Day-Ahead Market Enhancements

Appendix C:
Draft Technical Description of IFM-RUC

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1 INTRODUCTION

This technical paper describes the optimization problem formulation of the proposed Day-Ahead Market Enhancements (DAME) for discussion purposes. The DAME is an extension of the Integrated Forward Market (IFM) that includes the Flexible Ramp Up (FRU) and Flexible Ramp Down (FRD) products, also known in the context of the Day-Ahead Market as Imbalance Reserve Up (IRU) and Imbalance Reserve Down (IRD) products, respectively. The DAME also combines the functionality of the IFM and the Residual Unit Commitment (RUC) into one market application to realize efficiencies in procuring all Day-Ahead Market commodities simultaneously. The RUC capacity is replaced by two products, Residual Capacity Up (RCU) and Residual Capacity Down (RCD), priced at the cost of the FRU and FRD products, respectively. For a physical resource, the Day-Ahead Energy schedule plus the RCU and RCD awards amounts to the Reliability Energy schedule, which is analogous to the current RUC schedule. In the DAME, the FRU/FRD is reserved capacity above/below the Reliability Energy schedule that must be available for dispatch in the Real-Time Market (RTM) to meet granularity differences and upward/downward uncertainty from the Reliability Energy schedule to the demand forecast in the Fifteen-Minute Market (FMM). The granularity difference materializes because the DAME clears in hourly intervals producing hourly Reliability Energy schedules whereas the FMM clears in 15min intervals producing 15min FMM Energy schedules. The uncertainty is due to the net demand forecast error between the DAME and the FMM.

1.1 EXISTING DAY-AHEAD MARKET STRUCTURE

Currently the Day-Ahead Market includes three separate market applications that are executed in sequence: Market Power Mitigation (MPM), IFM, and RUC. The MPM is a trial IFM pass that identifies and mitigates bids based on specific criteria. The IFM commits resources, clears physical and virtual energy supply and demand schedules, and procures ancillary services awards. The RUC commits additional resources and schedules additional capacity beyond physical energy schedules to meet the day-ahead demand forecast while ignoring virtual energy schedules. The resources that are committed in IFM are modeled as must-run in RUC, i.e., they are kept online. Moreover, the energy schedules from these committed resources are protected in RUC with penalty functions seeking an incremental capacity solution on the IFM to meet the day-ahead demand forecast. Furthermore, ancillary services awarded in IFM are fixed in RUC.

1.2 DAY-AHEAD MARKET ENHANCEMENTS

The DAME will procure FRU/FRD to address granularity differences and uncertainty that may materialize in the FMM. The FRU/FRD awards in the DAME are hourly, like any other market commodity in the DAME; however, they are limited to a 15min ramp capability because they must be dispatchable in the FMM. Therefore, only 15min-dispatchable resources may qualify for FRU/FRD awards in the DAME. For the FRU/FRD DAME awards to be dispatchable in the FMM, they must carry a Must Offer Obligation (MOO), i.e., an energy bid must be submitted in the RTM for the corresponding resource capacity. The FRU/FRD

DAME awards expire in the FMM as the reserved capacity is either dispatched as energy or used to procure ancillary services or real-time FRU/FRD. The FRU/FRD awards procured in the FMM and the Real Time Dispatch (RTD) cover uncertainty materializing between the FMM and real time. For this reason, these FRU/FRD awards are limited to a 5min ramp capability because they must be dispatchable in the RTD. Therefore, only 5min-dispatchable resources may qualify for FRU/FRD awards in the FMM and RTD. Because of the structural differences between the FRU/FRD awards in the DAME and the RTM, there is no deviation settlement for them between the DAME and the FMM; however, there is a deviation settlement for FRU/FRD awards between the FMM and the RTD because they are essentially the same products that are re-procured in RTD.

The current Day-Ahead Market structure results in a suboptimal (higher cost) unit commitment solution because it is achieved in two stages with different objectives at each stage and because the commitment of the first stage (IFM) is locked in the second stage (RUC). For example, a unit that is committed in IFM may have insufficient capacity to meet the demand forecast leading to additional resource commitment in RUC, which could render the IFM commitment unnecessary. By contrast, the DAME will commit resources more efficiently in a single process by satisfying both IFM and RUC objectives simultaneously.

1.3 MARKET COMMODITIES IN THE DAY-AHEAD MARKET ENHANCEMENTS

Besides optimal resource commitment, the market commodities procured in the DAME are the following:

- Day-Ahead Energy schedules for physical and virtual resources;
- Flexible Ramp Up and Down awards for physical resources;
- Reliability Capacity Up and Down awards for physical resources;
- Day-Ahead Regulation Up and Down awards for physical resources;
- Day-Ahead Mileage Up and Down awards for physical resources;
- Day-Ahead Spinning Reserve awards for physical resources;
- Day-Ahead Non-Spinning Reserve awards for physical resources; and
- Day-Ahead Corrective Capacity awards for physical resources.[1]

2 ASSUMPTIONS

The optimization problem formulation for the DAME in this technical paper is based on the following assumptions:

- The optimal solution composed of the unit commitment and the cleared schedules and awards for the market commodities meets simultaneously the following objectives:

[1] With the deployment of the Contingency Modeling Enhancements (CME) functionality.

1) Physical and virtual day-ahead energy supply schedules balance physical and virtual day-ahead energy demand schedules and losses; this is currently accomplished by the power balance constraint in the IFM.
2) Physical reliability energy supply schedules balance the demand forecast; this is currently accomplished by the power balance constraint in the RUC.
3) Congestion management prevents violations of network constraints and preventive contingencies for both day-ahead energy and reliability energy schedules.
4) Ancillary services awards satisfy cascaded ancillary services requirements.
5) FRU/FRD awards satisfy FRU/FRD requirements.
6) Corrective capacity awards provide recovery from corrective transmission contingencies.[1]

- The objective function is the maximization of the total merchandizing surplus over the time horizon (the Trading Day) including the following:
  - the minimization of physical and virtual energy supply schedules cost;
  - the maximization of physical and virtual energy demand schedules benefit;
  - the minimization of the Start-Up Cost of committed resources;
  - the minimization of the Minimum Load Cost of committed resources;
  - the minimization of State Transition Cost of Multi-State Generators (MSGs);
  - the minimization of RCU/RCD awards cost;
  - the minimization of FRU/FRD awards cost; and
  - the minimization of ancillary services (Regulation, Mileage, Spinning and Non-Spinning Reserve, and Corrective Capacity) awards cost.
- All ancillary services procurement constraints are enforced to procure 100% of the relevant requirements. Similarly, FRU/FRD procurement constraints are enforced to procure the upper/lower percentile of the day-ahead uncertainty histogram without demand elasticity.
- Ancillary services and FRU/FRD are procured regionally with nested regions under the system region to satisfy minimum requirements for each region. The procurement of Corrective Capacity (CC) is locational through corrective contingency constraints using the Contingency Modeling Enhancements (CME) methodology.
- All applicable resource constraints are enforced:
  - resource capacity constraints;
  - unit commitment and state transition inter-temporal constraints; and
  - market commodity time domain and ramp-sharing constraints.
- All applicable transmission and generation constraints are enforced:

- network constraints for physical and virtual energy schedules for the base case and preventive transmission and/or generation contingencies;
- network constraints for physical and virtual energy schedules for corrective transmission contingencies;
- intertie scheduling limits for energy schedules and capacity awards;
- regional deliverability constraints for energy schedules and capacity awards;
- transmission and generation nomograms, including gas-burn constraints; and
- Minimum Online Capacity (MOC) constraints.

