Day-Ahead Market Enhancements

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 enhancement on the existing Day-Ahead Market (DAM), which includes the Integrated Forward Market (IFM) and the Residual Unit Commitment (RUC). The IFM enhancement introduces two new market commodities: imbalance reserve up (IRU) and imbalance reserve down (IRD). IRU/IRD is reserved 15min ramp capacity above/below the day-ahead energy schedule that must be available for dispatch in the Real-Time Market (RTM) to meet the demand forecast plus upward/downward uncertainty. IRU/IRD also meet the granularity difference between hourly schedules in the DAM and 15min schedules in the Fifteen Minute Market (FMM). The RUC enhancement also introduces two new market commodities: reliability capacity up (RCU) and reliability capacity down (RCD). RCU/RCD is reserved 60min ramp capacity above/below the day-ahead energy schedule that must be available for dispatch in the RTM to meet the RUC requirement, which is the algebraic difference between the demand forecast and physical supply schedules from the IFM. In that respect, the enhanced RUC replaces the RUC capacity in the current RUC with RCU to satisfy a positive RUC requirement and it introduces RCD to satisfy a negative RUC requirement. For a physical resource, the day-ahead energy schedule from the IFM, plus the RCU award, or minus the RCD award, amounts to the reliability schedule, which is analogous to the current RUC schedule.

1.1 EXISTING DAY-AHEAD MARKET STRUCTURE

Currently the DAM includes three sequential passes: the Market Power Mitigation (MPM), the IFM, and the RUC pass. The MPM pass 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. The RUC commits additional resources and procures additional capacity (RUC capacity) from physical resources above the day-ahead energy schedule to meet the day-ahead demand forecast while ignoring the IFM virtual supply/demand and load schedules. The resources that are committed in the IFM are kept online in the RUC. Moreover, the day-ahead 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 the IFM are fixed in the RUC.

1.2 DAY-AHEAD MARKET ENHANCEMENTS

The current Day-Ahead Market lacks a dedicated capacity product to address uncertainty that may materialize in real time, unlike the RTM that employs the Flexible Ramping Product (FRP). The RUC capacity is used instead to address positive uncertainty by using a high percentile for the demand forecast, but this capacity lacks the 15min ramp capability that is required for dispatch in the FMM, and there is no reserved capacity to address negative uncertainty. By contrast, the DAME will procure IRU and IRD with 15min ramp capability to address specifically positive and negative uncertainty, and RCU and RCD with 60min ramp capability to address separately a positive or negative RUC requirement based on the average demand forecast. Furthermore, IRU/IRD will address the granularity differences between the hourly schedules in the DAM and the 15min schedules and demand forecast in the FMM.

The IRU/IRD awards in the IFM are hourly, like any other market commodity in the DAME; however, they are limited by a 15min ramp capability because they must be fully dispatchable in the FMM. Therefore, only 15min-dispatchable resources may qualify for IRU/IRD awards in the IFM. Hourly dispatchable resources are not eligible for IRU/IRD awards, but they may qualify for RCU/RCD awards in the RUC because the latter are used to satisfy the hourly average demand forecast. Imbalance reserves and reliability capacity awards have a must-offer obligation (MOO) in the RTM, i.e., an energy bid must be submitted in the RTM for the corresponding resource capacity. Therefore, these day-ahead awards constitute available capacity that can be either dispatched as energy or used to procure FRP in the FMM.

As an additional reliability measure, the DAME will commit long-start resources for awarding imbalance reserves and/or reliability capacity that otherwise would be unavailable in the RTM. Furthermore, the time horizon of the RUC will be extended by a day or two to commit extra-long-start resources to meet the demand forecast and uncertainty requirements for the day(s) after the Trading Day.

The energy schedules, the ancillary services awards, and the IRU/IRD awards from the IFM solution are fixed in the RUC. Moreover, the resources that are committed in the IFM are kept online in the RUC. However, the RUC may commit additional resources to procure RCU. The RUC may also schedule a multi-state generating resource (MSG) in a different configuration than in the IFM, if that configuration supports the ancillary services and IRU/IRD awards. The RUC configuration may be at a higher or lower capacity range than the IFM configuration. Therefore, the RCU or RCD award may span capacity across different MSG configurations, including any capacity range between non-overlapping MSG configurations. The RUC commitment is considered advisory if the relevant inter-temporal constraints allow a potential revision in the RTM, otherwise it is financially binding overwriting any IFM commitment.

To ensure the deliverability of the IRU/IRD awards, IRU/IRD deployment scenarios are included in the IFM where the IRU/IRD awards are deployed to meet the IRU/IRD requirements while all network constraints are enforced. Similarly, the deliverability of RCU/RCD awards is ensured by enforcing network constraints in the RUC.

Because RCU/RCD is procured in the RUC based on submitted bids, another MPM pass is required after the IFM pass and before the RUC pass to mitigate potentially the bids used in the RUC. The MPM pass for the RUC (MPM-RUC) is a trial RUC pass that identifies and mitigates RCU/RCD bids based on similar criteria as the MPM pass for the IFM (MPM-IFM).

1.3 MARKET COMMODITIES IN THE DAY-AHEAD MARKET ENHANCEMENTS

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

- Day-ahead energy schedules for physical and virtual resources, and non-participating load;

- 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;
- Imbalance reserve up and down awards s; and
- Reliability capacity up or down awards for physical resources.

2 ASSUMPTIONS

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

- There are four sequential passes:
  1) MPM-IFM.
  2) IFM.
  3) MPM-RUC.
  4) RUC.
- The MPM-IFM is identical with the subsequent IFM, except that the submitted bids are used, and after the solution is obtained, these bids are tested for market power mitigation. The MPM-IFM is essentially a trial pass of the IFM where the following MPM principles apply at the solution:
  1) the impact of resource commitment, physical and virtual energy schedules, and imbalance reserve awards on the binding network constraints is quantified;
  2) the binding network constraints are classified as competitive or uncompetitive using the dynamic competitive path assessment (DCPA) method;
  3) the energy and IRU/IRD bids from resources that provide counter flow on the binding uncompetitive network constraints with net positive marginal price contributions from these constraints are mitigated above the competitive marginal price that does not include these contributions to the lower of the respective submitted bid or the default bid; and
  4) the mitigated energy and IRU/IRD bids are used instead of the submitted bids in the subsequent IFM pass.
- The IFM optimal solution consists of the resource commitment and the schedules and awards for the market commodities and their corresponding marginal prices, and it meets four objectives simultaneously:
  1) Cleared physical and virtual energy supply and demand bids are balanced; this is accomplished by the power balance constraint.

2) Ancillary services awards satisfy the ancillary services requirements; this is accomplished by the ancillary services procurement constraints.
3) IRU awards satisfy the upward uncertainty requirements; this is accomplished by the IRU procurement constraint.
4) IRD awards satisfy the downward uncertainty requirements; this is accomplished by the IRD procurement constraint.

- The IFM objective function is the maximization of the total merchandizing surplus over the IFM time horizon including the following:
  - the minimization of the cost of physical and virtual energy supply schedules;
  - the maximization of the benefit of virtual energy demand and load schedules;
  - the minimization of the start-up cost of committed resources;
  - the minimization of the minimum load cost of online resources;
  - the minimization of the state transition cost of multi-state generating resources;
  - the minimization of the cost of the ancillary services awards; and
  - the minimization of the cost of the IRU/IRD awards.
- The upward and downward uncertainty requirements for the IRU and the IRD are derived from the historical forecast error for demand, solar, and wind between the DAM and the FMM. To address the granularity differences between the DAM and the FMM, the IRU/IRD requirements for a given hour are calculated as the extreme historical error between the forecast in the four 15min intervals of that hour in the FMM and the hourly forecast in the DAM, within a specified confidence range. Furthermore, the hourly IRU/IRD requirements are adjusted to reflect the demand, solar, and wind forecasts for the Trading Day.
- The distribution of the IRU/IRD requirements in the IRU/IRD deployment scenarios in the IFM is divided among load, solar, and wind resources; the allocation factors are derived from historical data that reflect the relative contributions of these resource classes to the overall uncertainty.
- The MPM-RUC is identical with the subsequent RUC, except that the submitted reliability capacity bids are used, and after the solution is obtained, these bids are tested for market power mitigation. The MPM-RUC is essentially a trial pass of the RUC where the following MPM principles apply at the solution:

1) the impact of additional resource commitment and reliability capacity awards on the binding network constraints is quantified;
2) the binding network constraints are classified as competitive or uncompetitive using the DCPA method;
3) the RCU/RCD bids from resources that provide counter flow on the binding uncompetitive network constraints with net positive marginal price contributions from these constraints are mitigated above the competitive

marginal price that does not include these contributions to the lower of the respective submitted bid or the default bid; and

4) the mitigated RCU/RCD bids are used instead of the submitted bids in the subsequent RUC pass.

- The energy schedules, ancillary services awards, and imbalance reserve awards from the IFM solution are fixed in the RUC, whereas the virtual supply/demand and load schedules from the IFM solution are ignored. The RUC optimal solution consists of any additional resource commitment and the reliability capacity awards and their corresponding marginal prices, and it meets the following objective:
    - The physical energy supply schedules from the IFM solution and the reliability capacity awards balance the demand forecast; this is accomplished by the power balance constraint.
- The RUC objective function is the minimization of the total cost over the RUC time horizon including the following:
    - the minimization of the start-up cost of resources started up in the RUC;
    - the minimization of the minimum load cost of online resources started up or transitioned in the RUC;
    - the minimization of the state transition cost of multi-state generating resources transitioned in the RUC; and
    - the minimization of the cost of the RCU/RCD awards.
- Ancillary services are procured regionally in the IFM with nested regions under the system region to satisfy minimum requirements in each region. The procurement of IRU/IRD is locational through congestion management in the IRU/IRD deployment scenarios in the IFM. The procurement of RCU/RCD is also locational through congestion management in the RUC.
- All resource constraints are enforced in both the IFM and the RUC:
    - unit commitment inter-temporal constraints;
    - resource capacity and energy constraints; and
    - ramp capability constraints for the various market commodities.
- All applicable transmission constraints are enforced in both the IFM and the RUC:
    - network constraints for energy schedules and deployed capacity awards for the base case and preventive contingencies;
    - intertie scheduling limits for energy schedules and capacity awards;
    - transmission and generation nomograms, including gas burn constraints; and
    - minimum online capacity (MOC) constraints.
- Hourly intervals are used for the Trading Day in the IFM and the RUC, and hourly intervals for additional days in the RUC.

- Block hourly energy scheduling is available to hourly intertie resources in the IFM.
- Hourly energy scheduling is available to reliability demand response resources (RDRRs) and proxy demand resources (PDRs).
- Hourly intertie resources, hourly PDRs, and hourly RDRRs are not eligible for IRU/IRD awards in the IFM, but they are eligible for RCU/RCD awards in the RUC.
- The energy schedule, upward ancillary services awards, IRU awards, and RCU awards for Variable Energy Resources (VERs) are limited in the IFM and RUC by the corresponding hourly VER forecast. Furthermore, for VERs without sufficient RCU bids or no RCU bids, the RUC will use an extended RCU bid or the default RCU bid up to the corresponding hourly VER forecast to avoid over-commitment in anticipation of the associated energy supply in the RTM.

