Day-Ahead Market Enhancements

Appendix C: Draft Technical Description

George Angelidis, Ph.D.
Power System Technology Development

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1 INTRODUCTION

This technical paper describes the optimization problem formulation of the proposed Day-Ahead Market (DAM) enhancements for discussion purposes. The enhanced DAM combines the functionality of the Integrated Forward Market (IFM) and the Residual Unit Commitment (RUC) into one market application to realize efficiencies in procuring all Day-Ahead Market commodities simultaneously. RUC capacity is replaced by two new commodities: Imbalance Reserve Up (IRU) and Imbalance Reserve Down (IRD). IRU/IRD is reserved capacity above/below the Day-Ahead Schedule (DAS) that must be available for dispatch in the Real-Time Market (RTM) to meet the demand forecast plus upward/downward uncertainty. Furthermore, the enhanced DAM clears in 15min intervals producing a DAS with same granularity as the Fifteen-Minute Market (FMM) schedule, reducing load following and imbalance energy requirements in RTM.

1.1 EXISTING DAY-AHEAD MARKET STRUCTURE

Currently the Day-Ahead Market includes two separate market applications that are executed in sequence: IFM and RUC. The IFM commits resources, clears physical and virtual energy supply and demand schedules, and procures ancillary services. The RUC commits additional resources and schedules additional capacity beyond physical energy schedules to meet the 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 demand forecast. Furthermore, ancillary services awarded in IFM remain constant in RUC.

1.2 DAY-AHEAD MARKET ENHANCEMENTS

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 enhanced DAM will commit resources more efficiently in a single process by satisfying both IFM and RUC objectives simultaneously.

The current DAS at an hourly granularity does not provide sufficient flexibility required by sharp ramps that materialize in RTM due to ever-increasing levels of renewables. By contrast, the enhanced DAM will commit and schedule resources in the same 15min granularity as the FMM. Furthermore, the enhanced DAM will procure imbalance reserve to address uncertainty that may materialize in real time. Imbalance reserve will be effectively replaced by the Flexible Ramping Product (FRP) that is procured in the RTM, however, the enhanced DAM will commit long-start resources for that purpose that would otherwise be unavailable in RTM. The time horizon of the enhanced DAM can be extended by a day or two, using hourly intervals, to commit extra-long-start resources to meet the demand forecast and uncertainty.

1.3 MARKET COMMODITIES IN THE ENHANCED DAY-AHEAD MARKET

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

- Day-Ahead Energy schedules for physical and virtual resources;
- Imbalance Reserve Up and Down awards for physical resources;
- Day-Ahead Regulation Up and Down awards for physical resources;
- Day-Ahead Mileage Up and Down awards for physical resources;
- Day-Ahead Spinning Reserve awards for physical resources;
- Day-Ahead Non-Spinning Reserve awards for physical resources; and
- Day-Ahead Corrective Capacity awards for physical resources.

2 ASSUMPTIONS

The optimization problem formulation for the enhanced DAM 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 meet three objectives simultaneously:
  1) Balance cleared physical and virtual energy supply and demand bids; this is accomplished by the power balance constraint.
  2) Physical energy supply schedules plus IRU capacity must meet the demand forecast plus upward uncertainty requirements; this is accomplished by the IRU procurement constraint.
  3) Physical energy supply schedules minus IRD capacity must meet the demand forecast minus downward uncertainty requirements; this is accomplished by the IRD procurement constraint.
- The objective function is the maximization of the total merchandizing surplus 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;
  - the minimization of IRU/IRD capacity cost; and
  - the minimization of Ancillary Services (Regulation, Mileage, Spinning and Non-Spinning Reserve, and Corrective Capacity) awards cost.

- All Ancillary Services procurement constraints are enforced to procure 100% of the relevant requirements.
- All applicable resource constraints are enforced:
    - resource capacity constraints;
    - unit commitment inter-temporal constraints; and
    - commodity ramp-sharing constraints.
- All applicable transmission and generation constraints are enforced:
    - network constraints for physical and virtual Energy schedules for the base case and preventive transmission and/or generation contingencies;
    - network constraints for physical and virtual Energy schedules for corrective transmission contingencies;
    - intertie scheduling limits for Energy schedules and Ancillary Services awards;
    - transmission and generation nomograms, including gas-burn constraints; and
    - Minimum Online Capacity constraints.
- Daily Energy limit constraints are enforced.
- State of Charge (SOC) constraints are enforced for Limited Energy Storage Resources (LESRs).
- 15min intervals are used for the Trading Day and hourly intervals for additional days.
- Block hourly Energy scheduling is available to hourly intertie resources.
- Hourly Energy scheduling is available to Reliability Demand Response Resources (RDRRs).
- The Day-Ahead Market Power Mitigation (MPM) functionality is fully preserved; the MPM is essentially a "trial" pass of the DAM where the established MPM principles apply, namely:
    - the impact of resource commitment and physical and virtual Energy schedules on network constraints is quantified;
    - network constraints are classified as competitive or uncompetitive using the Dynamic Competitive Path Assessment (DCPA) method;
    - resources that provide congestion relief on uncompetitive network constraints are flagged for mitigation; and
    - commitment costs and Energy bids from resources flagged for mitigation are mitigated and used in the next and final DAM pass.
- The time horizon can be extended by 1-2 days after the Trading Day where virtual and non-participating load bids are ignored in the additional days to determine binding start-ups for extra-long-start resources while all other results are advisory. Hourly intervals can be used after the Trading Day.