Aside from MOC, which are unit commitment constraints, all transmission constraints are be formulated for both day-ahead energy and reliability energy schedules.

- Daily energy limit constraints are enforced.
- State of Charge (SOC) constraints are enforced for Limited Energy Storage Resources (LESRs).
- Hourly intervals are used for the time horizon spanning the Trading Day.
- Block hourly energy scheduling is available to hourly intertie resources.
- Hourly energy scheduling is available to hourly Proxy Demand Resources (PDRs) and hourly Reliability Demand Response Resources (RDRRs).
- The Day-Ahead MPM functionality is fully preserved; the MPM is essentially a trial pass of the DAME where the established MPM principles apply, namely:
  - the impact of resource commitment and physical and virtual energy schedules on network constraints is quantified;
  - network constraints are classified as competitive or uncompetitive using the Dynamic Competitive Path Assessment (DCPA) method;
  - resources that provide congestion relief on uncompetitive network constraints are flagged for mitigation; and
  - commitment costs[2] and energy bids from resources flagged for mitigation are mitigated for use in the DAME pass.

3 MATHEMATICAL FORMULATION

The focus of the mathematical formulation of the DAME in this technical paper is on the integration of FRU/FRD and RCU/RCD procurement with the energy scheduling and ancillary services procurement in a single optimization problem with hourly intervals. Emphasis is given on the particular elements that are required for this task. Known existing features that

[2] With the deployment of the Commitment Cost and Default Energy Bid Enhancements (CCDEBE) functionality.

apply in general to the Security Constrained Unit Commitment (SCUC) engine, such as unit commitment inter-temporal constraints, MSG modeling, block energy scheduling, contingency constraints, nomograms, energy and SOC limits, and soft constraint penalty relaxation or scarcity treatment, are not included for simplicity and because they do not materially affect the DAME.

3.1 NOTATION

The following notation is used in the problem formulation for the DAME in this technical paper:

i	Physical Resource index.
j	Virtual Resource index.
r	Region index (zero for system).
s	Scheduling Coordinator (SC) index.
k	Network constraint index.
t	Time period index (0 for initial condition).
T_{10}	Capacity Ancillary Services time domain (10min).
T_{15}	Flexible Ramp time domain (15min).
T_{60}	Time period duration (60min).
T_D	The number of time periods in the Trading Day (23-25), considering the short and long days due to daylight savings changes.
$\forall$	For all…
$\wedge$	Logical and…
$\cup$	Union…
$\rightarrow$	Leads to…
Δ	Denotes incremental values.
$\sim$	Denotes initial values from an AC power flow solution.
∂	Partial derivative operator.
S_r	Set of resources in region r.
S_s	Set of resources of Scheduling Coordinator s.
S_{10}	Set of Fast-Start Units ($SUT \le$ 10min) that can be certified to provide Non-Spinning Reserve from offline status (u = 0).
S_{15}	Set of 15min-start units ($SUT \le$ 15min) that can provide FRU from offline status (u = 0).
I_k	Set of import resources associated with ITC/ISL k.
E_k	Set of export resources associated with ITC/ISL k.
S_k	Set of intertie resources associated with ITC/ISL k; $S_k = I_k \cup E_k$.
$u_{i,t}$	Binary (0/1) variable indicating commitment status (offline/online) for Resource i in time period t.
$y_{i,t}$	Binary (0/1) variable indicating that Resource i has a start-up in time period t.
$\eta_{i,t}$	Binary (0/1) variable indicating that online Resource i can be shut-down in time period t.
C	Objective function.

$LOL_{i,t}$	Lower Operating Limit of Resource *i* in time period *t*.
$UOL_{i,t}$	Upper Operating Limit of Resource *i* in time period *t*.
$LRL_{i,t}$	Lower Regulating Limit of Resource *i* in time period *t*.
$URL_{i,t}$	Upper Regulating Limit of Resource *i* in time period *t*.
$LEL_{i,t}$	Lower Economic Limit of Resource *i* in time period *t*.
$UEL_{i,t}$	Upper Economic Limit of Resource *i* in time period *t*.
$CL_{i,t}$	Capacity Limit for Resource *i* in time period *t*; $UEL_{i,t} \leq CL_{i,t} \leq UOL_{i,t}$; it defaults to $UOL_{i,t}$.
$SUC_{i,t}$	Start-Up Cost for Resource *i* in time period *t*.
$SUT_{i,t}$	Start-Up Time for Resource *i* in time period *t*.
$MLC_{i,t}$	Minimum Load Cost for Resource *i* in time period *t*.
$EN_{i,t}$	Day-Ahead Energy schedule of Resource *i* in time period *t*; positive for supply (generation and imports) and negative for demand (demand response and exports).
$REN_{i,t}$	Reliability Energy schedule of Resource *i* in time period *t*; positive for supply (generation and imports) and negative for demand (demand response and exports).
$L_{i,t}$	Energy schedule of Non-Participating Load Resource *i* in time period *t*.
D_t	Demand forecast in time period *t*.
$FRU_{i,t}$	Flexible Ramp Up award of Resource *i* for potential delivery in time period *t*.
$FRD_{i,t}$	Flexible Ramp Down award of Resource *i* for potential delivery in time period *t*.
$RCU_{i,t}$	Reliability Capacity Up award of Resource *i* for potential delivery in time period *t*.
$RCD_{i,t}$	Reliability Capacity Down award of Resource *i* for potential delivery in time period *t*.
$SR_{i,t}$	Spinning Reserve award of Resource *i* in time period *t*.
$NR_{i,t}$	Non-Spinning Reserve award of Resource *i* in time period *t*.
$ASU_{i,t}$	Upward Ancillary Service award (the sum of Regulation Up, and Spinning and Non-Spinning Reserve awards) of Resource *i* in time period *t*.
$RUC_{i,t}$	Regulation Up capacity bid of Resource *i* in time period *t*.
$RDC_{i,t}$	Regulation Down capacity bid of Resource *i* in time period *t*.
$SRC_{i,t}$	Spinning Reserve capacity bid of Resource *i* in time period *t*.
$NRC_{i,t}$	Non-Spinning Reserve capacity bid of Resource *i* in time period *t*.
$ENP_{i,t}$	Energy bid price of Resource *i* in time period *t*.
$FRUP_{i,t}$	Flexible Ramp Up bid price of Resource *i* in time period *t*.
$FRDP_{i,t}$	Flexible Ramp Down bid price of Resource *i* in time period *t*.
$RUP_{i,t}$	Regulation Up bid price of Resource *i* in time period *t*.
$RDP_{i,t}$	Regulation Down bid price of Resource *i* in time period *t*.
SRP_i	Spinning Reserve bid price of Resource *i* in time period *t*.
$NRP_{i,t}$	Non-Spinning Reserve bid price of Resource *i* in time period *t*.