3 NOTATION

The following notation is used in the mathematical formulation for the IFM and RUC in this technical paper:

i	Resource/node index.
r	Ancillary services region index (zero for system).
m	Network constraint index.
k	Preventive contingency index.
g	Generation contingency index.
i_g	Node index for the generator outage of generation contingency g.
b	Gas-burn nomogram index.
o	Minimum Online Commitment constraint index.
n	Supplier index.
PS	Potentially pivotal supplier index.
t	Time period index (zero for initial condition).
^{r}	Superscript denoting RUC values.
^{k}	Superscript denoting preventive post-contingency values.
^{g}	Superscript denoting generation post-contingency values.
^{u}	Superscript denoting Imbalance Reserve Up deployment scenario values.
^{d}	Superscript denoting Imbalance Reserve Down deployment scenario values.
T_{10}	Ancillary services time domain (10min).
T_{15}	Imbalance reserve time domain (15min).
T_{60}	Time period duration (60min).
T	The number of time periods in the time horizon, considering the short and long days due to daylight savings changes.
N	The total number of suppliers.
$\forall$	For all…
$\therefore$	For…
$\in$	Member of…
$\notin$	Not member of…
$\wedge$	Logical and…

$\cup$	Union…
$\cap$	Intersection…
$\rightarrow$	Leads to…
Δ	Denotes incremental values from the previous iteration or incremental load adjustments in the IRU/IRD deployment scenarios.
∂	Partial derivative operator.
$\sim$	Accent denoting initial values from an AC power flow solution.
$'$	Prime denoting adjusted quantities.
S_r	Set of resources in ancillary services region *r*.
$S_{f,t}$	Set of online frequency-responsive resources in time period *t*.
S_b	Set of resources bound by gas-burn nomogram *b*.
S_o	Set of resources bound by Minimum Online Commitment constraint *o*.
S_{10}	Set of Fast-Start Units (*SUT* ≤ 10min) that can be certified to provide Non-Spinning Reserve from offline status (*u* = 0).
S_{15}	Set of 15min-start units (*SUT* ≤ 15min) that can be certified to provide IRU from offline status (*u* = 0).
S_{60}	Set of 60min-start units (*SUT* ≤ 60min) that can be certified to provide RCU 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.
S_{SVER}	Set of solar Variable Energy Resources.
S_{WVER}	Set of wind Variable Energy Resources.
S_{VER}	Set of Variable Energy Resources; $S_{VER} = S_{SVER} \cup S_{WVER}$.
S_{GR}	Set of generating resources.
S_{NGR}	Set of Non-Generator Resources.
S_n	Set of resources of Supplier *n*.
$PPS_{m,t}$	Set of resources of potential pivotal suppliers on network constraint *m* in time period *t*.
$FCS_{m,t}$	Set of resources of fringe competitive suppliers on network constraint *m* in time period *t*.
$u_{i,t}$	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 (offline/pumping).
$y_{i,t}$	Binary (0/1) variable indicating that Resource *i* has a start-up in time period *t*.
$w_{i,t}$	Binary (1/0) variable that is set if Resource *i* is must-run because of energy self-schedule, or regulation, spin, or online non-spin self-provision, or binding inter-temporal constraints. It is always 1 for NGRs that are always online.

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 physical 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*.
$L_{i,t}$	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*.
$IRU_{i,t}$	Imbalance Reserve Up award of Resource *i* in time period *t*.
$IRD_{i,t}$	Imbalance Reserve Down award of Resource *i* 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*.
$RCUBC_{i,t}$	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*.
$IRUBC_{i,t}$	Imbalance Reserve Up bid capacity of Resource *i* in time period *t*.
$IRDBC_{i,t}$	Imbalance Reserve 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*.
$ENBP_{i,t}$	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*.
$RCUBP_{i,t}$	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*.
$IRUBP_{i,t}$	Imbalance Reserve Up bid price of Resource *i* in time period *t*.
$IRDBP_{i,t}$	Imbalance Reserve 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*.
$IRUR_{t}$	Imbalance Reserve Up uncertainty requirement in time period *t*.
$IRDR_{t}$	Imbalance Reserve Down uncertainty requirement in time period *t*.
$IRULF_{t}$	Imbalance Reserve Up load allocation factor in time period *t*.
$IRUSF_{t}$	Imbalance Reserve Up solar allocation factor in time period *t*.
$IRUWF_{t}$	Imbalance Reserve Up wind allocation factor in time period *t*.
$IRDLF_{t}$	Imbalance Reserve Down load allocation factor in time period *t*.
$IRDSF_{t}$	Imbalance Reserve Down solar allocation factor in time period *t*.
$IRDWF_{t}$	Imbalance Reserve Down wind allocation factor in time period *t*.
$RUR_{r,t}$	Regulation Up requirement in ancillary services region *r* and time period *t*.
$RDR_{r,t}$	Regulation Down requirement in ancillary services region *r* and time period *t*.
$SRR_{r,t}$	Spinning Reserve requirement in ancillary services region *r* and time period *t*.
$NRR_{r,t}$	Non-Spinning Reserve requirement in ancillary services 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.
$Loss_{t}$	Transmission losses in time period *t*.
$LPF_{i,t}$	Loss penalty factor for Resource *i* in time period *t*.
$LDF_{i,t}$	Load distribution factor for node *i* in time period *t*.
$SDF_{i,t}$	Solar distribution factor for node *i* in time period *t*.
$WDF_{i,t}$	Wind distribution factor for node *i* in time period *t*.
$GLDF_{i,t}^{(g)}$	Generation Loss Distribution Factor for Resource *i* in time period *t* for generation contingency *g*.
$FS_{i,t}$	Solar forecast at node *i* in time period *t*.
$FW_{i,t}$	Wind forecast at node *i* in time period *t*.
$FV_{i,t}$	Generic VER forecast at node *i* in time period *t*.

$SF_{i,m,t}$	Shift factor for the energy injection of Resource *i* on network constraint *m* in time period *t*.
$SF'^{(g)}_{i,m,t}$	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 in generation contingency *g*.
$F_{m,t}$	Active power flow or scheduled flow due to 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*.
$\widetilde{LFL}_{m,t}$	Lower active power flow limit adjusted for reactive power flow on network constraint *m* in time period *t*.
$\widetilde{UFL}_{m,t}$	Upper active power flow limit adjusted for reactive power flow on network constraint *m* in time period *t*.
$GL_{b,t}$	Gas limit for gas-burn nomogram *b* 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 imbalance reserve and reliability capacity.
$\overline{EN}_i$	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* at the start of time period *t*.
$\overline{SOC}_{i,t}$	Maximum State of Charge for Limited Energy Storage Resource *i* at the start of time period *t*.
$\underline{SOC}_{i,t}$	Minimum State of Charge for Limited Energy Storage Resource *i* at the start of time period *t*.
$EN^{(+)}_{i,t}$	Energy discharge of Limited Energy Storage Resource *i* in time period *t*.
$EN^{(-)}_{i,t}$	Energy charge of Limited Energy Storage Resource *i* in time period *t*.
ARU_t	SOC attenuation factor for Regulation Up for Limited Energy Storage Resource *i* in time period *t*.
ARD_t	SOC attenuation factor for Regulation Down for Limited Energy Storage Resource *i* in time period *t*.
CF	Coverage factor for ancillary services awards for Limited Energy Storage Resources.
$WC_{i,m,t}$	Withheld supply counter flow from Resource *i* on network constraint *m* in time period *t*.
$\overline{SCF}_{i,m,t}$	Maximum supply counter flow from Resource *i* on network constraint *m* in time period *t*.
$\underline{SCF}_{i,m,t}$	Minimum supply counter flow from Resource *i* on network constraint *m* in time period *t*.

$DCF_{i,m,t}$	Demand for supply counter flow from Resource *i* on network constraint *m* in time period *t*.
$RSI_{m,t}$	Residual supply index of network constraint *m* 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 IRU deployment scenario constraint in time period *t*.
σ_t	Shadow price of IRD deployment scenario in time period *t*.
$\mu_{m,t}$	Shadow price of network constraint *m* in time period *t*.
$LMP_{i,t}$	Marginal Price for the Day-Ahead Energy schedule of Resource *i* in time period *t*.
$IRUMP_{i,t}$	Marginal Price for the Imbalance Reserve Up award of Resource *i* in time period *t*.
$IRDMP_{i,t}$	Marginal Price for the Imbalance Reserve Down award of Resource *i* in time period *t*.
$RCUMP_{i,t}$	Marginal Price for the Reliability Capacity Up award of Resource *i* in time period *t*.
$RCDMP_{i,t}$	Marginal Price for the Reliability Capacity Down award of Resource *i* in time period *t*.

Note: quantities in the downward direction (*RD*, *IRD*, *RCD*, and *RRD*) are non-negative.

4 IFM MATHEMATICAL FORMULATION

The focus of the mathematical formulation of IFM in this technical paper is on the integration of the IRU/IRD 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 procurement of IRU/IRD in IFM.

4.1 GENERAL PROBLEM FORMULATION

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

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

4.2 IMBALANCE RESERVE MODEL

This section gives an overview of the imbalance reserve model without ancillary services and network constraints for simplicity. Figure 1 below shows the three targets for day-ahead energy, imbalance reserve up, and imbalance reserve down in a given time interval.

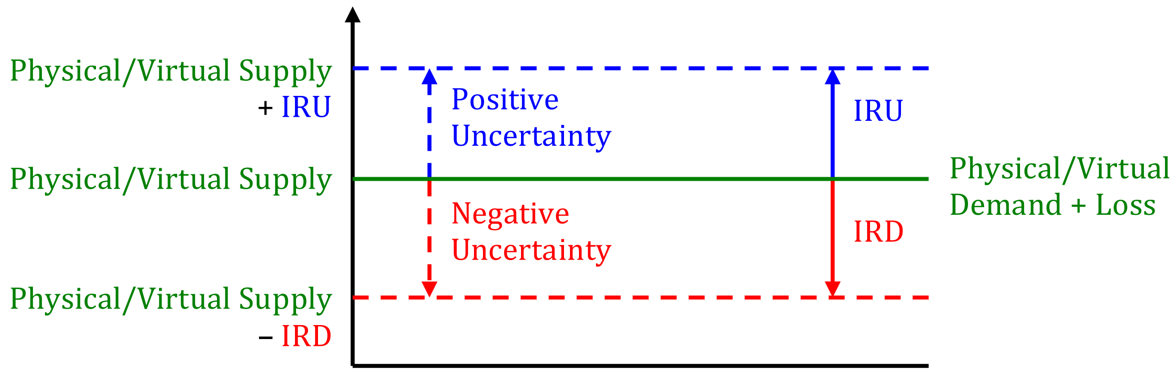

Figure 1. IFM targets for energy and imbalance reserves

The following constraints are enforced in IFM to meet these targets:

$$\left.\begin{array}{l}\sum_i EN_{i,t} + \sum_i VS_{i,t} = \sum_i L_{i,t} + \sum_i VD_{i,t} + Loss_t \\ \sum_i IRU_{i,t} \geq IRUR_t \\ \sum_i IRD_{i,t} \geq IRDR_t \end{array}\right\}, t = 1,2, \dots, T$$

VERs are eligible for both IRU and IRD awards, but their energy and upward capacity awards are limited by their VER forecast.

