2025 Rhode Island Climate Action Strategy Energy Master Plan

Pathways Model Technical Documentation

February 2025

1 Model Overview

Pathways is an economy-wide energy and greenhouse gas (GHG) emissions accounting model. Energy and Environmental Economics (E3) created the Pathways model to help policymakers, businesses, and other stakeholders analyze paths to achieving deep decarbonization of the economy. Pathways is not an optimization or general equilibrium model but instead allows for comparison of user-defined scenarios of future energy demand and emissions to explore the impacts and implications of potential climate and energy policies. Variables that impact final energy demand in the model (e.g., customer adoption of electric vehicles, amount of space heating demanded per household), are specified by the user. The Pathways model accounts for annual energy demands and greenhouse gas emissions from the following final energy demand and non-energy and/or non-combustion sources:

- Energy Demand Sectors
  - Residential
  - Commercial
  - Industrial
  - Transportation
- Non-Energy, Non-Combustion Sectors
  - Agriculture
  - Coal Mining
  - Natural Gas & Oil Systems
  - Industrial Processes & Product Use (IPPU)
  - Waste
  - Land-use, Land-use Change, & Forestry (LULUCF)

The sources from these sectors are categorized into one of three subsector types:

1. **Stock Rollover –** Subsectors where Pathways accounts for the stock rollover of energy-consuming devices in the economy. Here, final energy demands and direct emissions are calculated based on the total number of devices, demand for energy services (e.g., vehicle miles travelled, delivered heat), the fuel type of devices, and the efficiency of devices.

2. **Energy Only –** Subsectors where Pathways accounts for annual energy demands and direct emissions, but does not model stock rollover of devices due to a lack of high-quality, comprehensive data on device stocks, service demands, and efficiencies (e.g., industrial process heat).
3. **Emissions Only –** Subsectors where emissions are generated from sources other than energy demand and/or fuel combustion, so only the annual direct emissions are tracked (e.g., landfill methane leakage).

The final energy demands from Pathways are typically passed to energy supply models like the E3 RESOLVE model for electricity sector capacity expansion and the E3 fuels optimization module to determine the cost and emissions associated with meeting final energy demands under various resource and emissions constraints. Figure 1 below shows the process flow for a typical economy-wide analysis using Pathways in conjunction with these other tools. Using energy supply models to optimize electricity sector costs and emissions rates and fuel prices and blend levels is not required to generate economy-wide outputs using Pathways, as users also have the option to input pre-determined emissions rates and prices for all fuels within Pathways itself.

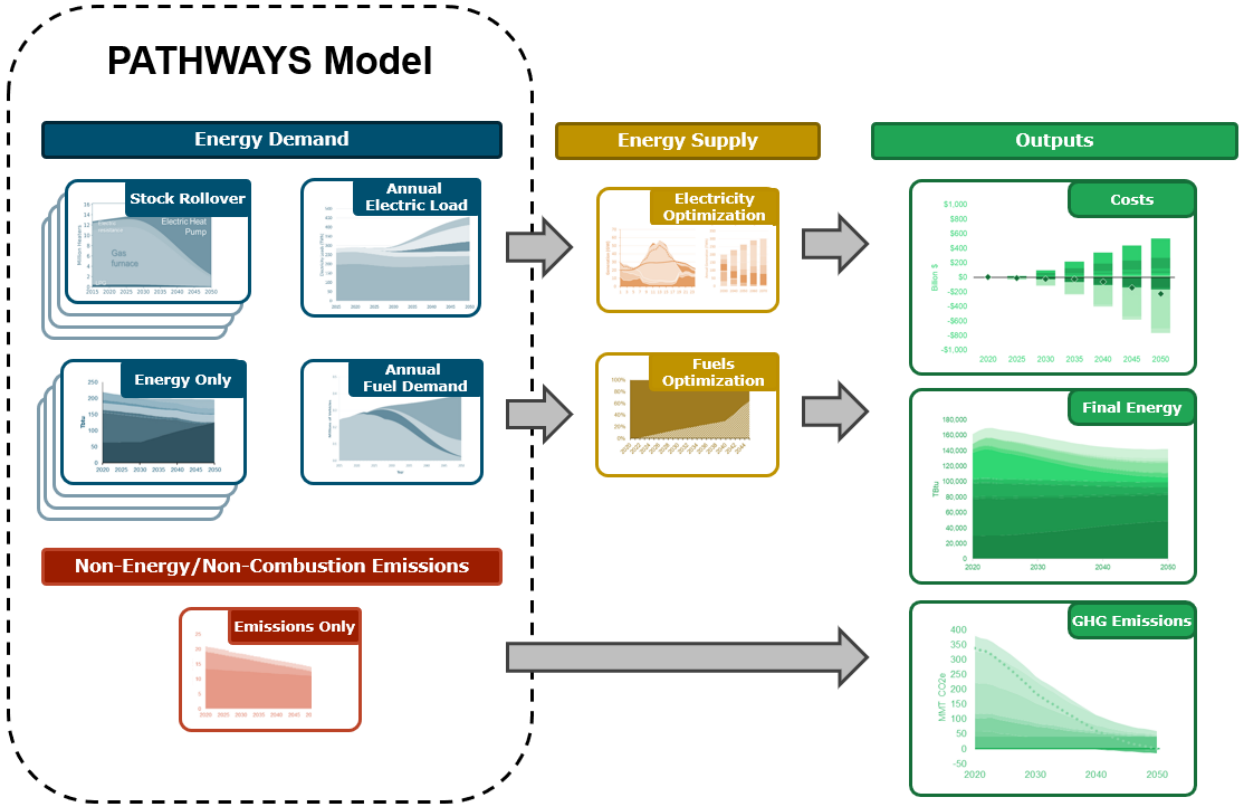

Figure 1. Flow chart of Pathways model used in conjunction with energy supply tools

2 Stock Rollover Subsectors

2.1 Overview

Pathways models 31 distinct stock rollover subsectors across the Residential, Commercial, and Transportation sectors. For each subsector, the total stock of devices and the share for each technology type is benchmarked in the base year using historical data.[1] For future years, the total stock is determined using growth rates for various key indicators (e.g., population). Table 1 below shows the default stock rollover subsectors in Pathways and the key drivers used to determine total device stocks in future years. The model takes as an input the average number of devices per key driver and uses that to calculate total device stocks (e.g., how many refrigerators per household).