$FRUR_{r,t}$	Flexible Ramp Up uncertainty requirement in Region *r* and time period *t*.
$FRDR_{r,t}$	Flexible Ramp Down uncertainty requirement in Region *r* and time period *t*.
$RUR_{r,t}$	Regulation Up requirement in Region *r* and time period *t*.
$RDR_{r,t}$	Regulation Down requirement in Region *r* and time period *t*.
$SRR_{r,t}$	Spinning Reserve requirement in Region *r* and time period *t*.
$NRR_{r,t}$	Non-Spinning Reserve requirement in Region *r* and time period *t*.
$ASUR_{r,t}$	Upward Ancillary Service requirement (the sum of Regulation Up, and Spinning and Non-Spinning Reserve requirements) in Region *r* and time period *t*.
$RRU_i(EN_{i,t}, \tau)$	Piecewise linear ramp up capability function of Resource *i* from its Energy schedule in time period *t* for time domain τ.
$RRD_i(EN_{i,t}, \tau)$	Piecewise linear ramp down capability function of Resource *i* from its Energy schedule in time period *t* for time domain τ.
$Loss_t$	Transmission losses in time period *t*.
$LPF_{i,t}$	Loss Penalty Factor for Resource *i* in time period *t*.
$SF_{i,k,t}$	Shift Factor for the energy injection schedule of Resource *i* on network constraint *k* in time period *t*.
$F_{k,t}$	Active power flow or scheduled flow on network constraint *k* in time period *t*.
$LFL_{k,t}$	Lower active power flow or scheduling limit (non-positive) on network constraint *k* in time period *t*.
$UFL_{k,t}$	Upper active power flow or scheduling limit on network constraint *k* in time period *t*.
$NEL_{r,t}$	N–1 simultaneous export transfer capability of Region *r* in time period *t*.
$NIL_{r,t}$	N–1 simultaneous import transfer capability of Region *r* in time period *t*.
α_t	Shared ramping coefficient for Regulation in time period *t*.
β_t	Shared ramping coefficient for Spinning Reserve in time period *t*.
γ_t	Shared ramping coefficient for Non-Spinning Reserve in time period *t*.
δ_t	Shared ramping coefficient for Flexible Ramp in time period *t*.
λ_t	Shadow price of day-ahead energy balance constraint in time period *t*.
ξ_t	Shadow price of reliability energy balance constraint in time period *t*.
ρ_t	Shadow price of FRU procurement constraint in time period *t*.
σ_t	Shadow price of FRD procurement constraint in time period *t*.
$RENNP_{i,t}$	Reliability Energy No Pay capacity of Resource *i* in time period *t*.
$FRUNP_{i,t}$	Flexible Ramp Up No Pay capacity of Resource *i* in time period *t*.
$FRDNP_{i,t}$	Flexible Ramp Down No Pay capacity of Resource *i* in time period *t*.
$RENC_t$	System Reliability Energy cost in time period *t*.
$FRUC_t$	System FRU cost in time period *t*.

$FRDC_t$	System FRD cost in time period t.
$ML_{i,t}$	Metered load of Non-Participating Load Resource i in time period t.
$\bar{\xi}_t$	Average Reliability Energy cost rate in time period t.
$\bar{\rho}_t$	Average FRU cost rate in time period t.
$\bar{\sigma}_t$	Average FRD cost rate in time period t.
$ML_{i,t}$	Metered load of Non-Participating Load Resource i in time period t.
$RENCD_{s,t}$	Reliability Energy cost billing determinant for SC s in time period t.
$FRUCD_{s,t}$	FRU cost billing determinant for SC s in time period t.
$FRDCD_{s,t}$	FRD cost billing determinant for SC s in time period t.
$RENC_{s,t}^{(1)}$	Reliability Energy tier-1 cost allocation to SC s in time period t.
$FRUC_{s,t}^{(1)}$	FRU tier-1 cost allocation to SC s in time period t.
$FRDC_{s,t}^{(1)}$	FRD tier-1 cost allocation to SC s in time period t.
$RENC_{s,t}^{(2)}$	Reliability Energy tier-2 cost allocation to SC s in time period t.
$FRDC_{s,t}^{(2)}$	FRD tier-2 cost allocation to SC s in time period t.
$FRUC_{s,t}^{(2)}$	FRU tier-2 cost allocation to SC s in time period t.

3.2 GENERAL PROBLEM FORMULATION

The DAME problem is a Mixed Integer Linear Programming (MILP) formulation of minimizing the objective function subject to equality and inequality constraints:

$$\begin{aligned} \min \quad & C(\mathbf{x}) \\ \text{s.t.} \quad & \mathbf{A}_{eq}\,\mathbf{x} = \mathbf{b}_{eq} \\ & \mathbf{A}\,\mathbf{x} \leq \mathbf{b} \end{aligned}$$

3.3 FLEXIBLE RAMP AND RELIABILITY CAPACITY MODEL

This section gives a brief overview of the Flexible Ramp and Reliability Capacity model without any ancillary services for simplicity. Figure 1 shows the energy and flexible ramp up and down targets in a given time interval.

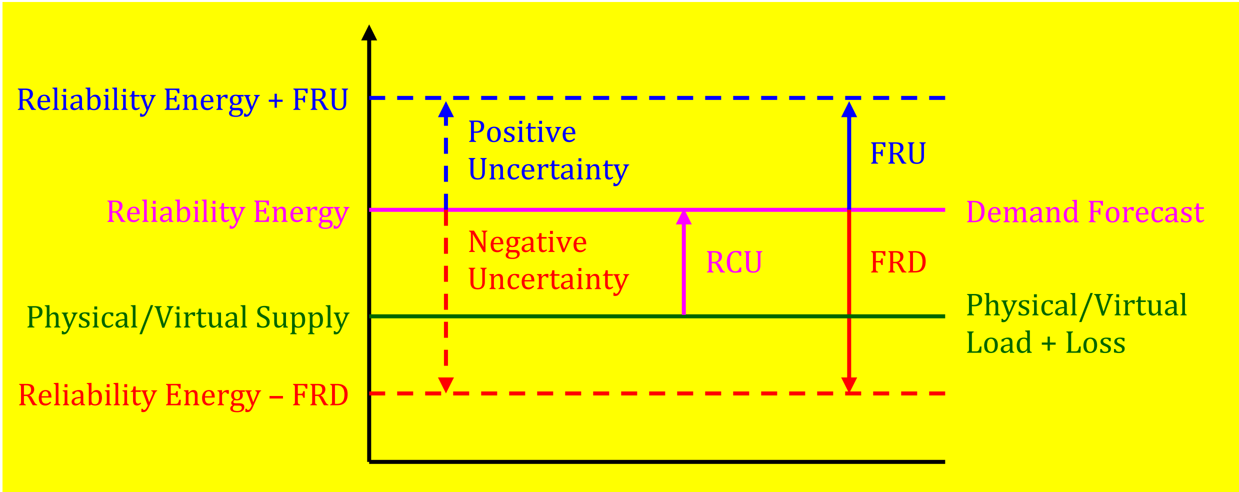

Figure 1. Energy and Flexible Ramp Up/Down targets

The constraints to meet these targets in the MILP problem are as follows:

$$\left.\begin{array}{l} \sum_i EN_{i,t} + \sum_j EN_{j,t} = \sum_i L_{i,t} + \sum_j L_{j,t} + Loss_t \\ \sum_i REN_{i,t} = D_t \\ \sum_i FRU_{i,t} \geq FRUR_t \\ \sum_i FRD_{i,t} \geq FRDR_t \end{array}\right\} ,t = 1,2, \dots ,T_D$$

FRU/FRD is ramping capacity between intervals reserved to meet uncertainty in the net demand forecast between the DAME and the FMM. Figure 2 shows the potential FRU/FRD awards for a physical resource in a given time interval that can be reserved based on its energy schedule in the previous time interval and its ramp capability.

