Regional Investment and Operations Model Description

The Regional Investment and Operations model (RIO) is a highly temporally resolved capacity expansion model that is designed to faithfully represent energy systems from today to all imagined futures. It does so with an emphasis on flexibility of resource and technology configurations, an understanding that the principal economic challenges of future electricity systems are managing periods of renewable under-generation (while providing reliable service) and renewable overgeneration (while making productive use of otherwise-curtailed energy), and an ability to look for solutions economy-wide through its unique sector coupling framework. The following technical documentation is meant as an introduction to the model's capabilities and an initiation to the types of questions and challenges posed by decarbonized energy systems.

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

1. Narrow resource-selection decisions

- Principally an investigation of the cost-effectiveness of individual thermal resources. Highly temporally resolved, but limited in terms of investment decisions. Doesn't ask the question of optimal resource selection, but operates as a screening curve for an individual resource.

2. Criteria pollutant analyses.

    - Emphasis on individual plant detail, pollution controls equipment, pollution permitting costs, and thermal power plant operations necessary to faithfully represent criteria pollutant emissions.

3. Near-term policy targets.

    - Analyses of 33% to 60% RPS policies don't require high temporal resolution. Emphasis on spatially and technologically resolved resource locations, performance, and transmission costs.

The initially imagined context of modeling platforms matters significantly in terms of emphasis and structural design. Capacity expansion modeling is, in principle, simple. Given infinite computing power, all capacity expansion models would be the same. The execution of capacity expansion modeling, however, comes when simplifications have to be made to make a problem tractable without significant deviations from the answer in the theoretically perfect model. Capacity expansion models designed to answer specific questions are inappropriate for analyzing others. RIO was designed from the ground-up to answer the questions posed by deeply decarbonize energy systems. That emphasis is reflected in the feature sets detailed here as well as the approaches used for core elements of any capacity expansion framework (e.g. system reliability). The opportunities for separation in terms of model emphasis and approach come principally in the areas of **Time** (temporal granularity), **Space** (spatial granularity), **Electricity Operations** and **Electricity Investment**, and **Sector Coupling**. [1]

1. Time

1.1. Time Compression

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

Table 1 Time Compression

	Description	Time Slices	Incremental Time Compression
Theoretical Maximum Time Slices	(60s/m*60m/h*8760h/y*30y)	9.46E8	
Parameterized Sub-Hourly Resource Performance	RIO parameterizes resource ramp rates and production reliability (wind/solar) to characterize resource performance without explicitly modeling sub-hourly operations	2.63E5	99.97%

[1] Tables with blue fonts are specific to an analysis. Other descriptions are generic to overall model functionality.

Year Slices	Instead of representing every year, where changes between system conditions and policy might be marginal, RIO establishes a schedule of the most critical years and model these specifically.	6.13E4	76.69%
Day Sampling/Day Linkages	Instead of representing every hour of the year, we day sample and create a synthetic year of fully-represent days (referred to as samples) and mapped energy balances (referred to as periods) in order to assess long-duration storage	8995	85.33%

The example above shows the example compression applied to a single representative weather year. That is to say, the load and resource shapes are representative of the coincident climactic conditions of a single historical weather year. The model uses parameterization to anticipate how this individual weather year may map to a broader historical record. Sometimes, an analysis requires the parameterization of multiple weather and hydro years to represent system conditions appropriately. In those cases, we select the same number of sampled days but these are linked together as multi-year representations of sample conditions.

1.2. Day Sampling

The challenge of day sampling in any modeling platform is faithfully representing both extreme conditions, which drive investment for system reliability, while also accurately representing annual averages for things like renewable resource capacity factors.

RIO automates the day sampling for every model year based on inputs supplied in the model setup process. Typical parameters used in day selection are shown in *Table 2*. All of these characteristics can be weighted based on assessed importance to the day sampling process. RIO can also differentially weight zones in the day-selection process, so if an analysis is principally focused on a single zone in a multi-zone model configuration, the model can weight day selection characteristics within that zone.