3 MATHEMATICAL FORMULATION

The focus of the mathematical formulation of the enhanced DAM in this technical paper is on the integration of IRU/IRD procurement with the energy scheduling and ancillary services procurement in a single optimization problem with 15min intervals for the Trading Day and hourly intervals for the extension of the time horizon past the Trading Day. 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 inter-temporal constraints, Multi-State Generator modeling, block energy scheduling, contingency constraints, nomograms, and soft constraint penalty relaxation or scarcity treatment, are not included for simplicity and because they do not materially affect the enhancements for the DAM.

3.1 NOTATION

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

i	Physical Resource index.
j	Virtual Resource index.
im	Import Resource index (used in ITC/ISL constraint formulation).
ex	Export Resource index (used in ITC/ISL constraint formulation).
k	Network constraint index.
t	Time period index (0 for initial condition).
T_{10}	Capacity Ancillary Services time domain (10 min).
T_{15}	Time period duration within the Trading Day (15 min).
T_{60}	Time period duration past the Trading Day (60 min).
T_D	The number of time periods in the Trading Day (92-100), considering the short and long days due to daylight savings changes.
T_H	The number of time periods in the time horizon that includes 1-2 additional days after the Trading Day (116-148).
S_{FSU}	Set of Fast-Start Units ($SUT \leq 10$min); they can be certified to provide Non-Spinning Reserve from offline status (u=0).
S_{SSU}	Set of Short-Start Units ($SUT \leq 15$min); they can provide IRU from offline status (u=0).
S_k	Set of intertie resources (including ETSRs) associated with ITC/ISL k.
^{DAM}	Superscript denoting DAM values.
^{FMM}	Superscript denoting FMM values.
^{RTD}	Superscript denoting RTD values.
$\forall$	For all…
$\rightarrow$	Leads to…
Δ	Denotes incremental values.
$\tilde{}$	Denotes initial values from an AC power flow solution.

∂	Partial derivative operator.
$u_{i,t}$	Binary variable indicating commitment status (online/offline) for Resource *i* in time period *t*.
$y_{i,t}$	Binary variable indicating that Resource *i* has a start-up in time period *t*.
$\eta_{i,t}$	Binary variable indicating that online Resource *i* can be shut-down in time period *t*.
$LOL_{i,t}$	Lower Operating Limit of Resource *i* in time period *t*.
$UOL_{i,t}$	Upper Operating Limit of Resource *i* in time period *t*.
$LRL_{i,t}$	Lower Regulating Limit of Resource *i* in time period *t*.
$URL_{i,t}$	Upper Regulating Limit of Resource *i* in time period *t*.
$LEL_{i,t}$	Lower Economic Limit of Resource *i* in time period *t*.
$UEL_{i,t}$	Upper Economic Limit of Resource *i* in time period *t*.
$CL_{i,t}$	Capacity Limit for Resource *i* in time period *t*; $UEL_{i,t} \leq CL_{i,t} \leq UOL_{i,t}$; it defaults to $UOL_{i,t}$.
$SUC_{i,t}$	Start-Up Cost for Resource *i* in time period *t*.
$SUT_{i,t}$	Start-Up Time for Resource *i* in time period *t*.
$MLC_{i,t}$	Minimum Load Cost for Resource *i* in time period *t*.
$EN_{i,t}$	Energy schedule of Resource *i* in time period *t*; positive for supply (generation and imports) and negative for demand (demand response and exports).
$MEN_{i,t}$	Metered Energy of Resource *i* in time period *t*.
$L_{i,t}$	Energy schedule of Non-Participating Load Resource *i* in time period *t*.
$IRU_{i,t}$	Imbalance Reserve Up capacity of Resource *i* for potential delivery in time period *t*.
$IRD_{i,t}$	Imbalance Reserve Down capacity of Resource *i* for potential delivery in time period *t*.
$FRU_{i,t}$	Flexible Ramping Up capacity of Resource *i* for potential delivery in time period *t*.
$FRD_{i,t}$	Flexible Ramping Down capacity 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*.
$RUC_{i,t}$	Regulation Up capacity bid of Resource *i* in time period *t*.
$RDC_{i,t}$	Regulation Down capacity bid of Resource *i* in time period *t*.
$SRC_{i,t}$	Spinning Reserve capacity bid of Resource *i* in time period *t*.
$NRC_{i,t}$	Non-Spinning Reserve capacity bid of Resource *i* in time period *t*.
$ENP_{i,t}$	Energy bid price of Resource *i* in time period *t*.
$IRUP_{i,t}$	Imbalance Reserve Up bid price of Resource *i* in time period *t*.
$IRDP_{i,t}$	Imbalance Reserve Down bid price of Resource *i* in time period *t*.
$RUP_{i,t}$	Regulation Up bid price of Resource *i* in time period *t*.

