Net-Zero America by 2050
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1. Background

Evolved Energy Research was retained in 2019 to use its modeling tools to explore infrastructure transitions to a low carbon economy in partnership with Princeton University. This document serves as a technical appendix to the modeling work done in EnergyPATHWAYS and RIO, which together outline the broad strokes of each decarbonization pathway. It documents the data, scenario assumptions, and basic methods used in the models. Accompanying this technical appendix is an Excel Sheet that lists data inputs for many of the technologies used in the study, along with fuel prices and resource supply curves—data that forms the backbone of the energy supply scenarios described below. The findings from the study itself are presented elsewhere.

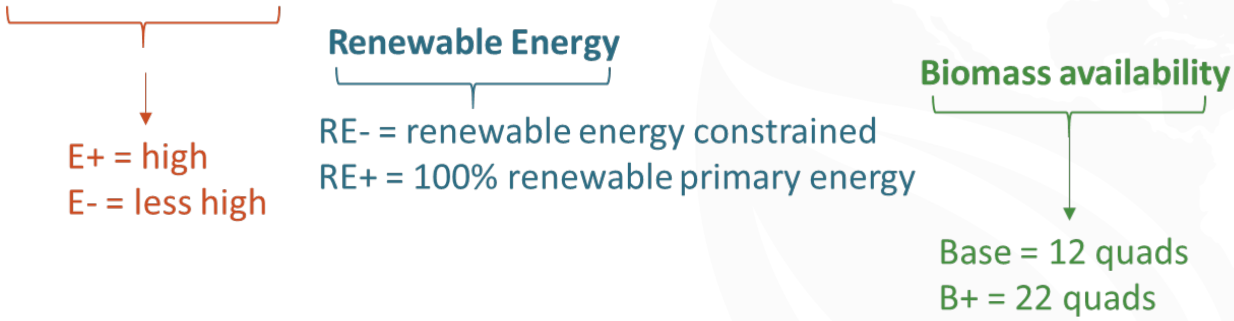
2. Scenario Descriptions

Scenarios are created from a set of assumptions that specify the demand side of the energy system, including service demand, end-use technology, and energy efficiency, plus constraints on the supply side of the energy system, including available resources and emissions targets. For this study we developed a total of nine different scenarios described in Table 1 with acronyms devised as shown in Figure 1. The key attributes of each are described in this section, first for the demand side and then for the supply side.

Table 1 Scenario acronyms and descriptions

Acronym	Scenario
REF	Reference
E+	High electrification, 12 quads biomass
E-	Less-high electrification, 12 quads biomass
E+ RE-	E+ and renewables (solar/wind) constrained at current build rate
E+ RE+	E+ and 100% primary energy from renewables by 2050
E+ B+	E+ and 22 quads biomass potential by 2050
E- B+	E- and 22 quads of biomass potential by 2050
E+ RE- B+	E+ RE- with 22 quads of biomass potential by 2050
E+ RE+ B+	E+ RE+ with 22 quads of biomass potential by 2050

Figure 1 Acronym communicates three key features of the scenario



2.1. Demand-Side

Demand-side scenarios vary with respect to the rates of electrification, all other assumptions are held constant between scenarios, including the cost and performance of a given technology. In addition, all scenarios have the same energy service projections as DOE's *Annual Energy Outlook 2019*, leading to easier comparison between pathways.

High efficiency trajectories were defined for many technologies and were adopted in both the E+ and E- scenarios. In aviation and industrial subsectors for which individual technologies were not tracked, percent-per-year efficiency improvements were used (defined in tables below).

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

Table 2 below summarizes the demand-side assumptions used within each scenario. In the next section, detailed assumptions for each demand case are provided, referencing the three case names (REF, E+, E-).

Table 2 Mapping from scenario names to demand-side cases

Scenario Name	Demand-side case
REF	Reference (REF)
E+	High electrification (E+)
E+ B+	High electrification (E+)

E+ RE-	High electrification (E+)
E+ RE- B+	High electrification (E+)
E+ RE+	High electrification (E+)
E+ RE+ B+	High electrification (E+)
E-	Less-high electrification (E-)
E- B+	Less-high electrification (E-)

2.1.1. Stock Rollover

The tables below show the sales shares (Table 3) and stock shares (Table 4) for four demand technology groups (Electrified Technologies, High Efficiency Technologies, Hydrogen Technologies, and Reference Technologies) by decade in each of the three demand cases. High efficiency refers to adoption of the best-available efficiency technology, but with no fuel switching. The full demand-side representation consists of more than 380 technology types across all subsectors and end-uses, but we aggregated some of them here to show broader trends in the input values. The sales shares in Table 3 are inputs to EnergyPATHWAYS, whereas the stock shares in Table 4 are outputs determined by the stock rollover for each subsector.

Table 3 Sales shares by scenario and technology group

Subsector	Technology Group	Demand Case	2020	2030	2040	2050
commercial air conditioning	High Efficiency	REF	3%	40%	42%	43%
commercial air conditioning	High Efficiency	E+	3%	87%	93%	92%
commercial air conditioning	High Efficiency	E-	3%	83%	93%	92%
commercial air conditioning	Reference	REF	97%	60%	58%	57%
commercial air conditioning	Reference	E+	97%	13%	7%	8%
commercial air conditioning	Reference	E-	97%	17%	7%	8%
commercial cooking	Electric	REF	32%	35%	35%	35%
commercial cooking	Electric	E+	32%	80%	87%	87%
commercial cooking	Electric	E-	32%	41%	71%	86%
commercial cooking	Reference	REF	68%	65%	65%	65%
commercial cooking	Reference	E+	68%	20%	13%	13%
commercial cooking	Reference	E-	68%	59%	29%	14%
commercial lighting	High Efficiency	REF	53%	86%	88%	88%
commercial lighting	High Efficiency	E+	49%	99%	100%	100%
commercial lighting	High Efficiency	E-	49%	99%	100%	100%
commercial lighting	Reference	REF	47%	14%	12%	12%

commercial lighting	Reference	E+	51%	1%	0%	0%
commercial lighting	Reference	E-	51%	1%	0%	0%
commercial refrigeration	High Efficiency	REF	0%	12%	15%	17%
commercial refrigeration	High Efficiency	E+	0%	88%	100%	100%
commercial refrigeration	High Efficiency	E-	0%	88%	100%	100%
commercial refrigeration	Reference	REF	100%	88%	85%	83%
commercial refrigeration	Reference	E+	100%	12%	0%	0%
commercial refrigeration	Reference	E-	100%	12%	0%	0%
commercial space heating	Electric	REF	11%	68%	98%	99%
commercial space heating	Electric	E+	11%	67%	99%	99%
commercial space heating	Electric	E-	11%	25%	62%	92%
commercial space heating	High Efficiency	REF	0%	0%	0%	0%
commercial space heating	High Efficiency	E+	0%	0%	0%	0%
commercial space heating	High Efficiency	E-	0%	0%	0%	0%
commercial space heating	Reference	REF	89%	32%	2%	1%
commercial space heating	Reference	E+	89%	33%	1%	1%
commercial space heating	Reference	E-	89%	75%	38%	8%
commercial ventilation	High Efficiency	E+	0%	87%	100%	100%
commercial ventilation	High Efficiency	E-	0%	87%	100%	100%
commercial ventilation	Reference	REF	100%	100%	100%	100%
commercial ventilation	Reference	E+	100%	13%	0%	0%
commercial ventilation	Reference	E-	100%	13%	0%	0%
commercial water heating	Electric	REF	5%	5%	5%	5%
commercial water heating	Electric	E+	5%	68%	100%	100%
commercial water heating	Electric	E-	5%	13%	59%	93%
commercial water heating	High Efficiency	REF	0%	0%	0%	0%
commercial water heating	High Efficiency	E+	0%	0%	0%	0%
commercial water heating	High Efficiency	E-	0%	0%	0%	0%
commercial water heating	Reference	REF	95%	95%	95%	95%
commercial water heating	Reference	E+	95%	32%	0%	0%
commercial water heating	Reference	E-	95%	87%	41%	7%
residential air conditioning	High Efficiency	REF	6%	22%	28%	24%
residential air conditioning	High Efficiency	E+	7%	90%	98%	98%
residential air conditioning	High Efficiency	E-	7%	87%	98%	98%
residential air conditioning	Reference	REF	94%	78%	72%	76%
residential air conditioning	Reference	E+	93%	10%	2%	2%
residential air conditioning	Reference	E-	93%	13%	2%	2%
residential building shell	High Efficiency	E+	0%	100%	100%	100%
residential building shell	High Efficiency	E-	0%	100%	100%	100%
residential building shell	Reference	REF	100%	100%	100%	100%
residential building shell	Reference	E+	100%	0%	0%	0%
residential building shell	Reference	E-	100%	0%	0%	0%
residential clothes drying	High Efficiency	REF	0%	0%	0%	0%

residential clothes drying	High Efficiency	E+	1%	87%	100%	100%
residential clothes drying	High Efficiency	E-	1%	87%	100%	100%
residential clothes drying	Reference	REF	100%	100%	100%	100%
residential clothes drying	Reference	E+	99%	13%	0%	0%
residential clothes drying	Reference	E-	99%	13%	0%	0%
residential clothes washing	High Efficiency	REF	0%	0%	0%	0%
residential clothes washing	High Efficiency	E+	1%	87%	100%	100%
residential clothes washing	High Efficiency	E-	1%	87%	100%	100%
residential clothes washing	Reference	REF	100%	100%	100%	100%
residential clothes washing	Reference	E+	99%	13%	0%	0%
residential clothes washing	Reference	E-	99%	13%	0%	0%
residential cooking	Electric	REF	61%	61%	61%	61%
residential cooking	Electric	E+	61%	95%	100%	100%
residential cooking	Electric	E-	61%	66%	88%	99%
residential cooking	Reference	REF	39%	39%	39%	39%
residential cooking	Reference	E+	39%	5%	0%	0%
residential cooking	Reference	E-	39%	34%	12%	1%
residential dishwashing	High Efficiency	E+	1%	87%	100%	100%
residential dishwashing	High Efficiency	E-	1%	87%	100%	100%
residential dishwashing	Reference	REF	100%	100%	100%	100%
residential dishwashing	Reference	E+	99%	13%	0%	0%
residential dishwashing	Reference	E-	99%	13%	0%	0%
residential freezing	High Efficiency	E+	1%	87%	100%	100%
residential freezing	High Efficiency	E-	1%	87%	100%	100%
residential freezing	Reference	REF	100%	100%	100%	100%
residential freezing	Reference	E+	99%	13%	0%	0%
residential freezing	Reference	E-	99%	13%	0%	0%
residential lighting	High Efficiency	REF	49%	80%	83%	81%
residential lighting	High Efficiency	E+	48%	100%	100%	100%
residential lighting	High Efficiency	E-	48%	100%	100%	100%
residential lighting	Reference	REF	51%	20%	17%	19%
residential lighting	Reference	E+	52%	0%	0%	0%
residential lighting	Reference	E-	52%	0%	0%	0%
residential refrigeration	High Efficiency	REF	0%	0%	0%	0%
residential refrigeration	High Efficiency	E+	1%	87%	100%	100%
residential refrigeration	High Efficiency	E-	1%	87%	100%	100%
residential refrigeration	Reference	REF	100%	100%	100%	100%
residential refrigeration	Reference	E+	99%	13%	0%	0%
residential refrigeration	Reference	E-	99%	13%	0%	0%
residential space heating	Electric	REF	34%	53%	55%	55%
residential space heating	Electric	E+	35%	77%	96%	96%
residential space heating	Electric	E-	35%	48%	73%	91%
residential space heating	High Efficiency	REF	0%	0%	0%	0%

residential space heating	High Efficiency	E+	0%	0%	0%	0%
residential space heating	High Efficiency	E-	0%	0%	0%	0%
residential space heating	Reference	REF	66%	47%	45%	45%
residential space heating	Reference	E+	65%	23%	4%	4%
residential space heating	Reference	E-	65%	52%	27%	9%
residential water heating	Electric	REF	40%	53%	54%	54%
residential water heating	Electric	E+	40%	82%	100%	100%
residential water heating	Electric	E-	40%	57%	79%	96%
residential water heating	High Efficiency	REF	0%	0%	0%	0%
residential water heating	High Efficiency	E+	0%	0%	0%	0%
residential water heating	High Efficiency	E-	0%	0%	0%	0%
residential water heating	Reference	REF	60%	47%	46%	46%
residential water heating	Reference	E+	60%	18%	0%	0%
residential water heating	Reference	E-	60%	43%	21%	4%
heavy duty trucks	Electric	REF	0%	0%	0%	0%
heavy duty trucks	Electric	E+	1%	19%	57%	60%
heavy duty trucks	Electric	E-	0%	4%	24%	51%
heavy duty trucks	High Efficiency	REF	0%	0%	0%	0%
heavy duty trucks	High Efficiency	E+	0%	0%	0%	0%
heavy duty trucks	High Efficiency	E-	0%	0%	0%	0%
heavy duty trucks	Reference	REF	100%	100%	100%	100%
heavy duty trucks	Reference	E+	99%	68%	4%	0%
heavy duty trucks	Reference	E-	99%	93%	61%	15%
heavy duty trucks	Hydrogen	REF	0%	0%	0%	0%
heavy duty trucks	Hydrogen	E+	0%	13%	38%	40%
heavy duty trucks	Hydrogen	E-	0%	3%	16%	34%
light duty autos	Electric	REF	7%	11%	16%	19%
light duty autos	Electric	E+	7%	62%	97%	100%
light duty autos	Electric	E-	3%	17%	57%	90%
light duty autos	High Efficiency	REF	8%	10%	11%	11%
light duty autos	High Efficiency	E+	8%	4%	0%	0%
light duty autos	High Efficiency	E-	8%	9%	5%	1%
light duty autos	Reference	REF	85%	79%	73%	70%
light duty autos	Reference	E+	85%	34%	3%	0%
light duty autos	Reference	E-	88%	73%	37%	9%
light duty autos	Hydrogen	REF	0%	0%	0%	0%
light duty autos	Hydrogen	E+	0%	0%	0%	0%
light duty autos	Hydrogen	E-	0%	0%	0%	0%
light duty trucks	Electric	REF	1%	2%	3%	5%
light duty trucks	Electric	E+	1%	32%	96%	100%
light duty trucks	Electric	E-	1%	7%	39%	85%
light duty trucks	High Efficiency	REF	2%	3%	4%	6%
light duty trucks	High Efficiency	E+	2%	2%	0%	0%

light duty trucks	High Efficiency	E-	2%	3%	3%	1%
light duty trucks	Reference	REF	98%	94%	92%	89%
light duty trucks	Reference	E+	97%	65%	4%	0%
light duty trucks	Reference	E-	97%	90%	58%	14%
light duty trucks	Hydrogen	REF	0%	0%	0%	0%
light duty trucks	Hydrogen	E+	0%	0%	0%	0%
light duty trucks	Hydrogen	E-	0%	0%	0%	0%
medium duty trucks	Electric	REF	0%	0%	1%	1%
medium duty trucks	Electric	E+	1%	25%	76%	80%
medium duty trucks	Electric	E-	1%	5%	31%	68%
medium duty trucks	High Efficiency	REF	0%	0%	0%	1%
medium duty trucks	High Efficiency	E+	0%	0%	0%	0%
medium duty trucks	High Efficiency	E-	0%	0%	0%	0%
medium duty trucks	Reference	REF	100%	99%	98%	98%
medium duty trucks	Reference	E+	99%	68%	4%	0%
medium duty trucks	Reference	E-	99%	93%	60%	15%
medium duty trucks	Hydrogen	REF	0%	0%	0%	0%
medium duty trucks	Hydrogen	E+	0%	6%	19%	20%
medium duty trucks	Hydrogen	E-	0%	1%	8%	17%
transit buses	Electric	REF	1%	1%	1%	1%
transit buses	Electric	E+	1%	32%	96%	100%
transit buses	Electric	E-	1%	7%	39%	85%
transit buses	High Efficiency	REF	19%	19%	19%	19%
transit buses	High Efficiency	E+	17%	12%	1%	0%
transit buses	High Efficiency	E-	17%	16%	11%	3%
transit buses	Reference	REF	80%	80%	80%	80%
transit buses	Reference	E+	82%	57%	4%	0%
transit buses	Reference	E-	82%	77%	50%	12%