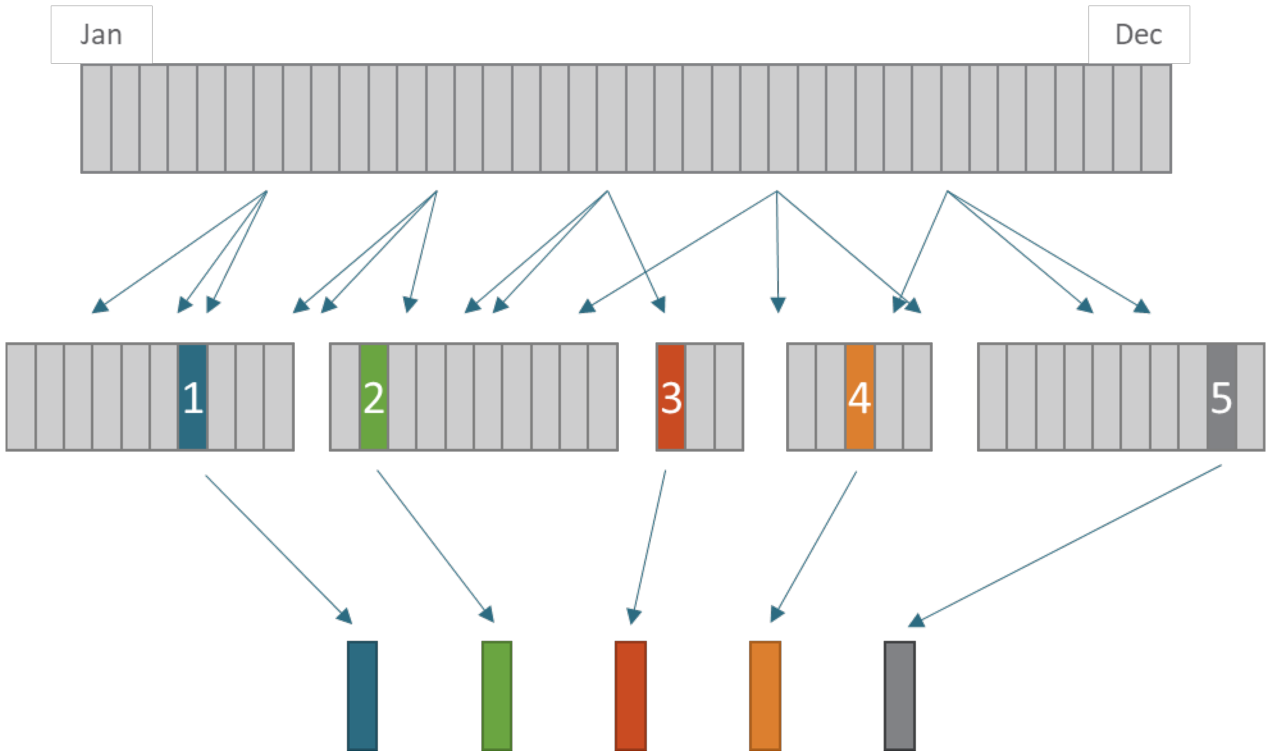
Table 2 Day Sampling Characteristics

Binning Characteristic	Description
Hydro Production	Important in hydro-dominated systems where daily historical hydro generation is a key factor in system reliability.
Hourly net load	Daily net load based on a first-order estimation of renewable deployment.
Hourly net load normalized by daily energy	Daily net load represented as a percentage of maximum daily net load.
Sum of daily net load energy	Daily net load represented as a total day sum.
Hourly net load fourth order polynomial coefficients	Model fits a 4th order polynomial to net load and uses the coefficients as part of the day clustering process.
Maximum net load	Maximum net load over the day.
Minimum net load	Minimum net load over the day.
Maximum net load ramp up	Maximum hourly ramp-up of net load.

Maximum net load ramp down	Maximum hourly ramp-down of net load.
Sum of net load overgeneration	Absolute value of the sum of net load when below 0.
sin(('dayofyear')/36.5/(np.pi/2))	Allows the algorithm to differentiate between Fall and Spring days (important for hydro)
cos(('dayofyear')/36.5/(np.pi/2))	Allows the algorithm to differentiate between Fall and Spring days (important for hydro)
Sum of gross load energy	Sum of daily end-use load.
Max load when solar is zero	Maximum night-time load (i.e. load when solar production ==0)
Standard deviation of net load	Standard deviation of net load from daily mean.
Renewable capacity factor	Daily capacity factors of specified renewable generation types (onshore wind, offshore wind, solar)

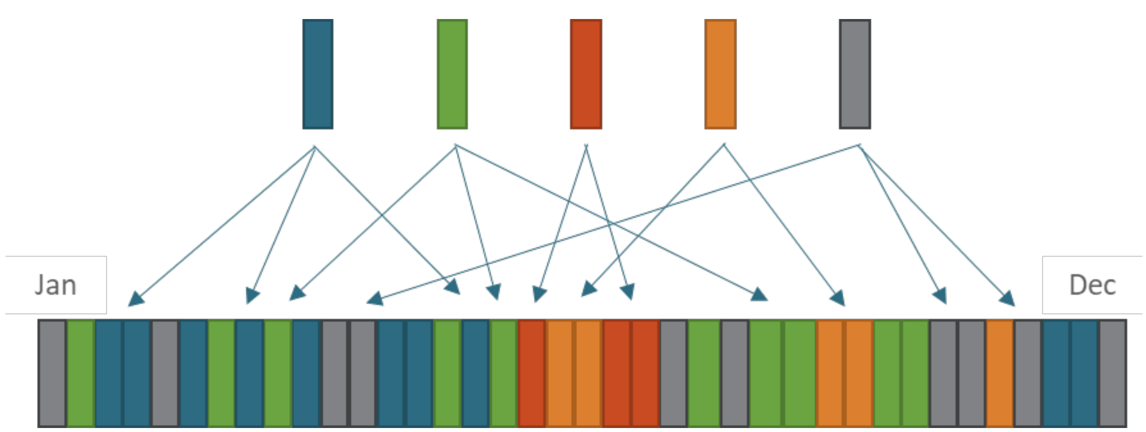
Once sampling characteristics have been selected, RIO uses clustering algorithms to bin representative days in each modeled year. This process is shown graphically in *Figure 1*. Each cluster in the second row represents days that have found to be statistically similar based on the supplied characteristics. The archetypal day within the cluster is then extracted and used as the representative day in the rest of the modeling process.

Figure 1 Day sampling



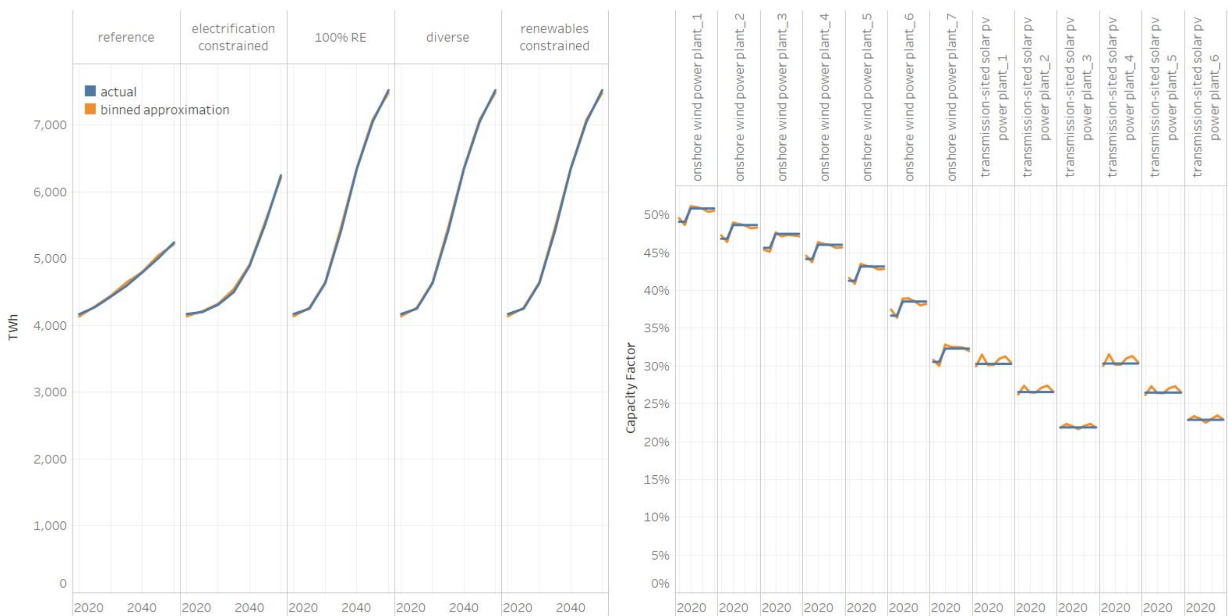
After the representative days are selected, the model synthesizes the year based on the cluster associations developed in the day sampling process. This creates a full 365-day representation based on a more limited set of daily operations.