IRU/IRD is ramp capacity reserved between hours to meet the greatest uncertainty that may materialize in the net demand forecast (demand forecast minus VER forecast) in any of the corresponding 15min FMM intervals within a confidence range (95%), adjusted to reflect demand, solar, and wind forecasts for the Trading Day. Therefore, IRU and IRD are 15min capacity awards because they must be fully dispatchable within a 15min interval. Figure 2 below shows the potential IRU/IRD awards for a physical resource in a given hour based on its ramp capability and its day-ahead energy schedules across consecutive hours.

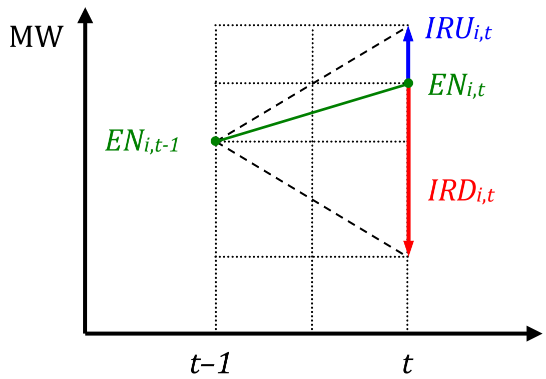

Figure 2. Imbalance reserve up and down awards

The dashed lines represent the upward and downward ramp capability of the resource from its day-ahead energy schedule in the previous hour. The change in the energy schedule across consecutive hours and the IRU/IRD awards share that ramp capability. The day-ahead energy schedules and IRU/IRD awards are constrained by the following set of capacity and ramp capability constraints:

$$\left.\begin{array}{l} LEL_{i,t} + IRD_{i,t} \leq EN_{i,t} \leq UEL_{i,t} - IRU_{i,t} \\ EN_{i,t} - EN_{i,t-1} \leq RRU_i\left(EN_{i,t-1}, T_{60}\right) - 4\,\delta\, IRU_{i,t} \\ EN_{i,t} - EN_{i,t-1} \geq -RRD_i\left(EN_{i,t-1}, T_{60}\right) + 4\,\delta\, IRD_{i,t} \end{array}\right\}, \forall i \wedge t = 1,2, \dots, T$$

The granularity adjustment factor (4) converts the 15min IRU/IRD awards to the hourly time domain of the energy schedule ramp. The capacity and ramp capability constraints are more complicated when considering ancillary services awards, as shown in §4.12 and §4.13, respectively.

4.3 OBJECTIVE FUNCTION

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

$$C = \sum_{t=1}^{T} \sum_{i} y_{i,t}\, SUC_{i,t} + \sum_{t=1}^{T} \sum_{i} u_{i,t}\, MLC_{i,t} - \sum_{t=1}^{T} \sum_{i \in S_{PSH}} v_{i,t}\, PC_{i,t} + \sum_{t=1}^{T} \sum_{i} u_{i,t} \left(EN_{i,t} - LOL_{i,t} \right) ENBP_{i,t} - \sum_{t=1}^{T} \sum_{i} L_{i,t}\, ENBP_{i,t} + \sum_{t=1}^{T} \sum_{i} VS_{i,t}\, VSBP_{i,t} - \sum_{t=1}^{T} \sum_{i} VD_{i,t}\, VDBP_{i,t} + \sum_{t=1}^{T} \sum_{i} RU_{i,t}\, RUBP_{i,t} + \sum_{t=1}^{T} \sum_{i} RD_{i,t}\, RDBP_{i,t} + \sum_{t=1}^{T} \sum_{i} SR_{i,t}\, SRBP_{i,t} + \sum_{t=1}^{T} \sum_{i} NR_{i,t}\, NRBP_{i,t} + \sum_{t=1}^{T} \sum_{i} IRU_{i,t}\, IRUBP_{i,t} + \sum_{t=1}^{T} \sum_{i} IRD_{i,t}\, IRDBP_{i,t}$$

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

$$u_{i,t} = 0 \rightarrow \left\{ \begin{matrix} EN_{i,t} = RU_{i,t} = RD_{i,t} = SR_{i,t} = IRD_{i,t} = 0 \\ NR_{i,t} = 0, \forall i \notin S_{10} \\ IRU_{i,t} = 0, \forall i \notin S_{15} \end{matrix} \right\}, \forall i \wedge t = 1,2, \dots, T$$

System Resources (SRs), Non-Generator Resources (NGRs), virtual resources, and non-participating load resources have no discontinuities or inter-temporal constraints and are always modeled as online ($u = 1$). Ancillary services and IRU/IRD can only be awarded to resources certified to provide them, but any physical resource, including VERs and Import/Export System Resources, can be certified to provide IRU/IRD, except for non-participating load resources, hourly intertie resources, and hourly PDRs and RDRRs. An energy bid is required for IRU/IRD awards.

4.4 POWER BALANCE CONSTRAINTS

The power balance constraints for the day-ahead energy schedules are 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 constraints for the day-ahead energy schedules are 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.

4.5 ANCILLARY SERVICES

The regional ancillary services procurement constraints are as follows:

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

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. IRU/IRD do not overlap or cascade with ancillary services because they are reserved capacity that can be dispatched irrespective of regulation or contingency response needs.

4.6 IMBALANCE RESERVES

The system-wide IRU/IRD procurement constraints are as follows:

$$\left.\begin{aligned}\sum_i IRU_{i,t} \geq IRUR_t \\ \sum_i IRD_{i,t} \geq IRDR_t\end{aligned}\right\}, t = 1,2, \dots, T$$

The IRU/IRD requirements for a given hour are calculated as the extreme historical difference between the highest/lowest net demand forecast over the four 15min intervals of that hour in FMM and the hourly net demand forecast in IFM, within a specified confidence range (95%), adjusted to reflect demand, solar, and wind forecasts for the Trading Day. With a nonzero cost for IRU/IRD awards, these constraints are binding (satisfied as equalities) at the optimal solution.

To ensure the deliverability of IRU/IRD awards, network constraints are enforced for IRU/IRD deployment scenarios where the IRU/IRD requirement is distributed to load and VER nodes while the IRU/IRD awards are dispatched to balance the system, respectively. Consequently, the IRU/IRD deployment scenarios simulate the deployment of IRU/IRD awards to meet the maximum upward/downward uncertainty that can materialize on the net demand forecast within a specified confidence range (95%). The resulting power flows on the transmission network are constrained by network constraints in the IRU/IRD deployment scenarios, as described in §4.9.2-§4.9.3, to ensure that if that maximum upward/downward uncertainty materializes, the IRU/IRD awards can be fully deployed to satisfy it without violating network constraints.

4.7 UPPER/LOWER CAPACITY BOUNDS

The ancillary services and IRU/IRD upper/lower bound constraints are as follows:

$$\left.\begin{aligned}0 \leq RD_{i,t} \leq RDBC_{i,t} \\ 0 \leq RU_{i,t} \leq RUBC_{i,t} \\ 0 \leq SR_{i,t} \leq SRBC_{i,t} \\ 0 \leq NR_{i,t} \leq NRBC_{i,t} \\ 0 \leq RCU_{i,t} \leq RCUBC_{i,t} \\ 0 \leq RCD_{i,t} \leq RCDBC_{i,t} \\ 0 \leq IRU_{i,t} \leq IRUBC_{i,t} \\ 0 \leq IRD_{i,t} \leq IRDBC_{i,t}\end{aligned}\right\}, \forall i \wedge t = 1,2, \dots, T$$

The ancillary services and IRU/IRD capacity bids are limited by the corresponding certified quantities. Capacity bids for IRU/IRD can be used to limit exposure to the Must Offer Obligation associated with the corresponding awards in RTM.

The ancillary services and IRU/IRD awards are further constrained by capacity and ramp capability constraints, described in §4.12 and §4.13, respectively.

4.8 NETWORK CONSTRAINTS

This section describes the various network constraints enforced in IFM.

4.8.1 Transmission Constraints

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

$$LFL_{m,t} \leq F_{m,t} \leq UFL_{m,t}, \forall m \wedge \ t = 1,2, \ldots, T$$

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 as follows:

$$\widetilde{LFL}_{m,t} \leq \tilde{F}_{m,t} + \sum_{i} \left(\Delta EN_{i,t} + \Delta VS_{i,t} - \Delta VD_{i,t} - \Delta L_{i,t} \right) SF_{i,m,t} \leq \widetilde{UFL}_{m,t}, \forall m \wedge t = 1,2, \ldots, T$$

The incremental energy injections are multiplied by the corresponding shift factors 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. The shift factors are calculated with reference the distributed load in the market footprint. The transmission constraint upper/lower active power flow limits are adjusted in each iteration to convert the respective MVA limits to MW limits accounting for reactive power flows at the previous AC power flow solution.

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

Transmission constraints are also enforced in the IRU/IRD deployment scenarios, as described in §4.9.2.

4.8.2 Scheduling Limits

The ancillary services and IRU/IRD awards from intertie resources associated with Intertie Transmission Corridor (ITC) or Intertie Scheduling Limit (ISL) constraints are limited by scheduling limits. The ITC/ISL constraints allow netting of import and export energy schedules, but they prevent netting among energy schedules and ancillary services or IRU/IRD awards because they are not simultaneously dispatched:

$$\left.\begin{array}{l}\max\left(0,\sum_{i\in S_m} EN_{i,t}\right)+\sum_{i\in I_m}\left(RU_{i,t}+SR_{i,t}+NR_{i,t}\right)+\sum_{i\in S_m} IRU_{i,t}\leq UFL_{m,t}\\ LFL_{m,t}\leq\min\left(0,\sum_{i\in S_m} EN_{i,t}\right)-\sum_{i\in I_m} RD_{i,t}-\sum_{i\in S_m} IRD_{i,t}\end{array}\right\},\forall m\wedge t=1,\dots,T$$

The ITC/ISL constraints are linearized as follows:

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

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. Virtual bids are not allowed on intertie resources. Ancillary services can only be provided by certified import resources. Hourly intertie resources are not eligible for IRU/IRD awards. 15min or dynamic intertie resources must be certified to provide IRU/IRD. For an export or a demand response resource, IRU dispatch is a decrease in the energy schedule, whereas IRD dispatch is an increase in the energy schedule.

Since IRU/IRD awards are reserved from intertie transmission capacity via ITC/ISL constraints, there is no reason to enforce these constraints in the IRU/IRD deployment scenarios when these IRU/IRD awards are deployed.