Table 1: Stock rollover subsectors in Pathways

Subsector	Key Driver
Residential Central Air Conditioning	Households
Residential Clothes Drying	Households
Residential Clothes Washing	Households

[1] The base year is typically the last year of available historical data.

Residential Cooking	Households
Residential Dishwashing	Households
Residential Freezing	Households
Residential Exterior Lighting	Households
Residential General Service Lighting	Households
Residential Linear Fluorescent Lighting	Households
Residential Reflector Lighting	Households
Residential Refrigeration	Households
Residential Room Air Conditioning	Households
Residential Single Family Space Heating	Households
Residential Multi Family Space Heating	Households
Residential Water Heating	Households
Commercial Air Conditioning	Commercial Square Footage
Commercial Cooking	Commercial Square Footage
Commercial General Service Lighting	Commercial Square Footage
Commercial HID Lighting	Commercial Square Footage
Commercial Linear Fluorescent Lighting	Commercial Square Footage
Commercial Refrigeration	Commercial Square Footage
Commercial Space Heating	Commercial Square Footage
Commercial Ventilation	Commercial Square Footage
Commercial Water Heating	Commercial Square Footage
Transportation Light Duty Cars	Population
Transportation Light Duty Trucks	Population
Transportation Light Medium Duty Trucks	Population
Transportation Medium Duty Trucks	Population
Transportation Heavy Duty Trucks (Short-haul)	Population
Transportation Heavy Duty Trucks (Long-haul)	Population
Transportation Buses	Population

The final energy demand from stock rollover subsectors is a function of the total number of devices, the service demands per device, the share of various technologies among the total number of devices, and the average efficiencies of these devices. Each year, the model retires devices based on survival profiles that determine the fraction of devices retired from year to year, and then sells new devices so that the total number of devices equals the amount calculated using the base year stocks and top down growth rates.

Users have the option of changing the market share for new device sales as a scenario input. Examples of user inputs are measures that lead to an increase in sales of more efficient devices with the same fuel type or measures that lead to an increase in sales of devices with a different fuel type (e.g., shifting sales of gasoline vehicles to battery electric vehicles). In addition, users can input service demand modifiers that change the underlying amount of energy services required, which in turn change the final energy demand (e.g., reducing vehicle miles travelled). One unique service demand modifier available for buildings is the deployment of more efficient building shells that reduce space heating and cooling needs. Unlike other service demand modifiers like behavioral conservation or VMT reductions, the model accounts for the capital costs of building shell measures that reduce service demands, although the user must specify the cost and percent reduction in heating and/or cooling demand associated with each efficient shell type. The section below walks through the calculations for stock rollover and energy demand.

2.2 Calculations

2.2.1 Stock Rollover Calculations

Stock rollover calculations are performed for each stock rollover subsector. The goal of the stock rollover calculations is to calculate the 3-dimensional stock array, A_{ijk}, which represents the number of devices that exist in year i of vintage j and device type k (e.g. for the light duty vehicles subsector in the year 2024, how many 2002 vintage gasoline internal combustion engine cars are on the road).

Key model inputs for the calculation of the stock array, A_{ijk}, include:

- A_{0jk}, the base year stock share
- r_i, the total number of devices that exist in year i across the entire subsector
- S_{ijk}, the survival profile matrix, which represents the percentage of devices that will survive from year $(i-1)$ to year i
- B_{ijk}, the natural retirement sales share, which represents the fraction of natural retirements in year i of vintage j that will be replaced with device type k. The value is typically the same across all vintages for a given year i.
- D_{ijk}, the early retirement sales share, which represents the fraction of early retirements in year i of vintage j that will be replaced with device type k. The value is typically the same across all vintages for a given year i.
- X_{ik}, the early retirement stock fraction, which represents the fraction of devices of type k that will be retired early in year i. Note: the vintage is not specified. The calculations assume that the oldest devices will be retired first.

Key intermediate calculated quantities include:

- P_{ijk}, the array of natural retirements occurring in year i of vintage j and device type k
- Q_{ijk}, the array of early retirements occurring in year i of vintage j and device type k
- Y_{ijk}, the array of sales occurring in year i of vintage j and device type k
- $\hat{A}_{ijk}$, the stock array in year i of vintage j and device type k after accounting for natural retirements, but **before** accounting for early retirements and sales
- $\tilde{A}_{ijk}$, the stock array in year i of vintage j and device type k after accounting for both natural and early retirements but **before** accounting for sales

The stock rollover calculations occur iteratively from years $(i = 1 \ldots n)$, assuming that stocks in year 0, A_{0jk}, are known. The following steps are performed for each successive year:

Step 1: subtract natural retirements

The first step is calculating the number of devices that will naturally retire given the starting stocks and the survival profile. The number of natural retirements, P_{ijk}, and the intermediate stock array, $\hat{A}_{ijk}$, are calculated as shown in Equations 2.1 and 2.2 below:

$$P_{ijk} = A_{(i-1)jk} * S_{ijk} \qquad 2.1$$

$$\hat{A}_{ijk} = A_{(i-1)jk} - P_{ijk} \qquad 2.2$$

Step 2: subtract early retirements

The second step is calculating the number of early retirements. Devices are retired from oldest to youngest, until the specified early retirement fraction, X_{ik} , is reached. The number of early retirements, Q_{ijk}, are thus calculated such that Equation 2.3 is satisfied:

$$\sum_{j} Q_{ijk} = X_{ik} * \sum_{j} \hat{A}_{ijk} \qquad 2.3$$

Intermediate stock array, $\tilde{A}_{ijk}$, represents the stock array **after** accounting for both natural and early retirements but **before** accounting for sales. $\tilde{A}_{ijk}$ is calculated as shown in Equation 2.4:

$$\tilde{A}_{ijk} = \hat{A}_{ijk} - Q_{ijk} \qquad 2.4$$

Step 3: add sales

After both natural and early retirements have been accounted for to produce the intermediate stock array, $\tilde{A}_{ijk}$, the third and final step in the calculation of the final stock array, A_{ijk}, is to add the anticipated sales. This is achieved by replacing natural and early retirements, as well as adding new devices to meet the total number of devices specified for the subsector, r_i. The sales, Y_{ijk}, are calculated as shown in Equation 2.5:

$$Y_{ijk} = \left(P_{ijk} * B_{ijk}\right) + \left(Q_{ijk} * D_{ijk}\right) + \left(r_i - \sum_{jk} \tilde{A}_{ijk}\right) * B_{ijk} \qquad 2.5$$

where

- P_{ijk} is the array of natural retirements occurring in year i of vintage j and device type k,
- B_{ijk} is the natural retirement sales share, which represents the fraction of natural retirements in year i of vintage j that will be replaced with device type k,
- Q_{ijk} is the array of early retirements occurring in year i of vintage j and device type k,
- D_{ijk} is the early retirement sales share, which represents the fraction of early retirements in year i of vintage j that will be replaced with device type k, and
- r_i is the total number of devices that exist in year i across the entire subsector.

The final stock array, A_{ijk}, is calculated by adding the sales, Y_{ijk}, to $\tilde{A}_{ijk}$ (the intermediate stock array coming out of the previous step), as shown in Equation 2.6:

$$A_{ijk} = \tilde{A}_{ijk} + Y_{ijk} \quad (2.6)$$

2.2.2 Energy Demand Calculations for Stock Rollover Subsectors

Once the stock rollover has been calculated, energy demands are calculated for each year i, device type k, and fuel type f. Key inputs for the energy demand calculations include:

- A_{ijk}, the final stock array defining the number of devices that exist in year i of vintage j and device type k. This is the main output of the stock rollover calculations.
- X_{ijkf}, the fuel share of service demand for fuel type f for devices in year i of vintage j and device type k. This represents the percentage of service demand that is served by a particular fuel type.
- F_{ijkf}, the efficiency of devices in year i of vintage j and device type k and fuel type f (in units of (MMBtu out)/(MMBtu in)).
- d_{ik}, the service demand in year i for device type k (in units of MMBtu/year)

The resulting energy demand, E^s_{ikf}, represents the energy demand year i for device type k and fuel type f. E^s_{ikf} is calculated as shown in Equation 2.7:

$$E^s_{ikf} = d_{ik} * \sum_j X_{ijkf} * (A_{ijk} \div F_{ijkf}) \quad (2.7)$$

The final energy demands are aggregated over all devices in the subsector to yield E^s_{if}, the total final energy demand for each year i and fuel type f as shown in Equation 2.8:

$$E^s_{if} = \sum_k E^s_{ikf} \quad (2.8)$$

Emissions resulting from these energy demands are dependent on the energy supply and are described in section 5.

2.2.3 Costs for Stock Rollover Subsectors

Three types of costs are calculated for devices within a stock rollover subsector:

1. **Device costs:** capital costs to purchase new devices. Overnight capital costs are calculated by multiplying annual device sales by the capital cost for each device. Annual levelized costs are calculated from the overnight costs assuming a financing rate and financing lifetime specified for each subsector.

2. **Operation and maintenance (O&M) costs:** annual costs associated with O&M for a specified device type. O&M costs are calculated by multiplying the total number of devices operating in a given year by the annual O&M cost for each individual device type.
3. **Fuel costs:** annual costs associated with fuel consumption for each device. Fuel costs are calculated by multiplying the energy demand for each device by the fuel price per MMBtu for the fuel it consumes.

2.3 Data Sources

Table 2 below lists the default data sources for key inputs to the stock rollover subsectors.

Table 2: Stock rollover default data sources

Subsector	Stocks	Service Demands	Device Efficiency	Device Costs
Residential Central Air Conditioning	EIA RECS[2]	EIA NEMS[3]	EIA NEMS	E3 2024
Residential Clothes Drying	EIA RECS	EIA NEMS	EIA NEMS	EIA NEMS
Residential Clothes Washing	EIA RECS	EIA NEMS	EIA NEMS	EIA NEMS
Residential Cooking	EIA RECS	EIA NEMS	EIA NEMS, Sweeney et al., 2014[4]	EIA NEMS
Residential Dishwashing	EIA RECS	EIA NEMS	EIA NEMS	EIA NEMS
Residential Freezing	EIA RECS	EIA NEMS	EIA NEMS	EIA NEMS
Residential Exterior Lighting	DOE 2020[5]	EIA NEMS	EIA NEMS	EIA NEMS
Residential General Service Lighting	DOE 2020	EIA NEMS	EIA NEMS	EIA NEMS
Residential Linear Fluorescent Lighting	DOE 2020	EIA NEMS	EIA NEMS	EIA NEMS
Residential Reflector Lighting	DOE 2020	EIA NEMS	EIA NEMS	EIA NEMS
Residential Refrigeration	EIA RECS	EIA NEMS	EIA NEMS	EIA NEMS
Residential Room Air Conditioning	EIA RECS	EIA NEMS	EIA NEMS	E3 2024
Residential Single Family Space Heating	EIA RECS	EIA NEMS	EIA NEMS,	E3 2024