Figure 2 Year synthesis



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

Figure 3 Example assessment of day binning performance



2. Space

2.1. Load Zones

RIO represents discrete demand/supply regions flexibly based on model run configurations. This zonal representation becomes the basic unit of constraint enforcement in the model formulation in terms of energy balances and electricity reliability provision. These zones can have unique enforced policy regimes, resource availability, hourly load and resource shapes, existing generators, etc. They can be linked to other zones with policy regimes, physical transmission ties that can be optimally constructed, and produced fuels (i.e. biofuels, hydrogen, etc.) and carbon (representing CO_2 pipelines) from other zones (see **Trading**).

Figure 4 Top-level zonal representation

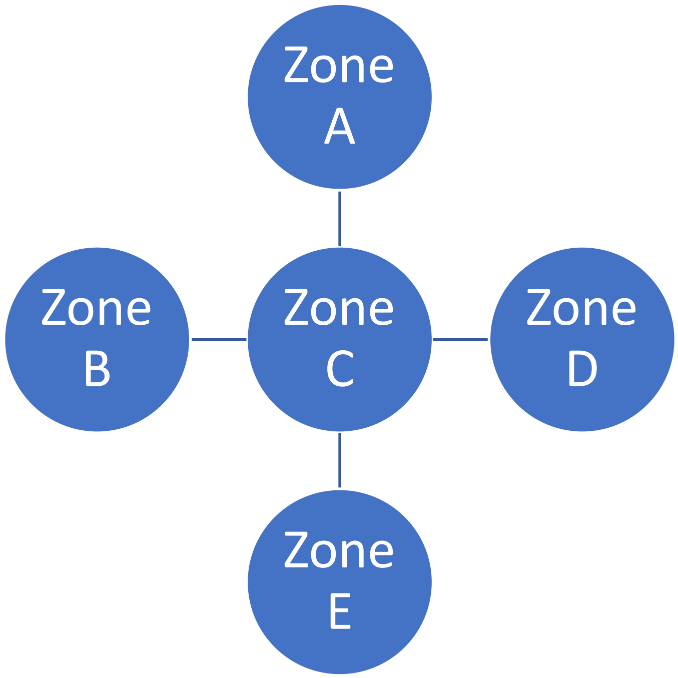
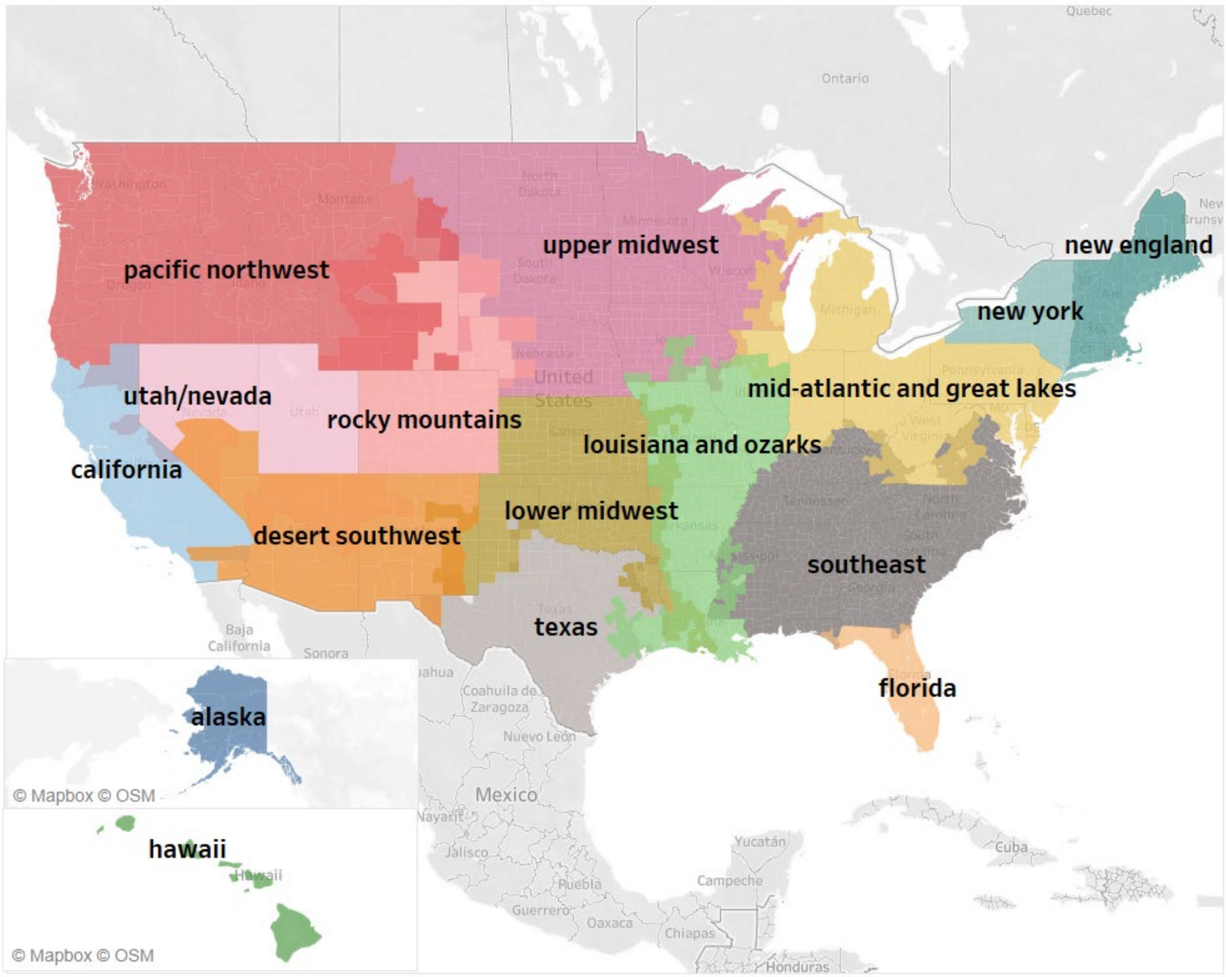


