems, which are solved for in the energy system component of RIO. This exogenous projection of baseline emissions is then reduced through selection of mitigation measures in the RIO optimization.

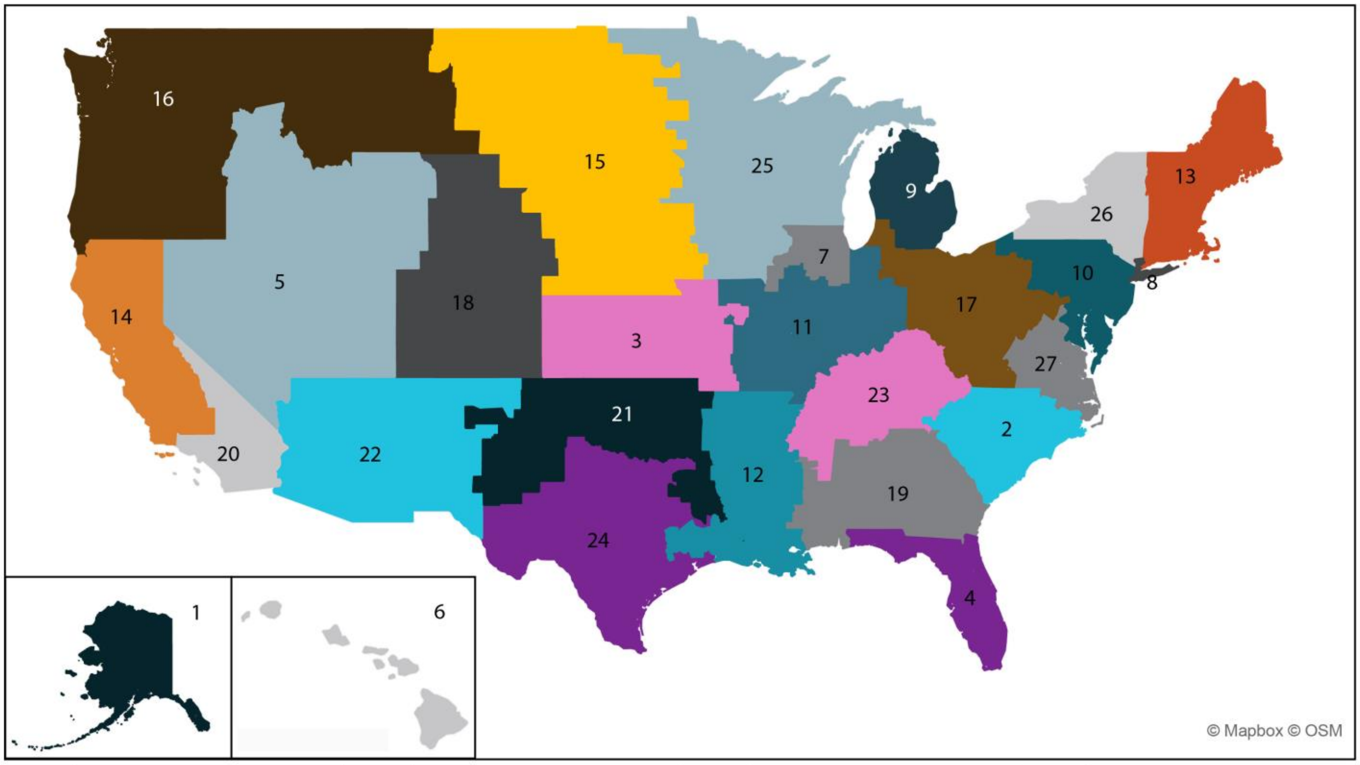
1.2. Database

EnergyPATHWAYS and RIO are numerical modeling platforms that can operate with flexible configurations of underlying data. As of 2023, EER has developed databases for the U.S., Europe, Australia, and Mexico that have been used to develop long-term low-carbon pathways. This analysis employs EER's U.S. database, which is the foundation of numerous country and state-level analyses.

1.3. Geography

In addition to being flexible in terms of underlying data, the models are flexible in the spatial granularity with which they can represent a geographic area. This is called our model topology and is used as the unit of differentiation for supply/demand balances (electricity and other blends), policy constraints, transmission constraints, resource availability (e.g. biomass), and technology availability. This analysis includes all electricity market module regions used by the EIA in Annual Energy Outlook 2023 and also includes representations of Hawaii and Alaska (the EIA models only the lower-48 electricity system). Within our database this 27-zone geographic representation is referenced as “US_EER,” which also shows up in output files with this column header. This representation follows NERC, ISO, and RTO regional boundaries. Our model zones use the geographic names from EIA’s National Energy Modeling System (NEMS) and do not conform to implied borders (ex. “Texas” does not map directly to state borders).

Figure 2 Zonal representation in EnergyPATHWAYS and RIO.



1	Alaska	8	Metropolitan New York	15	Northern Great Plains	22	Southwest
2	Carolinas	9	Michigan	16	Northwest	23	Tennessee Valley
3	Central Great Plains	10	Mid-Atlantic	17	Ohio Valley	24	Texas
4	Florida	11	Middle Mississippi Valley	18	Rockies	25	Upper Mississippi Valey
5	Great Basin	12	Mississippi Delta	19	Southeast	26	Upstate New York
6	Hawaii	13	New England	20	Southern California	27	Virginia
7	Metropolitan Chicago	14	Northern California	21	Southern Great Plains		

1.4. Temporal Representation

RIO is an optimization model that can be flexibly configured for different levels of temporal detail. A broader discussion of the approach EER uses for temporal representation can be referenced here (3.1.3). There are two principal components to this temporal representation: first, how many years are represented in the optimization; second, how many days are sampled in each modeled year. The 2023 ADP uses seven years to represent the thirty years between 2021 and 2050. In each modeled year, forty days are sampled based on load and renewable shapes from a 2011 historical weather year. As is explained further in section 3.1.3, different days are selected for different future years because increasing electrification and wind and solar development result in a different mix of 40 days providing the best approximation of a full year (365 days) of operations.

Table 1. Modeled days from the 2011 weather year used when modeling future operations for snapshot years.

2021	2025	2030	2035	2040	2045	2050
1/8/2021	1/4/2021	1/11/2021	1/11/2021	1/7/2021	1/3/2021	1/3/2021
1/10/2021	1/10/2021	1/12/2021	1/12/2021	1/13/2021	1/8/2021	1/7/2021
1/12/2021	1/12/2021	1/14/2021	1/19/2021	1/16/2021	1/12/2021	1/12/2021
1/21/2021	1/19/2021	1/21/2021	1/23/2021	1/22/2021	1/17/2021	1/21/2021
1/23/2021	1/21/2021	1/23/2021	1/26/2021	1/26/2021	1/23/2021	1/28/2021
1/30/2021	1/23/2021	1/31/2021	2/4/2021	1/28/2021	1/27/2021	1/30/2021
2/3/2021	1/31/2021	2/4/2021	2/6/2021	2/1/2021	2/1/2021	1/31/2021
2/4/2021	2/4/2021	2/6/2021	2/9/2021	2/6/2021	2/11/2021	2/4/2021
2/7/2021	2/9/2021	2/9/2021	2/11/2021	2/7/2021	2/16/2021	2/9/2021
2/11/2021	2/11/2021	2/11/2021	2/17/2021	2/9/2021	2/18/2021	2/11/2021
3/3/2021	2/24/2021	2/14/2021	2/20/2021	2/12/2021	2/22/2021	2/16/2021
3/5/2021	2/25/2021	2/17/2021	2/25/2021	2/14/2021	2/26/2021	2/18/2021
4/16/2021	5/28/2021	2/25/2021	3/7/2021	2/17/2021	2/28/2021	2/27/2021
5/10/2021	5/31/2021	3/8/2021	3/14/2021	3/3/2021	3/5/2021	3/1/2021
5/19/2021	6/2/2021	3/11/2021	3/20/2021	3/22/2021	3/9/2021	3/3/2021
5/27/2021	6/5/2021	3/31/2021	3/26/2021	3/29/2021	3/22/2021	3/6/2021
5/29/2021	6/12/2021	4/12/2021	4/1/2021	4/8/2021	3/28/2021	3/11/2021
5/31/2021	7/3/2021	4/28/2021	5/23/2021	4/16/2021	3/29/2021	3/15/2021
6/5/2021	7/10/2021	5/3/2021	5/28/2021	4/20/2021	4/13/2021	3/23/2021
6/10/2021	7/20/2021	5/21/2021	6/3/2021	4/26/2021	4/16/2021	3/26/2021
6/16/2021	7/31/2021	5/31/2021	6/7/2021	4/29/2021	4/30/2021	3/29/2021
7/5/2021	8/6/2021	6/1/2021	6/21/2021	5/15/2021	5/14/2021	4/16/2021
7/20/2021	8/18/2021	6/10/2021	7/6/2021	6/2/2021	5/23/2021	4/29/2021
7/23/2021	8/24/2021	7/3/2021	7/14/2021	6/6/2021	5/28/2021	5/8/2021
7/26/2021	8/27/2021	7/4/2021	7/17/2021	6/12/2021	6/7/2021	6/8/2021
7/30/2021	8/28/2021	7/15/2021	7/19/2021	6/30/2021	6/27/2021	7/26/2021
7/31/2021	8/31/2021	7/19/2021	8/29/2021	7/20/2021	7/24/2021	7/29/2021
8/14/2021	9/5/2021	7/22/2021	9/9/2021	9/4/2021	8/27/2021	8/28/2021
8/23/2021	9/6/2021	8/6/2021	9/14/2021	9/21/2021	9/6/2021	9/14/2021
8/27/2021	9/10/2021	8/24/2021	10/5/2021	11/1/2021	9/14/2021	9/17/2021
8/28/2021	9/26/2021	8/27/2021	10/22/2021	11/2/2021	9/23/2021	10/4/2021
9/3/2021	9/29/2021	9/5/2021	11/2/2021	11/4/2021	10/12/2021	10/12/2021
9/19/2021	10/5/2021	9/10/2021	11/5/2021	11/10/2021	10/28/2021	10/21/2021
9/29/2021	10/23/2021	9/26/2021	11/12/2021	11/22/2021	11/3/2021	10/27/2021
10/1/2021	11/10/2021	10/8/2021	11/14/2021	11/28/2021	11/6/2021	11/17/2021
10/3/2021	11/11/2021	10/16/2021	11/17/2021	12/1/2021	11/19/2021	11/19/2021
11/19/2021	11/16/2021	11/23/2021	11/19/2021	12/10/2021	11/28/2021	11/28/2021
11/27/2021	11/26/2021	12/6/2021	12/7/2021	12/11/2021	12/12/2021	12/6/2021

2021	2025	2030	2035	2040	2045	2050
12/6/2021	12/6/2021	12/13/2021	12/17/2021	12/21/2021	12/22/2021	12/12/2021
12/20/2021	12/30/2021	12/23/2021	12/26/2011	12/28/2021	12/29/2021	12/29/2021

1.5. General assumptions

The inputs below are configurable model inputs that were employed across all scenarios.

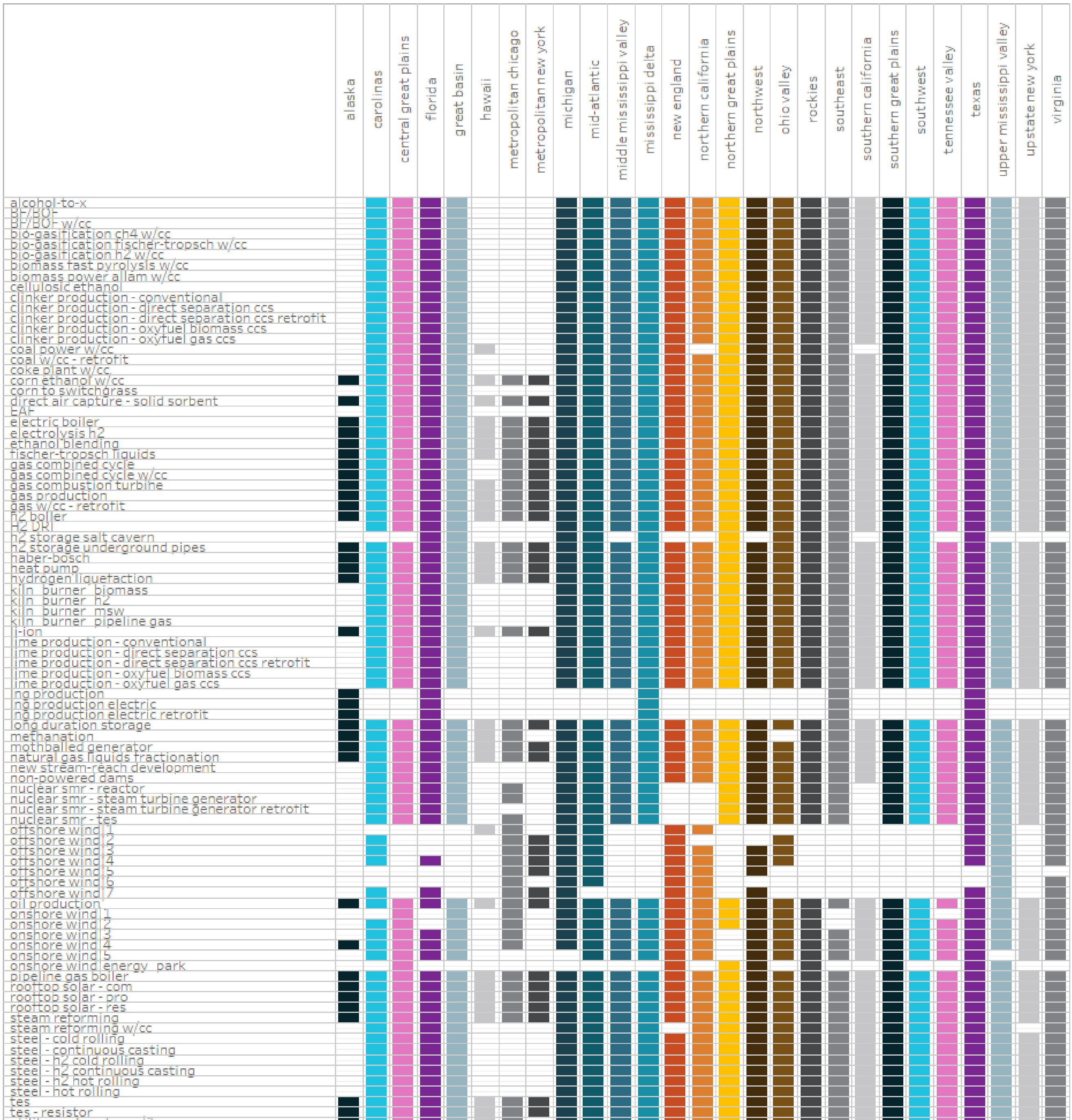
Table 2 General assumptions common to all scenarios

Assumption	Value	Notes
Societal discount rate	3%	Pure time preference used in the optimization
Demand side cost of capital	3-8% real	Real cost of capital, depending on subsector and assumed financing source
Cost of capital for electricity technologies	4-8% real	Real cost of capital, based on utility weighted average cost of capital
Cost of capital for fuel conversion technologies	8% real	Real cost of capital with additional risk due to market exposure
Cost of capital for non-energy industrial technologies	15% real	Real cost of capital with additional risk due to market exposure
Hydro year	Average	Based on long-run average of hydro generation (83)
Hydro energy constraint	Fixed Daily Energy budgets	Doesn't allow deviation for daily energy from historical record. Conservative assumption.
Number of electricity day samples	40	Electricity operations sampled with 40 days in each year (960 hours). The 40 days were chosen independently for future years based on clustering around gross load and renewable production features.
Generator retirements	Economic	Generators are assumed to retire at the end of a specified physical lifetime but can retire sooner to avoid fixed O&M cost in order to minimize total system cost.
Currency	USD	
Currency Year	2022	
Energy unit	GWh	
Mass Unit	hectotonne	
Volume Unit	Liter	
Distance Unit	kilometer	

1.6. RIO Technologies

RIO provides comprehensive representations of infrastructure for producing, converting, storing, and delivering energy. The figure below shows the energy technologies made available for deployment in each zone in the **Central** scenario.

Figure 3 RIO Technology Availability



Biomass is a heterogeneous resource that can become oversimplified in energy system models. Different biomass blends are used to separate feedstock types and the technologies that use them. Table 3 uses the Drop-In scenario as an example of the relationship between biomass blends and underlying feedstock types (84). Blank cells indicate that a particular feedstock cannot qualify for a particular blend. The accompanying data input catalog to ADP 2023 provides a mapping between technologies and the biomass blends on the efficiency tab.

Table 3 Biomass feedstock qualification using the Drop-In scenario as an example. (Exajoules)

From	biomass blend - dry	biomass blend - dry_herb	biomass blend - dry_high_ash	municipal waste blend	corn blend
existing herbaceous biomass	0.25	0.01			
existing waste biomass	0.22		0.02	0.02	
existing woody biomass	1.48		0.06		
barley straw	0.01	0			
citrus residues			0.03		
corn					2.67
corn stover	2.53	0.01			
corn to switchgrass	0.05	0			
cotton gin trash	0.04				
cotton residue	0.09				
eucalyptus	0.02		0.01		
food waste				0.1	
hardwood, lowland logging residues	0.05		0.01		
hardwood, lowland whole trees	0.23		0.02		
hardwood, upland logging residues	0.06		0.01		
hardwood, upland whole trees	0.3		0.03		
miscanthus	3.54	0.05			
mixedwood logging residues	0.03		0.01		
mixedwood whole trees	0.04		0.01		
municipal solid waste				0	
noncitrus residues	0.05	0			
oats straw	0	0			
other forest residue	0.19				
other forest thinnings	0.1				
paper and paperboard	0.23			0.05	
pine	0		0		
plastics	0			0	
poplar	0.57		0.06		
primary mill residue	0.01				
rice hulls			0.03		
rice straw			0.1		
rubber and leather			0.04	0.03	
secondary mill residue	0.06				
softwood, natural logging residues	0.07		0.01		
softwood, natural whole trees	0.09		0.02		
softwood, planted logging residues	0.06		0.01		
softwood, planted whole trees	0.14		0.01		
sorghum stubble	0.02	0			

sugarcane bagasse	0.07	0			
sugarcane trash			0.02		
switchgrass	2.56	0.05			
textiles	0.1		0.02	0.02	
tree nut residues	0.03		0		
wheat straw	0.39	0			
willow	0.28		0.04		
yard trimmings				0.06	

1.7. Scenarios

Scenarios are created from a set of assumptions that specify the demand side of the energy system, including service demand, end-use technology adoption rates, and energy efficiency, plus constraints on the economy-wide RIO optimization, including available resources and emissions targets. For this study we developed a total of 22 different scenarios & sensitivities. The key attributes of each are described in this section, first for the EnergyPATHWAYS demand side cases, and then scenario inputs to the RIO model.

1.7.1. EnergyPATHWAYS Demand-Side Cases

Three dimensions form the basis for differences in the demand-side across the runs: energy service demand; energy efficiency; and fuel-switching. Aside from these dimensions, all other assumptions are held constant between scenarios, including the cost and performance of a given technology.

Providing the same level of energy services across scenarios makes meaningful comparisons possible. All scenarios except for Low Demand have the same energy service projections as DOE's *Annual Energy Outlook 2023*. In the Low Demand scenario, we posited large reductions in energy services that are plausibly consistent with new patterns of development and cultural change in the United States, with the goal of understanding the impact such changes could have on decarbonization outcomes.

High efficiency trajectories were defined for many technologies and were adopted in all the low-carbon scenarios. In aviation and industrial subsectors for which individual technologies were not tracked, percent-per-year efficiency improvements were used.

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

The Table below summarizes the demand-side assumptions used in the scenarios. Four different demand-side cases were created to represent variations in service demand, efficiency, and fuel-switching:

- **Baseline** – AEO 2023 service demand with reference energy efficiency and fuel switching.[1]
- **IRA** – AEO 2023 service demand with fuel switching informed by the Princeton REPEAT project (mid-scenario).
- **Central** – AEO 2023 service demand with high energy efficiency and rapid fuel switching.
- **Slow Consumer Uptake**– AEO 2023 service demand with high energy efficiency and delayed fuel switching. (Fuel switching adoption slows by 20 years relative to the Central scenario)
- **Low Demand** – Low service demand, high energy efficiency and rapid fuel switching.

In the next section, detailed assumptions for each demand case are provided, referencing the demand case names above.

Table 4 Mapping from scenario names to demand-side cases

	Scenario Name	Demand Case Name	Service Demand	Energy Efficiency	Electrification
1	central	central	AEO 2023	central	central
2	low land	central	AEO 2023	central	central
3	baseline	baseline	AEO 2023	baseline	baseline
4	100% renewables	central	AEO 2023	central	central
5	low demand	low demand	low demand	central	central

[1] Includes AEO's assessment of impacts of IRA on consumer adoption, but these impacts are small compared to our own estimates.

