Day-Ahead Market Enhancements

Appendix C:
Draft Technical Description

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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, Reliability Capacity Up (RCU) and Reliability Capacity Down (RCD). For a physical resource, the Day-Ahead Energy schedule plus the RCU award, minus the RCD award, 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. The net demand is the difference between the demand and the Variable Energy Resource (VER) production. To address the granularity difference between the DAME and the FMM, the FRU/FRD requirements for a given hour are calculated as the extreme historical net demand forecast error between the four 15min intervals of that hour in the FMM and the net demand forecast in the DAME, within a specified confidence interval. Furthermore, the hourly FRU/FRD requirements are adjusted to reflect forecasted conditions for the Trading Day.

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;
- Reliability Energy schedules for physical resources; the difference between the reliability energy schedule and the day-ahead energy schedule is the Reliability Capacity Up or Down award.
- 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;
- Day-Ahead Flexible Ramp Up and Down awards for physical resources;
- Day-ahead post-corrective transmission contingency day-ahead energy and reliability energy schedules for physical resources;[1] the difference between the post-corrective

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

contingency energy schedule and the base-case energy schedule is the Corrective Capacity Up (CCU) or Corrective Capacity Down (CCD) award.

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) 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 ancillary services (regulation, mileage, spinning and non-spinning reserve) awards cost;
    - the minimization of RCU/RCD awards cost;
    - the minimization of FRU/FRD awards cost; and
    - the minimization of CCU/CCD 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 100% of the uncertainty requirements without demand elasticity.

- Ancillary services are procured regionally with nested regions under the system region to satisfy minimum requirements for each region. The procurement of FRU/FRD is locational through the FRU/FRD deployment scenarios. The procurement of corrective capacity is locational through corrective transmission contingency constraints.
- All resource constraints are enforced:
  - unit commitment and state transition inter-temporal constraints;
  - ramp capability constraints;
  - capacity constraints; and
  - energy constraints.
- All network 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;
  - FRU/FRD deployment scenarios;
  - transmission and generation nomograms, including gas-burn constraints; and
  - Minimum Online Capacity (MOC) constraints.

  Aside from MOC, which are unit commitment constraints, all network constraints are formulated for both day-ahead energy and reliability energy schedules.
- 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 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 counter flow 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 RCU/RCD, FRU/FRD, and CCU/CCD 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 apply in general to the Security Constrained Unit Commitment (SCUC) engine, such as unit commitment inter-temporal constraints, MSG modeling, block energy scheduling, nomograms, and soft constraint penalty relaxation or scarcity treatment, are not included for simplicity. These features do not materially affect the integration of IFM and RUC, or the procurement of FRU/FRD, RCU/RCD, and CCU/CCD in DAME.

3.1 NOTATION

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

i, j	Resource/node index.
r	Ancillary services region index (zero for system).
s	Scheduling Coordinator (SC) index.
m	Network constraint index.
k	Preventive contingency index.
c	Corrective transmission contingency index (0 for base case).
g	Generation contingency index.
i_g	Node index for the generator outage of generation contingency g.
n	Gas-burn nomogram index.
o	Minimum Online Commitment constraint index.
t	Time period index (0 for initial condition).
$^{(r)}$	Superscript denoting reliability energy values.
$^{(k)}$	Superscript denoting preventive post-contingency values.
$^{(c)}$	Superscript denoting corrective transmission post-contingency values.
$^{(g)}$	Superscript denoting generation post-contingency values.
$^{(u)}$	Superscript denoting Flexible Ramp Up deployment scenario values.
$^{(d)}$	Superscript denoting Flexible Ramp Down deployment scenario values.
T_{10}	Capacity Ancillary Services time domain (10min).
T_{15}	Flexible Ramp time domain (15min).
T_{20}	Corrective transmission contingency time domain (20min).

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

T_{30}	Sustained energy time period for contingency reserve dispatch (30min).
T_{60}	Time period duration (60min).
GAF	Granularity adjustment factor ($GAF = T_{15}/T_{60} = 1/4$).
T	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…
$\therefore$	For…
$\in$	Member of…
$\notin$	Not member of…
$\wedge$	Logical and…
$\cup$	Union…
$\rightarrow$	Leads to…
Δ	Denotes incremental values.
∂	Partial derivative operator.
$\tilde{}$	Accent denoting initial values from an AC power flow solution.
$'$	Prime denotes adjusted quantities, e.g., settlement quantities adjusted for No Pay.
S_r	Set of resources in Region r.
$S_{f,t}$	Set of online frequency-responsive resources in time period t.
S_n	Set of resources bound by gas-burn nomogram n.
S_o	Set of resources bound by Minimum Online Commitment constraint o.
S_s	Set of resources of Scheduling Coordinator s.
S_{10}	Set of Fast-Start Units ($SUT \leq$ 10min) that can be certified to provide Non-Spinning Reserve from offline status ($u = 0$).
S_{15}	Set of 15min-start units ($SUT \leq$ 15min) that can provide FRU from offline status ($u = 0$).
S_{20}	Set of 20min-start units ($SUT \leq$ 20min) that can provide corrective capacity from offline status ($u = 0$).
I_m	Set of import resources associated with ITC/ISL m.
E_m	Set of export resources associated with ITC/ISL m.
S_m	Set of intertie resources associated with ITC/ISL m; $S_m = I_m \cup E_m$.
S_{PSH}	Set of Pumped-Storage Hydro Resources.
S_{LESR}	Set of Limited Energy Storage Resources.
$u_{i,t}$	Binary (0/1) variable indicating commitment status (offline/online) for Resource i in time period t. For Pumped-Storage Hydro Resources, 1 indicates generating mode operation. For Limited Energy Storage Resources, 1 indicates discharging mode operation.
$v_{i,t}$	Binary (0/1) variable for Pumped-Storage Hydro Resources indicating pumping mode operation.
$y_{i,t}$	Binary (0/1) variable indicating that Resource i has a start-up in time period t.
$w_{i,g,t}$	Binary (0/1) variable identifying the node index for the generator outage of generation contingency g in time period t.
a_i	Energy-to-gas conversion factor for resource i.

$b_{i,o}$	Effectiveness factor of resource *i* in Minimum Online Commitment constraint *o*.
η_i	Pumping efficiency of Pumped-Storage Hydro Resource *i*, or charging efficiency of Limited Energy Storage Resource *i*.
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 $UOL_{i,t}$; it is used to limit ancillary services awards .
$LCL_{i,t}$	Lower Capacity Limit of Resource *i* in time period *t*.
$UCL_{i,t}$	Upper Capacity Limit of Resource *i* in time period *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*.
$PC_{i,t}$	Pumping cost for Pumped Storage Hydro Resource *i* in time period *t*.
$PL_{i,t}$	Pumping level for Pumped Storage Hydro 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).
$VS_{i,t}$	Day-Ahead Energy schedule of Virtual Supply Resource *i* in time period *t*.
$VD_{i,t}$	Day-Ahead Energy schedule of Virtual Demand Resource *i* in time period *t*.
$REN_{i,t}$	Reliability Energy schedule of Resource *i* in time period *t*; positive for supply (generation and imports) and negative for demand (demand response and exports).
$L_{i,t}$	Day-Ahead Energy schedule of Non-Participating Load Resource *i* in time period *t*.
D_t	Demand forecast in time period *t*.
$RCU_{i,t}$	Reliability Capacity Up award of Resource *i* in time period *t*.
$RCD_{i,t}$	Reliability Capacity Down award of Resource *i* 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*.
$RU_{i,t}$	Regulation Up award of Resource *i* in time period *t*.
$RD_{i,t}$	Regulation Down award of Resource *i* 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*.

$CCU_{i,t}^{(c)}$	Corrective Capacity Up award of Resource *i* in time period t for corrective transmission contingency *c*.
$CCD_{i,t}^{(c)}$	Corrective Capacity Down award of Resource *i* in time period *t* for corrective transmission contingency *c*.
$CCU_{i,t}$	Maximum of all Corrective Capacity Up awards of Resource *i* in time period *t* for all corrective transmission contingencies.
$CCD_{i,t}$	Maximum of all Corrective Capacity Down awards of Resource *i* in time period *t* for all corrective transmission contingencies.
$RCUBC_{i,t}$	Reliability Capacity Up bid capacity of Resource *i* in time period *t*.
$RCDBC_{i,t}$	Reliability Capacity Down bid capacity of Resource *i* in time period *t*.
$FRUBC_{i,t}$	Flexible Ramp Up bid capacity of Resource *i* in time period *t*.
$FRDBC_{i,t}$	Flexible Ramp Down bid capacity of Resource *i* in time period *t*.
$RUBC_{i,t}$	Regulation Up bid capacity of Resource *i* in time period *t*.
$RDBC_{i,t}$	Regulation Down bid capacity of Resource *i* in time period *t*.
$SRBC_{i,t}$	Spinning Reserve bid capacity of Resource *i* in time period *t*.
$NRBC_{i,t}$	Non-Spinning Reserve bid capacity of Resource *i* in time period *t*.
$CCUBC_{i,t}$	Corrective Capacity Up bid capacity of Resource *i* in time period *t* for all corrective transmission contingencies.
$CCDBC_{i,t}$	Corrective Capacity Down bid capacity of Resource *i* in time period *t* for all corrective transmission contingencies.
$ENBP_{i,t}$	Energy bid price of Resource *i* in time period *t*.
$VSBP_{i,t}$	Energy bid price of Virtual Supply Resource *i* in time period *t*.
$VDBP_{i,t}$	Energy bid price of Virtual Demand Resource *i* in time period *t*.
$LBP_{i,t}$	Energy bid price of Non-Participating Load Resource *i* in time period *t*.
$FRUBP_{i,t}$	Flexible Ramp Up bid price of Resource *i* in time period *t*.
$FRDBP_{i,t}$	Flexible Ramp Down bid price of Resource *i* in time period *t*.
$RCUBP_{i,t}$	Reliability Capacity Up bid price of Resource *i* in time period *t*.
$RCDBP_{i,t}$	Reliability Capacity Down bid price of Resource *i* in time period *t*.
$RUBP_{i,t}$	Regulation Up bid price of Resource *i* in time period *t*.
$RDBP_{i,t}$	Regulation Down bid price of Resource *i* in time period *t*.
$SRBP_{i}$	Spinning Reserve bid price of Resource *i* in time period *t*.
$NRBP_{i,t}$	Non-Spinning Reserve bid price of Resource *i* in time period *t*.
$CCUBP_{i,t}$	Corrective Capacity Up bid price of Resource *i* in time period *t* for all corrective transmission contingencies.
$CCDBP_{i,t}$	Corrective Capacity Down bid price of Resource *i* in time period *t* for all corrective transmission contingencies.
$FRUR_{t}$	Flexible Ramp Up uncertainty requirement in time period *t*.
$FRDR_{t}$	Flexible Ramp Down uncertainty requirement in 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*.

