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Model Formulations

Market clearing models, market design specifications, and dispatch simulation

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Abstract

This document provides various model formulations that will be implemented for the Energy Storage Participation Algorithm pilot competition (ESPA-Comp). It is not required for potential competitors to read this document, but doing so may be helpful to better understand the market clearing process, The market designs, and how resource dispatch and degradation will be modeled. This competition will assess the performance of different storage offer algorithms in terms of their ability to maximize the value of storage resources participating under three market designs that vary in complexity. The model formulations include a general market clearing optimization model and market design specifications. We provide specifications for three market designs to be tested in ESPA-Comp, which we call the two-settlement, multi-settlement, and rolling horizon forward markets. The market designs include different trading frequencies and offer formats. Storage resources participating in the market are provided with primitive values for the resource's physical capabilities, and they are provided with a storage offer format that their algorithms will be tasked with populating. A detailed physical model is used to assess each storage resource's ability to maintain its scheduled dispatch according to its state-of-charge, operating temperature, and other physical attributes.

Contents

1.0 Overview

This document describes a market clearing optimization model. We describe how this model is used in a market clearing procedure. We specify how the market clearing model and procedure can be instantiated with differing time parameters, including the overall model horizon, the duration of discrete time intervals within the horizon, and the partition of the horizon into a market settlement interval followed by a look ahead interval. In addition to these time parameters, some instantiations of the market clearing model might treat certain variables (such as discrete commitment variables) as fixed and might relax some constraints (such as intertemporal constraints). We show how some of these different instantiations of the market clearing model and procedure correspond to common real world electricity markets, such as a (near) real time market, a day ahead market, and others correspond to certain proposed electricity market arrangements. We then describe how these different instantiations can be run in sequence to simulate real or proposed market designs, such as the typical two-settlement day ahead and real time market, a multi-settlement intra-day market, and a rolling horizon forward market.

2.0 General Market Clearing Optimization Model

The general market clearing optimization model is a security constrained unit commitment (SCUC) model. This section gives an algebraic formulation of the market model.

The market model can be instantiated in several different ways, in particular using different time scales, and these different instantiations along with individual resource operation models can be solved in sequence to simulate the ongoing workings of an electricity market under various market rules and procedures. Section 3.0 describes how these rules and procedures are specified. Section 4.0 describes the physical simulation of each resource, which in some cases may be different from the quantities cleared in the market clearing optimization model.

The inputs of the market model include data on grid characteristics and a general discrete time horizon as well as bids and offers provided by demand and supply resources along with technical resource capabilities. The outputs include schedules of commitment status and dispatch of energy and ancillary products for each resource as well as market clearing prices of energy and ancillary products.

The output variable values are chosen so as to maximize the total market surplus subject to constraints on individual resource operation and on the system as a whole. Resource operation constraints include maximum and minimum real power output levels, ramping limits, must-run and planned outage, minimum uptime and downtime, and others specific to certain types of resources, such as state of charge management for storage. System-wide constraints include supply and demand balance for energy and ancillary products and security constraints preventing the power flows along lines from exceeding their limits. The market surplus maximization objective consists of the value to consumers derived from consuming energy, minus the cost to producers incurred by producing energy, minus penalties on violations of certain constraints that are treated as soft constraints. The value and cost of producing energy is modeled as typical economic supply and demand functions, with diminishing returns to scale. In addition to these convex cost and value features, the objective includes nonconvex startup, shutdown, and fixed operating (no load) costs. After the model is solved a first time to determine resource dispatch schedules, the discrete variables (which generally consist of the resource commitment variables) are fixed to their optimal values, and then the model is solved again. This second solve is a convex optimization problem and therefore produces Lagrange multipliers that are used as market clearing prices for energy and ancillary products.

The complete output of the market model is the schedules of commitments, dispatches, and prices of energy and ancillary resources. Each resource should then operate following the commitment and dispatch schedule and should pay or be paid for consumption or production of energy and ancillary products according to the market clearing prices. The market clearing property of this output is that, assuming the commitment variables are fixed to their values and assuming that the technical characteristics and bid or offer of each resource completely characterizes its operational costs, values, and capabilities, then each resource has no incentive to deviate from its scheduled dispatch. Of course, theorized incentives might not always match actual incentives, and scheduled deliveries might not always be fulfilled.

The following subsections describe individual features of the market model, including resource operation constraints, system constraints, and the market clearing procedure.

2.1 Market Attributes

2.1.1 Nomenclature

2.1.1.1 Sets and Indices

Indices

$h \in \mathcal{H}$	Market participants
$b \in \mathcal{B}$	Bid or offer blocks
$i, j \in \mathcal{I}$	Buses
$k \in \mathcal{K}$	Transmission lines
$n \in \mathcal{N}$	Market resources
$t \in \mathcal{T}$	Time intervals in the market clearing horizon

Subsets

$\mathcal{K}^{\mathrm{MON}} \subseteq \mathcal{K}$	Monitored transmission lines
$\mathcal{N}^{\mathrm{DEM}} \subset \mathcal{N}$	Demand resources
$\mathcal{N}^{\mathrm{GEN}} \subset \mathcal{N}$	Conventional generator resources
$\mathcal{N}^{\mathrm{REN}} \subset \mathcal{N}$	Renewable generator resources
$\mathcal{N}^{\mathrm{STR}} \subset \mathcal{N}$	Storage resources
$\mathcal{N}^{\mathrm{VIR}} \subset \mathcal{N}$	Virtual resources
$\mathcal{N}_h^{\mathrm{owner}} \subset \mathcal{N}$	Subset of market resources owned by a market participant h
$\mathcal{N}_i^{\mathrm{bus}} \subset \mathcal{N}$	Set of market resources connected to bus i.

Distinct elements

$i_n \in \mathcal{I}$	Bus connected to market resource n

2.1.1.2 Parameters

Table 2.1 lists the parameters of the market clearing model.

Table 2.1: Market Clearing Model Parameters

Symbol	Description	Format	Domain	Units
D_t	Duration of interval t	Float	Positive	Minutes
C^{en}	Energy imbalance penalty coefficient	Float	Positive	\$/MWh

Symbol	Description	Format	Domain	Units
C^{rgu}	Regulation up imbalance linear penalty coefficient	Float	Positive	\$/MWh
C^{rgu2}	Regulation up imbalance quadratic value coefficient	Float	Positive	\$/MW²h
C^{rgd}	Regulation down imbalance linear penalty coefficient	Float	Positive	\$/MWh
C^{rgd2}	Regulation down imbalance quadratic value coefficient, equal to slope of demand curve	Float	Positive	\$/MW²h
C^{spr}	Spinning reserve imbalance linear penalty coefficient	Float	Positive	\$/MWh
C^{spr2}	Spinning reserve imbalance quadratic value coefficient	Float	Positive	\$/MW²h
C^{nsp}	Non-spinning reserve imbalance linear penalty coefficient	Float	Positive	\$/MWh
C^{nsp2}	Non-spinning reserve imbalance quadratic value coefficient	Float	Positive	\$/MW²h
K^{rgu}	Regulation up requirement coefficient	Float	Unit interval	Unitless
K^{rgd}	Regulation down requirement coefficient	Float	Unit interval	Unitless
K^{spr}	Spinning reserve requirement coefficient	Float	Unit interval	Unitless
K^{nsp}	Non-spinning reserve requirement coefficient	Float	Unit interval	Unitless
$P_k^{\text{f,max}}$	Power flow limit on line k	Float	Positive	MW
$C^{\text{f+}}$	Line overload penalty coefficient	Float	Positive	\$/MWh
X_k	Reactance of series element of line k.	Float	Reals	pu
B_k	DC admittance of series element of line k. In our DC power flow model this is taken as the susceptance.	Float	Reals	pu
U_{kt}^{f}	In-service status of line k in interval t. Equal to 1 if in service, 0 else.	Integer	$\{0,1\}$	Unitless

2.1.1.3 Variables

Table 2.2 lists the variables of the market clearing model.

Table 2.2: Market Clearing Model Variables

Symbol	Description	Format	Domain	Units
z^{total}	Total market surplus objective, for maximization	Float	Free	\$
z_n	Surplus, equal to value accrued minus cost incurred, to resource n	Float	Free	\$

Symbol	Description	Format	Domain	Units
$z_{it}^{\mathrm{en}+}$	Penalty due to excess supply of energy at bus i in interval t	Float	Nonpositive	$
$z_{it}^{\mathrm{en}-}$	Penalty due to excess demand for energy at bus i in interval t	Float	Nonpositive	$
$z_{t}^{\mathrm{rgu}+}$	Surplus due to excess supply of regulation up in interval t	Float	Nonnegative	$
$z_{t}^{\mathrm{rgu}-}$	Penalty due to regulation up shortfall in interval t	Float	Nonpositive	$
$z_{t}^{\mathrm{rgd}+}$	Surplus due to excess supply of regulation down in interval t	Float	Nonnegative	$
$z_{t}^{\mathrm{rgd}-}$	Penalty due to regulation down shortfall in interval t	Float	Nonpositive	$
$z_{t}^{\mathrm{spr}+}$	Surplus due to excess supply of spinning reserve in interval t	Float	Nonnegative	$
$z_{t}^{\mathrm{spr}-}$	Penalty due to spinning reserve shortfall in interval t	Float	Nonpositive	$
$z_{t}^{\mathrm{nsp}+}$	Surplus due to excess supply of non-spinning reserve in interval t	Float	Nonnegative	$
$z_{t}^{\mathrm{nsp}-}$	Penalty due to non-spinning reserve shortfall in interval t	Float	Nonpositive	$
$z_{kt}^{\mathrm{f}+}$	Penalty due to line overload on line k in interval t	Float	Nonpositive	$
p_{nt}^{en}	Net energy injection from resource n in interval t. Energy supply is positive. Energy demand is negative.	Float	Free	MW
$p_{it}^{\mathrm{en}+}$	Excess supply of energy at bus i in interval t	Float	Nonnegative	MW
$p_{it}^{\mathrm{en}-}$	Excess demand for energy at bus i in interval t	Float	Nonnegative	MW
$\lambda_{it}^{\mathrm{en}}$	Price of energy at bus i in interval t	Float	Free	$/MWh
p_{kt}^{f}	Power flow on line k in interval t. Flow in the forward direction is positive. Flow in the backward direction is negative.	Float	Free	MW
$p_{kt}^{\mathrm{f}+}$	Overload on line k in interval t	Float	Nonnegative	MW
r_{nt}^{rgu}	Regulation up provided by (procured from) resource n in interval t	Float	Nonnegative	MW

Symbol	Description	Format	Domain	Units
r_{nt}^{rgd}	Regulation down provided by resource n in interval t	Float	Nonnegative	MW
r_{nt}^{spr}	Spinning reserve provided by resource n in interval t	Float	Nonnegative	MW
r_{nt}^{nsp}	Non-spinning reserve provided by resource n in interval t	Float	Nonnegative	MW
$r_{t}^{\text{rgu+}}$	Excess supply of regulation up in interval t	Float	Nonnegative	MW
$r_{t}^{\text{rgu}-}$	Reserve requirement shortage for regulation up in interval t	Float	Nonnegative	MW
$r_{t}^{\text{rgd+}}$	Excess supply of regulation down in interval t	Float	Nonnegative	MW
$r_{t}^{\text{rgd}-}$	Reserve requirement shortage for regulation down in interval t	Float	Nonnegative	MW
$r_{t}^{\text{spr+}}$	Excess supply of spinning reserve in interval t	Float	Nonnegative	MW
$r_{t}^{\text{spr}-}$	Reserve requirement shortage for spinning reserve in interval t	Float	Nonnegative	MW
$r_{t}^{\text{nsp+}}$	Excess supply of non-spinning reserve in interval t	Float	Nonnegative	MW
$r_{t}^{\text{nsp}-}$	Reserve requirement shortage for non-spinning reserve in interval t	Float	Nonnegative	MW
$r_{t}^{\text{rgu,req}}$	Regulation up requirement in interval t	Float	Nonnegative	MW
$r_{t}^{\text{rgd,req}}$	Regulation down requirement in interval t	Float	Nonnegative	MW
$r_{t}^{\text{spr,req}}$	Spinning reserve requirement in interval t	Float	Nonnegative	MW
$r_{t}^{\text{nsp,req}}$	Non-spinning reserve requirement in interval t	Float	Nonnegative	MW
λ_{t}^{rgu}	Price of regulation up in interval t	Float	Nonnegative	$/MWh
λ_{t}^{rgd}	Price of regulation down in interval t	Float	Nonnegative	$/MWh
λ_{t}^{spr}	Price of spinning reserve in interval t	Float	Nonnegative	$/MWh
$\lambda_{t}^{\text{nspr}}$	Price of non-spinning reserve in interval t	Float	Nonnegative	$/MWh
θ_{it}	Voltage angle of bus i in interval t.	Float	Reals	rad

2.1.2 Market timeline

This section describes how each market design's chronology is specified. First, terminology and definitions are introduced to describe the market clearing timeline. Physical, forward, and advisory attributes are then defined for the intervals included in each market clearing model, as well how those attributes are reflected in the formulation of the market clearing model.

The market's chronology requires introducing a vocabulary to describe offer periods, time horizons, settlement frequency, and other timing issues in a general manner. Terms are defined below:

Dates and Times:

- **Current Day (CD):** the current day in the simulation's chronology.
- **Current Hour (CH):** the current hour in the simulation's chronology.
- **Current Time (CT):** the current time period in the simulation's chronology.
- **Operating Day (OD):** the date when physical delivery will occur.
- **Operating Hour (OH):** the beginning of the hour when physical delivery will occur.
- **Operating Period (OP):** the time interval when physical delivery will occur.
- **Planning Day (PD):** the day after the current day in the simulation's chronology.
- **Planning Hour (PH):** the hour after the current hour in the simulation's chronology.
- **Start Period (SP):** the first time interval in the set of market clearing intervals.

Market Clearing Schedule:

- **Market Clearing Period:** the time interval when the market is cleared and the results are available for participants to review.
- **Market Clearing Schedule:** the list of market clearing periods when a specified market clearing optimization model will be instantiated and solved.
- **Market Clearing Intervals:** the set of time intervals ($\mathcal{T}$) included in the market clearing optimization model.
- **Offer Submission Period:** the time interval when market bids and offers are submitted to the market clearing algorithm. Submissions are required before the market is cleared and the results are posted, which may be minutes or hours before any of the periods in the market's time horizon.

Interval Types:

- **Interval Duration:** the duration of an interval t (D_t) in the market clearing horizon in minutes.
- **Physical Delivery Interval (PHYS):** the time interval in the real-time market that represents physical delivery of all products cleared by the market optimization.
- **Forward Interval (FWD):** a time interval in the market clearing optimization model that does not require physical delivery but is cleared and results in a financially binding schedule.
- **Advisory Interval (ADVS):** a time interval in the market clearing optimization model that does not require physical delivery and does not result in any financially binding schedules. These intervals are typically included to avoid "end-of-horizon" effects in the market clearing solution.

Date and time abbreviations (i.e., CT, OD, OH, and OP) facilitate a convenient way to specify the many dates and times that may occur in a simulation's chronology. Where appropriate, specific dates and times can be referenced from a tuple of the date and time abbreviation and an integer-valued number of minutes.

Using the above attributes, each market optimization model's timeline is specified according to Table 2.3 below.

Table 2.3: Market Timeline Specification

Attribute	Format	Units	Example
Starting Period	List of tuple of string and float	N/A, minutes	[("PD", 0)]
Unique identifier (UID)	String	N/A	"TSDAM_{SP}"
Offer Submission Period	Tuple of string and float	N/A, minutes	("CD", 540)
Market Clearing Period	Tuple of string and float	N/A, minutes	("CD", 720)
Interval Durations	List of tuple of integer and float	N/A, minutes	[(36, 60)]
Interval Types	List of tuple of integer and string	N/A, N/A	[(24, "FWD"), (12, "ADVS")]

The examples in Table 2.3 specify a two-settlement day ahead market timeline and are further explained below. Suppose that "CT" is "01/01/2024 12:00am".

- Starting period specification ("PD", 0) sets the starting period to "01/02/2024 12:00am"
- UID specification "TSDAM_{SP}" is evaluated and formatted as "TSDAM_20240102_0000".
- Offer submission period specification ("CD", 540) sets the offer submission period to 540 minutes after the beginning of the current day, which is "01/01/2024 9:00am".
- Market clearing period specification ("CD", 720) sets the market clearing period to 720 minutes after the beginning of the current day, which is "01/01/2024 12:00pm".
- Interval duration specification (36, 60) indicates that there are 36 intervals that each have a duration of 60 minutes.
- Interval type specification [(24, "FWD"), (12, "ADVS")] indicates that the first 24 intervals are financially binding and that the following 12 intervals are advisory schedules.