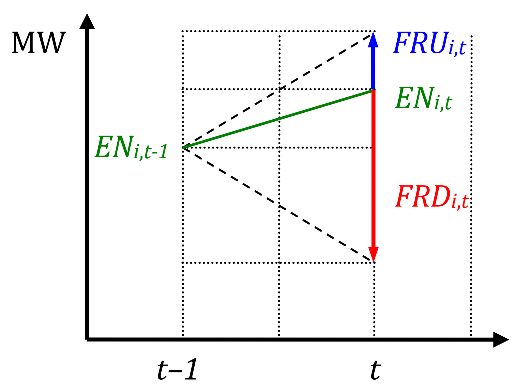

Figure 2. Energy and Flexible Ramp Up/Down ramp constraints

The dashed lines represent the upward and downward ramp capability of the resource from its energy schedule in the previous time interval. The FRU/FRD awards are limited by that ramp capability; they represent ramping capacity that is reserved from the scheduled ramp from the previous time interval to the next time interval and remains available to address any uncertainty that may materialize in FMM. Similar constraints are also formulated for the reliability energy schedules.

It is important to note that the energy schedules and FRU/FRD awards are calculated simultaneously by co-optimizing all commodities. They are constrained by the following set of capacity and ramp constraints:

$$\left.\begin{array}{l} LEL_{i,t} + FRD_{i,t} \leq EN_{i,t} \leq UEL_{i,t} - FRU_{i,t} \\ -RRD_i\left(EN_{i,t-1}, T_{60}\right) + FRD_{i,t} \leq EN_{i,t} - EN_{i,t-1} \leq RRU_i\left(EN_{i,t-1}, T_{60}\right) - FRU_{i,t} \\ LEL_{i,t} + FRD_{i,t} \leq REN_{i,t} \leq UEL_{i,t} - FRU_{i,t} \\ -RRD_i\left(REN_{i,t-1}, T_{60}\right) + FRD_{i,t} \leq REN_{i,t} - REN_{i,t-1} \leq RRU_i\left(REN_{i,t-1}, T_{60}\right) - FRU_{i,t} \\ FRD_{i,t} \leq RRD_i\left(EN_{i,t-1}, T_{15}\right) \\ FRU_{i,t} \leq RRU_i\left(EN_{i,t-1}, T_{15}\right) \\ \forall i \wedge t = 1,2, \dots, T_D \end{array}\right\},$$

These constraints are more complicated when considering ancillary services awards, as shown in §0 and §3.12.

The reliability energy schedules are related to the day-ahead energy schedules as follows:

$$\left.\begin{array}{l} 0 \leq RCU_{i,t} \geq REN_{i,t} - EN_{i,t} \\ 0 \leq RCD_{i,t} \geq EN_{i,t} - REN_{i,t} \end{array}\right\}, \forall i \wedge t = 1,2, \dots, T_D$$

These constraints and a non-zero cost for RCU/RCD allow either RCU to take value, resulting in a reliability energy schedule higher than the day-ahead energy schedule, or RCD to take value, resulting in a reliability energy schedule lower than the day-ahead energy schedule.

3.4 OBJECTIVE FUNCTION

The objective function, ignoring MSG state transitions and regulation mileage, and assuming flat (single segment) energy bids for simplicity, is as follows:

$$C = \sum_{t=1}^{T_D}\sum_{i} y_{i,t}\, SUC_{i,t} + \sum_{t=1}^{T_D}\sum_{i} u_{i,t}\, MLC_{i,t} + \sum_{t=1}^{T_D}\sum_{i}(EN_{i,t} - LOL_{i,t})\, ENP_{i,t} - \sum_{t=1}^{T_D}\sum_{i} L_{i,t}\, ENP_{i,t} + \sum_{t=1}^{T_D}\sum_{j} EN_{j,t}\, ENP_{j,t} - \sum_{t=1}^{T_D}\sum_{j} L_{j,t}\, ENP_{j,t} + \sum_{t=1}^{T_D}\sum_{i} RU_{i,t}\, RUP_{i,t} + \sum_{t=1}^{T_D}\sum_{i} RD_{i,t}\, RDP_{i,t} + \sum_{t=1}^{T_D}\sum_{i} SR_{i,t}\, SRP_{i,t} + \sum_{t=1}^{T_D}\sum_{i} NR_{i,t}\, NRP_{i,t} + \sum_{t=1}^{T_D}\sum_{i} FRU_{i,t}\, FRUP_{i,t} + \sum_{t=1}^{T_D}\sum_{i} FRD_{i,t}\, FRDP_{i,t} + \sum_{t=1}^{T_D}\sum_{i} RCU_{i,t}\, FRUP_{i,t} + \sum_{t=1}^{T_D}\sum_{i} RCD_{i,t}\, FRDP_{i,t}$$

All online services are zero when the resource is offline, whereas Non-Spinning Reserve can be provided by offline Fast-Start Units (FSUs) ($SUT \leq 10$min) and FRU can be provided by offline 15min-start units ($SUT \leq 15$min):

$$u_{i,t} = 0 \rightarrow \left\{ \begin{matrix} EN_{i,t} = RU_{i,t} = RD_{i,t} = SR_{i,t} = FRD_{i,t} = RCU_{i,t} = RCD_{i,t} = 0, \forall i \\ NR_{i,t} = 0, \forall i \notin S_{10} \\ FRU_{i,t} = 0, \forall i \notin S_{15} \end{matrix} \right\}, \quad t = 1,2,\ldots,T_D$$

System Resources (SRs), Non-Generator Resources (NGRs), virtual resources, and non-participating load resources have no discontinuities or inter-temporal constraints and are modeled as always online ($u = 1$). Capacity ancillary services and FRU/FRD can only be awarded to resources certified to provide them, but any physical resource and Import/Export System Resource can be certified to provide FRU/FRD, except for non-participating load resources, hourly intertie resources, and hourly PDR and RDRR. Any resource certified for FRU/FRD with energy bids can be awarded FRU/FRD.

3.5 POWER BALANCE CONSTRAINTS

The power balance constraint for the day-ahead energy schedules is as follows:

$$\sum_{i} EN_{i,t} + \sum_{j} EN_{j,t} = \sum_{i} L_{i,t} + \sum_{j} L_{j,t} + Loss_t, t = 1,2,\ldots,T_D$$

The transmission loss is a nonlinear function. In the initial SCUC iteration where there are no network constraints, it is approximated as a percentage of the demand forecast. In the subsequent SCUC iterations, the transmission loss is linearized at an AC power flow solution as follows:

$$Loss_t \cong \widetilde{Loss}_t + \sum_i \Delta EN_{i,t} \frac{\partial Loss_t}{\partial EN_{i,t}} + \sum_j \Delta EN_{j,t} \frac{\partial Loss_t}{\partial EN_{j,t}} + \sum_i \Delta L_{i,t} \frac{\partial Loss_t}{\partial L_{i,t}} + \sum_j \Delta L_{j,t} \frac{\partial Loss_t}{\partial L_{j,t}}, t = 1,2, \dots, T_D$$