Table 4 Stock shares by scenario and technology group

Subsector	Technology Group	Demand Case	2020	2030	2040	2050
commercial air conditioning	High Efficiency	REF	5%	17%	36%	39%
commercial air conditioning	High Efficiency	E+	5%	31%	74%	89%
commercial air conditioning	High Efficiency	E-	5%	28%	70%	88%
commercial air conditioning	Reference	REF	95%	83%	64%	61%
commercial air conditioning	Reference	E+	95%	69%	26%	11%
commercial air conditioning	Reference	E-	95%	72%	30%	12%
commercial cooking	Electric	REF	35%	34%	35%	35%
commercial cooking	Electric	E+	35%	53%	85%	87%
commercial cooking	Electric	E-	35%	37%	55%	80%
commercial cooking	Reference	REF	65%	66%	65%	65%
commercial cooking	Reference	E+	65%	47%	15%	13%

commercial cooking	Reference	E-	65%	63%	45%	20%
commercial lighting	High Efficiency	REF	39%	85%	93%	94%
commercial lighting	High Efficiency	E+	39%	92%	100%	100%
commercial lighting	High Efficiency	E-	39%	92%	100%	100%
commercial lighting	Reference	REF	61%	15%	7%	6%
commercial lighting	Reference	E+	61%	8%	0%	0%
commercial lighting	Reference	E-	61%	8%	0%	0%
commercial refrigeration	High Efficiency	REF	0%	9%	14%	17%
commercial refrigeration	High Efficiency	E+	0%	37%	90%	100%
commercial refrigeration	High Efficiency	E-	0%	37%	90%	100%
commercial refrigeration	Reference	REF	100%	91%	86%	83%
commercial refrigeration	Reference	E+	100%	63%	10%	0%
commercial refrigeration	Reference	E-	100%	63%	10%	0%
commercial space heating	Electric	REF	15%	29%	71%	92%
commercial space heating	Electric	E+	15%	27%	71%	94%
commercial space heating	Electric	E-	15%	19%	35%	66%
commercial space heating	High Efficiency	REF	0%	0%	0%	0%
commercial space heating	High Efficiency	E+	0%	0%	0%	0%
commercial space heating	High Efficiency	E-	0%	0%	0%	0%
commercial space heating	Reference	REF	85%	71%	29%	8%
commercial space heating	Reference	E+	85%	73%	29%	6%
commercial space heating	Reference	E-	85%	81%	65%	34%
commercial ventilation	High Efficiency	E+	0%	19%	67%	96%
commercial ventilation	High Efficiency	E-	0%	19%	67%	96%
commercial ventilation	Reference	REF	100%	100%	100%	100%
commercial ventilation	Reference	E+	100%	81%	33%	4%
commercial ventilation	Reference	E-	100%	81%	33%	4%
commercial water heating	Electric	REF	6%	6%	6%	6%
commercial water heating	Electric	E+	6%	23%	81%	99%
commercial water heating	Electric	E-	6%	8%	29%	73%
commercial water heating	High Efficiency	REF	0%	0%	0%	0%
commercial water heating	High Efficiency	E+	0%	0%	0%	0%
commercial water heating	High Efficiency	E-	0%	0%	0%	0%
commercial water heating	Reference	REF	94%	94%	94%	94%
commercial water heating	Reference	E+	94%	77%	19%	1%
commercial water heating	Reference	E-	94%	92%	71%	27%
residential air conditioning	High Efficiency	REF	8%	19%	25%	26%
residential air conditioning	High Efficiency	E+	8%	37%	87%	98%
residential air conditioning	High Efficiency	E-	8%	34%	85%	98%
residential air conditioning	Reference	REF	92%	81%	75%	74%
residential air conditioning	Reference	E+	92%	63%	13%	2%
residential air conditioning	Reference	E-	92%	66%	15%	2%
residential space heating	Electric	REF	36%	45%	52%	53%

residential space heating	Electric	E+	36%	47%	75%	91%
residential space heating	Electric	E-	36%	41%	53%	72%
residential space heating	High Efficiency	REF	0%	0%	0%	0%
residential space heating	High Efficiency	E+	0%	0%	0%	0%
residential space heating	High Efficiency	E-	0%	0%	0%	0%
residential space heating	Reference	REF	64%	55%	48%	47%
residential space heating	Reference	E+	64%	53%	25%	9%
residential space heating	Reference	E-	64%	59%	47%	28%
residential building shell	High Efficiency	E+	0%	16%	36%	55%
residential building shell	High Efficiency	E-	0%	16%	36%	55%
residential building shell	Reference	REF	100%	100%	100%	100%
residential building shell	Reference	E+	100%	84%	64%	45%
residential building shell	Reference	E-	100%	84%	64%	45%
residential clothes drying	High Efficiency	REF	0%	0%	0%	0%
residential clothes drying	High Efficiency	E+	0%	23%	81%	100%
residential clothes drying	High Efficiency	E-	0%	23%	81%	100%
residential clothes drying	Reference	REF	100%	100%	100%	100%
residential clothes drying	Reference	E+	100%	77%	19%	0%
residential clothes drying	Reference	E-	100%	77%	19%	0%
residential clothes washing	High Efficiency	REF	0%	0%	0%	0%
residential clothes washing	High Efficiency	E+	0%	24%	85%	100%
residential clothes washing	High Efficiency	E-	0%	24%	85%	100%
residential clothes washing	Reference	REF	100%	100%	100%	100%
residential clothes washing	Reference	E+	100%	76%	15%	0%
residential clothes washing	Reference	E-	100%	76%	15%	0%
residential cooking	Electric	REF	61%	61%	61%	61%
residential cooking	Electric	E+	61%	68%	89%	100%
residential cooking	Electric	E-	61%	62%	70%	87%
residential cooking	Reference	REF	39%	39%	39%	39%
residential cooking	Reference	E+	39%	32%	11%	0%
residential cooking	Reference	E-	39%	38%	30%	13%
residential dishwashing	High Efficiency	E+	0%	24%	85%	100%
residential dishwashing	High Efficiency	E-	0%	24%	85%	100%
residential dishwashing	Reference	REF	100%	100%	100%	100%
residential dishwashing	Reference	E+	100%	76%	15%	0%
residential dishwashing	Reference	E-	100%	76%	15%	0%
residential freezing	High Efficiency	E+	0%	17%	62%	93%
residential freezing	High Efficiency	E-	0%	17%	62%	93%
residential freezing	Reference	REF	100%	100%	100%	100%
residential freezing	Reference	E+	100%	83%	38%	7%
residential freezing	Reference	E-	100%	83%	38%	7%
residential lighting	High Efficiency	REF	68%	83%	81%	81%
residential lighting	High Efficiency	E+	68%	89%	92%	95%

residential lighting	High Efficiency	E-	68%	89%	92%	95%
residential lighting	Reference	REF	32%	17%	19%	19%
residential lighting	Reference	E+	32%	11%	8%	5%
residential lighting	Reference	E-	32%	11%	8%	5%
residential refrigeration	High Efficiency	REF	0%	0%	0%	0%
residential refrigeration	High Efficiency	E+	0%	21%	74%	98%
residential refrigeration	High Efficiency	E-	0%	21%	74%	98%
residential refrigeration	Reference	REF	100%	100%	100%	100%
residential refrigeration	Reference	E+	100%	79%	26%	2%
residential refrigeration	Reference	E-	100%	79%	26%	2%
residential water heating	Electric	REF	47%	59%	62%	62%
residential water heating	Electric	E+	47%	68%	95%	100%
residential water heating	Electric	E-	47%	60%	74%	92%
residential water heating	High Efficiency	REF	0%	0%	0%	0%
residential water heating	High Efficiency	E+	0%	0%	0%	0%
residential water heating	High Efficiency	E-	0%	0%	0%	0%
residential water heating	Reference	REF	53%	41%	38%	38%
residential water heating	Reference	E+	53%	32%	5%	0%
residential water heating	Reference	E-	53%	40%	26%	8%
heavy duty trucks	Electric	REF	0%	0%	0%	0%
heavy duty trucks	Electric	E+	0%	5%	34%	57%
heavy duty trucks	Electric	E-	0%	1%	10%	32%
heavy duty trucks	High Efficiency	REF	0%	0%	0%	0%
heavy duty trucks	High Efficiency	E+	0%	0%	0%	0%
heavy duty trucks	High Efficiency	E-	0%	0%	0%	0%
heavy duty trucks	Hydrogen	REF	0%	0%	0%	0%
heavy duty trucks	Hydrogen	E+	0%	3%	22%	38%
heavy duty trucks	Hydrogen	E-	0%	1%	6%	22%
heavy duty trucks	Reference	REF	100%	100%	100%	100%
heavy duty trucks	Reference	E+	100%	92%	44%	5%
heavy duty trucks	Reference	E-	100%	98%	84%	46%
light duty autos	Electric	REF	2%	8%	13%	17%
light duty autos	Electric	E+	2%	23%	72%	97%
light duty autos	Electric	E-	1%	7%	29%	67%
light duty autos	High Efficiency	REF	6%	8%	10%	11%
light duty autos	High Efficiency	E+	6%	7%	3%	0%
light duty autos	High Efficiency	E-	6%	8%	8%	4%
light duty autos	Hydrogen	REF	0%	0%	0%	0%
light duty autos	Hydrogen	E+	0%	0%	0%	0%
light duty autos	Hydrogen	E-	0%	0%	0%	0%
light duty autos	Reference	REF	92%	84%	77%	73%
light duty autos	Reference	E+	91%	70%	25%	3%
light duty autos	Reference	E-	92%	85%	63%	29%

light duty trucks	Electric	REF	0%	1%	2%	3%
light duty trucks	Electric	E+	0%	7%	54%	94%
light duty trucks	Electric	E-	0%	2%	15%	53%
light duty trucks	High Efficiency	REF	1%	2%	3%	5%
light duty trucks	High Efficiency	E+	1%	2%	1%	0%
light duty trucks	High Efficiency	E-	1%	2%	3%	2%
light duty trucks	Hydrogen	REF	0%	0%	0%	0%
light duty trucks	Hydrogen	E+	0%	0%	0%	0%
light duty trucks	Hydrogen	E-	0%	0%	0%	0%
light duty trucks	Reference	REF	99%	96%	94%	91%
light duty trucks	Reference	E+	99%	90%	44%	6%
light duty trucks	Reference	E-	99%	95%	81%	45%
medium duty trucks	Electric	REF	0%	0%	0%	1%
medium duty trucks	Electric	E+	0%	5%	39%	72%
medium duty trucks	Electric	E-	0%	2%	11%	39%
medium duty trucks	High Efficiency	REF	0%	0%	0%	0%
medium duty trucks	High Efficiency	E+	0%	0%	0%	0%
medium duty trucks	High Efficiency	E-	0%	0%	0%	0%
medium duty trucks	Hydrogen	REF	0%	0%	0%	0%
medium duty trucks	Hydrogen	E+	0%	1%	10%	18%
medium duty trucks	Hydrogen	E-	0%	0%	3%	10%
medium duty trucks	Reference	REF	100%	100%	99%	98%
medium duty trucks	Reference	E+	100%	93%	51%	10%
medium duty trucks	Reference	E-	100%	98%	86%	51%
transit buses	Electric	REF	0%	1%	1%	1%
transit buses	Electric	E+	0%	11%	72%	99%
transit buses	Electric	E-	0%	3%	21%	65%
transit buses	High Efficiency	REF	17%	19%	19%	19%
transit buses	High Efficiency	E+	17%	15%	5%	0%
transit buses	High Efficiency	E-	17%	17%	14%	6%
transit buses	Reference	REF	82%	80%	80%	80%
transit buses	Reference	E+	83%	74%	23%	1%
transit buses	Reference	E-	83%	80%	65%	29%

2.1.2. 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, provides the majority of final energy demand projections in our model. In scenario E+ and E- in subsectors where we did not have technology-level detail, we employed subsector-level estimates of energy efficiency (Table 5) and fuel switching (Table 6).

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 (Table 6). 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). These factors are given in Table 7.

Table 5. Energy efficiency measures

Sector	Subsector	Description
COMMERCIAL	OTHER	Year over year efficiency gains of 1%/year applied only in 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 only in 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 industry of 1%/year applied only in 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 6 Fuel switching measures

Sector	Subsector	Description
PRODUCTIVE	All – Buildings	75% of building fuel use (space heating) converted to electricity by 2050 (2070 in E-)
PRODUCTIVE	All – Process Heat	50% of fuel use converted to electricity by 2050 (2070 in E-); 25% converted to direct hydrogen use
PRODUCTIVE	All – Machine Drives	100% of fuel use converted to electricity by 2050 (2070 in E-)
PRODUCTIVE	AGRICULTURE – CROPS; CONSTRUCTION	75% of fuel use converted to electricity by 2050 (2070 in E-)

RESIDENTIAL	SECONDARY HEATING	90% of fuel demand for pipeline gas and 100% of fuel demand for LPG and diesel fuel is converted to electricity by 2050. (2070 in E-)
RESIDENTIAL	RESIDENTIAL OTHER	50% of LPG fuel demand and 90% of pipeline gas demand is switched to electricity by 2050 (2070 in E-)
COMMERCIAL	COMMERCIAL OTHER	70% of fuel demand for pipeline gas, diesel, and LPG is switched to electricity by 2050 (2070 in E-)
TRANSPORTATION	Passenger rail	70% of diesel switched to electricity by 2050 (2070 in E-)
TRANSPORTATION	Freight rail	50% of diesel switched to hydrogen by 2050 (2070 in E-)
TRANSPORTATION	School and intercity buses	90% of diesel and gasoline switched to electricity by 2050 (2070 in E-)
TRANSPORTATION	Shipping	50% of diesel and 25% fuel oil switched to hydrogen by 2050 (2070 in E-)
TRANSPORTATION	Recreational boats	50% of gasoline switched to electricity by 2050 (2070 in E-)
TRANSPORTATION	Motorcycles	70% of gasoline switched to electricity by 2040

Table 7 Ratio between LHV/HHV for different fuel conversions

Fuel switching measure	LHV/HHV ratio adjustment factor
Natural gas to hydrogen	1.036
Diesel to hydrogen	1.0747
LPG to hydrogen	1.06287

2.1.3. Flexible load

Flexible load constraints for RIO are generated with EnergyPATHWAYS using the assumptions in Table 8. The methodology by which load-shifting by flexible load is deployed is illustrated in Figure 2 and Figure 3. The native load shape is the base service demand shape without any flexibility applied. The sources used for native load shapes by subsector are given in Table 20. In addition to load shifting, industrial load shedding is assumed to remain at existing levels through 2050.

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Table 8 Flexible load for demand subsectors.

Service demand	Maximum service delay (hours)	Maximum service advance (hours)	Percent of load assumed flexible in 2050 (%)
Light duty vehicles	5	0	50%
Residential water heating	2	2	20%
Commercial water heating	2	2	20%

Figure 2 Building heating shape shown as an example of flexible load. The orange line is two hours delayed from the native shape, whereas the grey line is moved two hours sooner in time.

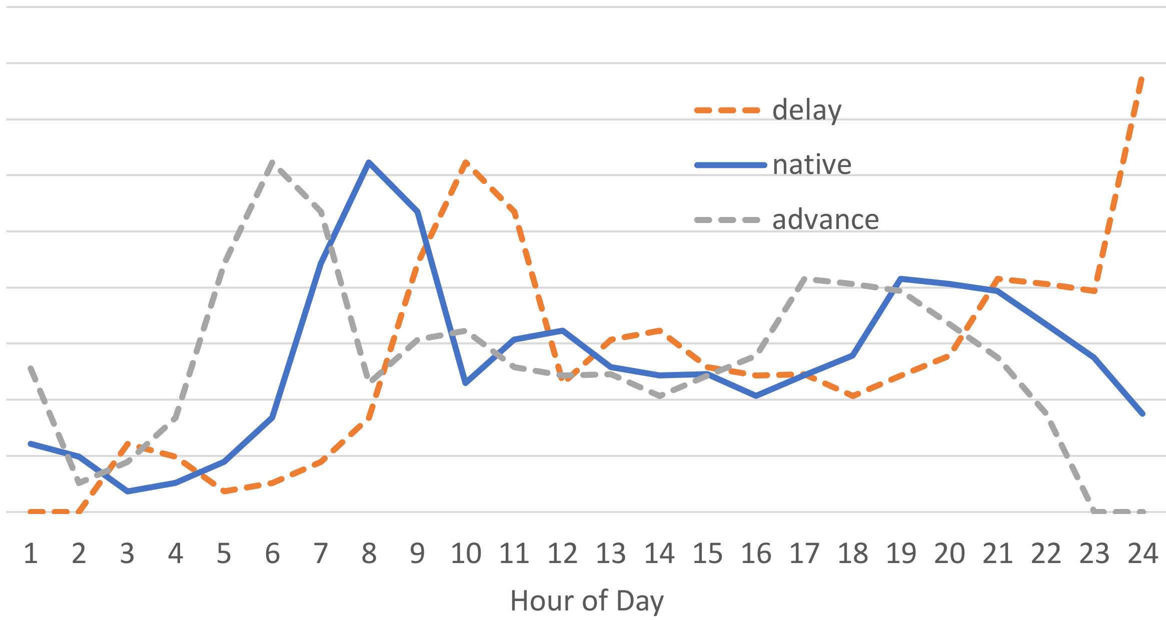
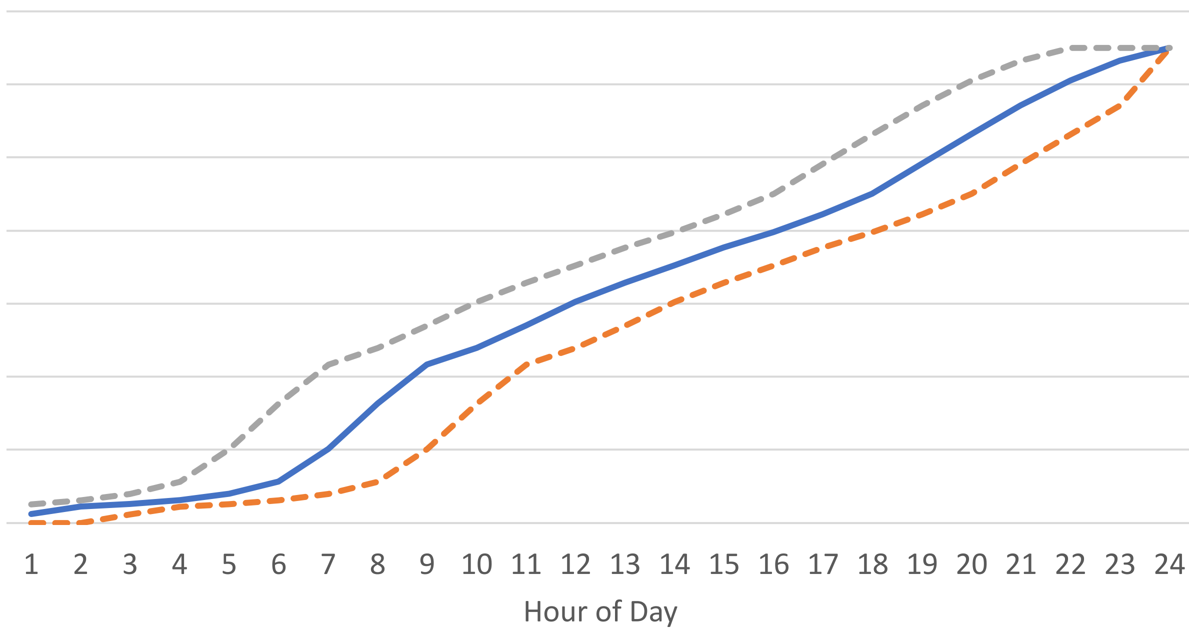


Figure 3 The delay or advance of service demand in time creates hourly cumulative energy constraints within RIO. Flexible load can shift between the grey and orange bounds, while respecting maximum and minimum power constraints.