$RRU_i(p,\tau)$	Piecewise linear ramp up capability function of Resource *i* from energy schedule *p* for time domain τ.
$RRD_i(p,\tau)$	Piecewise linear ramp down capability function of Resource *i* from energy schedule *p* for time domain τ.
$\underline{RRU}_{i,t}(\tau)$	Lowest ramp up capability within the applicable operating range of Resource *i* in time period *t* for time domain τ.
$\underline{RRD}_{i,t}(\tau)$	Lowest ramp down capability within the applicable operating range of Resource *i* in time period *t* for time domain τ.
$Loss_t$	Transmission losses in time period *t*.
$LPF_{i,t}$	Day-Ahead Energy schedule loss penalty factor for Resource *i* in time period *t*.
$RLPF_{i,t}$	Reliability Energy schedule loss penalty factor for Resource *i* in time period *t*.
$SF_{i,m,t}$	Shift factor for the energy injection schedule of Resource *i* on network constraint *m* in time period *t*.
$GLDF_{i,t}^{(g)}$	Generation Loss Distribution Factor for Resource *i* in time period *t* for generation contingency *g*.
$\overline{SF}_{i,m,t}^{(g)}$	Aggregate shift factor for the energy injection schedule of Resource *i* on network constraint *m* in time period *t* that reflects the distribution of lost/tripped generation of generation contingency g.
$F_{m,t}$	Active power flow or scheduled flow due to energy schedules on network constraint *m* in time period *t*.
$RF_{m,t}$	Active power flow or scheduled flow due to reliability energy schedules on network constraint *m* in time period *t*.
$LFL_{m,t}$	Lower active power flow or scheduling limit (non-positive) on network constraint *m* in time period *t*.
$UFL_{m,t}$	Upper active power flow or scheduling limit on network constraint *m* in time period *t*.
$GL_{n,t}$	Gas limit for gas-burn nomogram *n* in time period *t*.
$MOC_{o,t}$	Minimum online capacity for Minimum Online Commitment constraint *o* in time period *t*.
α	Shared ramping coefficient for Regulation.
β	Shared ramping coefficient for Spinning Reserve.
γ	Shared ramping coefficient for Non-Spinning Reserve.
δ	Shared ramping coefficient for Flexible Ramp.
$\overline{EN}_i$	Daily Maximum Energy Limit for Resource *i*.
$\underline{EN}_i$	Daily Minimum Energy Limit for Resource *i*.
$SOC_{i,t}$	State of Charge for Limited Energy Storage Resource *i* in time period *t*.
$\overline{SOC}_{i,t}$	Maximum State of Charge for Limited Energy Storage Resource *i* in time period *t*.
$\underline{SOC}_{i,t}$	Minimum State of Charge for Limited Energy Storage Resource *i* 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 deployment scenario constraint in time period *t*.
σ_t	Shadow price of FRD deployment scenario in time period *t*.
$\mu_{m,t}$	Shadow price of network constraint *m* in time period *t*.
$ENMP_{i,t}$	Marginal Price for the Day-Ahead Energy schedule of Resource *i* in time period *t*.
$VSMP_{i,t}$	Marginal Price for the Day-Ahead Energy schedule of Virtual Supply Resource *i* in time period *t*.
$VDMP_{i,t}$	Marginal Price for the Day-Ahead Energy schedule of Virtual Demand Resource *i* in time period *t*.
$LMP_{i,t}$	Marginal Price for the Day-Ahead Energy schedule of Non-Participating Load Resource *i* in time period *t*.
$RENMP_{i,t}$	Marginal Price for the Reliability Energy schedule of Resource *i* in time period *t*.
$FRUMP_{i,t}$	Marginal Price for the Flexible Ramp Up award of Resource *i* in time period *t*.
$FRDMP_{i,t}$	Marginal Price for the Flexible Ramp Down award of Resource *i* in time period *t*.
ENS_t	Net of all settlement charges for Day-Ahead Energy schedules in time period *t*.
$RENS_t$	Net of all settlement charges for Reliability Energy schedules in time period *t*.
$FRUS_t$	Net of all settlement charges for Flexible Ramp Up awards in time period *t*.
$FRDS_t$	Net of all settlement charges for Flexible Ramp Down awards in time period *t*.
CCC_t	System Corrective Capacity cost in time period t.
$ENML_t$	Day-Ahead Energy marginal loss cost in time period *t*.
$ENMC_t$	Day-Ahead Energy marginal congestion revenue in time period *t*.
$RENMC_t$	Reliability Energy marginal congestion revenue in time period *t*.
$RCUMC_t$	Reliability Capacity Up marginal congestion revenue in time period *t*.
$RCDMC_t$	Reliability Capacity Down marginal congestion revenue in time period *t*.
$FRUMC_t$	Flexible Ramp Up deployment scenario marginal congestion revenue in time period *t*.
$FDRMC_t$	Flexible Ramp Down deployment scenario marginal congestion revenue in time period *t*.
$ENLO_t$	Day-Ahead Energy marginal loss over-collection in time period *t*.
ENC_t	System EN capacitive cost in time period *t*.
$RCUC_t$	System RCU cost in time period *t*.
$RCDC_t$	System RCD cost in time period *t*.
$FRUC_t$	System FRU cost in time period *t*.
$FRDC_t$	System FRD cost in time period *t*.
$CRRV_{i,j,t}$	Per unit CRR Obligation notional value from node *i* to node *j* in time period *t*.

$CRRO_{i,j,t}$	Per unit CRR Option notional value from node *i* to node *j* in time period *t*.
$\bar{\xi}_t$	Average RCU cost rate in time period *t*.
$\underline{\xi}_t$	Average RCD 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*.
$ENCD_{s,t}$	ENC cost billing determinant for SC *s* in time period *t*.
$RCUCD_{s,t}$	RCU cost billing determinant for SC *s* in time period *t*.
$RCDCD_{s,t}$	RCD 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*.
$RCUC_{s,t}^{(1)}$	RCU 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*.
$RCDC_{s,t}^{(2)}$	RCD 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*.
$ENC_{s,t}$	ENC allocation to SC *s* in time period *t*.
$CCC_{s,t}$	System Corrective Capacity 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:

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

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 and Figure 2 below show the two scenarios for the energy and flexible ramp up and down targets in a given time interval.

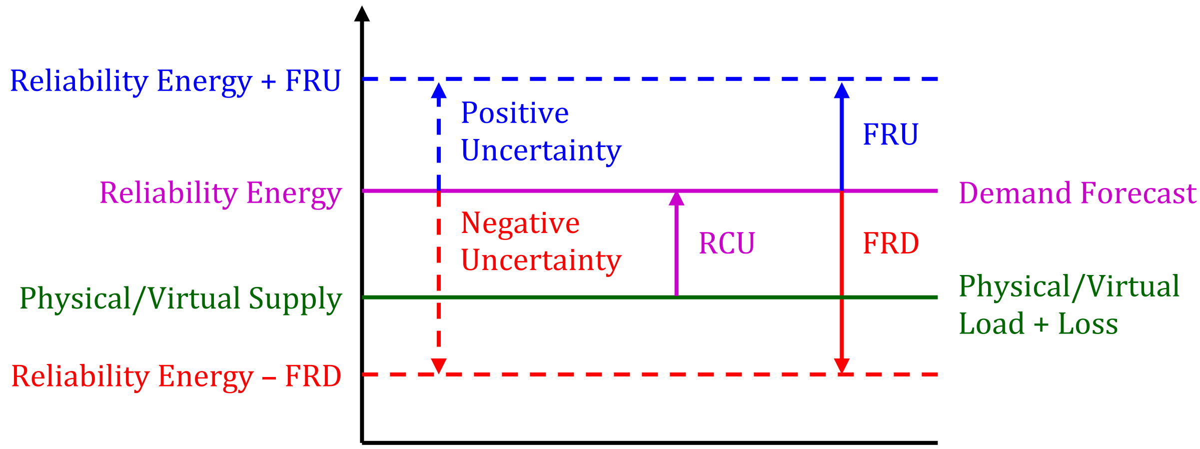

Figure 1. DAME targets when the energy clears below the demand forecast

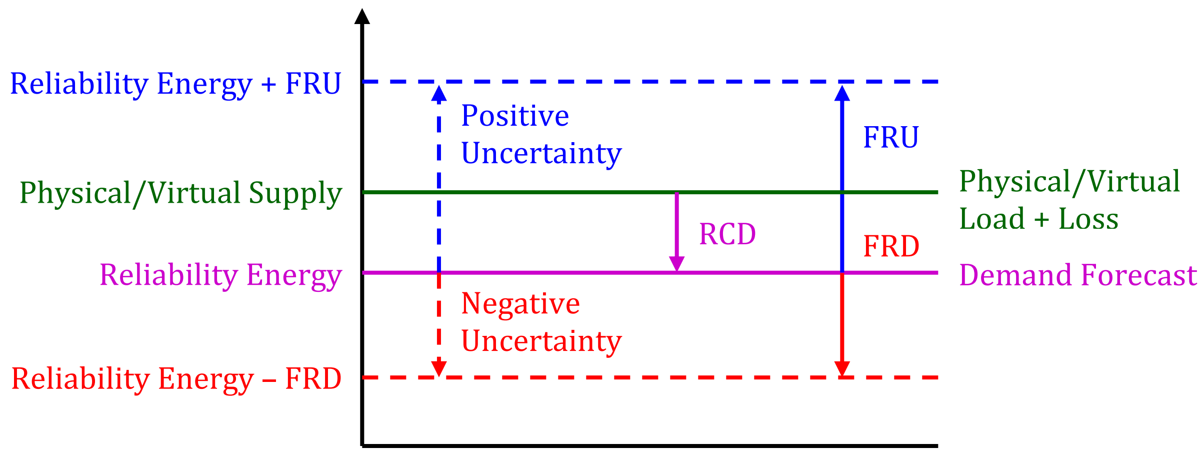

Figure 2. DAME targets when the energy clears above the demand forecast

Although the net system Reliability Capacity from all physical resources in the system is either positive (in the scenario shown in Figure 1) or negative (in the scenario shown in Figure 2), individual resources may have either a RCU or a RCD award in either scenario due to binding transmission constraints.

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

$$\left.\begin{array}{l} \sum_i EN_{i,t} + \sum_i VS_{i,t} = \sum_i L_{i,t} + \sum_i VD_{i,t} + Loss_t \\ \sum_i REN_{i,t} = \sum_i \left(EN_{i,t} + RCU_{i,t} - RCD_{i,t}\right) = D_t \\ \sum_i FRU_{i,t} \geq FRUR_t \\ \sum_i FRD_{i,t} \geq FRDR_t \end{array}\right\}, t = 1,2, \dots, T$$

FRU/FRD is ramping capacity between intervals reserved to meet uncertainty in the net demand forecast between the DAME and the FMM. Figure 3 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.

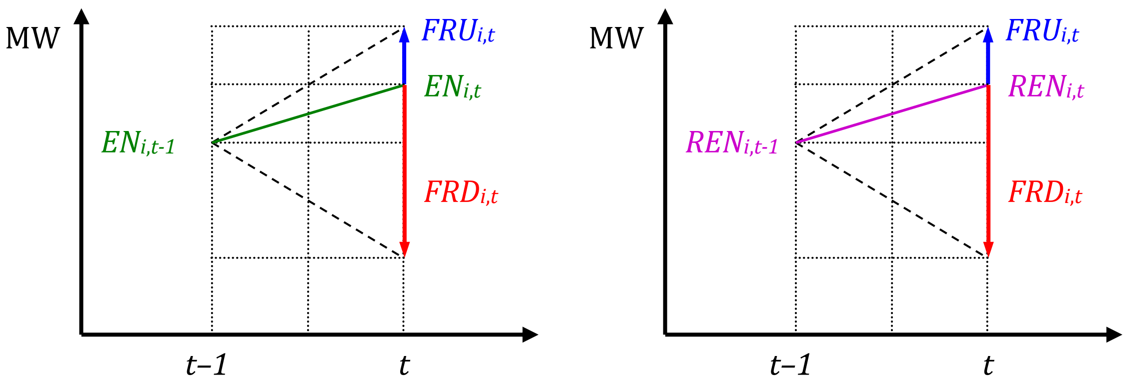

Figure 3. Energy schedules and flexible ramp up/down awards

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 that remains available to address any uncertainty that may materialize in FMM.

The day-ahead energy schedules, reliability 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 capability constraints:

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

The granularity adjustment factor (*GAF*) converts the hourly energy schedule ramp to the 15min time domain of FRU/FRD awards. Ramp capability and capacity constraints are formulated for both day-ahead energy and reliability energy schedules. These constraints are more complicated when considering ancillary services awards, as shown in §3.10 and §3.11, respectively.