[2] U.S. Department of Energy, Energy Information Administration. (2023). *Residential Energy Consumption Survey 2020*; https://www.eia.gov/consumption/residential/data/2020/
[3] U.S. Department of Energy, Energy Information Administration. (2023). *National Energy Modeling System*; https://www.eia.gov/outlooks/aeo/nems/documentation/
[4] Sweeney et al. (2014). *Induction Cooking Technology Design and Assessment*. https://www.aceee.org/files/proceedings/2014/data/papers/9-702.pdf
[5] U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy. (2020). *Adoption of Light-Emitting Diodes in Common Lighting Applications*; https://www.energy.gov/sites/default/files/2020/09/f78/ssl-led-adoption-aug2020.pdf

Subsector	Stocks	Service Demands	Device Efficiency	Device Costs
			E3 2024[6]	
Residential Multi Family Space Heating	EIA RECS	EIA NEMS	EIA NEMS, E3 2024	E3 2024
Residential Water Heating	EIA RECS	EIA NEMS	EIA NEMS	E3 2024
Commercial Air Conditioning	EIA CBECS 2018[7]	EIA NEMS	EIA NEMS	E3 Buildings Pro Forma[8]
Commercial Cooking	EIA CBECS 2018	EIA NEMS	EIA NEMS	EIA NEMS
Commercial General Service Lighting	DOE 2020	EIA NEMS	EIA NEMS	EIA NEMS
Commercial HID Lighting	DOE 2020	EIA NEMS	EIA NEMS	EIA NEMS
Commercial Linear Fluorescent Lighting	DOE 2020	EIA NEMS	EIA NEMS	EIA NEMS
Commercial Refrigeration	EIA CBECS 2018	EIA NEMS	EIA NEMS	EIA NEMS
Commercial Ventilation	EIA CBECS 2018	EIA NEMS	EIA NEMS	EIA NEMS
Commercial Space Heating	EIA CBECS 2018	EIA NEMS	EIA NEMS	E3 Buildings Pro Forma
Commercial Water Heating	EIA CBECS 2018	EIA NEMS	EIA NEMS	E3 Buildings Pro Forma
Transportation Light Duty Cars	RI MOVES[9]	RI MOVES	RI MOVES for existing ICE vehicle stock[10], EIA AEO 2023 for future year ICE vehicles[11], Slowik et al., 2022 for EVs [12]	Slowik et al., 2022
Transportation Light Duty Trucks	RI MOVES	RI MOVES	RI MOVES for existing ICE vehicle stock, EIA AEO 2023 for	Slowik et al., 2022

---

[6] E3. (2024). *Rhode Island Investigation into the Future of the Regulated Gas Distribution Business: Technical Analysis Report Docket 22-01-NG;* https://www.ethree.com/wp-content/uploads/2024/06/Docket-22-01-NG-E3-Technical-Analysis-Report.pdf

[7] U.S. Department of Energy, Energy Information Administration. (2022). *Commercial Building Energy Consumption Survey 2018*; https://www.eia.gov/consumption/commercial/data/2018/

[8] E3 Buildings Pro Forma estimates the cost and efficiencies of building appliances based on a range of state, utility, federal, and proprietary surveys of equipment characteristics and installation costs

[9] MOVES model outputs used in development of the *2022 Rhode Island Greenhouse Gas Inventory*, provided by Rhode Island Department of Environmental Management via email on December 30, 2024

[10] U.S. Department of Transportation, Bureau of Transportation Statistics. (2023). *National Transportation Statistics 2021*; https://www.bts.gov/topics/national-transportation-statistics

[11] U.S. Department of Energy, Energy Information Administration. (2023). *Annual Energy Outlook 2023*; https://www.eia.gov/outlooks/aeo/

[12] Slowik, P., Isenstadt, A., Pierce, L., Searle, S. (2022). *Assessment of Light-Duty Electric Vehicle Costs and Consumer Benefits in the United States in the 2022-2035 Time Frame*; https://theicct.org/wp-content/uploads/2022/10/ev-cost-benefits-2035-oct22.pdf

Subsector	Stocks	Service Demands	Device Efficiency	Device Costs
			future year ICE vehicles, Slowik et al., 2022 for EVs	
Transportation Light Medium Duty Trucks	RI MOVES	RI MOVES	RI MOVES for existing ICE vehicle stock, EIA AEO 2023 for future year vehicles	Mullholland, 2022[13]
Transportation Medium Duty Trucks	RI MOVES	RI MOVES	RI MOVES for existing ICE vehicle stock, EIA AEO 2023 for future year vehicles	Slowik et al., 2023[14]
Transportation Heavy Duty Trucks (Short-haul)	RI MOVES	RI MOVES	RI MOVES for existing ICE vehicle stock, EIA AEO 2023 for future year vehicles	Slowik et al., 2023
Transportation Heavy Duty Trucks (Long-haul)	RI MOVES	RI MOVES	RI MOVES for existing ICE vehicle stock, EIA AEO 2023 for future year vehicles	Slowik et al., 2023
Transportation Buses	RI MOVES	RI MOVES	ANL 2021[15]	Slowik et al., 2023

[13] Mulholland, E. (2022). *Cost of Electric Commercial Vans and Pickup Trucks in the United States Through 2040*; https://theicct.org/wp-content/uploads/2022/01/cost-ev-vans-pickups-us-2040-jan22.pdf

[14] Slowik et al. (2023). *Analyzing the Impact of the Inflation Reduction Act on Electric Vehicle Uptake in the United States*; https://theicct.org/wp-content/uploads/2023/01/ira-impact-evs-us-jan23-2.pdf

[15] U.S. Department of Energy, Argonne National Laboratory. (2023). *Vehicle Technologies and Hydrogen and Fuel Cell Technologies Research and Development Benefits Analysis*; https://vms.taps.anl.gov/reports/u-s-doe-vto-hfto-r-d-benefits-analysis-mdhd/

3 Energy Only Subsectors

3.1 Overview

Energy only subsectors represent the final energy demands and direct GHG emissions for categories where comprehensive data on equipment stock, efficiencies, and service demands are not readily available. These include manufacturing and non-manufacturing industrial sectors, off-road transportation and aviation, and miscellaneous energy end-uses in residential and commercial buildings. For all energy only subsectors, starting year energy demands are benchmarked to historical consumption. For industrial subsectors, business-as-usual changes in future year energy demand are applied by subsector and fuel type based on changes forecasted in EIA Annual Energy Outlook 2023. Changes in future year aviation energy demand are also taken from Annual Energy Outlook, while energy demand growth for miscellaneous residential and commercial end-uses is projected using the households and commercial square footage growth rates, respectively. Table 3 below lists the default energy only subsectors used in Pathways.