2.2. Supply-side

Energy supply portfolios are selected using the RIO optimization to meet energy demand and economy-wide emissions constraints at least cost. A straight-line emissions trajectory from 2020 to 2050 was assumed. This emissions constraint, in combination with four other key factors – fuel price/supply, renewables cost and performance, biomass supply, and land-use constraints – drive the differences in supply-side results across scenarios. The assumptions used for these variables for each of the nine scenarios are shown in Table 9.

2.2.1. Supply-side assumptions

Table 9 Scenario assumptions within RIO

	REF	E+	E-	E+ RE+	E+ RE-	E+ B+	E- B+	E+ RE+ B+	E+ RE- B+
2050 E&I CO2 Constraint	None	-0.17 Gt/year	-0.17 Gt/year	-0.17 Gt/year	-0.17 Gt/year	-0.17 Gt/year	-0.17 Gt/year	-0.17 Gt/year	-0.17 Gt/year
2050 Land CO2	-0.3 Gt/year	-0.85 Gt/year	-0.85 Gt/year	-0.85 Gt/year	-0.85 Gt/year	-0.85 Gt/year	-0.85 Gt/year	-0.85 Gt/year	-0.85 Gt/year
2050 Non-CO2	~2 Gt/year	1.02 Gt/year	1.02 Gt/year	1.02 Gt/year	1.02 Gt/year	1.02 Gt/year	1.02 Gt/year	1.02 Gt/year	1.02 Gt/year
2050 Biomass Potential	12 quads	12 quads	12 quads	12 quads	12 quads	22 quads	22 quads	22 quads	22 quads

Renewable build constraint across U.S. (solar/wind)	Capped at 10% growth rate	Capped at 10% growth rate	Capped at 10% growth rate	Capped at 10% growth rate	Capped at current build rates	Capped at 10% growth rate	Capped at 10% growth rate	Capped at 10% growth rate	Capped at current build rates
Fossil fuel use	Allowed	Allowed	Allowed	Zero by 2050	Allowed	Allowed	Allowed	Zero by 2050	Allowed
Fossil fuel prices	Low	Low	Low	Low	Low	Low	Low	Low	Low
Existing nuclear	50% @ 80-year	50% @ 80-year	50% @ 80-year	Retire after 60	50% @ 80-year	50% @ 80-year	50% @ 80-year	Retire after 60	50% @ 80-year
New nuclear	Disallowed in CA	Disallowed in CA	Disallowed in CA	Disallowed in all regions	Disallowed in CA	Disallowed in CA	Disallowed in CA	Disallowed in all regions	Disallowed in CA
CCS supply curve	1.9 Gt/year	1.9 Gt/year	1.9 Gt/year	Disallowed	Expanded (3 Gt/yr)	1.9 Gt/year	1.9 Gt/year	Disallowed	Expanded (3 Gt/yr)

In addition to the emissions constraint, existing state-level renewable portfolio standard policies were applied across all scenarios. In the case of zones that include multiple states, these policies were applied based on the load ratio share across the zone. Except in the near term within certain regions, the national emissions constraint is more binding than specific electricity policies.

Additional assumptions common to all scenarios that affect the optimization results within the RIO model are provided in Table 10 and Table 11 below.

Table 10 Assumption in RIO common to all scenarios

Assumption	Value	Notes
Societal discount rate	2%	Pure time preference used in the optimization
Demand side cost of capital	3-8% real	Real cost of capital, depending on subsector
Cost of capital for nuclear	6% real	Real cost of capital, includes a risk premium for nuclear
Cost of capital for offshore wind	5% real	Real cost of capital, includes a risk premium for offshore wind
Cost of capital for all other electricity technologies (including transmission)	4% real	Real cost of capital, based on utility weighted average cost of capital
Cost of capital for fuel conversion technologies	10% real	Real cost of capital
Weather year used in electricity system	2011	Weather-matched load, wind, and solar
Hydro year	Average	Based on long-run average of hydro generation

Number of electricity day samples	41	Electricity operations sampled with 41 days in each year (984 hours). The 41 days were chosen independently for future years based on clustering around gross load and renewable production features. This is discussed further in section 5.4.
Transmission expansion	10x	Inter-regional transmission expansion was limited to ten times existing path ratings.
Availability of Allam cycle	Post 2030	Allam cycle technologies were assumed available post 2030 in the electricity sector with 100% carbon capture.
Compound annual growth rate of renewable installations & nuclear	10% per year	Supply chain & installation rates assumed to apply to solar, wind, and nuclear
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.
Fuel conversion technology maximum capacity factors	85%	Applied to all fuel conversion technologies to create a limit on total energy throughput per unit capacity.
Minimum coal capacity factors	35%	Applied to emulate self-scheduled coal generation and to reflect that most utilities have elected to retire coal when utilization rates fall rather than keep the plant for peaking capacity. Older coal in the U.S. have high fixed O&M and inflexible operations, which make them a poor fit for peaking capacity.

Table 11 Supply-side capital equipment assumed lifetimes

Name	**Physical Lifetime (years)**	**Book life (years)**
advanced nuclear plant	60	40
biomass power plant	50	40
biomass w/ccu allam power plant	50	40
biomass w/ccu power plant	50	40
coal igcc power plant	40	40
coal igcc with ccu power plant	40	40
distribution-sited solar pv power plant	30	20
gas combined cycle ccu oxyfuel	40	40
gas combined cycle power plant	40	40
gas combined cycle power plant with ccu	40	40
gas combustion turbine power plant	40	40
geothermal power plant_1	30	30
landfill gas to electricity power plant	20	20

li-ion	10	10
pulverized coal combined cycle ccu oxyfuel	40	40
pulverized coal power plant	50	40
rooftop solar pv power plant	30	20
offshore wind fixed power plant	30	20
offshore wind floating power plant	30	20
transmission-sited solar pv power plant	30	20
onshore wind power plant	30	20
biomass -> sng w/ccu	25	15
biomass - > sng	25	15
cellulosic ethanol plant	25	15
direct air capture plant	40	15
electric boiler	30	15
corn ethanol plant	25	15
h2 natural gas reformation	25	15
h2 natural gas reformation w/ccu	25	15
industrial coal boiler	25	15
industrial distillate fuel oil boiler	20	15
industrial hydrogen boiler	20	15
industrial lpg boiler	20	15
industrial other petroleum boiler	20	15
industrial petroleum coke boiler	25	15
industrial pipeline gas boiler	20	15
industrial residual fuel oil oil boiler	20	15
BECCS hydrogen production -> hydrogen blend	25	15
ATR w/ccu -> hydrogen blend	25	15
biomass pyrolysis	25	15
central-station hydrogen electrolysis	20	15
Fischer-Tropsch liquid fuel synthesis from H_2 + CO_2	25	15
methane synthesis from H_2 + CO_2	25	15
biomass ft -> diesel w/ccu	25	15
biomass ft -> diesel	25	15

2.3. Data Sources

2.3.1. United States EnergyPATHWAYS Database

The EnergyPATHWAYS 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 the EnergyPATHWAYS Detailed Methodology section. The general approach is described in the Methodology Overview section. On the supply-side, EnergyPATHWAYS consists of interconnected nodes representing the production, transformation, and delivery of energy to demand subsectors. A detailed description of how the data discussed below is used in the supply-side calculations is found in in the section EnergyPATHWAYS supply-side.

2.3.1.1. Demand–Side Data Description

Table 12 lists all the subsectors in the EnergyPATHWAYS 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 the section Energy Demand Projection. Note that no subsectors were modeled in this study using method C, but it is included here for completeness and comparison purposes.

Table 12 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	A
residential	residential dishwashing	A
residential	residential refrigeration	A
residential	residential freezing	A
residential	residential cooking	B
residential	residential secondary heating	D
residential	residential other appliances	D
residential	residential clothes washing	A
residential	residential lighting	A
residential	residential other - electric	D
residential	residential air conditioning	B
residential	residential space heating	B
commercial	commercial water heating	A
commercial	commercial ventilation	A
commercial	office equipment (p.c.)	D
commercial	office equipment (non-p.c.)	D
commercial	commercial space heating	A
commercial	commercial air conditioning	A
commercial	commercial lighting	A
commercial	district services	D
commercial	commercial refrigeration	A
commercial	commercial cooking	A
commercial	commercial other	D
transportation	heavy duty trucks	A
transportation	international shipping	D
transportation	recreational boats	D
transportation	transit buses	A
transportation	military use	D
transportation	lubricants	D
transportation	medium duty trucks	A
transportation	aviation	D
transportation	motorcycles	D
transportation	domestic shipping	D
transportation	passenger rail	D
transportation	school and intercity buses	A
transportation	freight rail	D
transportation	light duty trucks	A
transportation	light duty autos	A
industry	metal and other non-metallic mining	D
industry	aluminum industry	D
industry	balance of manufacturing other	D
industry	plastic and rubber products	D

industry	wood products	D
industry	bulk chemicals	D
industry	glass and glass products	D
industry	cement	D
industry	agriculture-other	D
industry	agriculture-crops	D
industry	fabricated metal products	D
industry	machinery	D
industry	computer and electronic products	D
industry	transportation equipment	D
industry	construction	D
industry	iron and steel	D
industry	food and kindred products	D
industry	paper and allied products	D
industry	electrical equip., appliances, and components	D

Table 13 describes the input data used to populate stock representations in the subsectors that employ Method A, and Table 14 describes the energy service demand inputs for these subsectors.

Table 13. Demand stock data

Subsector	Unit	Service Demand Dependent	Driver	Input Data: Geography	Input Data: Year(s)	Additional Detail	Source
Residential Lighting	Bulbs	No	Total square footage	Census division	2009-2050	Housing types; Lighting category	AEO 2019
Residential Clothes Washing	Clothes washer	No	Households	Census division	2009	Housing types	RECS 2009
Residential Clothes Drying	Clothes dryer	No	Households	Census division	2009	Housing types	RECS 2009
Residential Dishwashing	Dishwashers per household	No	Households	Census division	2009	Housing types	RECS 2009
Residential Refrigeration	Cubic feet	No	Households	Census division	2009	Housing types	RECS 2009
Residential Freezing	Cubic feet	No	Households	Census division	2009	Housing types	RECS 2009
Commercial Water Heating	Capacity factor	Yes	Commercial square feet	Census division	2012	Building types	CBECS 2012
Commercial Space Heating	Capacity factor	Yes	Commercial square feet	Census division	2012	Building types	CBECS 2012

Commercial Air Conditioning	Capacity factor	Yes	Commercial square feet	Census division	2012	Building types	CBECS 2012
Commercial Lighting	Capacity factor	Yes	n/a	Census division	2012	Building types	CBECS 2012
Commercial Refrigeration	Capacity factor	Yes	Commercial square feet	Census division	2012	Building types	CBECS 2012
Commercial Cooking	Capacity factor	Yes	Commercial square feet	Census division	2012	Building types	CBECS 2012
Commercial Ventilation	Capacity factor	Yes	Commercial square feet	Census division	2012	Building types	CBECS 2012
Light Duty Autos	Cars	No	n/a	US*	2015-2050	n/a	AEO 2019
Light Duty Trucks	Trucks	No	n/a	US*	2015-2050	Light truck class	AEO 2019
Medium Duty Trucks	Truck	No	n/a	US*	2015-2050	n/a	AEO 2019
Heavy Duty Trucks	Truck	No	n/a	US*	2015-2050	n/a	AEO 2019
Transit Buses	Bus	Yes	n/a	US*	2014	n/a	De Vita et al.[1]

* Down-scaled to state level by vehicle registrations

Table 14. Service demand inputs

Subsector	Unit	Stock Dependent	Driver	Input Data: Geography	Input Data: Year(s)	Additional Detail	Source
Residential Lighting	klm-hr per housing unit	No	Total square feet	US	2012	Lighting category	Ashe et al.[2]
Residential Clothes Washing	Cu. Ft. Cycle	Yes	n/a	Census division	2009	Housing types	RECS 2009
Residential Clothes Drying	Pound	Yes	n/a	Census division	2009	Housing types	RECS 2009
Residential Dishwashing	Cycle	Yes	n/a	Census division	2009	Housing types	RECS 2009
Residential Refrigeration	Cu. Ft.	Yes	n/a	Census division	2009	Housing types	RECS 2009
Residential Freezing	Cu. Ft.	Yes	n/a	Census division	2009	Housing types	RECS 2009

[1] A. De Vita et al., "Technology pathways in decarbonisation scenarios" (Tractebel, Ecofys, E3-Modelling: Brussels, Belgium, 2018).

[2] M. Ashe et al., “2010 U.S. Lighting Market Characterization” (U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, 2012).

Commercial Water Heating	Terabtu	No	Commercial square feet	Census division	2012 - 2050	Building types	AEO 2019
Commercial Space Heating	Terabtu	No	Commercial square feet	Census division	2012 - 2050	Building types	RECS 2009, AEO 2019
Commercial Air Conditioning	Terabtu	No	Commercial square feet	Census division	2012 - 2050	Building types	AEO 2019
Commercial Lighting	gigalumen_year	No	Commercial square feet	Census division	2012 - 2050	Building types	AEO 2019
Commercial Refrigeration	Terabtu	No	Commercial square feet	Census division	2012 - 2050	Building types	AEO 2019
Commercial Cooking	Terabtu	No	Commercial square feet	Census division	2012 - 2050	Building types	AEO 2019
Commercial Ventilation	gigacubic_foot	No	Commercial square feet	Census division	2012 - 2050	Building types	AEO 2019
Light Duty Autos	Gigamile	No	n/a	US*	2015-2050		AEO 2019
Light Duty Trucks	Gigamile	No		US*	2015-2050	Light truck class	AEO 2019
Medium Duty Trucks	Mile	No		US*	2015-2050		AEO 2019
Heavy Duty Trucks	Mile	No	N/A	US*	2015-2050		AEO 2019
Transit Buses	Mile	No	Population	Census division	1995-2008		AEO 2017

* Down-scaled to state-level using vehicle miles traveled estimates.

Table 15 describes input data sources for stocks in subsectors that use Method B, and Table 16 describes input data sources for energy demand in these subsectors.

Table 15. Equipment stock data sources for Method B subsectors

Subsector	Unit	Service Demand Dependent	Driver	Input Data: Geography	Input Data: Year(s)	Additional Detail	Source
Residential Water Heating	Water heater	No	Households; Residential Heating Energy Share	Census division	2015-2050	Housing types	AEO 2019
Residential Space Heating	Space heater	No	Households; Residential Heating Energy Share; Heating Degree Days	Census division	2015-2050	Housing types	AEO 2019
Residential Air Conditioning	Air conditioner	No	Households; Cooling Degree Days; House Age Index	Census division	2015-2050	Housing types	AEO 2019

Residential Cooking	Cooktop	No	Households; Residential Heating Energy Share	Census division	2015-2050	Housing types	AEO 2019

Table 16. Energy demand data sources for Method B subsectors

Subsector	Unit	Driver	Input Data: Geography	Input Data: Year(s)	Additional Detail	Source
Residential Water Heating	MMBTU	Households; Residential Heating Energy Share	Census division	2015-2050	Housing types	AEO 2019
Residential Space Heating	MMBTU	Households; Residential Heating Energy Share; Heating Degree Days	Census division	2015-2050	Housing types	AEO 2019
Residential Air Conditioning	MMBTU	Households; Cooling Degree Days; House Age Index	Census division	2015-2050	Housing types	AEO 2019
Residential Cooking	MMBTU	Households; Residential Heating Energy Share	Census division	2015-2050	Housing types	AEO 2019

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 17.

Table 17. Demand technology inputs for Method B subsectors

Subsector	Technologies	Source
Residential Space Heating and Air Conditioning	Air source heat pump (ducted)	Cost: P. Jadun et al.[3] Efficiency: P. Jadun et al.
	Ductless mini-split heat pump	Cost: J. Dentz et al.[4] Efficiency: P. Jadun et al.
	Remainder	Navigant Consulting[5]
Residential Water Heating	Heat pump water heater	P. Jadun et al.
	Remainder	Navigant Consulting
Residential Remaining Subsectors	All	Navigant Consulting
	Air source heat pump	P. Jadun et al.