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

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

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:

$$
\begin{aligned}
C = & \sum_{t=1}^{T}\sum_{i} y_{i,t}\, SUC_{i,t} + \sum_{t=1}^{T}\sum_{i} u_{i,t}\, MLC_{i,t} - \sum_{t=1}^{T}\sum_{i \in S_{PSH}} v_{i,t}\, PC_{i,t} + \\
& \sum_{t=1}^{T}\sum_{i} u_{i,t}\left(EN_{i,t} - LOL_{i,t}\right) ENBP_{i,t} - \sum_{t=1}^{T}\sum_{i} L_{i,t}\, ENBP_{i,t} + \\
& \sum_{t=1}^{T}\sum_{i} VS_{i,t}\, VSBP_{i,t} - \sum_{t=1}^{T}\sum_{i} VD_{i,t}\, VDBP_{i,t} + \sum_{t=1}^{T}\sum_{i} RU_{i,t}\, RUBP_{i,t} + \\
& \sum_{t=1}^{T}\sum_{i} RD_{i,t}\, RDBP_{i,t} + \sum_{t=1}^{T}\sum_{i} SR_{i,t}\, SRBP_{i,t} + \sum_{t=1}^{T}\sum_{i} NR_{i,t}\, NRBP_{i,t} + \\
& \sum_{t=1}^{T}\sum_{i} RCU_{i,t}\, RCUBP_{i,t} + \sum_{t=1}^{T}\sum_{i} RCD_{i,t}\, RCDBP_{i,t} + \sum_{t=1}^{T}\sum_{i} FRU_{i,t}\, FRUBP_{i,t} + \\
& \sum_{t=1}^{T}\sum_{i} FRD_{i,t}\, FRDBP_{i,t} + \sum_{t=1}^{T}\sum_{i} CCU_{i,t}\, CCUBP_{i,t} + \sum_{t=1}^{T}\sum_{i} CCD_{i,t}\, CCDBP_{i,t}
\end{aligned}
$$

All online services are zero when the resource is offline, whereas Non-Spinning Reserve can be provided by offline Fast-Start Units (FSUs) ($SUT \le 10$min), FRU can be provided by offline 15min-start units ($SUT \le 15$min), and CCU can be provided by offline 20min-start units ($SUT \le 20$min):

$$
u_{i,t} = 0 \rightarrow \left\{
\begin{array}{c}
EN_{i,t} = RU_{i,t} = RD_{i,t} = SR_{i,t} = RCU_{i,t} = RCD_{i,t} = FRD_{i,t} = CCD_{i,t} = 0 \\
NR_{i,t} = 0, \forall i \notin S_{10} \\
FRU_{i,t} = 0, \forall i \notin S_{15} \\
CCU_{i,t} = 0, \forall i \notin S_{20}
\end{array}
\right\},
$$

$$\forall i \wedge t = 1,2,\ldots,T$$

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:

$$\sum_i EN_{i,t} + \sum_i VS_{i,t} = \sum_i L_{i,t} + \sum_i VD_{i,t} + Loss_t, t = 1,2, \dots, T$$

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:

$$Loss_t \cong \widetilde{Loss}_t + \sum_i \Delta EN_{i,t} \frac{\partial Loss_t}{\partial EN_{i,t}} + \sum_i \Delta VS_{i,t} \frac{\partial Loss_t}{\partial VS_{i,t}} - \sum_i \Delta L_{i,t} \frac{\partial Loss_t}{\partial L_{i,t}} - \sum_i \Delta VD_{i,t} \frac{\partial Loss_t}{\partial VD_{i,t}}, t = 1,2, \dots, T$$

Where:

$$\widetilde{Loss}_t = \sum_i \widetilde{EN}_{i,t} + \sum_i \widetilde{VS}_{i,t} - \sum_i \tilde{L}_{i,t} - \sum_i \widetilde{VD}_{i,t}, t = 1,2, \dots, T$$

$$\left.\begin{array}{l} \Delta EN_{i,t} = EN_{i,t} - \widetilde{EN}_{i,t} \\ \Delta VS_{i,t} = VS_{i,t} - \widetilde{VS}_{i,t} \\ \Delta L_{i,t} = L_{i,t} - \tilde{L}_{i,t} \\ \Delta VD_{i,t} = VD_{i,t} - \widetilde{VD}_{i,t} \\ \dfrac{\partial Loss_t}{\partial EN_{i,t}} = \dfrac{\partial Loss_t}{\partial VS_{i,t}} = -\dfrac{\partial Loss_t}{\partial L_{i,t}} = -\dfrac{\partial Loss_t}{\partial VD_{i,t}} = 1 - \dfrac{1}{LPF_{i,t}} \end{array}\right\}, \forall i \wedge t = 1,2, \dots, T$$

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

$$\sum_i \frac{\Delta EN_{i,t}}{LPF_{i,t}} + \sum_i \frac{\Delta VS_{i,t}}{LPF_{i,t}} - \sum_i \frac{\Delta L_{i,t}}{LPF_{i,t}} - \sum_i \frac{\Delta VD_{i,t}}{LPF_{i,t}} = 0, t = 1,2, \dots, T$$

The incremental energy injections are divided by the corresponding loss penalty factors to account for changes in transmission losses from the previous AC power flow solution. The loss penalty factors are derived from the Jacobian (matrix of first partial derivatives) of the AC power flow equations.

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

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

The demand forecast is distributed to the load nodes in the market footprint using load distribution factors that are adopted from the State Estimator solution for the relevant season, type of day, and time of day. The distributed load, 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:

$$\sum_{i} \frac{\Delta REN_{i,t}}{RLPF_{i,t}} = 0, t = 1,2, \dots , T$$

Note that different AC power flow solutions are used to linearize the losses in the day-ahead energy schedules and the reliability energy schedules.

3.6 ANCILLARY SERVICES PROCUREMENT CONSTRAINTS

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

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

The ancillary services 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 procurement of CCU/CCD is locational through corrective transmission 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:

$$\left.\begin{array}{r} \sum_{i} FRU_{i,t} \geq FRUR_{t} \\ \sum_{i} FRD_{i,t} \geq FRDR_{t} \end{array}\right\}, t = 1,2, \dots , T$$

The FRU/FRD uncertainty requirements are calculated as the extreme historical net demand forecast error between the four 15min intervals of the hour in the FMM and the net demand forecast in the DAME, within a specified confidence interval, adjusted to reflect forecasted conditions for the Trading Day.

To ensure the deliverability of FRU/FRD awards with respect to network constraints, the power balance constraint for the reliability energy schedules is combined with the FRU/FRD procurement constraints above to yield the following FRU/FRD deployment scenarios:

$$\left.\begin{array}{l}\sum_i REN_{i,t} + \sum_i FRU_{i,t} \geq D_t + FRUR_t \\ \sum_i REN_{i,t} - \sum_i FRD_{i,t} \leq D_t - FRDR_t\end{array}\right\}, t = 1,2, \ldots, T$$

With a nonzero cost for FRU/FRD awards, these constraints will be binding (satisfied as equalities) at the optimal solution. In these scenarios, the distributed demand forecast is increased/decreased pro rata by the FRU/FRD requirement while the FRU/FRD awards are dispatched to balance the system, respectively. Consequently, the FRU/FRD deployment scenarios simulate the deployment of FRU/FRD awards to meet the maximum upward/downward uncertainty that can materialize on top of the demand forecast within a specified confidence. The resulting power flows on the transmission network are constrained by network constraints in the FRU/FRD deployment scenarios, as described in §3.9.4, to ensure that if that maximum upward/downward uncertainty materializes, the FRU/FRD awards can be deployed to serve it without violating network constraints.

3.8 UPPER/LOWER CAPACITY BOUNDS

The ancillary services, RCU/RCD, FRU/FRD, and CCU/CCD upper/lower bound constraints are as follows:

$$\left.\begin{array}{l}0 \leq RD_{i,t} \leq RDBC_{i,t} \\ 0 \leq RU_{i,t} \leq RUBC_{i,t} \\ 0 \leq SR_{i,t} \leq SRBC_{i,t} \\ 0 \leq NR_{i,t} \leq NRBC_{i,t} \\ 0 \leq RCU_{i,t} \leq RCUBC_{i,t} \\ 0 \leq RCD_{i,t} \leq RCDBC_{i,t} \\ 0 \leq FRU_{i,t} \leq FRUBC_{i,t} \\ 0 \leq FRD_{i,t} \leq FRDBC_{i,t} \\ 0 \leq CCU_{i,t} \leq CCUBC_{i,t} \\ 0 \leq CCD_{i,t} \leq CCDBC_{i,t}\end{array}\right\}, \forall i \wedge t = 1,2, \ldots, T$$

The ancillary services, RCU/RCD, FRU/FRD, and CCU/CCD capacity bids are limited by the corresponding certified quantities. Capacity bids for RCU/RCD, FRU/FRD, and CRU/CRD can be used to limit exposure to the Must Offer Obligation associated with the corresponding awards in the RTM.

The ancillary services, RCU/RCD, FRU/FRD, and CCU/CCD awards are further constrained by ramp capability and capacity constraints, described in §3.10 and §3.11, respectively.

3.9 NETWORK CONSTRAINTS

This section describes the various network constraints enforced in the DAME.

3.9.1 Transmission Constraints

Transmission constraints are enforced for active energy flows on transmission elements in the base case as follows:

$$\left.\begin{array}{l} LFL_{m,t} \leq F_{m,t} \leq UFL_{m,t} \\ LFL_{m,t} \leq RF_{m,t} \leq UFL_{m,t} \end{array}\right\}, \forall m \wedge \ t = 1,2, \dots, T$$

These constraints are two-sided algebraic thermal limits (the lower limit is negative) on either single transmission lines and transformers, or a group of transmission lines (branch groups, flowgates, or transmission corridors). In the latter case, the limit may be a simultaneous power transfer capability limit.

These constraints are nonlinear, but they are linearized at an AC power flow solution are as follows:

$$\left.\begin{array}{l} LFL_{m,t} \leq \left(\begin{array}{c} \tilde{F}_{m,t} + \sum_i \Delta EN_{i,t}\, SF_{i,m,t} + \sum_i \Delta VS_{i,t}\, SF_{i,m,t} - \\ \sum_i \Delta L_{i,t}\, SF_{i,m,t} - \sum_i \Delta VD_{i,t}\, SF_{i,m,t} \end{array} \right) \leq UFL_{m,t} \\ LFL_{m,t} \leq \widetilde{RF}_{m,t} + \sum_i \Delta REN_{i,t}\, SF_{i,m,t} \leq UFL_{m,t} \end{array}\right\}, \forall m \wedge t = 1,2, \dots, T$$

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. Linear lossless shift factors are used in this linearization; they are derived from the imaginary part of the Nodal Admittance matrix of the transmission network; thus, they solely depend on the transmission network configuration. Different AC power flow solutions are required to linearize the transmission constraints for day-ahead energy and reliability energy schedules, but the shift factors are the same for both because they are injected on the same network.

Additional nodal constraints limit virtual and physical day-ahead energy schedules when the power flow solution reverts to DC.

3.9.2 Scheduling Limits

The ancillary services and FRU/FRD awards from intertie resources associated with Intertie Transmission Corridor (ITC) or Intertie Scheduling Limit (ISL) constraints are limited by these constraints. 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:

$$\left.\begin{array}{l}
\max\left(0, \sum_{i \in S_m} EN_{i,t}\right) + \sum_{i \in I_m}\left(RU_{i,t} + SR_{i,t} + NR_{i,t}\right) + \sum_{i \in S_m} FRU_{i,t} \le UFL_{m,t} \\
\max\left(0, \sum_{i \in S_m} REN_{i,t}\right) + \sum_{i \in I_m}\left(RU_{i,t} + SR_{i,t} + NR_{i,t}\right) + \sum_{i \in S_m} FRU_{i,t} \le UFL_{m,t} \\
LFL_{m,t} \le \min\left(0, \sum_{i \in S_m} EN_{i,t}\right) - \sum_{i \in I_m} RD_{i,t} - \sum_{i \in S_m} FRD_{i,t} \\
LFL_{m,t} \le \min\left(0, \sum_{i \in S_m} REN_{i,t}\right) - \sum_{i \in I_m} RD_{i,t} - \sum_{i \in S_m} FRD_{i,t}
\end{array}\right\},$$

$$\forall m \wedge t = 1, \dots, T$$

The ITC/ISL constraints are linearized as follows:

$$\left.\begin{array}{l}
\sum_{i \in S_m} EN_{i,t} + \sum_{i \in I_m}\left(RU_{i,t} + SR_{i,t} + NR_{i,t}\right) + \sum_{i \in S_m} FRU_{i,t} \le UFL_{m,t} \\
\sum_{i \in S_m} REN_{i,t} + \sum_{i \in I_m}\left(RU_{i,t} + SR_{i,t} + NR_{i,t}\right) + \sum_{i \in S_m} FRU_{i,t} \le UFL_{m,t} \\
\sum_{i \in I_m}\left(RU_{i,t} + SR_{i,t} + NR_{i,t}\right) + \sum_{i \in S_m} FRU_{i,t} \le UFL_{m,t} \\
LFL_{m,t} \le \sum_{i \in S_m} EN_{i,t} - \sum_{i \in I_m} RD_{i,t} - \sum_{i \in S_m} FRD_{i,t} \\
LFL_{m,t} \le \sum_{i \in S_m} REN_{i,t} - \sum_{i \in I_m} RD_{i,t} - \sum_{i \in S_m} FRD_{i,t} \\
LFL_{m,t} \le -\sum_{i \in I_m} RD_{i,t} - \sum_{i \in S_m} FRD_{i,t}
\end{array}\right\}, \forall m \wedge t = 1, \dots, T$$

In the case of ITC constraints, the set S_m includes all intertie resources bound by the ITC m, and in the case of ISL constraints, the set S_m includes all intertie resources associated with (tagged at) the corresponding intertie of the ISL m. 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.

3.9.3 Contingency Constraints

There are several different contingency constraints enforced in the DAME:

1) N–1 preventive transmission contingencies;
2) N–1–1 corrective transmission contingencies; and
3) G–1 generation/transmission contingencies.