$RDP_{i,t}$	Regulation Down bid price of Resource *i* in time period *t*.
SRP_i	Spinning Reserve bid price of Resource *i* in time period *t*.
$NRP_{i,t}$	Non-Spinning Reserve bid price of Resource *i* in time period *t*.
$IRUR_t$	Imbalance Reserve Up uncertainty requirement in time period *t*.
$IRDR_t$	Imbalance Reserve Down uncertainty requirement in time period *t*.
RUR_t	Regulation Up requirement in time period *t*.
RDR_t	Regulation Down requirement in time period *t*.
SRR_t	Spinning Reserve requirement in time period *t*.
NRR_t	Non-Spinning Reserve requirement in time period *t*.
$RRU_{i,T}(EN_{i,t})$	Piecewise linear ramp up capability function of Resource *i* from its Energy schedule in time period *t* for time domain *T*.
$RRD_{i,T}(EN_{i,t})$	Piecewise linear ramp down capability function of Resource *i* from its Energy schedule in time period *t* for time domain *T*.
D_t	Demand forecast (non-participating load and transmission losses) for time period *t*.
$Loss_t$	Transmission losses in time period *t*.
$LPF_{i,t}$	Loss Penalty Factor for Resource *i* in time period *t*.
$SF_{i,k,t}$	Shift Factor for the Energy injection schedule of Resource *i* on network constraint *k* in time period *t*.
$F_{k,t}$	Active power flow or scheduled flow on network constraint *k* in time period *t*.
$LFL_{k,t}$	Lower active power flow or scheduling limit (non-positive) on network constraint *k* in time period *t*.
$UFL_{k,t}$	Upper active power flow or scheduling limit on network constraint *k* in time period *t*.
$I_{im,t}$	Energy schedule of Import Resource *im* in time period *t* $(I_{im,t} = EN_{i,t})$; used in ITC/ISL constraint formulation.
$E_{ex,t}$	Energy schedule of Export Resource *ex* in time period *t* $(E_{ex,t} = -EN_{i,t})$; used in ITC/ISL constraint formulation.
C	Objective function.
α_t	Shared ramping coefficient for Regulation in time period *t*.
β_t	Shared ramping coefficient for Spinning Reserve in time period *t*.
γ_t	Shared ramping coefficient for Non-Spinning Reserve in time period *t*.
δ_t	Shared ramping coefficient for Imbalance Reserve in time period *t*.
λ_t	Shadow price of power balance constraint in time period *t*.
ρ_t	Shadow price of IRU/FRU procurement constraint in time period *t*.
σ_t	Shadow price of IRD/FRD procurement constraint in time period *t*.
RC_t	Reliability capacity in time period *t*.
$URCC_t$	Upward reliability capacity cost in time period *t*.
$DRCC_t$	Downward reliability capacity cost in time period *t*.
$USEC_t$	Upward scheduled energy cost in time period *t*.
$DSEC_t$	Downward scheduled energy cost in time period *t*.
UUC_t	Upward uncertainty cost in time period *t*.
DUC_t	Downward uncertainty cost in time period *t*.

3.2 GENERAL PROBLEM FORMULATION

The enhanced DAM 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 IMBALANCE RESERVE MODEL

This section gives a brief overview of the Imbalance Reserve model without any Ancillary Services for simplicity. Figure 1 shows the Energy and Imbalance Reserve targets in a given time interval.

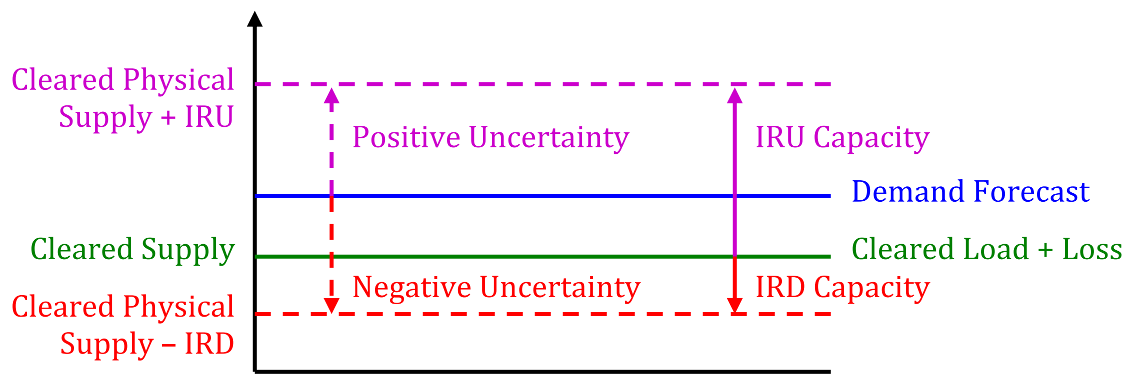

Figure 1. Energy and Imbalance Reserve targets

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

$$\left.\begin{aligned} &\sum_i EN_{i,t} + \sum_j EN_{j,t} = \sum_i L_{i,t} + \sum_j L_{j,t} + Loss_t \\ &\sum_i EN_{i,t} + \sum_i IRU_{i,t} \ge D_t + IRUR_t \\ &\sum_i EN_{i,t} - \sum_i IRD_{i,t} \le D_t - IRDR_t \end{aligned}\right\}, t = 1,2,\dots,T_D$$

Where IRU/IRD are ramping capacity products reserved to meet the demand forecast and uncertainty. The following figure shows the potential IRU/IRD capacity for a resource in a given time interval that can be reserved based on its Energy schedule in the previous time interval and its ramp capability.