Where:

$$\widetilde{Loss}_t = \sum_i \widetilde{EN}_{i,t} + \sum_j \widetilde{EN}_{j,t} - \sum_i \tilde{L}_{i,t} - \sum_j \tilde{L}_{j,t}, t = 1,2, \dots, T_D$$

$$\left.\begin{aligned} \Delta EN_{i,t} &= EN_{i,t} - \widetilde{EN}_{i,t} \\ \frac{\partial Loss_t}{\partial EN_{i,t}} &= 1 - \frac{1}{LPF_{i,t}} \end{aligned}\right\}, \forall i \wedge t = 1,2, \dots, T_D$$

$$\left.\begin{aligned} \Delta EN_{j,t} &= EN_{j,t} - \widetilde{EN}_{j,t} \\ \frac{\partial Loss_t}{\partial EN_{j,t}} &= 1 - \frac{1}{LPF_{j,t}} \end{aligned}\right\}, \forall j \wedge t = 1,2, \dots, T_D$$

$$\left.\begin{aligned} \Delta L_{i,t} &= L_{i,t} - \tilde{L}_{i,t} \\ \frac{\partial Loss_t}{\partial L_{i,t}} &= \frac{1}{LPF_{i,t}} - 1 \end{aligned}\right\}, \forall i \wedge t = 1,2, \dots, T_D$$

$$\left.\begin{aligned} \Delta L_{j,t} &= L_{j,t} - \tilde{L}_{j,t} \\ \frac{\partial Loss_t}{\partial L_{j,t}} &= \frac{1}{LPF_{j,t}} - 1 \end{aligned}\right\}, \forall j \wedge t = 1,2, \dots, T_D$$

Performing substitutions, the linearized power balance constraint for day-ahead energy schedules is as follows:

$$\sum_i \frac{\Delta EN_{i,t}}{LPF_{i,t}} + \sum_j \frac{\Delta EN_{j,t}}{LPF_{j,t}} - \sum_i \frac{\Delta L_{i,t}}{LPF_{i,t}} - \sum_j \frac{\Delta L_{j,t}}{LPF_{j,t}} = 0, t = 1,2, \dots, T_D$$

Where the incremental Energy injections are divided by the corresponding Loss Penalty Factors (LPFs) to account for changes in transmission losses from the previous AC power flow solution.

The power balance constraint for the reliability energy schedules is as follows:

$$\sum_i REN_{i,t} = D_t, t = 1,2, \dots, T_D$$

The demand forecast distribution to load nodes, accounting for transmission losses, is adjusted by the distributed load slack in the AC power flow solution, but it is not a variable in the SCUC, hence the linearized power balance constraint for the reliability energy schedules is as follows:

$$\sum_i \frac{\Delta REN_{i,t}}{LPF_{i,t}} = 0, t = 1,2, \dots, T_D$$

3.6 ANCILLARY SERVICES PROCUREMENT CONSTRAINTS

With regional ancillary services procurement, the constraints are as follows:

$$\left.\begin{array}{r}\sum_{i \in S_r} RD_{i,t} \geq RDR_{r,t} \\ \sum_{i \in S_r} RU_{i,t} \geq RUR_{r,t} \\ \sum_{i \in S_r} RU_{i,t} + \sum_{i \in S_r} SR_{i,t} \geq RUR_{r,t} + SRR_{r,t} \\ \sum_{i \in S_r} RU_{i,t} + \sum_{i \in S_r} SR_{i,t} + \sum_{i \in S_r} NR_{i,t} \geq RUR_{r,t} + SRR_{r,t} + NRR_{r,t}\end{array}\right\}, \forall r \wedge t = 1,2, \ldots, T_D$$

Where the regions are nested under the system region and the regional requirements are the minimum requirements for the region. Cascaded procurement is employed where higher quality services can meet the requirements for lower quality services. FRU/FRD do not overlap or cascade with capacity ancillary services because they are reserved capacity that can be dispatched or re-procured in real time irrespective of regulation or contingency response needs. The ancillary services and FRU/FRD awards in each region below the system are also constrained by regional deliverability constraints, described in §3.9.

The procurement of Corrective Capacity (CC) is locational through corrective contingency constraints using the Contingency Modeling Enhancements (CME) methodology.

3.7 FLEXIBLE RAMP PROCUREMENT CONSTRAINTS

The system-wide FRU/FRD procurement constraints are as follows:

$$\left.\begin{array}{r}\sum_{i} FRU_{i,t} \geq FRUR_t = FRUR_{0,t} \\ \sum_{i} FRD_{i,t} \geq FRDR_t = FRDR_{0,t}\end{array}\right\}, t = 1,2, \ldots, T_D$$

Where the FRU/FRD uncertainty requirements for the system region (r = 0) can be derived as an upper/lower percentile of the historical error in the net demand forecast between the DAME and the FMM. Unlike the nested regional procurement of capacity ancillary services, described in §0, instead of a similar regional FRU/FRD procurement, the regional deliverability constraints described in §3.9 are used without any minimum FRU/FRD requirements in each region below the system.

3.8 ANCILLARY SERVICES AND FLEXIBLE RAMP BOUNDS

The ancillary services and FRU/FRD upper/lower bound constraints are as follows:

$$\left.\begin{array}{c} 0 \leq RD_{i,t} \leq RDC_{i,t} \\ 0 \leq RU_{i,t} \leq RUC_{i,t} \\ 0 \leq SR_{i,t} \leq SRC_{i,t} \\ 0 \leq NR_{i,t} \leq NRC_{i,t} \\ 0 \leq FRU_{i,t} \\ 0 \leq FRD_{i,t} \end{array}\right\}, \forall i \wedge t = 1,2,\dots,T_D$$

Where the ancillary services capacity bids are limited by the corresponding certified quantities. There are no explicit upper bounds for FRU/FRD since there is no associated capacity bid for them, i.e., all available capacity under the energy bid above/below the energy schedule can be procured as FRU/FRD, except for non-participating load, hourly intertie resources, and hourly PDR and RDRR, which are not eligible for FRU/FRD. Similarly, there are no upper bounds for Corrective Capacity. The ancillary services and FRU/FRD awards are further constrained by ramp and capacity constraints, described in §0 and §3.12, respectively.

3.9 TIME DOMAIN CONSTRAINTS

The ancillary services time domain constraints for online resources are as follows:

$$\left.\begin{array}{l} RD_{i,t} \leq RRD_i(EN_{i,t}, T_{10}) \\ RU_{i,t} + SR_{i,t} + NR_{i,t} \leq RRU_i(EN_{i,t}, T_{10}) \end{array}\right\}, \forall i \wedge u_{i,t} = 1 \wedge t = 1,2,\dots,T_D$$

Where all upward ancillary services awards are simultaneously constrained by the 10min upward ramp capability from the energy schedule.

The time domain constraint for offline Non-Spinning Reserve is as follows:

$$NR_{i,t} \leq LOL_{i,t} + RRU_i(LOL_{i,t}, T_{10} - SUT_{i,t}), \forall i \in S_{10} \wedge u_{i,t} = 0 \wedge t = 1,2,\dots,T_D$$

Where the ramp up from LOL starts after the SUT has elapsed.

The flexible ramp time domain constraints for online resources are as follows:

$$\left.\begin{array}{l} FRD_{i,t} \leq RRD_i(EN_{i,t}, T_{15}) \\ FRU_{i,t} \leq RRU_i(EN_{i,t}, T_{15}) \end{array}\right\}, \forall i \wedge u_{i,t} = 1 \wedge t = 1,2,\dots,T_D$$

The time domain constraint for offline FRU is as follows:

$$FRU_{i,t} \leq LOL_{i,t} + RRU_i(LOL_{i,t}, T_{15} - SUT_{i,t}), \forall i \in S_{15} \wedge u_{i,t} = 0 \wedge t = 1,2,\dots,T_D$$

Where the ramp up from LOL starts after the SUT has elapsed.