[3] P. Jadun et al., "Electrification Futures Study: End-Use Electric Technology Cost and Performance Projections through 2050" (TP-6A20-70485, NREL, 2017; https://www.nrel.gov/docs/fy18osti/70485.pdf).

[4] J. Dentz et al., "Mini-Split Heat Pumps Multifamily Retrofit Feasibility Study" (U.S. Department of Energy; Office of Energy Efficiency and Renewable Energy, 2014).

[5] Navigant Consulting, "Updated Buildings Sector Appliance and Equipment Costs and Efficiencies" (U.S. Energy Information Administration, 2014;

Commercial Space Heating and Air Conditioning	Remainder	Navigant Consulting
Commercial Water Heating	Heat pump water heater	P. Jadun et al.
	Remainder	Navigant Consulting
Commercial Lighting	All	AEO 2017
Commercial Building Shell	All	AEO 2017
Light-duty Vehicles	Battery electric vehicle and plug-in hybrid electric vehicle	Cost: (BNE 2019[6], ICCT 2019[7], P. Jadun et al.) Efficiency: P. Jadun et al.
	Remainder	Efficiency: AEO 2019 Cost: AEO 2019
Medium Duty Vehicles	Battery electric	P. Jadun et al.
	Hydrogen fuel cell	E. den Boer et al.[8]
	Remainder (CNG, diesel, etc.)	TA Engineering[9]
Heavy Duty Vehicles	Battery electric	P. Jadun et al.
	Hydrogen fuel cell	L. Fulton, M. Miller[10]
	Reference diesel, gasoline and propane	TA Engineering
	Diesel hybrid and liquefied pipeline gas	TA Engineering
Transit Buses	All	P. Jadun et al.

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

Table 18. Energy demand data sources for Method D subsectors

Subsector	Unit	Driver	Input Data: Geography	Other Downscaling method	Input Data: Year(s)	Additional Detail	Source

[6] "Electric Vehicle Outlook" (Finance, Bloomberg New Energy, 2019; https://about.bnef.com/electric-vehicle-outlook/).

[7] N. Lutsey, M. Nicholas, “Update on Electric Vehicle Costs in the United States through 2030” (International Council on Clean Transportation, 2019; https://theicct.org/sites/default/files/publications/EV_cost_2020_2030_20190401.pdf).

[8] E. den Boer et al., “Zero Emissions Trucks: An Overview of State-of-the-Art Technologies and Their Potential” (CE Delft, 2013).

[9] TA Engineering Inc., “TRUCK5.1: Heavy Vehicle Market Penetration Model Documentation” (National Petroleum Council, 2012;

[10] L. Fulton, M. Miller, “Strategies for Transitioning to Low-Emissions Trucks” (UC Davis Institute of Transportation Studies, 2015; https://steps.ucdavis.edu/files/06-11-2015-STEPS-NCST-Low-carbon-Trucks-in-US-06-10-2015.pdf).

Residential computers and related	MMBTU	Households	Census division		2015-2050	Housing types; Computer equipment types	AEO 2019
Residential televisions and related	MMBTU	Households	Census division		2015-2050	Housing types; Television equipment types	AEO 2019
Residential Secondary Heating	MMBTU per household	Households; HDD	Census division		2015-2050	Housing types	AEO 2019
Residential other uses	MMBTU	Households	Census division		2015-2050	Housing types; Other equipment types	AEO 2019
Residential Furnace Fans	MMBTU	Households	Census division		2015-2050	Housing types	AEO 2019
Office Equipment (P.C.)	Quads	Commercial square footage	US		2015-2050		AEO 2019
Office Equipment (Non-P.C.)	Quads	Commercial square footage	US	Employment in all industries (NAICS, no code) 2007	2015-2050		AEO 2019
Commercial Other	Quads	Commercial square footage	Census Division	Employment in all industries (NAICS, no code) 2007	2015-2050	Building Types	AEO 2019
Non-CHP District Services	kilobtu per square feet	Commercial square footage	Census division	Households 2010	2012	Building Types	AEO 2019
CHP District Services	Terabtu	Commercial square footage	Census Division	Households 2010	2015-2050	Building types	AEO 2019
Domestic Shipping	Terabtu	Vessel Bunkering Sales	US		2015-2050		AEO 2019

Military Use	Terabtu	Military Air Bases (Count)	US		2015-2050		AEO 2019
Motorcycles	Terabtu	Motorcycle VMT	US		2015-2050		AEO 2019
Lubricants	Terabtu	Population	US		2015-2050		AEO 2019
International Shipping	Terabtu	Vessel Bunkering Sales	US		2015-2050		AEO 2019
Recreational Boats	Terabtu	n/a	US	Households 2010	2015-2050		AEO 2019
School and intercity buses	Terabtu	Passenger miles, population	US		2015-2050		AEO 2019
Passenger rail	Terabtu	Rail passenger miles	Census division	Rail Fuel Use	2015-2050	Passenger rail mode (commuter, intercity, transit)	AEO 2019
Freight rail	Terabtu	Historical non-coal freight miles	Census division	Rail Fuel Use	2015-2050	Industrial end-use category	AEO 2019
Aviation	Terabtu	Passenger-mile departures	US		2015-2050	Industrial end-use category	AEO 2019
Agriculture – Crops	Terabtu	GDP by Industry	Census region		2015 – 2050	Industrial end-use category	AEO 2019
Agriculture – Other	Terabtu	GDP by Industry	Census region		2015-2050	Industrial end-use category	AEO 2019
Aluminum Industry	Terabtu	Aluminum Production	Census region		2015-2050	Industrial end-use category	AEO 2019
Balance of Manufacturing Other	Terabtu	Value of Shipments by Industry	Census region		2015-2050	Industrial end-use category	AEO 2019
Bulk Chemicals	Terabtu	Facility Emissions by Industry	Census region		2015-2050	Industrial end-use category	AEO 2019

Cement	Terabtu	Facility Emissions by Industry	Census region		2015-2050	Industrial end-use category	AEO 2019
Cement CO2 Capture	Tonnes of Captured CO2	EPA Flight Data	Census Division		2020-2050	n/a	Princeton 2020[11]
Computer and Electronic Products	Terabtu	Value of Shipments by Industry	Census region		2015-2050	Industrial end-use category	AEO 2019
Construction	Terabtu	GDP by Industry	Census region		2015-2050	Industrial end-use category	AEO 2019
Electrical Equip., Appliances, and Components	Terabtu	Value of Shipments by Industry	Census region		2015-2050	Industrial end-use category	AEO 2019
Fabricated Metal Products	Terabtu	Value of Shipments by Industry	Census region		2015-2050	Industrial end-use category	AEO 2019
Food and Kindred Products	Terabtu	Facility Emissions by Industry	Census region		2015-2050	Industrial end-use category	AEO 2019
Glass and Glass Products	Terabtu	Facility Emissions by Industry	Census region		2015-2050	Industrial end-use category	AEO 2019
Iron and Steel	Terabtu	Facility Emissions by Industry	Census region		2015-2050	Industrial end-use category	Princeton 2020[11]
Lime	Terabtu	Facility Emissions by Industry	Census region		2015-2050	Industrial end-use category	AEO 2019
Machinery	Terabtu	Value of Shipments by Industry	Census region		2015-2050	Industrial end-use category	AEO 2019
Metal and Other Non-metallic Mining	Terabtu	GDP by Industry	Census region		2015-2050	Industrial end-use category	AEO 2019

[11] Net-Zero America Project, Princeton University, 2020.

Paper and Allied products	Terabtu	Facility Emissions by Industry	Census region		2015-2050	Industrial end-use category	AEO 2019
Plastic and Rubber Products	Terabtu	Value of Shipments by Industry	Census region		2015-2050	Industrial end-use category	AEO 2019
Transportation Equipment	Terabtu	Value of Shipments by Industry	Census region		2015-2050	Industrial end-use category	AEO 2019
Wood products	Terabtu	Value of Shipments by Industry	Census region		2015-2050	Industrial end-use category	AEO 2019

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 19 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 19. Demand Drivers

Driver	Geographic Granularity	Data Year (s)	Additional Detail	Source
Commercial Square Footage	Census Division	2015-2050	Building Types	AEO 2019
GDP by Industry	State	1997-2018		BEA 2012[12]
VOS by Industry	State	2012		Commodity Flow Survey [13]
Facility Emissions by Industry	State	2017	Industrial Subcategory	EPA 2018[14]
Aluminum Production	State	2017		EPA 2018

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[12] "Regional Economic Accounts: Annual GDP by State" (U.S. Bureau of Economic Analysis, 2012; https://apps.bea.gov/regional/downloadzip.cfm.

[13] "Transportation—Commodity Flow Survey: United States: 2012" (Publication EC12TCF-US, U.S. Census Bureau & U.S. Bureau of Transportation Statistics. 2015.)

[14] "2018 Greenhouse Gas Reporting Program." (U.S. Environmental Protection Agency, 2019; https://www.epa.gov/ghgreporting).

Household Heating Fuel Share	State	2017	Housing Type	Census Bureau, 2018[15]
House Age Index Share	State	2017		Census Bureau, 2018
Heating Degree Days	State	2000; 2017		National Weather Service[16]
Cooling Degree Days	State	2000; 2017		National Weather Service
Households	State	2017	Building Types	Census Bureau, 2018
LDV VMT	State	2017		DOT 2018[17]
LDA Registrations	State	2017		DOT 2018
LDT Registration	State	2017		DOT 2018
HDT Registrations	State	2017		DOT 2018
HDV VMT	State	2017		DOT 2018
MDV VMT	State	2017		DOT 2018
Motorcycle VMT	State	2017		DOT 2018

Table 20 shows the data sources for energy service demand load shapes by subsector, which are used to build system-level load shapes bottom-up.

Table 20. 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, 2012	FERC
Light-Duty Vehicles (LDVs)	All LDVs	United States	Month-hour-weekday/weekend average, separated	Evolved Energy Research analysis of 2016 National

[15] "2017 American Community Survey" (U.S. Census Bureau, 2018; http://factfinder.census.gov.)

[16] "Degree Days Statistics" (National Weather Service: Climate Prediction Center, Accessed November 1, 2019;

[17] Federal Highway Administration, "Highway Statistics" (Highway Statistics. U.S. Department of Transportation, 2018; https://www.fhwa.dot.gov/policyinformation/statistics.cfm).

			by home vs work charging	Household Travel Survey[18]
Water Heating (Gas Shape)	Residential hot water			Northwest Energy Efficiency Alliance Residential Building Stock Assessment Metering Study (Northwest)[19]
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[20]
Commercial Lighting Internal	Commercial lighting			
Commercial Refrigeration	Commercial refrigeration			
Commercial Ventilation	Commercial ventilation			
Commercial Office Equipment	Commercial office equipment			
Industrial Machine Drives	Machine drives			
Industrial Process Heating	Process heating			
Electric_furnace_res	Electric resistance heating technologies	IECC Climate Zone by state (114 total geographical regions)	Hourly, 2012 weather	Evolve Energy Research Regressions trained on NREL building simulations in select U.S. cities for a typical meteorological year and then run on county level HDD and CDD for 2102 from the National Oceanic and Atmospheric
Reference_central_ac_res	Central air conditioning technologies			
High_efficiency_central_ac_res	High-efficiency central air conditioning technologies			
Reference_room_ac_res	Room air conditioning technologies			
High_efficiency_room_ac_res	High-efficiency room air conditioning technologies			
Reference_heat_pump_heating_res	ASHPs			

18 https://nhts.ornl.gov/

19 https://neea.org/data/residential-building-stock-assessment

20 https://loadshape.epri.com/enduse

High_efficiency_heat_pump_heating_res	High-efficiency ASHPs			Administration (NOAA)[21]
Reference_heat_pump_cooling_res	ASHPs			
High_efficiency_heat_pump_cooling_res	High-efficiency ASHPs			
Chiller_com	Commercial chiller technologies			
Dx_ac_com	Direct expansion air conditioning technologies			
Boiler_com	Commercial boiler technologies			
Furnace_com	Commercial electric furnaces			
Flat shape	MDV and HDV charging	United States	n/a	n/a

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

2.3.1.2. Supply–Side Data Description

Table 21 shows the data sources used in EnergyPATHWAYS for resource potential, technology cost and performance, product costs, and delivery costs. The technology cost and efficiency numbers are compiled and listed in a companion Excel sheet to this appendix, along with resource supply curves for renewables, biomass, and carbon sequestration.

Table 21. Supply-side data sources

Data Category	Data Description	Supply Node	Source
Resource Potential	Binned resource potential (GWh) by state with associated resource performance (capacity factors) and transmission costs to reach load.	Transmission – sited Solar PV (3 resource bins); Onshore Wind (10 resource bins); Offshore Wind – Fixed (5 resource bins); Offshore Wind – Floating (10 resource bins); Geothermal	Eurek et al. 2017[22]

[21] Completed for and published in the Electrification Futures Study, 2008: https://www.nrel.gov/analysis/electrification-futures.html

[22] K. Eurek et al. "Regional Energy Deployment System (ReEDS) Model Documentation: Version 2016" (Publication TP-6A20-67067, NREL, 2017; www.nrel.gov/docs/fy17osti/67067.pdf).

Resource Potential	Binned resource potential of biomass resources by state with associated costs	Biomass Primary – Herbaceous; Biomass Primary – Wood; Biomass Primary – Waste; Biomass Primary – Corn	DOE 2016[23]
Resource Potential	Binned annual carbon sequestration injection potential by state with associated costs	Carbon Sequestration	Princeton 2020[24]
Product Costs	Commodity cost of natural gas at Henry Hub	Natural Gas Primary – Domestic	AEO 2019
Product Costs	Undelivered costs of refined fossil products	Refined Fossil Diesel; Refined Fossil Jet Fuel; Refined Fossil Kerosene; Refined Fossil Gasoline; Refined Fossil LPG	AEO 2019
Product Costs	Commodity cost of Brent oil	Oil Primary – Domestic; Oil Primary - International	AEO 2019
Delivery Infrastructure Costs	AEO transmission and delivery costs by Electricity Market Module region	Electricity Transmission Grid; Electricity Distribution Grid	AEO 2019
Delivery Infrastructure Costs	AEO transmission and delivery costs by census division and sector	Gas Transmission Pipeline; Gas Distribution Pipeline	AEO 2019
Delivery Infrastructure	AEO delivery costs by fuel product	Gasoline Delivery; Diesel Delivery; Jet Fuel; LPG Fuel Delivery; Kerosene Delivery	AEO 2019
Technology Cost and Performance	Renewable and conventional electric technology installed cost projections	Nuclear Power Plants; Onshore Wind Power Plants; Offshore Wind Power Plants; Transmission – Sited Solar PV Power Plants; Distribution – Sited Solar PV Power Plants; Rooftop PV Solar Power Plants; Combined – Cycle Gas Turbines; Coal Power Plants; Combined – Cycle Gas Power Plants with CCS; Coal Power Plants with CCS; Gas Combustion Turbines	ATB 2019[25]
Technology Cost and Performance	Electric fuel cost projections including electrolysis and fuel synthesis facilities	Central Hydrogen Grid Electrolysis; Synthesis of Fischer-Tropsch fuels from H2 + CO2; Synthesis of methane from H2 + CO2	Princeton 2020[24]
Technology Cost and Performance	Hydrogen Gas Reformation costs with and without carbon capture	H2 Natural Gas Reformation; H2 Natural Gas Reformation w/CCS	Princeton 2020[24]
Technology Cost and Performance	Nth plant Direct air capture costs for	Direct Air Capture with Sequestration; Direct Air Capture with Utilization	APS 2011

[23] M. H. Langholtz et al., "2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy" (Publication DOE/EE-1440, ORNL/TM-2016/160, Department of Energy, 2016; https://doi.org/10.2172/1271651).

[24] Net-Zero America Project, Princeton University, 2020.