	Scenario Name	Demand Case Name	Service Demand	Energy Efficiency	Electrification
7	drop-in	slow consumer uptake	AEO 2023	central	slow consumer uptake
8	slow consumer uptake	slow consumer uptake	AEO 2023	central	slow consumer uptake
9	IRA	IRA	AEO 2023	IRA	IRA
10	central + no IRA	central	AEO 2023	central	central
11	central + 50x30	central	AEO 2023	central	central

1.7.1.1. Stock Rollover

The tables below show the sales shares and stock shares for four demand technology groups: Electrified Technologies (**Electric**), High Efficiency Technologies (**HE**), Hydrogen Technologies (**H2**), and Reference Technologies (**Reference**) today, in 2030, and in 2050. The sales shares are inputs to EnergyPATHWAYS while the stock shares are a result determined by the stock rollover. The full demand-side representation consists of more than 200 technology types across all subsectors and end-uses, but we aggregated some of them here to show broader trends in the input values. The stock shares shown are determined by the stock rollover assumptions specified in the measure for each technology, the lifetimes of the infrastructure, and the methodology described in section 3.3.3.

Table 5 Sales shares by scenario and technology group

Subsector	Year	Demand Technology	baseline	central	IRA	low demand	slow consumer uptake
buses	2023	Baseline	98%	94%	95%	94%	97%
buses	2023	HE	2%	3%	2%	3%	2%
buses	2023	Electric		3%	3%	3%	1%
buses	2023	H2		0%	0%	0%	0%
buses	2030	Baseline	98%	50%	20%	50%	92%
buses	2030	HE	2%	0%	0%	0%	2%
buses	2030	Electric		46%	73%	46%	6%
buses	2030	H2		4%	7%	4%	0%
buses	2040	Baseline	98%	1%	20%	1%	53%
buses	2040	HE	2%	0%	0%	0%	1%
buses	2040	Electric		89%	73%	89%	42%

buses	2040	H2		10%	7%	10%	4%
buses	2050	Baseline	98%	0%	20%	0%	8%
buses	2050	HE	2%	0%	0%	0%	0%
buses	2050	Electric		90%	73%	90%	83%
buses	2050	H2		10%	7%	10%	9%
commercial air conditioning	2023	Baseline	87%	85%	85%	85%	86%
commercial air conditioning	2023	HE	14%	15%	15%	15%	14%
commercial air conditioning	2030	Baseline	87%	35%	39%	35%	28%
commercial air conditioning	2030	HE	13%	65%	61%	65%	72%
commercial air conditioning	2040	Baseline	87%	30%	35%	30%	21%
commercial air conditioning	2040	HE	14%	70%	65%	70%	79%
commercial air conditioning	2050	Baseline	86%	28%	33%	28%	23%
commercial air conditioning	2050	HE	14%	72%	67%	72%	77%
commercial cooking	2023	Baseline	67%	66%	67%	66%	66%
commercial cooking	2023	Electric	33%	34%	33%	34%	34%
commercial cooking	2030	Baseline	67%	39%	67%	39%	63%
commercial cooking	2030	Electric	33%	61%	33%	61%	37%
commercial cooking	2040	Baseline	67%	4%	67%	4%	37%
commercial cooking	2040	Electric	33%	96%	33%	96%	63%
commercial cooking	2050	Baseline	67%	3%	67%	3%	8%
commercial cooking	2050	Electric	33%	97%	33%	97%	92%
commercial lighting	2023	Baseline	55%	14%	55%	14%	14%
commercial lighting	2023	HE	45%	86%	45%	86%	86%
commercial lighting	2030	Baseline	57%	1%	57%	1%	1%
commercial lighting	2030	HE	43%	99%	43%	99%	99%
commercial lighting	2040	Baseline	57%	1%	57%	1%	1%
commercial lighting	2040	HE	43%	100%	43%	100%	100%
commercial lighting	2050	Baseline	58%	1%	58%	1%	1%
commercial lighting	2050	HE	43%	100%	43%	100%	100%
commercial refrigeration	2023	Baseline	100%	97%	100%	97%	97%
commercial refrigeration	2023	HE	0%	3%	0%	3%	3%
commercial refrigeration	2030	Baseline	100%	19%	100%	19%	19%
commercial refrigeration	2030	HE	0%	81%	0%	81%	81%
commercial refrigeration	2040	Baseline	100%	0%	100%	0%	0%
commercial refrigeration	2040	HE	0%	100%	0%	100%	100%
commercial refrigeration	2050	Baseline	100%	0%	100%	0%	0%
commercial refrigeration	2050	HE	0%	100%	0%	100%	100%
commercial space heating	2023	Baseline	86%	68%	74%	68%	77%
commercial space heating	2023	HE	3%	2%	3%	2%	3%
commercial space heating	2023	Electric	11%	30%	23%	30%	21%

commercial space heating	2030	Baseline	86%	8%	13%	8%	72%
commercial space heating	2030	HE	3%	1%	3%	1%	3%
commercial space heating	2030	Electric	11%	90%	84%	90%	25%
commercial space heating	2040	Baseline	86%	2%	13%	2%	38%
commercial space heating	2040	HE	3%	0%	3%	0%	1%
commercial space heating	2040	Electric	11%	98%	84%	98%	61%
commercial space heating	2050	Baseline	86%	2%	13%	2%	5%
commercial space heating	2050	HE	3%	0%	3%	0%	0%
commercial space heating	2050	Electric	11%	98%	84%	98%	94%
commercial ventilation	2023	Baseline	100%	87%	97%	87%	97%
commercial ventilation	2023	HE	0%	13%	3%	13%	3%
commercial ventilation	2030	Baseline	100%	3%	19%	3%	19%
commercial ventilation	2030	HE	0%	97%	81%	97%	81%
commercial ventilation	2040	Baseline	100%	0%	19%	0%	0%
commercial ventilation	2040	HE	0%	100%	81%	100%	100%
commercial ventilation	2050	Baseline	100%	0%	19%	0%	0%
commercial ventilation	2050	HE	0%	100%	81%	100%	100%
commercial water heating	2023	Baseline	49%	52%	49%	52%	49%
commercial water heating	2023	HE	45%	42%	45%	42%	45%
commercial water heating	2023	Electric	6%	7%	6%	7%	7%
commercial water heating	2030	Baseline	49%	30%	49%	30%	46%
commercial water heating	2030	HE	45%	24%	45%	24%	42%
commercial water heating	2030	Electric	6%	46%	6%	46%	12%
commercial water heating	2040	Baseline	49%	0%	49%	0%	26%
commercial water heating	2040	HE	45%	1%	45%	1%	24%
commercial water heating	2040	Electric	6%	99%	6%	99%	50%
commercial water heating	2050	Baseline	49%	0%	49%	0%	4%
commercial water heating	2050	HE	45%	0%	45%	0%	4%
commercial water heating	2050	Electric	6%	100%	6%	100%	92%
heavy duty trucks	2023	Baseline	100%	99%	100%	99%	100%
heavy duty trucks	2023	Electric	0%	1%	0%	1%	1%
heavy duty trucks	2023	H2	0%	0%	0%	0%	0%
heavy duty trucks	2030	Baseline	100%	44%	44%	44%	97%
heavy duty trucks	2030	Electric	0%	40%	40%	40%	2%
heavy duty trucks	2030	H2	0%	16%	16%	16%	1%
heavy duty trucks	2040	Baseline	100%	4%	36%	4%	74%
heavy duty trucks	2040	Electric	0%	70%	64%	70%	20%
heavy duty trucks	2040	H2	0%	26%	0%	26%	7%
heavy duty trucks	2050	Baseline	100%	0%	23%	0%	20%
heavy duty trucks	2050	Electric	0%	73%	70%	73%	57%

heavy duty trucks	2050	H2	0%	27%	7%	27%	23%
light duty autos	2023	Baseline	83%	86%	86%	86%	92%
light duty autos	2023	HE	6%	3%	3%	3%	3%
light duty autos	2023	Electric	11%	11%	11%	11%	5%
light duty autos	2023	H2	0%	0%	0%	0%	0%
light duty autos	2030	Baseline	74%	34%	44%	34%	80%
light duty autos	2030	HE	5%	1%	2%	1%	3%
light duty autos	2030	Electric	20%	63%	52%	63%	17%
light duty autos	2030	H2	0%	2%	2%	2%	0%
light duty autos	2040	Baseline	66%	0%	0%	0%	34%
light duty autos	2040	HE	8%	0%	0%	0%	1%
light duty autos	2040	Electric	26%	95%	96%	95%	63%
light duty autos	2040	H2	0%	5%	4%	5%	2%
light duty autos	2050	Baseline	62%	0%	0%	0%	6%
light duty autos	2050	HE	8%	0%	0%	0%	0%
light duty autos	2050	Electric	30%	95%	96%	95%	90%
light duty autos	2050	H2	0%	5%	4%	5%	5%
light duty trucks	2023	Baseline	93%	88%	88%	88%	98%
light duty trucks	2023	HE	4%	1%	1%	1%	1%
light duty trucks	2023	Electric	3%	11%	11%	11%	1%
light duty trucks	2023	H2	0%	0%	0%	0%	0%
light duty trucks	2030	Baseline	86%	45%	46%	45%	93%
light duty trucks	2030	HE	6%	0%	1%	0%	1%
light duty trucks	2030	Electric	8%	52%	52%	52%	6%
light duty trucks	2030	H2	0%	3%	2%	3%	0%
light duty trucks	2040	Baseline	82%	0%	0%	0%	53%
light duty trucks	2040	HE	7%	0%	0%	0%	1%
light duty trucks	2040	Electric	11%	90%	92%	90%	42%
light duty trucks	2040	H2	0%	10%	8%	10%	4%
light duty trucks	2050	Baseline	80%	0%	0%	0%	8%
light duty trucks	2050	HE	7%	0%	0%	0%	0%
light duty trucks	2050	Electric	13%	90%	92%	90%	83%
light duty trucks	2050	H2	0%	10%	8%	10%	9%
medium duty trucks	2023	Baseline	100%	99%	99%	99%	99%
medium duty trucks	2023	Electric	0%	1%	1%	1%	1%
medium duty trucks	2023	H2	0%	0%	0%	0%	0%
medium duty trucks	2030	Baseline	100%	50%	50%	50%	97%
medium duty trucks	2030	Electric	0%	44%	44%	44%	3%
medium duty trucks	2030	H2	0%	6%	6%	6%	1%
medium duty trucks	2040	Baseline	100%	6%	40%	6%	72%

medium duty trucks	2040	Electric	0%	75%	54%	75%	22%
medium duty trucks	2040	H2	0%	19%	6%	19%	6%
medium duty trucks	2050	Baseline	100%	0%	28%	0%	19%
medium duty trucks	2050	Electric	0%	80%	63%	80%	65%
medium duty trucks	2050	H2	0%	20%	9%	20%	16%
residential air conditioning	2023	Baseline	99%	94%	97%	94%	97%
residential air conditioning	2023	HE	1%	6%	4%	6%	3%
residential air conditioning	2030	Baseline	99%	49%	73%	49%	30%
residential air conditioning	2030	HE	1%	51%	28%	51%	70%
residential air conditioning	2040	Baseline	99%	60%	73%	60%	32%
residential air conditioning	2040	HE	1%	41%	27%	41%	68%
residential air conditioning	2050	Baseline	99%	57%	72%	57%	50%
residential air conditioning	2050	HE	1%	43%	28%	43%	50%
residential building shell	2023	Baseline	100%	86%	86%	86%	86%
residential building shell	2023	HE		14%	14%	14%	14%
residential building shell	2030	Baseline	100%	36%	57%	36%	36%
residential building shell	2030	HE		64%	43%	64%	64%
residential building shell	2040	Baseline	100%	0%	57%	0%	0%
residential building shell	2040	HE		100%	43%	100%	100%
residential building shell	2050	Baseline	100%	0%	57%	0%	0%
residential building shell	2050	HE		100%	43%	100%	100%
residential clothes drying	2023	Baseline	19%	18%	19%	18%	18%
residential clothes drying	2023	Electric	81%	82%	81%	82%	82%
residential clothes drying	2030	Baseline	19%	4%	19%	4%	4%
residential clothes drying	2030	Electric	81%	97%	81%	97%	97%
residential clothes drying	2040	Baseline	19%	0%	19%	0%	0%
residential clothes drying	2040	Electric	81%	100%	81%	100%	100%
residential clothes drying	2050	Baseline	19%	0%	19%	0%	0%
residential clothes drying	2050	Electric	81%	100%	81%	100%	100%
residential clothes washing	2023	Baseline	100%	97%	100%	97%	97%
residential clothes washing	2023	HE		3%		3%	3%
residential clothes washing	2030	Baseline	100%	19%	100%	19%	19%
residential clothes washing	2030	HE		81%		81%	81%
residential clothes washing	2040	Baseline	100%	0%	100%	0%	0%
residential clothes washing	2040	HE		100%		100%	100%
residential clothes washing	2050	Baseline	100%	0%	100%	0%	0%
residential clothes washing	2050	HE		100%		100%	100%
residential cooking	2023	Baseline	37%	35%	37%	35%	35%
residential cooking	2023	Electric	63%	65%	63%	65%	65%
residential cooking	2030	Baseline	39%	20%	39%	20%	34%

residential cooking	2030	Electric	61%	80%	61%	80%	66%
residential cooking	2040	Baseline	38%	0%	38%	0%	19%
residential cooking	2040	Electric	62%	100%	62%	100%	81%
residential cooking	2050	Baseline	41%	0%	41%	0%	3%
residential cooking	2050	Electric	59%	100%	59%	100%	97%
residential dishwashing	2023	Baseline	100%	97%	100%	97%	97%
residential dishwashing	2023	HE		3%		3%	3%
residential dishwashing	2030	Baseline	100%	19%	100%	19%	19%
residential dishwashing	2030	HE		81%		81%	81%
residential dishwashing	2040	Baseline	100%	0%	100%	0%	0%
residential dishwashing	2040	HE		100%		100%	100%
residential dishwashing	2050	Baseline	100%	0%	100%	0%	0%
residential dishwashing	2050	HE		100%		100%	100%
residential freezing	2023	Baseline	100%	97%	100%	97%	97%
residential freezing	2023	HE		3%		3%	3%
residential freezing	2030	Baseline	100%	19%	100%	19%	19%
residential freezing	2030	HE		81%		81%	81%
residential freezing	2040	Baseline	100%	0%	100%	0%	0%
residential freezing	2040	HE		100%		100%	100%
residential freezing	2050	Baseline	100%	0%	100%	0%	0%
residential freezing	2050	HE		100%		100%	100%
residential lighting	2023	Baseline	34%	34%	34%	34%	34%
residential lighting	2023	HE	66%	66%	66%	66%	66%
residential lighting	2030	Baseline	45%	45%	45%	45%	45%
residential lighting	2030	HE	55%	55%	55%	55%	55%
residential lighting	2040	Baseline	47%	47%	47%	47%	47%
residential lighting	2040	HE	53%	53%	53%	53%	53%
residential lighting	2050	Baseline	35%	35%	35%	35%	35%
residential lighting	2050	HE	66%	66%	66%	66%	66%
residential refrigeration	2023	Baseline	100%	97%	100%	97%	97%
residential refrigeration	2023	HE		3%		3%	3%
residential refrigeration	2030	Baseline	100%	19%	100%	19%	19%
residential refrigeration	2030	HE		81%		81%	81%
residential refrigeration	2040	Baseline	100%	0%	100%	0%	0%
residential refrigeration	2040	HE		100%		100%	100%
residential refrigeration	2050	Baseline	100%	0%	100%	0%	0%
residential refrigeration	2050	HE		100%		100%	100%
residential space heating	2023	Baseline	61%	56%	57%	56%	59%
residential space heating	2023	Electric	39%	44%	43%	44%	41%
residential space heating	2030	Baseline	61%	19%	34%	19%	56%

residential space heating	2030	Electric	39%	81%	66%	81%	44%
residential space heating	2040	Baseline	60%	3%	34%	3%	29%
residential space heating	2040	Electric	40%	97%	67%	97%	71%
residential space heating	2050	Baseline	60%	3%	33%	3%	4%
residential space heating	2050	Electric	40%	97%	67%	97%	96%
residential water heating	2023	Baseline	60%	57%	58%	57%	60%
residential water heating	2023	Electric	40%	43%	42%	43%	40%
residential water heating	2030	Baseline	61%	25%	44%	25%	57%
residential water heating	2030	Electric	39%	75%	56%	75%	43%
residential water heating	2040	Baseline	61%	0%	44%	0%	32%
residential water heating	2040	Electric	39%	100%	57%	100%	68%
residential water heating	2050	Baseline	61%	0%	43%	0%	5%
residential water heating	2050	Electric	39%	100%	57%	100%	95%

Table 6 Stock shares by scenario and technology group

Subsector	Year	Demand Technology	baseline	central	IRA	low demand	slow consumer uptake
buses	2023	Baseline	98%	97%	98%	97%	98%
buses	2023	HE	2%	2%	2%	2%	2%
buses	2023	Electric		0%	0%	0%	0%
buses	2023	H2		0%	0%	0%	0%
buses	2030	Baseline	98%	79%	73%	79%	96%
buses	2030	HE	2%	1%	2%	1%	2%
buses	2030	Electric		18%	24%	18%	2%
buses	2030	H2		1%	2%	1%	0%
buses	2040	Baseline	98%	15%	20%	15%	75%
buses	2040	HE	2%	0%	0%	0%	2%
buses	2040	Electric		77%	72%	77%	21%
buses	2040	H2		8%	7%	8%	2%
buses	2050	Baseline	98%	0%	20%	0%	25%
buses	2050	HE	2%	0%	0%	0%	1%
buses	2050	Electric		90%	73%	90%	67%
buses	2050	H2		10%	7%	10%	7%
commercial air conditioning	2023	Baseline	85%	85%	85%	85%	85%
commercial air conditioning	2023	HE	15%	15%	15%	15%	15%
commercial air conditioning	2030	Baseline	84%	70%	73%	70%	72%
commercial air conditioning	2030	HE	16%	30%	27%	30%	28%
commercial air conditioning	2040	Baseline	87%	43%	49%	43%	39%

commercial air conditioning	2040	HE	14%	57%	51%	57%	61%
commercial air conditioning	2050	Baseline	87%	27%	35%	27%	23%
commercial air conditioning	2050	HE	14%	73%	65%	73%	77%
commercial cooking	2023	Baseline	67%	67%	67%	67%	67%
commercial cooking	2023	Electric	33%	33%	33%	33%	33%
commercial cooking	2030	Baseline	67%	59%	67%	59%	66%
commercial cooking	2030	Electric	33%	41%	33%	41%	34%
commercial cooking	2040	Baseline	67%	15%	67%	15%	52%
commercial cooking	2040	Electric	33%	85%	33%	85%	48%
commercial cooking	2050	Baseline	67%	4%	67%	4%	21%
commercial cooking	2050	Electric	33%	97%	33%	97%	79%
commercial lighting	2023	Baseline	23%	17%	23%	17%	17%
commercial lighting	2023	HE	77%	83%	77%	83%	83%
commercial lighting	2030	Baseline	21%	1%	21%	1%	1%
commercial lighting	2030	HE	79%	99%	79%	99%	99%
commercial lighting	2040	Baseline	22%	0%	22%	0%	0%
commercial lighting	2040	HE	78%	100%	78%	100%	100%
commercial lighting	2050	Baseline	28%	0%	28%	0%	0%
commercial lighting	2050	HE	72%	100%	72%	100%	100%
commercial refrigeration	2023	Baseline	100%	100%	100%	100%	100%
commercial refrigeration	2023	HE	0%	0%	0%	0%	0%
commercial refrigeration	2030	Baseline	100%	77%	100%	77%	77%
commercial refrigeration	2030	HE	0%	23%	0%	23%	23%
commercial refrigeration	2040	Baseline	100%	13%	100%	13%	13%
commercial refrigeration	2040	HE	0%	87%	0%	87%	87%
commercial refrigeration	2050	Baseline	100%	0%	100%	0%	0%
commercial refrigeration	2050	HE	0%	100%	0%	100%	100%
commercial space heating	2023	Baseline	86%	84%	85%	84%	85%
commercial space heating	2023	HE	3%	3%	3%	3%	3%
commercial space heating	2023	Electric	12%	14%	13%	14%	13%
commercial space heating	2030	Baseline	85%	64%	67%	64%	80%
commercial space heating	2030	HE	3%	3%	3%	3%	3%
commercial space heating	2030	Electric	12%	34%	30%	34%	17%
commercial space heating	2040	Baseline	86%	22%	29%	22%	66%
commercial space heating	2040	HE	3%	1%	3%	1%	2%
commercial space heating	2040	Electric	12%	77%	68%	77%	32%
commercial space heating	2050	Baseline	86%	6%	17%	6%	37%
commercial space heating	2050	HE	3%	0%	3%	0%	1%
commercial space heating	2050	Electric	11%	94%	80%	94%	62%
commercial ventilation	2023	Baseline	100%	99%	100%	99%	100%