Table 3 Zonal Representation

Zones
Alaska
California
Desert Southwest
Florida
Hawaii
Louisiana and Ozarks

Lower Midwest
Mid-Atlantic and Great Lakes
New England
New York
Pacific Northwest
Rocky Mountains
Southeast
Texas
Upper Midwest
Utah/Nevada

Table 4 Zonal Representation (Map)



3. Electricity Operations

3.1. Generator Types

RIO allows for the definition of five broad categories of generators: thermal, fixed, hydro, storage, and flexible load resources. Each category requires different data inputs and is represented uniquely in terms of resource operational constraints, reliability contributions, and policy qualifications (i.e. contribution to clean electricity policy requirements).

Type	Existing/New	Generators

Thermal	Existing	Biomass Cogen (IPP)
Thermal	Existing	Biomass
Thermal	Existing	Coal IGCC
Thermal	Existing	Coal ST Cogen
Thermal	Existing	Coal ST Cogen (IPP)
Thermal	Existing	Distillate Oil CT
Thermal	Existing	Fossil Waste ST
Thermal	Existing	Gas CCGT Cogen
Thermal	Existing	Gas CCGT Cogen IPP
Thermal	Existing	Gas CCGT (5 heat rate bins)
Thermal	Existing	Gas CT Cogen
Thermal	Existing	Gas CT Cogen (IPP)
Thermal	Existing	Gas CT (5 heat rate bins)
Thermal	Existing	Gas ST Cogen
Thermal	Existing	Gas ST Cogen (IPP)
Thermal	Existing	Gas ST (5 heat rate bins)
Thermal	Existing	LFG
Thermal	Existing	MSW
Thermal	Existing	Nuclear
Thermal	Existing	Pet Coke ST Cogen
Thermal	Existing	Pulverized Coal (5 heat rate bins)
Thermal	Existing	Residual Oil CT IPP Cogen
Thermal	New	Gas CCGT
Thermal	New	Gas CT
Thermal	New	Advanced Nuclear
Thermal	New	Gas CCGT with CC (90% Capture)
Fixed	Existing	Onshore Wind
Fixed	Existing	Rooftop Solar PV
Fixed	Existing	Geothermal
Fixed	Existing	ROR Hydro
Fixed	Existing	Solar Thermal with Energy Storage
Fixed	Existing	Utility-Scale PV
Fixed	New	Non-Powered Dams
Fixed	New	Offshore Wind - Fixed (5 resource bins)
Fixed	New	Offshore Wind - Floating (10 resource bins)
Fixed	New	Onshore Wind (10 resource bins)
Fixed	New	Utility-Scale PV (6 resource bins)

Fixed	New	Rooftop PV
Fixed	New	Upgrades to Existing Hydro
Hydro	Existing	Dispatchable Hydro
Storage	Existing	Pumped Hydro
Storage	Existing	Li-Ion
Storage	New	Li-Ion
Storage	New	Long-Duration Storage
Storage	New	Distributed Li-Ion

3.2. Operational Constraints

The model uses unique sets of operating constraints for each resource types to model their hourly generation and ultimately contribution to satisfying the model's energy balance constraint.

3.2.1. Thermal

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

3.2.2. Fixed

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

3.2.3. Hydro

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

3.2.3.1. Fixed Daily Energy Budgets

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

3.2.3.2. Daily Cumulative Energy Constraints

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

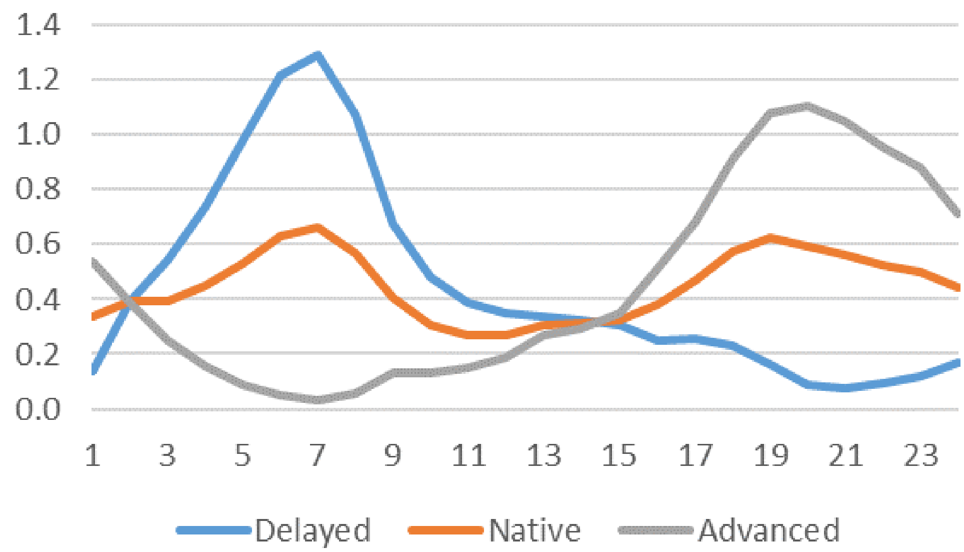
3.2.4. Storage

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

3.2.5. Flexible Load

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

Figure 5 Flexible Load Example Shape



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

3.2.6. Summary

A summary of the operational constraints for all technology types used in this analysis is shown below in *Table 3*.