[25] "Annual Technology Baseline" (National Renewable Energy Laboratory, 2019; https://atb.nrel.gov/electricity/2019/).

	sequestration and utilization		
Technology Cost and Performance	Gasification cost and efficiency of conversion including gas upgrading.	Biomass Gasification; Biomass Gasification with CCS	Princeton 2020[24]
Technology Cost and Performance	Cost and efficiency of renewable Fischer-Tropsch diesel production.	Renewable Diesel; Renewable Diesel with CCS	Princeton 2020[24]
Technology Cost and Performance	Cost and efficiency of industrial boilers	Electric Boilers; Other Boilers	P. Capros et al.[26]
Technology Cost and Performance	Cost and efficiency of other, existing power plant types	Fossil Steam Turbines; Coal Power Plants	T. L. Johnson [27]

[26] P. Capros et al., “Technology Pathways in Decarbonisation Scenarios” (Advanced System Studies for Energy Transition, 2018)

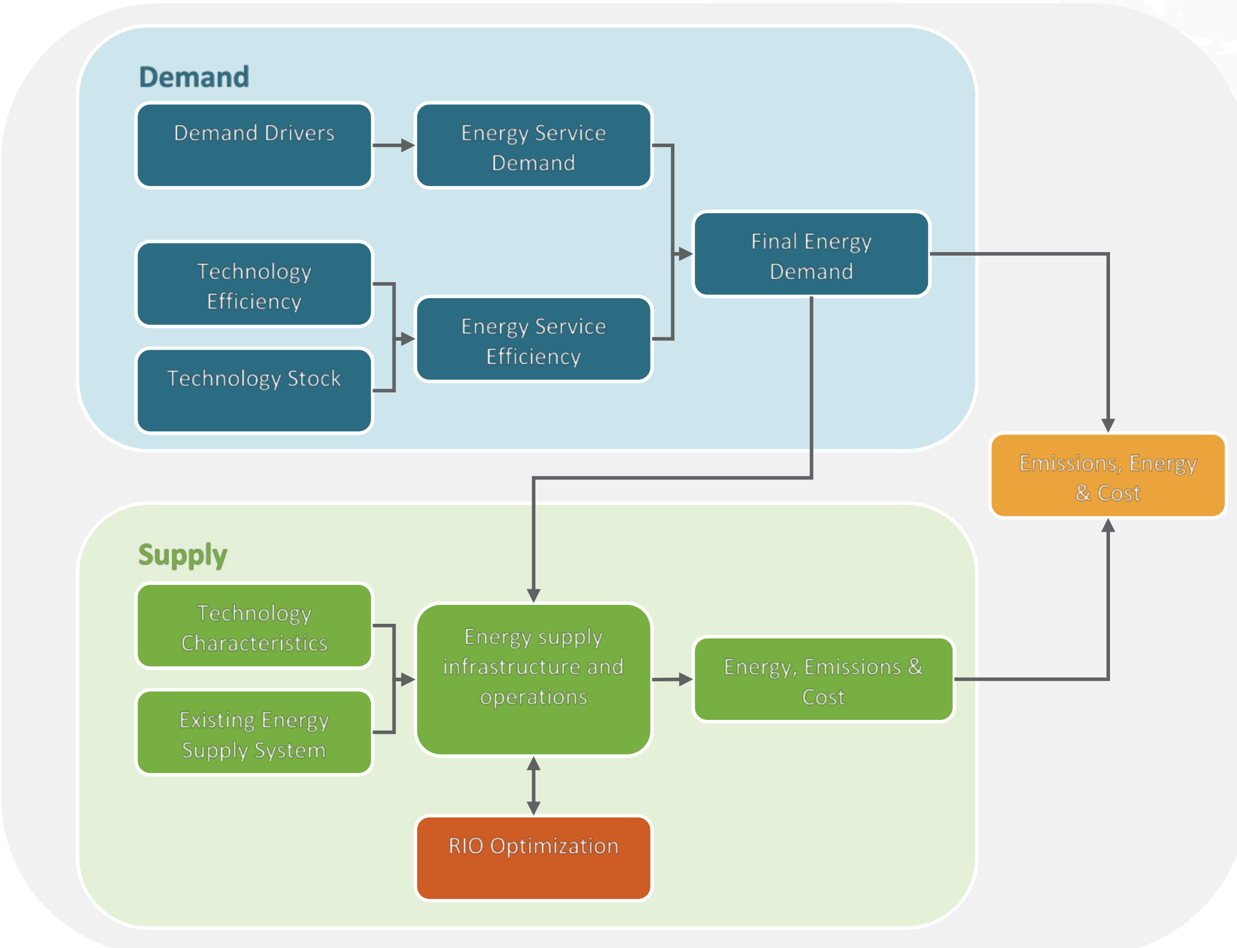
[27] T. L. Johnson, “MARKAL Scenario Analyses of Technology Options for the Electric Sector: The Impact on Air Quality” (Publication 600/R-06/114, EPA, 20006; https://nepis.epa.gov/Exe/ZyPDF.cgi/P10089YQ.PDF?Dockey=P10089YQ.PDF).

3. Methodology Overview

3.1. General Approach

The modeling work was performed using RIO and EnergyPATHWAYS (EP), 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, for each of sixteen geographic regions in the U.S. 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 analysis because it models in detail interactions among electricity generation, fuel production, and carbon capture, allowing it to accurately evaluate the economics of (idealized) coupling between these sectors; tracks storage state of charge over an entire year, allowing it to accurately assess balancing requirements in electricity systems with very high levels of VRE; and 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 full 30-year modeling period, 2020 – 2050. The steps of the modeling analysis are framed at a high level by the flow chart in Figure 4.

Figure 4 demand-side & supply-side model flow chart



3.2. EnergyPATHWAYS (EP)

On the demand side, we developed a model of US energy demand by sector across the economy**.** For this purpose we created a bottom-up stock-rollover model of all energy-using technologies in the economy called EnergyPATHWAYS (EP) 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. It accounts for the costs and emissions associated with producing, transforming, delivering, and consuming energy in an economy.

The model assumes decision-making stasis as a baseline. For example, when projecting energy demand for residential space heating, EP implicitly assumes that consumers will replace their water heater with a water heater of a similar type. This baseline does, however, include efficiency gains and technology development that are either required by codes and standards or can be reasonably anticipated based on techno-economic projections. Departures from the baseline are made explicitly in scenarios through the application of *measures*, which are explicit user-defined changes to the baseline. Measures can take the form of changes in sales shares, the adoption of a specific technology in a specific year, or in changes of stock, the total technology deployed in a specific year. Approximately 30 economic subsectors are represented by stock rollover, meaning the changes in stock as new stock is added and old stock is retired. Other sectors that lack the data to create a stock representation are modeled with aggregate energy demands that change over time.

Inputs to determining final energy demand include:

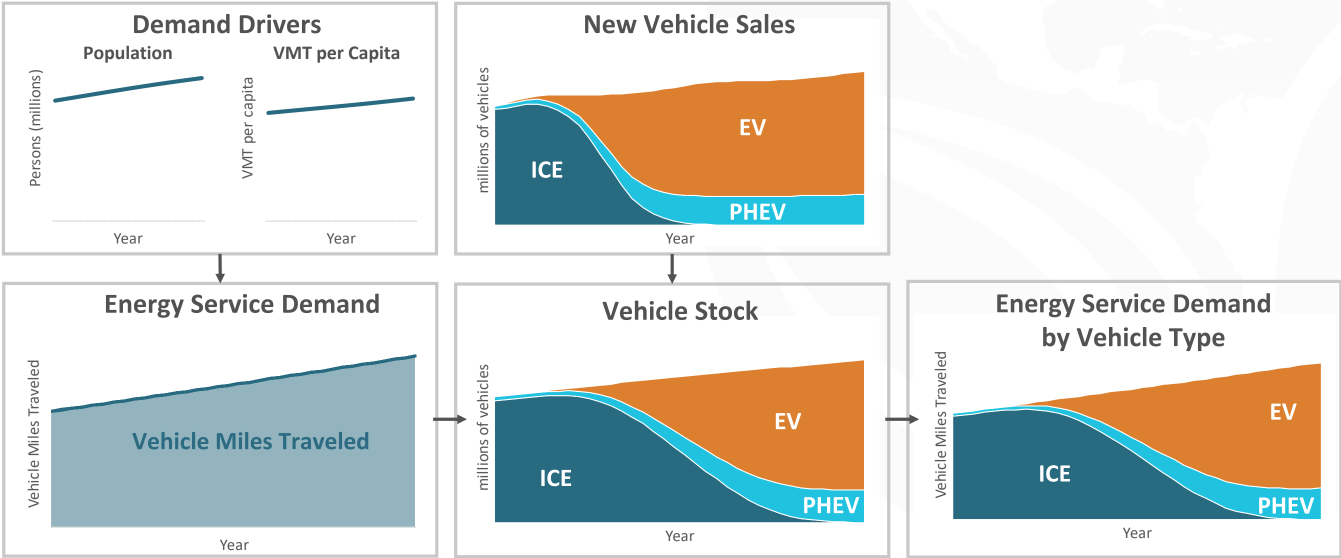
1. Demand drivers – the characteristics of the energy economy that determine how people consume energy and in what quantity over time. Examples include population, square footage of commercial building types, and vehicle miles traveled. Demand drivers are the basis for forecasting future demand for energy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

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

3. Technology stock – what quantity of each type of energy-using technology is present in the population and how that stock changes over time. For example, how many gasoline, diesel, and electric cars are on the road in each year. The composition of the stock in combination with the efficiency of each stock type for providing services is referred to as the service efficiency, fuel economy being a well-known example.

EP determines sectoral energy demand for every year over the model time horizon by dividing service demand by service efficiency. An example for the light duty vehicle sector is shown in Figure 5.

Figure 5 Example calculation of service demand for the light duty vehicle fleet

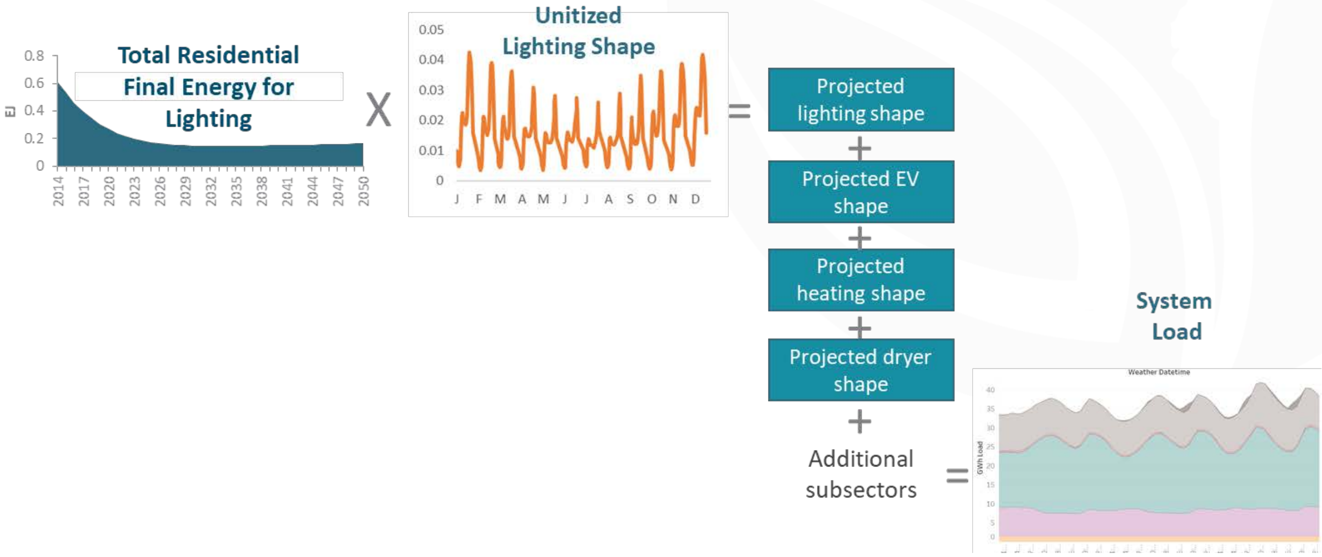


The demand drivers in this example include population and vehicle miles traveled per capita, both of which are increasing. The energy service demand – total vehicle miles traveled – is therefore also increasing. Vehicle sales are changing over time, as the economics of different options change and/or new policies are put in place. Vehicle sales and retirements produce changes in the composition of vehicle stock. By dividing service demand by service efficiency for each vehicle type in the stock, we obtain the final energy demand for electricity and fuels.

The aggregated final energy demand from this and all other sectors of the economy constitutes the final energy demand for the US as a whole that must be supplied through electricity and fuels. These demands form the inputs into the supply side optimization step of the modeling, with the supply determined separately for each region.

The supply side requires final energy demand by hour to dispatch electricity supply infrastructure subject to operating constraints, which is needed to find optimal supply infrastructure investments. Figure 6 provides an overview of the process of determining hourly load. Each electricity-consuming sub-sector in the model has an associated unitized annual load shape with hourly time steps. Electrical final energy is multiplied by the load shape to obtain the hourly load shape of each subsector. These are aggregated to obtain system load. Temporally resolved shapes are not used for other fuel consumption because in most cases, storage capability exists in sufficient quantity today, or is relatively inexpensive to build. In these cases, the patterns of fuel consumption were not judged to be of paramount importance, particularly when the volume of fuel consumption is declining and most fuel infrastructure under-utilized.

Figure 6 Producing hourly load shapes



3.3. Regional Investment and Operations Model (RIO)

On the supply side, we determined the least-cost investments in energy supply infrastructure and fuels to meet carbon and other constraints using a capacity expansion model we created called the Regional Investment and Operations model (RIO). At a high level, RIO optimizes investments and operations based on current energy system infrastructure, the final energy demand that must be met over the model time horizon, the technology and fuel options available over that time including their efficiency, operating, and cost characteristics, and clean energy goals (such as RPS, CES, and carbon intensity) at US-wide and regional geographies.

RIO blends capacity expansion and detailed sequential hourly system operations to capture the value each resource type can offer the system as part of an optimally dispatched portfolio. Rather than being a snapshot valuation, either as price taker with static prices, or during a single year in time, RIO captures the full set of dynamics over the lifetime of the system.

Investments that look attractive under current system conditions may not be cost effective over a lifetime of operations. RIO puts every investment into the lifetime context of future policy, fuel pricing, technology pricing, and demand side potential.

RIO can be differentiated from conventional planning tools along three dimensions:

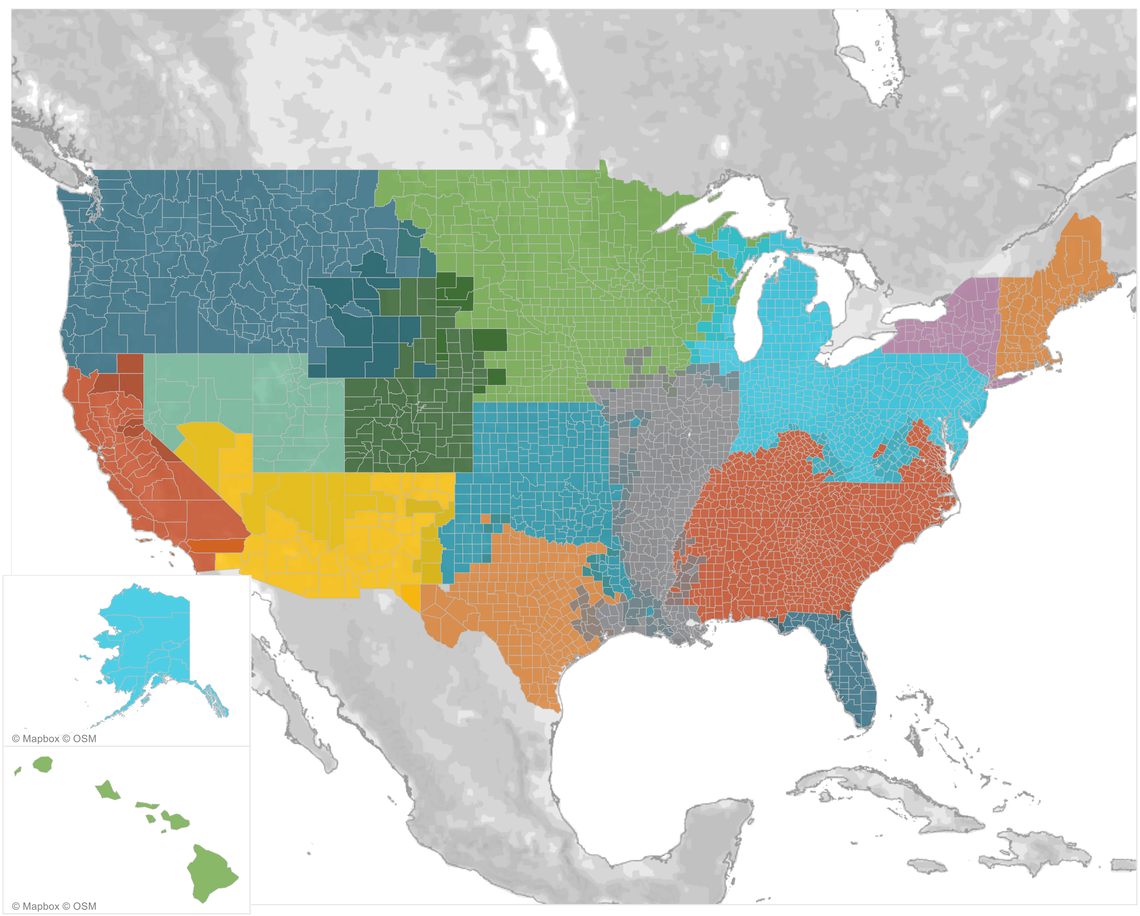
- **Optimal investment** – i.e., how well the model selects the least cost resource portfolio. RIO is distinctive in that it can select the least cost path through a rapidly expanding state space of options and accurately capture the operational benefits of new technologies and novel grid solutions. This is not possible using conventional production simulation approaches to planning. RIO also exceeds the capabilities of conventional capacity expansion models because it incorporates optimal investment in the energy economy beyond the electricity sector alone. This includes technologies such as long-term storage resources, biofuels production, electric fuel production, and complex retirement and repowering options for existing generation – those that other capacity expansion models struggle to deal with. RIO can also optimize investment in select demand-side resources that are appropriate to include in an optimization framework.

- **Temporal granularity** – i.e., how well the model can capture the timesteps necessary for optimal investment. This is the key metric in systems with high levels of variable generation (wind & solar) where correctly characterizing the various balancing solutions – short-duration batteries, long-duration storage, electric fuels, demand flexibility, biofuel use – requires high temporal resolution. RIO includes hourly operations that allow for optimal investment in all of these resource types. Capacity expansion models typically use longer time slices to model investments and consequently miss important system dynamics in balancing the electricity system reliably.