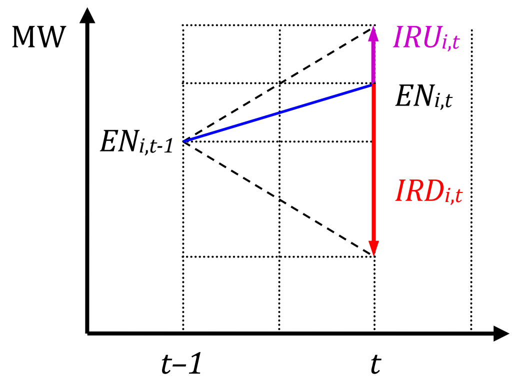

Figure 2. Energy and Imbalance Reserve ramp constraints

The dashed lines represent the upward and downward ramp capability of the resource from its Energy schedule in the previous time interval. The IRU/IRD capacity is limited by that ramp capability; it represents ramping capacity that is reserved from the scheduled ramp from the previous time interval to the next time interval and remains available to address the difference between the demand forecast and the scheduled load, plus any uncertainty that may materialize in real time.

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

$$\left.\begin{array}{l} LEL_{i,t} + IRD_{i,t} \leq EN_{i,t} \leq UEL_{i,t} - IRU_{i,t} \\ -RRD_{i,T_{15}}\left(EN_{i,t-1}\right) + IRD_{i,t} \leq EN_{i,t} - EN_{i,t-1} \leq RRU_{i,T_{15}}\left(EN_{i,t-1}\right) - IRU_{i,t} \end{array}\right\},$$
$$\forall i \wedge t = 1,2, \ldots, T_D$$

Where time period 0 denotes initial conditions. These constraints are more complicated when considering Ancillary Services awards, as shown in later sections.

The advisory Energy schedules and IRU/IRD capacity after the Trading Day are calculated optimally by extending the time horizon of the enhanced DAM past the Trading Day to meet the demand forecast and uncertainty, as follows:

$$\left.\begin{array}{l} \sum_i EN_{i,t} = D_t \\ \sum_i EN_{i,t} + \sum_i IRU_{i,t} \geq D_t + IRUR_t \\ \sum_i EN_{i,t} - \sum_i IRD_{i,t} \leq D_t - IRDR_t \end{array}\right\}, t = T_D + 1, \ldots, T_H$$

Where the bottom two constraints can be simplified as follows:

$$\left.\begin{array}{l}\sum_{i} IRU_{i,t} \geq IRUR_t \\ \sum_{i} IRD_{i,t} \geq IRDR_t\end{array}\right\}, t = T_D + 1, \dots, T_H$$

With the following set of capacity and ramp constraints:

$$\left.\begin{array}{l}LEL_{i,t} + IRD_{i,t} \leq EN_{i,t} \leq UEL_{i,t} - IRU_{i,t} \\ -RRD_{i,T_{60}}(EN_{i,t-1}) + IRD_{i,t} \leq EN_{i,t} - EN_{i,t-1} \leq RRU_{i,T_{60}}(EN_{i,t-1}) - IRU_{i,t}\end{array}\right\},$$
$$\forall i \wedge t = T_D + 1, \dots, T_H - 1$$

3.4 OBJECTIVE FUNCTION

The objective function, ignoring regulation mileage and assuming flat (single segment) Energy and IRU/IRD bids and no IRUR/IRDR elastic demand prices for simplicity, is as follows:

$$\begin{aligned}C = &\sum_{t=1}^{T_H}\sum_{i} y_{i,t}\, SUC_{i,t} + \sum_{t=1}^{T_H}\sum_{i} u_{i,t}\, MLC_{i,t} + \sum_{t=1}^{T_H}\sum_{i}\left(EN_{i,t} - LOL_{i,t}\right) ENP_{i,t} - \\ &\sum_{t=1}^{T_D}\sum_{i} L_{i,t}\, ENP_{i,t} + \sum_{t=1}^{T_D}\sum_{j} EN_{j,t}\, ENP_{j,t} - \sum_{t=1}^{T_D}\sum_{j} L_{j,t}\, ENP_{j,t} + \\ &\sum_{t=1}^{T_H}\sum_{i} RU_{i,t}\, RUP_{i,t} + \sum_{t=1}^{T_H}\sum_{i} RD_{i,t}\, RDP_{i,t} + \sum_{t=1}^{T_H}\sum_{i} SR_{i,t}\, SRP_{i,t} + \\ &\sum_{t=1}^{T_H}\sum_{i} NR_{i,t}\, NRP_{i,t} + \sum_{t=1}^{T_H}\sum_{i} IRU_{i,t}\, IRUP_{i,t} + \sum_{t=1}^{T_H}\sum_{i} IRD_{i,t}\, IRDP_{i,t}\end{aligned}$$

Where the cost contributions from non-participating load and virtual bids are limited to the Trading Day only. It is important to note that because the duration of the time period is not fixed throughout the time horizon, but it switches from 15min during the Trading Day to hourly afterwards, the cost contributions from MLC, Energy, Ancillary Services, and IRU/IRD during the Trading Day must be scaled down by $T_{15}/T_{60} = 0.25$. It is assumed here that this scaling factor is incorporated into the *MLC* and the bid prices for Energy, Ancillary Services, and IRU/IRD for the 15min intervals of the Trading Day.

All online services are zero when the resource is offline, whereas Non-Spinning Reserve can be provided by offline FSU (*SUT*≤10min) and IRU can be provided by offline SSU (*SUT*≤15min):

$$u_{i,t} = 0 \rightarrow \left\{\begin{array}{c}EN_{i,t} = RU_{i,t} = RD_{i,t} = SR_{i,t} = IRD_{i,t} = 0, \forall i \\ NR_{i,t} = 0, \forall i \notin S_{FSU} \\ IRU_{i,t} = 0, \forall i \notin S_{SSU}\end{array}\right\}, t = 1,2, \dots, T_H$$

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 IRU/IRD can only be awarded to resources certified to provide them, but any physical resource and Import/Export System Resource can be certified to provide IRU/IRD, except for non-participating load resources, hourly intertie resources, and hourly RDRR. Any resource certified for IRU/IRD with Energy bids can be awarded IRU/IRD.