commercial ventilation	2023	HE	0%	1%	0%	1%	0%
commercial ventilation	2030	Baseline	100%	81%	88%	81%	88%
commercial ventilation	2030	HE	0%	19%	12%	19%	12%
commercial ventilation	2040	Baseline	100%	36%	52%	36%	45%
commercial ventilation	2040	HE	0%	64%	48%	64%	55%
commercial ventilation	2050	Baseline	100%	5%	25%	5%	9%
commercial ventilation	2050	HE	0%	95%	75%	95%	91%
commercial water heating	2023	Baseline	45%	45%	45%	45%	45%
commercial water heating	2023	HE	49%	49%	49%	49%	49%
commercial water heating	2023	Electric	6%	6%	6%	6%	6%
commercial water heating	2030	Baseline	43%	40%	43%	40%	42%
commercial water heating	2030	HE	51%	45%	51%	45%	50%
commercial water heating	2030	Electric	6%	15%	6%	15%	8%
commercial water heating	2040	Baseline	49%	16%	49%	16%	40%
commercial water heating	2040	HE	45%	13%	45%	13%	37%
commercial water heating	2040	Electric	6%	71%	6%	71%	24%
commercial water heating	2050	Baseline	49%	1%	49%	1%	17%
commercial water heating	2050	HE	45%	1%	45%	1%	16%
commercial water heating	2050	Electric	6%	99%	6%	99%	67%
heavy duty trucks	2023	Baseline	100%	100%	100%	100%	100%
heavy duty trucks	2023	Electric	0%	0%	0%	0%	0%
heavy duty trucks	2023	H2	0%	0%	0%	0%	0%
heavy duty trucks	2030	Baseline	100%	86%	86%	86%	99%
heavy duty trucks	2030	Electric	0%	7%	7%	7%	1%
heavy duty trucks	2030	H2	0%	7%	7%	7%	0%
heavy duty trucks	2040	Baseline	100%	44%	55%	44%	91%
heavy duty trucks	2040	Electric	0%	41%	39%	41%	7%
heavy duty trucks	2040	H2	0%	15%	6%	15%	2%
heavy duty trucks	2050	Baseline	100%	9%	34%	9%	59%
heavy duty trucks	2050	Electric	0%	67%	63%	67%	30%
heavy duty trucks	2050	H2	0%	24%	4%	24%	11%
light duty autos	2023	Baseline	94%	95%	95%	95%	95%
light duty autos	2023	HE	3%	3%	3%	3%	3%
light duty autos	2023	Electric	3%	2%	2%	2%	2%
light duty autos	2023	H2	0%	0%	0%	0%	0%
light duty autos	2030	Baseline	87%	81%	82%	81%	91%
light duty autos	2030	HE	4%	3%	3%	3%	3%
light duty autos	2030	Electric	9%	16%	15%	16%	6%
light duty autos	2030	H2	0%	0%	0%	0%	0%
light duty autos	2040	Baseline	73%	31%	36%	31%	69%

light duty autos	2040	HE	6%	1%	1%	1%	2%
light duty autos	2040	Electric	21%	65%	60%	65%	28%
light duty autos	2040	H2	0%	3%	2%	3%	1%
light duty autos	2050	Baseline	66%	3%	5%	3%	30%
light duty autos	2050	HE	8%	0%	0%	0%	1%
light duty autos	2050	Electric	27%	92%	91%	92%	67%
light duty autos	2050	H2	0%	5%	4%	5%	3%
light duty trucks	2023	Baseline	98%	97%	97%	97%	98%
light duty trucks	2023	HE	2%	1%	1%	1%	1%
light duty trucks	2023	Electric	1%	2%	2%	2%	0%
light duty trucks	2023	H2	0%	0%	0%	0%	0%
light duty trucks	2030	Baseline	93%	81%	81%	81%	97%
light duty trucks	2030	HE	4%	1%	1%	1%	1%
light duty trucks	2030	Electric	4%	18%	18%	18%	2%
light duty trucks	2030	H2	0%	1%	0%	1%	0%
light duty trucks	2040	Baseline	86%	31%	34%	31%	82%
light duty trucks	2040	HE	6%	0%	0%	0%	1%
light duty trucks	2040	Electric	9%	63%	62%	63%	16%
light duty trucks	2040	H2	0%	6%	4%	6%	1%
light duty trucks	2050	Baseline	82%	4%	5%	4%	41%
light duty trucks	2050	HE	7%	0%	0%	0%	0%
light duty trucks	2050	Electric	11%	87%	88%	87%	53%
light duty trucks	2050	H2	0%	9%	8%	9%	6%
medium duty trucks	2023	Baseline	100%	100%	100%	100%	100%
medium duty trucks	2023	Electric	0%	0%	0%	0%	0%
medium duty trucks	2023	H2	0%	0%	0%	0%	0%
medium duty trucks	2030	Baseline	100%	88%	88%	88%	99%
medium duty trucks	2030	Electric	0%	11%	11%	11%	1%
medium duty trucks	2030	H2	0%	1%	1%	1%	0%
medium duty trucks	2040	Baseline	100%	52%	62%	52%	92%
medium duty trucks	2040	Electric	0%	40%	34%	40%	7%
medium duty trucks	2040	H2	0%	8%	4%	8%	2%
medium duty trucks	2050	Baseline	100%	12%	38%	12%	60%
medium duty trucks	2050	Electric	0%	71%	55%	71%	32%
medium duty trucks	2050	H2	0%	17%	7%	17%	8%
residential air conditioning	2023	Baseline	100%	99%	99%	99%	99%
residential air conditioning	2023	HE	1%	1%	1%	1%	1%
residential air conditioning	2030	Baseline	99%	83%	90%	83%	84%
residential air conditioning	2030	HE	1%	17%	10%	17%	16%
residential air conditioning	2040	Baseline	99%	59%	76%	59%	39%

residential air conditioning	2040	HE	1%	41%	24%	41%	61%
residential air conditioning	2050	Baseline	99%	58%	73%	58%	37%
residential air conditioning	2050	HE	1%	42%	27%	42%	63%
residential building shell	2023	Baseline	100%	99%	99%	99%	99%
residential building shell	2023	HE		1%	1%	1%	1%
residential building shell	2030	Baseline	100%	92%	93%	92%	92%
residential building shell	2030	HE		8%	7%	8%	8%
residential building shell	2040	Baseline	100%	71%	84%	71%	71%
residential building shell	2040	HE		29%	16%	29%	29%
residential building shell	2050	Baseline	100%	52%	76%	52%	52%
residential building shell	2050	HE		48%	24%	48%	48%
residential clothes drying	2023	Baseline	19%	19%	19%	19%	19%
residential clothes drying	2023	Electric	81%	81%	81%	81%	81%
residential clothes drying	2030	Baseline	19%	15%	19%	15%	15%
residential clothes drying	2030	Electric	81%	85%	81%	85%	85%
residential clothes drying	2040	Baseline	19%	4%	19%	4%	4%
residential clothes drying	2040	Electric	81%	96%	81%	96%	96%
residential clothes drying	2050	Baseline	19%	0%	19%	0%	0%
residential clothes drying	2050	Electric	81%	100%	81%	100%	100%
residential clothes washing	2023	Baseline	100%	100%	100%	100%	100%
residential clothes washing	2023	HE		0%		0%	0%
residential clothes washing	2030	Baseline	100%	82%	100%	82%	82%
residential clothes washing	2030	HE		19%		19%	19%
residential clothes washing	2040	Baseline	100%	18%	100%	18%	18%
residential clothes washing	2040	HE		82%		82%	82%
residential clothes washing	2050	Baseline	100%	0%	100%	0%	0%
residential clothes washing	2050	HE		100%		100%	100%
residential cooking	2023	Baseline	36%	36%	36%	36%	36%
residential cooking	2023	Electric	64%	64%	64%	64%	64%
residential cooking	2030	Baseline	37%	34%	37%	34%	36%
residential cooking	2030	Electric	63%	67%	63%	67%	65%
residential cooking	2040	Baseline	38%	17%	38%	17%	30%
residential cooking	2040	Electric	62%	84%	62%	84%	70%
residential cooking	2050	Baseline	39%	2%	39%	2%	17%
residential cooking	2050	Electric	61%	98%	61%	98%	83%
residential dishwashing	2023	Baseline	100%	100%	100%	100%	100%
residential dishwashing	2023	HE		0%		0%	0%
residential dishwashing	2030	Baseline	100%	81%	100%	81%	81%
residential dishwashing	2030	HE		19%		19%	19%
residential dishwashing	2040	Baseline	100%	16%	100%	16%	16%

residential dishwashing	2040	HE		84%		84%	84%
residential dishwashing	2050	Baseline	100%	0%	100%	0%	0%
residential dishwashing	2050	HE		100%		100%	100%
residential freezing	2023	Baseline	100%	100%	100%	100%	100%
residential freezing	2023	HE		0%		0%	0%
residential freezing	2030	Baseline	100%	87%	100%	87%	87%
residential freezing	2030	HE		13%		13%	13%
residential freezing	2040	Baseline	100%	41%	100%	41%	41%
residential freezing	2040	HE		59%		59%	59%
residential freezing	2050	Baseline	100%	8%	100%	8%	8%
residential freezing	2050	HE		92%		92%	92%
residential lighting	2023	Baseline	36%	36%	36%	36%	36%
residential lighting	2023	HE	64%	64%	64%	64%	64%
residential lighting	2030	Baseline	20%	20%	20%	20%	20%
residential lighting	2030	HE	80%	80%	80%	80%	80%
residential lighting	2040	Baseline	15%	15%	15%	15%	15%
residential lighting	2040	HE	85%	85%	85%	85%	85%
residential lighting	2050	Baseline	12%	12%	12%	12%	12%
residential lighting	2050	HE	89%	89%	89%	89%	89%
residential refrigeration	2023	Baseline	100%	100%	100%	100%	100%
residential refrigeration	2023	HE		0%		0%	0%
residential refrigeration	2030	Baseline	100%	83%	100%	83%	83%
residential refrigeration	2030	HE		17%		17%	17%
residential refrigeration	2040	Baseline	100%	29%	100%	29%	29%
residential refrigeration	2040	HE		71%		71%	71%
residential refrigeration	2050	Baseline	100%	2%	100%	2%	2%
residential refrigeration	2050	HE		98%		98%	98%
residential space heating	2023	Baseline	63%	63%	63%	63%	63%
residential space heating	2023	Electric	37%	37%	37%	37%	37%
residential space heating	2030	Baseline	63%	52%	54%	52%	61%
residential space heating	2030	Electric	37%	49%	46%	49%	39%
residential space heating	2040	Baseline	63%	23%	41%	23%	52%
residential space heating	2040	Electric	37%	77%	59%	77%	48%
residential space heating	2050	Baseline	62%	6%	36%	6%	28%
residential space heating	2050	Electric	38%	94%	64%	94%	72%
residential water heating	2023	Baseline	52%	52%	52%	52%	52%
residential water heating	2023	Electric	48%	49%	49%	49%	48%
residential water heating	2030	Baseline	52%	38%	43%	38%	50%
residential water heating	2030	Electric	48%	62%	57%	62%	50%
residential water heating	2040	Baseline	52%	6%	36%	6%	39%

residential water heating	2040	Electric	48%	94%	65%	94%	61%
residential water heating	2050	Baseline	52%	0%	35%	0%	13%
residential water heating	2050	Electric	48%	100%	65%	100%	88%

1.7.1.2. Subsector Energy Efficiency and Fuel Switching

The outputs of the stock rollover, when combined with the projected service demand that the technology stocks must supply, provide the majority of final energy demand projections in our model. In subsectors where we did not have technology-level detail, we employed subsector-level estimates of energy efficiency and fuel switching. Energy efficiency here means measures that increase the same-fuel efficiency of providing an energy service. Fuel switching, which can also contribute to end-use efficiency, means measures that change the share of a delivered energy service that is satisfied by a specific energy carrier. All final energy demand is modeled and presented with higher heating values (HHV). For that reason, HHV conversion efficiencies are used for all technologies in the study. Because only the lower heating value (LHV) of fuels are usable in most applications, adjustments were made when applying fuel switching measures where the ratio of LHV/HHV decreased (e.g. switching from natural gas to hydrogen in industrial process heating applications).

Table 7 Energy efficiency measures included in all net-zeros scenarios

Sector	Subsector	Description
COMMERCIAL	OTHER	Year over year efficiency gains for non-heavy industry of 1%/year applied to the decarbonization scenarios. Levelized cost of efficiency for all fuel types assessed at $10/MMBTU saved today escalating linearly to $20/MMBTU saved in 2050.
TRANSPORTATION	AVIATION	Year over year efficiency gains of 1.5% in jet fuel applied to the decarbonization scenarios. Levelized cost of efficiency for all fuel types assessed at $20/MMBTU saved today escalating linearly to $30/MMBTU saved for reductions in 2050.
PRODUCTIVE	VARIOUS	Year over year efficiency gains for non-heavy industry of 1%/year applied to the decarbonization scenarios. Levelized cost of efficiency for all fuel types assessed at $10/MMBTU saved today escalating linearly to $20/MMBTU saved in 2050.

Table 8 Fuel switching measures (% of Baseline Energy Switched to 'Energy-To')

Subsector	Energy -To	End-Use	Target Year	baseline	central	IRA	slow consumer uptake	low demand
agriculture-crops	electricity	hvac	2050		90			90
agriculture-crops	electricity	hvac	2070				90	
agriculture-crops	electricity	hvac	2045					
agriculture-crops	electricity	hvac	2060					
agriculture-crops	electricity	hvac	2050					
agriculture-crops	electricity	machine drives	2035		100			100
agriculture-crops	electricity	machine drives	2055				100	
agriculture-crops	electricity	machine drives	2030					
agriculture-crops	electricity	machine drives	2045					
agriculture-crops	electricity	machine drives	2035					
agriculture-crops	electricity	transport	2045		80			80
agriculture-crops	electricity	transport	2065				80	
agriculture-crops	electricity	transport	2040					
agriculture-crops	electricity	transport	2055					
agriculture-crops	electricity	transport	2045					
agriculture-crops	hydrogen	transport	2050		20			20
agriculture-crops	hydrogen	transport	2070				20	
agriculture-crops	hydrogen	transport	2045					
agriculture-crops	hydrogen	transport	2060					
agriculture-crops	hydrogen	transport	2050					
agriculture-other	electricity	hvac	2050		90			90
agriculture-other	electricity	hvac	2070				90	
agriculture-other	electricity	hvac	2045					
agriculture-other	electricity	hvac	2060					
agriculture-other	electricity	hvac	2050					
agriculture-other	electricity	machine drives	2035		100			100
agriculture-other	electricity	machine drives	2055				100	
agriculture-other	electricity	machine drives	2030					
agriculture-other	electricity	machine drives	2045					
agriculture-other	electricity	machine drives	2035					
agriculture-other	electricity	transport	2045		80			80
agriculture-other	electricity	transport	2065				80	
agriculture-other	electricity	transport	2040					

agriculture-other	electricity	transport	2055					
agriculture-other	electricity	transport	2045					
agriculture-other	hydrogen	transport	2050		20			20
agriculture-other	hydrogen	transport	2070				20	
agriculture-other	hydrogen	transport	2045					
agriculture-other	hydrogen	transport	2060					
agriculture-other	hydrogen	transport	2050					
aluminum industry	electricity	hvac	2050		90			90
aluminum industry	electricity	hvac	2070				90	
aluminum industry	electricity	hvac	2045					
aluminum industry	electricity	hvac	2060					
aluminum industry	electricity	hvac	2050					
aluminum industry	electricity	other	2050		75			75
aluminum industry	electricity	other	2070				75	
aluminum industry	electricity	other	2045					
aluminum industry	electricity	other	2060					
aluminum industry	electricity	other	2050					
aluminum industry	electricity	support	2050		75			75
aluminum industry	electricity	support	2070				75	
aluminum industry	electricity	support	2045					
aluminum industry	electricity	support	2060					
aluminum industry	electricity	support	2050					
aluminum industry	electricity	transport	2045		80			80
aluminum industry	electricity	transport	2065				80	
aluminum industry	electricity	transport	2040					
aluminum industry	electricity	transport	2055					
aluminum industry	electricity	transport	2045					
aluminum industry	hydrogen	transport	2050		20			20
aluminum industry	hydrogen	transport	2070				20	
aluminum industry	hydrogen	transport	2045					
aluminum industry	hydrogen	transport	2060					
aluminum industry	hydrogen	transport	2050					
balance of manufacturing other	electricity	heat	2050		100			100
balance of manufacturing other	electricity	heat	2070				100	
balance of manufacturing other	electricity	heat	2045					
balance of manufacturing other	electricity	heat	2060					
balance of manufacturing other	electricity	heat	2050					
balance of manufacturing other	hydrogen	heat	2050					
balance of manufacturing other	electricity	hvac	2050		90			90
balance of manufacturing other	electricity	hvac	2070				90	

balance of manufacturing other	electricity	hvac	2045					
balance of manufacturing other	electricity	hvac	2060					
balance of manufacturing other	electricity	hvac	2050					
balance of manufacturing other	electricity	integrated steam	2045		50			50
balance of manufacturing other	electricity	integrated steam	2065				50	
balance of manufacturing other	electricity	integrated steam	2045					
balance of manufacturing other	electricity	integrated steam	2060					
balance of manufacturing other	electricity	integrated steam	2045					
balance of manufacturing other	hydrogen	integrated steam	2050		20			20
balance of manufacturing other	hydrogen	integrated steam	2070				20	
balance of manufacturing other	hydrogen	integrated steam	2045					
balance of manufacturing other	hydrogen	integrated steam	2060					
balance of manufacturing other	hydrogen	integrated steam	2050					
balance of manufacturing other	electricity	machine drives	2035		100			100
balance of manufacturing other	electricity	machine drives	2055				100	
balance of manufacturing other	electricity	machine drives	2030					
balance of manufacturing other	electricity	machine drives	2045					
balance of manufacturing other	electricity	machine drives	2035					
balance of manufacturing other	electricity	other	2050		75			75
balance of manufacturing other	electricity	other	2070				75	
balance of manufacturing other	electricity	other	2045					
balance of manufacturing other	electricity	other	2060					
balance of manufacturing other	electricity	other	2050					
balance of manufacturing other	electricity	support	2050		75			75
balance of manufacturing other	electricity	support	2070				75	
balance of manufacturing other	electricity	support	2045					
balance of manufacturing other	electricity	support	2060					
balance of manufacturing other	electricity	support	2050					
balance of manufacturing other	electricity	transport	2045		80			80
balance of manufacturing other	electricity	transport	2065				80	
balance of manufacturing other	electricity	transport	2040					
balance of manufacturing other	electricity	transport	2055					
balance of manufacturing other	electricity	transport	2045					
balance of manufacturing other	hydrogen	transport	2050		20			20
balance of manufacturing other	hydrogen	transport	2070				20	
balance of manufacturing other	hydrogen	transport	2045					
balance of manufacturing other	hydrogen	transport	2060					
balance of manufacturing other	hydrogen	transport	2050					
bulk chemicals	electricity	heat	2050		50			50
bulk chemicals	electricity	heat	2070				50	

bulk chemicals	electricity	heat	2045					
bulk chemicals	electricity	heat	2060					
bulk chemicals	hydrogen	heat	2050		50			50
bulk chemicals	hydrogen	heat	2070				50	
bulk chemicals	hydrogen	heat	2045					
bulk chemicals	hydrogen	heat	2060					
bulk chemicals	hydrogen	heat	2050					
bulk chemicals	electricity	hvac	2050		90			90
bulk chemicals	electricity	hvac	2070				90	
bulk chemicals	electricity	hvac	2045					
bulk chemicals	electricity	hvac	2060					
bulk chemicals	electricity	hvac	2050					
bulk chemicals	electricity	integrated steam	2045		50			50
bulk chemicals	electricity	integrated steam	2065				50	
bulk chemicals	electricity	integrated steam	2045					
bulk chemicals	electricity	integrated steam	2060					
bulk chemicals	electricity	integrated steam	2045					
bulk chemicals	hydrogen	integrated steam	2050		20			20
bulk chemicals	hydrogen	integrated steam	2070				20	
bulk chemicals	hydrogen	integrated steam	2045					
bulk chemicals	hydrogen	integrated steam	2060					
bulk chemicals	hydrogen	integrated steam	2050					
bulk chemicals	electricity	machine drives	2035		100			100
bulk chemicals	electricity	machine drives	2055				100	
bulk chemicals	electricity	machine drives	2030					
bulk chemicals	electricity	machine drives	2045					
bulk chemicals	electricity	machine drives	2035					
bulk chemicals	electricity	other	2050		75			75
bulk chemicals	electricity	other	2070				75	
bulk chemicals	electricity	other	2045					
bulk chemicals	electricity	other	2060					
bulk chemicals	electricity	other	2050					
bulk chemicals	electricity	refrigeration	2040		100			100
bulk chemicals	electricity	refrigeration	2060				100	
bulk chemicals	electricity	refrigeration	2040					
bulk chemicals	electricity	refrigeration	2040					
bulk chemicals	electricity	refrigeration	2040					
bulk chemicals	electricity	support	2050		75			75
bulk chemicals	electricity	support	2070				75	
bulk chemicals	electricity	support	2045					