- **Spatial granularity** – i.e., how well the model can represent the locational aspects of electricity and fuels operations and planning. Due to the tradeoffs necessary to bring in additional temporal granularity, RIO uses a limited number of transmission zones to achieve reasonable run-times while still representing the full set of potential technological solutions, their detailed operational dynamics, and their costs. It allows for optimal investment in the transmission between those zones, allowing users to examine the tradeoffs between more decentralized, regional approaches to decarbonization versus coordination across regions.

Many regions of the US are highly interconnected to surrounding regions through electricity transmission and fuels supply. RIO represents these transmission zones and the constraints on transferring energy between them. The modeled regional topology of the US is shown in Figure 7 below. Constraints between regions start from present day electricity transmission capacity and include the planned transmission expansion. Transmission of electricity is allowed to expand between regions, depending on the scenario, by a maximum of ten times the present-day capacity. Expanding transmission has an associated cost per additional MW of capacity that is specific to each modeled transmission corridor (Table 21).

Figure 7 Model topology for RIO



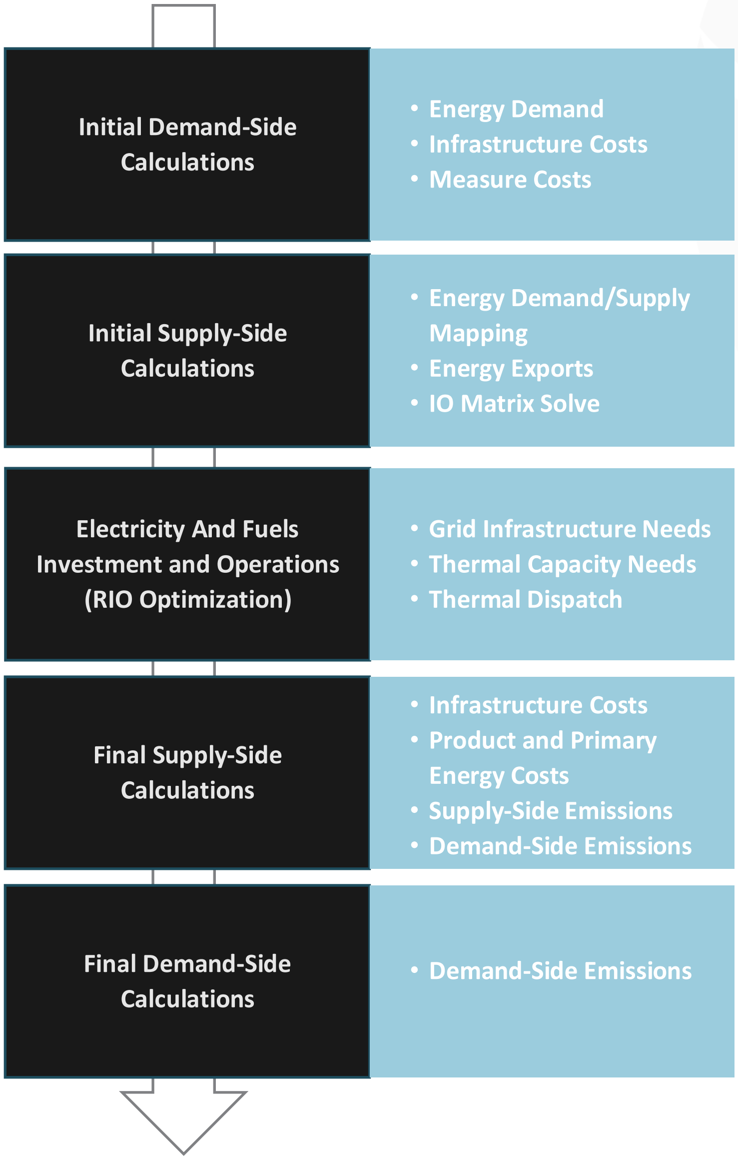
4. EnergyPATHWAYS Detailed Methodology

4.1. Model Structure

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

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.

Figure 8 shows the basic calculation steps for EnergyPATHWAYS and the outputs from each step.



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

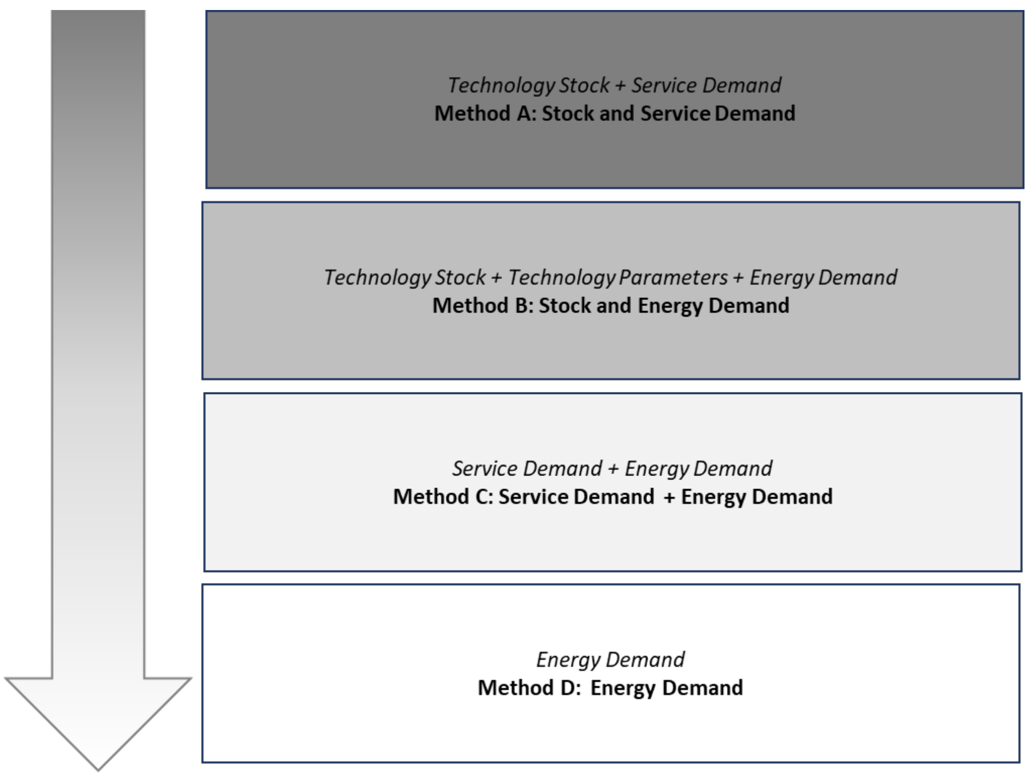
4.2. Subsectors

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

4.3. Energy Demand Projection

Data availability determines subsector granularity and informs the methods used in each subsector. The flow diagram below represents the decision matrix used to determine the methods – named A, B, C, D – used to model an individual energy demand subsector (Figure 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



4.3.1. Method A: Stock and Service Demand

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

Equation 1

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

Where

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

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

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

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

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

4.3.1.1. Service Demand Share (U)

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

Equation 2

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

Where

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

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

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

The calculation of these factors is detailed in the sections below

4.3.1.2. Technology Stock (S)

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

4.3.1.3. Initial Stock

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

Stock Decay and Replacement

EnergyPATHWAYS allows for technology stocks to decay using linear representations or Weibull distributions, which are typical functions used to represent technology reliability and failure rates. These parameters are governed by technology lifetime parameters[28]. 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)

[28] http://interstat.statjournals.net/YEAR/2000/articles/0010001.pdf

S_{2019} = 100

S_{a2019} = 50

S_{b2019} = 50

D_{2020} = 10

D_{a2020} = 5

D_{b2020} = 5

S_{2020} = 110

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

R_{a2020} = D_{a2020} = 5

R_{b2020} = D_{b2020} = 5

G_{a2020} = $\frac{D_{a2020}}{D_{2020}} * G_{2020}$ = 5/10 * 10 =5

G_{b2020} = $\frac{D_{b2020}}{D_{2020}} * G_{2020}$ = 5/10 * 10 = 5

N_{a2020} = $R_{a2020} + G_{a2020}$ = 5 + 5 = 10

N_{b2020} = $R_{b2020} + G_{b2020}$ = 5 + 5 = 10

S_{a2020} = $S_{a2019} + D_{a2020} + N_{a2020}$ = 50 – 5 + 10 = 55

S_{b2020} = $S_{b2019} + D_{b2020} + N_{b2020}$ = 50 – 5 + 10 = 55

After Sales Share Measure

S_{2019} = 100

S_{a2019} = 50

S_{b2019} = 50

D_{2020} = 10

D_{a2020} = 5

D_{b2020} = 5

S_{2020} = 110

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

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

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

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

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

N_{a2020} = $R_{a2020} + G_{a2020}$ = 8 + 8 = 16

$N_{b2020} = R_{b2020} + G_{b2020} = 2 + 2 = 4$

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

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

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

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

4.3.1.4. Service Demand Modifier (M)

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

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

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

S = Stock

x = Stock ratio

M = service demand modifier

U = service demand allocator

$S_{2019} = 100$

$S_{a2019} = 50$

$S_{a2020} = 50$

$x_{a2019} = \frac{S_{a2019}}{S_{2019}} = \frac{50}{100}$ = .5

$x_{b2019} = \frac{S_{b2019}}{S_{2019}} = \frac{50}{100}$ = .5

$M_{a2019} = 2$

$M_{b2019} = 1$

$U_{a2019} = \frac{S_{a2019} * M_{a2019}}{\sum_{t=a..b} S_{t2019} * M_{t2019}} = \frac{50*2}{150}$ = .667

$U_{b2019} = \frac{S_{b2019} * M_{b2019}}{\sum_{t=T} S_{t2019} * M_{t2019}} = \frac{50*1}{150}$ = .333

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

Equation 3

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

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.

4.3.1.5. Method B: Stock and Energy Demand

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

Equation 4

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

Where

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

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

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

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

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

Total Service Demand (D)

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

Equation 5

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

Where

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

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

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

4.3.1.6. Method C: Service and Service Efficiency

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

Equation 6

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

where

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

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

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

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

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

Energy Efficiency Savings (O)

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

4.3.1.7. Method D: Energy Demand

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

Equation 7

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

Where

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

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

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

4.3.1.8. Demand-Side Costs

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

4.3.1.9. Technology Stock Costs

EnergyPATHWAYS uses vintaged technology cost characteristics as well as the calculated stock rollover to calculate the total costs associated with technology used to provide energy services.[29]

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

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

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

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

Technology Stock Capital Costs

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

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

Equation 8

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

Where

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

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

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

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

Levelized Capital Costs (W)

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

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

Where

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

d_t = Discount rate of technology t

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

l_t^{book}= Book life of technology t

Technology Stock Installation Costs

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

Technology Stock Fuel Switching Costs

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

4.3.1.10. Technology Stock Fixed Operations and Maintenance Costs

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

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

Where

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

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

4.3.1.11. Measure Costs

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

4.3.1.12. Energy Efficiency Measure Costs

Energy efficiency costs shown in Table 5 are costs associated the reduction of energy demand. These are representative of incremental equipment costs or costs associated with non-technology interventions like behavioral energy efficiency.

Equation 9

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

Where

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

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

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

4.4. EnergyPATHWAYS supply-side

4.4.1. Supply Nodes

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

4.4.2. I/O Matrix

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

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

a. Electric Grid

b. Gas Power Plant

c. Gas Transmission Pipeline

d. Primary Natural Gas

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

1. The gas transmission pipeline has a loss factor of 2% from leakage. It also uses grid electricity to power compressor stations and requires .05 units of grid electricity for every unit of delivered gas.

2. The gas power plant has a heat rate of 8530 Btu/kWh, which means that it requires 2.5 (8530 Btu/kWh/3412 Btu/kWh) units of gas from the transmission pipeline for every unit of electricity generation.

3. The electricity grid has a loss factor of 5%, so it needs 1.05 units of electricity generation to deliver 1 unit of electricity to its terminus.

The I/O matrix for this system is shown in tabular form in Table 22 as well as in matrix form in the equation below.

Table 22. Tabular I/O Matrix

	Natural Gas	Gas Transmission Pipeline	Gas Power Plant	Electric Grid
Natural Gas		1.02		
Gas Transmission Pipeline			2.5	
Gas Power Plant				1.05
Electric Grid		.05		

Equation 10

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

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

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

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

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

This gives us the following result:

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

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

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

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

2. **Delivery Nodes –** Delivery nodes represent infrastructure specified at a non-technology level. The gas transmission pipeline is an example of a delivery node. A transmission pipeline system is the aggregation of miles of pipeline, hundreds of compressor stations, and storage facilities. We represent it as an aggregation of these components. The role of delivery nodes is to deliver the outputs of one supply node to a different physical location in the system required so that they can be used as inputs to another supply node. In the above example, gas transmission pipelines deliver natural gas from gas fields to gas power plants, which are not co-located with the resource. A full list of the delivery nodes in EnergyPATHWAYS is given in Table 23.

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

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

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

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

Table 23 EnergyPATHWAYS supply-side delivery nodes

EnergyPATHWAYS Delivery Nodes
Coal - Rail Delivery
Coal - End-Use Delivery
Diesel End-Use Delivery
Electricity Distribution Grid
Electricity Transmission Grid
Gas Distribution Pipeline
Gas Transmission Pipeline
Hydrogen Fueling Stations
Liquid Hydrogen Truck Delivery
LPG Feedstock Delivery
Lubricants Delivery
Motor Gasoline End-Use Delivery
Petrochemical Feedstock Delivery
Pipeline Gas Feedstock Delivery
Residual Fuel-Oil End-Use Delivery

4.4.3. Energy Flows

4.4.3.1. Coefficient Determination (A – Matrix)

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

4.4.3.2. Conversion Nodes

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

Equation 11

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

Where

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

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

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

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

4.4.3.3. Energy Demands

Demand Mapping

To help develop the (d) term in the matrix calculations described in section 4.4.2, EnergyPATHWAYS must map the demand for energy carriers calculated on the demand-side to specific supply-nodes. In the simplified energy system example, electricity as a final energy carrier, for example, maps to the Electric Grid supply node.

Energy Export Specifications

In addition to demand-side energy requirements, the energy supply system must also meet export demands, that is demand for energy products that aren't used to satisfy domestic energy service demands, but instead are sent to other countries. These products aren't ultimately consumed in the model, but their upstream impacts must still be accounted for. Within the Net-Zero America Study, these fossil fuel exports are not optimized in RIO and are treated outside of the annual emissions constraints. These exports are trended to zero between 2020 and 2030 under the assumption that excess international supply due to other nations decarbonizing reduces demand for U.S. exports. This is separate from general assumptions about domestic production for domestic consumption, which continues. Exports could continue past 2030 without fundamentally changing any of the study's findings, but with the caveat this would lead to additional emissions from extraction.

Total Demand

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

Equation 12

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

Where

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

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

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

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

4.5. Infrastructure Requirements

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

4.5.1. Delivery Nodes

The infrastructure capacity required is determined by Equation 13 below:

Equation 13

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

Where

u_{yr}[30] = Utilization (capacity) factor in year y in region r

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

h = Hours in a year, or 8760

4.5.2. Conversion Nodes

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

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

Equation 14

---

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

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

Where

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

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

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

4.6. Emissions

There are two categories of greenhouse gas emissions in the model. First, there are physical emissions. These are traditional emissions associated with the combustion of fuels, and they represent the greenhouse gas emissions embodied in a unit of energy. For example, natural gas has an emissions rate of 53.06 kG/MMBTU of consumption while coal has an emissions rate of 95.52 kG/MMBTU[31]. Physical emissions are accounted for on the supply-side in the supply nodes where fuels are consumed, which can occur in primary, product, delivery, and conversion nodes. Emissions, or consumption, coefficients, that is the units of fuel consumed can be a subset of energy coefficients. While the gas transmission pipeline may require 1.03 units of natural gas, it only consumes 0.03 units. Gas power plants, however, consume all 2.5 units of gas required. Equation 15 shows the calculation of physical emissions in a node:

Equation 15

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

Where

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

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

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

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

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

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

The second type of emissions are accounting emissions. These are not associated with the consumption of energy products elsewhere in the energy system. Instead, these are a function of energy production in a node[32]. Accounting emissions rates are commonly associated with carbon capture and sequestration supply nodes or with biomass. Accounting emissions are calculated using:

Equation 16

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

Where

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

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

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

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

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

Where

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

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

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

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

4.7. Costs

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

4.7.1. Primary and Product Nodes

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

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

Where

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

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

w_{yr}= Exogenous cost input for node in year y in region r

4.7.2. Delivery Nodes

Delivery node cost inputs are entered as per-energy unit tariffs. We use and adjust for any changes for the ratio of on-the-books capital assets and node throughput. This is done to account for dramatic changes in the utilization rate of capital assets in these nodes. This allows EnergyPATHWAYS to calculate and demonstrate potential death spirals for energy delivery systems, where the demand for energy from a node declines faster than the capital assets can depreciate.[33]. This pegs the tariff of the delivery node to the existing utilization rates of capital assets and increases them when that relationship diverges.