Table 5 Operational Constraints by Technology

Category	Parameter	Thermal	Fixed	Hydro	Storage	Flexible Load

Operations	Min annual capacity factor	☑		☑		
Operations	Max annual capacity factor	☑	☑	☑		
Operations	Ramp rates	☑		☑		
Operations	P-min			☑		☑
Operations	Startup Costs					
Operations	Shutdown Costs					
Operations	Curtailment		☑	☑		
Operations	Hourly Production Shape	☑ (when must-run)	☑	☑ (p-min and p-max)		☑
Operations	Short-Term State-of-Charge Constraints (or equivalent)				☑	☑

Operations	Long-Duration Storage			☑	☑	

3.3. Reliability Contribution

RIO assesses two type of reserves that represent contributions to system reliability: operational reserves (typically referred to as ancillary services) and planning reserves. The section below details how the contribution towards reserves is determined for resources of each type.

3.3.1. Operating Reserves

While traditional electricity markets have multiple upward reserve requirements enforced with different required response times, we simplify these overall and downward reserve products into a single upward and downward reserve requirement. This reserve requirement is a function of load (to capture within hour deviations from the average as well as account for forecast error) as well as the addition of variable renewable resources, which can meaningfully contribute to within-hour net load fluctuations that can contribute to the need for additional reserve requirements.

3.3.1.1. Thermal

Thermal resources contribute to upward reserves as a function of resource eligibility and operating points. Upward reserves can be provided between P_{max} and the hourly energy output of the resource. Downward reserves can be provided between the hourly energy output of the resource and P_{min} (or zero when operating states are not enforced).

3.3.1.2. Fixed

Fixed resources contribute to upward reserves equal to the amount of their hourly curtailment. This hourly curtailment represents available energy that is foregone that can be “uncurtailed” within the hour to contribute to operating reserves. Downward reserves are able to be contributed to based on the hourly energy output of the resource, representing an available amount that can be curtailed within the hour.

3.3.1.3. Hydro

Subject to resource qualification, hydro can contribute to upward and downward operating reserves based on the distance between hydro's hourly energy output and its P_{max} (upward reserves) or P_{min} (downward reserves).

3.3.1.4. Storage

Storage contributes to operating reserves based on its current energy setpoint (charging or discharging). Availability to contribute to upward reserves within the hour is equal to the hourly charging of the resource plus residual available discharging capacity (P_{max} net of hourly scheduled power output). Availability contribute to downward reserves is equal to the hourly discharge of the resource + residual available charging capacity (P_{max} net of hourly scheduled power input).

3.3.1.5. Flexible Load

We do not currently parameterize the provision of operating reserves from flexible load.

3.3.2. Planning Reserves

Planning reserves are used to ensure a system has adequate capacity to meet load in all anticipated conditions (assessed on a statistical basis). This includes meeting load during extreme weather events, significant droughts of renewable production, and unforced outages of thermal capacity. Historically, reserves have been assessed in a probabilistic manner. Each hour's loss of load probability (a measure of the likelihood of the inability for the system's supply to meet its demand obligations) could be assessed independently of other hours. That made the problem tractable from a system planning perspective. Resource capacities and their expected contribution to meeting loads in each hour could be determined exogenously and run through Monte Carlo simulations.

In capacity expansion modeling, such statistical techniques are not computationally tractable. In many frameworks, a simplification of each resource's contributions towards reliability (using resource-specific factor like Net Qualifying Capacity) is used to approximate this approach. However, this misunderstands the reliability economics of deeply decarbonized energy systems. They are not, principally, a capacity issue. That is, solving net load peaks of limited duration is actually quite inexpensive. Solving net load peaks of longer duration increases the expense and limits the number of resources that can be economically competitive. They are also not an individual resource issue, but a system issue. They are the confluence of renewable resource builds, thermal builds and fuel availability, storage buildout and charging/discharging patterns), and the behavior of opportunistic loads (like hydrogen electrolysis). RIO takes a dynamic approach which assess the hourly reliability of every resource type dynamically to create systems that can operate reliably in an economic and policy environment where traditional approaches and metrics have been rendered inadequate.

3.3.2.1. Thermal

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

3.3.2.2. Fixed

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

3.3.2.3. Hydro

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

3.3.2.4. Storage

Similar to hydro resources, storage resources must maintain states of charge to support their reliable discharge. We therefore credit storage for capacity contributions only when generating (and add a capacity obligation to their charge schedule). This contribution is derated by a forced outage rate on the storage resource as well as a derate associated with the reliability of the energy in the storage reservoir. When the discharge is supported by long-term charge/discharge behaviors, we additionally derate capacity contributions by residual state of charge, parameterizing the uncertainty that the reservoir will be full when called upon to provide reliability.

3.3.2.5. Flexible Load

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

3.3.2.6. Transmission

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

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

3.4. Clean Electricity Policy Contributions

Resources make contributions towards clean electricity policy based on resource-specific contribution factors.

3.4.1. Thermal

Thermal resources are unique in that they can contribute to clean electricity policy via two potential pathways:

3.4.1.1. Burnertip Crediting

This is primarily used for resources that employ carbon capture technologies. We can allow a resource to qualify as “clean” above a certain capture threshold or allow resources to qualify as clean based on their carbon capture rate. It can also be used for resources like nuclear or biomass power plants.

3.4.1.2. Fuel Crediting

This is the principal avenue for crediting resources like nuclear and biomass or crediting gas power plants burning zero-carbon fuels. We assign the clean designation to the fuel inputs instead of the generator. Producing clean energy from these plants generates an obligation (**Sector Coupling**) for the fuels. In the case of a nuclear power plant, this is straightforward. Uranium is considered a "clean" fuel and thus all fuel burn by the nuclear plant is considered clean and the generation from the nuclear plant is all considered by the model to be "clean". For gas power plants, where the fuel can be traditional natural gas or other zero-carbon fuel substitutes, this is more complex. The model calculates the amount of clean electricity that the gas power plants can generate based on the amount of clean fuel produced by the model (H2 electrolysis, ammonia, etc.) and sent to those generators.