bulk chemicals	electricity	support	2060					
bulk chemicals	electricity	support	2050					
bulk chemicals	electricity	transport	2045		80			80
bulk chemicals	electricity	transport	2065				80	
bulk chemicals	electricity	transport	2040					
bulk chemicals	electricity	transport	2055					
bulk chemicals	electricity	transport	2045					
bulk chemicals	hydrogen	transport	2050		20			20
bulk chemicals	hydrogen	transport	2070				20	
bulk chemicals	hydrogen	transport	2045					
bulk chemicals	hydrogen	transport	2060					
bulk chemicals	hydrogen	transport	2050					
cement	electricity	hvac	2050		90			90
cement	electricity	hvac	2070				90	
cement	electricity	hvac	2045					
cement	electricity	hvac	2060					
cement	electricity	hvac	2050					
cement	electricity	support	2050		75			75
cement	electricity	support	2070				75	
cement	electricity	support	2045					
cement	electricity	support	2060					
cement	electricity	support	2050					
cement	electricity	transport	2045		80			80
cement	electricity	transport	2065				80	
cement	electricity	transport	2040					
cement	electricity	transport	2055					
cement	electricity	transport	2045					
cement	hydrogen	transport	2050		20			20
cement	hydrogen	transport	2070				20	
cement	hydrogen	transport	2045					
cement	hydrogen	transport	2060					
cement	hydrogen	transport	2050					
commercial other	electricity	all	2045		90			90
commercial other	electricity	all	2045		100			100
commercial other	electricity	all	2065				90	
commercial other	electricity	all	2065				100	
commercial other	electricity	all	2045					
commercial other	electricity	all	2045					
commercial other	electricity	all	2060					
commercial other	electricity	all	2060					

commercial other	electricity	all	2045					
commercial other	electricity	all	2045					
commercial unspecified	electricity	all	2045		90			90
commercial unspecified	electricity	all	2065				90	
commercial unspecified	electricity	all	2045					
commercial unspecified	electricity	all	2060					
commercial unspecified	electricity	all	2045					
computer and electronic products	electricity	heat	2050		100			100
computer and electronic products	electricity	heat	2070				100	
computer and electronic products	electricity	heat	2045					
computer and electronic products	electricity	heat	2060					
computer and electronic products	electricity	heat	2050					
computer and electronic products	hydrogen	heat	2050					
computer and electronic products	electricity	hvac	2050		90			90
computer and electronic products	electricity	hvac	2070				90	
computer and electronic products	electricity	hvac	2045					
computer and electronic products	electricity	hvac	2060					
computer and electronic products	electricity	hvac	2050					
computer and electronic products	electricity	integrated steam	2045		50			50
computer and electronic products	electricity	integrated steam	2065				50	
computer and electronic products	electricity	integrated steam	2045					
computer and electronic products	electricity	integrated steam	2060					
computer and electronic products	electricity	integrated steam	2045					
computer and electronic products	hydrogen	integrated steam	2050		20			20
computer and electronic products	hydrogen	integrated steam	2070				20	
computer and electronic products	hydrogen	integrated steam	2045					
computer and electronic products	hydrogen	integrated steam	2060					
computer and electronic products	hydrogen	integrated steam	2050					
computer and electronic products	electricity	machine drives	2035		100			100
computer and electronic products	electricity	machine drives	2055				100	
computer and electronic products	electricity	machine drives	2030					
computer and electronic products	electricity	machine drives	2045					
computer and electronic products	electricity	machine drives	2035					
computer and electronic products	electricity	other	2050		75			75
computer and electronic products	electricity	other	2070				75	
computer and electronic products	electricity	other	2045					
computer and electronic products	electricity	other	2060					
computer and electronic products	electricity	other	2050					
computer and electronic products	electricity	support	2050		75			75
computer and electronic products	electricity	support	2070				75	

computer and electronic products	electricity	support	2045					
computer and electronic products	electricity	support	2060					
computer and electronic products	electricity	support	2050					
computer and electronic products	electricity	transport	2045		80			80
computer and electronic products	electricity	transport	2065				80	
computer and electronic products	electricity	transport	2040					
computer and electronic products	electricity	transport	2055					
computer and electronic products	electricity	transport	2045					
computer and electronic products	hydrogen	transport	2050		20			20
computer and electronic products	hydrogen	transport	2070				20	
computer and electronic products	hydrogen	transport	2045					
computer and electronic products	hydrogen	transport	2060					
computer and electronic products	hydrogen	transport	2050					
construction	electricity	other	2050		50			50
construction	electricity	other	2070				50	
construction	electricity	other	2045					
construction	electricity	other	2060					
construction	electricity	other	2050					
construction	hydrogen	other	2050		20			20
construction	hydrogen	other	2070				20	
construction	hydrogen	other	2045					
construction	hydrogen	other	2060					
construction	hydrogen	other	2050					
domestic shipping	ammonia	all	2050		50			50
domestic shipping	ammonia	all	2070				50	
domestic shipping	ammonia	all	2045					
domestic shipping	ammonia	all	2060					
domestic shipping	ammonia	all	2050					
domestic shipping	electricity	all	2050		10			10
domestic shipping	electricity	all	2070				10	
domestic shipping	electricity	all	2045					
domestic shipping	electricity	all	2060					
domestic shipping	electricity	all	2050					
domestic shipping	hydrogen	all	2050		20			20
domestic shipping	hydrogen	all	2070				20	
domestic shipping	hydrogen	all	2045					
domestic shipping	hydrogen	all	2060					
domestic shipping	hydrogen	all	2050					
electrical equip., appliances, and components	electricity	heat	2050		100			100
electrical equip., appliances, and components	electricity	heat	2070				100	

electrical equip., appliances, and components	electricity	heat	2045					
electrical equip., appliances, and components	electricity	heat	2060					
electrical equip., appliances, and components	electricity	heat	2050					
electrical equip., appliances, and components	hydrogen	heat	2050					
electrical equip., appliances, and components	electricity	hvac	2050		90			90
electrical equip., appliances, and components	electricity	hvac	2070				90	
electrical equip., appliances, and components	electricity	hvac	2045					
electrical equip., appliances, and components	electricity	hvac	2060					
electrical equip., appliances, and components	electricity	hvac	2050					
electrical equip., appliances, and components	electricity	integrated steam	2045		50			50
electrical equip., appliances, and components	electricity	integrated steam	2065				50	
electrical equip., appliances, and components	electricity	integrated steam	2045					
electrical equip., appliances, and components	electricity	integrated steam	2060					
electrical equip., appliances, and components	electricity	integrated steam	2045					
electrical equip., appliances, and components	hydrogen	integrated steam	2050		20			20
electrical equip., appliances, and components	hydrogen	integrated steam	2070				20	
electrical equip., appliances, and components	hydrogen	integrated steam	2045					
electrical equip., appliances, and components	hydrogen	integrated steam	2060					
electrical equip., appliances, and components	hydrogen	integrated steam	2050					
electrical equip., appliances, and components	electricity	machine drives	2035		100			100
electrical equip., appliances, and components	electricity	machine drives	2055				100	
electrical equip., appliances, and components	electricity	machine drives	2030					
electrical equip., appliances, and components	electricity	machine drives	2045					
electrical equip., appliances, and components	electricity	machine drives	2035					
electrical equip., appliances, and components	electricity	other	2050		75			75
electrical equip., appliances, and components	electricity	other	2070				75	
electrical equip., appliances, and components	electricity	other	2045					
electrical equip., appliances, and components	electricity	other	2060					
electrical equip., appliances, and components	electricity	other	2050					
electrical equip., appliances, and components	electricity	refrigeration	2040		100			100
electrical equip., appliances, and components	electricity	refrigeration	2060				100	
electrical equip., appliances, and components	electricity	refrigeration	2040					
electrical equip., appliances, and components	electricity	refrigeration	2040					
electrical equip., appliances, and components	electricity	refrigeration	2040					
electrical equip., appliances, and components	electricity	support	2050		75			75
electrical equip., appliances, and components	electricity	support	2070				75	
electrical equip., appliances, and components	electricity	support	2045					
electrical equip., appliances, and components	electricity	support	2060					
electrical equip., appliances, and components	electricity	support	2050					
electrical equip., appliances, and components	electricity	transport	2045		80			80

electrical equip., appliances, and components	electricity	transport	2065				80	
electrical equip., appliances, and components	electricity	transport	2040					
electrical equip., appliances, and components	electricity	transport	2055					
electrical equip., appliances, and components	electricity	transport	2045					
electrical equip., appliances, and components	hydrogen	transport	2050		20			20
electrical equip., appliances, and components	hydrogen	transport	2070				20	
electrical equip., appliances, and components	hydrogen	transport	2045					
electrical equip., appliances, and components	hydrogen	transport	2060					
electrical equip., appliances, and components	hydrogen	transport	2050					
fabricated metal products	electricity	heat	2050		100			100
fabricated metal products	electricity	heat	2070				100	
fabricated metal products	electricity	heat	2045					
fabricated metal products	electricity	heat	2060					
fabricated metal products	electricity	heat	2050					
fabricated metal products	hydrogen	heat	2050					
fabricated metal products	electricity	hvac	2050		90			90
fabricated metal products	electricity	hvac	2070				90	
fabricated metal products	electricity	hvac	2045					
fabricated metal products	electricity	hvac	2060					
fabricated metal products	electricity	hvac	2050					
fabricated metal products	electricity	integrated steam	2045		50			50
fabricated metal products	electricity	integrated steam	2065				50	
fabricated metal products	electricity	integrated steam	2045					
fabricated metal products	electricity	integrated steam	2060					
fabricated metal products	electricity	integrated steam	2045					
fabricated metal products	hydrogen	integrated steam	2050		20			20
fabricated metal products	hydrogen	integrated steam	2070				20	
fabricated metal products	hydrogen	integrated steam	2045					
fabricated metal products	hydrogen	integrated steam	2060					
fabricated metal products	hydrogen	integrated steam	2050					
fabricated metal products	electricity	machine drives	2035		100			100
fabricated metal products	electricity	machine drives	2055				100	
fabricated metal products	electricity	machine drives	2030					
fabricated metal products	electricity	machine drives	2045					
fabricated metal products	electricity	machine drives	2035					
fabricated metal products	electricity	other	2050		75			75
fabricated metal products	electricity	other	2070				75	
fabricated metal products	electricity	other	2045					
fabricated metal products	electricity	other	2060					
fabricated metal products	electricity	other	2050					

fabricated metal products	electricity	refrigeration	2040		100			100
fabricated metal products	electricity	refrigeration	2060				100	
fabricated metal products	electricity	refrigeration	2040					
fabricated metal products	electricity	refrigeration	2040					
fabricated metal products	electricity	refrigeration	2040					
fabricated metal products	electricity	support	2050		75			75
fabricated metal products	electricity	support	2070				75	
fabricated metal products	electricity	support	2045					
fabricated metal products	electricity	support	2060					
fabricated metal products	electricity	support	2050					
fabricated metal products	electricity	transport	2045		80			80
fabricated metal products	electricity	transport	2065				80	
fabricated metal products	electricity	transport	2040					
fabricated metal products	electricity	transport	2055					
fabricated metal products	electricity	transport	2045					
fabricated metal products	hydrogen	transport	2050		20			20
fabricated metal products	hydrogen	transport	2070				20	
fabricated metal products	hydrogen	transport	2045					
fabricated metal products	hydrogen	transport	2060					
fabricated metal products	hydrogen	transport	2050					
food and kindred products	electricity	heat	2050		100			100
food and kindred products	electricity	heat	2070				100	
food and kindred products	electricity	heat	2045					
food and kindred products	electricity	heat	2060					
food and kindred products	electricity	heat	2050					
food and kindred products	electricity	hvac	2050		90			90
food and kindred products	electricity	hvac	2070				90	
food and kindred products	electricity	hvac	2045					
food and kindred products	electricity	hvac	2060					
food and kindred products	electricity	hvac	2050					
food and kindred products	electricity	integrated steam	2045		80			80
food and kindred products	electricity	integrated steam	2065				80	
food and kindred products	electricity	integrated steam	2045					
food and kindred products	electricity	integrated steam	2060					
food and kindred products	electricity	integrated steam	2045					
food and kindred products	hydrogen	integrated steam	2050		20			20
food and kindred products	hydrogen	integrated steam	2070				20	
food and kindred products	hydrogen	integrated steam	2045					
food and kindred products	hydrogen	integrated steam	2060					
food and kindred products	hydrogen	integrated steam	2050					

food and kindred products	electricity	machine drives	2035		100			100
food and kindred products	electricity	machine drives	2055				100	
food and kindred products	electricity	machine drives	2030					
food and kindred products	electricity	machine drives	2045					
food and kindred products	electricity	machine drives	2035					
food and kindred products	electricity	other	2050		75			75
food and kindred products	electricity	other	2070				75	
food and kindred products	electricity	other	2045					
food and kindred products	electricity	other	2060					
food and kindred products	electricity	other	2050					
food and kindred products	electricity	refrigeration	2040		100			100
food and kindred products	electricity	refrigeration	2060				100	
food and kindred products	electricity	refrigeration	2040					
food and kindred products	electricity	refrigeration	2040					
food and kindred products	electricity	refrigeration	2040					
food and kindred products	electricity	support	2050		75			75
food and kindred products	electricity	support	2070				75	
food and kindred products	electricity	support	2045					
food and kindred products	electricity	support	2060					
food and kindred products	electricity	support	2050					
food and kindred products	electricity	transport	2045		80			80
food and kindred products	electricity	transport	2065				80	
food and kindred products	electricity	transport	2040					
food and kindred products	electricity	transport	2055					
food and kindred products	electricity	transport	2045					
food and kindred products	hydrogen	transport	2050		20			20
food and kindred products	hydrogen	transport	2070				20	
food and kindred products	hydrogen	transport	2045					
food and kindred products	hydrogen	transport	2060					
food and kindred products	hydrogen	transport	2050					
freight rail	electricity	all	2050		20			20
freight rail	electricity	all	2070				20	
freight rail	electricity	all	2045					
freight rail	electricity	all	2060					
freight rail	electricity	all	2050					
freight rail	hydrogen	all	2050		70			70
freight rail	hydrogen	all	2070				70	
freight rail	hydrogen	all	2045					
freight rail	hydrogen	all	2060					
freight rail	hydrogen	all	2050					

glass and glass products	electricity	heat	2050		25			25
glass and glass products	electricity	heat	2070				25	
glass and glass products	electricity	heat	2045					
glass and glass products	electricity	heat	2060					
glass and glass products	hydrogen	heat	2050		25			25
glass and glass products	hydrogen	heat	2070				25	
glass and glass products	hydrogen	heat	2045					
glass and glass products	hydrogen	heat	2060					
glass and glass products	hydrogen	heat	2050					
glass and glass products	electricity	hvac	2050		90			90
glass and glass products	electricity	hvac	2070				90	
glass and glass products	electricity	hvac	2045					
glass and glass products	electricity	hvac	2060					
glass and glass products	electricity	hvac	2050					
glass and glass products	electricity	integrated steam	2045		50			50
glass and glass products	electricity	integrated steam	2065				50	
glass and glass products	electricity	integrated steam	2045					
glass and glass products	electricity	integrated steam	2060					
glass and glass products	electricity	integrated steam	2045					
glass and glass products	hydrogen	integrated steam	2050		20			20
glass and glass products	hydrogen	integrated steam	2070				20	
glass and glass products	hydrogen	integrated steam	2045					
glass and glass products	hydrogen	integrated steam	2060					
glass and glass products	hydrogen	integrated steam	2050					
international shipping	ammonia	all	2050		60			60
international shipping	ammonia	all	2070				60	
international shipping	ammonia	all	2045					
international shipping	ammonia	all	2060					
international shipping	ammonia	all	2050					
international shipping	hydrogen	all	2050		20			20
international shipping	hydrogen	all	2070				20	
international shipping	hydrogen	all	2045					
international shipping	hydrogen	all	2060					
international shipping	hydrogen	all	2050					
iron and steel	hydrogen	heat	2050		100			100
iron and steel	hydrogen	heat	2070				100	
iron and steel	hydrogen	heat	2045					
iron and steel	hydrogen	heat	2060					
iron and steel	hydrogen	heat	2050					
iron and steel	electricity	hvac	2050		100			100

iron and steel	electricity	hvac	2070				100	
iron and steel	electricity	hvac	2045					
iron and steel	electricity	hvac	2060					
iron and steel	electricity	hvac	2050					
iron and steel	electricity	machine drives	2050		100			100
iron and steel	electricity	machine drives	2070				100	
iron and steel	electricity	machine drives	2045					
iron and steel	electricity	machine drives	2060					
iron and steel	electricity	machine drives	2050					
iron and steel	electricity	other	2050		3			3
iron and steel	electricity	other	2070				3	
iron and steel	electricity	other	2045					
iron and steel	electricity	other	2060					
iron and steel	electricity	other	2050					
iron and steel	hydrogen	other	2050		97			97
iron and steel	hydrogen	other	2070				97	
iron and steel	hydrogen	other	2045					
iron and steel	hydrogen	other	2060					
iron and steel	hydrogen	other	2050					
iron and steel	electricity	transport	2045		80			80
iron and steel	electricity	transport	2065				80	
iron and steel	electricity	transport	2040					
iron and steel	electricity	transport	2055					
iron and steel	electricity	transport	2045					
machinery	electricity	heat	2050		100			100
machinery	electricity	heat	2070				100	
machinery	electricity	heat	2045					
machinery	electricity	heat	2060					
machinery	electricity	heat	2050					
machinery	hydrogen	heat	2050					
machinery	electricity	hvac	2050		90			90
machinery	electricity	hvac	2070				90	
machinery	electricity	hvac	2045					
machinery	electricity	hvac	2060					
machinery	electricity	hvac	2050					
machinery	electricity	integrated steam	2045		50			50
machinery	electricity	integrated steam	2065				50	
machinery	electricity	integrated steam	2045					
machinery	electricity	integrated steam	2060					
machinery	electricity	integrated steam	2045					

machinery	hydrogen	integrated steam	2050		20			20
machinery	hydrogen	integrated steam	2070				20	
machinery	hydrogen	integrated steam	2045					
machinery	hydrogen	integrated steam	2060					
machinery	hydrogen	integrated steam	2050					
machinery	electricity	machine drives	2035		100			100
machinery	electricity	machine drives	2055				100	
machinery	electricity	machine drives	2030					
machinery	electricity	machine drives	2045					
machinery	electricity	machine drives	2035					
machinery	electricity	other	2050		75			75
machinery	electricity	other	2070				75	
machinery	electricity	other	2045					
machinery	electricity	other	2060					
machinery	electricity	other	2050					
machinery	electricity	refrigeration	2040		100			100
machinery	electricity	refrigeration	2060				100	
machinery	electricity	refrigeration	2040					
machinery	electricity	refrigeration	2040					
machinery	electricity	refrigeration	2040					
machinery	electricity	support	2050		75			75
machinery	electricity	support	2070				75	
machinery	electricity	support	2045					
machinery	electricity	support	2060					
machinery	electricity	support	2050					
machinery	electricity	transport	2045		80			80
machinery	electricity	transport	2065				80	
machinery	electricity	transport	2040					
machinery	electricity	transport	2055					
machinery	electricity	transport	2045					
machinery	hydrogen	transport	2050		20			20
machinery	hydrogen	transport	2070				20	
machinery	hydrogen	transport	2045					
machinery	hydrogen	transport	2060					
machinery	hydrogen	transport	2050					
metal and other non-metallic mining	electricity	mining	2040		80			80
metal and other non-metallic mining	electricity	mining	2060				80	
metal and other non-metallic mining	electricity	mining	2040					
metal and other non-metallic mining	electricity	mining	2040					
metal and other non-metallic mining	electricity	mining	2040					