4.8.3 Contingency Constraints

There are two different contingency constraints enforced in IFM:

1) N–1 preventive transmission contingencies; and

2) G–1 or N–1+RAS generation/transmission contingencies.

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

$$\widetilde{LFL}_{m,t}^{(k)}\leq\tilde{F}_{m,t}^{(k)}+\sum_{i}\left(\Delta EN_{i,t}+\Delta VS_{i,t}-\Delta VD_{i,t}-\Delta L_{i,t}\right)SF_{i,m,t}^{(k)}\leq\widetilde{UFL}_{m,t}^{(k)},\forall k,m\wedge t=1,2,\dots,T$$

No additional control variables are introduced. The difference is that the upper/lower active power 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 per hour per contingency are required to linearize the transmission constraints in each post-contingency case, but they can be easily derived from the AC power flow solutions for the base 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 available capacity of these generators:

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

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

$$\widetilde{LFL}_{m,t}^{(g)} \leq \tilde{F}_{m,t}^{(g)} + \sum_i \left(\Delta EN_{i,t}^{(g)} + \Delta VS_{i,t} - \Delta VD_{i,t} - \Delta L_{i,t} \right) SF_{i,m,t}^{(g)} \leq \widetilde{UFL}_{m,t}^{(g)},$$
$$\forall g, m \wedge t = 1,2, \dots, T$$

The difference is that the constraints are formulated for the post-contingency physical resource day-ahead energy schedules, which are dependent variables that reflect the distribution of lost/tripped generation. The upper/lower active power 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 per hour per contingency are required to linearize the transmission constraints in each post-contingency case.

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

$$SF'^{(g)}_{i,m,t} = \left\{\begin{array}{ll} \sum_{i \neq i_g} GLDF_{i,t}^{(g)}\, SF_{i,m,t}^{(g)} & \therefore i = i_g \\ SF_{i,m,t}^{(g)} & \therefore i \neq i_g \end{array}\right\}, \forall i, g \wedge t = 1,2, \dots, T$$

Then, assuming that there are no virtual or non-participating load resources at node i_g, the linearized generation/transmission contingency constraints can be written as follows:

$$\widetilde{LFL}_{m,t}^{(g)} \leq \tilde{F}_{m,t}^{(g)} + \sum_i \left(\Delta EN_{i,t} + \Delta VS_{i,t} - \Delta VD_{i,t} - \Delta L_{i,t} \right) SF'^{(g)}_{i,m,t} \leq \widetilde{UFL}_{m,t}^{(g)},$$
$$\forall g, m \wedge t = 1,2, \dots, T$$

Contingency constraints are also enforced in the IRU/IRD deployment scenarios, as described in §4.9.3.

4.9 IMBALANCE RESERVE DEPLOYMENT SCENARIOS

This section describes the IRU/IRD deployment scenarios where the IRU/IRD awards are deployed to meet the IRU/IRD requirements while all network constraints are enforced.

4.9.1 Imbalance Reserve Requirement Distribution

In the IRU/IRD deployment scenarios, the IRU/IRD awards are fully deployed while the IRU/IRD requirements are distributed to load and VER nodes, superimposed on the load and VER schedules. The distribution of the IRU/IRD requirements is divided among load, solar, and wind resources using allocation factors derived from historical data that reflect the relative contributions of these resource classes to the net demand forecast uncertainty.

The IRU requirement component for load is distributed in the IRU deployment scenario as a positive load change, whereas the IRD requirement component for load is distributed in the IRD deployment scenario as a negative load change. The distribution of these requirement components to the load nodes uses the same load distribution factors that are used to distribute the demand forecast in RUC:

$$\left.\begin{aligned} \Delta L_{i,t}^{(u)} &= LDF_{i,t}\; IRULF_t\; IRUR_t, \forall i \\ \Delta L_{i,t}^{(d)} &= -LDF_{i,t}\; IRDLF_t\; IRDR_t, \forall i \end{aligned}\right\}, t = 1,2, \dots, T$$

The IRU requirement components for solar and wind are distributed in the IRU deployment scenario as a positive load change, whereas the IRD requirement components for solar and wind are distributed in the IRD deployment scenario as a negative load change. The distribution of these requirement components to the solar and wind VER nodes is in proportion to the respective VER forecast:

$$\left.\begin{aligned} \Delta L_{i,t}^{(u)} &= SDF_{i,t}\; IRUSF_t\; IRUR_t, \forall i \in S_{SVER} \\ \Delta L_{i,t}^{(u)} &= WDF_{i,j,t}\; IRUWF_t\; IRUR_t, \forall i \in S_{WVER} \\ \Delta L_{i,t}^{(d)} &= -SDF_{i,t}\; IRDSF_t\; IRDR_t, \forall i \in S_{SVER} \\ \Delta L_{i,t}^{(d)} &= -WDF_{i,t} IRDWF_t\; IRDR_t, \forall i \in S_{WVER} \end{aligned}\right\}, t = 1,2, \dots, T$$

Where the solar/wind distribution factors are derived as follows:

$$\left.\begin{aligned} SDF_{i,t} &= \frac{FS_{i,t}}{\sum_i FS_{i,t}}, \forall i \in S_{SVER} \\ WDF_{i,t} &= \frac{FW_{i,t}}{\sum_i FW_{i,t}}, \forall i \in S_{WVER} \end{aligned}\right\}, t = 1,2, \dots, T$$

4.9.2 Transmission Constraints in Imbalance Reserve Deployment Scenarios

To ensure the deliverability of IRU/IRD awards with respect to network constraints, transmission constraints are also enforced in the IRU/IRD deployment scenarios, as follows:

$$\left.\begin{array}{l} \widetilde{LFL}_{m,t}^{(u)} \leq \tilde{F}_{m,t}^{(u)} + \sum_{i} \left(\Delta EN_{i,t} + \Delta IRU_{i,t} + \Delta VS_{i,t} - \Delta VD_{i,t} - \Delta L_{i,t} \right) SF_{i,m,t} \leq \widetilde{UFL}_{m,t}^{(u)} \\ \widetilde{LFL}_{m,t}^{(d)} \leq \tilde{F}_{m,t}^{(d)} + \sum_{i} \left(\Delta EN_{i,t} - \Delta IRD_{i,t} + \Delta VS_{i,t} - \Delta VD_{i,t} - \Delta L_{i,t} \right) SF_{i,m,t} \leq \widetilde{UFL}_{m,t}^{(d)} \end{array}\right\},$$
$$\forall m \wedge t = 1,2, \dots, T$$

Two additional AC power flows per interval are needed, one for each of the IRU/IRD deployment scenarios. The incremental energy and IRU/IRD injection changes from the previous iteration are multiplied by the corresponding shift factors for the relevant transmission constraint to account for changes in the active power flow from the AC power flow solution. The transmission constraint upper/lower active power flow limits are adjusted in each iteration to convert the respective MVA limits to MW limits accounting for reactive power flows at the previous AC power flow solution. The effect of transmission losses due to the deployment of IRU/IRD awards and the distribution of the IRU/IRD requirements are included in the AC power flow solution. The shift factors in the IRU/IRD deployment scenarios are the same as the ones in the base scenario because the transmission network is the same; however, the critical constraints are different in general.

4.9.3 Contingency Constraints in Imbalance Reserve Deployment Scenarios

To ensure the deliverability of IRU/IRD awards with respect to network constraints, contingency constraints are also enforced in the IRU/IRD deployment scenarios, as follows:

$$\left.\begin{array}{l} \widetilde{LFL}_{m,t}^{(k,u)} \leq \tilde{F}_{m,t}^{(k,u)} + \sum_{i} \left(\Delta EN_{i,t} + \Delta IRU_{i,t} + \Delta VS_{i,t} - \Delta VD_{i,t} - \Delta L_{i,t} \right) SF_{i,m,t}^{(k)} \leq \widetilde{UFL}_{m,t}^{(k,u)} \\ \widetilde{LFL}_{m,t}^{(k,d)} \leq \tilde{F}_{m,t}^{(k,d)} + \sum_{i} \left(\Delta EN_{i,t} - \Delta IRD_{i,t} + \Delta VS_{i,t} - \Delta VD_{i,t} - \Delta L_{i,t} \right) SF_{i,m,t}^{(k)} \leq \widetilde{UFL}_{m,t}^{(k,d)} \end{array}\right\},$$
$$\forall k, m \wedge t = 1,2, \dots, T$$

$$\left.\begin{array}{l} \widetilde{LFL}_{m,t}^{(g,u)} \leq \tilde{F}_{m,t}^{(g,u)} + \sum_{i} \left(\Delta EN_{i,t} + \Delta IRU_{i,t} + \Delta VS_{i,t} - \Delta VD_{i,t} - \Delta L_{i,t} \right) SF'^{(g)}_{i,m,t} \leq \widetilde{UFL}_{m,t}^{(g,u)} \\ \widetilde{LFL}_{m,t}^{(g,d)} \leq \tilde{F}_{m,t}^{(g,d)} + \sum_{i} \left(\Delta EN_{i,t} - \Delta IRD_{i,t} + \Delta VS_{i,t} - \Delta VD_{i,t} - \Delta L_{i,t} \right) SF'^{(g)}_{i,m,t} \leq \widetilde{UFL}_{m,t}^{(g,d)} \end{array}\right\},$$
$$\forall g, m \wedge t = 1,2, \dots, T$$

Two additional AC power flows per hour per contingency are needed to linearize the transmission constraints in each post-contingency case, one for each of the IRU/IRD deployment scenarios. The effect of transmission losses due to the deployment of IRU/IRD awards and the distribution of the IRU/IRD requirements are included in the AC power flow solution. The shift factors in the IRU/IRD deployment scenarios are the same as the ones in the base scenario because the transmission network is the same for the same contingency; however, the critical contingencies and constraints are different in general.

4.10 GAS-BURN NOMOGRAMS

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

$$\sum_{i \in S_b} a_i \left(EN_{i,t} + IRU_{i,t} \right) \leq GL_{b,t}, \forall b \wedge t = 1,2, \dots, T$$

4.11 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:

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

4.12 CAPACITY CONSTRAINTS

This section describes the resource capacity constraints. In IFM, an energy bid is required for day-ahead energy schedules and IRU/IRD awards, but not for Regulation or Spinning and Non-Spinning Reserve awards. Therefore, day-ahead energy schedules and IRU/IRD awards 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:

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

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

The LEL is equal to the energy self-schedule, if one is submitted, or to LCL otherwise.

The capacity constraints for online physical resources are as follows:

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

The capacity constraints for offline physical resources are as follows:

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

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

The capacity constraints for 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 energy bid curve for virtual demand and non-participating load is monotonically decreasing.