Note that the specification imposes a requirement that the interval durations and interval types will specify the same number of intervals. In addition, the specification must result in an offer submission period and market clearing period that have not yet occurred in the market's chronology. This property can be confirmed by initializing a new market clearing model each time when the simulation's chronology results in a new UID. The market's offer submission period and market clearing period can be generated when the new UID is generated, and the initialization is validated if both periods occur sometime after the simulation chronology's current time.

Each market is instantiated in a simulation environment that sequences time and determines when a particular market clearing model should be instantiated and solved. The algorithm describes how this simulation controls the passage of time and when to initiate the market clearing processes.

1. List of market UIDs $M = [\emptyset]$
2. Current time $t = T_0$
3. Generate candidate UID m from current time t.

4. If $m \notin M$, initialize new market and generate its offer submission period and market clearing period. $M = M + m$.
5. For each $m \in M$:
   a. If the offer submission period is t, then collect offer data, initialize model, and solve.
   b. If the market clearing period is t, report the model solution and market clearing settlements to market participants.
   c. If the market clearing period is less than t, delete the market. $M = M - m$.
6. $t = t + 1$. Return to Step 3.

Participants in ESPA-Comp will need to design their algorithms so that offer data in the correct format will be submitted at the correct time in Step 5a and so that they collect their market settlements in Step 5b. Implementation details for those tasks are included in the Participation Guide document.

2.1.3 System parameters

The market includes some parameters that that are part of the market design, such as the duration of market clearing intervals or various requirements related to reserve products. These parameters are defined in Table 2.4 below and will be applied throughout the constraint formulations in Sections 2.2 and 2.3.

Table 2.4: Market Attributes

Symbol	Description	Format	Units
D_t	Duration of interval t	Float	Minutes
D^{spr}	Response duration requirement for spinning reserve provided by energy storage	Float	Minutes
D^{nsp}	Response duration requirement for non-spinning reserve provided by energy storage	Float	Minutes
T^{spr}	Response time requirement for spinning reserve	Float	Minutes
T^{nsp}	Response time requirement for non-spinning reserve	Float	Minutes

2.2 System Constraints

System constraints define how the market is cleared. The formulation is implemented with slack variables on each system constraint as a way of ensuring that the resulting optimization problem is not infeasible. Typically, large penalties are applied to the slack variables. The system-level constraints include the total market surplus, power balance at each bus, line flow limits on each transmission line, and system-wide requirements for ancillary products. Losses, voltage, and reactive power are not considered.

2.2.1 Market surplus objective

The objective is to maximize total market surplus, defined as value minus cost minus penalties. Each component of the objective is assumed positive by convention.

$$z^{\text{total}} = \sum_{n\in\mathcal{N}} z_n + \sum_{k\in\mathcal{K}^{\text{MON}},t\in\mathcal{T}} z_{kt}^{\text{f+}} + \sum_{i\in\mathcal{I},t\in\mathcal{T}} (z_{it}^{\text{en+}} + z_{it}^{\text{en-}}) + \sum_{t\in\mathcal{T}} \left(z_t^{\text{rgu-}} + z_t^{\text{rgu+}} + z_t^{\text{rgd-}} + z_t^{\text{rgd+}} + z_t^{\text{spr+}} + z_t^{\text{spr-}} + z_t^{\text{nsp+}} + z_t^{\text{nsp-}}\right) \quad (1)$$

2.2.2 Bus voltage angle

In order to formulate a lossless DC power flow and balance model, voltage angle variables θ_{it} are introduced for each bus i and each time interval t. These variables are modeled as unconstrained. In this context it is not necessary to fix the voltage angle at a reference bus.

2.2.3 Line flow

The flow on each transmission line in each time interval is modeled by a DC flow model as the line admittance times the difference between the voltage angles at the from and to buses:

$$p_{kt}^{\text{f}} = -U_{kt}^{\text{f}} B_k (\theta_{it} - \theta_{i't}) \qquad \forall k \in \mathcal{K}, t \in \mathcal{T}, i = i_k^{\text{fr}}, i' = i_k^{\text{to}} \quad (2)$$

2.2.4 Power balance

Power balance constraints are imposed at each bus and each time interval. Violations of power balance incur penalties appearing in the objective. The constraints are formulated as excess supply plus net absorption into transmission elements equals excess demand plus net injection from market resources. Energy prices λ_{it}^{en} are derived from the Lagrange multipliers on the power balance constraints. Specifically, the Lagrange multipliers $D_t \lambda_{it}^{\text{en}}$ are set up to correspond to the change in the optimal market surplus objective value caused by a small increase in the net injection of power to bus i in interval t with all discrete variables fixed. Note that the interval duration parameter D_t is included to appropriately convert units from $/MW in the multiplier $D_t \lambda_{it}^{\text{en}}$ to $/MWh in the price λ_{it}^{en}.

The power balance constraints are:

$$p_{it}^{\text{en+}} + \sum_{k\in\mathcal{K}_i^{\text{fr}}} p_{kt}^{\text{f}} - \sum_{k\in\mathcal{K}_i^{\text{to}}} p_{kt}^{\text{f}} = p_{it}^{\text{en-}} + \sum_{n\in\mathcal{N}_i} p_{nt}^{\text{en}} \qquad (\perp D_t \lambda_{it}^{\text{en}})\ \forall i \in \mathcal{I}, t \in \mathcal{T} \quad (3)$$

The slack variables on the power balance constraints are nonnegative.

$$p_{it}^{\text{en+}}, p_{it}^{\text{en-}} \geq 0 \qquad \forall i \in \mathcal{I}, t \in \mathcal{T} \quad (4)$$

The slack variables contribute penalties to the objective based on the power balance violation (imbalance) cost.

$$z_{it}^{\text{en+}} = -D_t C^{\text{en}} p_{it}^{\text{en+}} \qquad \forall i \in \mathcal{I}, t \in \mathcal{T} \quad (5)$$

$$z_{it}^{\text{en-}} = -D_t C^{\text{en}} p_{it}^{\text{en-}} \qquad \forall i \in \mathcal{I}, t \in \mathcal{T} \quad (6)$$

2.2.5 Line flow limits

Power flows on lines are subject to limits, and violations incur penalties appearing in the objective. The line flow limit constraints are:

$$p_{kt}^{\mathrm{f}} \leq P_k^{\mathrm{f,max}} + p_{kt}^{\mathrm{f+}} \qquad \forall k \in \mathcal{K}^{\mathrm{MON}}, t \in \mathcal{T} \tag{7}$$

$$-p_{kt}^{\mathrm{f}} \leq P_k^{\mathrm{f,max}} + p_{kt}^{f+} \qquad \forall k \in \mathcal{K}^{\mathrm{MON}}, t \in \mathcal{T} \tag{8}$$

The slack variables for line flow limit constraints are:

$$p_{kt}^{\mathrm{f+}} \geq 0 \qquad \forall k \in \mathcal{K}^{\mathrm{MON}}, t \in \mathcal{T} \tag{9}$$

The contributions of the slack variables to the objective are:

$$z_{kt}^{\mathrm{f+}} = -D_t C^{\mathrm{f+}} p_{kt}^{\mathrm{f+}} \qquad \forall k \in \mathcal{K}^{\mathrm{MON}}, t \in \mathcal{T} \tag{10}$$

2.2.6 Ancillary service products

Regulation up, regulation down, spinning reserve, and non-spinning reserve are subject to requirements. These requirements depend endogenously on the dispatch and commitment. Ancillary service product balance constraints ensure that the total procured amount of each product meets the requirement with slack variables appearing in the objective to model downward sloping ancillary product demand curves. Ancillary product prices λ_t^{rgd}, λ_t^{rgu}, λ_t^{spr}, and λ_t^{nsp} are derived from Lagrange multipliers on the balance constraints. Specifically, the Lagrange multipliers $D_t\lambda_t^{\mathrm{rgd}}$, $D_t\lambda_t^{\mathrm{rgu}}$, $D_t\lambda_t^{\mathrm{spr}}$, and $D_t\lambda_t^{\mathrm{nsp}}$ are set up to correspond to the change in the market surplus objective caused by a small decrease in the required quantity of the corresponding products. As with energy prices, the interval duration parameter D_t is included in the multiplier to convert units from $/MW to $/MWh for market prices.

The ancillary product balance constraints are:

$$r_t^{\mathrm{rgd+}} + r_t^{\mathrm{rgd,req}} \leq r_t^{\mathrm{rgd-}} + \sum_{n\in\mathcal{N}} r_{nt}^{\mathrm{rgd}} \qquad \left(\perp D_t\lambda_t^{\mathrm{rgd}} \geq 0\right) \forall t \in \mathcal{T} \tag{11}$$

$$r_t^{\mathrm{rgu+}} + r_t^{\mathrm{rgu,req}} \leq r_t^{\mathrm{rgu-}} + \sum_{n\in\mathcal{N}} r_{nt}^{\mathrm{rgu}} \qquad \left(\perp D_t\lambda_t^{\mathrm{rgu}} \geq 0\right) \forall t \in \mathcal{T} \tag{12}$$

$$r_t^{\mathrm{spr+}} + r_t^{\mathrm{rgu,req}} + r_t^{\mathrm{spr,req}} \leq r_t^{\mathrm{spr-}} + \sum_{n\in\mathcal{N}} r_{nt}^{\mathrm{rgu}} + \sum_{n\in\mathcal{N}} r_{nt}^{\mathrm{spr}} \qquad \left(\perp D_t\lambda_t^{\mathrm{spr}} \geq 0\right) \forall t \in \mathcal{T} \tag{13}$$

$$\begin{aligned} r_t^{\mathrm{nsp+}} + r_t^{\mathrm{rgu,req}} + r_t^{\mathrm{spr,req}} + r_t^{\mathrm{nsp,req}} \\ \leq r_t^{\mathrm{nsp-}} + \sum_{n\in\mathcal{N}} r_{nt}^{\mathrm{rgu}} + \sum_{n\in\mathcal{N}} r_{nt}^{\mathrm{spr}} \\ + \sum_{n\in\mathcal{N}} r_{nt}^{\mathrm{nsp}} \end{aligned} \qquad \left(\perp D_t\lambda_t^{\mathrm{nsp}} \geq 0\right) \forall t \in \mathcal{T} \tag{14}$$

The slack variables are nonnegative:

$$r_t^{\mathrm{rgu+}}, r_t^{\mathrm{rgu-}}, r_t^{\mathrm{rgd+}}, r_t^{\mathrm{rgd-}}, r_t^{\mathrm{spr+}}, r_t^{\mathrm{spr-}}, r_t^{\mathrm{nsp+}} r_t^{\mathrm{nsp-}} \geq 0 \qquad \forall t \in \mathcal{T} \tag{15}$$

The contributions of the slack variables to the objective include reserve excess block terms to model a downward sloping ancillary product demand curve capturing the diminishing, but positive, marginal benefit to the system of supply beyond the requirement:

$$z_t^{\text{rgu+}} \le D_t \sum_{b \epsilon \mathcal{B}} C_b^{\text{rgu}} r_{tb}^{\text{rgu+}} \qquad \forall t \in \mathcal{T} \qquad (16)$$

$$z_t^{\text{rgu}-} = -D_t C_0^{\text{rgu}} r_t^{\text{rgu}-} \qquad \forall t \in \mathcal{T} \qquad (17)$$

$$z_t^{\text{rgd+}} \le D_t \sum_{b \epsilon \mathcal{B}} C_b^{\text{rgd}} r_{tb}^{\text{rgd+}} \qquad \forall t \in \mathcal{T} \qquad (18)$$

$$z_t^{\text{rgd}-} = -D_t C_0^{\text{rgd}} r_t^{\text{rgd}-} \qquad \forall t \in \mathcal{T} \qquad (19)$$

$$z_t^{\text{spr+}} \le D_t \sum_{b \epsilon \mathcal{B}} C_b^{\text{spr}} r_{tb}^{\text{spr+}} \qquad \forall t \in \mathcal{T} \qquad (20)$$

$$z_t^{\text{spr}-} = -D_t C_0^{\text{spr}} r_t^{\text{spr}-} \qquad \forall t \in \mathcal{T} \qquad (21)$$

$$z_t^{\text{nsp+}} \le D_t \sum_{b \epsilon \mathcal{B}} C_b^{\text{nsp}} r_{tb}^{\text{nsp+}} \qquad \forall t \in \mathcal{T} \qquad (22)$$

$$z_t^{\text{nsp}-} = -D_t C_0^{\text{nsp}} r_t^{\text{nsp}-} \qquad \forall t \in \mathcal{T} \qquad (23)$$

To allow a stepped demand function for reserves that are in excess of the system requirement, excess reserve procurement variables are partitioned into blocks $b \in \mathcal{B}$, where the values assigned to each block are C_b^{rgu}, C_b^{rgu}, C_b^{spr}, and C_b^{nsp}. The maximum excess quantity in each block is modeled as follows.

$$r_{tb}^{\text{rgu+}} \le R_b^{\text{rgu+}} \qquad \forall b \in \mathcal{B}, t \in \mathcal{T} \qquad (24)$$

$$r_{tb}^{\text{rgd+}} \le R_b^{\text{rgd+}} \qquad \forall b \in \mathcal{B}, t \in \mathcal{T} \qquad (25)$$

$$r_{tb}^{\text{spr+}} \le R_b^{\text{spr+}} \qquad \forall b \in \mathcal{B}, t \in \mathcal{T} \qquad (26)$$

$$r_{tb}^{\text{nsp+}} \le R_b^{\text{nsp+}} \qquad \forall b \in \mathcal{B}, t \in \mathcal{T} \qquad (27)$$

The regulation up and down requirements are formulated endogenously as a prescribed multiple of the total energy injection over resources requiring regulation:

$$r_t^{\text{rgu,req}} \ge -K^{\text{rgu}} \sum_{n \in \mathcal{N}^{\text{DEM}}} p_{nt}^{\text{en}} \qquad \forall t \in \mathcal{T} \qquad (28)$$

$$r_t^{\text{rgd,req}} \ge -K^{\text{rgd}} \sum_{n \in \mathcal{N}^{\text{DEM}}} p_{nt}^{\text{en}} \qquad \forall t \in \mathcal{T} \qquad (29)$$

The endogenous spinning and non-spinning reserve requirements are formulated as a prescribed multiple of the largest resource energy injection:

$$r_t^{\text{spr,req}} \ge K^{\text{spr}} p_{nt}^{\text{en}} \qquad \forall n \in \mathcal{N}, t \in \mathcal{T} \qquad (30)$$

$$r_t^{\text{nsp,req}} \ge K^{\text{nsp}} p_{nt}^{\text{en}} \qquad \forall n \in \mathcal{N}, t \in \mathcal{T} \qquad (31)$$

The reserve requirements are nonnegative:

$$r_t^{\text{rgu,req}}, r_t^{\text{rgd,req}}, r_t^{\text{spr,req}}, r_t^{\text{nsp,req}} \geq 0 \qquad \forall t \in \mathcal{T} \qquad (32)$$

2.3 Resource Constraints

Resources enter the system constraints based on their contribution to market surplus, z_n, the power they inject or withdraw from the system, p_{nt}^{en}, and their contribution to reserves, r_{nt}^{rgu}, r_{nt}^{rgd}, r_{nt}^{spr}, and r_{nt}^{nsp}. Resource offer formats determine the feasible region for these variables by specifying the parameters and constraints that will be included in the market clearing optimization model.

The following resource types are modeled:

- Energy storage resources $(n \in N^{\text{STR}})$ are described in Section 2.3.1.
- Conventional generators $(n \in N^{\text{GEN}})$ are described in Section 2.3.2.
- Renewable generators $(n \in N^{\text{REN}})$ are described in Section 2.3.3.
- Demand $(n \in N^{\text{DEM}})$ is described in Section 2.3.4.
- Virtual bids $(n \in N^{\text{VIR}})$ are described in Section 2.3.5.

2.3.1 Energy storage

Storage resources are modeled in the market clearing engine using relatively simple models. The models presented in this section are commonly used to simulate storage resources in optimal system dispatch studies. Depending on the rules of a particular market simulation, some model parameters might be fixed at a default value or particular constraints might be deactivated.