3.4.2. Fixed and Hydro

Fixed and Hydro resources are credited based on exogenous factors (input as a share of generation by year and zone).

3.4.3. Storage and Flexible Load

Storage and Flexible Load resources do not contribute towards clean electricity requirements. For storage, their charging and discharging losses increase clean electricity obligations.

3.4.4. Credit Trading

The previous section simplifies the complexity of resource crediting options available in the modeling by implicitly assuming that resource contributions towards clean electricity policy are made in the zones in which the resource is physically located. This is not always the case, and has explicitly not been the case in regions like California where a significant share of current clean electricity contributions are made by resources out-of-state. To address this, we allow resource credits to be assigned to zones other than where they physically exist.

Table 4 shows the resource eligibility matrix for two resources. The Onshore Wind resource is eligible to produce clean electricity credits in Zone A (where it is physically located) as well as

Zone C. The Solar PV resource is eligible to produce clean energy credits in Zone B (where it is located) as well as Zone C.

Table 6 Resource Credit Eligibility Matrix

Resource	Zone A	Zone B	Zone C
Onshore Wind Zone A	□		□
Solar PV Zone B		□	□

These out-of-zone resources can contribute towards clean electricity policy in two potential ways:

3.4.4.1. Unbundled Credits

Undelivered credits are accounting allocations of resource credits. They are not required to be associated (temporally) with the generation that produced them. They function as credit offsets for the zone they are assigned to.

3.4.4.2. Delivered Credits

Delivered credits to a zone are credits that are supported, on an hourly basis. Transmission imports must exceed the hourly credit assignment.

Zonal inputs constrain the share of credits that can come via either of these two methods.

3.4.5. Transmission Trading

In lieu of assigning generator-specific credit allocations described in the section above, the model can also deem import/export credit obligations along transmission corridors. For example, a corridor between Zone A and Zone B can be given a credit obligation value of 1. In this instance, this would necessitate all import energy flows to Zone A be supported by 100% clean electricity from Zone B.

4. Electricity Investment

4.1. Generation Investment

RIO allows for four types of capacity decisions for each of its principal generator types:

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

Details about these decision types are included below.

4.1.1. New Builds

New construction decisions are based on an assessment of the cost share of a resource installed in any model year. This cost share represents the realized levelized cost streams based on the selected modeled years. The example below shows how this is calculated for an example resource installed in 2020. We assess the costs of that resource *in* the years that we model (i.e. vintaged new build decisions) *for* the years which we model (i.e. the payments made in the modeled years for resources installed).

Table 7 New resource cost schedule

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
NPV	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

$1,000.00	$96.34	$96.34	$96.34	$96.34	$96.34	$96.34	$96.34	$96.34	$96.34	$96.34	$96.34	$96.34	$96.34	$96.34	$96.34
$262.36	$96.34					$96.34					$96.34				

4.1.2. Extensions

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

4.1.3. Repowers

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

4.1.4. Retirements

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

4.2. Transmission Investment

4.2.1. Transmission

In addition to investing in new generation, the model can invest in the expansion of transmission corridors to deliver additional energy between zones. The cost of this transmission investment is assessed in a similar manner to that of newly built generation. The model can support multiple corridors between zones with differentiated costs of expansion.

5. Sector Coupling

RIO's sector coupling framework allows for the optimization of the entire energy supply-side including electricity, fuels, heat, and carbon management as well as demand-side decisions like electric vehicle adoption. This separates it from traditional capacity expansion frameworks which focus exclusively on electricity. To the extent any sector coupling opportunities (i.e. electrolysis) are represented at all in these models, they're represented with exogenously specified inputs.

5.1. Framework Description

The RIO optimization framework includes the building blocks shown in *Table 6* to represent and optimize these sectors. The model allows for the flexible configuration of these components in order to best represent specific energy systems. A list of commodities; conversions; blends; and demand-subsectors conventionally used in EER modeling is shown in *Table 9*.

Table 8 Sector Coupling Framework Definitions

Category	Definition	Inputs
Commodity	Exogenously specified commodity type defined with price, emissions rates and available volumes. The commodity can be a unit of energy (i.e. MMBTU), mass (i.e. kilogram), or volume (i.e. liter). This allows representation of fuels,	Cost; Emissions Intensity; Available Supply; Optional – Marginal Cost Supply Curve

	carbon capture and management, and other processes like desalination.	
Conversion	Capital investment defined with cost of production capacity and efficiency of production (blend x -> blend y and/or electricity->blend y)	Capital Cost; Fixed OM; Variable OM; Efficiency; Max Deployment Rates; Max/Min Utilization Rates
Blend	Aggregation point for commodities and conversion outputs. All inputs (conversion and products) are drop-ins for an individual blend.	Storage Costs; Max Input Ratios (i.e. blend caps)
Endogenous End-Use	End-use energy service (i.e. light-duty autos) represented in RIO represented with energy service demand projections and technology stocks	Technology Cost and Performance; Service Demand

Table 7 shows how these elements interact, with commodities and conversion inflows satisfying the demand for blends, and endogenous end-uses, exogenous end-use demand, electricity generation outflows, and conversion outflows demanding blends.