The UOL and UEL for VERs are limited by their VER forecast:

$$\left.\begin{array}{l} UOL_{i,t} \leq FV_{i,t} \\ UEL_{i,t} \leq FV_{i,t} \end{array}\right\}, \forall i \in S_{VER} \wedge t = 1,2,\ldots,T$$

4.13 RAMP CAPABILITY CONSTRAINTS

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

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

The ramp capability constraints for offline Non-Spinning Reserve are as follows:

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

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

Similarly, the ramp capability constraints for offline IRU are as follows:

$$NR_{i,t} + IRU_{i,t} \leq LOL_{i,t} + RRU_i\left(LOL_{i,t}, T_{15} - SUT_{i,t}\right), \forall i \in S_{15} \wedge u_{i,t} = 0 \wedge t = 1,2,\ldots,T$$

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

Capacity awards and day-ahead energy schedule changes across hours share the resource dynamic ramp capability. For resources that are online across intervals, these constraints are as follows:

$$\left.\begin{array}{l} EN_{i,t} - EN_{i,t-1} \leq \left(\begin{array}{c} RRU_i\left(EN_{i,t-1}, T_{60}\right) - \alpha \dfrac{RU_{i,t-1} + RU_{i,t}}{2} - \\ \beta \dfrac{SR_{i,t-1} + SR_{i,t}}{2} - \gamma \dfrac{NR_{i,t-1} + NR_{i,t}}{2} - 4\,\delta\, IRU_{i,t} \end{array}\right) \\ EN_{i,t} - EN_{i,t-1} \geq -RRD_i\left(EN_{i,t-1}, T_{60}\right) + \alpha \dfrac{RD_{i,t-1} + RD_{i,t}}{2} + 4\,\delta\, IRD_{i,t} \end{array}\right\}, \forall i \wedge t = 1,2,\ldots,T$$

Where the ancillary servicers awards may be different during the ramp across the midpoints of consecutive hours, whereas the imbalance reserve awards align fully with that ramp. The granularity adjustment factor (4) converts the 15min IRU/IRD awards to the hourly time domain of the energy schedule ramp.

For resources that start up at the beginning of an hour, the ramp capability constraints are as follows:

$$EN_{i,t} \leq LOL_{i,t} + RRU_i\left(LOL_{i,t}, T_{60}/2\right) - \alpha\, RU_{i,t} - \beta\, SR_{i,t} - \gamma\, NR_{i,t} - 2\, \delta\, IRU_{i,t},$$
$$\forall i \wedge u_{i,t-1} = 0 \wedge u_{i,t} = 1 \wedge t = 1,2, \dots, T$$

Where the ramp up from the LOL is for half of the interval ramp. The granularity adjustment factor (2) converts the 15min IRU awards to the half-hourly time domain of the energy schedule ramp from the beginning of the hour.

For resources that shut down at the end of an hour, the ramp capability constraints are as follows:

$$EN_{i,t} \leq LOL_{i,t} + RRU_i\left(LOL_{i,t}, T_{60}/2\right) - \alpha\, RD_{i,t} - 2\, \delta\, IRD_{i,t},$$
$$\forall i \wedge u_{i,t} = 1 \wedge u_{i,t+1} = 0 \wedge t = 1,2, \dots, T-1$$

Where the ramp down to LOL is for half of the interval ramp. The granularity adjustment factor (2) converts the 15min IRD awards to the half-hourly time domain of the energy schedule ramp to the end of the hour. Resources are never shut down in the last interval of the time horizon.

The shared ramping coefficients (α, β, γ, and δ) specify how the various commodities share the resource ramp capability. The ramp capability constraint reserves ramp capability for the ancillary services and IRU/IRD awards over the ramp between consecutive hour 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 IRU/IRD, whereas smaller coefficients may be used to reserve ramp capability for contingency reserves.

4.14 ENERGY CONSTRAINTS

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

a) Daily energy limits; and

b) State of Charge (SOC) limits.

Daily energy limits restrict the hourly day-ahead 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:

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

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:

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

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

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

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

PSH resources may only have IRU/IRD awards in generating mode.

The SOC limits constrain the energy schedules, ancillary services awards, and IRU/IRD awards for Limited Energy Storage Resources (LESR), a specific type of a 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:

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

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

$$\left.\begin{array}{l} SOC_{i,t-1} - RU_{i,t} - SR_{i,t} - NR_{i,t} - IRU_{i,t} \geq \underline{SOC}_{i,t} \\ SOC_{i,t-1} + \eta_i\left(RD_{i,t} + IRD_{i,t}\right) \leq \overline{SOC}_{i,t} \end{array}\right\}, \forall i \in S_{LESR} \wedge t = 1,2,\dots,T$$

With the energy storage enhancements initiative, the following SOC attenuation constraints are introduced:

$$\left.\begin{array}{l} SOC_{i,t}^{(u)} = SOC_{i,t-1}^{(u)} - EN_{i,t}^{(+)} - \eta_i\,EN_{i,t}^{(-)} - ARU_t\,RU_{i,t} \geq \underline{SOC}_{i,t} \\ SOC_{i,t}^{(d)} = SOC_{i,t-1}^{(d)} - EN_{i,t}^{(+)} - \eta_i\,EN_{i,t}^{(-)} + \eta_i\,ARD_t\,RD_{i,t} \leq \overline{SOC}_{i,t} \end{array}\right\}, \forall i \in S_{LESR} \wedge t = 1,2,\dots,T$$

Where upper and lower SOC profiles are tracked separately to prevent cancelation of upward and downward capacity services in the SOC attenuation constraints.

Furthermore, the following opposite dispatchable energy bid requirements are also introduced:

$$\left. \begin{array}{l} CF\ RU_{i,t} \leq -LCL_{i,t} - RD_{i,t} \\ CF\ RU_{i,t} \leq \min(0, -LEL_{i,t}) \\ CF\ RD_{i,t} \leq UCL_{i,t} - RU_{i,t} \\ CF\ RD_{i,t} \leq \min(0, UEL_{i,t}) \end{array} \right\}, \forall i \in S_{LESR} \wedge t = 1,2, \ldots, T$$

Note that for NGR in general, LOL, LEL, LRL, and LCL may be negative. If there is a discharging or charging self-schedule, the LEL is equal to the discharging self-schedule, or the UEL is equal to the charging self-schedule.

4.15 MARKET POWER MITIGATION

This section describes the MPM-IFM, which is identical with the subsequent IFM, except that the submitted energy and IRU/IRD bids are used, and after the solution is obtained, these bids are tested for market power mitigation. The mitigated energy and IRU/IRD bids are then used instead of the submitted bids in the subsequent IFM.

The binding network constraints at the MPM-IFM solution are classified as competitive or uncompetitive using the dynamic competitive path assessment (DCPA) method. DCPA calculates the residual supply index for each binding transmission constraint based on the three largest pivotal suppliers (RSI-3) with the highest supply counter flow contributions to the constraint. DCPA considers only generating resources and NGRs that provide a counter flow (with negative shift factors) to binding transmission constraints (formulated as a "≤" inequality constraint). DCPA does not consider demand resources because there is no mitigation for demand resources as they have no incentive to exercise market power to elevate the marginal prices at which energy or capacity awards are settled. Furthermore, intertie and virtual supply resources are excluded from the RSI calculation because they are considered fringe competitive suppliers under all circumstances.

The maximum and minimum supply counter flow from a resource to a binding network constraint in the base case or a contingency of any scenario are calculated as follows:

$$\left. \begin{array}{l} \overline{SCF}_{i,m,t} = -\min(0, SF_{i,m,t}) \min(UCL_{i,t} - RU_{i,t} - SR_{i,t} - NR_{i,t}, UEL_{i,t}) \\ \underline{SCF}_{i,m,t} = -w_{i,t} \min(0, SF_{i,m,t}) \max(LCL_{i,t} + RD_{i,t}, LEL_{i,t}) \\ \overline{SCF}^{(k)}_{i,m,t} = -\min\left(0, SF^{(k)}_{i,m,t}\right) \min(UCL_{i,t} - RU_{i,t} - SR_{i,t} - NR_{i,t}, UEL_{i,t}) \\ \underline{SCF}^{(k)}_{i,m,t} = -w_{i,t} \min\left(0, SF^{(k)}_{i,m,t}\right) \max(LCL_{i,t} + RD_{i,t}, LEL_{i,t}) \\ \overline{SCF}^{(g)}_{i,m,t} = -\min\left(0, {SF'}^{(g)}_{i,m,t}\right) \min(UCL_{i,t} - RU_{i,t} - SR_{i,t} - NR_{i,t}, UEL_{i,t}) \\ \underline{SCF}^{(g)}_{i,m,t} = -w_{i,t} \min\left(0, {SF'}^{(g)}_{i,m,t}\right) \max(LCL_{i,t} + RD_{i,t}, LEL_{i,t}) \end{array} \right\},$$

$$\forall i \in S_{GR} \cup S_{NGR}, \forall m, t = 1,2 \ldots, T$$

Only ancillary services self-provisions are included in these calculations. Ancillary services and IRU/IRD awards are not included because they are co-optimized in IFM. If a resource can be shut down (it does not apply to NGR), its minimum supply counter flow is zero. The LCL for NGR may be negative. Although the maximum and minimum supply counter flow are the same for a given resource and binding constraint in all scenarios, the set of binding constraints are different in general among the scenarios. To simplify the mathematical formulation, we will ignore the different contingencies and use the base case to refer collectively to all binding constraints in all scenarios.

The maximum supply counter flow that can be withheld from a resource on a binding transmission constraint is derived as follows:

$$WC_{i,m,t} = \overline{SCF}_{i,m,t} - \underline{SCF}_{i,m,t}, \forall i, m, t$$

The aggregate withheld supply counter flow per supplier portfolio is used to rank suppliers to determine the top three suppliers as potentially pivotal suppliers:

$$\left\{\begin{array}{c} PPS_{m,t} = S_{PS_1} \cup S_{PS_2} \cup S_{PS_3} \\ \sum_{i \in S_{PS_1}} WC_{i,m,t} = \max\left(\left\{\sum_{i \in S_n} WC_{i,m,t}, n = 1,2, \dots, N\right\}\right) \\ \sum_{i \in S_{PS_2}} WC_{i,m,t} = \max\left(\left\{\sum_{i \in S_n} WC_{i,m,t}, n = 1,2, \dots, N \wedge n \neq PS_1\right\}\right) \\ \sum_{i \in S_{PS_3}} WC_{i,m,t} = \max\left(\left\{\sum_{i \in S_n} WC_{i,m,t}, n = 1,2, \dots, N \wedge n \neq PS_1 \wedge n \neq PS_2\right\}\right) \end{array}\right\}, \forall m, t$$

The remaining suppliers are classified as fringe competitive suppliers:

$$FCS_{m,t} = \cup\{S_n, n = 1,2, \dots, N \wedge n \neq PS_1 \wedge n \neq PS_2 \wedge n \neq PS_3\}, \forall m, t$$

The demand for supply counter flow from a resource on a binding transmission constraint in a scenario is calculated as follows:

$$\left.\begin{array}{l} DCF_{i,m,t} = -\min\left(0, SF_{i,m,t}\right)\ EN_{i,t} \\ DCF_{i,m,t}^{(u)} = -\min\left(0, SF_{i,m,t}\right)\ \left(EN_{i,t} + IRU_{i,t}\right) \\ DCF_{i,m,t}^{(d)} = -\min\left(0, SF_{i,m,t}\right)\ \left(EN_{i,t} - IRD_{i,t}\right) \end{array}\right\}, \forall i, m, t$$