A more complex model of energy storage, based on a charge reservoir model, is used to simulate the physical dispatch of storage devices and is described in Section 4.1. Energy storage resources that are not competing in ESPA-Comp are also modeled this storage participation model not simulated by the charge reservoir model counterpart.

Table 2.5 lists the parameters that can be submitted in a storage resource offer.

Table 2.5: Storage Offer Format

Symbol	Description	Format	Units
C_{nbt}^{ch}	Cost incurred per MWh dispatched in charging quantity block b in interval t	Array of float	\$/MWh
C_{nbt}^{dc}	Cost incurred per MWh dispatched in discharging quantity block b in interval t	Array of float	\$/MWh
C_{nt}^{rgu}	Cost incurred per MWh of regulation up reserve	Array of float	\$/MWh
C_{nt}^{rgd}	Cost incurred per MWh of regulation down	Array of float	\$/MWh
C_{nt}^{spr}	Cost incurred per MWh of spinning reserve	Array of float	\$/MWh
C_{nt}^{nsp}	Cost incurred per MWh of non-spinning reserve	Array of float	\$/MWh
C_{nbt}^{SoC}	Cost incurred per MWh in state-of-charge at the end of interval t	Array of float	\$/MWh
$P_{nt}^{\text{max,ch}}$	Maximum dispatch level while charging	Float	MW
$P_{nt}^{\text{max,dc}}$	Maximum dispatch level while discharging	Float	MW

Symbol	Description	Format	Units
P_{nbt}^{ch}	Incremental battery charge quantity (negative dispatch) in block b	Vector of float	MW
P_{nbt}^{dc}	Incremental battery discharge quantity (positive dispatch) in block b	Vector of float	MW
R_{n}^{dn}	Maximum decrease in dispatch level	Float	MW/min
R_{n}^{up}	Maximum increase in dispatch level	Float	MW/min
S_{nb}^{offer}	Incremental state-of-charge offer block b	Vector of float	MWh
S_{n}^{end}	Desired minimum state-of-charge at the end of the dispatch horizon	Float	MWh
S_{n}^{start}	State-of-charge at the beginning of the dispatch horizon	Float	MWh
S_{n}^{max}	Maximum state-of-charge of the storage resource	Float	MWh
S_{n}^{min}	Minimum state-of-charge of the storage resource	Float	MWh
η_{n}^{ch}	Battery efficiency during charging mode	Float	%
η_{n}^{dc}	Battery efficiency during discharging mode	Float	%

Table 2.6 lists the variables that are optimized in the market clearing optimization model.

Table 2.6: Storage Model Variables

Symbol	Description	Domain	Units
p_{nt}^{en}	Net energy dispatch of the storage resource in interval t	Free	MW
p_{nt}^{ch}	Charging level of the storage resource in interval t	Nonnegative	MW
p_{nt}^{dc}	Discharging level of the storage resource in interval t	Nonnegative	MW
p_{nbt}^{chq}	Auxiliary dispatch variable for charging quantity block b	Nonnegative	MW
p_{nbt}^{dcq}	Auxiliary dispatch variable for discharging quantity block b	Nonnegative	MW
σ_{nt}	State-of-charge at the end of interval t	Nonnegative	MWh
$\sigma_{nbt}^{\text{offer}}$	Auxiliary state-of-charge variable for stored energy quantity block b	Nonnegative	MWh
r_{nt}^{rgu}	Regulation reserve up provided in interval t	Nonnegative	MW
r_{nt}^{rgd}	Regulation reserve down provided in interval t	Nonnegative	MW
r_{nt}^{spr}	Spinning reserve provided in interval t	Nonnegative	MW
r_{nt}^{nsp}	Non-spinning reserve provided in interval t	Nonnegative	MW
u_{nt}	Charging status of the storage resource during interval t	Binary	Unitless
z_{n}	Total value of storage utilization	Free	$
z_{n}^{en}	Value of storage dispatch	Free	$
z_{n}^{SoC}	Value of stored energy	Free	$
z_{n}^{rgu}	Value of providing regulation up reserve	Free	$
z_{n}^{rgd}	Value of providing regulation down reserve	Free	$
z_{n}^{spr}	Value of providing spinning reserve	Free	$
z_{n}^{nsp}	Value of providing non-spinning reserve	Free	$

The total cost of the storage resource is the sum of dispatch and reserve costs.

$$z_n = z_n^{\text{en}} + z_n^{\text{SoC}} + z_n^{\text{rgu}} + z_n^{\text{rgd}} + z_n^{\text{spr}} + z_n^{\text{nsp}} \qquad \forall n \in N^{\text{STR}} \qquad (33)$$

Dispatch costs are calculated from a bid curve that potentially includes multiple segments.

$$z_n^{\mathrm{en}} = -\sum_{t\in\mathcal{T}} D_t \sum_{b\in\mathcal{B}} \left(C_{nbt}^{\mathrm{dc}}\, p_{nbt}^{\mathrm{dcq}} - C_{nbt}^{\mathrm{ch}}\, p_{nbt}^{\mathrm{chq}}\right) \qquad \forall n \in N^{\mathrm{STR}} \qquad (34)$$

Stored energy costs are calculated similarly but are based on the resource's state of charge.

$$z_n^{\mathrm{SoC}} = -\sum_{t\in\mathcal{T}} \sum_{b\in\mathcal{B}} C_{nbt}^{\mathrm{SoC}}\, \sigma_{nbt}^{\mathrm{offer}} \qquad \forall n \in N^{\mathrm{STR}} \qquad (35)$$

Reserve bid costs are calculated based on a single bid price segment.

$$z_n^{\mathrm{rgu}} = -\sum_{t\in\mathcal{T}} D_t C_{nt}^{\mathrm{rgu}}\, r_{nt}^{\mathrm{rgu}} \qquad \forall n \in N^{\mathrm{STR}} \qquad (36)$$

$$z_n^{\mathrm{rgd}} = -\sum_{t\in\mathcal{T}} D_t C_{nt}^{\mathrm{rgd}}\, r_{nt}^{\mathrm{rgd}} \qquad \forall n \in N^{\mathrm{STR}} \qquad (37)$$

$$z_n^{\mathrm{spr}} = -\sum_{t\in\mathcal{T}} D_t C_{nt}^{\mathrm{spr}}\, r_{nt}^{\mathrm{spr}} \qquad \forall n \in N^{\mathrm{STR}} \qquad (38)$$

$$z_n^{\mathrm{nsp}} = -\sum_{t\in\mathcal{T}} D_t C_{nt}^{\mathrm{nsp}}\, r_{nt}^{\mathrm{nsp}} \qquad \forall n \in N^{\mathrm{STR}} \qquad (39)$$

The auxiliary variables for charging and discharging quantity blocks are constrained to sum to the total charge and discharge levels.

$$\sum_{b\in\mathcal{B}} p_{nbt}^{\mathrm{chq}} - p_{nt}^{\mathrm{ch}} = 0 \qquad \forall t \in \mathcal{T}, n \in N^{\mathrm{STR}} \qquad (40)$$

$$\sum_{b\in\mathcal{B}} p_{nbt}^{\mathrm{dcq}} - p_{nt}^{\mathrm{dc}} = 0 \qquad \forall t \in \mathcal{T}, n \in N^{\mathrm{STR}} \qquad (41)$$

Auxiliary variables for state-of-charge offer blocks are similarly summed to be equal to the total state-of-charge.

$$\sum_{b\in\mathcal{B}} \sigma_{nbt}^{\mathrm{offer}} - \sigma_{nt} = 0 \qquad \forall t \in \mathcal{T}, n \in N^{\mathrm{STR}} \qquad (42)$$

The storage resource's net dispatch is its total discharging dispatch minus total charging dispatch.

$$p_{nt}^{\mathrm{en}} = p_{nt}^{\mathrm{dc}} - p_{nt}^{\mathrm{ch}} \qquad \forall t \in \mathcal{T}, n \in N^{\mathrm{STR}} \qquad (43)$$

Charge and discharge dispatch are given a lower limit of zero and upper limits according to the resource offer data.

$$0 \le p_{nt}^{\mathrm{ch}} \le P_n^{\mathrm{max,ch}}\, u_{nt} \qquad \forall t \in \mathcal{T}, n \in N^{\mathrm{STR}} \qquad (44)$$

$$0 \le p_{nt}^{\mathrm{dc}} \le P_n^{\mathrm{max,dc}}(1 - u_{nt}) \qquad \forall t \in \mathcal{T}, n \in N^{\mathrm{STR}} \qquad (45)$$

Auxiliary variables for the charge, discharge, and state-of-charge offer blocks are upper bounded.

$$p_{nbt}^{\text{chq}} \leq P_{nbt}^{\text{ch}} \qquad \forall t \in \mathcal{T}, b \in \mathcal{B}, n \in N^{\text{STR}} \qquad (46)$$

$$p_{nbt}^{\text{dcq}} \leq P_{nbt}^{\text{dc}} \qquad \forall t \in \mathcal{T}, b \in \mathcal{B}, n \in N^{\text{STR}} \qquad (47)$$

$$\sigma_{nbt}^{\text{offer}} \leq S_{nb}^{\text{offer}} \qquad \forall t \in \mathcal{T}, b \in \mathcal{B}, n \in N^{\text{STR}} \qquad (48)$$

The storage resource must have available dispatch capacity to provide reserves.

$$p_{nt}^{\text{en}} + r_{nt}^{\text{rgu}} + r_{nt}^{\text{spr}} + r_{nt}^{\text{nsp}} \leq P_{n}^{\text{max,dc}} \qquad \forall t \in \mathcal{T}, n \in N^{\text{STR}} \qquad (49)$$

$$-p_{nt}^{\text{en}} + r_{nt}^{\text{rgd}} \leq P_{n}^{\text{max,ch}} \qquad \forall t \in \mathcal{T}, n \in N^{\text{STR}} \qquad (50)$$

The storage resource also must have available energy capacity to provide reserves.

$$\sigma_{nt} - D^{\text{rgu}} r_{nt}^{\text{rgu}} - D^{\text{spr}} r_{nt}^{\text{spr}} - D^{\text{nsp}} r_{nt}^{\text{nsp}} \geq S_{n}^{\text{min}} \qquad \forall t \in \mathcal{T}, n \in N^{\text{STR}} \qquad (51)$$

$$\sigma_{nt} + D^{\text{rgd}} r_{nt}^{\text{rgd}} \leq S_{n}^{\text{max}} \qquad \forall t \in \mathcal{T}, n \in N^{\text{STR}} \qquad (52)$$

The storage device’s net dispatch is constrained by its ramp-up and ramp-down capability.

$$p_{nt}^{\text{en}} - p_{nt-1}^{\text{en}} \leq D_t R_{n}^{\text{up}} \qquad \forall t \in \mathcal{T}, n \in N^{\text{STR}} \qquad (53)$$

$$p_{nt-1}^{\text{en}} - p_{nt}^{\text{en}} \leq D_t R_{n}^{\text{dn}} \qquad \forall t \in \mathcal{T}, n \in N^{\text{STR}} \qquad (54)$$

The storage resource must also have the ramp capability to provide reserves. Higher quality reserve products (i.e., those with a faster response time requirement) are deducted from the available ramping capability for lower quality reserve products.

$$r_{nt}^{\text{rgu}} + r_{nt}^{\text{spr}} \leq T^{\text{spr}} R_{n}^{\text{up}} \qquad \forall t \in \mathcal{T}, n \in N^{\text{STR}} \qquad (55)$$

$$r_{nt}^{\text{rgu}} + r_{nt}^{\text{spr}} + r_{nt}^{\text{nsp}} \leq T^{\text{nsp}} R_{n}^{\text{up}} \qquad \forall t \in \mathcal{T}, n \in N^{\text{STR}} \qquad (56)$$

Unlike a conventional generator, the battery is assumed to be always available for dispatch, so there is no commitment status requirement for regulation or spinning reserve.

The resource’s state-of-charge progresses according to a linear energy conservation constraint.

$$\sigma_{nt} = \sigma_{n,t-1} + D_t \left(\eta_{n}^{\text{ch}} p_{nt}^{\text{ch}} - \frac{1}{\eta_{n}^{\text{dc}}} p_{nt}^{\text{dc}} \right) \qquad \forall t \in \mathcal{T}, n \in N^{\text{STR}} \qquad (57)$$

$$\sigma_{n,T^{S}-1} = S_{n}^{\text{start}} \qquad \forall n \in N^{\text{STR}} \qquad (58)$$

$$\sigma_{n,T^{E}} \geq S_{n}^{\text{end}} \qquad \forall n \in N^{\text{STR}} \qquad (59)$$

State-of-charge is constrained between its upper and lower bounds.

$$S_n^{\min} \le \sigma_{nt} \le S_n^{\max} \qquad \forall t \in \mathcal{T}, n \in N^{\text{STR}} \qquad (60)$$

The storage resource's charging status is a binary variable.

$$u_{nt} \in \{0,1\} \qquad \forall t \in \mathcal{T}, n \in N^{\text{STR}} \qquad (61)$$

Lastly, the resource's nonnegativity constraints.

$$p_{nt}^{\text{ch}}, p_{nt}^{\text{dc}}, p_{nbt}^{\text{chq}}, p_{nbt}^{\text{dcq}}, r_{nt}^{\text{rgu}}, r_{nt}^{\text{rgd}}, r_{nt}^{\text{spr}}, r_{nt}^{\text{nsp}} \ge 0 \qquad \forall t \in \mathcal{T}, b \in \mathcal{B}, n \in N^{\text{STR}} \qquad (62)$$

2.3.2 Conventional generators

Generator offers are defined as supply that is injected into a specific time and location in the network topology. Conventional generators may include any fuel-based power generation technology, including coal combustion turbines, natural gas combustion turbines, natural gas combined cycle combustion turbines, and nuclear plants.

The presented models are commonly used to simulate conventional generation resources in optimal system dispatch studies. Because these resources are not controlled by ESPA-Comp participants, they are each given a set of resource attributes and offer parameters that do not change throughout the course of the market simulation. It is assumed that the resource is capable of meeting its cleared dispatch quantities unless it is on a forced outage.

The resource set $n \in \mathcal{N}^{\text{GEN}}$ is designated for conventional generators. The following attributes are the "primitive" values that are used to derive the resource's offer parameters.

Table 2.7: Conventional Generator Attributes

Symbol	Description	Format	Units
A_n^{fuel}	Type of fuel	String	N/A
A_n^{adder}	Fuel price adder to deliver fuel to generator	Float	$/mmBTU
A_{nb}^{heatrate}	Heat rate if producing in block b	Vector of float	mmBTU/MW
A_n^{sutime}	Time for generator to start up	Float	Minutes
A_n^{sdtime}	Time for generator to shut down	Float	Minutes
A_n^{csu}	Non-fuel start up cost	Float	$
A_n^{cop}	Non-fuel operating cost	Float	$
A_n^{csd}	Non-fuel shut down cost	Float	$
A^{rampup}	Maximum dispatch increase per minute	Float	MW/minute
A_n^{rampdn}	Maximum dispatch decrease per minute	Float	MW/minute
A_n^{minup}	Minimum length of time online after a start-up	Float	Minutes
A_n^{mindn}	Minimum length of time offline after a shut-down	Float	Minutes
A_n^{csu}	Fixed cost to start up	Float	$
A_n^{cop}	Fixed cost to operate	Float	$/minute
A_n^{csd}	Fixed cost to shut down	Float	$
A_{nb}^{block}	Maximum dispatch quantity in block b	Vector of float	MW
A_n^{pmin}	Minimum dispatch level when online	Float	MW
A_n^{pmax}	Maximum dispatch level	Float	MW

Symbol	Description	Format	Units
A_n^{rgu}	Maximum regulation reserve up	Float	MW
A_n^{rgd}	Maximum regulation reserve down	Float	MW

Table 2.8 lists the parameters that can be submitted in a conventional generator offer. Conventional generator offers include information on production costs, minimum and maximum production limits, minimum up time and down time, ramp rates, and start-up/shut-down attributes. Before each market clearing interval, each generator can re-offer their marginal cost curve and fixed start-up, operating, and shut-down costs. Parameters for minimum and maximum operating level, minimum up-time and down-time, ramp rates, and reserve capacity are physical parameters that are not allowed to be bid into the market.