3.5 POWER BALANCE CONSTRAINTS

The power balance constraints are as follows:

$$\sum_i EN_{i,t} + \sum_j EN_{j,t} = \sum_i L_{i,t} + \sum_j L_{j,t} + Loss_t, t = 1,2, \dots, T_D$$

$$\sum_i EN_{i,t} = D_t = \sum_i L_{i,t} + Loss_t, t = T_D + 1, \dots, T_H$$

Where after the Trading Day the demand forecast net of losses is distributed to load nodes using Load Distribution Factors (LDFs). For presentation purposes, it is convenient to consider that the virtual schedules are zero past the Trading Day so that the power balance constraints can be written collectively in the same form as follows:

$$\sum_i EN_{i,t} + \sum_j EN_{j,t} = \sum_i L_{i,t} + \sum_j L_{j,t} + Loss_t, t = 1,2, \dots, T_H$$

$$EN_{j,t} = L_{j,t} = 0, \forall j \wedge t = T_D + 1, \dots, T_H$$

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

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

Where:

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

$$\left.\begin{array}{l} \Delta EN_{i,t} = EN_{i,t} - \widetilde{EN}_{i,t} \\ \dfrac{\partial Loss_t}{\partial EN_{i,t}} = 1 - \dfrac{1}{LPF_{i,t}} \end{array}\right\}, \forall i \wedge t = 1,2, \dots, T_H$$

$$\left.\begin{array}{l} \Delta EN_{j,t} = EN_{j,t} - \widetilde{EN}_{j,t} \\ \dfrac{\partial Loss_t}{\partial EN_{j,t}} = 1 - \dfrac{1}{LPF_{j,t}} \end{array}\right\}, \forall j \wedge t = 1,2, \dots, T_H$$

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

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

The non-participating load is adjusted by the distributed load slack in the AC power flow solution, but it is not a variable in the SCUC after the Trading Day, hence the linearized power balance constraints are as follows:

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

$$\sum_i \frac{\Delta EN_{i,t}}{LPF_{i,t}} = 0, t = T_D + 1,\dots,T_H$$

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

3.6 IMBALANCE RESERVE PROCUREMENT CONSTRAINTS

Assuming for simplicity system-wide Imbalance Reserve procurement and inelastic demand, the IRU/IRD procurement constraints are as follows:

$$\left.\begin{aligned} \sum_i EN_{i,t} + \sum_i IRU_{i,t} \geq D_t + IRUR_t \\ \sum_i EN_{i,t} - \sum_i IRD_{i,t} \leq D_t - IRDR_t \end{aligned}\right\}, t = 1,2,\dots,T_D$$

$$\left.\begin{aligned} \sum_i IRU_{i,t} \geq IRUR_t \\ \sum_i IRD_{i,t} \geq IRDR_t \end{aligned}\right\}, t = T_D + 1,\dots,T_H$$

Where the Imbalance Reserve uncertainty requirements are derived as a percentile of historical net demand (demand minus VER production) forecast error between the DAM and the RTM.

3.7 NETWORK CONSTRAINTS

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

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

$$LFL_{k,t} \leq F_{k,t} \cong \tilde{F}_{k,t} + \sum_i \Delta EN_{i,t}\, SF_{i,k,t} \leq UFL_{k,t}, \forall k \wedge \ t = T_D + 1, \dots, T_H$$

Where the incremental Energy injections are multiplied by the corresponding shift factor for the relevant network constraint to account for changes in the active power flow from the AC power flow solution. Additional nodal constraints limit virtual and physical Energy schedules in the Trading Day when the power flow solution reverts to DC. Virtual bids and non-participating load are not present in the linearized physical network constraints after the Trading Day.

The IRU/IRD from intertie resources associated with Intertie Transmission Corridor (ITC) or Intertie Scheduling Limit (ISL) constraints are constrained by these constraints along with all other relevant commodities as follows:

$$\left.\begin{array}{c} \sum_{im \in S_k} \left(I_{im,t} + RU_{im,t} + SR_{im,t} + NR_{im,t} + IRU_{im,t}\right) - \sum_{ex \in S_k} \left(E_{ex,t} - IRU_{ex,t}\right) \leq UFL_{k,t} \\ \sum_{im \in S_k} \left(RU_{im,t} + SR_{im,t} + NR_{im,t} + IRU_{im,t}\right) + \sum_{ex \in S_k} IRU_{ex,t} \leq UFL_{k,t} \\ LFL_{k,t} \leq \sum_{im \in S_k} \left(I_{im,t} - RD_{im,t} - IRD_{im,t}\right) - \sum_{ex \in S_k} \left(E_{ex,t} + IRD_{ex,t}\right) \\ LFL_{k,t} \leq - \sum_{im \in S_k} \left(RD_{im,t} + IRD_{im,t}\right) - \sum_{ex \in S_k} IRD_{ex,t} \end{array}\right\},$$

$$\forall k \wedge t = 1, \dots, T_H$$

Where in the case of ITC constraints, the set S_k includes all intertie resources bound by the ITC k, and in the case of ISL constraints, the set S_k includes all intertie resources associated with (tagged at) the corresponding intertie of the ISL k. For ITC/ISL constraints, the upper limit is an import limit, whereas the lower limit is an algebraic export limit. By convention, the import direction in ITC constraints is into the associated BAA, and the import direction in ISL constraints is into the "from" BAA of the associated intertie. Virtual bids are not allowed on intertie resources and capacity ancillary services can only be provided by import resources, whereas IRU/IRD can be provided by both import and export resources, except for hourly intertie resources.