Table 3: Energy only subsectors in Pathways

Subsector	Growth Rate
Residential Other	Households
Commercial Other	Commercial Square Footage
Transportation Aviation	EIA AEO23 Demand Growth for Jet Fuel
Transportation Other	N/A
Industry Aluminum	EIA AEO23 Demand Growth by Individual Fuel and Subsector
Industry Cement and Lime	
Industry Chemicals	
Industry Food	
Industry Glass	
Industry Iron and Steel	
Industry Metal Based Durables	
Industry Other	
Industry Paper	
Industry Plastics	
Industry Refining	
Industry Wood Products	
Industry Agriculture	
Industry Construction	
Industry Mining and Upstream Oil and Gas	

Once the baseline growth in energy demand is determined, users can specify either energy efficiency measures to reduce final energy consumption or fuel-switching measures to convert energy demand from one fuel to another. A third option for some stationary sources of CO_2 emissions is to apply CCS. The share of final emissions from a specific fuel and subsector that will be captured annually is specified by the user along with the technical characteristics of the CCS equipment like capital and operating costs, capture rate, and energy demands. The section below walks through the calculations for final energy demands in the energy only subsectors.

3.2 Calculations

3.2.1 Energy Demand Calculations for Energy Only Subsectors

As mentioned in the overview, the final energy demands in energy only subsectors account for both fuel-switching measures to convert energy demand from one fuel to another, and energy efficiency measures to reduce the final energy consumption. The final result is E_{if}^{I}, the final energy demand in year i for fuel type f across the subsector.

Key inputs for the energy demand calculations in energy only subsectors include:

- E_{if}^{I0}, the default energy demand in year i for fuel type f
- W_{ifg}, the percentage of energy demand in year i to be converted from fuel type f to fuel type g
- V_{ifg}, the energy efficiency factor in year i when converting from fuel type f to fuel type g (e.g. if switching from a natural gas boiler to an electric heat pump that is 3X more efficient, this value would be 300%)
- R_{if}, the energy efficiency reduction fraction for energy efficiency measures. This represents the % of final energy demand that will be reduced as a result of the measure

Intermediate calculated values include:

- $\hat{E}_{if}^{I}$, the energy demand in year i for fuel type f **after** fuel switching has been accounted for but **before** energy efficiency measures have been applied

Step 1: account for fuel-switching

First, fuel-switching is applied to the default energy demand trajectories for each fuel. This calculation:

1. starts with the default energy demand trajectory, E_{if}^{I0},
2. subtracts energy demands that will be switching from fuel type f to other fuel types, and then
3. adds fuel demands that will be switching from other fuel types to fuel type f, accounting for the conversion efficiency.

The intermediate energy demand accounting for fuel switching, $\hat{E}_{if}^{I}$, is calculated as shown in Equation 3.1:

$$\hat{E}_{if}^{I}, = E_{if}^{I0} - \sum_{g}\left(E_{if}^{I0} * W_{ifg}\right) + \sum_{g}\left(E_{if}^{I0} * W_{igf} \div V_{igf}\right) \qquad 3.1$$

Step 2: account for energy-efficiency measures

After fuel-switching has been accounted for, energy efficiency measures are applied to the intermediate energy demands, $\hat{E}^{I}_{if}$, to produce the final energy demands, E^{I}_{if}. The energy efficiency reduction fraction, R_{if}, is applied to calculate the final energy demands, E^{I}_{if}, as shown in Equation 3.2:

$$E^{I}_{if}, = \hat{E}_{if} * (1 - R_{if}) \qquad 3.2$$

Emissions resulting from these energy demands are dependent on the energy supply and are described in section 5. In cases where CCS is applied within a subsector, energy demands associated with CCS operations are also accounted for.

3.2.2 Costs for Energy Only Subsectors

Although device stocks are not explicitly modeled for energy only subsectors, the capital costs that would be associated with equipment upgrades are represented as levelized annual costs on a dollars per MMBtu basis. These include:

- **Fuel-switching costs:** annual levelized costs representing capital investments needed to purchase equipment associated with fuel-switching (e.g. the levelized incremental capital cost of an industrial heat pump replacing a natural gas boiler).
- **Efficiency costs:** annual levelized costs representing capital investments needed to purchase equipment associated with energy efficiency measures (e.g. the levelized incremental capital cost of efficient boilers relative to conventional boilers).

Annual costs that are accounted for in energy only subsectors include:

- **Fuel costs:** annual costs associated with fuel consumption in the subsector. Fuel costs are calculated by multiplying the final energy demand by the fuel cost per MMBtu of the fuel consumed.

If CCS is applied in the subsector, additional CCS costs will also be accounted for. These are described further in section 5.

3.3 Data Sources

Table 4 below lists the default data sources for key inputs to the energy only subsectors.