Table 2.8: Conventional Generator Offer Format

Symbol	Description	Format	Units
C_{nbt}^{en}	Marginal cost of dispatch in block b in period t	Vector of float	$/MWh
C_{nt}^{su}	Fixed cost of generator n to start up in interval$t$	Vector of float	$
C_{nt}^{op}	Fixed cost of generator n to operate in interval t	Vector of float	$/min
C_{nt}^{sd}	Fixed cost of generator n to shut down in interval t	Vector of float	$
P_{nb}	Maximum production of generator n in block b	Vector of float	MW
P_n^{min}	Minimum production if generator n is online	Float	MW
P_n^{max}	Maximum production of generator n	Float	MW
T_n^{up}	Minimum amount of time online after a start-up by generator n	Float	Minutes
T_n^{dn}	Minimum amount of time offline after a shut-down by generator n	Float	Minutes
U_{n0}^{op}	Operating status in the previous period	Integer	N/A
U_{nt}^{out}	Outage status in period t	Integer	N/A
R_n^{up}	Maximum dispatch increase per minute by generator n	Float	MW/min
R_n^{dn}	Maximum dispatch decrease per minute by generator n	Float	MW/min

Table 2.9 below shows the expressions used to calculate offer format parameters from the resource's primitive attributes.

Table 2.9: Default Offer Parameter Expressions

Symbol	Derivation Expression	Data Source
C_{nbt}^{en}	$\left(C_t^{\mathrm{fuel}}\left(A_n^{\mathrm{fuel}}\right) + A_n^{\mathrm{adder}}\right) * A_{nb}^{\mathrm{heatrate}}$	Static attributes
C_{nt}^{su}	$A^{\mathrm{csu}} + \frac{1}{2} C_{n1}^{\mathrm{en}} A_n^{\mathrm{pmin}} A_n^{\mathrm{sutime}}$	Static attributes
C_{nt}^{op}	A_n^{cop}	Static attributes
C_{nt}^{sd}	$A_n^{\mathrm{csd}} + \frac{1}{2} C_{n1}^{\mathrm{en}} A_n^{\mathrm{pmin}} A_n^{\mathrm{sdtime}}$	Static attributes
P_{nb}	A_{nb}^{block}	Static attributes
P_n^{min}	A_n^{pmin}	Static attributes
P_n^{max}	A_n^{pmax}	Static attributes
T_n^{up}	A_n^{minup}	Static attributes
T_n^{dn}	A_n^{mindn}	Static attributes

Symbol	Derivation Expression	Data Source
U_{n0}^{op}	u_{n1}^{op*}	Previous market solution
R_n^{up}	A_n^{rampup}	Static attributes
R_n^{dn}	A_n^{rampdn}	Static attributes

Table 2.10 lists the variables that are optimized in the market clearing optimization model.

Table 2.10: Conventional Generator Model Variables

Symbol	Description	Domain	Units
p_{nt}^{en}	Total dispatch of the generator n in period t	Nonnegative	MW
p_{nbt}	Auxiliary dispatch variable for quantity block b in period t	Nonnegative	MW
r_{nt}^{rgu}	Regulation reserve up provided in period t	Nonnegative	MW
r_{nt}^{rgd}	Regulation reserve down provided in period t	Nonnegative	MW
r_{nt}^{spr}	Spinning reserve provided in period t	Nonnegative	MW
r_{nt}^{nsp}	Non-spinning reserve provided in period t	Nonnegative	MW
u_{nt}	Commitment status of generator n in period t	Binary	Unitless
z_n	Total cost of generator commitment and dispatch	Free	$
c_n^{en}	Cost of generator dispatch	Free	$
c_n^{SoC}	Cost of stored energy	Free	$
c_n^{rgu}	Cost of regulation up reserve	Free	$
c_n^{rgd}	Cost of regulation down reserve	Free	$
c_n^{spr}	Cost of spinning reserve	Free	$
c_n^{nsp}	Cost of non-spinning reserve	Free	$

The following constraints are included in market clearing for any resource $n \in N^{\mathrm{GEN}}$.

Total surplus:

$$z_n = z_n^{\mathrm{en}} + z_n^{\mathrm{su}} + z_n^{\mathrm{op}} + z_n^{\mathrm{sd}} + z_n^{\mathrm{rgu}} + z_n^{\mathrm{rgd}} \qquad \forall n \in \mathcal{N}^{\mathrm{GEN}} \qquad (63)$$

Energy cost:

$$z_n^{\mathrm{en}} = -\sum_{t \in \mathcal{T}} D_t \sum_{b \in \mathcal{B}} C_{nbt}^{\mathrm{en}} p_{ntb} \qquad \forall n \in \mathcal{N}^{\mathrm{GEN}} \qquad (64)$$

Start-up cost:

$$z_n^{\mathrm{su}} = -\sum_{t \in \mathcal{T}} C_{nt}^{\mathrm{su}} u_{nt}^{\mathrm{su}} \qquad \forall n \in \mathcal{N}^{\mathrm{GEN}} \qquad (65)$$

No-load cost:

$$z_n^{\mathrm{op}} = -\sum_{t \in \mathcal{T}} C_{nt}^{\mathrm{op}} u_{nt}^{\mathrm{op}} \qquad \forall n \in \mathcal{N}^{\mathrm{GEN}} \qquad (66)$$

Shut-down cost:

$$z_n^{\mathrm{sd}} = -\sum_{t \in \mathcal{T}} C_{nt}^{\mathrm{sd}} u_{nt}^{\mathrm{sd}} \qquad \forall n \in \mathcal{N}^{\mathrm{GEN}} \qquad (67)$$

Total energy:

$$p_{nt}^{\mathrm{en}} = \sum_{b \in \mathcal{B}} p_{ntb} \qquad \forall t \in \mathcal{T}, n \in \mathcal{N}^{\mathrm{GEN}} \qquad (68)$$

Offer block bounds:

$$0 \leq p_{ntb} \leq P_{nb} \qquad \forall b \in \mathcal{B}, t \in \mathcal{T}, n \in \mathcal{N}^{\mathrm{GEN}} \qquad (69)$$

Production bounds:

$$P_n^{\min} u_{nt}^{\mathrm{op}} \leq p_{nt}^{\mathrm{en}} \leq P_n^{\max} u_{nt}^{\mathrm{op}} \qquad \forall t \in \mathcal{T}, n \in \mathcal{N}^{\mathrm{GEN}} \qquad (70)$$

Regulation capacity up:

$$p_{nt}^{\mathrm{en}} + p_{nt}^{\mathrm{rgu}} \leq P_n^{\max} u_{nt}^{\mathrm{op}} \qquad \forall t \in \mathcal{T}, n \in \mathcal{N}^{\mathrm{GEN}} \qquad (71)$$

Regulation capacity down:

$$p_{nt}^{\mathrm{en}} - p_{nt}^{\mathrm{rgd}} \geq P_n^{\min} u_{nt}^{\mathrm{op}} \qquad \forall t \in \mathcal{T}, n \in \mathcal{N}^{\mathrm{GEN}} \qquad (72)$$

On-line reserve capacity:

$$p_{nt}^{\mathrm{en}} + p_{nt}^{\mathrm{rgu}} + p_{nt}^{\mathrm{spr}} \leq P_n^{\max} u_{nt}^{\mathrm{op}} \qquad \forall t \in \mathcal{T}, n \in \mathcal{N}^{\mathrm{GEN}} \qquad (73)$$

Total reserve capacity:

$$p_{nt}^{\mathrm{en}} + p_{nt}^{\mathrm{rgu}} + p_{nt}^{\mathrm{spr}} + p_{nt}^{\mathrm{nsp}} \leq P_n^{\max} \qquad \forall t \in \mathcal{T}, n \in \mathcal{N}^{\mathrm{GEN}} \qquad (74)$$

Regulation up and down qualification:

$$p_{nt}^{\mathrm{rgu}} \leq P_n^{\mathrm{rgu}} \qquad \forall t \in \mathcal{T}, n \in \mathcal{N}^{\mathrm{GEN}} \qquad (75)$$

$$p_{nt}^{\mathrm{rgd}} \leq P_n^{\mathrm{rgd}} \qquad \forall t \in \mathcal{T}, n \in \mathcal{N}^{\mathrm{GEN}} \qquad (76)$$

Reserve ramping capability:

$$p_{nt}^{\mathrm{rgu}} + p_{nt}^{\mathrm{spr}} \leq T^{\mathrm{spr}} R_n^{\mathrm{up}} \qquad \forall t \in \mathcal{T}, n \in \mathcal{N}^{\mathrm{GEN}} \qquad (77)$$

$$p_{nt}^{\mathrm{rgu}} + p_{nt}^{\mathrm{spr}} + p_{nt}^{\mathrm{nsp}} \leq T^{\mathrm{nsp}} R_n^{\mathrm{up}}$$

Minimum uptime:

$$u_{nt}^{\mathrm{op}} \geq \sum_{\tau=\max(t-T_n^{\mathrm{up}}+1, T^{\mathrm{B}})}^{t} u_{n\tau}^{\mathrm{su}} + 1\delta\left(t - T^{\mathrm{B}} + T_{n,0}^{\mathrm{up}} > T_n^{\mathrm{up}}\right) \qquad \forall t \in \mathcal{T}, n \in \mathcal{N}^{\mathrm{GEN}} \qquad (78)$$

Minimum downtime:

$$u_{nt}^{\mathrm{op}} \leq 1 - \sum_{\tau=\max(t-T_n^{\mathrm{dn}}+1, T^{\mathrm{B}})}^{t} u_{n\tau}^{\mathrm{sd}} - 1\delta\left(t - T^{\mathrm{B}} + T_{n,0}^{\mathrm{dn}} > T_n^{\mathrm{dn}}\right) \quad \forall t \in \mathcal{T}, n \in \mathcal{N}^{\mathrm{GEN}} \quad (79)$$

Ramp-up and ramp-down:

$$p_{nt}^{\mathrm{en}} - p_{nt-1}^{\mathrm{en}} \leq \left(P_n^{\mathrm{min}} + D_t R_n^{\mathrm{up}}\right) u_{nt}^{\mathrm{op}} - P_n^{\mathrm{min}} u_{nt-1}^{\mathrm{op}} - D_t R_n^{\mathrm{up}} u_{nt}^{\mathrm{su}} \quad \forall t \in \mathcal{T}, n \in \mathcal{N}^{\mathrm{GEN}} \quad (80)$$

$$p_{nt-1}^{\mathrm{en}} - p_{nt}^{\mathrm{en}} \leq \left(P_n^{\mathrm{min}} + D_t R_n^{\mathrm{dn}}\right) u_{nt-1}^{\mathrm{op}} - P_n^{\mathrm{min}} u_{nt}^{\mathrm{op}} - D_t R_n^{\mathrm{dn}} u_{nt}^{\mathrm{sd}} \quad \forall t \in \mathcal{T}, n \in \mathcal{N}^{\mathrm{GEN}} \quad (81)$$

Commitment logic:

$$u_{nt}^{\mathrm{su}} - u_{nt}^{\mathrm{sd}} = u_{nt}^{\mathrm{op}} - u_{nt-1}^{\mathrm{op}} \quad \forall t \in \mathcal{T} \setminus T^S, n \in \mathcal{N}^{\mathrm{GEN}} \quad (82)$$

$$u_{nT^S}^{\mathrm{su}} - u_{nT^S}^{\mathrm{sd}} = u_{nT^S}^{\mathrm{op}} - U_{n0}^{\mathrm{op}} \quad \forall n \in \mathcal{N}^{\mathrm{GEN}} \quad (83)$$

Lastly, the generator's variable domains:

$$p_{nt}^{\mathrm{en}}, p_{ntb}, r_{nt}^{\mathrm{rgu}}, r_{nt}^{\mathrm{rgd}}, r_{nt}^{\mathrm{spr}}, r_{nt}^{\mathrm{nsp}} \geq 0 \quad \forall t \in \mathcal{T}, b \in \mathcal{B}, n \in N^{\mathrm{GEN}} \quad (84)$$

$$u_{nt}^{\mathrm{op}}, u_{nt}^{\mathrm{su}}, u_{nt}^{\mathrm{sd}} \in \{0,1\} \quad \forall t \in \mathcal{T}, n \in N^{\mathrm{GEN}} \quad (85)$$

2.3.3 Renewable generators

Renewable offers are defined as supply that is injected into a specific time and location in the network topology. Renewable generators include solar and wind resources. Weather uncertainty is a large factor in the output of renewable generators and is discussed in greater detail in Section 4.3.

The presented models are commonly used to simulate renewable generation resources in optimal system dispatch studies. Because these resources are not controlled by ESPA-Comp participants, they are each given a set of resource attributes and offer parameters that do not change throughout the course of the market simulation. It is assumed that the resource is capable of meeting its cleared dispatch quantities.

Table 2.11 lists the parameters that can be submitted in a renewable generator offer. Renewable generators can submit time-dependent offer data for their minimum and maximum operating limits and marginal cost. Time-dependent operating limits allow these resources to submit their expected output which may change throughout the day. The marginal cost offer may also vary throughout the day, for example, to reflect production tax credits. Renewable generators may provide regulation and spinning reserves but not non-spinning reserves. No fixed costs, ramp rates, or other commitment-related parameters are included in the renewable generator offer format.

Table 2.11: Renewable Generator Offer Format

Symbol	Description	Format	Biddable
C_{ntb}^{en}	Marginal cost of generator n if producing in block b at time t	Vector of float	Yes
P_{ntb}	Maximum production in block b at time t	Vector of float	Yes

Symbol	Description	Format	Biddable
$P_{\mathrm{nt}}^{\min}$	Minimum total production of generator n at time t	Float	Yes
$P_{\mathrm{nt}}^{\max}$	Maximum total production of generator n at time t	Float	Yes
R_n^{up}	Maximum dispatch increase by generator n within a single period	Float	No
R_n^{dn}	Maximum dispatch decrease by generator n within a single period	Float	No

Table 2.12 lists the variables that are optimized in the market clearing optimization model.

Table 2.12: Renewable Generator Model Variables

Symbol	Description	Domain	Units
p_{nt}^{en}	Total dispatch of the generator n in period t	Nonnegative	MW
p_{nbt}	Auxiliary dispatch variable for quantity block b in period t	Nonnegative	MW
r_{nt}^{rgu}	Regulation reserve up provided in period t	Nonnegative	MW
r_{nt}^{rgd}	Regulation reserve down provided in period t	Nonnegative	MW
r_{nt}^{spr}	Spinning reserve provided in period t	Nonnegative	MW
z_n	Total cost of generator dispatch	Free	$
c_n^{en}	Cost of generator dispatch	Free	$
c_n^{rgu}	Cost of regulation up reserve	Free	$
c_n^{rgd}	Cost of regulation down reserve	Free	$
c_n^{spr}	Cost of spinning reserve	Free	$

The following constraints are included in market clearing for any resource $n \in N^{\mathrm{VRE}}$.

Total cost:

$$z_n = -\sum_t D_t \sum_b C_{nbt}^{\mathrm{en}} \, p_{ntb} \qquad \forall n \in N^{\mathrm{VRE}} \qquad (86)$$

Total energy:

$$p_{nt}^{\mathrm{en}} = \sum_b p_{ntb} \qquad \forall n \in N^{\mathrm{VRE}} \qquad (87)$$

Offer block bounds:

$$0 \le p_{ntb} \le P_{nbt} \qquad \forall b \in \mathcal{B}, t \in \mathcal{T}, n \in \mathcal{N}^{\mathrm{VRE}} \qquad (88)$$

Total production bounds:

$$P_{nt}^{\min} \leq p_{nt}^{\text{en}} \leq P_{nt}^{\max} \qquad \forall\, t \in \mathcal{T}, n \in \mathcal{N}^{\text{VRE}} \qquad (89)$$

Reserve dispatch capacity up:

$$p_{nt}^{\text{en}} + r_{nt}^{\text{rgu}} + r_{nt}^{\text{spr}} \leq P_{\text{n}}^{\max} \qquad \forall\, t \in \mathcal{T}, n \in \mathcal{N}^{\text{VRE}} \qquad (90)$$

Reserve dispatch capacity down:

$$p_{nt}^{\text{en}} - r_{nt}^{\text{rgd}} \geq P_{\text{n}}^{\min} \qquad \forall\, t \in \mathcal{T}, n \in \mathcal{N}^{\text{VRE}} \qquad (91)$$

Reserve ramping capacity up:

$$r_{nt}^{\text{rgu}} + r_{nt}^{\text{spr}} \leq T^{\text{spr}} R_{n}^{\text{up}} \qquad \forall\, t \in \mathcal{T}, n \in \mathcal{N}^{\text{VRE}} \qquad (92)$$

Variable domains:

$$p_{ntb}, p_{nt}^{\text{en}}, r_{nt}^{\text{rgu}}, r_{nt}^{\text{rgd}}, r_{nt}^{\text{spr}} \geq 0 \qquad \forall b \in \mathcal{B}, t \in \mathcal{T}, n \in \mathcal{N}^{\text{VRE}} \qquad (93)$$

2.3.4 Demand

Demand's participation in the electricity market is the counterweight to supply; both sides must be balanced. That is, the demand side is not a static part of the market clearing. Demand participates in the market by submitting bids for the maximum price they are willing to consume energy. Active participation from the demand side is a nascent part of electricity markets. Accordingly, the demand participation model presented here is relatively simple.