3.8 ANCILLARY SERVICES PROCUREMENT CONSTRAINTS

Assuming for simplicity system-wide Ancillary Services procurement, the constraints are as follows:

$$\left.\begin{array}{r}\sum_i RD_{i,t} \geq RDR_t \\ \sum_i RU_{i,t} \geq RUR_t \\ \sum_i RU_{i,t} + \sum_i SR_{i,t} \geq RUR_t + SRR_t \\ \sum_i RU_{i,t} + \sum_i SR_{i,t} + \sum_i NR_{i,t} \geq RUR_t + SRR_t + NRR_t\end{array}\right\}, t = 1,2, \dots, T_H$$

Note the cascaded procurement where higher quality services can meet the requirements for lower quality services. IRU/IRD do not overlap or cascade with capacity Ancillary Services because they are reserved capacity that will be converted to Energy and/or FRP in real time irrespective of regulation or contingency response needs.

3.9 ANCILLARY SERVICES AND IMBALANCE RESERVE BOUNDS

The Ancillary Services and Imbalance Reserve upper/lower bound constraints are as follows:

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

Where the Ancillary Services capacity bids are limited by the corresponding certified quantities. There are no explicit upper bounds for IRU/IRD since there is no associated capacity bid for them, i.e., all available capacity under the Energy bid above/below the Energy schedule can be procured as IRU/IRD, except for non-participating load, hourly intertie resources and hourly RDRR, which are not eligible for IRU/IRD. The Ancillary Services and Imbalance Reserves are further constrained by capacity and ramp constraints, described in the following sections.

3.10 ANCILLARY SERVICES TIME DOMAIN CONSTRAINTS

The Ancillary Services time domain constraints for online resources are as follows:

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

Where all upward Ancillary Services are simultaneously constrained by the 10min upward ramp capability from the Energy schedule.

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

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

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

3.11 SHARED RAMPING CONSTRAINTS

All Resource commodities, i.e., Energy, Ancillary Services, and Imbalance Reserves, are simultaneously constrained by the shared ramping constraints. For resources that remain online across time intervals, the shared ramping constraints are as follows:

$$\left.\begin{array}{l} EN_{i,t} - EN_{i,t-1} \geq -RRD_{i,T_{15}}\left(EN_{i,t-1}\right) + \alpha_t \dfrac{RD_{i,t-1} + RD_{i,t}}{2} + \delta_t\, IRD_{i,t} \\ EN_{i,t} - EN_{i,t-1} \leq RRU_{i,T_{15}}\left(EN_{i,t-1}\right) - \alpha_t \dfrac{RU_{i,t-1} + RU_{i,t}}{2} - \\ \qquad \beta_t \dfrac{SR_{i,t-1} + SR_{i,t}}{2} - \gamma_t \dfrac{NR_{i,t-1} + NR_{i,t}}{2} - \delta_t\, IRU_{i,t} \end{array}\right\},$$
$$\forall i \wedge u_{i,t-1} = u_{i,t} = 1 \wedge t = 1,2, \dots, T_D$$

$$\left.\begin{array}{l} EN_{i,t} - EN_{i,t-1} \geq -RRD_{i,T_{60}}\left(EN_{i,t-1}\right) + \alpha_t \dfrac{RD_{i,t-1} + RD_{i,t}}{2} + \delta_t\, IRD_{i,t} \\ EN_{i,t} - EN_{i,t-1} \leq RRU_{i,T_{60}}\left(EN_{i,t-1}\right) - \alpha_t \dfrac{RU_{i,t-1} + RU_{i,t}}{2} - \\ \qquad \beta_t \dfrac{SR_{i,t-1} + SR_{i,t}}{2} - \gamma_t \dfrac{NR_{i,t-1} + NR_{i,t}}{2} - \delta_t\, IRU_{i,t} \end{array}\right\},$$
$$\forall i \wedge u_{i,t-1} = u_{i,t} = 1 \wedge t = T_D + 1, \dots, T_H$$

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

$$EN_{i,t} \leq LOL_{i,t} + RRU_{i,T_{15}/2}\left(LOL_{i,t}\right) - \alpha_t\, RU_{i,t} - \beta_t\, SR_{i,t} - \gamma_t\, NR_{i,t} - \delta_t\, IRU_{i,t},$$
$$\forall i \wedge u_{i,t-1} = 0 \wedge u_{i,t} = 1 \wedge t = 1,2, \dots, T_D$$

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

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

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

$$EN_{i,t} \leq LOL_{i,t} + RRU_{i,T_{15}/2}\left(LOL_{i,t}\right) - \alpha_t\, RD_{i,t} - \delta_t\, IRD_{i,t}\},$$
$$\forall i \wedge u_{i,t} = 1 \wedge u_{i,t+1} = 0 \wedge t = 1,2, \dots, T_D$$

$$EN_{i,t} \leq LOL_{i,t} + RRD_{i,T_{60}/2}\left(LOL_{i,t}\right) - \alpha_t\, RD_{i,t} - \delta_t\, IRD_{i,t}\},$$
$$\forall i \wedge u_{i,t} = 1 \wedge u_{i,t+1} = 0 \wedge t = T_D + 1, \dots, T_H - 1$$