metal and other non-metallic mining	hydrogen	mining	2045		20			20
metal and other non-metallic mining	hydrogen	mining	2065				20	
metal and other non-metallic mining	hydrogen	mining	2045					
metal and other non-metallic mining	hydrogen	mining	2060					
metal and other non-metallic mining	hydrogen	mining	2045					
motorcycles	electricity	all	2040		100			100
motorcycles	electricity	all	2060				100	
paper and allied products	electricity	heat	2050		100			100
paper and allied products	electricity	heat	2070				100	
paper and allied products	electricity	heat	2045					
paper and allied products	electricity	heat	2060					
paper and allied products	electricity	heat	2050					
paper and allied products	hydrogen	heat	2050					
paper and allied products	electricity	hvac	2050		90			90
paper and allied products	electricity	hvac	2070				90	
paper and allied products	electricity	hvac	2045					
paper and allied products	electricity	hvac	2060					
paper and allied products	electricity	hvac	2050					
paper and allied products	electricity	integrated steam	2045		50			50
paper and allied products	electricity	integrated steam	2065				50	
paper and allied products	electricity	integrated steam	2045					
paper and allied products	electricity	integrated steam	2060					
paper and allied products	electricity	integrated steam	2045					
paper and allied products	hydrogen	integrated steam	2050		20			20
paper and allied products	hydrogen	integrated steam	2070				20	
paper and allied products	hydrogen	integrated steam	2045					
paper and allied products	hydrogen	integrated steam	2060					
paper and allied products	hydrogen	integrated steam	2050					
paper and allied products	electricity	support	2050		75			75
paper and allied products	electricity	support	2070				75	
paper and allied products	electricity	support	2045					
paper and allied products	electricity	support	2060					
paper and allied products	electricity	support	2050					
paper and allied products	electricity	transport	2045		80			80
paper and allied products	electricity	transport	2065				80	
paper and allied products	electricity	transport	2040					
paper and allied products	electricity	transport	2055					
paper and allied products	electricity	transport	2045					
paper and allied products	hydrogen	transport	2050		20			20
paper and allied products	hydrogen	transport	2070				20	

paper and allied products	hydrogen	transport	2045					
paper and allied products	hydrogen	transport	2060					
paper and allied products	hydrogen	transport	2050					
passenger rail	electricity	all	2035		80			80
passenger rail	electricity	all	2055				80	
passenger rail	electricity	all	2035					
passenger rail	electricity	all	2035					
passenger rail	electricity	all	2035					
passenger rail	hydrogen	all	2045		20			20
passenger rail	hydrogen	all	2065				20	
passenger rail	hydrogen	all	2045					
passenger rail	hydrogen	all	2060					
passenger rail	hydrogen	all	2045					
plastic and rubber products	electricity	heat	2050		100			100
plastic and rubber products	electricity	heat	2070				100	
plastic and rubber products	electricity	heat	2045					
plastic and rubber products	electricity	heat	2060					
plastic and rubber products	electricity	heat	2050					
plastic and rubber products	hydrogen	heat	2050					
plastic and rubber products	electricity	hvac	2050		90			90
plastic and rubber products	electricity	hvac	2070				90	
plastic and rubber products	electricity	hvac	2045					
plastic and rubber products	electricity	hvac	2060					
plastic and rubber products	electricity	hvac	2050					
plastic and rubber products	electricity	integrated steam	2045		50			50
plastic and rubber products	electricity	integrated steam	2065				50	
plastic and rubber products	electricity	integrated steam	2045					
plastic and rubber products	electricity	integrated steam	2060					
plastic and rubber products	electricity	integrated steam	2045					
plastic and rubber products	hydrogen	integrated steam	2050		20			20
plastic and rubber products	hydrogen	integrated steam	2070				20	
plastic and rubber products	hydrogen	integrated steam	2045					
plastic and rubber products	hydrogen	integrated steam	2060					
plastic and rubber products	hydrogen	integrated steam	2050					
plastic and rubber products	electricity	machine drives	2035		100			100
plastic and rubber products	electricity	machine drives	2055				100	
plastic and rubber products	electricity	machine drives	2030					
plastic and rubber products	electricity	machine drives	2045					
plastic and rubber products	electricity	machine drives	2035					
plastic and rubber products	electricity	other	2050		75			75

plastic and rubber products	electricity	other	2070				75	
plastic and rubber products	electricity	other	2045					
plastic and rubber products	electricity	other	2060					
plastic and rubber products	electricity	other	2050					
plastic and rubber products	electricity	support	2050		75			75
plastic and rubber products	electricity	support	2070				75	
plastic and rubber products	electricity	support	2045					
plastic and rubber products	electricity	support	2060					
plastic and rubber products	electricity	support	2050					
plastic and rubber products	electricity	transport	2045		80			80
plastic and rubber products	electricity	transport	2065				80	
plastic and rubber products	electricity	transport	2040					
plastic and rubber products	electricity	transport	2055					
plastic and rubber products	electricity	transport	2045					
plastic and rubber products	hydrogen	transport	2050		20			20
plastic and rubber products	hydrogen	transport	2070				20	
plastic and rubber products	hydrogen	transport	2045					
plastic and rubber products	hydrogen	transport	2060					
plastic and rubber products	hydrogen	transport	2050					
recreational boats	electricity	all	2050		16			16
recreational boats	electricity	all	2050		64			64
recreational boats	electricity	all	2070				16	
recreational boats	electricity	all	2070				64	
recreational boats	electricity	all	2045					
recreational boats	electricity	all	2045					
recreational boats	electricity	all	2060					
recreational boats	electricity	all	2060					
recreational boats	electricity	all	2050					
recreational boats	hydrogen	all	2050		64			64
recreational boats	hydrogen	all	2050		16			16
recreational boats	hydrogen	all	2070				64	
recreational boats	hydrogen	all	2070				16	
recreational boats	hydrogen	all	2045					
recreational boats	hydrogen	all	2045					
recreational boats	hydrogen	all	2060					
recreational boats	hydrogen	all	2060					
recreational boats	hydrogen	all	2050					
residential other uses	electricity	all	2045		90			90
residential other uses	electricity	all	2065				90	
residential other uses	electricity	all	2045					

residential other uses	electricity	all	2060					
residential other uses	electricity	all	2045					
residential secondary heating	electricity	all	2045		80			80
residential secondary heating	electricity	all	2065				80	
residential secondary heating	electricity	all	2045					
residential secondary heating	electricity	all	2060					
residential secondary heating	electricity	all	2045					
transportation equipment	electricity	heat	2050		100			100
transportation equipment	electricity	heat	2070				100	
transportation equipment	electricity	heat	2045					
transportation equipment	electricity	heat	2060					
transportation equipment	electricity	heat	2050					
transportation equipment	hydrogen	heat	2050					
transportation equipment	electricity	hvac	2050		90			90
transportation equipment	electricity	hvac	2070				90	
transportation equipment	electricity	hvac	2045					
transportation equipment	electricity	hvac	2060					
transportation equipment	electricity	hvac	2050					
transportation equipment	electricity	integrated steam	2045		50			50
transportation equipment	electricity	integrated steam	2065				50	
transportation equipment	electricity	integrated steam	2045					
transportation equipment	electricity	integrated steam	2060					
transportation equipment	electricity	integrated steam	2045					
transportation equipment	hydrogen	integrated steam	2050		20			20
transportation equipment	hydrogen	integrated steam	2070				20	
transportation equipment	hydrogen	integrated steam	2045					
transportation equipment	hydrogen	integrated steam	2060					
transportation equipment	hydrogen	integrated steam	2050					
transportation equipment	electricity	machine drives	2035		100			100
transportation equipment	electricity	machine drives	2055				100	
transportation equipment	electricity	machine drives	2030					
transportation equipment	electricity	machine drives	2045					
transportation equipment	electricity	machine drives	2035					
transportation equipment	electricity	other	2050		75			75
transportation equipment	electricity	other	2070				75	
transportation equipment	electricity	other	2045					
transportation equipment	electricity	other	2060					
transportation equipment	electricity	other	2050					
transportation equipment	electricity	refrigeration	2040		100			100
transportation equipment	electricity	refrigeration	2060				100	

transportation equipment	electricity	refrigeration	2040					
transportation equipment	electricity	refrigeration	2040					
transportation equipment	electricity	refrigeration	2040					
transportation equipment	electricity	support	2050		75			75
transportation equipment	electricity	support	2070				75	
transportation equipment	electricity	support	2045					
transportation equipment	electricity	support	2060					
transportation equipment	electricity	support	2050					
transportation equipment	electricity	transport	2045		80			80
transportation equipment	electricity	transport	2065				80	
transportation equipment	electricity	transport	2040					
transportation equipment	electricity	transport	2055					
transportation equipment	electricity	transport	2045					
transportation equipment	hydrogen	transport	2050		20			20
transportation equipment	hydrogen	transport	2070				20	
transportation equipment	hydrogen	transport	2045					
transportation equipment	hydrogen	transport	2060					
transportation equipment	hydrogen	transport	2050					
wood products	electricity	heat	2050		100			100
wood products	electricity	heat	2070				100	
wood products	electricity	heat	2045					
wood products	electricity	heat	2060					
wood products	electricity	heat	2050					
wood products	hydrogen	heat	2050					
wood products	electricity	hvac	2050		90			90
wood products	electricity	hvac	2070				90	
wood products	electricity	hvac	2045					
wood products	electricity	hvac	2060					
wood products	electricity	hvac	2050					
wood products	electricity	integrated steam	2045		50			50
wood products	electricity	integrated steam	2065				50	
wood products	electricity	integrated steam	2045					
wood products	electricity	integrated steam	2060					
wood products	electricity	integrated steam	2045					
wood products	hydrogen	integrated steam	2050		20			20
wood products	hydrogen	integrated steam	2070				20	
wood products	hydrogen	integrated steam	2045					
wood products	hydrogen	integrated steam	2060					
wood products	hydrogen	integrated steam	2050					
wood products	electricity	machine drives	2035		100			100

wood products	electricity	machine drives	2055				100	
wood products	electricity	machine drives	2030					
wood products	electricity	machine drives	2045					
wood products	electricity	machine drives	2035					
wood products	electricity	other	2050		75			75
wood products	electricity	other	2070				75	
wood products	electricity	other	2045					
wood products	electricity	other	2060					
wood products	electricity	other	2050					
wood products	electricity	refrigeration	2040		100			100
wood products	electricity	refrigeration	2060				100	
wood products	electricity	refrigeration	2040					
wood products	electricity	refrigeration	2040					
wood products	electricity	refrigeration	2040					
wood products	electricity	transport	2045		80			80
wood products	electricity	transport	2065				80	
wood products	electricity	transport	2040					
wood products	electricity	transport	2055					
wood products	electricity	transport	2045					
wood products	hydrogen	transport	2050		20			20
wood products	hydrogen	transport	2070				20	
wood products	hydrogen	transport	2045					
wood products	hydrogen	transport	2060					
wood products	hydrogen	transport	2050					

1.7.1.3. Service Reductions in Low Demand Scenario

Table 9 shows energy service reductions in the Low Demand scenario. Reductions were assumed to increase linearly to 2050.

Table 9 Service demand reductions to 2050 for the Low Demand scenario

Sector	Subsector	2050 Service Reduction
commercial	commercial air conditioning	20%
commercial	commercial cooking	0%
commercial	commercial lighting	20%
commercial	commercial other	20%
commercial	commercial refrigeration	0%
commercial	commercial space heating	20%
commercial	commercial ventilation	20%

Sector	Subsector	2050 Service Reduction
commercial	commercial water heating	0%
commercial	district services	20%
commercial	office equipment (non-p.c.)	0%
commercial	office equipment (p.c.)	0%
productive	agriculture-crops	20%
productive	agriculture-other	20%
productive	aluminum industry	20%
productive	balance of manufacturing other	20%
productive	bulk chemicals	20%
productive	cement	50%
productive	computer and electronic products	20%
productive	construction	20%
productive	electrical equip., appliances, and components	20%
productive	fabricated metal products	20%
productive	food and kindred products	20%
productive	glass and glass products	20%
productive	iron and steel	20%
productive	lime	20%
productive	machinery	20%
productive	metal and other non-metallic mining	20%
productive	Other Non-Energy CO2	20%
productive	paper and allied products	20%
productive	plastic and rubber products	20%
productive	transportation equipment	20%
productive	wood products	20%
residential	residential air conditioning	20%
residential	residential clothes drying	0%
residential	residential clothes washing	0%
residential	residential computers and related	0%
residential	residential cooking	0%
residential	residential dishwashing	0%
residential	residential freezing	0%
residential	residential furnace fans	20%
residential	residential lighting	20%
residential	residential other uses	20%
residential	residential refrigeration	0%
residential	residential secondary heating	20%
residential	residential space heating	20%
residential	residential televisions and related	20%

Sector	Subsector	2050 Service Reduction
residential	residential water heating	0%
transportation	aviation	20%
transportation	domestic shipping	20%
transportation	freight rail	20%
transportation	heavy duty trucks	20%
transportation	international shipping	20%
transportation	light duty autos	40%
transportation	light duty trucks	40%
transportation	lubricants	20%
transportation	medium duty trucks	20%
transportation	military use	20%
transportation	motorcycles	20%
transportation	passenger rail	0%
transportation	recreational boats	20%
Transportation	buses	0%

1.7.2. RIO Scenario Parameters

Economy-wide portfolios are selected using the RIO optimization to meet energy demand and economy-wide emissions constraints at least cost. The composition of the optimized portfolio is determined by the emissions constraint, in combination with land/resource constraints, imposed cost penalties or assumed breakthroughs, and other inputs such as technology availability. Table 9 shows the assumptions used for each scenario, identified where they deviate from **Central** scenario assumptions.

Table 10 RIO Scenario parameters

Scenario Name	Additional Land/Resource Constraints[2]	IRA Tax Credits Included	Emissions Targets
central	Reference supply curves	Yes	Zero net annual CO_2e in 2050 - straight-line reduction path from today
central 50x30			Zero net annual CO_2e in 2050 – 50% reduction by 2030 and then straight-line path to 2050
central no IRA		No	
IRA			None

[2] Detailed table with technology growth rates provided in ADP 2023 Main Report.

Scenario Name	Additional Land/Resource Constraints[2]	IRA Tax Credits Included	Emissions Targets
low land	18 Mha (50% of optimized **central** scenario land use). 2.3% of all U.S. land.		
baseline		No	None
100% renewables	No fossil fuel or uranium available by 2050		
low demand			
drop-in	Max build constraints: Utility PV 15 GW/year; Onshore wind 7.5 GW/year; Offshore wind 7.5 GW/year.		
slow consumer uptake			

S2. Data

The database used in this analysis to represent the United States energy economy has high geographical resolution for technology stocks; technology cost and performance; built infrastructure and resource potential, and high temporal resolution for electricity loads by end-use and for renewable (wind and solar) 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 65 energy-using demand subsectors. *Subsectors*, such as residential space heating, refer to energy use associated with the delivery of an energy service. A detailed description of the methods EnergyPATHWAYS uses to project energy-service demand, energy demand, and ultimately cost and emissions associated with the performance of that service is found below in section S3. The general approach is described above in sections 1.1.1 and 3.3.3.

2.1. Demand–Side Data Description

Table 10 lists all the subsectors in the U.S. Database, grouped by demand sector. It also specifies the methods (A, B, C, D) used to calculate energy demand in each subsector. These methods are described in detail in section 3.3.3.

Table 11 Sectors, subsectors, and methods of energy demand projection

Sector	Subsector	Method
residential	residential water heating	B
residential	residential furnace fans	D
residential	residential clothes drying	B
residential	residential dishwashing	B
residential	residential refrigeration	B
residential	residential freezing	B
residential	residential cooking	B
residential	residential secondary heating	D
residential	residential other appliances	D
residential	residential clothes washing	B
residential	residential lighting	B
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

Sector	Subsector	Method
transportation	light duty autos	A
productive	metal and other non-metallic mining	D
productive	aluminum industry	D
productive	balance of manufacturing other	D
productive	plastic and rubber products	D
productive	wood products	D
productive	bulk chemicals	D
productive	glass and glass products	D
productive	cement	D
productive	agriculture-other	D
productive	agriculture-crops	D
productive	fabricated metal products	D
productive	machinery	D
productive	computer and electronic products	D
productive	transportation equipment	D
productive	construction	D
productive	iron and steel	D
productive	food and kindred products	D
productive	paper and allied products	D
productive	electrical equip., appliances, and components	D

The methods for representing demand-side subsectors are described in section S3. Table 11 describes the input data used to populate stock representations in the subsectors that employ Method A and Method B (3.3.3.1, 3.3.3.2), and Table 12 describes the energy service demand inputs for these subsectors.

Table 12 Demand stock data for Method A/B Subsectors

Subsector	Input Unit	Stock Unit	Service Demand Dependent	Driver	Input Data: Geography	Input Data: Year(s)	Additional Detail	Source
Residential Lighting	Bulbs	Bulbs	No	Households	Census division	2015-2050	Housing types; Lighting category	(38)
Residential Clothes Washing	Clothes washer	Clothes washer	No	Households	Census division	2015-2050	Housing types	(38)
Residential Clothes Drying	Clothes dryer	Clothes dryer	No	Households	Census division	2015-2050	Housing types	(38)
Residential Dishwashing	Dishwasher	Dishwasher	No	Households	Census division	2015-2050	Housing types	(38)

Subsector	Input Unit	Stock Unit	Service Demand Dependent	Driver	Input Data: Geography	Input Data: Year(s)	Additional Detail	Source
Residential Refrigeration	Refrigerator	Refrigerator	No	Households	Census division	2015-2050	Housing types	(38)
Residential Freezing	Freezer	Freezer	No	Households	Census division	2015-2050	Housing types	(38)
Residential Water Heating	Water heater	Water heater	No	Households; Residential Heating Energy Share	Census division	2015-2050	Housing types	(38)
Residential Space Heating	Space heater	Space heater	No	Households; Residential Heating Energy Share	Census division	2015-2050	Housing types	(38)
Residential Air Conditioning	Air conditioner	Air conditioner	No	Households; Average Household Income	Census division	2015-2050	Housing types	(38)
Residential Cooking	Cooktop	Cooktop	No	Households; Residential Heating Energy Share	Census division	2015-2050	Housing types	(38)
Commercial Water Heating	Capacity factor	Btu/Hour	Yes		Census division	2012	Building types	(38)
Commercial Space Heating	Capacity factor	Btu/hour	Yes		Census division	2012	Building types	(38)
Commercial Air Conditioning	Capacity factor	Btu/hour	Yes		Census division	2012	Building types	(38)
Commercial Lighting	Capacity factor	Lumen/hour	Yes		Census division	2012	Building types	(38)
Commercial Refrigeration	Capacity factor	Btu/hour	Yes		Census division	2012	Building types	(38)
Commercial Cooking	Capacity factor	Btu/hour	Yes		Census division	2012	Building types	(38)
Commercial Ventilation	Capacity factor	Cubic-Foot/hour	Yes		Census division	2012	Building types	(38)
Light Duty Autos	Car	Car	No		US*	2015-2050		(38)
Light Duty Trucks	Truck	Truck	No		US*	2015-2050		(38)
Medium Duty Trucks	Truck	Truck	No		US*	2015-2050		(38)
Heavy Duty Trucks	Truck	Truck	No		US*	2015-2050		(38)
Buses	Bus	Bus	Yes		State	2014	Bus types	(8)

* Downscaled with vehicle registrations

Table 13 Energy/Service demand inputs for Method A/B Subsectors

Subsector	Input Unit	Service Demand Unit	Stock Dependent	Driver	Input Data: Geography	Input Data: Year(s)	Additional Detail	Source
Residential Lighting	Btu	Lumen-hour	No	Total square feet	US	2012	Lighting category	(38)
Residential Clothes Washing	Btu	Cubic foot-cycle	No	n/a	Census division	2009	Housing types	(38)
Residential Clothes Drying	Btu	Lbs.	No	n/a	Census division	2009	Housing types	(38)
Residential Dishwashing	Btu	Cycle	No	n/a	Census division	2009	Housing types	(38)
Residential Refrigeration	Btu	Cubic foot	No	n/a	Census division	2009	Housing types	(38)
Residential Freezing	Btu	Cubic foot	No	n/a	Census division	2009	Housing types	(38)
Residential Water Heating	Btu	Btu	No	Households; Residential Heating Energy Share	Census division	2015-2050	Housing types	(38)
Residential Space Heating	Btu	Btu	No	Households; Residential Heating Energy Share; Heating Degree Days	Census division	2015-2050	Housing types	(38)
Residential Air Conditioning	Btu	Btu	No	Households; Cooling Degree Days; House Age Index	Census division	2015-2050	Housing types	(38)
Residential Cooking	Btu	Btu	No	Households; Residential Heating Energy Share	Census division	2015-2050	Housing types	(38)
Commercial Refrigeration	Btu	Btu	No	Commercial square feet	Census division	2013 - 2050	Building types	(38)
Commercial Cooking	Btu	Btu	No	Commercial square feet	Census division	2013 - 2050	Building types	(38)
Commercial Ventilation	Cubic Foot	Cubic Foot	No	Commercial square feet	Census division	2013 - 2050	Building types	(38)
Light Duty Autos	Mile	Mile	No	LDA VMT	US	2015-2050		(38)
Light Duty Trucks	Mile	Mile	No	LDT VMT	US	2015-2050		(38)
Medium Duty Trucks	Mile	Mile	No	MDV VMT	US	2015-2050		(38)
Heavy Duty Trucks	Mile	Mile	No	HDV VMT	US	2015-2050		(38)
Buses	Mile	Mile	No	Population	State	2014	Bus Category	(36)

Demand subsectors with technology stocks also require technology-specific parameters for cost and performance. These input sources by subsector and technology-type are shown in Table 13.