The presented models are commonly used to simulate load curtailment in optimal system dispatch studies. Because the demand-side is not controlled by ESPA-Comp participants, they are each given a set of attributes and bid parameters that do not change throughout the course of the market simulation. It is assumed that demand is capable of meeting its cleared energy consumption quantities. The terms "demand" and "load" are used somewhat interchangeably; typically, "demand" connotes an economic context while "load" connotes a power systems context.

Table 2.13 lists the parameters that are submitted in a demand bid. Loads submit time-dependent bid data for their minimum and maximum energy consumption limits and marginal value. Time-dependent operating limits allow these participants to submit their expected energy consumption, which may change throughout the day, as well as their potential for flexibility in throughout the day. The marginal value bid may also vary throughout the day, for example, to reflect the value of energy consumption for different economic uses. The formulation does not currently allow loads to provide regulation or reserves. No fixed costs, ramp rates, or other commitment-related parameters are included in the demand bid format.

Table 2.13: Demand Bid Format

Symbol	Description	Format	Biddable
B_{ntb}^{en}	Marginal value or benefit of load n if consuming energy in block b in interval t	Vector of float	Yes

Symbol	Description	Format	Biddable
P_{ntb}	Quantity of energy consumption in block b in interval t	Vector of float	Yes
$P_{\mathrm{nt}}^{\mathrm{min}}$	Minimum total energy consumption of load n in interval t	Float	Yes
$P_{\mathrm{nt}}^{\mathrm{max}}$	Maximum total energy consumption of load n in interval t	Float	Yes

Error! Reference source not found. lists the variables that are optimized in the market clearing optimization model.

Table 2.14: Demand Model Variables

Symbol	Description	Domain	Units
p_{nt}^{en}	Total power injection of load n in period t (negative for power withdrawal)	Free	MW
p_{nbt}	Auxiliary variable for quantity block b in period t	Nonnegative	MW
z_n	Total value of energy consumption	Free	$

The following constraints are included in market clearing for any resource $n \in N^{\mathrm{DEM}}$.

Total value:

$$z_n = \sum_t D_t \sum_b B_{nbt}^{\mathrm{en}} p_{ntb} \qquad \forall n \in N^{\mathrm{DEM}} \qquad (94)$$

Total energy consumption:

$$p_{nt}^{\mathrm{en}} = -\sum_b p_{ntb} \qquad \forall t \in \mathcal{T}, n \in N^{\mathrm{DEM}} \qquad (95)$$

Bid block bounds:

$$0 \le p_{ntb} \le P_{nbt} \qquad \forall b \in \mathcal{B}, t \in \mathcal{T}, n \in N^{\mathrm{DEM}} \qquad (96)$$

Total consumption bounds:

$$P_{nt}^{\mathrm{min}} \le -p_{nt}^{\mathrm{en}} \le P_{nt}^{\mathrm{max}} \qquad \forall t \in \mathcal{T}, n \in N^{\mathrm{DEM}} \qquad (97)$$

Variable domains:

$$p_{ntb}, p_{nt}^{\mathrm{en}} \ge 0 \qquad \forall b \in \mathcal{B}, t \in \mathcal{T}, n \in \mathcal{N}^{\mathrm{DEM}} \qquad (98)$$

2.3.5 Virtual bids

Virtual bids are a purely financial mode of market participation that is not connected to any physical resource. Because virtual bids are not connected to any physical resource, their physical dispatch (i.e., in the prompt period of the real time market) is by definition zero. However, this does not mean that virtual participation cannot be profitable or that it cannot improve system dispatch. Virtual bids can be placed in forward periods to, in effect, increase or decrease system demand at specified nodes in the system. Offers to provide virtual supply are called INCs (for energy "increment"), and bids to purchase virtual demand are called DECs (for energy "decrement").

The market participants who submit INCs (or DECs) will receive (or pay) the LMP for the amount of virtual supply (or demand) cleared in a forward market. Then, the virtual bid must be zeroed out for the bid's physical dispatch. If an INC was cleared to supply energy in forward periods, then it must purchase its forward position in the real-time market (i.e., it becomes a demand). Conversely, if a DEC was cleared to purchased energy in forward periods, then it must re-sell that energy back into the real-time market (i.e., it becomes a supplier). INCs are profitable if the forward LMP is higher than the real-time LMP, and DECs are profitable if the forward LMP is lower than the real time LMP.

Table 2.15 lists the parameters that are submitted in a virtual bid. Virtual bids must specify the bus location of the virtual resource. The bid data fields are time-dependent and consist of a vector of quantity blocks and a vector of prices. DECs are specified if the quantity block is negative, and INCs are specified if the quantity is positive. The marginal value bid may also vary throughout the day, for example, to reflect the value of energy consumption for different economic uses. The formulation does not currently allow loads to provide regulation or reserves. No fixed costs, ramp rates, or other commitment-related parameters are included in the demand bid format.

Table 2.15: Virtual Bid Format

Symbol	Description	Format	Units
B_{ntb}^{dec}	Virtual bid price for DEC block b in interval t	Vector of float	$/MWh
C_{ntb}^{inc}	Virtual offer price for INC block b in interval t	Vector of float	$/MWh
P_{ntb}^{dec}	Virtual DEC bid quantity block b in interval t	Vector of float	MW
P_{ntb}^{inc}	Virtual INC offer quantity block b in interval t	Vector of float	MW
i	Bus location of virtual bid	String	N/A

The bus location i is used to define the set of resources modeled at node n, denoted $n \in N(i)$.

Error! Reference source not found. lists the variables that are optimized in the market clearing optimization model.

Table 2.16: Demand Model Variables

Symbol	Description	Domain	Units
p_{nt}^{en}	Total cleared virtual supply or demand in period t	Free	MW
p_{nbt}	Cleared virtual supply or demand from quantity block b in period t	Free	MW

Symbol	Description	Domain	Units
z_n	Total value of virtual bid	Free	$

The following constraints are included in market clearing for any resource $n \in N^{\text{VIR}}$.

Total value:

$$z_n = \sum_t D_t \sum_b \left(B_{nbt}^{\text{dec}} p_{ntb}^{\text{dec}} - C_{nbt}^{\text{inc}} p_{ntb}^{\text{inc}}\right) \qquad \forall n \in N^{\text{VIR}} \qquad (99)$$

Total energy consumption:

$$p_{nt}^{\text{en}} = \sum_b \left(p_{ntb}^{\text{inc}} - p_{ntb}^{\text{dec}}\right) \qquad \forall t \in \mathcal{T}, n \in N^{\text{VIR}} \qquad (100)$$

Bid block bounds:

$$0 \le p_{ntb}^{\text{dec}} \le P_{nbt}^{\text{dec}} \qquad \forall b \in \mathcal{B}, t \in \mathcal{T}, n \in N^{\text{VIR}} \qquad (101)$$

$$0 \le p_{ntb}^{\text{inc}} \le P_{nbt}^{\text{inc}} \qquad \forall b \in \mathcal{B}, t \in \mathcal{T}, n \in N^{\text{VIR}} \qquad (102)$$

Variable domains:

$$p_{nT^{\text{S}}}^{\text{en}}, p_{nT^{\text{S}}b}^{\text{dec}}, p_{nT^{\text{S}}b}^{\text{inc}} = 0 \qquad \forall b \in \mathcal{B}, n \in N^{\text{VIR}} \qquad (103)$$

$$p_{nt}^{\text{en}}, p_{ntb}^{\text{dec}}, p_{ntb}^{\text{inc}} \ge 0 \qquad \forall b \in \mathcal{B}, t \in \mathcal{T} \setminus T^{\text{S}}, n \in N^{\text{VIR}} \qquad (104)$$

2.4 Market Clearing

This section describes the solution procedure for a single market clearing instance, including how various parameters in the above formulation are derived and how the Lagrange multipliers are transformed into market clearing prices. The overall market clearing procedure is as follows:

1. Input bids/offers from individual resources (as described in Tables Table 2.5, Table 2.8, Table 2.11, Table 2.13, and Table 2.15) and static market data (as described below in Section 2.4.3).

2. Solve market clearing optimization MIP model (Eqns. (1)-(104)).

3. Fix discrete variables (including commitments) to their values from the MIP solution.

4. Solve market clearing optimization LP model for continuous variables (including dispatch of energy and ancillary products) and Lagrange multipliers.

5. Compute prices for energy and ancillary products from Lagrange multipliers (as described below in Section 2.4.1).

6. Output commitment, dispatch, and prices.

Additional detail about the input and output data formats is provided in the Participation Guide document.

2.4.1 Computation of prices

Lagrange multipliers are obtained from solving the market clearing optimization model as an LP with the discrete variables fixed to given values. Then, prices are computed from the Lagrange multipliers as follows.

First, the bus-indexed energy prices λ_{it}^{en} and the system-wide ancillary product prices λ_t^{rgu}, λ_t^{rgd}, λ_t^{spr}, and λ_t^{nsp} are computed from the associated Lagrange multipliers by dividing the multipliers by D_t, as indicated in the associated constraints. The energy price λ_{it}^{en} is also called the Locational Marginal Price or LMP. The ancillary product prices λ_t^{rgu}, λ_t^{rgd}, λ_t^{spr}, and λ_t^{nsp} are also called Market Clearing Prices or MCPs.

Then, the resource-indexed energy prices λ_{nt}^{en} faced by participants in market settlement are simply the appropriate bus-indexed energy prices:

$$\lambda_{nt}^{\text{en}} = \lambda_{it}^{\text{en}} \qquad \forall n \in \mathcal{N}, t \in \mathcal{T}, i = i_n \qquad (105)$$

2.4.2 Physical, forward, and advisory periods

Each market clearing model includes time periods that will either require physical delivery, forward settlement, or advisory dispatch. These three types of time periods are described as follows:

- Physical delivery is only required when the market clearing interval represents the Operating Period that will occur in the next five minutes.
- Forward settlement periods specify that the resource's incremental dispatch schedule will be compensated according to the market clearing prices in those periods, according to that market clearing solution.
- Advisory dispatch is neither physically nor financially binding, but the dispatch schedule and prices from these periods are sent to market participants for informational purposes.

Before every market clearing, each resource's forward position is calculated for each of the time intervals in the market clearing horizon. This forward position is stored in the parameter P_{nt}^{fwd}, which will be calculated explicitly as shown below. Given the forward positions P_{nt}^{fwd} and the resource's dispatch quantity p_{nt}^{en}, the resource's market clearing quantities are determined from the following constraint:

$$p_{nt}^{\text{en}} = p_{nt}^{\Delta} + P_{nt}^{\text{fwd,en}} \qquad \forall n \in \mathcal{N}, t \in \mathcal{T} \qquad (106)$$

Based on the resource constraints described in Section 2.3, the resource's total dispatch p_{nt}^{en} is required to be a feasible offer, and the resource's cleared quantity $p_{nt}^{\Delta\text{en}}$ is the deviation of the new schedule from the resource's previous forward position. When the resource's market revenues or payments are calculated, they are only based on the cleared quantity $p_{nt}^{\Delta\text{en}}$. That is, there are two versions of the resource's schedule:

- p_{nt}^{en}: the resource's cleared quantity; the amount it is scheduled to produce or consume.

- $p_{nt}^{\Delta\text{en}}$: the resource's settlement quantity; the quantity that the resource is paid (or pays) at the market's LMP.

The previous forward quantities $P_{nt}^{\text{fwd,en}}$ have already been cleared, so only settling the $p_{nt}^{\Delta\text{en}}$ quantity therefore avoids double counting production or consumption that was already purchased in a forward position.

The forward position is the sum of previous forwards that were cleared in the set of markets that included interval t, $m \in \mathcal{M}(t)$.

$$P_{nt}^{\text{fwd,en}} = \sum_{m\in\mathcal{M}(t)} \sum_{t'\in\mathcal{T}(m,t)} p_{nt'}^{\text{fwd,en}(m)} \qquad \forall n \in \mathcal{N}, t \in \mathcal{T} \qquad (107)$$

Note that a time index from one market clearing model may be within the time horizon of another market clearing model, yet that time index may not appear in the latter model's time intervals. This can often occur because longer horizon models typically have longer interval durations, and shorter horizon models will model many time indices that occur between the time indices of the other model. For that reason, the set $t' \in \mathcal{T}(m,t)$ is defined as the single time interval index in market m that contains the time index t; e.g., if $t =$ 6:25am in a real time market model, then t' would be 6:00am.

Forward positions for the reserve products are also calculated and included in the model.

$$p_{nt}^{\text{rgu}} = p_{nt}^{\Delta\text{rgu}} + P_{nt}^{\text{fwd,rgu}} \qquad \forall n \in \mathcal{N}, t \in \mathcal{T} \qquad (108)$$

$$p_{nt}^{\text{rgd}} = p_{nt}^{\Delta\text{rgd}} + P_{nt}^{\text{fwd,rgd}} \qquad \forall n \in \mathcal{N}, t \in \mathcal{T} \qquad (109)$$

$$p_{nt}^{\text{spr}} = p_{nt}^{\Delta\text{spr}} + P_{nt}^{\text{fwd,spr}} \qquad \forall n \in \mathcal{N}, t \in \mathcal{T} \qquad (110)$$

$$p_{nt}^{\text{nsp}} = p_{nt}^{\Delta\text{nsp}} + P_{nt}^{\text{fwd,nsp}} \qquad \forall n \in \mathcal{N}, t \in \mathcal{T} \qquad (111)$$

$$P_{nt}^{\text{fwd.rgu}} = \sum_{m\in\mathcal{M}(t)} \sum_{t'\in\mathcal{T}(m,t)} p_{nt'}^{\text{fwd,rgu}(m)} \qquad \forall n \in \mathcal{N}, t \in \mathcal{T} \qquad (112)$$

$$P_{nt}^{\text{fwd,rgd}} = \sum_{m\in\mathcal{M}(t)} \sum_{t'\in\mathcal{T}(m,t)} p_{nt'}^{\text{fwd,rgd}(m)} \qquad \forall n \in \mathcal{N}, t \in \mathcal{T} \qquad (113)$$

$$P_{nt}^{\text{fwd,spr}} = \sum_{m\in\mathcal{M}(t)} \sum_{t'\in\mathcal{T}(m,t)} p_{nt'}^{\text{fwd,spr}(m)} \qquad \forall n \in \mathcal{N}, t \in \mathcal{T} \qquad (114)$$

$$P_{nt}^{\text{fwd,nsp}} = \sum_{m\in\mathcal{M}(t)} \sum_{t'\in\mathcal{T}(m,t)} p_{nt'}^{\text{fwd,nsp}(m)} \qquad \forall n \in \mathcal{N}, t \in \mathcal{T} \qquad (115)$$

2.4.3 Preparation of static market data

Market data that does not need to change from one run of the market clearing procedure to the next is called static data. Static data includes some technical cost and capability data of the resources that would be known to the market administrator and also some system data such as topology and other characteristics of the transmission network. Some of this static data can be read from input files once for the whole market simulation. The rest of the static data needs to be constructed from the input data.

2.4.3.1 Construction of transmission network parameters

The DC admittance parameters B_k^{sr} are computed from the series reactance values X_k^{sr} according to the standard DC power flow model, specifically using the susceptance:

$$B_k^{sr} = -\frac{1}{X_k^{sr}} \ \forall k \in \mathcal{K}$$

2.4.3.2 Construction of Reserve Demand Curves

Reserves are procured by the system operator to buffer against variation and uncertainty in supply and demand. Reserves are procured according to a reserve requirement quantity, reserve violation penalty, and a sloped reserve demand curve for reserves procured in excess of the reserve requirement. Although this set up is formulated as a flat violation penalty for a reserve shortage and a sloped demand curve for excess reserves, this reserve procurement valuation scheme in whole will be referred to as the reserve demand curve. Figure 1 below illustrates the general form of the reserve demand curves.