Equation 17

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

Where

C_{yr} = Total costs of delivery node in year y in region r

S_{yr}= Physical stock of delivery node in year y in region r

S_{yr}^{fin} = Financial stock of delivery node in year y in region r

u_{yr} = Exogenously specified utilization rate of delivery node in year y in region r

q = Share of tariff related to throughput-related capital assets, which are the only share of the tariff subjected to this adjustment.

w_{yr} = Exogenous tariff input for delivery node in year y in region r

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

4.7.3. Conversion Nodes

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

Equation 18

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

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

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

C_{yr}^{vom} = Total levelized variable operations and maintenance costs in year y in region r

There is no difference in the calculation of the capital, installation, and fixed O&M terms from the demand-side, so reference calculation for calculating those components of technology stocks in section 4.3.1.9.

4.7.3.1. Variable O&M Costs

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

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

Where

C_{yr}^{vom} = Total levelized variable operations and maintenance costs in year y in region r

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

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

w_{tvry}^{vom} = Exogenous input of variable operations and maintenance costs for technology t of vintage v in region r in year y

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

4.7.4. Electric Storage Nodes

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

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

Where

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

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

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

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

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

C_{yr}^{vom} = Total levelized variable operations and maintenance costs in year y in region r

4.7.4.1. Electricity Capacity Costs

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

Equation 19

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

Where

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

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

d_t = Exogenously specified discharge duration of technology t

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

5. RIO Detailed Methodology

5.1. EnergyPATHWAYS/RIO Integration

The EnergyPATHWAYS/RIO integration is a multi-step process where:

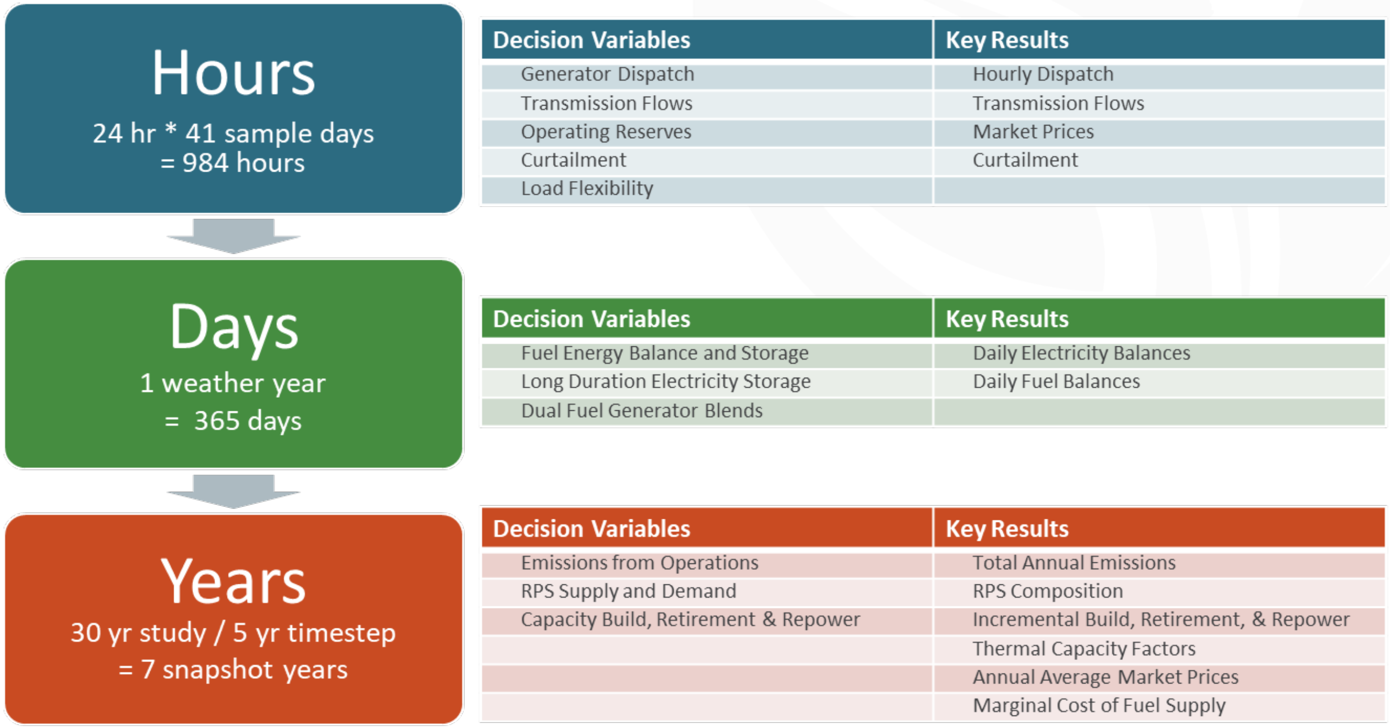
- EnergyPATHWAYS is used to define energy demand scenarios as parameterizations for RIO optimizations.
- RIO is used to optimize investments in EnergyPATHWAYS conversion supply nodes and determine optimal blends of fuel components.
- Optimized energy decisions are returned to EnergyPATHWAYS where they are input into the EnergyPATHWAYS accounting framework as stock measures or blend measures. This allows us to validate and represent the optimal scenario with the comprehensive accounting detail of EnergyPATHWAYS.

5.2. Overview

RIO is a model that sets up a linear optimization problem with the decision variables relating to capacity build and operational decisions on the supply-side of the energy system. RIO minimizes the net present value (using a 2% societal discount rate) of total energy system costs over the modeling period. Operational and capacity expansion decisions are co-optimized with perfect foresight in a single optimization problem with approximately 15 million decision variables. This problem formulation means that multiple timescales are simultaneously relevant, as shown in Figure 10.

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

Figure 10 RIO decision variables and results for each of the represented timescales



5.3. Feature List

Table 24 provides a full feature list for RIO along with the specific configuration for the Net Zero America study. The following sections provide additional model detail that highlight some of the key features.

Table 24 RIO feature list

Feature	Settings used for the Net Zero America Study
Optimal generator selection	All generator types listed in Table 11.
Optimal energy storage selection	Optimal selection of energy & capacity, priced separately.
Long duration storage	Enabled with tracking of long duration state of charge across 365 days.
Optimal transmission selection	Enabled for all paths with potential capped at 10x current path ratings.

Optimal fuel technologies	Flexible framework allowing for selection and operations of any fuel conversion and supply infrastructure. Fuel conversions that consume electricity allowed to co-optimize operations with electricity generation.
Fuels storage	Optimal build and state-of-charge tracking over 365 days for hydrogen.
Dual fuel generators	All existing and new gas generators capable of burning a hythane mix of up to 60% hydrogen.
Flexible load	Traditional load shedding and a detailed framework with cumulative energy constraints for end-use flexible loads, as given in section 2.1.3.
Number of zones	16 zones co-optimized in RIO
Number of resource bins	15 NREL TRG bins for wind and 6 bins for solar PV per zone. Details included in the accompanying Excel sheet.
Year timestep	Model run for the years 2020, 2025, 2030, 2035, 2040, 2045, 2050.
Hours modeled per year	41 sample days and 984 hours.
Weather years	Weather year 2011.
Sampled days in each modeled year	Each year selects a different sample of 41 days to model based on changing load shapes and an estimated renewable penetration under decarbonization. These factors change the days that are most critical to represent to capture emissions & economics as well as reliability events.
Perfect foresight	RIO has perfect foresight because all model time periods are simultaneously solved. This is important in models looking at rapid decarbonization to avoid sub-optimal near-term decisions in light of long-term goals.
Electricity reliability	Determined endogenously with user-specified parameters adjusting the conservatism of the calculation given in Table 25.
Renewable capacity value	Determined endogenously as pre-computed values can have little utility with increasing electrification and changes in system load shape
Load shapes	Built bottom-up from EnergyPATHWAY.
Generator retirements	Announced retirements enforced, otherwise optimized endogenously
Generator repower/extension	Solved endogenously
Annual carbon emissions constraints	Straight-line national cap from 2020 to zero CO_2e emissions in 2050. Energy and industrial emissions capped at -170 MMT in 2050 to offset non-CO_2 emissions.
Cumulative carbon emission constraints	None applied
Carbon taxes	None applied
RPS/CES	Existing state policy (2019) set a minimum level of renewables/clean electricity.
RPS/CES qualification	Existing RPS/CES policy qualification is based on current state policy
Annual resource build constraints	Annual maximum builds by resource group defined with compound growth rates of 10%.
Cumulative resource build constraints	Early limits on nuclear and Allam cycle CCS. Potential constraints enforced for all renewables, as outlined in the accompanying Excel workbook.
Land-use constraints	No global constraint applied

Fuel prices	Specified exogenously for fossil and with supply curves for biomass and carbon sequestration. Inputs provided in the accompanying Excel workbook.
Biomass allocation	Determined endogenously between electricity and fuels
Carbon sequestration allocation	Determined endogenously between electricity, fuels, and industry

5.4. Day Sampling

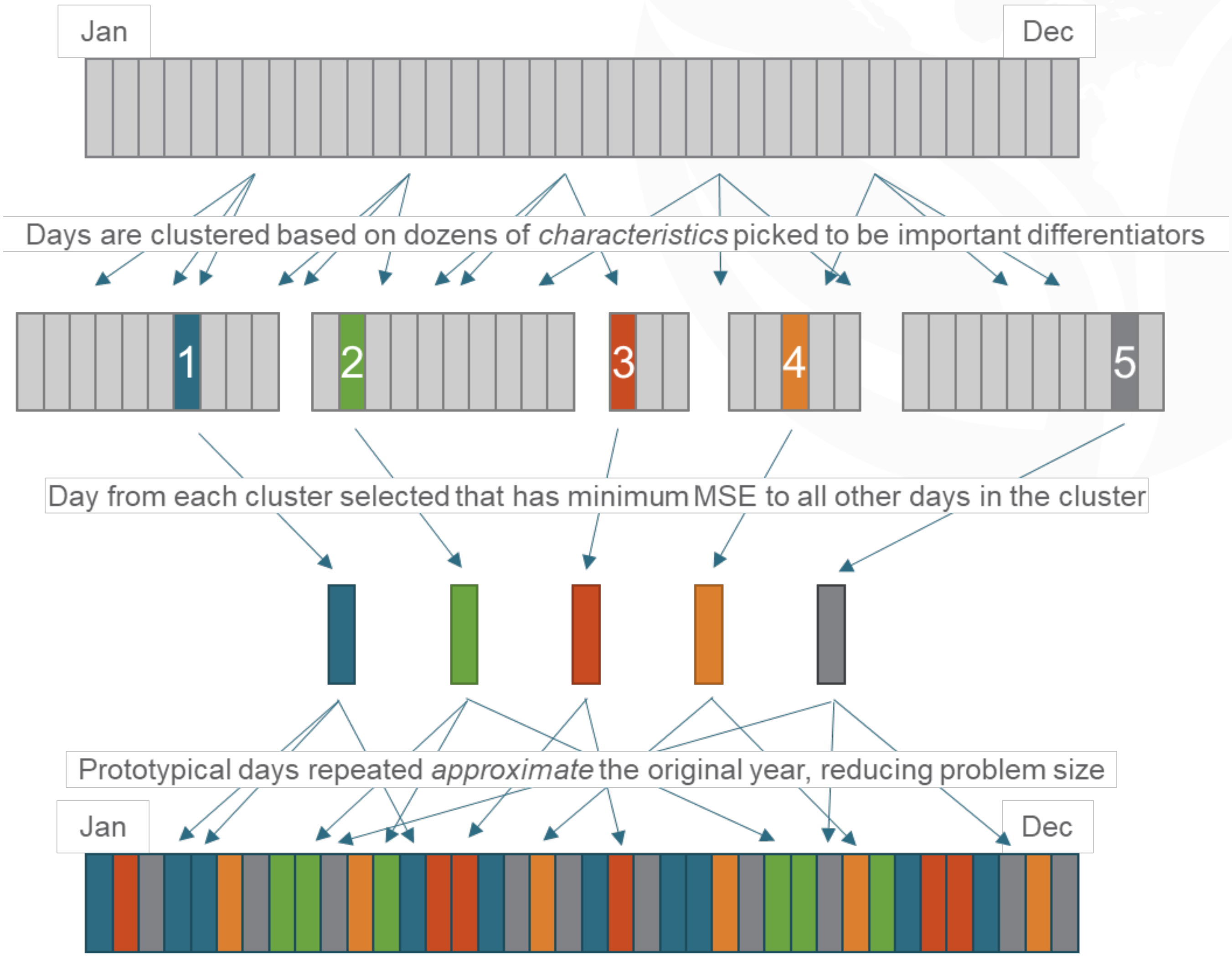
RIO utilizes the 8760 hourly profiles for electricity demand and generation from EnergyPATHWAYS and optimizes operations for a subset of representative days (sample days) and maps them to the rest of the year. Operations are performed over sequential hourly timesteps. To ensure that the sample days can reasonably represent the full set of days over the year, RIO uses clustering algorithms on the initial 8760 data sets. The clustering process is designed to identify days that represent a diverse set of potential system conditions, including different fixed generation profiles and load shapes. The number of sample days impacts the total runtime of the model. A balance is struck in the day selection process between representation of system conditions through number of sample days, and model runtime. Clustering and sample day selection occurs for each model year in the time horizon. This process is shown in Figure 11. The starting dataset is the EnergyPATHWAYS load and generation shapes, scaled to system conditions for the model year being sampled and mapped. Load shapes come directly from EnergyPATWHAYS demand-side runs.

The coincidence of fixed generation profiles (i.e. renewables) and load, determine when important events for investment decision making occur during the year. For example, during times of high load but low renewable output. One challenge when pre-selecting a set of sample days is that the most important days to include depend on decisions endogenous to RIO (e.g. how many renewables to build of what type). To overcome this, day sampling performance is tested against a wide range of renewable build configurations in an effort to ensure whatever build results in RIO does not suffer from poor statistical sampling.

As Figure 11 shows, the scaled historical days are clustered based on a number of characteristics. These include different metrics describing every day in the data set. Examples include peak daily load, peak daily net load, lowest daily solar output, largest daily ramping event, etc. The result is a set of clusters of days with similar characteristics. One day within each cluster is selected to represent the rest by minimizing mean square error (MSE). Weights between the features are chosen by the model users and significant iteration is used to arrive at a set of sample days that gives good performance statistics. The sampling performance is primarily judged on whether the electricity load in the sampled days sums to the correct annual load and that renewable capacity factors are correctly assessed across all regions.

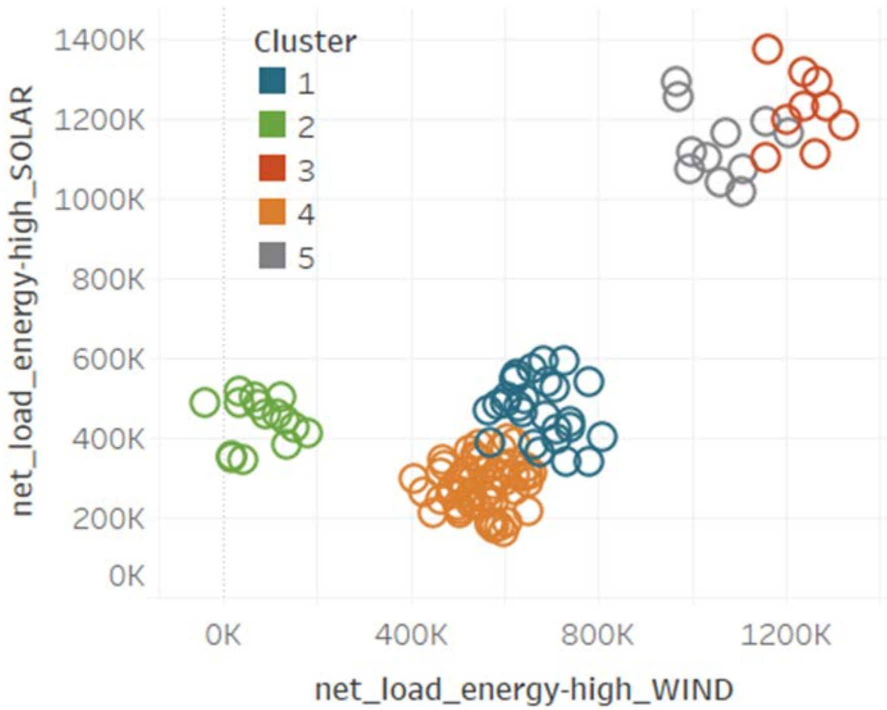
As described in the previous section, RIO determines short-term operations for each of these representative days. For long-term operations, each representative day is mapped back to the chronological historical data series, with the representative day in place of every other day from its cluster.

Figure 11 Conceptual diagram of sampling and day matching process



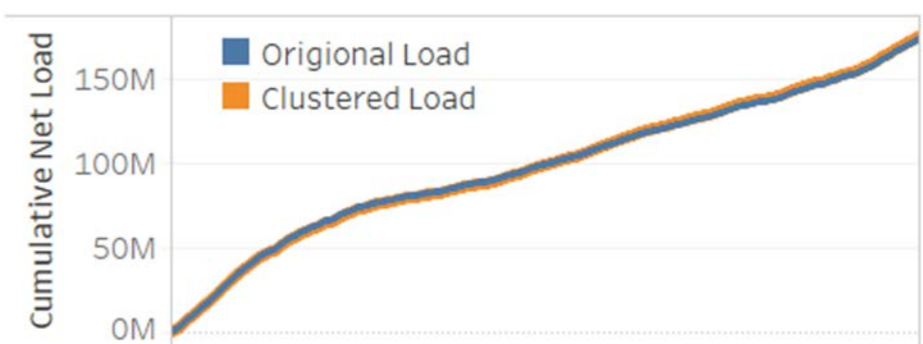
The clustering process depends on many characteristics of the coincident load and renewable shapes and uses statistical clustering algorithms to determine the best set of sample days. Figure 12 shows a simple, two characteristic, example of clustering. In this case the two characteristics are net load with high proportional solar build and net load with high proportional wind build. It is important to select sample days that both represent the full spectrum of potential net load, as well as be representative for both the solar and the wind case. The clustering algorithm has identified 5 clusters (a low number, but appropriate for the conceptual example) that ensure the sample days will represent the full range of net load differences among days and remain representative regardless of whether RIO chooses to build a high solar system or a high wind system. In the Net-Zero America Study, a total of 41 sample days were used.