Table 14 Demand technology inputs for Method A/B subsectors

Subsector	Technologies	Source
Residential Space Heating and Air Conditioning	Air source heat pump (ducted)	Cost: EER Analysis, (26) Efficiency: (17)
	Remainder	(26)
Residential Water Heating	Heat pump water heater	Cost: (26) Efficiency: (17)
	Remainder	(26)
Residential Remaining Stock Subsectors	All	(26)
Commercial Space Heating and Air Conditioning	Air source heat pump	Cost: (26) Efficiency: (17)
	Remainder	(26)
Commercial Water Heating	Heat pump water heater	Cost: (26) Efficiency: (17)
	Remainder	(26)
Commercial Lighting	All	(36)
Commercial Remaining Stock Subsectors	All	(26)
Light-duty Vehicles	Battery electric vehicle and plug-in hybrid electric vehicle	Cost: (11, 22, 17) Efficiency: (17)
	Remainder	Efficiency: (38) Cost: (38)
Medium Duty Vehicles	Battery electric	(17)
	Hydrogen fuel cell	(7)
	Remainder (CNG, diesel, etc.)	(29)
Heavy Duty Vehicles	Battery electric	(17)
	Hydrogen fuel cell	(14)
	Reference diesel, gasoline and propane	(29)
	Diesel hybrid and liquefied pipeline gas	(29)
Transit Buses	All	(17, 8)

Table 14 shows the data sources for service demand projections for subsectors represented with Method C (3.3.3.3), and Table 15 shows the data sources for service efficiency for these subsectors.

Table 16 shows baseline energy demand projection input data sources for subsectors employing Method D (3.3.3.4).

Table 15 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	Btu	Households	Census division		2015-2050	Housing types; Computer equipment types	(38)
Residential televisions and related	Btu	Households	Census division		2015-2050	Housing types; Television equipment types	(38)
Residential Secondary Heating	Btu	Households; HDD	Census division		2015-2050	Housing types	(38)
Residential other uses	Btu	Households	Census division		2015-2050	Housing types; Other equipment types	(38)
Residential Furnace Fans	Btu	Households	Census division		2015-2050	Housing types	(38)
Office Equipment (P.C.)	Btu	Commercial square footage	US		2015-2050		(38)
Office Equipment (Non-P.C.)	Btu	Commercial square footage	US	Employment in all industries (NAICS, no code) 2007	2015-2050		(38)
Commercial Other	Btu	Commercial square footage	Census Division	Employment in all industries (NAICS, no code) 2007	2015-2050	Building Types	(38)
Non-CHP District Services	Btu	Commercial square footage	Census division	Households 2010	2012	Building Types	(36)
CHP District Services	Btu	Commercial square footage	Census Division	Households 2010	2015-2050	Building types	(38)
Domestic Shipping	Btu	Vessel Bunkering Sales	US		2021-2050		(38)
Military Use	Btu	Jet Fuel Sales	US		2021-2050		(38)
Motorcycles	Btu	Motorcycle VMT	US		2021-2050		(38)
Lubricants	Btu	Population	US		2021-2050		(38)
International Shipping	Btu	Vessel Bunkering Sales	US		2021-2050		(38)
Recreational Boats	Btu		US	Households 2010	2021-2050		(38)
Passenger rail	Btu	Rail passenger miles	Census division	Rail Fuel Use	2021-2050	Passenger rail mode (commuter, intercity, transit)	(38)
Freight rail	Btu	Historical non-coal freight miles	Census division	Rail Fuel Use	2021-2050		(38)
Aviation	Btu	Passenger-mile departures	US		2021-2050		(38)
Agriculture – Crops	Btu	Industrial Energy Data Book	Census region		2015 – 2050	Industrial end-use category	(38)

Subsector	Unit	Driver	Input Data: Geography	Other Downscaling method	Input Data: Year(s)	Additional Detail	Source
Agriculture – Other	Btu	Industrial Energy Data Book	Census region		2015-2050	Industrial end-use category	(38)
Aluminum Industry	Btu	Industrial Energy Data Book	Census region		2015-2050	Industrial end-use category	(38)
Balance of Manufacturing Other	Btu	Industrial Energy Data Book	Census region		2015-2050	Industrial end-use category	(38)
Bulk Chemicals	Btu	Industrial Energy Data Book	Census region		2015-2050	Industrial end-use category	(38)
Cement	Btu	Industrial Energy Data Book	Census region		2015-2050	Industrial end-use category	(38)
Computer and Electronic Products	Btu	Industrial Energy Data Book	Census region		2015-2050	Industrial end-use category	(38)
Construction	Btu	Industrial Energy Data Book	Census region		2015-2050	Industrial end-use category	(38)
Electrical Equip., Appliances, and Components	Btu	Industrial Energy Data Book	Census region		2015-2050	Industrial end-use category	(38)
Fabricated Metal Products	Btu	Industrial Energy Data Book	Census region		2015-2050	Industrial end-use category	(38)
Food and Kindred Products	Btu	Industrial Energy Data Book	Census region		2015-2050	Industrial end-use category	(38)
Glass and Glass Products	Btu	Industrial Energy Data Book	Census region		2015-2050	Industrial end-use category	(38)
Iron and Steel	Btu	Industrial Energy Data Book	Census region		2015-2050	Industrial end-use category	(38)
Lime	Btu	Industrial Energy Data Book	Census region		2015-2050	Industrial end-use category	(38)
Machinery	Btu	Industrial Energy Data Book	Census region		2015-2050	Industrial end-use category	(38)
Metal and Other Non-metallic Mining	Btu	Industrial Energy Data Book	Census region		2015-2050	Industrial end-use category	(38)
Paper and Allied products	Btu	Industrial Energy Data Book	Census region		2015-2050	Industrial end-use category	(38)
Plastic and Rubber Products	Btu	Industrial Energy Data Book	Census region		2015-2050	Industrial end-use category	(38)

Subsector	Unit	Driver	Input Data: Geography	Other Downscaling method	Input Data: Year(s)	Additional Detail	Source
Transportation Equipment	Btu	Industrial Energy Data Book	Census region		2015-2050	Industrial end-use category	(38)
Wood products	Btu	Industrial Energy Data Book	Census region		2015-2050	Industrial end-use category	(38)

Energy service demand in the model in general is taken from the AEO. In cases where additional granularity is needed for downscaling or to show an underlying trend, *demand drivers* are used (listed as 'driver' in the tables above and below). Table 17 describes the data used for this purpose including the original level of geographical granularity. This data is then mapped to the model's selected geographies as required.

Table 16 Demand Drivers

Driver	Geographic Granularity	Data Year (s)	Additional Detail	Source
Commercial Square Footage	Census Division	2015-2050	Building Types	(38)
Industrial Energy Data Book	County	2018		(48)
Household Heating Fuel Share	State	2017	Housing Type	(31)
House Age Index Share	State	2017		(31)
Heating Degree Days	State	2000; 2017		(25)
Cooling Degree Days	State	2000; 2017		(25)
Households	State	2015-2050	Building Types	(38)
LDV VMT	State	2017		(13)
LDA Registrations	State	2017		(13)
LDT Registration	State	2017		(13)
HDT Registrations	State	2017		(13)
HDV VMT	State	2017		(13)
MDV VMT	State	2017		(13)
Motorcycle VMT	State	2017		(13)

Table 18 shows the data sources for energy service demand load shapes by subsector, which are used to build system-level load shapes bottom-up.

Table 17 Load shape sources

Shape Name	Used By	Input Data Geography	Input Temporal Resolution	Source
Bulk Electricity 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, 2011	(41)
Water Heating (Gas Shape)	Residential hot water	United States	Month, weekday/weekend, hour	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			
com_fuel_electric_heatpump_hybrid	ASHP hybrid electric commercial technologies	IECC Climate Zone by state (114 total geographical regions)	Hourly, 2011 weather	Evolve Energy Research Regressions trained on county level building simulations from ResStock and ComStock
com_general_space_cooling	Commercial air conditioning			
com_general_space_heating	Commercial non-heat pump heating			

Shape Name	Used By	Input Data Geography	Input Temporal Resolution	Source
com_heatpump	Commercial heat pumps			models. Training data for TMY and 2018 use used to produce load data for 2006-2020. Weather year 2011 used for this study.
com_ventilation	Commercial ventilation			
res_fuel_electric_heatpump_hybrid	ASHP hybrid electric residential technologies			
res_furnace_fan	Residential furnace fans			
res_general_space_cooling	Residential air conditioning			
res_general_space_heating	Residential non-heat pump heating			
res_heatpump	Residential heat pumps			
EV	Light duty vehicles, motorcycles			Evolve Energy Research Regressions based on hourly temperature, the evi-pro-lite charging tool, and National Household Transportation Survey data.
MHDV_charging	MDV and HDV charging	United States	Day of week and hour	Lawrence Berkley National Laboratory HEVI-LOAD Tool (79)

*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.

https://www.nrel.gov/buildings/end-use-load-profiles.html

2.2. Supply–Side Data Description

The supply-side data used in RIO has a high-level of geographic granularity in terms of resource availability for biomass, renewable energy, geologic sequestration, etc. It also has very detailed technology representations for both electricity technologies as well non-electricity technologies like fuel conversion, direct air capture, and hydrogen production.

Table 18 Supply-side technology data sources

Sector	Technology	Capital Costs	Fixed OM	Variable OM	Efficiency/Capacity Factor	Resource Potential
Energy	alcohol-to-x	(74)	(74)	(74)	(74)	
Energy	bio-gasification ch4	(15)	(15)	(15)	(15)	

Sector	Technology	Capital Costs	Fixed OM	Variable OM	Efficiency/Capacity Factor	Resource Potential
Energy	bio-gasification ch4 w/cc	(15)	(15)	(15)	(15)	
Energy	bio-gasification fischer-tropsch	(15)	(15)	(15)	(15)	
Energy	bio-gasification fischer-tropsch w/cc	(15)	(15)	(15)	(15)	
Energy	bio-gasification h2 w/cc	(15;52)	(15;52)	(15;52)	(15;52)	
Energy	biomass fast pyrolysis	(46)	(46)	(46)	(46)	
Energy	biomass fast pyrolysis w/cc	(46)	(46)	(46)	(46)	
Energy	biomass power	(24)	(24)	(24)	(24)	
Energy	biomass power allam w/cc	(46)	(46)	(46)	(46)	
Energy	coal w/cc - retrofit	(23)	(23)	(23)	(23)	
Energy	corn ethanol w/cc	(54)	(54)	(54)	(54)	
Energy	direct air capture – solid sorbent	(81)	(81)	(81)	EER Analysis; (80)	
Energy	electric boiler	(41)	(41)	(41)	By Assumption	
Energy	electrolysis h2	(55)	(55)	(55)	(56)	
Energy	fischer-tropsch liquids	(57)	(57)	(57)	(58)	
Energy	gas combined cycle	(23)	(23)	(23)	(23)	
Energy	gas combined cycle w/cc	(23)	(23)	(23)	(23)	
Energy	gas combustion turbine	(23)	(23)	(23)	(23)	
Energy	gas production	None	None	None	(38)	(38)
Energy	gas w/cc - retrofit	(23)	(23)	(23)	(23)	
Energy	h2 boiler	(41)	(41)	(41)	By Assumption	
Energy	h2 storage salt cavern	(60)	(60)	(60)	By Assumption	(60)
Energy	h2 storage underground pipes	(60)	(60)	(60)	By Assumption	
Energy	haber-bosch	(62)	(62)	(62)	(63)	
Energy	heat pump		(41)	(41)	By Assumption	
Energy	HEFA jet fuel	(64)	(64)	(64)	(65)	
Energy	li-ion	(23)	(23)	(23)	(23)	
Energy	lng production	(82)	(82)	(82)	(82)	
Energy	lng production – electric	(82)	(82)	(82)	(82)	
Energy	lng production – electric retrofit	(82)	(82)	(82)	(82)	
Energy	long duration storage	(73)	(73)	(73)	(73)	
Energy	methanation	(57)	(57)	(57)	(57)	
Energy	new stream-reach development	(12)	(12)	(12)	(12)	(12)
Energy	non-powered dams	(12)	(12)	(12)	(12)	(12)
Energy	nuclear smr - reactor	(69)	(69)	(69)	(69)	
Energy	nuclear smr - steam turbine generator	(69)	(69)	(69)	(69)	
Energy	nuclear smr - steam turbine generator retrofit	By Assumption	By Assumptio n	(69)	(69)	

Sector	Technology	Capital Costs	Fixed OM	Variable OM	Efficiency/Capacity Factor	Resource Potential
Energy	nuclear smr - tes	(68)	(68)	(68)	(68)	
Energy	offshore wind	(23)	(23)	(23)	(23)	Princeton Analysis
Energy	oil production					
Energy	onshore wind	(23)	(23)	(23)	(23)	Princeton Analysis
Energy	pipeline gas boiler	(41)	(41)	(41)	By Assumption	
Energy	rooftop solar - com	(23)	(23)	(23)	(23)	
Energy	rooftop solar - pro	(23)	(23)	(23)	(23)	
Energy	rooftop solar - res	(23)	(23)	(23)	(23)	
Energy	steam reforming	(56)	(56)	(56)	(56)	
Energy	steam reforming w/cc	(56)	(56)	(56)	(56)	
Energy	tes	(68)	(68)	(68)	(68)	
Energy	tes - resistor	(68)	(68)	(68)	(68)	
Energy	upgrades to existing hydro	(12)	(12)	(12)	Based on existing hydro	(12)
Energy	utility-scale solar pv	(23)	(23)	(23)	(23)	Princeton Analysis
Iron and Steel	blast furnace	(38)	(38)	(38)	(38)	
Iron and Steel	blast furnace w/cc	(38;20)	(38;20)	(38;20)	(38;20)	
Cement	clinker production - conventional	(75)	(75)	(75)	(75)	
Cement	clinker production - direct separation ccs	(75)	(75)	(75)	(75)	
Cement	clinker production - direct separation ccs retrofit	(75)	(75)	(75)	(75)	
Cement	clinker production - oxyfuel biomass ccs	(75)	(75)	(75)	(75)	
Cement	clinker production - oxyfuel gas ccs	(75)	(75)	(75)	(75)	
Iron and Steel	coke plant w/cc	(38;20;77)	(38;20)	(38;20)	(38;20)	
Iron and Steel	DRI	(38)	(38)	(38)	(76)	
Iron and Steel	EAF	(38)	(38)	(38)	(76)	
Iron and Steel	H2 DRI	(38)	(38)	(38)	(76)	
Lime	lime production - conventional	(38)	(38)	(38)	(38)	
Lime	lime production - direct separation ccs	(38;75)	(38;75)	(38;75)	(38;75)	
Lime	lime production - direct separation ccs retrofit	(38;75)	(38;75)	(38;75)	(38;75)	
Lime	lime production - oxyfuel biomass ccs	(38;75)	(38;75)	(38;75)	(38;75)	
Lime	lime production - oxyfuel gas ccs	(38;75)	(38;75)	(38;75)	(38;75)	

Table 19 RIO Commodity Inputs

Category	Commodity	Potential	Cost
energy system	corn	Existing	By Assumption
energy system	existing herbaceous biomass	(21)	By Assumption
energy system	miscanthus - corn ethanol land	(46)	(46)
energy system	miscanthus - crp land	(46)	(46)
energy system	existing waste biomass	(21)	By Assumption
energy system	existing woody biomass	(21)	By Assumption
energy system	geologic co2 sequestration	(33)	(33)
energy system	coal	(38)	(38)
energy system	AD - LFG	(51)	(51)
energy system	AD - Animal Manure	(51)	(51)
energy system	AD - WRRF	(51)	(51)
energy system	AD - Food Waste	(51)	(51)
energy system	hardwood, lowland logging residues	(21)	(21)
energy system	hardwood, upland logging residues	(21)	(21)
energy system	mixedwood logging residues	(21)	(21)
energy system	softwood, natural logging residues	(21)	(21)
energy system	softwood, planted logging residues	(21)	(21)
energy system	willow	(21)	(21)
energy system	poplar	(21)	(21)
energy system	mixedwood whole trees	(21)	(21)
energy system	softwood, natural whole trees	(21)	(21)
energy system	softwood, planted whole trees	(21)	(21)
energy system	barley straw	(21)	(21)
energy system	hardwood, lowland whole trees	(21)	(21)
energy system	wheat straw	(21)	(21)
energy system	hardwood, upland whole trees	(21)	(21)
energy system	corn stover	(21)	(21)
energy system	sorghum stubble	(21)	(21)
energy system	oats straw	(21)	(21)
energy system	switchgrass	(21)	(21)
energy system	pine	(21)	(21)
energy system	miscanthus	(21)	(21)
energy system	eucalyptus	(21)	(21)
energy system	biomass sorghum	(21)	(21)
energy system	energy cane	(21)	(21)
energy system	cotton gin trash	(21)	(21)
energy system	cotton residue	(21)	(21)
energy system	rice hulls	(21)	(21)

Category	Commodity	Potential	Cost
energy system	rice straw	(21)	(21)
energy system	citrus residues	(21)	(21)
energy system	noncitrus residues	(21)	(21)
energy system	paper and paperboard	(21)	(21)
energy system	plastics	(21)	(21)
energy system	rubber and leather	(21)	(21)
energy system	textiles	(21)	(21)
energy system	tree nut residues	(21)	(21)
energy system	yard trimmings	(21)	(21)
energy system	food waste	(21)	(21)
energy system	other forest residue	(21)	(21)
energy system	primary mill residue	(21)	(21)
energy system	secondary mill residue	(21)	(21)
energy system	sugarcane bagasse	(21)	(21)
energy system	sugarcane trash	(21)	(21)
energy system	other forest thinnings	(21)	(21)
energy system	Soybean oil	(65)	Commodity Indices
energy system	Canola oil	(65)	Commodity Indices
energy system	Corn oil	(65)	Commodity Indices
energy system	Yellow grease	(65)	Commodity Indices
energy system	Tallow	(65)	Commodity Indices
energy system	White grease	(65)	Commodity Indices
energy system	Poultry fat	(65)	Commodity Indices
energy system	Other FOGs	(65)	Commodity Indices
land sector	land sink - baseline	(78)	
land sector	reforestation	(49)	(49)
land sector	fire mgmt	(49)	(49)
land sector	avoided forest conv	(49)	(49)
land sector	urban reforestation	(49)	(49)
land sector	improved plantation	(49)	(49)
land sector	avoided grassland conv	(49)	(49)
land sector	cover crops	(49)	(49)
land sector	alley cropping	(49)	(49)
land sector	windbreaks	(49)	(49)
land sector	grazing optimization	(49)	(49)
land sector	grassland restoration	(49)	(49)
land sector	legumes in pastures	(49)	(49)
land sector	peatland restoration	(49)	(49)
land sector	avoided seagrass loss	(49)	(49)

Category	Commodity	Potential	Cost
land sector	seagrass restoration	(49)	(49)
non-co2	aerosols/meterd dose inhalers: f-gases reductions	(50)	(50)
non-co2	aluminum production: f-gases reductions	(50)	(50)
non-co2	coal mining: ch4 reductions	(50)	(50)
non-co2	croplands: n2o reductions	(50)	(50)
non-co2	electric power systems: f-gases reductions	(50)	(50)
non-co2	fire extinguishers: f-gases reductions	(50)	(50)
non-co2	foam blowing: f-gases reductions	(50)	(50)
non-co2	hcfc-22 production: f-gases reductions	(50)	(50)
non-co2	landfills: ch4 reductions	(50)	(50)
non-co2	livestock: ch4 reductions	(50)	(50)
non-co2	livestock: n2o reductions	(50)	(50)
non-co2	magnesium production: f-gases reductions	(50)	(50)
non-co2	nitric and adipic acid production: n2o reductions	(50)	(50)
non-co2	pv cell manufacturing: f-gases reductions	(50)	(50)
non-co2	refrigeration and air conditioning equipment: f-gases reductions	(50)	(50)
non-co2	rice cultivation: ch4 reductions	(50)	(50)
non-co2	semiconductor manufacturing: f-gases reductions	(50)	(50)
non-co2	solvents: f-gases reductions	(50)	(50)
non-co2	wastewater: ch4 reductions	(50)	(50)
non-co2	wastewater: n2o reductions	(50)	(50)

Table 20 RIO blend delivery cost sources

Blend	Delivery Costs
coal blend	(38)
diesel blend	(38)
gasoline blend	(38)
hydrogen blend	(69)
jet fuel blend	(38)
kerosene blend	(38)
lpg blend	(38)
pipeline gas blend	(38)
fuel oil blend	(38)
electricity	(38)

S3. Models

3.1. RIO

3.1.1. Overview

RIO is a highly temporally-resolved capacity expansion model that is designed to faithfully represent energy systems from today to any imagined future. It does so with an emphasis on flexibility of resource and technology configurations. RIO also includes a parameterization of the land-use and non-energy, non-CO_2 sectors, allowing for the representation of truly economy-wide emissions reduction pathways.