Table 4: Energy only default data sources

<table>
<tr><th>Subsector</th><th>Base Year Energy Demand</th><th>Energy Efficiency Costs</th><th>Electrification Costs</th><th>CCS Costs</th></tr>
<tr><td>Residential Other</td><td>EIA SEDS[16], RIDEM[17]</td><td rowspan="2">Schiller et al., 2020[18] and Frick et al., 2021[19]</td><td rowspan="2">Smillie et al., 2024[20]</td><td rowspan="2">N/A</td></tr>
<tr><td>Commercial Other</td><td>EIA SEDS, RIDEM</td></tr>
<tr><td>Transportation Aviation</td><td rowspan="2">EIA SEDS, RIDEM</td><td rowspan="2">N/A</td><td rowspan="2">N/A</td><td rowspan="2">N/A</td></tr>
<tr><td>Transportation Other</td></tr>
<tr><td>Industry Aluminum</td><td rowspan="15">NREL IEDB 2018[21], EIA SEDS, RIDEM</td><td rowspan="12">Schiller et al., 2020 and Frick et al., 2021</td><td rowspan="12">Zuberi et al., 2022[22] and DOE 2023[23]</td><td rowspan="12">NETL 2014[24]</td></tr>
<tr><td>Industry Cement and Lime</td></tr>
<tr><td>Industry Chemicals</td></tr>
<tr><td>Industry Food</td></tr>
<tr><td>Industry Glass</td></tr>
<tr><td>Industry Iron and Steel</td></tr>
<tr><td>Industry Metal Based Durables</td></tr>
<tr><td>Industry Other</td></tr>
<tr><td>Industry Paper</td></tr>
<tr><td>Industry Plastics</td></tr>
<tr><td>Industry Refining</td></tr>
<tr><td>Industry Wood Products</td></tr>
<tr><td>Industry Agriculture</td><td rowspan="3">N/A</td><td rowspan="3">Levelized cost of electrification for heavy-duty trucking used as proxy for off-road industrial equipment</td><td>N/A</td></tr>
<tr><td>Industry Construction</td><td>N/A</td></tr>
<tr><td>Industry Mining and Upstream Oil and Gas</td><td>NETL 2014</td></tr>
</table>

---

[16] U.S. Department of Energy, Energy Information Administration. (2023). *State Energy Data System: 1960-2021 (complete)*; https://www.eia.gov/state/seds/seds-data-complete.php

[17] Rhode Island Department of Environmental Management. (2024). *2022 Rhode Island Greenhouse Gas Inventory*; https://dem.ri.gov/environmental-protection-bureau/air-resources/rhode-island-greenhouse-gas-inventory

[18] Schiller, S., Hoffman, I., Murphy, S., Leventis, G., Schwartz, L. (2020). *Cost of saving natural gas through efficiency programs funded by utility customers 2012-2017*; https://eta-publications.lbl.gov/sites/default/files/cose_natural_gas_final_report_20200513.pdf

[19] Frick, N., Murphy, S., Miller, C., Pigman, M. (2021). *Still the One: Efficiency Remains a Cost-Effective Electricity Resource*; https://eta-publications.lbl.gov/sites/default/files/cose_cspd_analysis_2021_final_v3.pdf

[20] S. Smillie, D. Alberga, R. Loken, S. Bharadwaj, T. Clark, A. Mahone, "Measuring Economic Potential for Decarbonization Industrial Heat," Energy and Environmental Economics, Inc., October 2024; https://www.ethree.com/wp-content/uploads/2024/10/CAELP-E3-Industrial-Electrification-Report.pdf

[21] U.S. Department of Energy, National Renewable Energy Laboratory. (2019). *2018 Industrial Energy Data Book*; https://data.nrel.gov/submissions/122

[22] Zuberi, M., Hasanbeigi, A., Morrow, W. (2022). *Electrification of U.S. Manufacturing with Industrial Heat Pumps*; https://eta-publications.lbl.gov/sites/default/files/us_industrial_heat_pump-final.pdf

[23] U.S. Department of Energy. (2023). *Pathways to Commercial Liftoff: Industrial Decarbonization*; https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Industrial-Decarb.pdf

[24] U.S. Department of Energy, National Energy Technology Laboratory. (2014). *Cost of Capturing CO2 from Industrial Sources*; https://www.netl.doe.gov/projects/files/CostofCapturingCO2fromIndustrialSources_011014.pdf

4 Emissions Only Subsectors

4.1 Overview

Emissions only subsectors represent GHG emissions from non-energy and/or non-combustion related sources and emissions sinks from land use and forestry. For these sources, annual emissions are entered into the model directly as metric tons by pollutant type. The four pollutant types represented in Pathways are CO_2, CH_4, N_2O, and CO_2e (CO_2e is used for fluorinated gases like HFCs, PFCs, SF_6, and NF_3). Base year emissions sources and sinks are typically benchmarked to state-level data from EPA, but in this case are benchmarked directly to the 2022 Rhode Island Greenhouse Gas Inventory. Table 5 below lists the default emissions only sectors and subsectors used in Pathways.

Table 5: Emissions only subsectors in Pathways

Sector	Subsector	Pollutant
Agriculture	Liming	CO2
	Urea Fertilization	CO2
	Enteric Fermentation	CH4
	Manure Management CH4	CH4
	Rice Cultivation	CH4
	Residue Burning CH4	CH4
	Manure Management N2O	N2O
	Soil Management	N2O
	Residue Burning N2O	N2O
Coal Mining	Active Coal Mines	CH4
	Abandoned Coal Mines	CH4
Natural Gas and Oil Systems	Natural Gas Systems CO2	CO2
	Petroleum Systems CO2	CO2
	Abandoned Oil and Gas Wells CO2	CO2
	Natural Gas Systems CH4	CH4
	Petroleum Systems CH4	CH4
	Abandoned Oil and Gas Wells CH4	CH4
	Natural Gas Systems N2O	N2O
	Petroleum Systems N2O	N2O
Industrial Processes and Product Use (IPPU)	Cement Production	CO2
	Lime Production	CO2
	Other Process Uses of Carbonates	CO2
	Glass Production	CO2
	Soda Ash Production	CO2
	Carbon Dioxide Consumption	CO2
	Titanium Dioxide Production	CO2
	Aluminum Production CO2	CO2
	Iron and Steel Production CO2	CO2
	Ferroalloy Production CO2	CO2