The N–1 preventive transmission contingencies are similar to the transmission contingencies in the base case:

$$\left.\begin{array}{l} LFL_{m,t}^{(k)} \leq \begin{pmatrix} \tilde{F}_{m,t}^{(k)} + \sum_i \Delta EN_{i,t}\, SF_{i,m,t}^{(k)} + \sum_i \Delta VS_{i,t}\, SF_{i,m,t}^{(k)} - \\ \sum_i \Delta L_{i,t}\, SF_{i,m,t}^{(k)} - \sum_i \Delta VD_{i,t}\, SF_{i,m,t}^{(k)} \end{pmatrix} \leq UFL_{m,t}^{(k)} \\ LFL_{m,t}^{(k)} \leq \widetilde{RF}_{m,t}^{(k)} + \sum_i \Delta REN_{i,t}\, SF_{i,m,t}^{(k)} \leq UFL_{m,t}^{(k)} \end{array}\right\}, \forall k, m \wedge t = 1,2, \dots, T$$

No additional control variables are introduced. The difference is that the upper/lower flow limits are emergency limits and the shift factors reflect the changed network topology in the post-contingency case after the loss of the associated transmission element. Different AC power flow solutions are required to linearize the transmission constraints for day-ahead energy and reliability energy schedules in the post-contingency case, but they can be easily derived from the power flow solutions for the base case.

The corrective transmission contingency model was described in the Contingency Modeling Enhancements (CME) initiative as an expansion of the N–1 preventive contingency model to enforce N–1–1 transmission contingencies in corrective mode. The N–1 preventive contingency model can also be expanded to enforce generation contingencies or simultaneous transmission and generation contingencies, as described in the Generation Contingency and Remedial Action Scheme Model (GCARM) initiative. In this model, the generation contingency is a G–1 contingency event and the simultaneous transmission and generation contingency is an N–1 transmission contingency with a Remedial Action Scheme (RAS) that trips one or more generating resources. The salient features of these two types of contingency models are as follows:

Feature	Corrective Transmission Contingency	Generation/Transmission Contingency
Contingency type	N–1–1	G–1 or N–1+RAS
Corrective action	Redispatch	Generation loss distribution
Corrective time period	20min	Immediate
Post-corrective transmission limits	N–1–1 limit (may be lower than base case limit) on affected transmission corridor; normal limits on other transmission elements	Emergency limits on all transmission elements
Contingency reserve dispatch	No	No

The base case is solved simultaneously with all contingencies in preventive and corrective mode, co-optimizing all commodities such as energy and ancillary services.

The corrective transmission contingency model employs an optimal corrective capacity dispatch over the corrective time period; therefore, post-corrective contingency control variables must be introduced in the formulation for physical resources. The linearized post-corrective contingency power balance constraints are as follows:

$$\left.\begin{array}{l}\sum_i \frac{\Delta EN_{i,t}^{(c)}}{LPF_{i,t}^{(c)}} + \sum_i \frac{\Delta VS_{i,t}}{LPF_{i,t}^{(c)}} - \sum_i \frac{\Delta L_{i,t}}{LPF_{i,t}^{(c)}} - \sum_i \frac{\Delta VD_{i,t}}{LPF_{i,t}^{(c)}} = 0 \\ \sum_i \frac{\Delta REN_{i,t}^{(c)}}{RLPF_{i,t}^{(c)}} = 0\end{array}\right\}, \forall c \wedge t = 1,2, \dots, T$$

The post-corrective contingency energy schedules of physical resources with corrective capacity bids are related to the base-case energy schedules as follows:

$$\left.\begin{array}{l}0 \le CCU_{i,t}^{(c)} \ge EN_{i,t}^{(c)} - EN_{i,t} \\ 0 \le CCD_{i,t}^{(c)} \ge EN_{i,t} - EN_{i,t}^{(c)} \\ 0 \le CCU_{i,t}^{(c)} \ge REN_{i,t}^{(c)} - REN_{i,t} \\ 0 \le CCD_{i,t}^{(c)} \ge REN_{i,t} - REN_{i,t}^{(c)}\end{array}\right\}, \forall i, c \wedge t = 1,2, \dots, T$$

The maximum CCU/CCD over all corrective contingency transmission constraints, used for cost contributions in the objective function, is derived as follows:

$$\left.\begin{array}{l}0 \le CCU_{i,t} \ge CCU_{i,t}^{(c)} \\ 0 \le CCD_{i,t} \ge CCD_{i,t}^{(c)}\end{array}\right\}, \forall i, c \wedge t = 1,2, \dots, T$$

The post-corrective contingency day-ahead energy and reliability energy schedules are constrained by ramp capability constraints from the base case energy schedules, as described in §3.10, and by capacity constraints, as described in §3.11.

The linearized corrective transmission contingency constraints are similar to the N–1 preventive transmission constraints:

$$\left.\begin{array}{l} LFL_{m,t}^{(c)} \le \left(\begin{array}{c} \tilde{F}_{m,t}^{(c)} + \sum_i \Delta EN_{i,t}^{(c)} \, SF_{i,m,t}^{(c)} + \sum_i \Delta VS_{i,t} \, SF_{i,m,t}^{(c)} - \\ \sum_i \Delta L_{i,t} \, SF_{i,m,t}^{(c)} - \sum_i \Delta VD_{i,t} \, SF_{i,m,t}^{(c)} \end{array} \right) \le UFL_{m,t}^{(c)} \\ LFL_{m,t}^{(c)} \le \widetilde{RF}_{m,t}^{(c)} + \sum_i \Delta REN_{i,t}^{(c)} \, SF_{i,m,t}^{(c)} \le UFL_{m,t}^{(c)} \end{array}\right\}, \forall c, m \wedge t = 1,2, \dots, T$$

The difference is that the constraints are formulated for the post-corrective contingency day-ahead energy and reliability energy schedules. Furthermore, the upper/lower flow limits are the corresponding N–1–1 limits and the shift factors reflect the changed network topology in the post-corrective contingency case after the loss of the associated transmission element. Different AC power flow solutions are required to linearize the transmission constraints for day-ahead energy and reliability energy schedules in the post-corrective contingency case.

The corrective time for the G–1 or N–1+RAS generation/transmission contingency is assumed instantaneous with an immediate distribution of the lost or tripped generation over all online frequency responsive generators in the Full Network Model (FNM). The distribution is assumed pro rata on the maximum capacity of these generators:

$$\left.\begin{array}{l} \left.\begin{array}{l} EN_{i,t}^{(g)} = EN_{i,t} + EN_{i_g,t} \, GLDF_{i,t}^{(g)} \\ REN_{i,t}^{(g)} = REN_{i,t} + REN_{i_g,t} \, GLDF_{i,t}^{(g)} \end{array}\right\}, \forall i \\ GLDF_{i_g,t}^{(g)} = -1 \\ GLDF_{i,t}^{(g)} = 0, \forall i \notin S_{f,t} \wedge i \neq i_g \\ GLDF_{i,t}^{(g)} = \dfrac{UOL_{i,t}}{\sum_{\substack{i \in S_{f,t} \\ i \neq i_g}} UOL_{i,t}}, \forall i \in S_{f,t} \wedge i \neq i_g \end{array}\right\}, \forall g \wedge t = 1,2, \dots, T$$

The linearized generation/transmission contingency constraints are similar to the N–1 preventive transmission constraints:

$$\left.\begin{array}{l} LFL_{m,t}^{(g)} \le \left(\begin{array}{c} \tilde{F}_{m,t}^{(g)} + \sum_i \Delta EN_{i,t}^{(g)} \, SF_{i,m,t}^{(g)} + \sum_i \Delta VS_{i,t} \, SF_{i,m,t}^{(g)} - \\ \sum_i \Delta L_{i,t} \, SF_{i,m,t}^{(g)} - \sum_i \Delta VD_{i,t} \, SF_{i,m,t}^{(g)} \end{array} \right) \le UFL_{m,t}^{(g)} \\ LFL_{m,t}^{(g)} \le \widetilde{RF}_{m,t}^{(g)} + \sum_i \Delta REN_{i,t}^{(g)} \, SF_{i,m,t}^{(g)} \le UFL_{m,t}^{(g)} \end{array}\right\},$$
$$\forall g, m \wedge t = 1,2, \dots, T$$

The difference is that the constraints are formulated for the post-contingency day-ahead energy and reliability energy schedules, which are dependent variables that reflect the distribution of lost/tripped generation. The upper/lower flow limits are the emergency limits and the shift factors reflect the changed network topology in the post-contingency case after the loss of the associated transmission element, if any. Different AC power flow solutions are required to linearize the transmission constraints for day-ahead energy and reliability energy schedules in the post-contingency case.

To express these constraints in terms of the base-case control variables, it is convenient to define the following binary variable:

$$w_{i,g,t} = \begin{Bmatrix} 1 \therefore i = i_g \\ 0 \therefore i \neq i_g \end{Bmatrix}, \forall i, g \wedge t = 1,2, \dots, T$$

Then, the aggregate shift factor that reflects the distribution of lost/tripped generation can be defined as follows:

$$\overline{SF}_{i,m,t}^{(g)} = SF_{i,m,t}^{(g)} + w_{i,g,t} \sum_{j} GLDF_{j,t}^{(g)} \, SF_{j,m,t}^{(g)}, \forall i, m, g \wedge t = 1,2, \dots, T$$

The linearized generation/transmission contingency constraints can then be written as follows:

$$\left.\begin{aligned} & LFL_{m,t}^{(g)} \leq \begin{pmatrix} \tilde{F}_{m,t}^{(g)} + \sum_{i} \Delta EN_{i,t} \, \overline{SF}_{i,m,t}^{(g)} + \sum_{i} \Delta VS_{i,t} \, SF_{i,m,t}^{(g)} - \\ \sum_{i} \Delta L_{i,t} \, SF_{i,m,t}^{(g)} - \sum_{i} \Delta VD_{i,t} \, SF_{i,m,t}^{(g)} \end{pmatrix} \leq UFL_{m,t}^{(g)} \\ & LFL_{m,t}^{(g)} \leq \widetilde{RF}_{m,t}^{(g)} + \sum_{i} \Delta REN_{i,t} \, \overline{SF}_{i,m,t}^{(g)} \leq UFL_{m,t}^{(g)} \end{aligned}\right\},$$

$$\forall g, m \wedge t = 1,2, \dots, T$$

3.9.4 Flexible Ramp Deployment Scenario Transmission Constraints

To ensure the deliverability of FRU/FRD awards with respect to network constraints, transmission constraints are formulated for the FRU/FRD deployment scenarios, as follows:

$$\left.\begin{aligned} LFL_{m,t} \leq \widetilde{RF}_{m,t} + \sum_{i} \left(\Delta REN_{i,t} + FRU_{i,t}\right) SF_{i,m,t} \leq UFL_{m,t} \\ LFL_{m,t} \leq \widetilde{RF}_{m,t} + \sum_{i} \left(\Delta REN_{i,t} - FRD_{i,t}\right) SF_{i,m,t} \leq UFL_{m,t} \end{aligned}\right\}, \forall m \wedge t = 1,2, \dots, T$$

For simplicity and performance, the same linearization from the AC power flow solution for the reliability energy schedules is used, assuming no incremental transmission losses due to the deployment of FRU/FRD awards. The same simplification can be applied to contingency constraints for the deployment scenarios:

$$\left.\begin{aligned} LFL_{m,t}^{(k)} \leq \widetilde{RF}_{m,t}^{(k)} + \sum_{i} \left(\Delta REN_{i,t} + FRU_{i,t}\right) SF_{i,m,t}^{(k)} \leq UFL_{m,t}^{(k)} \\ LFL_{m,t}^{(k)} \leq \widetilde{RF}_{m,t}^{(k)} + \sum_{i} \left(\Delta REN_{i,t} - FRD_{i,t}\right) SF_{i,m,t}^{(k)} \leq UFL_{m,t}^{(k)} \end{aligned}\right\}, \forall k, m \wedge t = 1,2, \dots, T$$

$$\left.\begin{aligned} LFL_{m,t}^{(c)} \le \widetilde{RF}_{m,t}^{(c)} + \sum_i \left(\Delta REN_{i,t}^{(c)} + FRU_{i,t}\right) SF_{i,m,t}^{(c)} \le UFL_{m,t}^{(c)} \\ LFL_{m,t}^{(c)} \le \widetilde{RF}_{m,t}^{(c)} + \sum_i \left(\Delta REN_{i,t}^{(c)} - FRD_{i,t}\right) SF_{i,m,t}^{(c)} \le UFL_{m,t}^{(c)} \end{aligned}\right\}, \forall c, m \wedge t = 1,2, \dots, T$$

$$\left.\begin{aligned} LFL_{m,t}^{(g)} \le \widetilde{RF}_{m,t}^{(g)} + \sum_i \left(\Delta REN_{i,t}^{(g)} + FRU_{i,t}\right) \overline{SF}_{i,m,t}^{(g)} \le UFL_{m,t}^{(g)} \\ LFL_{m,t}^{(g)} \le \widetilde{RF}_{m,t}^{(g)} + \sum_i \left(\Delta REN_{i,t}^{(g)} - FRD_{i,t}\right) \overline{SF}_{i,m,t}^{(g)} \le UFL_{m,t}^{(g)} \end{aligned}\right\}, \forall g, m \wedge t = 1,2, \dots, T$$

3.9.5 Critical Network Constraints

From the preceding sections, it is clear that there are many different cases in formulating a given network constraint: the base case, the various contingencies, and the FRU/FRD deployment scenarios. However, for performance reasons, only the critical network constraints at each iteration are enforced in the SCUC; these constraints are the ones where the AC power flow is close to the corresponding upper or lower limit within a configurable relative tolerance. A given network constraint may be critical in more than one case, but it may be sufficient to enforce the constraint only in the most critical case where the system is stressed the highest. For example, it may be sufficient to enforce network constraints on reliability energy schedules only in the FRU deployment scenario during load on-ramps and peak net demand hours and only in the FRD deployment scenario during load off-ramps and low net demand hours.