The Residual Supply Index for a binding transmission constraint in a scenario is then derived as follows:

$$\left.\begin{aligned} RSI_{m,t} &= \frac{\sum_{i \in FCS_{m,t}} \overline{SCF}_{i,m,t} + \sum_{i \in PPS_{m,t}} \underline{SCF}_{i,m,t}}{\sum_i DCF_{i,m,t}} \\ RSI_{m,t}^{(u)} &= \frac{\sum_{i \in FCS_{m,t}} \overline{SCF}_{i,m,t} + \sum_{i \in PPS_{m,t}} \underline{SCF}_{i,m,t}}{\sum_i DCF_{i,m,t}^{(u)}} \\ RSI_{m,t}^{(d)} &= \frac{\sum_{i \in FCS_{m,t}} \overline{SCF}_{i,m,t} + \sum_{i \in PPS_{m,t}} \underline{SCF}_{i,m,t}}{\sum_i DCF_{i,m,t}^{(d)}} \end{aligned}\right\}, \forall m, t$$

This metric determines whether the total demand for supply counter flow can be met by the maximum supply counter flow from fringe competitive suppliers while the potentially pivotal suppliers withhold their supply counter flow providing only the minimum possible. If the Residual Supply Index is less than one, the binding transmission constraint is deemed uncompetitive because it cannot be satisfied without selecting at least one bid from a pivotal supplier who can then exercise market power. For binding constraints in the IRU/IRD deployment scenarios, the supply counter flow can be provided by either energy or IRU/IRD bids.

The marginal congestion contributions by binding transmission constraints to the locational marginal price for energy and IRU/IRD for a resource are shown in §6. If the net marginal congestion contribution from uncompetitive binding transmission constraints is positive, the corresponding bid is mitigated above the competitive marginal price to the lower of the respective submitted bid or the default bid. The competitive marginal price is the portion of the marginal price that does not include marginal congestion contributions from uncompetitive binding transmission constraints.

5 RUC MATHEMATICAL FORMULATION

The focus of the mathematical formulation of RUC in this technical paper is on the RCU/RCD procurement. 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, nomograms, and soft constraint penalty relaxation or scarcity treatment, are not included for simplicity. These features do not materially affect the procurement of RCU/RCD in RUC.

5.1 GENERAL PROBLEM FORMULATION

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

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

5.2 RELIABILITY CAPACITY MODEL

This section gives an overview of the reliability capacity model without ancillary services and network constraints for simplicity. Figure 3 and Figure 4 below show the two cases for the reliability capacity up and down targets in a given time interval.

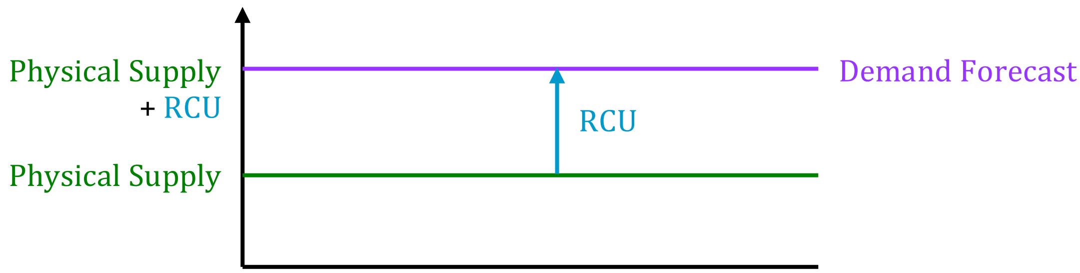

Figure 3. RUC target when physical supply clears in IFM below the demand forecast

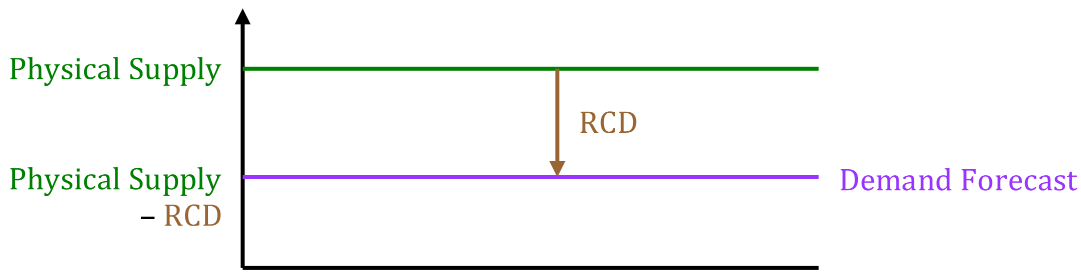

Figure 4. RUC target when physical supply clears in IFM above the demand forecast

Although the net system reliability capacity from all physical resources in the system is either upward (in the case shown in Figure 3) or downward (in the case shown in Figure 4), individual resources may have either a RCU or a RCD award in either case due to binding transmission constraints. The RCU/RCD awards are deployed above/below the day-ahead energy schedules from IFM to meet the demand forecast:

$$\sum_i \left(EN_{i,t} + RCU_{i,t} - RCD_{i,t}\right) = D_t, t = 1,2, \dots, T$$

The day-ahead energy schedules are fixed in RUC at the IFM solution. VERs are eligible for both RCU and RCD awards, but their RCU awards are limited by their VER forecast. Because it is expected that VERs will bid in RTM to be dispatched up to their forecast, a RCU bid is required for VERs even if there have no energy bids to avoid over-commitment and over-procurement in RUC

RCU/RCD is ramp capacity reserved between hours to meet the difference between the hourly average demand forecast and the hourly physical resource day-ahead energy schedules. Therefore, RCU and RCD are 60min capacity awards. Figure 5 shows the potential RCU/RCD awards for a physical resource in a given hour that can be reserved based on its ramp capability and its reliability energy schedules across consecutive hours.

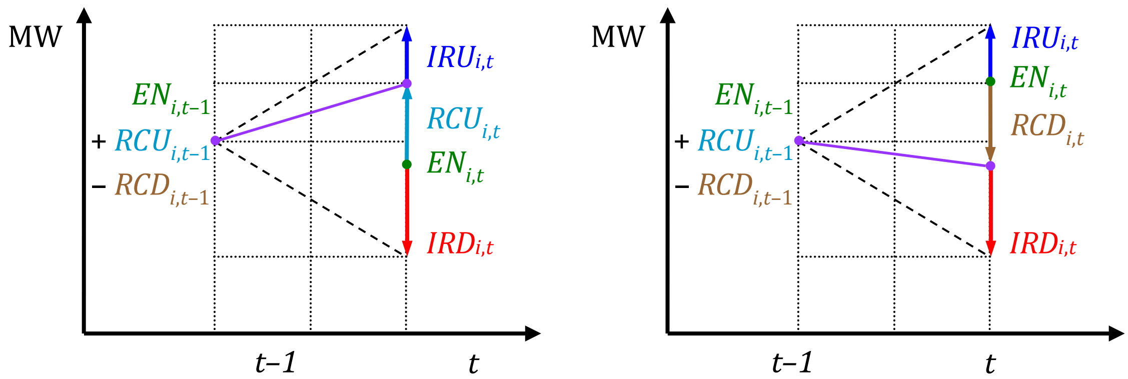

Figure 5. Reliability capacity up or down awards

The dashed lines represent the upward and downward ramp capability of the resource from its reliability capacity deployment in the previous time interval. The reliability capacity awards are constrained by the following set of capacity and ramp capability constraints:

$$\left.\begin{array}{l} LEL_{i,t} + IRD_{i,t} \leq EN_{i,t} + RCU_{i,t} - RCD_{i,t} \leq UEL_{i,t} - IRU_{i,t} \\ \begin{pmatrix} EN_{i,t} + RCU_{i,t} - RCD_{i,t} - \\ EN_{i,t-1} - RCU_{i,t-1} + RCD_{i,t-1} \end{pmatrix} \leq RRU_i\left(EN_{i,t-1} + RCU_{i,t-1} - RCD_{i,t-1}, T_{60}\right) - 4\,\delta\, IRU_{i,t} \\ \begin{pmatrix} EN_{i,t} + RCU_{i,t} - RCD_{i,t} - \\ EN_{i,t-1} - RCU_{i,t-1} + RCD_{i,t-1} \end{pmatrix} \geq -RRD_i\left(EN_{i,t-1} + RCU_{i,t-1} - RCD_{i,t-1}, T_{60}\right) + 4\,\delta\, IRD_{i,t} \end{array}\right\},$$
$$\forall i \wedge t = 1,2,\ldots,T$$

The energy schedules, ancillary services awards, and IRU/IRD awards are fixed in RUC at the IFM solution. The granularity adjustment factor (4) converts the 15min IRU/IRD awards to the hourly time domain of the energy schedule ramp. The capacity and ramp capability constraints are more complicated when considering ancillary services awards, as shown in §5.10 and §5.11, respectively.

5.3 OBJECTIVE FUNCTION

The objective function, ignoring MSG state transitions for simplicity, is as follows:

$$C = \sum_{t=1}^{T}\sum_{i} y_{i,t}\, SUC_{i,t} + \sum_{t=1}^{T}\sum_{i} u_{i,t}\, MLC_{i,t} - \sum_{t=1}^{T}\sum_{i \in S_{PSH}} v_{i,t}\, PC_{i,t} + \sum_{t=1}^{T}\sum_{i} RCU_{i,t}\, RCUBP_{i,t} + \sum_{t=1}^{T}\sum_{i} RCD_{i,t}\, RCDBP_{i,t}$$

The objective function includes the commitment cost of resources that are started up in RUC. Resources that are committed in IFM are kept online in RUC. However, all feasible MSG online transitions are allowed. Therefore, the RCU and RCD awards may span capacity between non-overlapping MSG configurations if they are scheduled in RUC to a different configuration than in IFM. The RCU and RCD awards are zero when the resource is offline, except for RCU that can be provided by offline resources that can start within 60min ($SUT \leq 60$min):

$$u_{i,t} = 0 \rightarrow \begin{Bmatrix} EN_{i,t} = RCD_{i,t} = 0 \\ RCU_{i,t} = 0, \forall i \notin S_{60} \end{Bmatrix}, \forall i \wedge t = 1,2, \dots, T$$

System Resources (SRs) and Non-Generator Resources (NGRs) have no discontinuities or inter-temporal constraints and are always modeled as online ($u = 1$). RCU/RCD can only be awarded to resources certified to provide them, but any physical resource, including VERs and Import/Export System Resources, can be certified to provide RCU/RCD. An energy bid is required for RCU/RCD awards, except for VERs where a RCU bid is required even in the absence of an energy bid, even for VERs that are not scheduled in the IFM.