Figure 12 Simple, two characteristic, example of clustering



Mapping the clustered days back to the chronological historical dataset, the newly created year of sample days can be validated by checking that metrics describing the original historical dataset match those of the new set. Cumulative net load in Figure 13 is one example. These are related to the characteristics used to select the sample days in the clustering process such as peak load, largest ramp etc. and the distribution of these over the whole year.

Figure 13 Comparison of original and clustered load



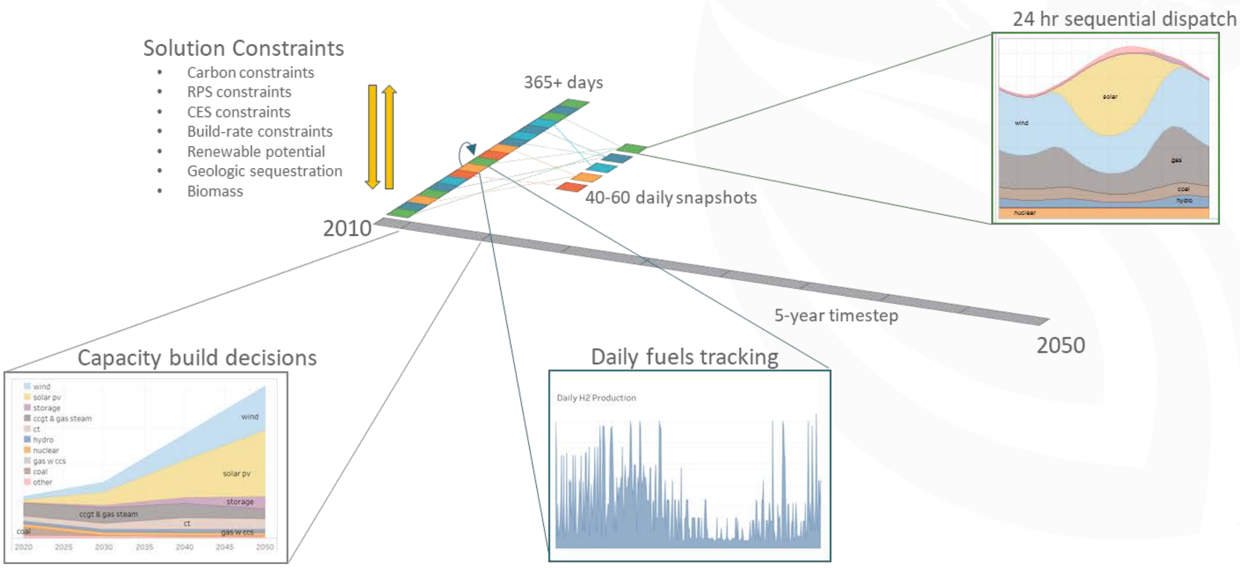
5.5. Operations

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

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

Operational decisions determine the value of one investment over another, so it is important to capture the detailed contributions and interactions of the many different types of resource that RIO can build. The overall RIO operational framework is shown in Figure 14.

Figure 14 RIO operations framework



5.5.1. Thermal Generator Operations

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

RIO can constrain operations based on constraints that are similar to those used in production simulation[34]. Plant-level operational constrains[35] were ignored for the purpose of this study as they have secondary importance when modeling large regional zones and add significant computational complexity. Representing these factors would have disallowed focus on other

[34] Production simulation is a class of electricity models intended to represent dispatch and operations on short timescales. Care is taken to represent as many of the real-world constrains and factors as possible. This class of model is frequently used to forecast market prices or examine system operations in detail.

[35] Ignored constraints include ramp rates (except for hydro), unit commitment, minimum up & down times.

modeling aspects of higher importance in decarbonized energy systems (e.g. operation of electrolysis and hydrogen storage), heat rate curves.

5.5.2. Impoundment Hydro Operating Constraints

Operation of hydro at large damns is constrained by historical data on how fast the hydro system can ramp, the minimum and maximum discharge by hour, and the degree to which hydro energy can be shifted from one period to another. Summed daily hydro output must fall within a cumulative energy envelope that allows up to 2 weeks of shift (forward or backward) in the dispatch compared to historical levels. Run of river hydro is treated separately with fixed profiles based on historical operations.

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

5.5.3. Storage Operating Constraints

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

5.5.4. Transmission constraints

RIO uses a pipe-flow constraint formulation[36]. 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[37]. Transmission losses are specified by path and are assumed to be 1% per hundred miles. Transmission hurdles are also applied to represent `friction' in electricity trading between zones. These costs are not 'true' costs, but instead represent a penalty on transmission flows, which is added to the objective function, and are important to include to represent balkanization of the U.S. power system. Hurdle rates start from a benchmark against historical flows and range from \$2-8/MWh in 2020 before converging at \$5/MWh in 2040.

5.6. Reliability

The conditions that will stress electricity systems in the future and define reliability need will shift in nature compared to today, as shown in Figure 15. 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.

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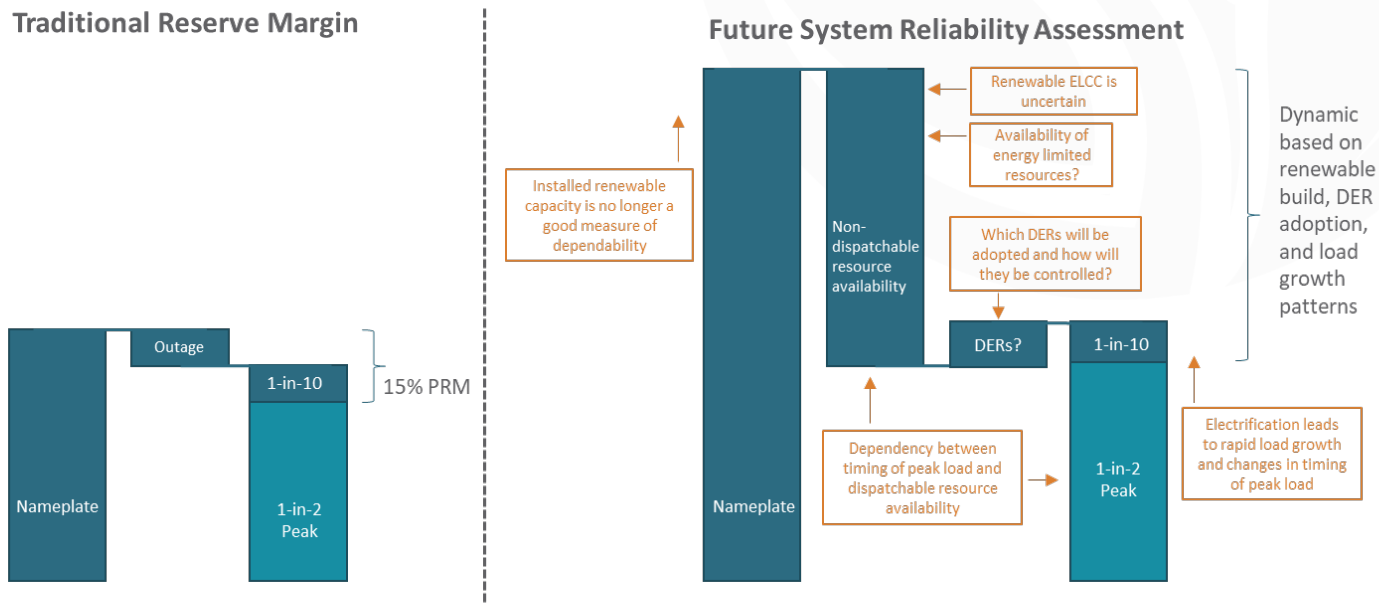
[36] See this NREL presentation for more information and contrast against DC power-flow constraint formulations: https://www.nrel.gov/docs/fy17osti/68929.pdf

[37] When creating pipe-flow constraints based on actual AC power flow and generator locations, it sometimes happens that the best real-world approximation is a transmission line with asymmetrical flow constraints.

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 15 Reliability framework in high renewable systems[38]



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.

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[38] PRM: planning reserve margin

ELCC: effective load carrying capability, a metric and methodology used to assess the reliability of generators

DER: distributed energy resources (e.g. rooftop solar)

5.6.1. Dependability

The dependable contribution from thermal resources is derated nameplate, reflecting forced outage rates. Renewable dependable contribution is the derated hourly output, reflecting that renewable output could be even lower than expected. For energy constrained resources such as hydro and storage, dependable contribution is derated hourly output. By using derated hourly output we can capture both the risk that it is not available because of forced outage, and the risk that it is not available because it has exhausted its stored energy supply. Dependability factors used for the Net Zero America study are shown in Table 25. For thermal generators, these are based on forced outage rates; for variable generation and load, the dependability is based on the variability observed within day-bins described in section 5.4; and for transmission, the value is typical of what might be used in regional planning studies based on the authors' prior experience.

Table 25 Dependability factors used when enforcing RIO reliability constraints

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

5.6.2. Resource build decisions

Concurrently with optimal operational decisions, the model makes resource build decisions that together produce the lowest total system cost. The capacity build options include building new capacity or extending the lifetime of an existing generator (e.g. nuclear). The addition of new capacity is limited by the rate at which capacity can be constructed year on year, and the cumulative quantity of that resource that can be built (e.g. constraint on total wind capacity in a region).

Generators remain online in the model as defined by its lifetime in Table 11 unless the model chooses to retire them early. By retiring a resource, annual fixed O&M is saved for all those years it otherwise would have operated. This is primarily applicable for existing generators with coal, in particular, retired early in the study period to both reduce emissions and avoid ongoing O&M cost.

5.7. Fuels

In addition to electricity, RIO optimizes the composition of fuels that are used in electric generators and that go to satisfy final energy demands, calculated in EnergyPATHWAYS. RIO fuels operate around the concept of a 'blend fuel' shown in Figure 16. Each fuel blend may be supplied using 'product fuels', which are basically commodities (e.g. dry biomass, fossil diesel) that are specified at a price and quantity, or blends can be supplied with fuel conversions, which can convert one blend fuel into another or convert electricity into a fuel (e.g. electrolysis). A mapping between blend fuels and their inputs is given in Table 26. Each blend fuel can be used to satisfy final energy demand, used in a power plant, or used in another fuel conversion process.

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

Fuel conversions that consume or produce electricity[39] can be specified as flexible or inflexible on an hourly basis. Electrolysis and electric boilers are assumed to operate flexibly with no constrains on hour-to-hour ramping, all other conversion technologies, including direct air capture, are not flexible hour-by-hour, but are flexible between days.

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

Figure 16 RIO fuels framework

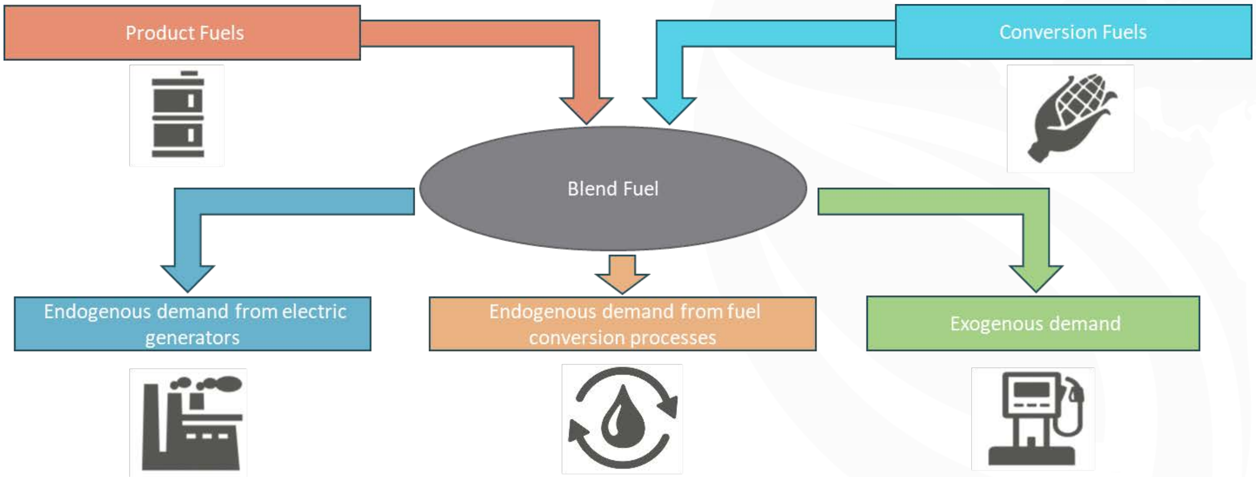

Table 26 RIO fuel blend inputs

Blend	Conversion or Product Input	Max Blend Fraction by Energy
biomass blend - corn	biomass primary - corn_4	1
biomass blend - solids	biomass primary - herbaceous	1
biomass blend - solids	biomass primary - wood	1
biomass blend - waste	biomass primary - waste	1
biomass burial blend	biomass burial	1
biomass burial blend	biomass sequestration	1
co2 utilization blend	direct air capture plant	1
co2 utilization blend	industrial demand-side capture (cement)	1
carbon sequestration	co2 utilization blend	1
coal blend	biomass pyrolysis	1
coal blend	biomass pyrolysis w/ccu	1
coal blend	coal primary - domestic_1	1
coke blend	biomass pyrolysis	1
coke blend	biomass pyrolysis w/ccu	1
coke blend	coke product	1
diesel blend	biomass ft -> diesel	1
diesel blend	biomass ft -> diesel w/ccu	1
diesel blend	synthetic liquids [40]	1
diesel blend	refined fossil diesel product	1

[40] The technology modeled is Fischer Tropsch, which draw from the hydrogen blend and captured carbon blends within RIO. The source of hydrogen varies across scenarios, thus the term ‘synthetic’ can sometimes mean bio-derived and other times electricity derived.

gasoline blend	cellulosic ethanol plant	1
gasoline blend	corn ethanol plant	1
gasoline blend	synthetic liquids	1
gasoline blend	refined fossil gasoline product	1
hydrogen blend	autothermal reforming hydrogen production w/ccu	1
hydrogen blend	BECCS hydrogen production -> hydrogen blend	1
hydrogen blend	central-station hydrogen electrolysis	1
hydrogen blend	h2 natural gas reformation	1
hydrogen blend	h2 natural gas reformation w/ccu	1
industrial co2 blend	industrial co2	1
jet fuel blend	biomass ft -> diesel	1
jet fuel blend	biomass ft -> diesel w/ccu	1
jet fuel blend	synthetic liquids	1
jet fuel blend	refined fossil jet fuel product	1
kerosene blend	refined fossil kerosene product	1
landfill gas blend	landfill gas_1	1
lpg blend	biomass ft -> diesel	1
lpg blend	biomass ft -> diesel w/ccu	1
lpg blend	synthetic liquids	1
lpg blend	refined fossil lpg product	1
oil blend	biomass pyrolysis	1
oil blend	biomass pyrolysis w/ccu	1
oil blend	oil primary - domestic_1	1
oil blend	synthetic liquids	1
petroleum coke blend	biomass pyrolysis	1
petroleum coke blend	biomass pyrolysis w/ccu	1
petroleum coke blend	petroleum coke product	1
pipeline gas blend	biomass - > sng	1
pipeline gas blend	biomass -> sng w/ccu	1
pipeline gas blend	central-station hydrogen electrolysis	0.07
pipeline gas blend	h2 natural gas reformation	0
pipeline gas blend	h2 natural gas reformation w/ccu	0
pipeline gas blend	natural gas primary - domestic_1	1
pipeline gas blend	synthetic gas [41]	1
product and bunkering co2 blend	product and bunkering co2	1
residual fossil fuel oil blend	biomass ft -> diesel	1
residual fossil fuel oil blend	biomass ft -> diesel w/ccu	1

[41] The technology modeled is methanation, which draw from the hydrogen blend and captured carbon blends within RIO. The source of hydrogen varies across scenarios, thus the term 'synthetic' can sometimes mean bio-derived and other times electricity derived.

residual fossil fuel oil blend	synthetic liquids	1
residual fossil fuel oil blend	residual fossil fuel oil product	1
steam blend	electric boiler	1
steam blend	industrial coal boiler	1
steam blend	industrial distillate fuel oil boiler	1
steam blend	industrial hydrogen boiler	1
steam blend	industrial lpg boiler	1
steam blend	industrial other petroleum boiler	1
steam blend	industrial petroleum coke boiler	1
steam blend	industrial pipeline gas boiler	1
steam blend	industrial residual fuel oil oil boiler	1
still gas blend	biomass pyrolysis	1
still gas blend	biomass pyrolysis w/ccu	1
still gas blend	still gas product	1
uranium blend	uranium product	1

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