3.9.6 Gas-Burn Nomograms

The gas-burn nomogram constraints ensure that the aggregate gas consumption required to support the reliability energy schedules of natural gas resources in specific gas procurement regions does not exceed limits imposed by the natural gas availability and transmission system. These constraints are as follows:

$$\left.\begin{aligned} \sum_{i \in S_n} a_i \, EN_{i,t} \le GL_{n,t} \\ \sum_{i \in S_n} a_i \, REN_{i,t} \le GL_{n,t} \end{aligned}\right\}, \forall n, t = 1,2, \dots, T$$

3.9.7 Minimum Online Commitment Constraints

The Minimum Online Commitment (MOC) constraints ensure aggregate online generation capacity that is required in certain system areas for reliability, typically voltage support. These are unit commitment constraints formulated as follows:

$$\sum_{i \in S_o} b_{i,o} \, u_{i,t} \, UOL_{i,t} \ge MOC_{o,t}, \forall o, t = 1,2, \dots, T$$

3.10 RAMP CAPABILITY CONSTRAINTS

This section describes the ramp capability constraints. The ancillary services awards are simultaneously constrained by the 10min ramp capability from the energy schedules, as follows:

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

The ramp capability constraint for offline Non-Spinning Reserve is as follows:

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

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

Similarly, the post-corrective energy schedules of corrective transmission contingencies are limited by the 20min ramp capability from the corresponding schedules in the base case, as follows:

$$\left.\begin{array}{l} -RRD_i\left(EN_{i,t}, T_{20}\right) \leq EN_{i,t}^{(c)} - EN_{i,t} \leq RRU_i\left(EN_{i,t}, T_{20}\right) \\ -RRD_i\left(REN_{i,t}, T_{20}\right) \leq REN_{i,t}^{(c)} - REN_{i,t} \leq RRU_i\left(REN_{i,t}, T_{20}\right) \end{array}\right\}, \forall i, c \wedge u_{i,t} = 1 \wedge t = 1,2, \dots, T$$

For offline resources with CCU bids, this constraint is as follows:

$$EN_{i,t}^{(c)} \leq LOL_{i,t} + RRU_i\left(LOL_{i,t}, T_{20} - SUT_{i,t}\right), \forall i \in S_{20} \wedge u_{i,t} = 0 \wedge t = 1,2, \dots, T$$

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

Capacity ancillary services can be dispatched at any time during the ramp between hourly schedules; hence, the performance hit for using the dynamic ramp capability from the average hourly energy schedules in the above constraints is not justified. A more conservative approach is used instead, formulating the constraints with the lowest ramp capability within the applicable operating range of the resource, calculated as follows:

$$\left.\begin{array}{l} \underline{RRU}_{i,t}(T_{10}) = \min\left(RRU(p_i, T_{10})\Big|_{p_i=\max\left(LOL_{i,t}, LEL_{i,t}\right)}^{p_i=UOL_{i,t}-RRD\left(UOL_{i,t}, T_{10}\right)}\right) \\ \underline{RRD}_{i,t}(T_{10}) = \min\left(RRD(p_i, T_{10})\Big|_{p_i=LOL_{i,t}+RRU\left(LOL_{i,t}, T_{10}\right)}^{p_i=UOL_{i,t}}\right) \\ \underline{RRU}_{i,t}(T_{20}) = \min\left(RRU(p_i, T_{20})\Big|_{p_i=\max\left(LOL_{i,t}, LEL_{i,t}\right)}^{p_i=\min\left(UOL_{i,t}, UEL_{i,t}\right)-RRD\left(\min\left(UOL_{i,t}, UEL_{i,t}\right), T_{20}\right)}\right) \\ \underline{RRD}_{i,t}(T_{20}) = \min\left(RRD(p_i, T_{20})\Big|_{p_i=\max\left(LOL_{i,t}, LEL_{i,t}\right)+RRU\left(\max\left(LOL_{i,t}, LEL_{i,t}\right), T_{20}\right)}^{p_i=\min\left(UOL_{i,t}, UEL_{i,t}\right)}\right) \end{array}\right\},$$

$$\forall i \wedge u_{i,t} = 1 \wedge t = 1,2, \dots, T$$

Although capacity ancillary services can be dispatched at any time, FRU/FRD awards are deployed from the energy schedules; hence, the dynamic ramp capability should be used for ramp capability constraints on FRU/FRD awards. The FRU/FRD awards are simultaneously constrained with energy schedules by the dynamic 15min ramp capability, as follows:

$$\left.\begin{array}{l} GAF\ (EN_{i,t} - EN_{i,t-1}) \le RRU_i(EN_{i,t-1}, T_{15}) - \delta\ FRU_{i,t} \\ GAF\ (EN_{i,t} - EN_{i,t-1}) \ge -RRD_i(EN_{i,t-1}, T_{15}) + \delta\ FRD_{i,t} \\ GAF\ (REN_{i,t} - REN_{i,t-1}) \le RRU_i(REN_{i,t-1}, T_{15}) - \delta\ FRU_{i,t} \\ GAF\ (REN_{i,t} - REN_{i,t-1}) \ge -RRD_i(REN_{i,t-1}, T_{15}) + \delta\ FRD_{i,t} \end{array}\right\}, \forall i \wedge u_{i,t} = 1 \wedge t = 1,2, \dots, T$$

The granularity adjustment factor (*GAF*) converts the hourly energy schedule ramp to the 15min time domain of FRU/FRD awards.

The ramp capability constraint for offline FRU is as follows:

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

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

The energy schedules and the ancillary services and FRU/FRD awards are simultaneously constrained by 60min dynamic ramp capability constraints. For resources that remain online across time intervals, these constraints are as follows:

$$\left.\begin{array}{l} EN_{i,t} - EN_{i,t-1} \le RRU_i(EN_{i,t-1}, T_{60}) - \alpha\ RU_{i,t} - \beta\ SR_{i,t} - \gamma\ NR_{i,t} - \delta\ FRU_{i,t} \\ EN_{i,t} - EN_{i,t-1} \ge -RRD_i(EN_{i,t-1}, T_{60}) + \alpha\ RD_{i,t} + \delta\ FRD_{i,t} \\ REN_{i,t} - REN_{i,t-1} \le RRU_i(REN_{i,t-1}, T_{60}) - \alpha\ RU_{i,t} - \beta\ SR_{i,t} - \gamma\ NR_{i,t} - \delta\ FRU_{i,t} \\ REN_{i,t} - REN_{i,t-1} \ge -RRD_i(REN_{i,t-1}, T_{60}) + \alpha\ RD_{i,t} + \delta\ FRD_{i,t} \end{array}\right\},$$
$$\forall i \wedge u_{i,t-1} = u_{i,t} = 1 \wedge t = 1,2, \dots, T$$

For resources that start up, the ramp capability constraints are as follows:

$$\left.\begin{array}{l} EN_{i,t} \le LOL_{i,t} + RRU_i(LOL_{i,t}, T_{60}/2) - \alpha\ RU_{i,t} - \beta\ SR_{i,t} - \gamma\ NR_{i,t} - \delta\ FRU_{i,t} \\ REN_{i,t} \le LOL_{i,t} + RRU_i(LOL_{i,t}, T_{60}/2) - \alpha\ RU_{i,t} - \beta\ SR_{i,t} - \gamma\ NR_{i,t} - \delta\ FRU_{i,t} \end{array}\right\},$$
$$\forall i \wedge u_{i,t-1} = 0 \wedge u_{i,t} = 1 \wedge t = 1,2, \dots, T$$

Where the ramp up from LOL is for half of the interval ramp.

For resources that shut down, the ramp capability constraints are as follows:

$$\left.\begin{array}{l} EN_{i,t} \le LOL_{i,t} + RRU_i(LOL_{i,t}, T_{60}/2) - \alpha\ RD_{i,t} - \delta\ FRD_{i,t} \\ REN_{i,t} \le LOL_{i,t} + RRU_i(LOL_{i,t}, T_{60}/2) - \alpha\ RD_{i,t} - \delta\ FRD_{i,t} \end{array}\right\},$$
$$\forall i \wedge u_{i,t} = 1 \wedge u_{i,t+1} = 0 \wedge t = 1,2, \dots, T-1$$

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

The shared ramping coefficients specify how the various commodities share the resource ramp capability. The ramp capability 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. 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.

3.11 CAPACITY CONSTRAINTS

This section describes the 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:

$$\left.\begin{array}{l} RU_{i,t}+RD_{i,t}>0 \rightarrow \begin{cases} UCL_{i,t}=\min\left(UOL_{i,t},URL_{i,t},CL_{i,t}\right) \\ LCL_{i,t}=\max\left(LOL_{i,t},LRL_{i,t}\right) \end{cases} \\ \left.\begin{array}{l} RU_{i,t}+RD_{i,t}=0 \\ SR_{i,t}+NR_{i,t}>0 \end{array}\right\} \rightarrow \begin{cases} UCL_{i,t}=\min\left(UOL_{i,t},CL_{i,t}\right) \\ LCL_{i,t}=LOL_{i,t} \end{cases} \\ RU_{i,t}+RD_{i,t}+SR_{i,t}+NR_{i,t}=0 \rightarrow \begin{cases} UCL_{i,t}=UOL_{i,t} \\ LCL_{i,t}=LOL_{i,t} \end{cases} \end{array}\right\}, \forall i \wedge t=1,2,\ldots,T$$

$$\left.\begin{array}{l} UEL'_{i,t}=\min\left(UCL_{i,t},UEL_{i,t}\right) \\ LEL'_{i,t}=\max\left(LCL_{i,t},LEL_{i,t}\right) \end{array}\right\}, \forall i \wedge t=1,2,\ldots,T$$

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

$$\left.\begin{array}{l} EN_{i,t} \leq UCL_{i,t}-RU_{i,t}-SR_{i,t}-NR_{i,t}-FRU_{i,t} \\ LCL_{i,t}+RD_{i,t}+FRD_{i,t} \leq EN_{i,t} \\ LEL'_{i,t}+FRD_{i,t} \leq EN_{i,t} \leq UEL'_{i,t}-FRU_{i,t} \\ REN_{i,t} \leq UCL_{i,t}-RU_{i,t}-SR_{i,t}-NR_{i,t}-FRU_{i,t} \\ LCL_{i,t}+RD_{i,t}+FRD_{i,t} \leq REN_{i,t} \\ LEL'_{i,t}+FRD_{i,t} \leq REN_{i,t} \leq UEL'_{i,t}-FRU_{i,t} \end{array}\right\}, \forall i \wedge u_{i,t}=1 \wedge t=1,2,\ldots,T$$

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

$$NR_{i,t} \leq UCL_{i,t}, \forall i \in S_{10} \wedge u_{i,t}=0 \wedge t=1,2,\ldots,T$$

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

The capacity constraints for the day-ahead energy schedules of virtual and non-participating load resources are as follows:

$$\left.\begin{array}{l} LEL_{i,t} \leq VS_{i,t} \leq UEL_{i,t} \\ LEL_{it} \leq VD_{i,} \leq UEL_{it} \\ LEL_{i,t} \leq L_{i,t} \leq UEL_{i,t} \end{array}\right\}, \forall i,t=1,2,\ldots,T$$

The price curve for virtual demand and load is monotonically decreasing; the LEL is either zero or equal to the self-schedule, if submitted.

The capacity constraints for the post-corrective contingency energy schedules are as follows:

$$\left.\begin{array}{l}EN_{i,t}^{(c)} \leq UCL_{i,t} - RU_{i,t} - SR_{i,t} - NR_{i,t} - FRU_{i,t} \\ LCL_{i,t} + RD_{i,t} + FRD_{i,t} \leq EN_{i,t}^{(c)} \\ LEL'_{i,t} + FRD_{i,t} \leq EN_{i,t}^{(c)} \leq UEL'_{i,t} - FRU_{i,t} \\ REN_{i,t}^{(c)} \leq UCL_{i,t} - RU_{i,t} - SR_{i,t} - NR_{i,t} - FRU_{i,t} \\ LCL_{i,t} + RD_{i,t} + FRD_{i,t} \leq REN_{i,t}^{(c)} \\ LEL'_{i,t} + FRD_{i,t} \leq REN_{i,t}^{(c)} \leq UEL'_{i,t} - FRU_{i,t}\end{array}\right\}, \forall i, c \wedge u_{i,t} = 1 \wedge t = 1,2,\ldots,T$$

These constraints assume that corrective capacity may not overlap with other ancillary services.