5.4 POWER BALANCE CONSTRAINTS

The power balance constraints for the deployment of the reliability capacity awards are as follows:

$$\sum_i \left(EN_{i,t} + RCU_{i,t} - RCD_{i,t} \right) = D_t, t = 1,2, \dots, T$$

Where the energy schedules are fixed from the IFM. 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 constraints are as follows:

$$\sum_i \frac{\left(\Delta RCU_{i,t} - \Delta RCD_{i,t} \right)}{LPF_{i,t}^{(r)}} = 0, t = 1,2, \dots, T$$

The incremental reliability capacity awards 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 and they are different from the ones used in IFM because the power flow solution is different.

5.5 ANCILLARY SERVICES

The ancillary services awards are fixed in RUC at their IFM solution.

5.6 IMBALANCE RESERVES

The IRU/IRD awards are fixed in RUC at their IFM solution.

5.7 UPPER/LOWER CAPACITY BOUNDS

The RCU/RCD upper/lower bound constraints are as follows:

$$\left.\begin{array}{l} 0 \leq RCU_{i,t} \leq RCUBC_{i,t} \\ 0 \leq RCD_{i,t} \leq RCDBC_{i,t} \end{array}\right\}, \forall i \wedge t = 1,2, \dots, T$$

The RCU/RCD capacity bids are limited by the corresponding certified quantities. Capacity bids for RCU/RCD can be used to limit exposure to the Must Offer Obligation associated with the corresponding awards in RTM.

The ancillary services, RCU/RCD, and IRU/IRD awards are further constrained by capacity and ramp capability constraints, described in §5.10 and §5.11, respectively.

5.8 NETWORK CONSTRAINTS

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

5.8.1 Transmission Constraints

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

$$LFL_{m,t} \leq F_{m,t}^{(r)} \leq UFL_{m,t}, \forall m \wedge \ t = 1,2, \dots, T$$

The transmission limits in the RUC are the same as those enforced in the IFM.

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

$$\widetilde{LFL}_{m,t}^{(r)} \leq \tilde{F}_{m,t}^{(r)} + \sum_{i} \left(\Delta RCU_{i,t} - \Delta RCD_{i,t} \right) SF_{i,m,t} \leq \widetilde{UFL}_{m,t}^{(r)}, \forall m \wedge t = 1,2, \dots, T$$

The shift factors in the RUC base case are the same as the ones in the IFM base case because the transmission network is the same; however, the set of critical constraints is different in general.

5.8.2 Scheduling Limits

The ancillary services and RCU/RCD/IRU/IRD awards from intertie resources associated with ITC or ISL constraints are limited by scheduling limits. The ITC/ISL constraints allow netting of import and export energy schedules, but they prevent netting among energy schedules and ancillary services or RCU/RCD/IRU/IRD awards because they are not simultaneously dispatched:

$$\left.\begin{array}{l}\sum_{i\in S_m}\left(EN_{i,t}+RCU_{i,t}-RCD_{i,t}\right)+\sum_{i\in I_m}\left(RU_{i,t}+SR_{i,t}+NR_{i,t}\right)+\sum_{i\in S_m}\left(RCU_{i,t}+IRU_{i,t}\right)\leq UFL_{m,t}\\ \sum_{i\in I_m}\left(RU_{i,t}+SR_{i,t}+NR_{i,t}\right)+\sum_{i\in S_m}\left(RCU_{i,t}+IRU_{i,t}\right)\leq UFL_{m,t}\\ LFL_{m,t}\leq\sum_{i\in S_m}\left(EN_{i,t}+RCU_{i,t}-RCD_{i,t}\right)-\sum_{i\in I_m}RD_{i,t}-\sum_{i\in S_m}\left(RCD_{i,t}+IRD_{i,t}\right)\\ LFL_{m,t}\leq-\sum_{i\in I_m}RD_{i,t}-\sum_{i\in S_m}\left(RCD_{i,t}+IRD_{i,t}\right)\\ \forall m\wedge t=1,\ldots,T\end{array}\right\},$$

The scheduling limits in RUC are the same as those enforced in IFM. Hourly intertie resources are eligible for RCU/RCD awards. For an export or a demand response resource, RCU dispatch is a decrease in the energy schedule, whereas RCD dispatch is an increase in the energy schedule.

5.8.3 Contingency Constraints

There are two different contingency constraints enforced in RUC, similarly to IFM:

1) N–1 preventive transmission contingencies; and
2) G–1 or N–1+RAS generation/transmission contingencies.

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

$$\widetilde{LFL}_{m,t}^{(k,r)}\leq\tilde{F}_{m,t}^{(k,r)}+\sum_{i}\left(\Delta RCU_{i,t}-\Delta RCD_{i,t}\right)SF_{i,m,t}^{(k)}\leq\widetilde{UFL}_{m,t}^{(k,r)},\forall k,m\wedge t=1,2,\ldots,T$$

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 per hour per contingency are required to linearize the transmission constraints in each post-contingency case, but they can be easily derived from the AC power flow solutions for the base 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 FNM. The distribution is assumed pro rata on the maximum available capacity of these generators:

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

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

$$\widetilde{LFL}_{m,t}^{(g,r)} \leq \tilde{F}_{m,t}^{(g,r)} + \sum_i \left(\Delta RCU_{i,t}^{(g)} - \Delta RCD_{i,t}^{(g)}\right) SF_{i,m,t}^{(g)} \leq \widetilde{UFL}_{m,t}^{(g,r)}, \forall g, m \wedge t = 1,2, \dots, T$$

The difference is that the constraints are formulated for the post-contingency reliability capacity deployment, which are dependent variables that reflect the distribution of lost/tripped generation. The upper/lower active power 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 per hour per contingency are required to linearize the transmission constraints in each post-contingency case.

These constraints can be expressed in terms of the base-case control variables as follows:

$$\widetilde{LFL}_{m,t}^{(g,r)} \leq \tilde{F}_{m,t}^{(g,r)} + \sum_i \left(\Delta RCU_{i,t} - \Delta RCD_{i,t}\right) SF'^{(g)}_{i,m,t} \leq \widetilde{UFL}_{m,t}^{(g,r)}, \forall g, m \wedge t = 1,2, \dots, T$$

Where:

$$SF'^{(g)}_{i,m,t} = \left\{\begin{array}{ll} \sum_{i \neq i_g} GLDF_{i,t}^{(g)} \, SF_{i,m,t}^{(g)} & \therefore i = i_g \\ SF_{i,m,t}^{(g)} & \therefore i \neq i_g \end{array}\right\}, \forall i, g \wedge t = 1,2, \dots, T$$

5.9 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:

$$\sum_{i \in S_b} a_i \left(EN_{i,t} + RCU_{i,t} - RCD_{i,t} + IRU_{i,t}\right) \leq GL_{b,t}, \forall b, t = 1,2, \dots, T$$

5.10 CAPACITY CONSTRAINTS

This section describes the resource capacity constraints. In RUC, an energy bid is required for RCU/RCD awards, except for VERs. The capacity constraints for online physical resources are as follows:

$$\left.\begin{array}{l} EN_{i,t} + RCU_{i,t} - RCD_{i,t} \leq UCL_{i,t} - RU_{i,t} - SR_{i,t} - NR_{i,t} - IRU_{i,t} \\ LCL_{i,t} + RD_{i,t} + IRD_{i,t} \leq EN_{i,t} + RCU_{i,t} - RCD_{i,t} \end{array}\right\},$$
$$\forall i \wedge u_{i,t} = 1 \wedge t = 1,2,\ldots,T$$

$$LEL'_{i,t} + IRD_{i,t} \leq EN_{i,t} + RCU_{i,t} - RCD_{i,t} \leq UEL'_{i,t} - IRU_{i,t},$$
$$\forall i \notin S_{VER} \wedge u_{i,t} = 1 \wedge t = 1,2,\ldots,T$$

The capacity constraints for offline physical resources are as follows:

$$NR_{i,t} + RCU_{i,t} + IRU_{i,t} \leq UCL_{i,t}, \forall i \in S_{60} \wedge i \wedge u_{i,t} = 0 \wedge t = 1,2,\ldots,T$$

$$RCU_{i,t} + IRU_{i,t} \leq UEL'_{i,t}, \forall i \in S_{60} - S_{VER} \wedge i \wedge u_{i,t} = 0 \wedge t = 1,2,\ldots,T$$

The UOL and UEL for VERs are limited by their VER forecast.

5.11 RAMP CAPABILITY CONSTRAINTS

This section describes the resource ramp capability constraints. For resources that are online across time intervals, these constraints are as follows:

$$\left.\begin{array}{l} REN_{i,t} - REN_{i,t-1} \leq RRU_i\left(REN_{i,t-1}, T_{60}\right) - \alpha\, RU_{i,t} - \beta\, SR_{i,t} - \gamma\, NR_{i,t} - 4\,\delta\, IRU_{i,t} \\ REN_{i,t} - REN_{i,t-1} \geq -RRD_i\left(REN_{i,t-1}, T_{60}\right) + \alpha\, RD_{i,t} + 4\,\delta\, IRD_{i,t} \end{array}\right\},$$
$$\forall i \wedge t = 1,2,\ldots,T$$

$$\left.\begin{array}{l} \begin{pmatrix} EN_{i,t} + RCU_{i,t} - RCD_{i,t} - \\ EN_{i,t-1} - RCU_{i,t-1} + RCD_{i,t-1} \end{pmatrix} \leq \begin{pmatrix} RRU_i\left(EN_{i,t-1} + RCU_{i,t-1} - RCD_{i,t-1}, T_{60}\right) - \\ \alpha\, \dfrac{RU_{i,t-1} + RU_{i,t}}{2} - \beta\, \dfrac{SR_{i,t-1} + SR_{i,t}}{2} - \\ \gamma\, \dfrac{NR_{i,t-1} + NR_{i,t}}{2} - 4\,\delta\, IRU_{i,t} \end{pmatrix} \\ \begin{pmatrix} EN_{i,t} + RCU_{i,t} - RCD_{i,t} - \\ EN_{i,t-1} - RCU_{i,t-1} + RCD_{i,t-1} \end{pmatrix} \geq \begin{pmatrix} -RRD_i\left(EN_{i,t-1} + RCU_{i,t-1} - RCD_{i,t-1}, T_{60}\right) + \\ \alpha\, \dfrac{RD_{i,t-1} + RD_{i,t}}{2} + 4\,\delta\, IRD_{i,t} \end{pmatrix} \end{array}\right\},$$
$$\forall i \wedge t = 1,2,\ldots,T$$

The granularity adjustment factor (4) converts the 15min IRU/IRD awards to the hourly time domain of the energy schedule ramp.

For resources that start up at the beginning of an hour, the ramp capability constraints are as follows:

$$EN_{i,t} + RCU_{i,t} - RCD_{i,t} \leq$$
$$LOL_{i,t} + RRU_i\left(LOL_{i,t}, T_{60}/2\right) - \alpha\, RU_{i,t} - \beta\, SR_{i,t} - \gamma\, NR_{i,t} - 2\,\delta\, IRU_{i,t},$$
$$\forall i \wedge u_{i,t-1} = 0 \wedge u_{i,t} = 1 \wedge t = 1,2,\ldots,T$$

Where the ramp up from the LOL is for half of the interval ramp. The granularity adjustment factor (2) converts the 15min IRU awards to the half-hourly time domain of the energy schedule ramp.