3.10 NETWORK CONSTRAINTS

The linearized physical network constraints at an AC power flow solution are as follows:

$$LFL_{k,t} \le F_{k,t} \cong \tilde{F}_{k,t} + \sum_i \Delta EN_{i,t}\, SF_{i,k,t} + \sum_j \Delta EN_{j,t}\, SF_{j,k,t} - \sum_i \Delta L_{i,t}\, SF_{i,k,t} - \sum_j \Delta L_{j,t}\, SF_{j,k,t} \le UFL_{k,t}, \forall k \wedge\ t = 1,2,\ldots,T_D$$

Where the incremental energy injections are multiplied by the corresponding shift factor for the relevant network constraint to account for changes in the active power flow from the AC power flow solution. Additional nodal constraints limit virtual and physical energy schedules when the power flow solution reverts to DC. These constraints are also formulated for the reliability energy schedules.

The FRU/FRD awards from intertie resources associated with Intertie Transmission Corridor (ITC) or Intertie Scheduling Limit (ISL) constraints are limited by these constraints along with all other relevant commodities. The ITC/ISL constraint formulation allows netting of import and export energy schedules, but it prevents netting among energy schedules, ancillary services awards, and FRU/FRD awards because they are not simultaneously dispatched:

$$\left.\begin{array}{l} \max\left(0, \sum_{i\in S_k} EN_{i,t}\right) + \sum_{i\in I_k}\left(RU_{i,t} + SR_{i,t} + NR_{i,t}\right) + \sum_{i\in S_k} FRU_{i,t} \le UFL_{k,t} \\ LFL_{k,t} \le \min\left(0, \sum_{i\in S_k} EN_{i,t}\right) - \sum_{i\in I_k} RD_{i,t} - \sum_{i\in S_k} FRD_{i,t} \end{array}\right\}, \forall k \wedge t = 1,\ldots,T_D$$

The ITC/ISL constraints are linearized as follows:

$$\left.\begin{array}{l} \sum_{i\in S_k} EN_{i,t} + \sum_{i\in I_k}\left(RU_{i,t} + SR_{i,t} + NR_{i,t}\right) + \sum_{i\in S_k} FRU_{i,t} \le UFL_{k,t} \\ \sum_{i\in I_k}\left(RU_{i,t} + SR_{i,t} + NR_{i,t}\right) + \sum_{i\in S_k} FRU_{i,t} \le UFL_{k,t} \\ LFL_{k,t} \le \sum_{i\in S_k} EN_{i,t} - \sum_{i\in I_k} RD_{i,t} - \sum_{i\in S_k} FRD_{i,t} \\ LFL_{k,t} \le -\sum_{i\in I_k} RD_{i,t} - \sum_{i\in S_k} FRD_{i,t} \end{array}\right\}, \forall k \wedge t = 1,\ldots,T_D$$

Where in the case of ITC constraints, the set S_k includes all intertie resources bound by the ITC k, and in the case of ISL constraints, the set S_k includes all intertie resources associated with (tagged at) the corresponding intertie of the ISL k. For ITC/ISL constraints, the upper limit is an import limit, whereas the lower limit is an algebraic export limit. By convention, the import direction in ITC constraints is into the associated BAA, and the import direction in ISL constraints is into the "from" BAA of the associated intertie. Virtual bids are not allowed on intertie resources and capacity ancillary services can only be provided by certified import resources, whereas FRU/FRD can be provided by both import and export resources, except for hourly intertie resources. For an export or a demand response resource, FRU dispatch is a decrease in the energy schedule, whereas FRD dispatch is an increase in the energy schedule. These constraints are also formulated for the reliability energy schedules.

To prevent procuring ancillary services and FRU/FRD awards in regions below the system in excess of the N–1 simultaneous export/import transfer capability of these regions, the energy schedules, ancillary services, and FRU/FRD awards in each region below the system are constrained by regional deliverability constraints. These constraints reserve transmission capacity on the regional transmission interface for reliability energy and capacity exports and imports out of and into the region, as follows:

$$\left.\begin{array}{l} \max\left(0, \sum_{i\in S_r} REN_{i,t} - D_{r,t}\right) + \max\left(0, \sum_{i\in S_r} ASU_{i,t} - ASUR_{r,t}\right) + \\ \max\left(0, \sum_{i\in S_r} FRU_{i,t} - FRUR_{r,t}, FRDR_{r,t} - \sum_{i\in S_r} FRD_{i,t}\right) \le NEL_{r,t} \\ \max\left(0, D_{r,t} - \sum_{i\in S_r} REN_{i,t}\right) + \max\left(0, \sum_{i\in S_r} RD_{i,t} - RDR_{r,t}\right) + \\ \max\left(0, \sum_{i\in S_r} FRD_{i,t} - FRDR_{r,t}, FRUR_{r,t} - \sum_{i\in S_r} FRU_{i,t}\right) \le NIL_{r,t} \end{array}\right\}, \forall r > 0 \wedge t = 1, \ldots, T_D$$

Where the upward ancillary services are bundled together because of their cascaded procurement:

$$ASU_{i,t} = RU_{i,t} + SR_{i,t} + NR_{i,t}, \forall i \wedge t = 1,2, \ldots, T_D$$

$$ASUR_{r,t} = RUR_{r,t} + SRR_{r,t} + NRR_{r,t}, \forall r \wedge t = 1,2, \ldots, T_D$$

The FRU/FRD uncertainty requirements for a region can be derived as an upper/lower percentile of the historical error in the net demand forecast of the region between the DAME and the FMM, or as a load ratio share of the system uncertainty requirements. The nested regional deliverability constraints permit a flexible procurement of FRU/FRD where there is no minimum regional requirement, unlike the procurement of capacity ancillary services; however, transmission capacity is reserved as needed on the regional transmission interface to import FRU/FRD to satisfy the regional requirement or to export surplus FRU/FRD in excess of the regional requirement. This approach results in the most efficient overall procurement of FRU/FRD. The approach can also be applied to ancillary services by removing the minimum ancillary services regional requirements and adding one additional term for ancillary services imports into the region.

When such a regional constraint is binding in the optimal solution, its shadow price will affect the marginal prices of all market commodities in the region, namely the reliability energy, capacity ancillary services, and flexible ramp.

The max terms in the regional deliverability constraints allow energy schedules in opposite directions to net, but they prevent netting of capacity awards with energy schedules. FRU awards are not dispatched simultaneously with FRD awards in a region because either positive or negative uncertainty may materialize, but not both; therefore, the higher of FRU exports or FRD imports needs to be reserved in the export direction, and the higher of FRD exports or FRU imports needs to be reserved in the import direction.

The max terms in the regional deliverability constraints must be linearized in the MILP optimization engine. An upper bound constraint on a sum of positive differences is linearized by formulating the constraint in all possible combinations where the positive differences can take a positive value. For example, for two positive difference terms:

$$\max(0, a) + \max(0, b) \leq c \geq 0 \Leftrightarrow \begin{cases} a \leq c \\ b \leq c \\ a + b \leq c \end{cases}$$

Furthermore, an upper bound constraint on a max function with multiple terms is linearized by formulating the constraint for all terms, as follows:

$$\max(0, a, b) \leq c \geq 0 \Leftrightarrow \begin{cases} a \leq c \\ b \leq c \end{cases}$$

Therefore, the regional deliverability constraints will result in 9 linear constraints per direction, per region, per interval; nevertheless, only the critical constraints are enforced in a MILP solver.