3.12 ENERGY LIMIT CONSTRAINTS

Energy limit constraints apply to resources that have energy limitations. There are two kinds of energy limit constraints in the DAME:

a) Daily energy limits; and

b) State of Charge (SOC) limits.

Daily energy limits restrict the hourly energy schedules so that the total energy production over the Trading Day is limited by a maximum daily energy limit. These constraints are typically enforced for resources with a limited fuel supply, such as hydro resources with water reservoirs and water management limitations. The daily energy limits are formulated as follows:

$$\sum_{t=1}^{T} EN_{i,t} \leq \overline{EN}_i$$

$$\sum_{t=1}^{T} REN_{i,t} \leq \overline{EN}_i$$

For Pumped-Storage Hydro (PSH) Resources that can operate in either generating mode (positive energy schedule) or pumping mode (negative energy schedule), the daily energy limit constraints are two-sided; they limit the total algebraic energy production over the Trading Day between a negative minimum and a positive maximum daily energy limit, as follows:

$$\underline{EN}_i \leq \sum_{t=1}^{T} \left(u_{i,t} + v_{i,t}\,\eta_i\right) EN_{i,t} \leq \overline{EN}_i$$

$$\underline{EN}_i \leq \sum_{t=1}^{T} \left(u_{i,t} + v_{i,t}\,\eta_i\right) REN_{i,t} \leq \overline{EN}_i$$

Where the pumping energy is multiplied by the pumping efficiency and the operating modes are mutually exclusive:

$$\left.\begin{array}{l} u_{i,t} = 1 \rightarrow EN_{i,t} \geq 0 \wedge REN_{i,t} \geq 0 \\ v_{i,t} = 1 \rightarrow EN_{i,t} = REN_{i,t} = -PL_{i,t} \\ u_{i,t} = v_{i,t} = 0 \rightarrow EN_{i,t} = REN_{i,t} = 0 \\ u_{i,t} + v_{i,t} \leq 1 \end{array}\right\}, \forall i \in S_{PSH} \wedge t = 1,2, \dots, T$$

The SOC limits constrain the energy schedules, ancillary services awards, and FRU/FRD awards for Limited Energy Storage Resources (LESR), a specific type of NGR that can operate in either discharging (positive energy schedule) or charging mode (negative energy schedule). The SOC for a LESR is calculated as follows:

$$\left.\begin{array}{l} SOC_{i,t} = SOC_{i,t-1} - \dfrac{EN_{i,t-1}^{(+)} + EN_{i,t}^{(+)} + \eta_i \left(EN_{i,t-1}^{(-)} + EN_{i,t}^{(-)}\right)}{2} \\ 0 \leq EN_{i,t}^{(+)} \leq u_{i,t}\, UEL'_{i,t} \\ \left(1 - u_{i,t}\right) LEL'_{i,t} \leq EN_{i,t}^{(-)} \leq 0 \\ EN_{i,t} = EN_{i,t}^{(+)} + EN_{i,t}^{(-)} \end{array}\right\}, \forall i \in S_{LESR} \wedge t = 1,2, \dots, T$$

Where the charging energy is multiplied by the charging efficiency. Then, the SOC limit constraints are formulated as follows:

$$\left.\begin{array}{l} \underline{SOC}_{i,t} + \left(RU_{i,t} + SR_{i,t} + NR_{i,t}\right) \dfrac{T_{30}}{T_{60}} + FRU_{i,t} \dfrac{T_{15}}{T_{60}} \leq SOC_{i,t} \\ SOC_{i,t} \leq \overline{SOC}_{i,t} - \eta_i \left(RD_{i,t} + FRD_{i,t}\right) \dfrac{T_{15}}{T_{60}} \end{array}\right\}, \forall i \in S_{LESR} \wedge t = 1,2, \dots, T$$

The granularity adjustment factors convert the energy dispatch of the 15min capacity services to the hourly time domain of the SOC. A sustained 30min energy period is used for contingency reserves, and for regulation up that can substitute for contingency reserves through the cascaded ancillary services procurement discussed in §3.6.

4 PRICE FORMATION AND SETTLEMENT

This section presents the price formation and settlement for day-ahead and reliability energy schedules, and RCU/RCD, FRU/FRD, and CCU/CCD awards in the DAME, along with the associated cost allocations. The marginal prices for these commodities for each interval in the Trading Day are derived from the shadow prices of the power balance and FRU/FRD deployment scenario constraints:

$$\left.\begin{array}{ll}
\sum_i \frac{\Delta EN_{i,t}}{LPF_{i,t}} + \sum_i \frac{\Delta VS_{i,t}}{LPF_{i,t}} - \sum_i \frac{\Delta L_{i,t}}{LPF_{i,t}} - \sum_i \frac{\Delta VD_{i,t}}{LPF_{i,t}} = 0 & \lambda_t \\
\sum_i \frac{\Delta REN_{i,t}}{RLPF_{i,t}} = 0 & \xi_t \\
\sum_i REN_{i,t} + \sum_i FRU_{i,t} \geq D_t + FRUR_t & \rho_t \\
\sum_i REN_{i,t} - \sum_i FRD_{i,t} \leq D_t - FRDR_t & \sigma_t
\end{array}\right\}, t = 1,2, \dots, T$$

$$\left.\begin{array}{ll}
\sum_i \frac{\Delta EN_{i,t}^{(c)}}{LPF_{i,t}^{(c)}} + \sum_i \frac{\Delta VS_{i,t}}{LPF_{i,t}^{(c)}} - \sum_i \frac{\Delta L_{i,t}}{LPF_{i,t}^{(c)}} - \sum_i \frac{\Delta VD_{i,t}}{LPF_{i,t}^{(c)}} = 0 & \lambda_t^{(c)} \\
\sum_i \frac{\Delta REN_{i,t}^{(c)}}{RLPF_{i,t}^{(c)}} = 0 & \xi_t^{(c)}
\end{array}\right\}, \forall c \wedge t = 1,2, \dots, T$$

There are additional price contributions from binding network constraints in the base case and contingencies. The reliability capacity (RCU/RCD) is embedded in the reliability energy schedule, but its settlement is separated out for cost allocation purposes. The settlement for post-corrective contingency energy schedules encompasses the settlement for the corrective capacity (CCU/CCD) for the respective contingency.

4.1 DAY-AHEAD MARGINAL PRICES

Including the contributions from binding transmission constraints, described in §3.9, the marginal prices of the commodities in the DAME are calculated as follows:

$$ENMP_{i,t} = \frac{\lambda_t}{LPF_{i,t}} - \sum_m SF_{i,m,t}\,\mu_{m,t} - \sum_k \sum_m SF_{i,m,t}^{(k)}\,\mu_{m,t}^{(k)} - \sum_g \sum_m \overline{SF}_{i,m,t}^{(g)}\,\mu_{m,t}^{(g)},$$
$$\forall i \wedge t = 1,2, \dots, T$$

$$VSMP_{i,t} = VDMP_{i,t} = LMP_{i,t} =$$
$$\frac{\lambda_t}{LPF_{i,t}} + \sum_c \frac{\lambda_t^{(c)}}{LPF_{i,t}^{(c)}} - \sum_m SF_{i,m,t}\,\mu_{m,t} - \sum_k \sum_m SF_{i,m,t}^{(k)}\,\mu_{m,t}^{(k)} -$$
$$\sum_c \sum_m SF_{i,m,t}^{(c)}\,\mu_{m,t}^{(c)} - \sum_g \sum_m SF_{i,m,t}^{(g)}\,\mu_{m,t}^{(g)}, \forall i \wedge t = 1,2, \dots, T$$

$$RENMP_{i,t} = \frac{\xi_t}{RLPF_{i,t}} + \rho_t + \sigma_t - \sum_m SF_{i,m,t}\, \mu_{m,t}^{(r)} - \sum_k \sum_m SF_{i,m,t}^{(k)}\, \mu_{m,t}^{(r,k)} - \sum_g \sum_m \overline{SF}_{i,m,t}^{(g)}\, \mu_{m,t}^{(r,g)} - \sum_m SF_{i,m,t}\, \mu_{m,t}^{(u)} - \sum_k \sum_m SF_{i,m,t}^{(k)}\, \mu_{m,t}^{(u,k)} - \sum_c \sum_m SF_{i,m,t}^{(c)}\, \mu_{m,t}^{(u,c)} - \sum_g \sum_m \overline{SF}_{i,m,t}^{(g)}\, \mu_{m,t}^{(u,g)} - \sum_m SF_{i,m,t}\, \mu_{m,t}^{(d)} - \sum_k \sum_m SF_{i,m,t}^{(k)}\, \mu_{m,t}^{(d,k)} - \sum_c \sum_m SF_{i,m,t}^{(c)}\, \mu_{m,t}^{(d,c)} - \sum_g \sum_m \overline{SF}_{i,m,t}^{(g)}\, \mu_{m,t}^{(d,g)},$$
$$\forall i \wedge t = 1,2,\ldots,T$$

$$FRUMP_{i,t} = \rho_t - \sum_m SF_{i,m,t}\, \mu_{m,t}^{(u)} - \sum_k \sum_m SF_{i,m,t}^{(k)}\, \mu_{m,t}^{(u,k)} - \sum_c \sum_m SF_{i,m,t}^{(c)}\, \mu_{m,t}^{(u,c)} - \sum_g \sum_m \overline{SF}_{i,m,t}^{(g)}\, \mu_{m,t}^{(u,g)}, \forall i \wedge t = 1,2,\ldots,T$$

$$FRDMP_{i,t} = -\sigma_t + \sum_m SF_{i,m,t}\, \mu_{m,t}^{(d)} + \sum_k \sum_m SF_{i,m,t}^{(k)}\, \mu_{m,t}^{(d,k)} + \sum_c \sum_m SF_{i,m,t}^{(c)}\, \mu_{m,t}^{(d,c)} + \sum_g \sum_m \overline{SF}_{i,m,t}^{(g)}\, \mu_{m,t}^{(d,g)}, \forall i \wedge t = 1,2,\ldots,T$$

$$ENMP_{i,t}^{(c)} = \frac{\lambda_t^{(c)}}{LPF_{i,t}^{(c)}} - \sum_m SF_{i,m,t}^{(c)}\, \mu_{m,t}^{(c)}, \forall i, c \wedge t = 1,2,\ldots,T$$

$$RENMP_{i,t}^{(c)} = \frac{\xi_t^{(c)}}{LPF_{i,t}^{(c)}} - \sum_m SF_{i,m,t}^{(c)}\, \mu_{m,t}^{(r,c)}, \forall i, c \wedge t = 1,2,\ldots,T$$

4.2 DAY-AHEAD ENERGY SETTLEMENT

The net day-ahead energy settlement is as follows:

$$
\begin{aligned}
ENS_t = & -\sum_i \left(EN_{i,t}\, ENMP_{i,t}\right) - \sum_i \left(VS_{i,t}\, VSMP_{i,t}\right) + \sum_i \left(VD_{i,t}\, VDMP_{i,t}\right) + \\
& \sum_i \left(L_{i,t}\, LMP_{i,t}\right) - \sum_c \sum_i \left(EN_{i,t}^{(c)}\, ENMP_{i,t}^{(c)}\right) = \\
& \lambda_t \sum_i \left(-EN_{i,t} - VS_{i,t} + VD_{i,t} + L_{i,t}\right) + \\
& \sum_c \lambda_t^{(c)} \sum_i \left(-EN_{i,t}^{(c)} - VS_{i,t} + VD_{i,t} + L_{i,t}\right) + \\
& \lambda_t \sum_i \left(-EN_{i,t} - VS_{i,t} + VD_{i,t} + L_{i,t}\right)\left(\frac{1}{LPF_{i,t}} - 1\right) + \\
& \sum_c \lambda_t^{(c)} \sum_i \left(-EN_{i,t}^{(c)} - VS_{i,t} + VD_{i,t} + L_{i,t}\right)\left(\frac{1}{LPF_{i,t}^{(c)}} - 1\right) - \\
& \sum_i \left(-EN_{i,t} - VS_{i,t} + VD_{i,t} + L_{i,t}\right)\left(\sum_m SF_{i,m,t}\, \mu_{m,t} + \sum_k \sum_m SF_{i,m,t}^{(k)}\, \mu_{m,t}^{(k)} + \right. \\
& \left. \sum_g \sum_m \overline{SF}_{i,m,t}^{(g)}\, \mu_{m,t}^{(g)}\right) - \sum_c \sum_i \left(-EN_{i,t}^{(c)} - VS_{i,t} + VD_{i,t} + L_{i,t}\right) \sum_m SF_{i,m,t}^{(c)}\, \mu_{m,t}^{(c)} = \\
& \left[-\lambda_t\, Loss_t - \sum_c \lambda_t^{(c)}\, Loss_t^{(c)} + ENML_t + \sum_c ENML_t^{(c)}\right] + ENMC + \\
& \sum_c ENMC_t^{(c)} = ENLO_t + ENMC + \sum_c ENMC_t^{(c)}\, , t = 1,2,\ldots,T
\end{aligned}
$$

The day-ahead marginal transmission loss over-collection (*ENLO*) is allocated to metered demand. The day-ahead marginal congestion revenue (*ENMC*) is deposited to the CRR Balancing Account to fund Congestion Revenue Rights using the CRR-1B allocation method, except for the day-ahead post-corrective contingency marginal congestion revenue that is allocated as a system cost to metered demand. Corrective transmission contingencies are not included in the CRR Simultaneous Feasibility Test (SFT).