For resources that shut down at the end of an hour, the ramp capability constraints are as follows:

$$EN_{i,t} + RCU_{i,t} - RCD_{i,t} \leq LOL_{i,t} + RRU_i\left(LOL_{i,t}, T_{60}/2\right) - \alpha\, RD_{i,t} - 2\,\delta\, IRD_{i,t},$$
$$\forall i \wedge u_{i,t} = 1 \wedge u_{i,t+1} = 0 \wedge t = 1,2, \dots, T-1$$

Where the ramp down to LOL is for half of the interval ramp. The granularity adjustment factor (2) converts the 15min IRD awards to the half-hourly time domain of the energy schedule ramp. Resources are never shut down in the last interval of the time horizon.

5.12 ENERGY CONSTRAINTS

Energy constraints apply to resources that have energy limitations. There are two kinds of energy constraints in the RUC, similarly to IFM:

c) Daily energy limits; and

d) 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:

$$\sum_{t=1}^{T}\left(EN_{i,t} + RCU_{i,t} - RCD_{i,t} + IRU_{i,t}\right) \leq \overline{EN}_i$$

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:

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

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

Where the pumping energy is multiplied by the pumping efficiency (η) and the operating modes are mutually exclusive and determined in IFM, unless the resource is not scheduled in IFM. PSH resources may only have RCU/RCD awards in generating mode.

The SOC limits constrain the reliability energy schedules 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 operating modes are determined in IFM, unless the resource is not scheduled in IFM.

The RCU/RCD awards are constrained by the SOC constraints as follows:

$$\left.\begin{array}{l} SOC_{i,t-1} - RU_{i,t} - SR_{i,t} - NR_{i,t} - IRU_{i,t} - RCU_{i,t} \geq \underline{SOC}_{i,t} \\ SOC_{i,t-1} + \eta_i \left(RD_{i,t} + IRD_{i,t} + RCD_{i,t}\right) \leq \overline{SOC}_{i,t} \end{array}\right\}, \forall i \in S_{LESR} \wedge t = 1,2, \dots, T$$

5.13 MARKET POWER MITIGATION

This section describes the MPM-RUC, which is identical with the subsequent RUC, except that the submitted RCU/RCD bids are used, and after the solution is obtained, these bids are tested for market power mitigation. The mitigated RCU/RCD bids are then used instead of the submitted bids in the subsequent RUC.

The binding network constraints at the MPM-RUC solution are classified as competitive or uncompetitive using the DCPA method, exactly the same way as in MPM-IFM, described in §4.15. DCPA calculates the residual supply index for each binding transmission constraint based on the three largest pivotal suppliers (RSI-3) with the highest supply counter flow contributions to the constraint.

There is a single RCU/RCD deployment scenario in RUC, where the energy schedules, the ancillary services awards, and the IRU/IRD awards are fixed at the IFM solution. The maximum and minimum supply counter flow from a resource to a binding network constraint in the base case or a contingency are calculated as follows:

$$\left.\begin{array}{l} \overline{SCF}_{i,m,t} = -\min\left(0, SF_{i,m,t}\right) \min\left(UCL_{i,t} - RU_{i,t} - SR_{i,t} - NR_{i,t} - IRU_{i,t}, UEL_{i,t} - IRU_{i,t}\right) \\ \underline{SCF}_{i,m,t} = -w_{i,t} \min\left(0, SF_{i,m,t}\right) \max\left(LCL_{i,t} + RD_{i,t} + IRD_{i,t}, LEL_{i,t} + IRD_{i,t}\right) \\ \overline{SCF}_{i,m,t}^{(k)} = -\min\left(0, SF_{i,m,t}^{(k)}\right) \min\left(UCL_{i,t} - RU_{i,t} - SR_{i,t} - NR_{i,t} - IRU_{i,t}, UEL_{i,t} - IRU_{i,t}\right) \\ \underline{SCF}_{i,m,t}^{(k)} = -w_{i,t} \min\left(0, SF_{i,m,t}^{(k)}\right) \max\left(LCL_{i,t} + RD_{i,t} + IRD_{i,t}, LEL_{i,t} + IRD_{i,t}\right) \\ \overline{SCF}_{i,m,t}^{(g)} = -\min\left(0, SF'^{(g)}_{i,m,t}\right) \min\left(UCL_{i,t} - RU_{i,t} - SR_{i,t} - NR_{i,t} - IRU_{i,t}, UEL_{i,t} - IRU_{i,t}\right) \\ \underline{SCF}_{i,m,t}^{(g)} = -w_{i,t} \min\left(0, SF'^{(g)}_{i,m,t}\right) \max\left(LCL_{i,t} + RD_{i,t} + IRD_{i,t}, LEL_{i,t} + IRD_{i,t}\right) \end{array}\right\},$$

$$\forall i \in S_{GR} \cup S_{NGR}, \forall m, t = 1,2 \dots, T$$

Both ancillary services self-provisions and awards, as well as IRU/IRD awards are included in these calculations, because they are fixed in RUC. RCU/RCD awards are not included because they are co-optimized in RUC. If a resource can be shut down (it does not apply to NGR), its minimum supply counter flow is zero. Resources committed in IFM are must-run in RUC; however, resources committed in RUC are cyclable and can be shut down. The LCL for NGR may be negative. For VERs without energy bids, UEL is considered equal to UCL in the formulae above. To simplify the mathematical formulation, we will ignore the different contingencies and use the base case to refer collectively to all binding constraints.

The process for the determination of potentially pivotal suppliers and fringe competitive suppliers is the same as in MPM-IFM, described in §4.15.

The demand for supply counter flow from a resource on a binding transmission constraint is calculated as follows:

$$DCF_{i,m,t} = -\min(0, SF_{i,m,t})\ (EN_{i,t} + RCU_{i,t} - RCD_{i,t}), \forall i, m, t$$

The Residual Supply Index for a binding transmission constraint is then derived as follows:

$$RSI_{m,t} = \frac{\sum_{i \in FCS_{m,t}} \overline{SCF}_{i,m,t} + \sum_{i \in PPS_{m,t}} \underline{SCF}_{i,m,t}}{\sum_i DCF_{i,m,t}}, \forall m, t$$

This metric determines whether the total demand for supply counter flow can be met by the maximum supply counter flow from fringe competitive suppliers while the potentially pivotal suppliers withhold their supply counter flow providing only the minimum possible. If the Residual Supply Index is less than one, the binding transmission constraint is deemed uncompetitive because it cannot be satisfied without selecting at least one RCU/RCD bid from a pivotal supplier who can then exercise market power.

The marginal congestion contributions by binding transmission constraints to the locational marginal price for RCU/RCD for a resource are shown in §6. If the net marginal congestion contribution from uncompetitive binding transmission constraints is positive, the corresponding bid is mitigated above the competitive marginal price to the lower of the respective submitted bid or the default bid. The competitive marginal price is the portion of the marginal price that does not include marginal congestion contributions from uncompetitive binding transmission constraints.

6 PRICE FORMATION

This section presents the price formation for the day-ahead energy schedules and the IRU/IRD/RCU/RCD awards. The marginal prices for these commodities for each hour in the Trading Day are derived from the shadow prices of the power balance constraints for day-ahead energy schedules, and the IRU/IRD/RCU/RCD procurement constraints:

$$\left.\begin{array}{ll}
\sum_i \frac{\Delta EN_{i,t}}{LPF_{i,t}} + \sum_i \frac{\Delta VS_{i,t}}{LPF_{i,t}} - \sum_i \frac{\Delta L_{i,t}}{LPF_{i,t}} - \sum_i \frac{\Delta VD_{i,t}}{LPF_{i,t}} = 0 & \lambda_t \\
\sum_i IRU_{i,t} \geq IRUR_t & \rho_t \\
\sum_i IRD_{i,t} \geq IRDR_t & \sigma_t \\
\sum_i (EN_{i,t} + RCU_{i,t} - RCD_{i,t}) = D_t & \xi_t
\end{array}\right\}, t = 1,2, \ldots, T$$

Where the day-ahead energy schedules are fixed in RUC. There are additional price contributions from binding network constraints enforced in IFM and RUC, described in §4.8 and §5.8, respectively. Including these contributions, the marginal prices of the commodities are derived as follows:

$$
\left.
\begin{aligned}
LMP_{i,t} &= \frac{\lambda_t}{LPF_{i,t}} - \sum_m SF_{i,m,t}\,\mu_{m,t} - \sum_k \sum_m SF_{i,m,t}^{(k)}\,\mu_{m,t}^{(k)} - \sum_g \sum_m SF'^{(g)}_{i,m,t}\,\mu_{m,t}^{(g)} - \\
&\quad \sum_m SF_{i,m,t}\,\mu_{m,t}^{(u)} - \sum_k \sum_m SF_{i,m,t}^{(k)}\,\mu_{m,t}^{(k,u)} - \sum_g \sum_m SF'^{(g)}_{i,m,t}\,\mu_{m,t}^{(g,u)} - \\
&\quad \sum_m SF_{i,m,t}\,\mu_{m,t}^{(d)} - \sum_k \sum_m SF_{i,m,t}^{(k)}\,\mu_{m,t}^{(k,d)} - \sum_g \sum_m SF'^{(g)}_{i,m,t}\,\mu_{m,t}^{(g,d)} \\
IRUMP_{i,t} &= \rho_t - \sum_m SF_{i,m,t}\,\mu_{m,t}^{(u)} - \sum_k \sum_m SF_{i,m,t}^{(k)}\,\mu_{m,t}^{(k,u)} - \sum_g \sum_m SF'^{(g)}_{i,m,t}\,\mu_{m,t}^{(g,u)} \\
IRDMP_{i,t} &= \sigma_t + \sum_m SF_{i,m,t}\,\mu_{m,t}^{(d)} + \sum_k \sum_m SF_{i,m,t}^{(k)}\,\mu_{m,t}^{(k,d)} + \sum_g \sum_m SF'^{(g)}_{i,m,t}\,\mu_{m,t}^{(g,d)} \\
RCUMP_{i,t} &= \frac{\xi_t}{LPF_{i,t}^{(r)}} - \sum_m SF_{i,m,t}\,\mu_{m,t}^{(r)} - \sum_k \sum_m SF_{i,m,t}^{(k)}\,\mu_{m,t}^{(k,r)} - \sum_g \sum_m SF'^{(g)}_{i,m,t}\,\mu_{m,t}^{(g,r)} \\
RCDMP_{i,t} &= -\frac{\xi_t}{LPF_{i,t}^{(r)}} + \sum_m SF_{i,m,t}\,\mu_{m,t}^{(r)} + \sum_k \sum_m SF_{i,m,t}^{(k)}\,\mu_{m,t}^{(k,r)} + \sum_g \sum_m SF'^{(g)}_{i,m,t}\,\mu_{m,t}^{(g,r)}
\end{aligned}
\right\},
$$

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