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

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

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

$$\gamma_t \frac{NR_{i,t-1} + NR_{i,t}}{2} + \delta_t \, IRU_{i,t} \leq LOL_{i,t} + RRU_{i,T_{60}-SUT_{i,t}}\left(LOL_{i,t}\right),$$
$$\forall i \in S_{SSU} \wedge u_{i,t-1} = u_{i,t} = 0 \wedge t = T_D + 1, \dots, T_H$$

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

The shared ramping coefficients specify how the various commodities share the resource ramp capability. The shared ramp constraint reserves ramp capability for the average Ancillary Services awards across the ramp between the time interval midpoints, whereas IRU/IRD align exactly with that ramp. A coefficient of 1 reserves all the ramp capability that is required for a service that ramps concurrently with Energy, such as Regulation and Imbalance Reserve, whereas smaller coefficients reserve ramp capability for services that may ramp only for a portion of the time interval, such as 10min contingency reserves. Therefore, subject to performance tuning, the shared ramping coefficients can be set as follows:

$$\left.\begin{array}{l} \alpha_t = \delta_t = 1 \\ \beta_t = \gamma_t = 2/3 \end{array}\right\}, t = 1,2, \dots, T_D$$

$$\left.\begin{array}{l} \alpha_t = \delta_t = 1 \\ \beta_t = \gamma_t = 1/6 \end{array}\right\}, t = T_D + 1, \dots, T_H$$

3.12 RESOURCE CAPACITY CONSTRAINTS

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

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

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

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

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

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

And for offline resources:

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

4 PRICE FORMATION AND SETTLEMENT

This section presents the price formation for Energy and IRU/IRD in the enhanced DAM. Ignoring marginal transmission losses and congestion contributions, the marginal prices for these commodities for each interval in the Trading Day are derived from the shadow prices of the three constraints used to achieve the enhanced DAM objectives:

$$\begin{array}{ll} \sum_i EN_{i,t} + \sum_j EN_{j,t} = \sum_i L_{i,t} + \sum_j L_{j,t} & \lambda_t \\ \sum_i EN_{i,t} + \sum_i IRU_{i,t} \geq D_t + IRUR_t & \rho_t \\ \sum_i EN_{i,t} - \sum_i IRD_{i,t} \leq D_t - IRDR_t & \sigma_t \end{array}$$

By observation, the marginal prices for Energy and IRU/IRD are as follows:

$$\begin{array}{cc} EN_{i,t} & \lambda_t + \rho_t + \sigma_t \\ EN_{j,t}, L_{i,t}, L_{j,t} & \lambda_t \\ IRU_{i,t} & \rho_t \\ IRD_{i,t} & -\sigma_t \end{array}$$

Note that under normal conditions, $\sigma \leq 0$ for a "≤" inequality constraint, hence the settlement for IRD is actually a payment, as it is for IRU. The marginal price for Energy from physical resources is different than that for virtual resources and non-participating load. This is because virtual and non-participating load schedules contribute only to the power balance constraint, whereas physical resource schedules contribute also to the IRU and IRD procurement constraints. Specifically, physical resource schedules have positive contributions in meeting the IRU target, hence the payment by ρ, and negative contributions in meeting the IRD target, hence the charge by σ.

To avoid the complexity of different marginal Energy prices for different resource types at the same location, we can bundle the Energy schedule of physical resources along with their IRU/IRD capacity as IRU/IRD awards with the following marginal prices:

$$\begin{array}{cc} EN_{i,t}, EN_{j,t}, L_{i,t}, L_{j,t} & \lambda_t \\ EN_{i,t} + IRU_{i,t} & \rho_t \\ EN_{i,t} - IRD_{i,t} & \sigma_t \end{array}$$

This is a useful transformation that also allows for a deviation settlement in the RTM where IRU/IRD are dispatched as Energy or re-procured as Flexible Ramping Up (FRU) or Flexible Ramping Down (FRD) capacity (or capacity Ancillary Services):

DAM	FMM	RTD
$\left(EN_{i,t}^{DAM} + IRU_{i,t}^{DAM}\right) \rho_t^{DAM}$	$\left[\left(EN_{i,t}^{FMM} + FRU_{i,t}^{FMM}\right) - \left(EN_{i,t}^{DAM} + IRU_{i,t}^{DAM}\right)\right] \rho_t^{FMM}$	$\left[\left(EN_{i,t}^{RTD} + FRU_{i,t}^{RTD}\right) - \left(EN_{i,t}^{FMM} + FRU_{i,t}^{FMM}\right)\right] \rho_t^{RTD}$
$\left(EN_{i,t}^{DAM} - IRD_{i,t}^{DAM}\right) \sigma_t^{DAM}$	$\left[\left(EN_{i,t}^{FMM} - FRD_{i,t}^{FMM}\right) - \left(EN_{i,t}^{DAM} - IRD_{i,t}^{DAM}\right)\right] \sigma_t^{FMM}$	$\left[\left(EN_{i,t}^{RTD} - FRD_{i,t}^{RTD}\right) - \left(EN_{i,t}^{FMM} - FRD_{i,t}^{FMM}\right)\right] \sigma_t^{RTD}$

Where ρ and σ in the RTM are the marginal prices for FRU and FRD, respectively. This transformation essentially folds the Forecasted Movement settlement into the FRU/FRD award settlement.