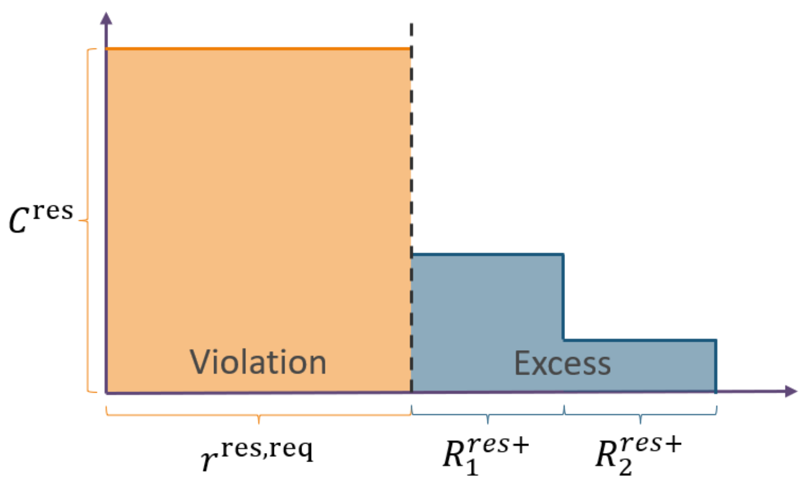

Figure 1: Reserve Demand Curve Illustration

As shown in Figure 1, any reserve procurement less than p^{req} is penalized at a constant rate of C^{res} \$/MWh. Reserve procurement in excess of p^{req} adds additional value to the market surplus objective. This formulation is equivalent to a single "demand curve" or a single "violation curve" but is split into violation and excess components for convenience and its expressed relation to the reserve requirement quantities. Note that the reserve demand quantity can be any positive number, and any $C^{\text{res2}} > 0$ would be valid for the slope of the demand curve. Note that the formulations in Section 2.2.6 imply continuity between the violation penalty and excess supply curves.

3.0 Market Design Specifications

This section describe the market design specifications that competitors will participate in. Each market design specification provides a complete description of when each market clearing will occur, the market's time horizon, the duration of each interval, and the settlement type of each interval. Each market clearing instance will collect bids and offers for the time periods specified in each market's timeline specifications. The model configuration section describes which constraints are active or inactive in each market design. Lastly, each market design has an offer restriction section that describes requirements for the data submitted in each resource's bid or offer. Bids and offers that do not conform to the specifications and requirements in this section will be replaced with default values or projected onto the set of allowable data intervals.

3.1 Two-Settlement Market

The two-settlement market is a typical ISO market design implementation. Bids and offers are cleared in the day ahead market in one hour increments for a 24-hour horizon, followed by real time market clearing in 5-minute increments. Both the day ahead and real time market can be solved with look ahead windows that extend beyond the market clearing horizon. This creates a *two-settlement* system since each resource is settled twice – once in the day ahead market and once in the real time market.

Day-ahead and real-time market designs allow more complex resource modeling software compared to market designs with more frequent market settlements. Consequently, the day-ahead and real time market configuration offers the broadest menu of possible offer formats for storage resources.

3.1.1 Timeline specification

The two-settlement design has two market clearing timeline specifications for the day ahead and real time markets, shown in Table 3.1 and Table 3.2 respectively:

Table 3.1: Two-Settlement Day-Ahead Market Timeline Specification

Attribute	Specification
Starting Period	[(“PD”, 0)]
UID	“TSDAM_{SP}”
Offer Submission Period	(“CD”, 540)
Market Clearing Period	(“CD”, 720)
Interval Durations	[(36, 60)]
Interval Types	[(24, ”FWD”), (12, “ADVS”)]

Table 3.2: Two-Settlement, Real-Time Market Timeline Specification

Attribute	Specification
Starting Period	[(“PH”, 0), (“PH”, 5), (“PH”, 10), (“PH”, 15), (“PH”, 20), (“PH”, 25), (“PH”, 30), (“PH”, 35), (“PH”, 40), (“PH”, 45), (“PH”, 50), (“PH”, 55)]
UID	“TSRTM_{SP}”
Offer Submission Period	(“SP”, -60)
Market Clearing Period	(“SP”, -5)
Interval Durations	[(36, 5)]
Interval Types	[(1, “PHYS”), (35, ”ADVS”)]

3.1.2 Model configuration

Table 3.3 describes which storage resource constraints are active or inactive in the two-settlement market design. Non-storage resources are not controlled by ESPA-Comp participants and are therefore always modeled as described in Section 2.3.

Table 3.3: Two-Settlement Storage Model Configuration

Eqn.	Description	Activation Conditions
(33)	Total resource cost	Active
(34)	Dispatch cost	Active if $C_{bt}^{\mathrm{ch}} < 0$ or $C_{bt}^{\mathrm{dc}} > 0$
(35)	State-of-Charge cost	Active if $C_{nbt}^{\mathrm{SoC}} > 0$
(36)–(39)	Reserves cost	Active
(40), (41)	Dispatch auxiliary variables	Active if $C_{bt}^{\mathrm{ch}} < 0$ or $C_{bt}^{\mathrm{dc}} > 0$
(42)	State-of-charge auxiliary variables	Active if $C_{nbt}^{\mathrm{SoC}} > 0$
(43)	Net dispatch	Active
(44), (45)	Charge status disjunction	Active
(46)–(48)	Auxiliary variable upper bounds	Active
(49), (50)	Reserve dispatch capacity	Active
(51), (52)	Reserve energy capacity	Active
(53), (54)	Ramping constraints	Active
(55), (56)	Reserve ramping capacity	Active
(57)–(59)	State-of-charge progression	Deactivate (59) if $C_{bt}^{\mathrm{SoC}} > 0$
(60)	State-of-charge bounds	Active
(61)	Charge status	Active
(62)	Nonnegativity	Active

3.1.3 Offer restrictions

Some storage offer parameters are not compatible with all market designs. Similarly, some storage offer parameters cannot be simultaneously submitted if other specific offer parameters are also submitted. Table 3.4 describes these restrictions for the two-settlement market. The perpendicular symbol (⊥) denotes symbols than cannot be simultaneously submitted (i.e., a complementarity restriction).

Table 3.4: Two-Settlement Storage Offer Restrictions

Symbol	Value Restriction	Symbol Restriction	Size restriction
C_{nt}^{ch}	Nonpositive	$\perp C_{bt}^{\mathrm{SoC}}$	$\{b\} \leq 10$
C_{nt}^{dc}	Nonnegative	$\perp C_{bt}^{\mathrm{SoC}}$	$\{b\} \leq 10$
C_{nt}^{rgu}	Nonnegative		Scalar
C_{nt}^{rgd}	Nonnegative		Scalar
C_{nt}^{spr}	Nonnegative		Scalar
C_{nt}^{nsp}	Nonnegative		Scalar
C_{nt}^{SoC}	None	$\perp C_{bt}^{\mathrm{ch}}, \perp C_{bt}^{\mathrm{dc}}$	$\{b\} \leq 10$
$P_{nt}^{\mathrm{max,ch}}$	Nonnegative		Scalar
$P_{nt}^{\mathrm{max,dc}}$	Nonnegative		Scalar
P_{nbt}^{ch}	Nonnegative		$\{b\} \leq 10$
P_{nbt}^{dc}	Nonnegative		$\{b\} \leq 10$
R_{n}^{dn}	Nonnegative		Scalar
R_{n}^{up}	Nonnegative		Scalar
S_{nbt}^{offer}	None	$\perp C_{bt}^{\mathrm{ch}}, \perp C_{bt}^{\mathrm{dc}}$	$\{b\} \leq 10$
S_{n}^{end}	Nonnegative	$\perp C_{bt}^{\mathrm{SoC}}$	Scalar

Symbol	Value Restriction	Symbol Restriction	Size restriction
S_n^{start}	Nonnegative		Scalar
$S^{\max}$	Nonnegative		Scalar
$S^{\min}$	Nonnegative		Scalar
η^{ch}	Unit interval		Scalar
η^{dc}	Unit interval		Scalar

3.2 Multi-Settlement Market

The multi-settlement market augments the two-settlement market design with additional forward market settlements. For simplicity, this market design is implemented using the same basic configurations as the two-settlement market except that look ahead horizon in the real time market includes 23 forward market clearing intervals. This creates a *multi-settlement* system since each resource is settled multiple times – once in the day ahead market and then 24 additional times in the real time market.

Like the two-settlement design, the multi-settlement market also allow more complex resource modeling software compared to market designs with more frequent market settlements. Consequently, the two-settlement market configuration offers the broadest menu of possible offer formats for storage resources.

3.2.1 Timeline specification

The multi-settlement design also has two market clearing timeline specifications for the day ahead and real time markets, shown in Table 3.5 and Table 3.6 respectively:

Table 3.5: Multi-Settlement Day-Ahead Market Timeline Specification

Attribute	Specification
Starting Period	[(“PD”, 0)]
UID	“MSDAM_{SP}”
Offer Submission Period	(“CD”, 540)
Market Clearing Period	(“CD”, 720)
Interval Durations	[(36, 60)]
Interval Types	[(24, ”FWD”), (12, “ADVS”)]

Table 3.6: Multi-Settlement, Real-Time Market Timeline Specification

Attribute	Specification
Starting Period	[(“PH”, 0), (“PH”, 5), (“PH”, 10), (“PH”, 15), (“PH”, 20), (“PH”, 25), (“PH”, 30), (“PH”, 35), (“PH”, 40), (“PH”, 45), (“PH”, 50), (“PH”, 55)]
UID	“TSRTM_{SP}”
Offer Submission Period	(“SP”, -60)
Market Clearing Period	(“SP”, -5)
Interval Durations	[(36, 5)]
Interval Types	[(1, “PHYS”), (23, ”FWD”), (12, “ADVS”)]

3.2.2 Model configuration

Table 3.7 describes which storage resource constraints are active or inactive in the multi-settlement market design. Non-storage resources are not controlled by ESPA-Comp participants and are therefore always modeled as described in Section 2.3.

Table 3.7: Multi-settlement Storage Model Configuration

Eqn.	Description	Activation Conditions
(33)	Total resource cost	Active

Eqn.	Description	Activation Conditions
(34)	Dispatch cost	Active if $C_{bt}^{\text{ch}} < 0$ or $C_{bt}^{\text{dc}} > 0$
(35)	State-of-Charge cost	Active if $C_{nbt}^{\text{SoC}} > 0$
(36)–(39)	Reserves cost	Active
(40), (41)	Dispatch auxiliary variables	Active if $C_{bt}^{\text{ch}} < 0$ or $C_{bt}^{\text{dc}} > 0$
(42)	State-of-charge auxiliary variables	Active if $C_{nbt}^{\text{SoC}} > 0$
(43)	Net dispatch	Active
(44), (45)	Charge status disjunction	Active
(46)–(48)	Auxiliary variable upper bounds	Active
(49), (50)	Reserve dispatch capacity	Active
(51), (52)	Reserve energy capacity	Active
(53), (54)	Ramping constraints	Active
(55), (56)	Reserve ramping capacity	Active
(57)–(59)	State-of-charge progression	Deactivate (59) if $C_{bt}^{\text{SoC}} > 0$
(60)	State-of-charge bounds	Active
(61)	Charge status	Active
(62)	Nonnegativity	Active

3.2.3 Offer restrictions

Some storage offer parameters are not compatible with all market designs. Similarly, some storage offer parameters cannot be simultaneously submitted if other specific offer parameters are also submitted. Table 3.8 describes these restrictions for the multi-settlement market. The perpendicular symbol (⊥) denotes symbols than cannot be simultaneously submitted (i.e., a complementarity restriction).

Table 3.8: Multi-settlement Storage Offer Restrictions

Symbol	Value Restriction	Symbol Restriction	Size restriction
C_{nt}^{ch}	Nonpositive	$\perp C_{bt}^{\text{SoC}}$	$\{b\} \leq 10$
C_{nt}^{dc}	Nonnegative	$\perp C_{bt}^{\text{SoC}}$	$\{b\} \leq 10$
C_{nt}^{rgu}	Nonnegative		Scalar
C_{nt}^{rgd}	Nonnegative		Scalar
C_{nt}^{spr}	Nonnegative		Scalar
C_{nt}^{nsp}	Nonnegative		Scalar
C_{nt}^{SoC}	None	$\perp C_{bt}^{\text{ch}}, \perp C_{bt}^{\text{dc}}$	$\{b\} \leq 10$
$P_{nt}^{\text{max,ch}}$	Nonnegative		Scalar
$P_{nt}^{\text{max,dc}}$	Nonnegative		Scalar
P_{nbt}^{ch}	Nonnegative		$\{b\} \leq 10$
P_{nbt}^{dc}	Nonnegative		$\{b\} \leq 10$
R_{n}^{dn}	Nonnegative		Scalar
R_{n}^{up}	Nonnegative		Scalar
S_{nbt}^{offer}	None	$\perp C_{bt}^{\text{ch}}, \perp C_{bt}^{\text{dc}}$	$\{b\} \leq 10$
S_{n}^{end}	Nonnegative	$\perp C_{bt}^{\text{SoC}}$	Scalar
S_{n}^{start}	Nonnegative		Scalar
S^{max}	Nonnegative		Scalar
S^{min}	Nonnegative		Scalar
η^{ch}	Unit interval		Scalar
η^{dc}	Unit interval		Scalar

3.3 Rolling Horizon Forward Market

The rolling horizon forward market is conceptually simpler than typical ISO market designs except that it allows much more opportunities to resettle a resource's forward cleared quantities. Instead of distinct day ahead and real time markets, the rolling horizon forward market is always cleared every 5 minutes. Various model horizons are solved at different market clearing intervals within the hour:

- At the top of every hour, a 36 hour horizon model is solved that includes 5-minute intervals in the first two hours, 15-minute intervals over the middle 10 hours, and 1-hour increments through the last 24 hours.
- At each of the remaining 15-minute intervals (0:15, 0:30, and 0:45), a 12 hour horizon model is solved that includes 5-minute intervals in the first two hours and 15-minute intervals over the last 10 hours.
- At each of the remaining 5-minute intervals (0:05, 0:10, 0:20, 0:25, 0:35, 0:40, 0:50, and 0:55), a 2 hour horizon model is solved that includes 5-minute intervals over the entire model horizon.

We term the above system a *rolling horizon forward* market since each resource's physical schedule depends on frequently updating its forward position in a series of market clearings that continually roll forward in time. Each resource's position may be resettled many times.

The rolling horizon forward market design allows more frequent market settlements and therefore sacrifices the more complex resource modeling software used in the previous market designs. Consequently, the rolling horizon forward market configuration offers a substantially narrower menu of possible offer formats for storage resources.

3.3.1 Timeline specification

The rolling horizon forward market design has six total market clearing timeline specifications: one for the 36 hour market, three for the 12 hour market, and two for the 2 hour market, shown in Table 3.9, Table 3.10, Table 3.11, Table 3.12, Table 3.13, and Table 3.14, respectively:

Table 3.9: Rolling Horizon Forward Market 36 Timeline Specification

Attribute	Specification
Starting Period	[("PH", 0)]
UID	"RFM36_{SP}"
Offer Submission Period	("SP", -60)
Market Clearing Period	("SP", -5)
Interval Durations	[(24, 5), (40, 15), (24, 60)]
Interval Types	[(1, "PHYS"), (87, "FWD")]

Table 3.10: Rolling Horizon Forward Market 12A Timeline Specification

Attribute	Specification
Starting Period	[("PH", 15)]
UID	"RFM12a_{SP}"
Offer Submission Period	("SP", -60)
Market Clearing Period	("SP", -5)
Interval Durations	[(24, 5), (39, 15)]
Interval Types	[(1, "PHYS"), (62, "FWD")]

Table 3.11: Rolling Horizon Forward Market 12B Timeline Specification

Attribute	Specification
Starting Period	[("PH", 30)]

Attribute	Specification
UID	"RFM12b_{SP}"
Offer Submission Period	("SP", -60)
Market Clearing Period	("SP", -5)
Interval Durations	[(24, 5), (38, 15)]
Interval Types	[(1, "PHYS"), (61, "FWD")]

Table 3.12: Rolling Horizon Forward Market 12C Timeline Specification

Attribute	Specification
Starting Period	[("PH", 45)]
UID	"RFM12c_{SP}"
Offer Submission Period	("SP", -60)
Market Clearing Period	("SP", -5)
Interval Durations	[(24, 5), (37, 15)]
Interval Types	[(1, "PHYS"), (60, "FWD")]

Table 3.13: Rolling Horizon Forward Market 2A Timeline Specification

Attribute	Specification
Starting Period	[("PH", 5), ("PH", 20), ("PH", 35), ("PH", 50)]
UID	"RFM2a_{SP}"
Offer Submission Period	("SP", -60)
Market Clearing Period	("SP", -5)
Interval Durations	[(23, 5)]
Interval Types	[(1, "PHYS"), (22, "FWD")]

Table 3.14: Rolling Horizon Forward Market 2B Timeline Specification

Attribute	Specification
Starting Period	[("PH", 10), ("PH", 25), ("PH", 40), ("PH", 55)]
UID	"RFM2b_{SP}"
Offer Submission Period	("SP", -60)
Market Clearing Period	("SP", -5)
Interval Durations	[(22, 5)]
Interval Types	[(1, "PHYS"), (21, "FWD")]

3.3.2 Model configuration

Table 3.15 describes which storage resource constraints are active or inactive in the rolling horizon forward market design. Non-storage resources are not controlled by ESPA-Comp participants and are therefore always modeled as described in Section 2.3.