Capacity expansion modeling typically refers to a linear optimization modeling framework that optimizes *investments in* and *operations of* electricity systems; These are forward-looking models that effectively trade off costs in building (i.e. generator investments) and running (i.e. generator fuel costs) the system subject to a variety of constraints including electricity policy and emissions targets. These modeling frameworks have been used in the past for a variety of purposes. Some of the main historical applications of capacity expansion models include:

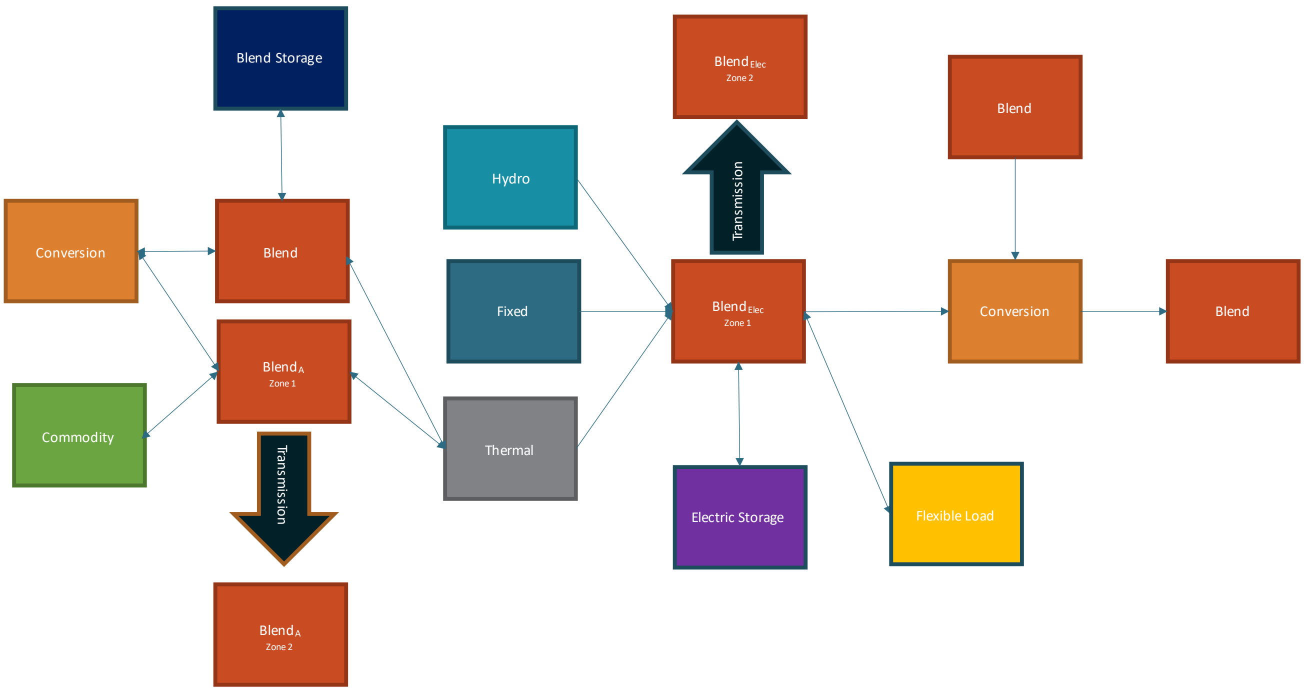
1. Narrow resource-selection decisions
    - Principally an investigation of the cost-effectiveness of individual thermal resources. Highly temporally resolved, but limited in terms of investment decisions. It doesn't ask the question of universal resource selection, but operates as a screening curve for an individual resource.
2. Criteria pollutant analyses.
    - Emphasis on individual plant detail, pollution control equipment, pollution permitting costs, and thermal power plant operations necessary to faithfully represent criteria pollutant emissions.
3. Near-term policy targets.
    - Principally for analysis of RPS policies with up to 50% renewable penetration. These analyses often don't cross thresholds wherein higher temporal resolution becomes critical; the emphasis is on spatially and technologically resolved resource locations, performance, and transmission costs.

The historical applications of capacity expansion matter because the initially intended context and objectives of modeling platforms significantly affect their emphasis and structural design. Capacity expansion modeling is, in principle, simple. Given infinite computing power, all capacity expansion models would be the same. However, in developing real capacity expansion models in a world with computational limits, simplifications have to be made to make a problem tractable without significant deviations from the answer that woud be provided by a theoretically perfect model.

Capacity expansion models designed to answer one set of questions are generally inappropriate for analyzing others. RIO was designed from the ground-up to answer the questions posed by deep decarbonization. In addition to the core elements of any capacity expansion framework (e.g. system reliability), the deep decarbonization emphasis is reflected in the design and features of the RIO model. These include its ability to balance temporal and spatial representations; and economy-wide approach that reduces analytical boundary conditions and identifies unique sector coupling opportunities; and a unique flexibility in technologies. The sections below provide a high-level overview of the analytical framework in RIO.

3.1.2. Model Components

Figure 4 RIO model component schematic



3.1.2.1. Blend

Blends represent aggregation points in the model. The fundamental characteristic of blends is fungibility with regards to inputs. So, for example, pipeline gas (blend) may be decarbonized with a reduction in natural gas being displaced with biogas. This is an altered composition of the inputs to the blend, but the users of that blend are still demanding the same product of pipeline gas, so there is substitutability for inputs while maintaining the same output. These blends are where end-use demands calculated by EnergyPATHWAYS are seen by the model and where intraregional transmission and distribution costs and infrastructure are determined.

- Key Input Characteristics: Costs, Losses, Inputs, Operational Timestep, Physical/Non-Physical
- Ex. Pipeline Gas, Diesel Fuel, CO_2 Utilization, Hydrogen

3.1.2.2. Conversion

Conversions are supply technologies that *convert* blends to other blends. They can be specified with multiple input blends and can themselves be inputs to other blends.

- Key Input Characteristics: Efficiency (input blends), Capital Cost, Fixed OM, Variable OM, Output Blends, Electricity Reliability Required, Operational Timestep, Tradability (between zones)
- Ex. Bio – Fuels, Direct Air Capture, Electrolysis

3.1.2.3. Commodity

Commodities are a model component that can be used in a variety of different ways but are unique in that they are not represented with capacity build decisions. They are instead viewed as discrete products by the model.

- Key Input Characteristics: Potential, Cost, Emissions, Tradability (between zones)
- Ex. Biomass feedstocks, Natural gas primary energy, Geologic sequestration potential

3.1.2.4. Blend Storage

Blend storage technologies allow for the storing of blend throughput where the model is tracking the balance of supply and demand on a sub-annual basis.

- Key Inputs: Capital Cost, Fixed O&M, Variable O&M, Efficiency, Operational Timestep
- Ex. Salt Cavern H2 Storage, Thermal Energy Storage

3.1.2.5. Thermal Power Plant

Thermal powerplants are technologies that take an input of a blend (other than electricity) and produce electricity. They can also have coproducts that are blends. For example, a CHP plant may produce electricity with steam as a coproduct.

- Key Inputs: Capital Cost, Fixed O&M, Variable O&M, Efficiency, Dual Fuel (T/F), Ramp Rate, Min. Annual Capacity Factor, Maximum Annual Capacity Factor, Eligible to Provide Ancillary Services (T/F), Dependability
- Ex. Combined-Cycle Gas Power Plants, Coal Power Plants

3.1.2.6. Fixed Power Plant

Fixed powerplants are technologies that have "fixed" output potential, like wind and solar that dictate their generation of electricity on an hourly basis.

- Key Inputs: Capital Cost, Fixed O&M, Variable O&M, Hourly Capacity Factors, Eligibe to Provide Ancillary Services (T/F)
- Ex. Onshore Wind, Utility-Scale Solar PV

3.1.2.7. Hydro

Hydro powerplants are technologies that can generate electricity between an envelope of minimum and maximum hourly capacity factors with the additional constraint of energy budgets (i.e. cumulative capacity factors) applied over longer timescales.

- Key Inputs: Capital Cost, Fixed O&M, Variable O&M, Hourly Capacity Factors (Min/Max), Energy Budgets, Eligible to Provide Ancillary Services (T/F), Dependability,
- Ex. Dispatchable Hydro

3.1.2.8. Electricity Storage

Electricity storage technologies are those that can charge or discharge electricity hourly.

- Key Inputs: Capital Cost, Fixed O&M, Variable O&M, Efficiency, Self-Discharge Rate, Minimum Duration, Maximum Duration, Eligible to Provide Ancillary Services (T/F)
- Ex. Li-Ion, Vanadium Flow, Long Duration Storage

3.1.2.9. Flexible Load

Flexible loads are able to increment or decrement energy from a base electricity load. They are constrained by maximum hourly increment or decrement amounts and the maximum timescale of the energy shift. For example, if a load (ex. Residential water heating) has a maximum shift of four hours, load decremented in hr_0 would have to be offset by a load increment by hr_4.

- Key Inputs: % of Load Flexible, Maximum Advance (hours), Maximum Delay (hours), Variable Cost (cost of energy deviated from load setpoint).
- Ex. Water Heating, Air Conditioning, Space Heating, Light-Duty Autos, Light-Duty Trucks

3.1.2.10. Transmission

Transmission allows for the transfer of blend throughput from a blend in one zone to a blend in another zone. In practice, transmission functionality is used principally to represent electricity transmission or pipelines.

- Key Inputs: Capital Cost, Fixed O&M, Losses, Operational Timestep, Hurdle Rates, Dependability (Electric Transmission-Only), Deemed Emissions Rates (Electric Transmission-Only)
- Ex. Electricity Transmission, H2 Pipelines, Ammonia Pipelines, CO_2 Pipelines

3.1.3. Temporal Representation

RIO's representation of time is unique in that it can represent both short-term and long-term system operations simultaneously while maintaining problem tractability. This requires compressing the theoretical maximum number of represented time-slices to a more tractable number.

Table 21 Time parameterization examples

Temporal representation	Description	Time Slices
Theoretical Maximum Time Slices	(60s/m*60m/h*8760h/y*30y)	9.46E8

Parameterized Sub-Hourly Resource Performance	RIO parameterizes resource ramp rates and production reliability (wind/solar) to characterize resource performance without explicitly modeling sub-hourly operations	2.63E5
Year Slices	Instead of representing every year, where changes between system conditions and policy might be marginal, RIO establishes a schedule of the most critical years and model these specifically.	6.13E4
Day Sampling/Day Linkages	Instead of representing every hour of the year, we day sample and create a synthetic year of fully-represent days (referred to as samples) and mapped energy balances (referred to as periods) in order to assess long-duration storage	8995

3.1.3.1. Day Sampling

RIO utilizes the 8760 hourly profiles for electricity demand EnergyPATHWAYS, technology-specific generation profiles for wind and solar, 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 challenge of day sampling in any modeling platform is faithfully representing both extreme conditions, which drive investment for system reliability, while also accurately representing annual averages for things like renewable resource capacity factors. 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.

RIO automates the day sampling for every model year based on inputs supplied in the model setup process. The parameters used for day binning are shown in Table 22.

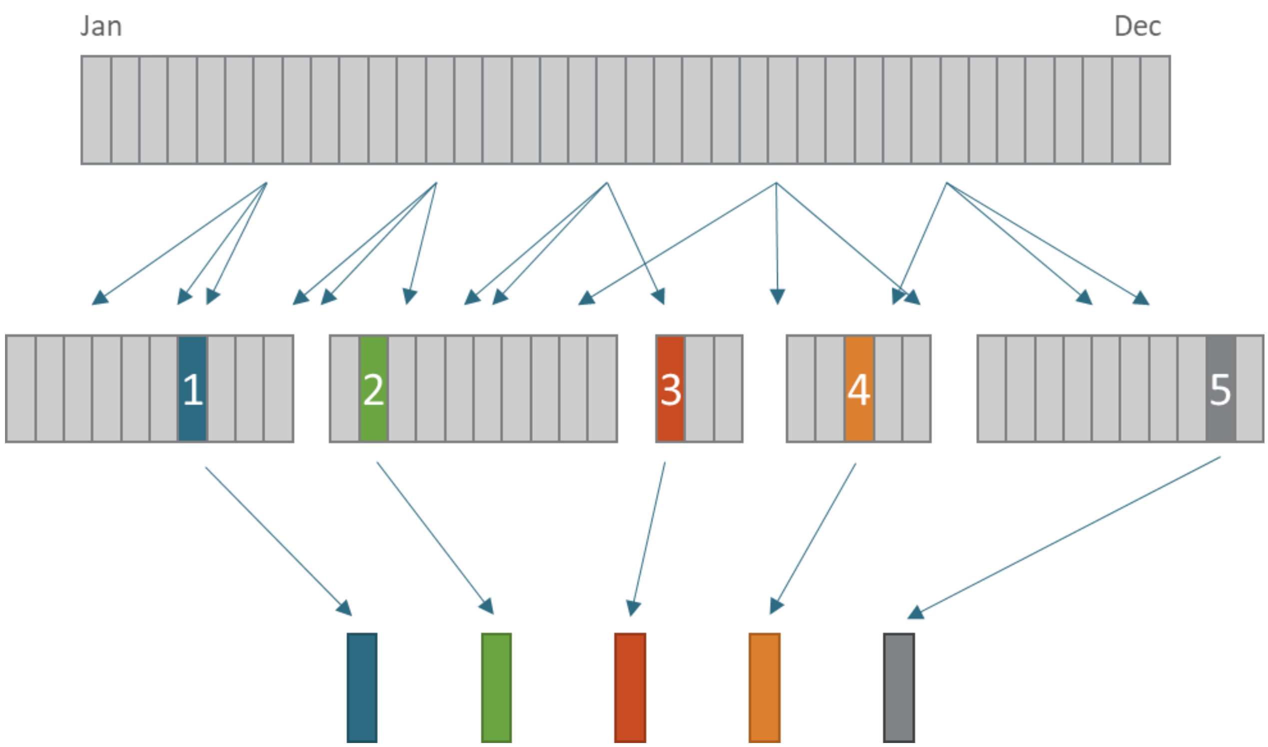
Table 22 Day sampling characteristics

Binning Characteristic	Description
Hourly net load	Daily net load based on a first-order estimation of renewable deployment.
Maximum net load	Maximum net load over the day.
Sum of net load energy	Sum of daily net load
Sum of gross load energy	Sum of daily end-use load.

Day of year	Variable representing when during the year the day occurs
Renewable capacity factor	Daily capacity factors of specified renewable generation types (onshore wind, offshore wind, solar)

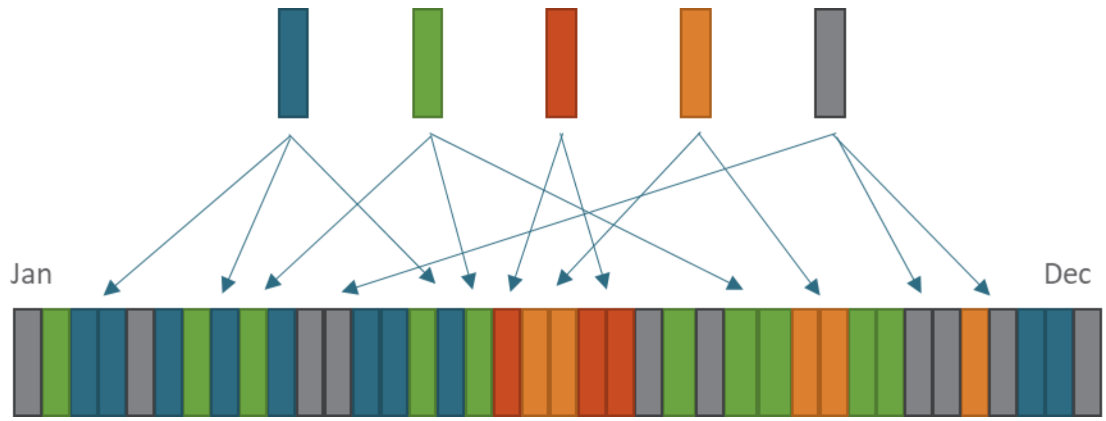
Once sampling characteristics have been selected, RIO uses clustering algorithms to bin representative days in each modeled year. This process is shown graphically in Figure 5. Each cluster in the second row represents days that were found to be statistically similar based on the supplied characteristics. The archetypal day within the cluster is then extracted and used as the representative day in the rest of the modeling process.

Figure 5 Day clustering to create day samples



After the representative days are selected, the model synthesizes the year based on the cluster associations developed in the day sampling process. This creates a full 365-day representation composed of a reduced set of daily operations, shown in Figure 6.

Figure 6 Full year synthesis based on day samples



RIO provides an assessment of day sampling performance to allow for tuning of day selection weights and characteristics in order to best represent the system being modeled.

3.1.4. Spatial Representation

RIO represents discrete demand/supply regions flexibly based on model run configurations. This zonal representation becomes the basic unit of constraint enforcement in the model formulation in terms of energy balances and electricity reliability provision. These zones can have unique enforced policy regimes, resource availability, hourly load and resource shapes, existing generators, etc. They can be linked to other zones with policy regimes and physical transmission ties.

3.1.5. Other Model Features

3.1.5.1. Operations

Time sequential operations are an important component of determining the value of a portfolio of energy system resources. These model components 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 (supply the needs of the system in every zone at every modeled timescale) and whether it is cheaper than other portfolios. RIO determines the least-cost system constrained by the operational realities of the portfolio technologies.

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.

Thermal

Thermal resources are resources that convert the thermal energy embodied in fuel (e.g. coal, gas, uranium) into electricity. Because the production of electricity is only dependent on fuel inputs, many of these resources are dispatchable (i.e. they can adjust their electricity output based on grid conditions). This dispatchability is limited by additional constraints. For example, if they make steam as a co-product for industrial uses, they are often limited in dispatchability given the need to satisfy multiple demands. Additionally, ramp rates and startup and shutdown operations limit their ability to respond to grid conditions over a certain timeframe.

Fixed

Fixed resources refer to resources that have a “fixed” or endogenously determined hourly output shape. This resource categorization is generally reserved for renewable resources like solar and wind. Unlike thermal resources, the dispatchability of such resources is limited to the ability to “turn off” or curtail their anticipated output.

Hydro

The hydro resource characterization is used for reservoir hydro resources that can change their output profiles subject to water availability, reservoir characteristics, and minimum and maximum operating capacities. Hydro systems (combinations of pumps, turbines, and reservoirs oftentimes existing in series with one another) are complex and are generally represented in the model as a fleet, where systemwide operational constraints can be parameterized from historical data. We generally use historical minimum and maximum output levels monthly, parameterized from historical hydro years. We have two methodologies for enforcing energy budgets in our sample days.

Fixed daily energy budgets

This represents the most conservative approach for representing hydro availability because it presupposes no day-to-day flexibility in the allocation of hydro energy budgets. We sample historical hydro output and the hydro fleet has to allocate that energy budget across the day subject to p_{min} and p_{max} constraints.

Daily cumulative energy constraints

This methodology takes advantage of RIO's unique linking of sample days across the year into a cumulative energy balance representation. In this methodology, analogous to the one used for long-duration electricity storage, we track cumulative hydro output that results from optimized sample output. This hydro output schedule (across the entire year) is constrained by input parameters which establish a temporal envelope in which hydro output can deviate from historical conditions. If we establish a long temporal envelope (i.e. by using an input parameter that establishes an envelope where hydro generation can lead or lag by>30 days) then the hydro has a large amount of temporal flexibility in how it can allocate its energy budget. This can be helpful in addressing seasonal energy balances that arise with the penetration of large amounts of renewable energy.