3.11 SHARED RAMPING CONSTRAINTS

All resource commodities, i.e., energy, ancillary services, and FRU/FRD, are simultaneously constrained by the shared ramping constraints. For resources that remain online across time intervals, the shared ramping constraints are as follows:

$$\left.\begin{array}{l} EN_{i,t} - EN_{i,t-1} \geq -RRD_i\left(EN_{i,t-1}, T_{60}\right) + \alpha_t \dfrac{RD_{i,t-1} + RD_{i,t}}{2} + \delta_t\, FRD_{i,t} \\ EN_{i,t} - EN_{i,t-1} \leq RRU_i\left(EN_{i,t-1}, T_{60}\right) - \alpha_t \dfrac{RU_{i,t-1} + RU_{i,t}}{2} - \\ \qquad \beta_t \dfrac{SR_{i,t-1} + SR_{i,t}}{2} - \gamma_t \dfrac{NR_{i,t-1} + NR_{i,t}}{2} - \delta_t\, FRU_{i,t} \end{array}\right\},$$
$$\forall i \wedge u_{i,t-1} = u_{i,t} = 1 \wedge t = 1,2,\ldots,T_D$$

For resources that start up, the shared ramping constraints are as follows:

$$EN_{i,t} \leq LOL_{i,t} + RRU_i\left(LOL_{i,t}, T_{60}/2\right) - \alpha_t \frac{RU_{i,t}}{2} - \beta_t \frac{SR_{i,t}}{2} - \gamma_t \frac{NR_{i,t}}{2} - \delta_t \frac{FRU_{i,t}}{2},$$
$$\forall i \wedge u_{i,t-1} = 0 \wedge u_{i,t} = 1 \wedge t = 1,2,\ldots,T_D$$

Where half of the interval ramp is used to ramp up from LOL.

For resources that shut down, the shared ramping constraints are as follows:

$$EN_{i,t} \leq LOL_{i,t} + RRU_i\left(LOL_{i,t}, T_{60}/2\right) - \alpha_t \frac{RD_{i,t}}{2} - \delta_t \frac{FRD_{i,t}}{2}\Big\},$$

$$\forall i \wedge u_{i,t} = 1 \wedge u_{i,t+1} = 0 \wedge t = 1,2,\dots,T_D$$

Where half of the interval ramp is used to ramp down to LOL.

These constraints are also formulated for the reliability energy schedules.

For resources that remain offline across time intervals, the shared ramping constraints are as follows:

$$\gamma_t \frac{NR_{i,t}}{2} + \delta_t \frac{FRU_{i,t}}{2} \leq LOL_{i,t} + RRU_i\left(LOL_{i,t}, T_{15} - SUT_{i,t}\right),$$
$$\forall i \in S_{15} \wedge u_{i,t-1} = u_{i,t} = 0 \wedge t = 1,2,\dots,T_D$$

Where the ramp up from the LOL starts after the SUT has elapsed.

The shared ramping coefficients specify how the various commodities share the resource ramp capability. The shared ramping constraint reserves ramp capability for the ancillary services and FRU/FRD awards over the ramp between the time interval midpoints or the half ramp after startup or before shutdown; ancillary services awards may differ during that ramp, whereas FRU/FRD awards align exactly with that ramp. A coefficient of one reserves all the ramp capability that is required for a service that is continuously dispatched concurrently with energy, such as Regulation and FRU/FRD, whereas smaller coefficients may be used to reserve ramp capability for contingency reserves.

3.12 RESOURCE CAPACITY CONSTRAINTS

This section describes the resource capacity constraints. In the DAM, an energy bid is required for energy schedules and FRU/FRD, but not for Regulation or Spinning and Non-Spinning Reserve awards. Therefore, energy schedules and FRU/FRD are limited by the LEL/UEL, whereas Regulation and Spinning/Non-Spinning Reserve awards are limited by the CL and the LOL/UOL, or the LRL/URL if there are Regulation awards. To formulate the resource capacity constraints generally for all cases, it is convenient to define upper and lower capacity limits as follows:

$$\left.\begin{array}{l}
RU_{i,t} + RD_{i,t} > 0 \rightarrow \begin{cases} UOL'_{i,t} = \min\left(UOL_{i,t}, URL_{i,t}, CL_{i,t}\right) \\ LOL'_{i,t} = \max\left(LOL_{i,t}, LRL_{i,t}\right) \end{cases} \\
\left.\begin{array}{l} RU_{i,t} + RD_{i,t} = 0 \\ SR_{i,t} + NR_{i,t} > 0 \end{array}\right\} \rightarrow \begin{cases} UOL'_{i,t} = \min\left(UOL_{i,t}, CL_{i,t}\right) \\ LOL'_{i,t} = LOL_{i,t} \end{cases} \\
RU_{i,t} + RD_{i,t} + SR_{i,t} + NR_{i,t} = 0 \rightarrow \begin{cases} UOL'_{i,t} = UOL_{i,t} \\ LOL'_{i,t} = LOL_{i,t} \end{cases}
\end{array}\right\}, \forall i \wedge t = 1,2,\dots,T_D$$

$$\left.\begin{array}{l}
UEL'_{i,t} = \min\left(UOL'_{i,t}, UEL_{i,t}\right) \\
LEL'_{i,t} = \left(1 - \eta_{i,t}\right) \max\left(LOL'_{i,t}, LEL_{i,t}\right)
\end{array}\right\}, \forall i \wedge t = 1,2,\dots,T_D$$

Where zero is used instead of the LEL if the resource can be shut down, which is possible when there is no energy self-schedule (LEL is equal to LOL), no online ancillary services, and the inter-temporal constraints allow it. In this case, the FRD can span the LOL.

Then, the capacity constraints for online resources are as follows:

$$\left.\begin{array}{l} EN_{i,t} \leq UOL'_{i,t} - RU_{i,t} - SR_{i,t} - NR_{i,t} - FRU_{i,t} \\ LOL'_{i,t} + RD_{i,t} + FRD_{i,t} \leq EN_{i,t} \\ LEL'_{i,t} + FRD_{i,t} \leq EN_{i,t} \leq UEL'_{i,t} - FRU_{i,t} \end{array}\right\}, \forall i \wedge u_{i,t} = 1 \wedge t = 1,2, \dots, T_D$$

These constraints are also formulated for the reliability energy schedules.