Table 9 Sector Coupling Framework

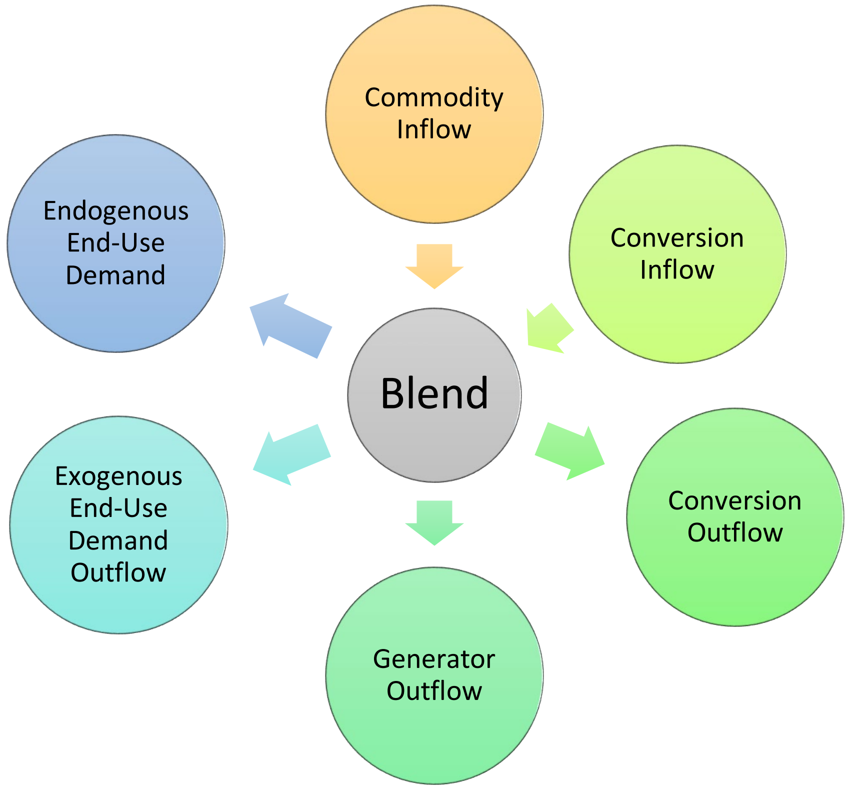
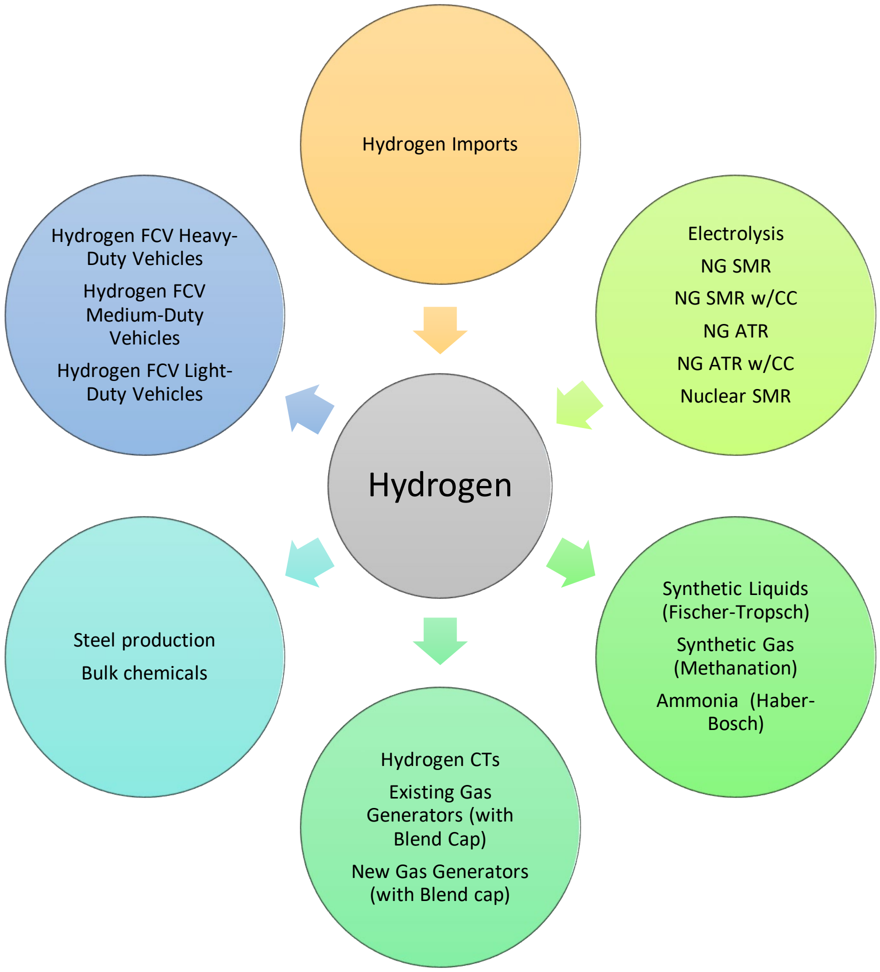


Table 8 shows this with the example of the hydrogen blend, with examples of each type of inflow and outflow.

Table 10 Sector Coupling Framework – Hydrogen Example



This of course shows a single blend, but the blends are linked with inflows and outflows of conversions. So, in this example, the hydrogen blend and pipeline gas blend are connected with the synthetic gas conversion technology, which demands hydrogen to produce pipeline gas. These types of interactions are critical to the modeling of low-carbon energy systems and this framework allows for the comprehensive accounting of these types of flows.

The orange arrow (to electricity) shown in the top right of *Table 8* is also a critical component of the linkages between model decisions. Where conversion technologies use electricity, the behavior of these loads are represented hourly within the electricity dispatch. This allows these loads to deploy in concert with highly renewable systems, moderating the levels of economic curtailment the system sees by demanding electricity in hours with surplus renewable generation while also being able to run off during hours where there is renewable under-generation. This linkage ultimately connects the electricity, heat, fuels, and carbon management sectors of the economy and is necessary for the representation of low-carbon energy systems.

The orange arrow (from electricity) shown in the bottom left of *Table 8* completes the loop between electricity and fuel supply. Generators demand hydrogen in this case, which, for purposes of clean electricity accounting, may be required to be "green hydrogen" in order to qualify as a clean resource. This allows for the representation of a fully internally consistent electricity supply, with resources like electrolysis demanding electricity, storing that energy, and potentially returning that energy to the electricity system at a later time either directly as hydrogen or in the form of synthetic methane.