4.3 NO PAY

The day-ahead energy schedules, including the day-ahead post-corrective contingency energy schedules, are subject to a deviation settlement in RTM. Therefore, there is no need for a No Pay mechanism for them. However, the reliability energy schedules, including the reliability post-corrective contingency energy schedules, are not subject to a deviation settlement in FMM. The same is true for the day-ahead FRU/FRD awards. Consequently, a No Pay mechanism is required for the portions of these commodities that are unavailable in FMM due to outages and derates. However, for simplicity, No Pay is not applied to the reliability post-corrective contingency energy schedules, relying on the deviation settlement of the day-ahead post-corrective contingency energy schedules to capture the effect of outages.

The No Pay is applied in the following priority sequence from higher to lower quality services: RU/RD, SR, NR, RCU/RCD, and FRU/FRD. The No Pay quantities for these commodities are subtracted prior to the cost allocation as follows:

$$\left.\begin{array}{l}
RU'_{i,t} = RU_{i,t} - \max\left(0, RU_{i,t} - UCL_{i,t} + LEL'_{i,t}\right) \\
RD'_{i,t} = RD_{i,t} - \max\left(0, RD_{i,t} - \min\left(UCL_{i,t} - RU'_{i,t}, UEL'_{i,t}\right) + LCL_{i,t}\right) \\
SR'_{i,t} = SR_{i,t} - \max\left(0, SR_{i,t} - \min\left(UCL_{i,t} - RU'_{i,t}, UEL'_{i,t}\right) + \max\left(LEL'_{i,t}, +LCL_{i,t} + RD'_{i,t}\right)\right) \\
NR'_{i,t} = NR_{i,t} - \max\left(0, \begin{pmatrix} SR'_{i,t} + NR_{i,t} - \min\left(UCL_{i,t} - RU'_{i,t}, UEL'_{i,t}\right) + \\ \max\left(LEL'_{i,t}, +LCL_{i,t} + RD'_{i,t}\right) \end{pmatrix}\right) \\
FRU'_{i,t} = FRU_{i,t} - \min\left(FRU_{i,t}, \begin{pmatrix} \max\left(0, \begin{pmatrix} SR'_{i,t} + NR'_{i,t} + RCU_{i,t} + FRU_{i,t} - \\ \min\left(UCL_{i,t} - RU'_{i,t}, UEL'_{i,t}\right) + EN_{i,t} \end{pmatrix}\right) + \\ \max\left(0, \max\left(LEL'_{i,t}, +LCL_{i,t} + RD'_{i,t}\right) - EN_{i,t} - RCU_{i,t}\right) \end{pmatrix}\right) \\
RCU'_{i,t} = RCU_{i,t} - \min\left(RCU_{i,t}, \begin{pmatrix} \max\left(0, \begin{pmatrix} SR'_{i,t} + NR'_{i,t} + RCU_{i,t} + FRU'_{i,t} - \\ \min\left(UCL_{i,t} - RU'_{i,t}, UEL'_{i,t}\right) + EN_{i,t} \end{pmatrix}\right) + \\ \max\left(0, \max\left(LEL'_{i,t}, +LCL_{i,t} + RD'_{i,t}\right) - EN_{i,t}\right) \end{pmatrix}\right) \\
EN'_{i,t} = EN_{i,t} - \max\left(0, SR'_{i,t} + NR'_{i,t} + RCU'_{i,t} + FRU'_{i,t} - \min\left(UCL_{i,t} - RU'_{i,t}, UEL'_{i,t}\right) + EN_{i,t}\right) \\
FRD'_{i,t} = FRD_{i,t} - \min\left(FRD_{i,t}, \begin{pmatrix} \max\left(0, \begin{pmatrix} RCD_{i,t} + FRD_{i,t} - EN_{i,t} + \\ \max\left(LEL'_{i,t}, +LCL_{i,t} + RD'_{i,t}\right) \end{pmatrix}\right) + \\ \max\left(0, EN_{i,t} - RCU_{i,t} - EN'_{i,t}\right) \end{pmatrix}\right) \\
RCD'_{i,t} = RCD_{i,t} - \min\left(RCD_{i,t}, \begin{pmatrix} \max\left(0, \begin{pmatrix} RCD_{i,t} + FRD'_{i,t} - EN_{i,t} + \\ \max\left(LEL'_{i,t}, +LCL_{i,t} + RD'_{i,t}\right) \end{pmatrix}\right) + \\ \max\left(0, EN_{i,t} - EN'_{i,t}\right) \end{pmatrix}\right) \\
REN'_{i,t} = EN'_{i,t} + RCU'_{i,t} - RCD'_{i,t} \\
\forall i \wedge t = 1,2, \ldots, T
\end{array}\right\},$$

RU/RD, SR, and NR awards have relative positions on the resource available capacity range and can slide up or down to maximize their preservations. RU, SR, and NR awards may become unavailable because of Pmax derates, and RD awards may become unavailable because of Pmin rerates. Furthermore, RU/RD do not require an energy bid since they are not dispatched by RTM, but AGC; by contrast, SR and NR awards require an energy bid in RTM to be available for dispatch. RCU/RCD and FRU/FRD awards, have absolute positions on the resource available capacity range; hence they can become unavailable by both Pmax derates and Pmin rerates.

4.4 RELIABILITY ENERGY SETTLEMENT

The net reliability energy settlement is as follows:

$$RENS_t = -\sum_i \left(REN'_{i,t}\ ENMP_{i,t}\right) - \sum_c \sum_i \left(REN'^{(c)}_{i,t}\ RENMP^{(c)}_{i,t}\right) =$$

$$-\sum_i \left(\frac{\xi_t}{RLPF_{i,t}} + \rho_t + \sigma_t\right) REN'_{i,t} - \sum_c \sum_i \frac{\xi^{(c)}_t}{RLPF^{(c)}_{i,t}} REN'^{(c)}_{i,t} +$$

$$\sum_i REN'_{i,t} \Bigg(\sum_m SF_{i,m,t}\ \mu^{(r)}_{m,t} + \sum_k \sum_m SF^{(k)}_{i,m,t}\ \mu^{(r,k)}_{m,t} + \sum_g \sum_m \overline{SF}^{(g)}_{i,m,t}\ \mu^{(r,g)}_{m,t} +$$

$$\sum_m SF_{i,m,t}\ \mu^{(u)}_{m,t} + \sum_k \sum_m SF^{(k)}_{i,m,t}\ \mu^{(u,k)}_{m,t} + \sum_c \sum_m SF^{(c)}_{i,m,t}\ \mu^{(u,c)}_{m,t} +$$

$$\sum_g \sum_m \overline{SF}^{(g)}_{i,m,t}\ \mu^{(u,g)}_{m,t} + \sum_m SF_{i,m,t}\ \mu^{(d)}_{m,t} + \sum_k \sum_m SF^{(k)}_{i,m,t}\ \mu^{(d,k)}_{m,t} +$$

$$\sum_c \sum_m SF^{(c)}_{i,m,t}\ \mu^{(d,c)}_{m,t} + \sum_g \sum_m \overline{SF}^{(g)}_{i,m,t}\ \mu^{(d,g)}_{m,t} \Bigg) +$$

$$\sum_c \sum_i REN'^{(c)}_{i,t} \sum_m SF^{(c)}_{i,m,t}\ \mu^{(r,c)}_{m,t} =$$

$$\left[-\sum_i \left(\frac{\xi_t}{RLPF_{i,t}} + \rho_t + \sigma_t\right) EN'_{i,t}\right] + ENMC^{(r)}_t + ENMC^{(u)}_t + ENMC^{(d)}_t +$$

$$\left[-\sum_i \left(\frac{\xi_t}{RLPF_{i,t}} + \rho_t + \sigma_t\right) RCU'_{i,t} + RCUMC^{(r)}_t + RCUMC^{(u)}_t + RCUMC^{(d)}_t\right] +$$

$$\left[\sum_i \left(\frac{\xi_t}{RLPF_{i,t}} + \rho_t + \sigma_t\right) RCD'_{i,t} + RCDMC^{(r)}_t + RCDMC^{(u)}_t + RCDMC^{(d)}_t\right] -$$

$$\sum_c \xi^{(c)}_t \sum_i \frac{REN'^{(c)}_{i,t}}{RLPF^{(c)}_{i,t}} + \sum_c RENMC^{(c)}_t =$$

$$ENC_t + ENMC^{(r,u,d)}_t + RCUC_t + RCDC_t - \sum_c \xi^{(c)}_t \sum_i \frac{REN'^{(c)}_{i,t}}{RLPF^{(c)}_{i,t}} +$$

$$\sum_c RENMC^{(c)}_t\ , t = 1,2,\dots,T$$

The capacitive cost of EN (*ENC*) and the cost of RCU/RCD are broken out for cost allocation purposes. The RCU/RCD cost includes the corresponding marginal congestion revenue. The marginal congestion revenue due to day-ahead energy schedules (*ENMC*) is deposited to the CRR Balancing Account to fund CRRs using the CRR-1B allocation method. The post-corrective contingency reliability marginal energy/loss/congestion cost is allocated as a system cost to metered demand. Corrective transmission contingencies are not included in the CRR SFT.

4.5 FLEXIBLE RAMP UP SETTLEMENT

The net day-ahead flexible ramp up settlement is as follows:

$$FRUS_t = -\sum_i \left(FRU'_{i,t}\ FRUMP_{i,t}\right) = -\rho_t \sum_i FRU'_{i,t} + \sum_i FRU'_{i,t} \left(\sum_m SF_{i,m,t}\ \mu_{m,t}^{(u)} + \sum_k \sum_m SF_{i,m,t}^{(k)}\ \mu_{m,t}^{(u,k)} + \sum_c \sum_m SF_{i,m,t}^{(c)}\ \mu_{m,t}^{(u,c)} + \sum_g \sum_m \overline{SF}_{i,m,t}^{(g)}\ \mu_{m,t}^{(u,g)}\right) = \left[-\rho_t \sum_i FRU'_{i,t} + FRUMC_t\right] + \sum_c FRUMC_t^{(c)} = FRUC_t + \sum_c FRUMC_t^{(c)}\ , t = 1,2,\ldots,T$$

The cost of FRU, including the corresponding marginal congestion revenue, is broken out for cost allocation purposes. The post-corrective contingency FRU deployment marginal congestion cost is allocated as a system cost to metered demand. Corrective transmission contingencies are not included in the CRR SFT.

4.6 FLEXIBLE RAMP DOWN SETTLEMENT

The net day-ahead flexible ramp down settlement is as follows:

$$FRDS_t = -\sum_i \left(FRD'_{i,t}\ FRDMP_{i,t}\right) = \sigma_t \sum_i FRD'_{i,t} - \sum_i FRD'_{i,t} \left(\sum_m SF_{i,m,t}\ \mu_{m,t}^{(d)} + \sum_k \sum_m SF_{i,m,t}^{(k)}\ \mu_{m,t}^{(d,k)} + \sum_c \sum_m SF_{i,m,t}^{(c)}\ \mu_{m,t}^{(d,c)} + \sum_g \sum_m \overline{SF}_{i,m,t}^{(g)}\ \mu_{m,t}^{(d,g)}\right) = \left[\sigma_t \sum_i FRD'_{i,t} + FRDMC_t\right] + \sum_c FRDMC_t^{(c)} = FRDC_t + \sum_c FRDMC_t^{(c)}\ , t = 1,2,\ldots,T$$

The cost of FRD, including the corresponding marginal congestion revenue, is broken out for cost allocation purposes. The post-corrective contingency FRD deployment marginal congestion cost is allocated as a system cost to metered demand. Corrective transmission contingencies are not included in the CRR SFT.