Similarly, the capacity constraints for offline resources are as follows:

$$NR_{i,t} \leq UOL'_{i,t}, \forall i \in S_{10} \wedge u_{i,t} = 0 \wedge t = 1,2, \dots, T_D$$

$$\left.\begin{array}{l} NR_{i,t} + FRU_{i,t} \leq UOL'_{i,t} \\ FRU_{i,t} \leq UEL'_{i,t} \end{array}\right\}, \forall i \in S_{15} \wedge u_{i,t} = 0 \wedge t = 1,2, \dots, T_D$$

4 PRICE FORMATION AND SETTLEMENT

This section presents the price formation for day-ahead energy, reliability energy, and FRU/FRD in the DAME. Ignoring marginal transmission loss and congestion contributions, the marginal prices for these commodities for each interval in the Trading Day are derived from the shadow prices of the four constraints used to achieve the DAME targets:

$$\sum_i EN_{i,t} + \sum_j EN_{j,t} - \sum_i L_{i,t} - \sum_j L_{j,t} = 0 \quad \lambda_t$$

$$\sum_i REN_{i,t} = D_t \quad \xi_t$$

$$\sum_i FRU_{i,t} \geq FRUR_t \quad \rho_t$$

$$\sum_i FRD_{i,t} \geq FRDR_t \quad \sigma_t$$

Where the marginal reliability energy price (ξ) is a capacity price driven by the capacity costs of RCU/RCD, which are the same as the FRU/FRD bids, and not by the energy bids. By observation, the marginal prices for day-ahead energy, reliability energy, and FRU/FRD are as follows:

$EN_{i,t}, EN_{j,t}$	λ_t
$L_{i,t}, L_{j,t}$	$-\lambda_t$
$REN_{i,t}$	ξ_t
$FRU_{i,t}$	ρ_t
$FRD_{i,t}$	σ_t

These prices receive locational and regional adjustments for marginal transmission loss and marginal transmission congestion for binding network constraints, including the regional deliverability constraints described in §3.9.

The settlement for Reliability Energy can be expressed as follows:

$$\sum_i REN_{i,t}\,\xi_{i,t} = \sum_i \left(EN_{i,t} + RCU_{i,t} - RCD_{i,t}\right)\xi_{i,t}$$

Where ξ can be viewed as the marginal price for RCU/RCD. For a given resource and interval, either RCU or RCD may take value, but not both. The day-ahead energy schedule for physical resources is paid that marginal price because the associated capacity contributes in meeting the demand forecast. RCU is also paid that price for the same reason, whereas RCD is charged that price because the capacity associated with the day-ahead energy schedule should be reduced to meet the demand forecast.

The day-ahead energy settlement is revenue neutral, except for marginal transmission loss over-collection and congestion revenue, which can be allocated using existing allocation methods. There would not be a Congestion Revenue Right (CRR) hedge for ancillary services and FRU/FRD award price differences across congested regional interfaces because the CRR model does not include capacity products. Furthermore, the CRR model would not include regional reliability energy constraints because the regional deliverability constraints are formulated for reliability energy and not for day-ahead energy; the reliability energy is essentially a capacity product.

The cost for the reliability energy and the FRU/FRD awards would be allocated using a system-wide cost allocation method analogous to the existing RUC cost allocation, as follows:

Cost	Cost Allocation	
	Tier 1	Tier 2
FRU Cost	In proportion to net negative demand deviation plus net virtual supply, if system virtual supply exceeds system virtual demand, up to an average FRU cost rate	Remaining cost in proportion to metered demand
FRD Cost	In proportion to net positive demand deviation plus net virtual demand, if system virtual demand exceeds system virtual supply, up to an average FRD cost rate	Remaining cost in proportion to metered demand
REN Cost	In proportion to net negative demand deviation plus net virtual supply, if system virtual supply exceeds system virtual demand, up to an average REN cost rate	Remaining cost in proportion to metered demand

No Pay charges for FRU/FRD awards and reliability energy schedules that are unavailable in FMM, must be subtracted from the FRU/FRD and the reliability energy cost, respectively, prior to the cost allocation. Therefore, the FRU/FRD/REN system cost for allocation is calculated as follows:

$$\left.\begin{aligned} FRUC_t &= \sum_i (FRU_{i,t} - FRUNP_{i,t})\,\rho_{i,t} \\ FRDC_t &= \sum_i (FRD_{i,t} - FRDNP_{i,t})\,\sigma_{i,t} \\ RENC_t &= \sum_i (REN_{i,t} - RENNP_{i,t})\,\xi_{i,t} \end{aligned}\right\} t = 1,2,\dots,T_D$$

Then, the average FRU/FRD/REN cost rate is derived as follows:

$$\left.\begin{aligned} \bar{\rho}_t &= \frac{FRUC_t}{\sum_i (FRU_{i,t} - FRUNP_{i,t})} \\ \bar{\sigma}_t &= \frac{FRDC_t}{\sum_i (FRD_{i,t} - FRDNP_{i,t})} \\ \bar{\xi}_t &= \frac{RENC_t}{\sum_i (REN_{i,t} - RENNP_{i,t})} \end{aligned}\right\} t = 1,2,\dots,T_D$$

The demand deviation for a non-participating load resource is calculated as the difference between the hourly day-ahead energy schedule and the hourly meter. Therefore, the billing determinants for FRU/FRD/REN tier-1 cost allocation to Scheduling Coordinators are calculated as follows:

$$\left.\begin{aligned} FRUCD_{s,t} &= \max\left(0, \sum_{i \in S_s} (ML_{i,t} - L_{i,t})\right) + \frac{\max\left(0, \sum_{j \in S_s} (EN_{j,t} - L_{j,t})\right)}{\sum_s \max\left(0, \sum_{j \in S_s} (EN_{j,t} - L_{j,t})\right)} \max\left(0, \sum_j (EN_{j,t} - L_{j,t})\right) \\ FRDCD_{s,t} &= \max\left(0, \sum_{i \in S_s} (L_{i,t} - ML_{i,t})\right) + \frac{\max\left(0, \sum_{j \in S_s} (L_{j,t} - EN_{j,t})\right)}{\sum_s \max\left(0, \sum_{j \in S_s} (L_{j,t} - EN_{j,t})\right)} \max\left(0, \sum_j (L_{j,t} - EN_{j,t})\right) \\ RENCD_{s,t} &= FRUCD_{s,t} \end{aligned}\right\},$$

$\forall s, t = 1,2,\dots,T_D$

Then, the FRU/FRD/REN tier-1 cost allocation to Scheduling Coordinators is calculated as follows:

$$\left.\begin{aligned} FRUC_{s,t}^{(1)} &= \min\left(FRUCD_{s,t}\,\bar{\rho}_t, \frac{FRUCD_{s,t}}{\sum_s FRUCD_{s,t}}\,FRUC_t\right) \\ FRDC_{s,t}^{(1)} &= \min\left(FRDCD_{s,t}\,\bar{\sigma}_t, \frac{FRDCD_{s,t}}{\sum_s FRDCD_{s,t}}\,FRDC_t\right) \\ RENC_{s,t}^{(1)} &= \min\left(RENCD_{s,t}\,\bar{\xi}_t, \frac{RENCD_{s,t}}{\sum_s RENCD_{s,t}}\,RENC_t\right) \end{aligned}\right\}, \forall s, t = 1,2,\dots,T_D$$

Subsequently, the FRU/FRD/REN tier-2 cost allocation to Scheduling Coordinators is calculated as follows:

$$\left.\begin{aligned} FRUC_{s,t}^{(2)} &= \frac{\sum_{i \in S_s} ML_{i,t}}{\sum_i ML_{i,t}} \left(FRUC_t - \sum_s FRUC_{s,t}^{(1)} \right) \\ FRDC_{s,t}^{(2)} &= \frac{\sum_{i \in S_s} ML_{i,t}}{\sum_i ML_{i,t}} \left(FRDC_t - \sum_s FRDC_{s,t}^{(1)} \right) \\ RENC_{s,t}^{(2)} &= \frac{\sum_{i \in S_s} ML_{i,t}}{\sum_i ML_{i,t}} \left(RENC_t - \sum_s RENC_{s,t}^{(1)} \right) \end{aligned}\right\}, \forall s, t = 1,2, \dots, T_D$$