Table 11 Sector Coupling Building Blocks

Category	Name
Commodity	Biomass – Corn
Commodity	Biomass – Woody
Commodity	Biomass - Herbaceous
Commodity	Biomass – Waste
Commodity	Carbon Sequestration
Commodity	Coal
Commodity	Coke
Commodity	Landfill Gas
Commodity	Natural Gas

Commodity	Oil
Commodity	Petroleum Coke
Commodity	Fossil Diesel
Commodity	Fossil Gasoline
Commodity	Fossil Jet Fuel
Commodity	Fossil Kerosene
Commodity	Fossil LPG
Commodity	Fossil Residual Fuel Oil
Commodity	Still Gas
Commodity	Uranium
Conversion	Biomass – SNG
Conversion	Biomass – SNG w/CC
Conversion	Electrolysis
Conversion	Cellulosic Ethanol
Conversion	Direct Air Capture
Conversion	Electric Boiler
Conversion	Pipeline Gas Boiler
Conversion	Coal Boiler

Conversion	Hydrogen Boiler
Conversion	Petroleum Coke Boiler
Conversion	Fuel Oil Boiler
Conversion	Corn Ethanol
Conversion	Corn Ethanol w/CC
Conversion	Biomass – FT Diesel
Conversion	Biomass – FT Diesel w/CC
Conversion	BECC – Hydrogen
Conversion	Biomass – Pyrolysis
Conversion	Biomass – Pyrolysis w/CC
Conversion	Ammonia
Conversion	H2 – to – Liquids (FT)
Conversion	H2 – to – Gas (Methanation)
Blend	Biomass – Solids
Blend	Biomass – Waste
Blend	Biomass – Corn
Blend	CO2 Utilization
Blend	Coal

Blend	Coke
Blend	Diesel
Blend	Gasoline
Blend	Hydrogen
Blend	Jet Fuel
Blend	Kerosene
Blend	Landfill Gas
Blend	LPG
Blend	Oil
Blend	Petroleum Coke
Blend	Pipeline Gas
Blend	Residual Fuel Oil
Blend	Steam
Blend	Uranium

5.2. Additional Feature Description

5.2.1. Blend Storage

Blend inflows and outflows can be tracked with a time resolution as short as a day. Deviations in time between inflows and outflows can be significant for blends like hydrogen, and costs of using hydrogen to store energy is non-trivial. In these cases, we track the “state of charge” for the blend and assess a cost for this storage capacity.

5.2.2. Trading

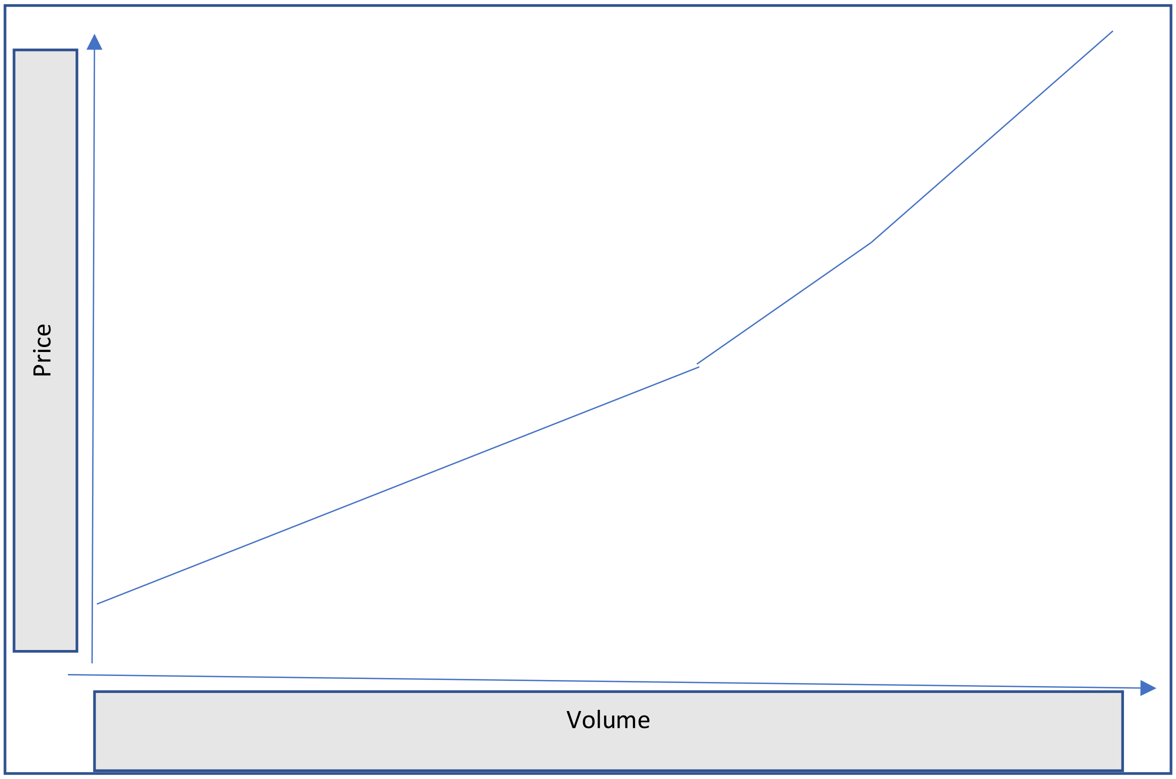
Any conversion or commodity can be assigned a trade eligibility matrix (i.e. zone-from and zone-to combination) and delivery cost between zones. This allows a representation of infrastructure like long-distance pipelines for hydrogen/ammonia/co2 and allows the demand for blends to be supplied by conversions or commodities from other zones.

Table 12 Example eligibility matrix for a conversion technology

Zone From/Zone To	Zone A	Zone B	Zone C
Zone A	□		□
Zone B		□	
Zone C			□

5.2.3. Marginal Cost Supply Curves

Where appropriate, all commodity price curves can be input as marginal cost supply curves. This can be useful for commodities like natural gas, where the marginal price seen by generators is dependent on volumes. These can be implemented zonally or globally (i.e. commodity price depends on volumes demanded within a zone or within all model zones).


Price
Volume