	Ammonia Production	CO2
	Urea Consumption	CO2
	Phosphoric Acid Production	CO2
	Petrochemical Production CO2	CO2
	Carbide Production and Consumption CO2	CO2
	Lead Production	CO2
	Zinc Production	CO2
	Magnesium Production and Processing CO2	CO2
	Petrochemical Production CH4	CH4
	Carbide Production and Consumption CH4	CH4
	Iron and Steel Production CH4	CH4
	Ferroalloy Production CH4	CH4
	Adipic Acid Production	N2O
	Nitric Acid Production	N2O
	N2O from Product Uses	N2O
	Caprolactam and Others Production	N2O
	Electronics Industry N2O	N2O
	ODS Substitutes	CO2e
	HCFC-22 Production	CO2e
	Magnesium Production and Processing	CO2e
	Aluminum Production	CO2e
	Electronics Industry	CO2e
	Electrical Transmission and Distribution	CO2e
Waste	Waste Combustion CO2	CO2
	Landfills	CH4
	Wastewater Treatment CH4	CH4
	Composting CH4	CH4
	Anaerobic Digestion	CH4
	Waste Combustion CH4	CH4
	Wastewater Treatment N2O	N2O
	Waste Combustion N2O	N2O
	Composting N2O	N2O
Land-Use, Land-Use Change, and Forestry (LULUCF)	LULUCF CH4 Sources	CH4
	LULUCF N2O Sources	N2O
	LULUCF Carbon Stock Change	CO2

After the baseline trend for future year non-energy and/or non-combustion emissions has been determined, the user can specify annual emissions reductions as a percentage below the baseline trend for individual sources along with measure costs on a $/ton of pollutant basis.

4.2 Calculations

4.2.1 Emissions Calculations for Emissions Only Subsectors

The final emissions for an emissions only subsector, γ_{ip}, are calculated for each year i and pollutant p. Tracked pollutants typically include the most common greenhouse gases (i.e. CO2, CH4, and N2O). The final emissions, γ_{ip}, are calculated as shown in Equation 4.1:

$$\gamma_{ip} = \gamma_{ip}^{0} - \alpha_{ip} \qquad 4.1$$

where:

- γ_{ip}^{0} is the default emission value for year i and pollutant p, and
- α_{ip} is the quantity of emissions to be reduced via mitigation measures for year i and pollutant p.

In some cases, CCS may be applied to an emissions only subsector (e.g. cement production). Impacts from CCS are described further in section 5.

4.2.2 Cost Calculations for Emissions Only Subsectors

Annual costs associated with emissions reductions in emissions only subsectors are tracked within the model. These **emissions only reduction costs** are calculated by multiplying the annual emissions reductions, α_{ip}, by the input cost on a $/ton basis.

If CCS is applied in the subsector, additional CCS costs will also be accounted for. These are described further in section 5.

4.3 Data Sources

Table 6 below lists the default data sources for key inputs to the emissions only subsectors.

Table 6: Emissions only default data sources

Sector	Sources	Base Year Emissions	Growth Rate	Mitigation Potential and Costs
Agriculture	*All agriculture sources*	RIDEM	EPA State-Level Non-CO2 Report[25]	EPA State-Level Non-CO2 Report
Coal Mining	*All coal mining sources*	RIDEM	EPA State-Level Non-CO2 Report	EPA State-Level Non-CO2 Report

[25] U.S. Environmental Protection Agency. (2023). *U.S. State-level Non-CO_2 GHG Mitigation Report*; https://www.epa.gov/global-mitigation-non-co2-greenhouse-gases/us-state-level-non-co2-ghg-mitigation-report

Natural Gas and Oil Systems	*CH4 emissions sources*	RIDEM	EPA State-Level Non-CO2 Report	EPA State-Level Non-CO2 Report
	CO2 emissions sources	RIDEM	Aligned with methane growth	NETL 2014 for CCS on natural gas processing facilities
Industrial Processes and Product Use (IPPU)	*ODS Substitutes*	RIDEM	BAU forecast from EPA regulatory impact analysis for HFC rulemaking[26]	Emissions reductions forecast from EPA HFC rulemaking
	Cement and Lime Production CO2	RIDEM	Aligned with energy demand growth rates from EIA AEO23	NETL 2014 for CCS on cement production
	Iron and Steel Production CO2	RIDEM	Aligned with energy demand growth rates from EIA AEO23	NETL 2014 for CCS on iron and steel production
	All other IPPU sources	RIDEM	EPA State-Level Non-CO2 Report	EPA State-Level Non-CO2 Report
Waste	*CH4 emissions sources*	RIDEM	EPA State-Level Non-CO2 Report	EPA State-Level Non-CO2 Report
Land-Use, Land-Use Change, Forestry (LULUCF)	*Carbon sinks*	RIDEM	*Held flat pending input from state agencies and stakeholders on land sink trends*	Fargione et al., 2018[27]

5 Energy Supply

Pathways generates annual energy demands by fuel type, stocks and sales of energy consuming devices, and GHG emissions from non-energy/non-combustion sources. The energy demands by fuel type from Pathways can be passed to a set of energy supply optimization tools like E3's RESOLVE electricity sector capacity expansion model and E3's fuels optimization module. RESOLVE calculates optimal long-term electricity generation and transmission investments subject to reliability, policy, and technical constraints. The fuels optimization module calculates what production and allocation of low carbon fuels like biofuels, electrolytic fuels, and fossil fuels with

[26] U.S. Environmental Protection Agency. (2022). *Regulatory Impact Analysis for Phasing Down Production and Consumption of Hydrofluorocarbons (HFCS)*; https://www.epa.gov/system/files/documents/2022-07/RIA%20for%20Phasing%20Down%20Production%20and%20Consumption%20of%20Hydrofluorocarbons%20%28HFCs%29.pdf

[27] Fargione, J. et al. (2018). *Natural Climate Solutions for the United States*; https://www.science.org/doi/10.1126/sciadv.aat1869

negative emissions technology, provides the lowest cost portfolio that meets final energy demands and economy-wide emissions targets. Both RESOLVE and the fuels optimization tool provide emissions rates and prices for electricity and fuels, respectively, that are used to calculate final economy-wide emissions and costs.