The No Pay settlement for Uninstructed Imbalance Energy (UIE) is as follows:

UIE	No Pay Charge
$MEN_{i,t} - EN_{i,t}^{RTD} > 0$	$\left(MEN_{i,t} - EN_{i,t}^{RTD}\right) \sigma_t^{RTD} - \min\left(MEN_{i,t} - EN_{i,t}^{RTD}, FRU_{i,t}^{RTD}\right) \rho_t^{RTD}$
$MEN_{i,t} - EN_{i,t}^{RTD} < 0$	$\left(MEN_{i,t} - EN_{i,t}^{RTD}\right) \rho_t^{RTD} - \max\left(MEN_{i,t} - EN_{i,t}^{RTD}, -FRD_{i,t}^{RTD}\right) \sigma_t^{RTD}$

Specifically, positive UIE is charged the FRD price for the Energy surplus and takes back the FRU payment at the FRU price for its conversion to Energy that receives a separate Energy settlement. Similarly, negative UIE is charged the FRU price for the Energy shortfall and takes back the FRD payment at the FRD price for its lack of Energy that receives a separate Energy settlement.

The transformation also allows for a comprehensive cost allocation of the IRU/IRD and FRU/FRD products across markets. In fact, separating the reliability capacity portion of IRU/IRD that covers the gap between the demand forecast and the scheduled physical supply:

$$RC_t = D_t - \sum_i EN_{i,t}\,, t = 1,2, \dots, T_D$$

Allows for the associated reliability cost to be allocated using a cost allocation method analogous to the existing RUC cost allocation:

Reliability Cost	Cost Allocation	
	Tier 1	Tier 2
$\max(0, RC_t)\ \rho_t^{DAM}$	In proportion to net negative demand deviation plus net virtual supply, up to a user rate of ρ_t^{DAM}	Remaining cost to metered demand

Reliability Cost	Cost Allocation	
	Tier 1	Tier 2
$-\min(0, RC_t)\ \sigma_t^{DAM}$	In proportion to net positive demand deviation plus net virtual demand, up to a user rate of $-\sigma_t^{DAM}$	Remaining cost to metered demand

Extracting the reliability cost from the cost of the IRU/IRD capacity leaves the cost of positive and negative uncertainty across markets that can be allocated similarly to the existing FRU/FRD uncertainty cost allocation:

Uncertainty Cost	Cost Allocation
$\left(\sum_i IRU_{i,t}^{DAM} - \max(0, RC_t)\right) \rho_t^{DAM} + \sum_i \left(FRU_{i,t}^{FMM} - IRU_{i,t}^{DAM}\right) \rho_t^{FMM} + \sum_i \left(FRU_{i,t}^{RTD} - FRU_{i,t}^{FMM}\right) \rho_t^{RTD} - \sum_i \min\left(\max\left(0, MEN_{i,t} - EN_{i,t}^{RTD}\right), FRU_{i,t}^{RTD}\right) \rho_t^{RTD}$	Positive uncertainty cost allocated to upward uncertainty movement in each category (Supply, Interties, Load)
$-\left(\sum_i IRD_{i,t}^{DAM} + \min(0, RC_t)\right) \sigma_t^{DAM} - \sum_i \left(FRD_{i,t}^{FMM} - IRD_{i,t}^{DAM}\right) \sigma_t^{FMM} - \sum_i \left(FRD_{i,t}^{RTD} - FRD_{i,t}^{FMM}\right) \sigma_t^{RTD} - \sum_i \max\left(\min\left(0, MEN_{i,t} - EN_{i,t}^{RTD}\right), -FRD_{i,t}^{RTD}\right) \sigma_t^{RTD}$	Negative uncertainty cost allocated to downward uncertainty movement in each category (Supply, Interties, Load)

The remaining cost is due to the energy schedule portion of the IRU/IRD awards across markets that can be allocated similarly to the Forecasted Movement cost allocation:

Scheduled Energy Cost	Cost Allocation
$\sum_i EN_{i,t}^{DAM}\ \rho_t^{DAM} +$ $\sum_i \left(EN_{i,t}^{FMM} - EN_{i,t}^{DAM}\right)\ \rho_t^{FMM} +$ $\sum_i \left(EN_{i,t}^{RTD} - EN_{i,t}^{FMM}\right)\ \rho_t^{RTD} +$ $\sum_i \min\left(0, MEN_{i,t} - EN_{i,t}^{RTD}\right)\ \rho_t^{RTD} +$ $\sum_i EN_{i,t}^{DAM}\ \sigma_t^{DAM} +$ $\sum_i \left(EN_{i,t}^{FMM} - EN_{i,t}^{DAM}\right)\ \sigma_t^{FMM} +$ $\sum_i \left(EN_{i,t}^{RTD} - EN_{i,t}^{FMM}\right)\ \sigma_t^{RTD} +$ $\sum_i \max\left(0, MEN_{i,t} - EN_{i,t}^{RTD}\right)\ \sigma_t^{RTD}$	To metered demand

Note that the settlement is based on energy quantities that incorporate energy schedule ramping for $EN_{i,t}^{RTD}$ over the 5min dispatch interval. Moreover, because prices are expressed in $/MWh, for settlement at a 5min granularity the energy and capacity quantities must be converted to MWh by dividing by 12.