Table 3.15: Rolling Horizon Forward Storage Model Configuration

Eqn.	Description	Activation Conditions
(33)	Total resource cost	Active
(34)	Dispatch cost	Active
(35)	State-of-Charge cost	Deactivated
(36)–(39)	Reserves cost	Active
(40), (41)	Dispatch auxiliary variables	Active
(42)	State-of-charge auxiliary variables	Deactivated
(43)	Net dispatch	Active
(44), (45)	Charge status disjunction	Deactivated
(46)–(48)	Auxiliary variable upper bounds	Active
(49), (50)	Reserve dispatch capacity	Active
(51), (52)	Reserve energy capacity	Deactivated
(53), (54)	Ramping constraints	Deactivated
(55), (56)	Reserve ramping capacity	Active

Eqn.	Description	Activation Conditions
(57)–(59)	State-of-charge progression	Deactivated
(60)	State-of-charge bounds	Deactivated
(61)	Charge status	Deactivated
(62)	Nonnegativity	Active

3.3.3 Offer restrictions

Some storage offer parameters are not compatible with all market designs. Similarly, some storage offer parameters cannot be simultaneously submitted if other specific offer parameters are also submitted. Table 3.16 describes these restrictions for the rolling horizon forward market. The perpendicular symbol (⊥) denotes symbols than cannot be simultaneously submitted (i.e., a complementarity restriction).

Table 3.16: Rolling Horizon Forward Storage Offer Restrictions

Symbol	Value Restriction	Symbol Restriction	Size restriction
C_{nt}^{ch}	Nonpositive		$\{b\} \leq 10$
C_{nt}^{dc}	Nonnegative		$\{b\} \leq 10$
C_{nt}^{rgu}	Nonnegative		Scalar
C_{nt}^{rgd}	Nonnegative		Scalar
C_{nt}^{spr}	Nonnegative		Scalar
C_{nt}^{nsp}	Nonnegative		Scalar
C_{nt}^{SoC}	Disallowed		
$P_{nt}^{\text{max,ch}}$	Nonnegative		Scalar
$P_{nt}^{\text{max,dc}}$	Nonnegative		Scalar
P_{nbt}^{ch}	Nonnegative		$\{b\} \leq 10$
P_{nbt}^{dc}	Nonnegative		$\{b\} \leq 10$
R_n^{dn}	Disallowed		
R_n^{up}	Disallowed		
S_{nbt}^{offer}	Disallowed		
S_n^{end}	Disallowed		
S_n^{start}	Disallowed		
S^{max}	Disallowed		
S^{min}	Disallowed		
η^{ch}	Disallowed		
η^{dc}	Disallowed		

4.0 Resource Simulation

All resource performance is stochastic. The dependence of wind, solar, and load on weather is well known, but uncertainty effects all components of the electric grid. Devices may fail, freeze, or overheat. Assets physically depreciate and further increase the probability of failure. Transport systems and supply chains may fail or become congested. This section describes how these probabilities are incorporated in the dispatch simulation of resources included in the market simulation.

At the conclusion of each physical market clearing, the dispatch of each resource is simulated to produce a “ground truth” energy production or consumption quantity that determines the final delivered quantities used in market settlements. This final simulation step is especially important for storage resources, which use the output of this simulation to determine their not only the actual quantities charged or discharged, but also the actual amount of stored energy after each period and the accumulation of degradation costs. The relevant models are described in Section 4.1.

The remaining resource types (conventional generators, renewable generators, and demand) are simulated based on the outcome of random variables. The simulation for conventional generators, described in Section 4.2, determines whether or not the generator fails and is unable to produce energy. Renewable generation and load are based on a Monte Carlo simulation described in Section 4.3 that uses synthetic data, based on historical data, to simulate realistic weather patterns for wind, solar, and load outcomes.

4.1 Energy Storage

ESPA-Comp focuses on the participation of storage resources in electricity markets, which is detailed in this section. Competitors will be allocated an energy storage resource that will be simulated by a charge reservoir model (also called an equivalent circuit model), which models the electrical relationship between the battery’s open circuit voltage, terminal voltage, electrical current and DC-to-AC power conversion. Non-competitor storage resources will be assumed capable of operating according to the energy storage model described in Section 2.3.1.

The charge reservoir model is based on an equivalent circuit model with electrical current flowing in and out of the storage device. Physical performance of the battery (internal losses, conversion efficiency, and operating temperature) are estimated based on current and voltages in the equivalent circuit model.

While the charge reservoir model will be used to simulate competitor batteries in ESPA-Comp, this model is not available in the market clearing model described in Section 2.0. Depending on the specific market design being simulated, competitors instead offer into the market using the energy storage models described in Section 2.3.1 and according to possible offer restrictions specified in the market designs in Section 3.0.

The following subsections first describe the parameters for the general physical attributes of storage resources. Then, a model is formulated to determine the battery’s charge and discharge, state-of-charge, internal losses, and operating temperature. The last subsection describes how degradation costs are calculated.

4.1.1 Physical attributes

The charge reservoir model can be used to model chemical batteries, including lithium-ion, sodium-sulfur, flow, zinc-air, and lead-acid batteries. Each technology type has distinct resource attributes. Lithium-ion batteries are the most common type of battery for grid-scale storage applications due to high energy density, long life cycle, and low cost. Other battery technologies can offer advantages in terms of cost, efficiency, duration, or other attributes. Some battery technologies are relatively mature while others are still in their early stages of development, and it remains unclear which technology will become most prevalent in the future. The following formulation may be generally applicable for any of these technology types. Note that for the purposes of ESPA-Comp, each competitor will be allocated a Lithium Ion battery, but the precise attributes will be determined later.

The resource set $n \in \mathcal{N}^{\mathrm{STR}}$ is designated for storage resources. However, for ease of comprehension, the following sections will drop the resource index notation.

Table 4.1: Charge Reservoir Battery Attributes

Symbol	Description	Format	Units
A^{imax}	Maximum current charge into battery n	Float	A
A^{imin}	Maximum current discharge from battery n	Float	A
A^{vmax}	Maximum voltage of battery n	Float	V
A^{vmin}	Minimum voltage of battery n	Float	V
A^{Ccap}	Charge capacity of battery n	Float	Ah
$A^{\mathrm{DoD,0}}$	0-order depth-of-discharge degradation coefficient of battery n	Float	$
$A^{\mathrm{DoD,1}}$	1st-order depth-of-discharge degradation coefficient of battery n	Float	$
$A^{\mathrm{DoD,2}}$	2nd-order depth-of-discharge degradation coefficient of battery n	Float	$
$A^{\mathrm{DoD,3}}$	3rd-order depth-of-discharge degradation coefficient of battery n	Float	$
$A^{\mathrm{DoD,4}}$	4th-order depth-of-discharge degradation coefficient of battery n	Float	$
A^{eff}	Coulombic efficiency of battery n	Float	%
$A^{\mathrm{inv,0}}$	0th-order inverter efficiency coefficient of battery n	Float	MW
$A^{\mathrm{inv,1}}$	1st order inverter efficiency coefficient of battery n	Float	Unitless
$A^{\mathrm{inv,2}}$	2nd-ord inverter efficiency coefficient of battery n	Float	MW^{-1}
A^{Ksoc}	State-of-charge degradation constant of battery n	Float	Unitless
A^{Ktherm}	Thermal degradation constant of battery n	Float	Unitless
A^{Ktime}	Time degradation constant of battery n	Float	Unitless
A^{life}	Rated cycle-life of battery n	Float	Cycles
$A^{\mathrm{oc,0}}$	0th-order open-circuit voltage coefficient of battery n	Float	V
$A^{\mathrm{oc,1}}$	1st-order open-circuit voltage coefficient of battery n	Float	V/Ah
$A^{\mathrm{oc,2}}$	2nd-order open-circuit voltage coefficient of battery n	Float	V/Ah^2
$A^{\mathrm{oc,3}}$	3rd-order open-circuit voltage coefficient of battery n	Float	V/Ah^3
A^{pmax}	Maximum discharge power of battery n	Float	MW
A^{pmin}	Maximum charge power of battery n	Float	MW
A^{resis}	Internal resistance of battery n	Float	mΩ
A^{sinit}	Initial state-of-charge of battery n	Float	%
A^{smax}	Maximum state-of-charge of battery n	Float	%
A^{smin}	Minimum state-of-charge of battery n	Float	%
A^{SoCref}	Reference SoC of battery n	Float	%

Symbol	Description	Format	Units
A^{TCap}	Thermal capacity of battery n	Float	J / °C
A^{Tinit}	Initial temperature of battery n	Float	°C
A^{Tmax}	Maximum temperature of battery n	Float	°C
A^{Tref}	Reference temperature of battery n	Float	°C
A^{Utherm}	Thermal transmittance between the surface of battery n and the environment	Float	W / °C
C^{EoL}	End-of-Life cost of battery n	Float	$

4.1.2 Dispatch simulation

The battery's desired dispatch level is projected onto the battery's physical constraints as follows. The dispatch simulation will be performed by the simulation platform; however, participant's are free to choose how or whether to model their resource's dispatch for the purpose of formulating their offers. A zero-order equivalent cycle model, similar to Rosewater, *et al*. (2019), see Figure 2, is implemented to minimize deviation from the desired dispatch level. Resistive heating and conduction-based cooling parameters are included to model battery temperature limits.

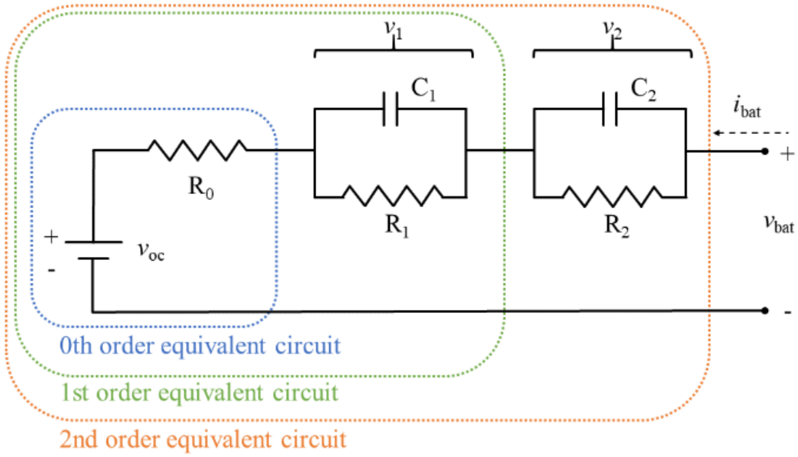

Figure 2: Equivalent Circuit Model of a Storage Resource

Dispatch simulation performs the calculation for a function from $\mathbb{R}^4 \rightarrow \mathbb{R}^7$, where the input argument to the function is a desired dispatch level p^0, the interval beginning state-of-charge σ_{t-1}, the interval-beginning cell temperature ϑ_{t-1}, and the ambient temperature T_t^{env}; the output data is the storage resource's actual AC power dispatch p, DC power output p^{dc}, DC current through the battery i^{bat}, battery open circuit voltage v^{oc}, battery terminal voltage v^{bat}, interval-ending state-of-charge σ_t; and interval-ending cell temperature ϑ_t. These input and output values are described in Table 4.2. The model is not solved for forward market settlements, which are not constrained to be physically feasible.

As in the previous section, the resource index notation is dropped. Time indices are included when relevant.

Table 4.2: Dispatch Simulation Input/Output for Equivalent Circuit Model

Symbol	Description	Input/Output	Units
i^{bat}	DC current through the battery	Output	A
p	AC power dispatch	Output	kW
p^0	Desired dispatch level	Input	kW

Symbol	Description	Input/Output	Units
p^{dc}	DC power output	Output	kW
v^{bat}	Battery terminal voltage	Output	V
v^{oc}	Battery open circuit voltage	Output	V
σ_t	Interval-ending state-of-charge	Output	Ah
σ_{t-1}	Interval-beginning state-of-charge	Input	Ah
ϑ_t	Interval-ending cell temperature	Output	°C
ϑ_{t-1}	Interval-beginning cell temperature	Input	°C
T_t^{env}	Ambient temperature	Input	°C

The simulation model is formulated as follows:

Minimize dispatch deviation:

$$\min p^+ + p^- \tag{116}$$

Desired dispatch level p^0 is battery n's target value for its actual dispatch, p:

$$p = p^0 + p^+ - p^- \tag{117}$$

However, the actual dispatch p is aggregated from individual cells and needs to be scaled down to th

The DC power from N^{c} individual battery cells is summed and then passed through an AC/DC power inverter that assumes a quadratic conversion efficiency function:

$$N^{\text{c}} p^{\text{dc}} = A^{\text{inv},2} p^2 + A^{\text{inv},1} p + A^{\text{inv},0} \tag{118}$$

Battery DC power output is based on Ohm's law:

$$p^{\text{dc}} = i^{\text{bat}} v^{\text{bat}} / 1000 \tag{119}$$

Battery voltage, open circuit voltage, and voltage drop over the resistor are related by KVL:

$$v^{\text{bat}} = v^{\text{oc}} + A^{\text{resis}} i^{\text{bat}} \tag{120}$$

Battery open-circuit voltage is modeled by a cubic function of the state-of-charge:

$$v^{\text{oc}} = A^{\text{oc},3} \sigma_{nt}^3 + A^{\text{oc},2} \sigma_{nt}^2 + A^{\text{oc},1} \sigma_{nt} + A^{\text{oc},0} \tag{121}$$

Battery current is split into two variables for flow in or out of the battery:

$$i^{\text{bat}} = i^{\text{in}} - i^{\text{out}} \tag{122}$$

Battery state-of-charge progresses based on the current in and out of the device:

$$A^{\text{Ccap}} (\sigma_t - \sigma_{t-1}) = D_t \left(A^{\text{eff}} i^{\text{in}} - i^{\text{out}} \right) \tag{123}$$

Battery temperature progresses based on resistive heating and conduction-based cooling:

$$A^{\text{Tcap}} (\vartheta_t - \vartheta_{t-1}) = D_t \left(A^{\text{resis}} \left(i^{\text{bat}} \right)^2 + A^{\text{Utherm}} (T_t^{\text{env}} - \vartheta_t) \right) \tag{124}$$

A complementarity condition can be placed on current in and out of the battery, but likely is not necessary:

$$i^{\text{in}} i^{\text{out}} = 0 \quad (125)$$

Minimum and maximum power rating, state-of-charge, current rating, and voltage are all based on the battery's design parameters:

$$A^{\text{pmin}} \le p \le A^{\text{pmax}} \quad (126)$$

$$A^{\text{smin}} \le \sigma_t \le A^{\text{smax}} \quad (127)$$

$$A^{\text{imin}} \le i^{\text{bat}} \le A^{\text{imax}} \quad (128)$$

$$A^{\text{vmin}} \le v^{\text{bat}} \le A^{\text{vmax}} \quad (129)$$

$$A^{\text{Tmin}} \le \vartheta_t \le A^{\text{Tmax}} \quad (130)$$

4.1.3 Degradation cost

Battery degradation is calculated periodically, at an interval of Δt, based on the regularization method presented in Rosewater, *et al.* (2019). The degradation cost in each interval, $c^{\text{degradation}}$, is the product of the battery's end-of-life (EoL) cost, C^{EoL}, times the device's incremental loss in state-of-health (SoH), d^{SoH}.

$$c^{\text{degradation}} = C^{\text{EoL}} \frac{\partial \text{SoH}}{\partial t} \Delta t \quad (131)$$