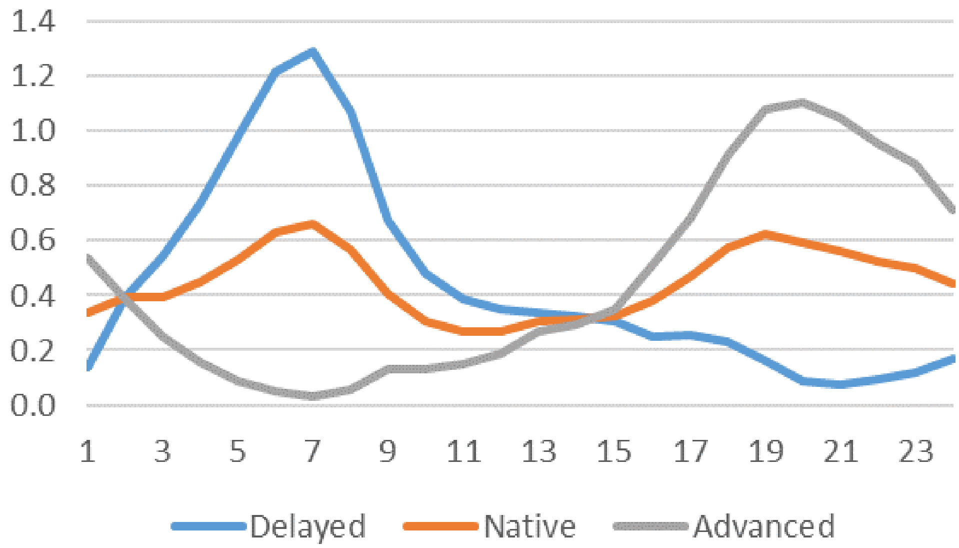
Electricity Storage

Electricity storage is subject to constraints on its input and output power (enforced by limiting such charging and discharging to less than the installed capacity of the resource) as well as state of charge constraints. We assess the necessary investment in storage reservoir capacity as the maximum of short-term state-of-charge (SOC) (assessed within the sample day and assessed hourly) and long-term SOC (assessed with the persistence of storage input/output energy balances across periods). We calculate an availability of short-term SOC based on temporal envelope input parameters that enforce conservatism in daily operations based on the need to reserve SOC to address longer-term imbalances. An input of "annual" completely bifurcates the battery SOC between short and long-term imbalances. An input of “monthly” allows for a monthly reallocation of battery SOC based on system conditions. For example, this would reflect a scenario where it is predictable to system planners on a monthly basis how much SOC needs to be maintained to address longer-term imbalances.

Flexible Load

Flexible loads are end-use loads (electric vehicles, space heating, water heating, etc.) where there can be a delay in the delivery of electricity to a customer without incurring significant costs in terms of customer utility. This is referred to as “latent flexibility”, though there may be necessary investments needed to unlock this flexibility (e.g. controls, smart meters, etc.). RIO models these flexible loads using flexibility envelopes parameterized with the share of end-use energy that is deemed flexible (analogous to customer participation rates) along with the number of hours this energy can be advanced (moved ahead in time from when demand would otherwise occur) or delayed (moved back in time). We parameterize end-use loads differently based on the inherent characteristics of the shape of the native service demand. EVs, for example, have a service demand shape based on a statistical assessment of the arrival time of uncharged batteries to chargers (i.e. the shape peaks when vehicles are likely to be arriving home with less than fully charged batteries). Given this definition, charging can’t be advanced from the native shape (i.e. moved ahead to a time before vehicles arrive home) but it can be delayed. For thermal end-uses, there can be advances or delays, reflecting the ability to pre-heat or pre-cool as well as the ability to delay demand for electricity by taking advantage of lags in temperature changes.

Figure 7 Flexible Load Example Shape



The realized end-use load has to stay within the delayed/advanced energy envelopes. That can be accomplished with deviations above and below the native load shapes. Tighter advance/delay windows and smaller shares of eligible load that is flexible establish more narrow opportunities for load flexibility.

Conversion

Conversion technologies maintain operational flexibility based on user input. Flexibility can be maintained on an hourly basis (similar to electricity generation technologies); sample-day basis (i.e. output has to be the same across all hours on a sample day but can vary between sample days); or annual basis (output has to be flat across all hours of the year). This framework is used to represent the operational realities of non-electricity technologies (e.g. a petroleum refinery doesn't ramp its output on an hourly basis) and to reduce the computational requirements of the model where hourly operational representations are superfluous.

Blend Storage

Flexibility for blend storage technologies can be maintained on an hourly or sample-day basis. This allows regimes for short-term and long-term operations as well as regimes for only long-term operations (with no ability to balance on an hourly basis) for blend storage technologies.

Transmission

RIO uses a pipe-flow constraint formulation[3]. 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.

Blends

Blend supply and demand balances can be enforced on either an hourly, sample-day, or annual basis depending on user input. For blends with potentially significant storage costs, hourly supply/demand balances should be enforced. Electricity is a unique blend where supply/demand must be maintained hourly and is also subject to additional reliability constraints discuss in 3.1.5.2.

3.1.5.2. Electricity Reliability

Electricity is a unique energy product that requires not just an operational representation of meeting supply/demand balances based on the model conditions, but a representation of the likelihood that the modeled conditions are not exhaustive of all potential conditions that the electricity system may face that would threaten this supply and demand balance. This is necessitated due to the possibility that renewable generation conditions may be worse than forecasted and represented in the sample-days; generators and transmission lines may experience unexpected outages; and climactic conditions may create hourly (or sub-hourly) load peaks that exceed represented conditions.

Planning reserves are used to ensure a system has adequate capacity to meet load in all anticipated conditions (assessed on a statistical basis). This includes meeting load during extreme weather events, significant droughts of renewable production, and unforced outages of thermal capacity. Historically, reserves have been assessed in a probabilistic manner. Each hour's loss of load probability (a measure of the likelihood of the inability for the system's supply to meet its demand obligations) could be

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

assessed independently of other hours. That made the problem tractable from a system planning perspective. Resource capacities and their expected contribution to meeting loads in each hour could be determined exogenously and run through Monte Carlo simulations. In capacity expansion modeling, such statistical techniques are not computationally tractable. There have been attempts to apply this statistical approach to capacity expansion modeling, with all generators getting a reliability value with a pre-calculated statistical methodology. However, this misunderstands the reliability economics of deeply decarbonized energy systems by those attempting it because:

- At high levels of renewable penetration, the most critical reliability times are only somewhat correlated with end-use load levels. For example, an extremely low-wind day in the Northeast with average load levels is much more critical from a reliability standpoint than an average wind day with elevated load levels. This endogeneity means that it's impossible to determine a-priori when the "reliability events" will occur, which is implicit in models that pre-select super peak periods.

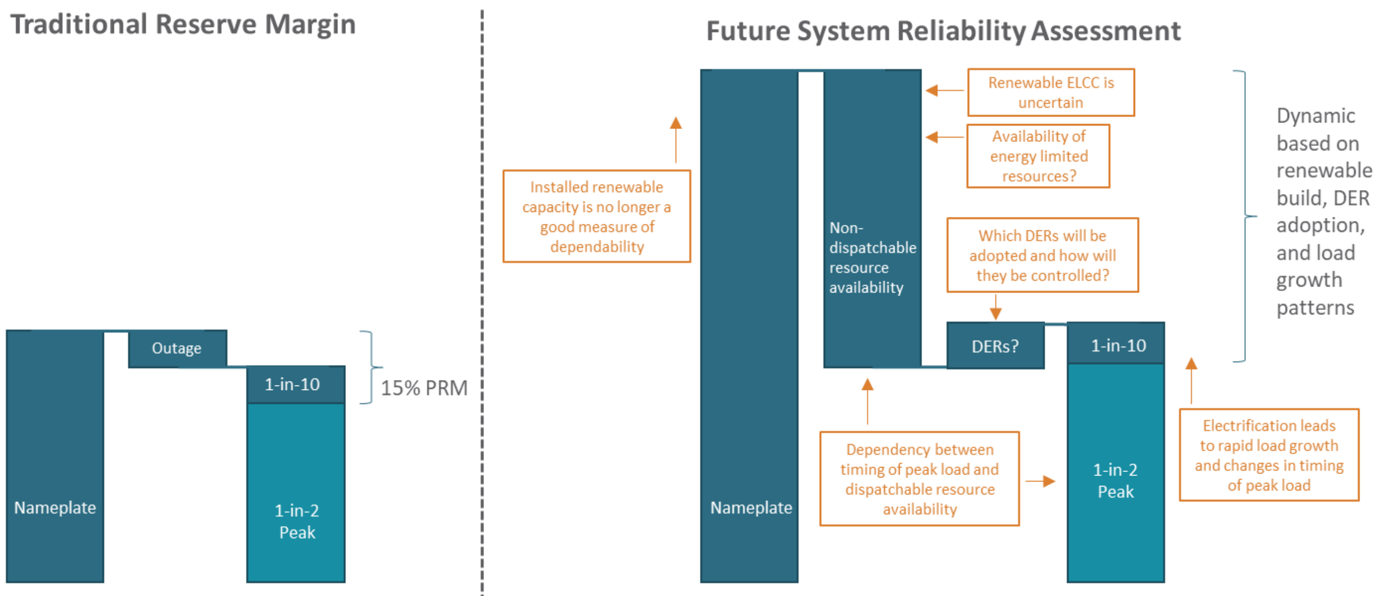
- Reliability events in the future with large amounts of duration-limited resources (i.e. energy storage) are persistence events and the "state-of-charge" of these resources during reliability events is determined by the portfolio of resources that have been built during the capacity expansion and so can't be pre-calculated.

- The must-serve requirement of electricity loads is heterogeneous on an hourly basis. Flexible-loads (end-use loads and things like electrolyzers) don't require reliable provision even on an hourly basis, and the importance of load participation means that they have to be included in the reliability calculation in a dynamic way.

All of this is to emphasize that the conditions that will stress electricity systems in the future and define reliability needs will shift in nature compared to today, shown in Figure 8. Capacity is the principal 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.

Figure 8 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.

Thermal

Thermal resources are the only resources that RIO credits entirely with their latent potential to deliver energy. Thermal resources are considered fuel-secure within the framework of the RIO model. That means that, even when not generating, they could do so in the event of contingency conditions. We derate this potential by each resource's forced outage rate, which represents the share of time that the resource may be unavailable over the year on an unplanned basis. For a fleet of generators, this represents the share of nameplate capacity that can be expected to be available in any single hour.

Fixed

Fixed resources contribute to reliability based on the combination of hourly energy output and curtailment. Hourly energy output is the actual contribution to providing energy, and curtailment represents the ability to do so under contingency conditions. We derate this hourly energy output to represent potential underproduction (from forecast error) and to represent a broader set of expectations for renewable production not represented in the weather years we are using within the optimization.

Hydro

Hydro resources, due to their energy budgets, are duration-limited. This necessitates that we credit their capacity contribution only when realized in energy output. If we credited their nameplate capacity (or P_{max} values in each hour) we would overstate their potential to maintain this sustained peaking capability. Increasing the assumed flexibility of hydro generators—by increasing the window of Daily cumulative energy constraints—we can increase the potential capacity contributions of hydro resources. This contribution is additionally derated by a value that represents the unforced outage rate of hydro resources.

Electricity Storage

Similar to hydro resources, storage resources must maintain states of charge to support their reliable discharge. We therefore credit storage for capacity contributions only when generating (and add a capacity obligation to their charge schedule). This contribution is derated by a forced outage rate on the storage resource, as well as a derate associated with the reliability of the energy in the storage reservoir.

When the discharge is supported by long-term charge/discharge behaviors, we additionally derate capacity contributions by residual state of charge, parameterizing the uncertainty that the reservoir will be full when called upon to provide reliability.

Flexible Load

Flexible load capacity contributions are realized when load is shifted away from critical capacity hours. This is therefore a "realized" dynamic capacity contribution, not an exogenous, deemed value.

Transmission

We also assess the contribution of transmission imports and their reliability contributions. Instead of using deemed import reliability, we assess the reliability of transmission corridors as a combination of corridor characteristics (i.e. do they represent system n-1 conditions; forced outage rates, etc.) as well as their ability to support their physical transfer capacity with energy. This is determined within the optimization, and, for a single zone, represents the capacity for other zones to provide energy when necessary to support the reliability contributions of the line. This is a combination of available capacity in other zones, load and resource diversity between zones, and policy considerations around the types of energy allowed for import.

For zones who are exporting, this supported export flow becomes a reliability obligation within the zone. This approach symmetrically credits and obligates zones so that capacity can be assessed in the entire system concurrently.

Conversion

The electricity demanded by conversion technologies also received a dependability factor. For technologies that are not deemed must-serve load, this electricity demand is not included in the planning reserve calculation. The supply/demand balance for this load must still be maintained, however.

3.1.5.3. Investment Decisions

Concurrently with optimal operational decisions, the model makes resource build decisions that together produce the lowest total system cost. RIO allows for four types of capacity decisions for each of its supply technology types (thermal, fixed, hydro, electricity storage, conversion, blend storage):

1. New Build
2. Extensions
3. Repowers
4. Retirements

Details about these decision types are included below.

3.1.5.4. New Builds

New construction decisions are based on an assessment of the cost share of a resource installed in any model year. This cost share represents the realized levelized cost streams based on the selected modeled years. The example below shows how this is calculated for an example resource installed in 2022. We assess the costs of that resource *in* the years that we model (i.e. vintaged new build decisions) *for* the years which we model (i.e. the payments made in the modeled years for resources installed).

Table 23 New resource cost schedule

	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
NPV	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$1,000	$96	$96	$96	$96	$96	$96	$96	$96	$96	$96	$96	$96	$96	$96	$96
$262	$96					$96					$96				

3.1.5.5. Extensions

Extensions are decisions to maintain capacity at the end of its useful life. The model includes specified extension costs that are generally lower than the cost of newly built resources. The lifetimes of such extensions are also model inputs. The costs are implemented with the same structure used in New Builds.

3.1.5.6. Repowers

Repowers are decisions to bring capacity back online after a period of defined dormancy. This repower represents "mothballing" a plant before bringing it back for further use. The costs are implemented with the same structure used in New Builds.

3.1.5.7. Retirements

Retirements are a decision made during the duration of a plant's life. When changing economic and policy conditions creates an environment where the plant's value to the system is less than its ongoing costs (i.e. fixed O&M), the model will retire the plant in order to realize the ongoing cost savings.

3.1.5.8. Transmission Investment

In addition to investing in new generation, the model can invest in the expansion of transmission corridors to deliver additional energy between zones. The cost of this transmission investment is assessed in a similar manner to that of newly built supply technologies, though the model doesn't maintain the ability to retire new transmission assets.

3.2. EnergyPATHWAYS/RIO Integration

EnergyPATHWAYS is used to define energy demand scenarios that provide input parameters for RIO optimizations. These input parameters include hourly demand shapes for energy carriers like electricity, hydrogen, and pipeline gas. They also include total end-use demand for all energy carriers as well as total demand-side equipment costs, which are used to calculate total energy system costs in RIO.

3.3. EnergyPATHWAYS

3.3.1. Overview

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.

The model works using decision-making "stasis" as a baseline. This means, for example, that when projecting energy demand for residential space heating, EnergyPATHWAYS implicitly assumes that consumers will replace their water heater with a water heater of a similar type. This baseline does, however, include efficiency gains and technology development required by codes and standards or reasonably anticipated based on techno-economic projections. If there are deviations from the current system in terms of technology deployment, these are made explicit in our scenario with the application of measures, which represent explicit user-defined changes to the baseline. These can take the form of adjustments of sales shares measures (changes in the relative penetration of technology adoption in a defined year) or of stock measures (changes to the amount of technology deployment by a defined year).

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 energy flows, emissions, and costs of the modeled energy system.

The sections below describe the EnergyPATHWAYS demand-calculation methods in detail.

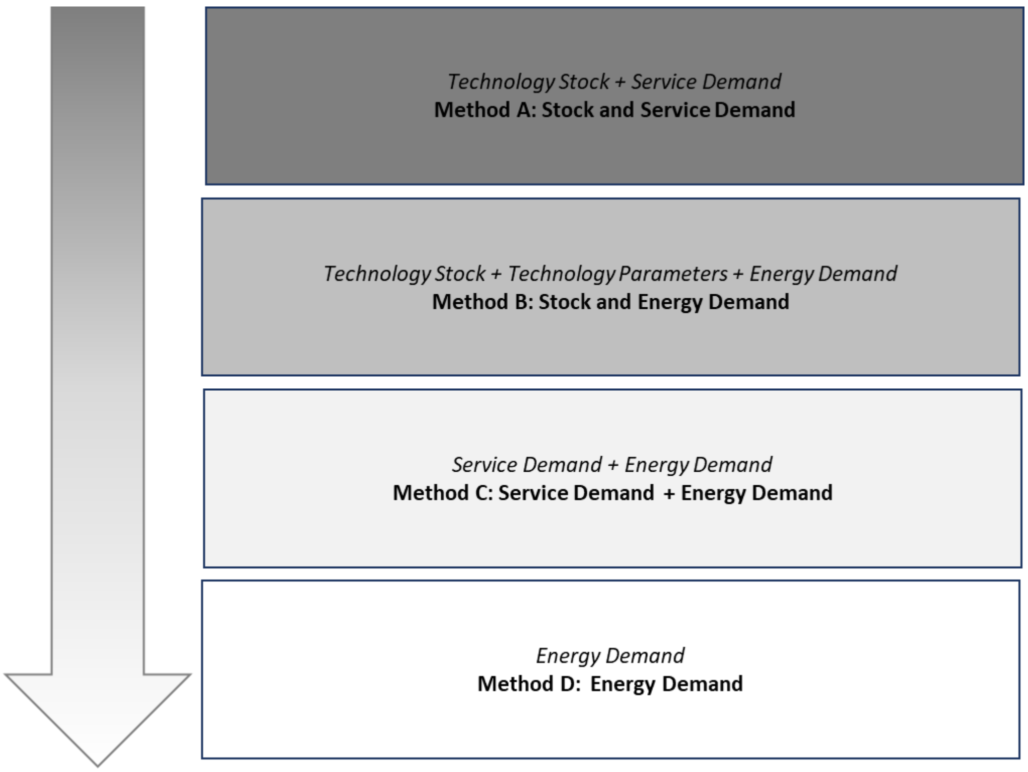
3.3.2. Subsectors

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 depend 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.

3.3.3. 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 9). 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 9 Methods for projecting energy demand



3.3.3.1. 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.

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

Technology Stock (S)

The composition of the technology stock is governed by stock-rollover mechanics in the model, technology inputs (lifetime parameters, technology decay parameters), 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.

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

Before Measure (i.e. Baseline)

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

<u>After Sales Share Measure</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} = $D_{2020} * H_{a2020}$ = 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 in influencing 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.

Stock Specification Measures

EnergyPATHWAYS also allows for stock specification measures, which create exogenous specification of technology stocks along the year index (i.e. existing stock in a year), as opposed to sales share measures which operate along the vintage index (i.e. sales in a year). They both interact with the same basic stock rollover mechanics in the model but are interpreted differently by the model.

In the example below, EnergyPATHWAYS replicates the stock in 2020 of our previous sales share example where Technology A is 61 units in 2020 and Technology B is 49 Units.

After Stock Specification Measure

S_{2019} = 100

S_{a2019} = 50

S_{b2019} = 50

D_{2020} = 10

D_{a2020} = 5

D_{b2020} = 5

S_{2020} = 110

$G_{2020} = S_{2020} - S_{2019} = 110 - 100 = 10$

$N_{a2020} = S_{a2020} - S_{a2019} + D_{a2020}$ = 61 – 50 + 5 = 16

$S_{b2020} = S_{2020} - S_{a2020}$ = 110 – 61 = 49

$N_{b2020} = S_{b2020} - S_{b2019} + D_{b2020}$ = 49 – 50 + 5 = 4

$H_{a2020} = \frac{N_{a2020}}{N_{2020}} = .8$

$H_{b2020} = \frac{N_{b2020}}{N_{2020}} = .2$

$R_{a2020} = D_{2020} * H_{a2020} = 10 * .8 = 8$

$R_{b2020} = D_{2020} * H_{b2020} = 10 * .2 = 2$

$G_{a2020} = G_{2020} * H_{a2020} = 10 * .8 = 8$

$G_{b2020} = G_{2020} * H_{b2020} = 10 * .2 = 2$

The model uses the stock specifications to produce sales shares that result in the specified stock. Where a stock specification measure requires more new sales than are available through natural rollover decay and stock growth, the model early-retires infrastructure to increase the pool of available sales based on the probability of retirement for given combination of vintage and technology. The model separately tracks physical and financial lifetimes, so even though technologies may be taken out of service, they are still paid for. Further discussion of this accounting can be found in 3.3.4.1.

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.[4]

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

[4] EnergyPATHWAYS again ignores the index of vintage (v) for simplicity, but this is an important index to reflect technology utilization determined by age.

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

$$M_{tyr} = \frac{s_{tyr}}{d_{tyr}}$$

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.

3.3.3.2. 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

3.3.3.3. 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.

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.

3.3.3.4. 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

3.3.4. Demand-Side Costs

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

3.3.4.1. 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.[5]

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

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

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

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

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[5] 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).

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 accounts 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.

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

Where

S_{tvyr}^{fs} = Financial stock associated with fuel-switched equipment installations

W_{tvr}^{fs} = Levelized fuel-switching costs for technology t for vintage v in region r

d_t = Discount rate of technology t

z_{tvr}^{fs} = Fuel switching costs for technology t in vintage v in region r

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

3.3.4.2. 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 EnergyPATHWAYS does 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 uses analogous inputs like capital costs and useful lives to calculate measure costs.

Service Demand Measure Costs

Service demand measure costs are costs associated with achieving service demand reductions. In many cases, no costs are assessed for these activities as they represent conservation or improved land-use planning that occurs at zero or negative-costs.

Equation 9

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

Where

C_{yr}^{sd} = Total service demand measure costs

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

W_{mvr}^{sd} = Levelized per-unit service demand reduction costs

Energy Efficiency Measure Costs

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

Equation 10

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

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

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