Pathways can still be used to calculate economy-wide results on its own without the use of energy supply optimization models, but requires the user to enter predetermined annual emissions rates and prices for electricity and emissions rates, prices, and fuel blends for all liquid and gaseous fuel types. The default assumptions for fuel prices in Pathways are taken from the Reference case forecast in EIA AEO23.

5.1 Calculation of Economy-wide Emissions

Once the economy-wide energy supply has been determined for a scenario, economy-wide emissions can be calculated within the Pathways model. Economy-wide emissions include direct emissions from combusted fuels, indirect emissions from electricity, non-energy/non-combustion emissions, and any negative emissions that occur through CCS or negative emissions technologies (e.g. direct air capture). Emissions are calculated for each subsector that is modeled. Non-energy/non-combustion emissions are calculated as described in section 4. Other types of modeled emissions and their calculations are described in the subsequent sections.

5.1.1 Calculation of Emissions from Fuels

The final energy demands for stock rollover subsectors and energy only subsectors are represented by E_{if}^{S} and E_{if}^{I} respectively for each year i for fuel type f. The final energy demand for a general subsector year i for fuel type f will henceforth be denoted by E_{if}.

Energy demands for each fuel type f can potentially be served by a number of different candidate fuels c (e.g. energy demands for the "Natural Gas" fuel type might be served by candidate fuels "Fossil Natural Gas" or "Renewable Natural Gas"). The share of fuel demand in year i for fuel type f that is served by each candidate fuel c is denoted by ρ_{ifc}, and may be determined by either the user directly as an input or by an optimization calculation in a subsequent energy supply tool. For many candidate fuels, ρ_{ifc} does not change over time. However, in some instances, it may vary with time (e.g. a declining emissions factors for grid electricity). The subsector energy demands for each final fuel are translated to subsector energy demands for each candidate fuel as shown in Equation 5.1:

$$E_{ic} = \sum_{f} (E_{if} * \rho_{ifc}) \qquad 5.1$$

The emissions factors, β_{icp}, are known for each year i, candidate fuel c, and pollutant p (i.e. each GHG modeled). The default emissions factors in Pathways come from the EPA Emission Factors Hub and use AR5, 100-year global warming potentials[28]. Subsector emissions, γ_{ip}, for each year i pollutant p are calculated as shown below:

$$\gamma_{ip} = \sum_{c}(E_{ic} * \beta_{icp}) \quad 5.2$$

5.1.2 Captured Emissions from CCS and Negative Emissions Technologies

Final subsector emissions account for any negative emissions that are captured through CCS. CCS can be applied to both energy only subsectors and emissions only subsector as specified by the user. CCS is assumed to capture CO2. Key CCS inputs for energy only subsectors include:

- E_{if}, final energy demand for a general subsector year i for fuel type f (output of prior model calculations)
- τ_{if}, the percentage of operations that CCS will be applied to in year i for the combustion of fuel type f (e.g. for an energy only subsector, CCS might be applied to 90% of operations where coal is being combusted)
- μ_{if}, the capture rate for CCS applied to in year i for the combustion of fuel type f
- β_f, the gross CO2 emission factor for fuel type f (i.e. the metric tons of CO2 emitted per MMBtu of fuel type f consumed)

The emissions captured in year i, γ_i^{CCS}, are calculated as shown in Equation 5.3:

$$\gamma_i^{CCS} = \sum_{f}(E_{if} * \beta_f * \tau_{if} * \mu_{if}) \quad 5.3$$

For emissions only subsectors, the CCS will be applied to a fraction of the subsector emissions. In this case, the CCS will not be capturing emissions from combusted fuels. The captured emissions are instead calculated as shown in Equation 5.4:

$$\gamma_i^{CCS} = \gamma_i * \tau_i * \mu_i \quad 5.4$$

where:

- γ_i are the CO2 emissions for the emissions only subsector in year i absent any CCS,
- τ_i is the percentage of operations that CCS will be applied to in year i, and
- μ_i is the capture rate for CCS applied to in year i

CCS equipment also demands energy to operate. Emissions associated with these energy demands are accounted for in the subsector where the CCS is applied.

---

[28] U.S. Environmental Protection Agency. (2025). *Emission Factors for Greenhouse Gas Inventories*; https://www.epa.gov/system/files/documents/2025-01/ghg-emission-factors-hub-2025.pdf

In some cases, other negative emissions technologies (NETs) may also be represented (e.g. direct air capture). NETs are treated in the same way as CCS, except that the captured emissions from NETs are specified directly as a model input rather than being calculated, as they are not tied directly to emissions from other subsectors. Energy demands and costs for NETs are calculated using the same methodology as described for CCS.

5.1.2.1 Additional CCS Energy Demands

If CCS is applied in the subsector, then the additional energy demands associated with running the CCS equipment will also be accounted for. Key inputs to calculate these energy demands are:

- ε_{if}^{CCS}, the energy demand required to operate any CCS equipment in year i of fuel type f per metric ton of captured CO2
- γ_{i}^{CCS}, the metric tons of captured CO2 in year i across the subsector

The additional energy demand to run the CCS equipment, E_{if}^{CCS} is calculated as shown in Equation 5.5:

$$E_{if}^{CCS} = \varepsilon_{if}^{CCS} * \gamma_{i}^{CCS} \qquad 5.5$$

5.1.2.2 Additional CCS Costs

If CCS is applied in the subsector, then the additional costs associated with purchasing and running the CCS equipment will also be accounted for. These include:

- **CCS capital costs:** the annual levelized cost of incremental CCS capacity. This is calculated by levelizing the overnight capital cost of the equipment based on an assumed financing rate and financing lifetime.
- **CCS operation and maintenance (O&M) costs:** the annual variable costs associated with operating and maintaining the CCS equipment.
- **Fuel costs:** annual costs associated with fuel consumption in the by the CCS equipment.