This section describes the steps to calculate $c^{\text{degradation}}$. The battery's state-of-heath is assumed to be an exponential decay function that includes factors from cyclic degradation, thermal stress, state-of-charge, and depth-of-discharge. Specifically, the battery's state-of-health is a function with the following form:

$$\text{SoH} = H = e^{-f} \quad (132)$$

where,

$$f = F^{\text{t}} F^{\text{S}} F^{\text{T}} + \sum_{i \in \mathcal{C}} D_i F^{\text{D}} F^{\text{S}} F^{\text{T}} \quad (133)$$

$$F^{\text{t}} = K^{\text{time}}\, t \quad (134)$$

$$F^{\text{T}} = e^{K^{\text{therm}}(\bar{\vartheta} - A^{\text{Tref}})\frac{A^{\text{Tref}}}{\bar{\vartheta}}} \quad (135)$$

$$F^{\text{S}} = e^{K^{\text{SoC}}(\bar{\sigma} - A^{\text{SoCref}})} \quad (136)$$

$$F^{\text{D}} = A^{\text{DoD,0}} + A^{\text{DoD,1}}\bar{\delta} + A^{\text{DoD,2}}\,\bar{\delta}^2 + A^{\text{DoD,3}}\,\bar{\delta}^3 + A^{\text{DoD,4}}\bar{\delta}^4 \quad (137)$$

Further, the total degradation cost $c^{\text{degradation}}$ will be calculated in four separate components for the effects of cycling, thermal stress, state-of-charge, and depth-of-discharge on the battery's state-of-health.

$$c^{\text{degradation}} = c^{\text{cyc}} + c^{\text{therm}} + c^{\text{SoC}} + c^{\text{DoD}} \tag{138}$$

Definitions and procedures to calculate the various components above will be provided in the rest of this section. Various constants related to the battery's thermal, state-of-charge, and depth-of-discharge properties will be based on the incremental degradation rate, which is the derivative of SoH with respect to time:

$$\frac{\partial \text{SoH}}{\partial t} = \dot{H} = -K^{\text{time}} F^{\text{S}} F^{\text{T}} e^{-f} \tag{139}$$

Derived constants are also calculated based on assumed state-of-charge, u; temperature, $\bar{\vartheta}$; and depth-of-discharge, $\bar{\delta}$; of the battery. We calculate averages from the output of the battery's dispatch simulation for the values of $\bar{\sigma}$, $\bar{\vartheta}$, and $\bar{\delta}$.

$$\bar{\sigma} \coloneqq \frac{1}{\Delta t} \sum_{t=t^0}^{t^0+\Delta t} \sigma_t \tag{140}$$

$$\bar{\vartheta} \coloneqq \frac{1}{\Delta t} \sum_{t=t^0}^{t^0+\Delta t} \vartheta_t \tag{141}$$

Cycles are determined by the algorithm described by Downing and Socie (1982). We describe our implementation below:

7. Obtain a vector of the battery's state-of-charge profile, $S = [\sigma_t \,:\, t \in \{t^0, \ldots, t^0 + \Delta t\}]$.
8. Remove all non-peak and non-trough values from S; i.e., keeping the first and last element of S and then removing any elements σ_t if σ_t is a local maximum or local minimum (which can be tested: $(\sigma_t - \sigma_{t-1})(\sigma_{t+1} - \sigma_t) > 0$).
9. Let $\hat{S}$ be this new vector of peaks and troughs. Reorder $\hat{S}$ so that the highest peak occurs first, and then append this peak value to also be the last element in $\hat{S}$.
10. Create empty vectors R and D.
11. If $\hat{S}$ is empty, stop. Otherwise, remove the first element from $\hat{S}$ and insert it to the beginning of R.
12. If the length of R is less than 3, repeat Step 5.
13. Let $X = abs(R_1 - R_2)$ and $Y = abs(R_2 - R_3)$.
14. If $X \geq Y$, append the value Y to vector D and then remove elements R_2 and R_3 from R.
15. Go to Step 5.

Each cycle is then given an index $i \in \mathcal{C}$, where $\mathcal{C}$ is the set of the elements in vector S. Note that the elements of D are D_i and are used in the expression for the rate of state-of-health degradation, f. The average depth-of-discharge is calculated below.

$$\bar{\delta} \coloneqq \frac{1}{|\mathcal{C}|} \sum_{i \in \mathcal{C}} D_i \tag{142}$$

Each degradation cost component will now be presented. First, cyclic degradation is calculated based on the change in time Δt, end-of-life cost C^{EoL}, coulombic efficiency A^{eff}, rated cycle life A^{life}, and charge capacity A^{cap}, and the L-1 norm of the battery's charge profile.

$$i^{\mathrm{bat}} \coloneqq \left[i_{t'}^{\mathrm{bat}} : t' \in \{t - \Delta T, \dots, t\}\right] \tag{143}$$

$$c^{\mathrm{cyc}} = \frac{\Delta t\, C^{\mathrm{EoL}}}{\left(1 + \frac{1}{A^{\mathrm{eff}}}\right) A^{\mathrm{life}} A^{\mathrm{Ccap}}} \left\| i^{\mathrm{bat}} \right\|_1 \tag{144}$$

Next, thermal degradation is calculated based on the battery's average temperature, internal resistance, heat capacity, average state-of-charge, and average depth-of-discharge. A thermal degradation factor for the effect of temperature on degradation rate is described below.

$$K^{\mathrm{T}} = \frac{\partial^2 \mathrm{SoH}}{\partial t \partial \vartheta} = \frac{\partial}{\partial \vartheta}\left(-K^{\mathrm{t}} F^{\mathrm{S}} F^{\mathrm{T}} e^{-f}\right) \tag{145}$$

The derivative value is implemented numerically using a two-sided finite difference approximation using a small epsilon value $\varepsilon > 0$, as shown below.

$$F^{\mathrm{T}+} = e^{K^{\mathrm{therm}}(\bar{\vartheta} + \varepsilon - A^{\mathrm{Tref}})\frac{A^{\mathrm{Tref}}}{\bar{\vartheta} + \varepsilon}} \tag{146}$$

$$F^{\mathrm{T}-} = e^{K^{\mathrm{therm}}(\bar{\vartheta} - \varepsilon - A^{\mathrm{Tref}})\frac{A^{\mathrm{Tref}}}{\bar{\vartheta} - \varepsilon}} \tag{147}$$

$$f^{T+} = F^{\mathrm{t}} F^{\mathrm{S}} F^{\mathrm{T}+} + \sum_{i \in \mathcal{C}} w_i F^{\mathrm{D}} F^{\mathrm{S}} F^{\mathrm{T}+} \tag{148}$$

$$f^{T-} = F^{\mathrm{t}} F^{\mathrm{S}} F^{\mathrm{T}-} + \sum_{i \in \mathcal{C}} w_i F^{\mathrm{D}} F^{\mathrm{S}} F^{\mathrm{T}-} \tag{149}$$

$$\dot{H}^{T+} = -K^{\mathrm{time}} F^{\mathrm{S}} F^{\mathrm{T}+} e^{-f^{T+}} \tag{150}$$

$$\dot{H}^{T-} = -K^{\mathrm{time}} F^{\mathrm{S}} F^{\mathrm{T}-} e^{-f^{T-}} \tag{151}$$

$$K^{\mathrm{T}} = \frac{\dot{H}^{T+} - \dot{H}^{T-}}{2\varepsilon} \tag{152}$$

Given the time interval Δt, end-of-life cost C^{EoL}, thermal degradation factor K^{T}, internal resistance A^{resis}, thermal capacity A^{Tcap}, and the L-2 norm of the battery's charge profile, the total thermal degradation is calculated below.

$$c^{\mathrm{therm}} = \frac{\Delta t^2\, C^{\mathrm{EoL}} K^T A^{\mathrm{resis}}}{A^{\mathrm{Tcap}}} \left\| i^{\mathrm{bat}} \right\|_2^2 \tag{153}$$

Degradation due to the battery's state-of-charge profile is illustrated next. As performed for thermal degradation, a state-of-charge-based degradation factor is calculated to estimate the effect of state-of-charge on the battery's degradation rate.

$$K^{\mathrm{S}} = \frac{\partial^2 \mathrm{SoH}}{\partial t \partial \sigma} = \frac{\partial}{\partial \sigma}\left(-K^{\mathrm{t}} F^{\mathrm{S}} F^{\mathrm{T}} e^{-f}\right) \tag{154}$$

Similarly to the previous derivation, the above derivative value is implemented numerically using a two-sided finite difference approximation using a small epsilon value $\varepsilon > 0$, shown below.

$$F^{\mathrm{S}+} = e^{K^{\mathrm{SoC}}(\bar{\sigma}+\varepsilon-A^{\mathrm{SoCref}})} \quad (155)$$

$$F^{\mathrm{S}-} = e^{K^{\mathrm{SoC}}(\bar{\sigma}-\varepsilon-A^{\mathrm{SoCref}})} \quad (156)$$

$$f^{S+} = F^{\mathrm{t}} F^{\mathrm{S}+} F^{\mathrm{T}} + \sum_{i \in C} w_i F^{\mathrm{D}} F^{\mathrm{S}+} F^{\mathrm{T}} \quad (157)$$

$$f^{S-} = F^{\mathrm{t}} F^{\mathrm{S}-} F^{\mathrm{T}} + \sum_{i \in C} w_i F^{\mathrm{D}} F^{\mathrm{S}-} F^{\mathrm{T}} \quad (158)$$

$$\dot{H}^{S+} = -K^{\mathrm{time}} F^{\mathrm{S}+} F^{\mathrm{T}} e^{-f^{S+}} \quad (159)$$

$$\dot{H}^{S-} = -K^{\mathrm{time}} F^{\mathrm{S}-} F^{\mathrm{T}} e^{-f^{S-}} \quad (160)$$

$$K^{\mathrm{S}} = \frac{\dot{H}^{S+} - \dot{H}^{S-}}{2\varepsilon} \quad (161)$$

Given the time interval Δt, end-of-life cost C^{EoL}, state-of-charge degradation factor K^{S}, and the battery's average state-of-charge, the total state-of-charge-based degradation is calculated below.

$$c^{\mathrm{SoC}} = \Delta t \, C^{\mathrm{EoL}} K^{\mathrm{S}} \bar{\sigma} \quad (162)$$

Lastly, we derive the cost of degradation due to the battery's depth-of-discharge. The depth-of-discharge-based degradation factor is calculated to estimate the effect of depth-of-discharge on the battery's degradation rate.

$$K^{\mathrm{D}} = \frac{\partial^2 \mathrm{SoH}}{\partial t \partial \delta} = \frac{\partial}{\partial \delta}\left(-K^{\mathrm{t}} F^{\mathrm{S}} F^{\mathrm{T}} e^{-f}\right) \quad (163)$$

Unlike in previous derivations, the variable of interest, $\bar{\delta}$, only appears in the cubic polynomial definition of F^{D}, and is therefore implemented analytically, shown below.

$$\dot{F^{D}} = A^{\mathrm{DoD},1} + 2A^{\mathrm{DoD},2}\,\bar{\delta} + 3A^{\mathrm{DoD},3}\,\bar{\delta}^2 + 4A^{\mathrm{DoD},4}\bar{\delta}^3 \quad (164)$$

$$K^{\mathrm{D}} = -K^{\mathrm{t}} F^{\mathrm{T}} F^{\mathrm{S}} \dot{F^{D}} e^{f} \quad (165)$$

The depth-of-discharge component of degradation costs is then calculated as follows.

$$c^{\mathrm{DoD}} = C^{\mathrm{EoL}} K^{\mathrm{D}} \bar{\delta} \quad (166)$$

Given the above equations, each storage resource's dispatch simulation will be used to determine degradation costs. Precise attributes for this calculation, such as the relevant parameters in Table 4.1 and the calculation period ΔT, will be determined later.

4.2 Conventional Generators

Generators may fail and be forced offline for numerous reasons. Turbine may have mechanical failures, faulty insulation may cause an electrical fault, fuel supplies may become unavailable, or human error may propagate a simple issue into a major emergency. The simulation includes simple probabilistic elements to model these emergencies.

4.2.1 Outage duration

The outline of this outage simulation is as follows. Each generator n is assigned a forced outage rate F that represents the percentage of time that it is expected to be offline. Each generator is also assigned a set of probabilities ρ_n^ω that it will go into forced outage at some point over the next 60 days. Each outage scenario ω lasts for a of duration ΔT^ω days. For simplicity, it will be assumed that no more than two outages can occur within 60 days. The quantities F, ρ_n^ω, and ΔT^ω are related as shown below:

$$F = \frac{1}{60}\left(\sum_{\omega\in\Omega} \Delta T^\omega \rho_n^\omega \prod_{\omega'\in\Omega\setminus\omega} \left(1-\rho_n^{\omega'}\right) + \sum_{\omega,\omega'\in\Omega} \left(\Delta T^\omega + \Delta T^{\omega'}\right)\rho_n^\omega \rho_n^{\omega'} \prod_{\omega''\in\Omega\setminus\{\omega,\omega'\}} \left(1-\rho_n^{\omega''}\right)\right) \tag{167}$$

Table 4.3 provides an example of outage probabilities and durations.

Table 4.3: Conventional Generator Outage Probability Example

Event (ω)	Probability	Duration
A	5%	8 hours
B	2%	1 day
C	1%	5 days
D	0.5%	3 weeks

4.2.2 Probability scaling

Given that ρ_n^ω is the probability of outage ω occurring within the 60 days, we downscale the to the probability that the generator n goes on outage during a 5 minute interval, $\rho_n^{5\text{min},\omega}$. First, we downscale to an intermediate probability that the generator goes on outage during a day. Note that there are 288 5-minute intervals in a day and 60 days, so a total of 17,280 5-minute intervals.

$$\rho_n^\omega = 1 - \left(1-\rho_n^{5\text{min},\omega}\right)^{17280} \tag{168}$$

Numerically this is better to calculate $\rho_n^{5\text{min},\omega}$ by using logarithms:

$$17280 \log\left(1-\rho_n^{5\text{min},\omega}\right) = \log\left(1-\rho_n^\omega\right) \tag{169}$$

Which results in the following estimate of the 5-minute probability:

$$\rho_n^{5\text{min},\omega} = 1 - e^{\frac{1}{17280}\log\left(1-\rho_n^\omega\right)} \tag{170}$$

For example, given a 5% probability of the failure event ω occurring over the next 60 days, the above gives an estimate of 2.97e-6 of the failure occurring in a single 5-minute interval.

4.2.3 Implementation in resource data

Throughout the market simulation, the outcome of potential outages is simulated for each generator according to its 5-minute outage probabilities. In cases when an outage occurs, the following steps are performed for the generator n that is now on forced outage:

1. The generator's physical dispatch is set to 0.
2. The generator's market offer function is updated to reflect outage status U_{nt}^{out} for the duration of the outage.

4.3 Wind, Solar, and Load

Wind, solar, and load forecasts may change frequently throughout the day. For wind and solar, these changes are mostly driven by the weather. Load forecasts may reflect not only changes in the weather but also employment patterns, social events, and other random occurrences.

To simulate realistic weather patterns and load uncertainty, Monte Carlo simulations will be implemented using existing methods. Consistent with typical current practices, point forecasts will be available to ESPA-Comp participants' algorithms throughout the simulation. These forecasts will cover at least the time horizon included in the market clearing models and will include forecasts for wind, solar, and load at various zones in the market topology. Near term forecasts will generally be more accurate than longer-term forecasts. However, participants are certainly welcome to identify weaknesses in the provided forecasts or to attempt to improve them.

Various methods may be used to generate the synthetic forecast and actual data to be used in the simulation. Details of specific methods may unduly influence competitor's strategies and will not be provided in this document. In general, a statistical interpolation of the forecast timeseries can be applied as new realizations are gathered (see Rutherford 1972). Synthetic realizations can also be simulated by Monte Carlo techniques that preserve temporal and geographical dependences among the data (Carmona and Yang 2022). The methods require input timeseries data of forecasted and actual wind, solar, and load. As needed, available datasets can be interpolated to 5-mintute resolution and may be modified through affine transformation or other means to obscure the original data.

The model parameters P_{nt}^{max} for $n \in \{\mathcal{N}^{\text{REN}}, \mathcal{N}^{\text{DEM}}\}$ will take values from simulated forecast data. This data will be separated by resource type (wind, solar, or load) and aggregated into network location (specifics to be determined). While each individual resource's offer to the market will contain its individual resource forecast data, only aggregated data will be available to the ESPA-Comp competitors. Future updates will provide more information about the frequency that the forecast data will be updated and how competitor algorithms will be able to access it.

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