4.7 CONGESTION REVENUE RIGHTS

A single Congestion Revenue Right (CRR) can be used to hedge all the congestion cost in the DAME irrespective of its source, day-ahead or reliability energy schedules, and flexible ramp up/down deployment, except for corrective transmission contingencies; the latter are not included in the CRR SFT. Therefore, the notional value of a 1MW CRR Obligation from node *i* to node *j* is defined as follows:

$$CRRV_{i,j,t} = \sum_{m}\left(SF_{i,m,t} - SF_{j,m,t}\right)\mu_{m,t} + \sum_{k}\sum_{m}\left(SF_{i,m,t}^{(k)} - SF_{j,m,t}^{(k)}\right)\mu_{m,t}^{(k)} + \sum_{g}\sum_{m}\left(\overline{SF}_{i,m,t}^{(g)} - \overline{SF}_{j,m,t}^{(g)}\right)\mu_{m,t}^{(g)} + \sum_{m}\left(SF_{i,m,t} - SF_{j,m,t}\right)\mu_{m,t}^{(r)} + \sum_{k}\sum_{m}\left(SF_{i,m,t}^{(k)} - SF_{j,m,t}^{(k)}\right)\mu_{m,t}^{(r,k)} + \sum_{g}\sum_{m}\left(\overline{SF}_{i,m,t}^{(g)} - \overline{SF}_{j,m,t}^{(g)}\right)\mu_{m,t}^{(r,g)} + \sum_{m}\left(SF_{i,m,t} - SF_{j,m,t}\right)\mu_{m,t}^{(u)} + \sum_{k}\sum_{m}\left(SF_{i,m,t}^{(k)} - SF_{j,m,t}^{(k)}\right)\mu_{m,t}^{(u,k)} + \sum_{g}\sum_{m}\left(\overline{SF}_{i,m,t}^{(g)} - \overline{SF}_{j,m,t}^{(g)}\right)\mu_{m,t}^{(u,g)} + \sum_{m}\left(SF_{i,m,t} - SF_{j,m,t}\right)\mu_{m,t}^{(d)} + \sum_{k}\sum_{m}\left(SF_{i,m,t}^{(k)} - SF_{j,m,t}^{(k)}\right)\mu_{m,t}^{(d,k)} + \sum_{g}\sum_{m}\left(\overline{SF}_{i,m,t}^{(g)} - \overline{SF}_{j,m,t}^{(g)}\right)\mu_{m,t}^{(d,g)}, t = 1,2,\ldots,T$$

Similarly, the notional value of a 1MW CRR Option from node *i* to node *j* is defined as follows:

$$CRRO_{i,j,t} = \max\left(0, \sum_{m}\left(SF_{i,m,t} - SF_{j,m,t}\right)\mu_{m,t} + \sum_{k}\sum_{m}\left(SF_{i,m,t}^{(k)} - SF_{j,m,t}^{(k)}\right)\mu_{m,t}^{(k)} + \sum_{g}\sum_{m}\left(\overline{SF}_{i,m,t}^{(g)} - \overline{SF}_{j,m,t}^{(g)}\right)\mu_{m,t}^{(g)} + \sum_{m}\left(SF_{i,m,t} - SF_{j,m,t}\right)\mu_{m,t}^{(r)} + \sum_{k}\sum_{m}\left(SF_{i,m,t}^{(k)} - SF_{j,m,t}^{(k)}\right)\mu_{m,t}^{(r,k)} + \sum_{g}\sum_{m}\left(\overline{SF}_{i,m,t}^{(g)} - \overline{SF}_{j,m,t}^{(g)}\right)\mu_{m,t}^{(r,g)} + \sum_{m}\left(SF_{i,m,t} - SF_{j,m,t}\right)\mu_{m,t}^{(u)} + \sum_{k}\sum_{m}\left(SF_{i,m,t}^{(k)} - SF_{j,m,t}^{(k)}\right)\mu_{m,t}^{(u,k)} + \sum_{g}\sum_{m}\left(\overline{SF}_{i,m,t}^{(g)} - \overline{SF}_{j,m,t}^{(g)}\right)\mu_{m,t}^{(u,g)} + \sum_{m}\left(SF_{i,m,t} - SF_{j,m,t}\right)\mu_{m,t}^{(d)} + \sum_{k}\sum_{m}\left(SF_{i,m,t}^{(k)} - SF_{j,m,t}^{(k)}\right)\mu_{m,t}^{(d,k)} + \sum_{g}\sum_{m}\left(\overline{SF}_{i,m,t}^{(g)} - \overline{SF}_{j,m,t}^{(g)}\right)\mu_{m,t}^{(d,g)}\right), t = 1,2,\ldots,T$$

The actual CRR settlement is accomplished through the CRR-1B method where congestion revenue shortfall on a transmission constraint that persists after the monthly netting of revenue shortfalls and surpluses on that constraint is allocated pro rata on the CRR flow contributions in the direction of congestion. The CRR flow contributions from CRR Obligations are netted by CRR Holder, whereas the CRR flow contributions from CRR Options are processed individually. The details of the CRR-1B method are beyond the scope of this technical description.

4.8 COST ALLOCATION

The system-wide capacitive cost of day-ahead energy (ENC) is broken out of the reliability energy (REN) settlement and it is allocated to the cleared load and net virtual demand schedules. The cost allocation method for the cost of RCU/RCD and FRU/FRD is analogous to the current two-tier RUC cost allocation. The following table summarizes the cost allocation in the DAME:

Cost	Cost Allocation	
	Tier 1	Tier 2
RCU cost (*RCUC*)	In proportion to net negative demand deviation plus net virtual supply, if system virtual supply exceeds system virtual demand, up to an average RCU cost rate	Remaining cost in proportion to metered demand
RCD cost (*RCDC*)	In proportion to net positive demand deviation plus net virtual demand, if system virtual demand exceeds system virtual supply, up to an average RCD cost rate	Remaining cost in proportion to metered demand
FRU Cost (*FRUC*)	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 (*FRDC*)	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
Capacitive Energy cost (*ENC*)	In proportion to scheduled load plus net virtual demand, if system virtual demand exceeds system virtual supply	

The average RCU/RCD/FRU/FRD cost rate is derived as follows:

$$\left.\begin{aligned} \bar{\xi}_t &= \frac{RCUC_t}{\sum_i \left(RCU'_{i,t}\right)} \\ \underline{\xi}_t &= \frac{RCDC_t}{\sum_i \left(RCD'_{i,t}\right)} \\ \bar{\rho}_t &= \frac{FRUC_t}{\sum_i \left(FRU'_{i,t}\right)} \\ \bar{\sigma}_t &= \frac{FRDC_t}{\sum_i \left(FRD'_{i,t}\right)} \end{aligned}\right\}, t = 1,2, \dots, T$$

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 ENC/RCU/RCD/FRU/FRD tier-1 cost allocation to Scheduling Coordinators are calculated as follows:

$$\left.\begin{aligned} ENCD_{s,t} &= \sum_{i \in S_s} L_{i,t} + \frac{\max\left(0, \sum_{i \in S_s}\left(VD_{i,t} - VS_{i,t}\right)\right)}{\sum_s \max\left(0, \sum_{i \in S_s}\left(VD_{i,t} - VS_{i,t}\right)\right)} \max\left(0, \sum_i \left(VD_{i,t} - VS_{i,t}\right)\right) \\ RCUCD_{s,t} &= \max\left(0, \sum_{i \in S_s}\left(ML_{i,t} - L_{i,t}\right)\right) + \frac{\max\left(0, \sum_{i \in S_s}\left(VS_{i,t} - VD_{i,t}\right)\right)}{\sum_s \max\left(0, \sum_{i \in S_s}\left(VS_{i,t} - VD_{i,t}\right)\right)} \max\left(0, \sum_i \left(VS_{i,t} - VD_{i,t}\right)\right) \\ RCDCD_{s,t} &= \max\left(0, \sum_{i \in S_s}\left(L_{i,t} - ML_{i,t}\right)\right) + \frac{\max\left(0, \sum_{i \in S_s}\left(VD_{i,t} - VS_{i,t}\right)\right)}{\sum_s \max\left(0, \sum_{i \in S_s}\left(VD_{i,t} - VS_{i,t}\right)\right)} \max\left(0, \sum_i \left(VD_{i,t} - VS_{i,t}\right)\right) \\ FRUCD_{s,t} &= \max\left(0, \sum_{i \in S_s}\left(ML_{i,t} - L_{i,t}\right)\right) + \frac{\max\left(0, \sum_{i \in S_s}\left(VS_{i,t} - VD_{i,t}\right)\right)}{\sum_s \max\left(0, \sum_{i \in S_s}\left(VS_{i,t} - VD_{i,t}\right)\right)} \max\left(0, \sum_i \left(VS_{i,t} - VD_{i,t}\right)\right) \\ FRDCD_{s,t} &= \max\left(0, \sum_{i \in S_s}\left(L_{i,t} - ML_{i,t}\right)\right) + \frac{\max\left(0, \sum_{i \in S_s}\left(VD_{i,t} - VS_{i,t}\right)\right)}{\sum_s \max\left(0, \sum_{i \in S_s}\left(VD_{i,t} - VS_{i,t}\right)\right)} \max\left(0, \sum_i \left(VD_{i,t} - VS_{i,t}\right)\right) \end{aligned}\right\},$$

$\forall s \wedge t = 1,2, \dots, T$

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

$$\left.\begin{aligned} RCUC_{s,t}^{(1)} &= \min\left(RCUCD_{s,t}\, \bar{\xi}_t, \frac{RCUCD_{s,t}}{\sum_s RCUCD_{s,t}}\, RCUC_t\right) \\ RCDC_{s,t}^{(1)} &= \min\left(RCDCD_{s,t}\, \underline{\xi}_t, \frac{RCDCD_{s,t}}{\sum_s RCDCD_{s,t}}\, RCDC_t\right) \\ FRUC_{s,t}^{(1)} &= \min\left(FRUCD_{s,t}\, \bar{\rho}_t, \frac{FRUCD_{s,t}}{\sum_s FRUCD_{s,t}}\, FRUC_t\right) \\ FRDC_{s,t}^{(1)} &= \min\left(FRDCD_{s,t}\, \bar{\sigma}_t, \frac{FRDCD_{s,t}}{\sum_s FRDCD_{s,t}}\, FRDC_t\right) \end{aligned}\right\}, \forall s \wedge t = 1,2, \dots, T$$

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

$$\left.\begin{aligned} RCUC_{s,t}^{(2)} &= \frac{\sum_{i \in S_s} ML_{i,t}}{\sum_i ML_{i,t}} \left(RCUC_t - \sum_s RCUC_{s,t}^{(1)} \right) \\ RCDC_{s,t}^{(2)} &= \frac{\sum_{i \in S_s} ML_{i,t}}{\sum_i ML_{i,t}} \left(RCDC_t - \sum_s RCDC_{s,t}^{(1)} \right) \\ FRUC_{s,t}^{(2)} &= \frac{\sum_{i \in S_s} ML_{i,t}}{\sum_i ML_{i,t}} \left(FRUC_t - \sum_s FRUC_{s,t}^{(1)} \right) \\ FRDC_{s,t}^{(2)} &= \frac{\sum_{i \in S_s} ML_{i,t}}{\sum_i ML_{i,t}} \left(FRDC_t - \sum_s FRDC_{s,t}^{(1)} \right) \end{aligned}\right\}, \forall s \wedge t = 1,2, \dots, T$$

Finally, the Capacitive Energy cost (ENC) allocation to Scheduling Coordinators is calculated as follows:

$$ENC_{s,t} = \frac{ENCD_{s,t}}{\sum_s ENCD_{s,t}} ENC_t, \forall s \wedge t = 1,2, \dots, T$$

The post-corrective contingency marginal energy/loss/congestion cost that was extracted from the EN, REN, FRU, and FRD settlement is as follows:

$$CCC_t = -\sum_c \xi_t^{(c)} \sum_i \frac{REN_{i,t}^{\prime(c)}}{RLPF_{i,t}^{(c)}} + \sum_c \left(ENMC_t^{(c)} + RENMC_t^{(c)} + FRUMC_t^{(c)} + FRDMC_t^{(c)} \right),$$
$$t = 1,2, \dots, T$$

As mentioned in the previous sections, this cost is allocated as a system cost to metered demand:

$$CCC_{s,t} = \frac{\sum_{i \in S_s} ML_{i,t_{s,t}}}{\sum_i ML_{i,t}} CCC_t, \forall s \wedge t = 1,2, \dots, T$$