Day-Ahead Market Enhancements

Appendix B:
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 includes the new Imbalance Reserve Up (IRU) and Imbalance Reserve Down (IRD) products. In the RUC enhancement, the RUC capacity is replaced by two new products: Reliability Capacity Up (RCU) and Reliability Capacity Down (RCD). 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 energy schedule, which is analogous to the current RUC schedule. In the IFM, the IRU/IRD award is reserved capacity above/below the day-ahead energy schedule that must be available for dispatch in the Real-Time Market (RTM) to meet granularity differences and upward/downward uncertainty that may materialize in the Fifteen-Minute Market (FMM). The granularity differences are because the DAM clears in hourly intervals producing hourly day-ahead energy schedules whereas the FMM clears in 15min intervals producing 15min FMM energy schedules. The uncertainty is due to the net demand forecast error between the DAM and the FMM. The net demand forecast is the difference between the demand forecast and the total Variable Energy Resource (VER) forecast. 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 net demand forecast error between the four 15min intervals of that hour in the FMM and the net demand forecast in the DAM, within a specified confidence range. Furthermore, the hourly IRU/IRD requirements are adjusted to reflect demand, solar, and wind forecasts for the Trading Day.

1.1 EXISTING DAY-AHEAD MARKET STRUCTURE

Currently the Day-Ahead Market includes three separate market applications that are executed in sequence: IFM Market Power Mitigation (IFM-MPM), IFM, and RUC. The IFM-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 awards. The RUC commits additional resources and schedules additional capacity from physical resources above or below day-ahead energy schedules to meet the day-ahead demand forecast while ignoring virtual resources. The resources that are committed in IFM are modeled as must-run in RUC, i.e., they are kept online. Moreover, the day-ahead energy schedules from these committed resources are fixed in RUC seeking an incremental or decremental capacity solution on the IFM to meet the day-ahead demand forecast. Furthermore, ancillary services awarded in IFM are also fixed in RUC.

1.2 DAY-AHEAD MARKET ENHANCEMENTS

The DAME enhancements in IFM will procure IRU/IRD to address granularity differences and uncertainty that may materialize 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. For the IRU/IRD and RCU/RCD awards to be dispatchable in the FMM, they must carry a Must Offer Obligation (MOO), i.e., an energy bid must be submitted in the RTM for the corresponding resource capacity.

To ensure the deliverability of 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 and before the RUC to mitigate potentially these bids before the RUC. The RUC-MPM pass is a trial RUC pass that identifies and mitigates RCU/RCD bids based on similar criteria as the IFM-MPM pass. Therefore, the DAME pass sequence is as follows:

1) IFM-MPM for mitigating submitted bids for energy and ancillary services, including IRU/IRD bids.
2) IFM for optimally committing resources, scheduling day-ahead energy, and awarding ancillary services including IRU/IRD.
3) RUC-MPM for mitigating submitted bids for RCU/RCD.
4) RUC for optimally committing additional resources and awarding RCU/RCD.

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;
- Reliability energy schedules for physical resources; the difference between the reliability energy schedule and the day-ahead energy schedule is the Reliability Capacity Up or Down award.
- Day-ahead Regulation Up and Down awards for physical resources;
- Day-ahead Mileage Up and Down awards for physical resources;
- Day-ahead Spinning Reserve awards for physical resources;
- Day-ahead Non-Spinning Reserve awards for physical resources; and
- Imbalance Reserve Up and Down awards for physical resources.

2 ASSUMPTIONS

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

- The optimal solution in IFM, composed of the unit commitment and the cleared energy schedules and capacity awards for the market commodities in IFM, meets simultaneously the following objectives:
    1) Physical and virtual day-ahead energy supply schedules balance physical and virtual day-ahead energy demand schedules, non-participating load schedules, and losses; this is accomplished by the power balance constraint in IFM.
    2) Congestion management prevents violations of network constraints and preventive contingencies for:
        a) day-ahead energy schedules;
        b) day-ahead energy schedules plus the deployment of IRU awards; and
        c) day-ahead energy schedules minus the deployment of IRD awards.
    3) Ancillary services awards satisfy cascaded ancillary services requirements.
    4) IRU/IRD awards satisfy IRU/IRD requirements.
- The optimal solution in RUC, composed of the additional unit commitment and the reliability energy schedules, meets simultaneously the following objectives:
    1) Physical reliability energy schedules balance the demand forecast that includes losses; this is accomplished by the power balance constraint in RUC.
    2) Congestion management prevents violations of network constraints and preventive contingencies for reliability energy schedules.
    3) Ancillary services awards are fixed.
    4) IRU/IRD awards are fixed.
- The objective function in IFM is the maximization of the total merchandizing surplus over the IFM time horizon (the Trading Day) including the following:
    - the minimization of physical and virtual energy supply schedules cost;
    - the maximization of physical and virtual energy demand and non-participating load schedules benefit;
    - the minimization of the Start-Up Cost of resources with start-ups;
    - the minimization of the Minimum Load Cost of online resources;
    - the minimization of the State Transition Cost of Multi-State Generators (MSGs) with state transitions;
    - the minimization of ancillary services (regulation, mileage, spinning and non-spinning reserve) awards cost; and

- the minimization of IRU/IRD awards cost.
- The objective function in RUC is the minimization of the total cost over the RUC time horizon including the following:
  - the minimization of the Start-Up Cost of resources with RUC start-ups;
  - the minimization of the Minimum Load Cost of online resources committed in RUC;
  - the minimization of State Transition Cost of Multi-State Generators (MSGs) for state transitions in RUC; and
  - the minimization of RCU/RCD awards cost.
- All ancillary services procurement constraints are enforced in IFM to procure 100% of the relevant requirements. Similarly, IRU/IRD procurement constraints are enforced to procure 100% of the uncertainty requirements in IFM.
- Ancillary services are procured regionally in 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 IFM. The procurement of RCU/RCD is also locational through congestion management in RUC.
- All resource constraints are enforced in both IFM and RUC:
  - unit commitment and state transition inter-temporal constraints;
  - capacity constraints;
  - ramp capability constraints; and
  - energy constraints.
- All network constraints are enforced:
  - network constraints in IFM for physical and virtual energy and non-participating load schedules for the base case and preventive transmission and/or generation contingencies, for the base scenario and the IRU/IRD deployment scenarios;
  - network constraints in RUC for reliability energy schedules for the base case and preventive transmission and/or generation contingencies;
  - intertie scheduling limits for energy schedules and capacity awards in both IFM and RUC;
  - transmission and generation nomograms, including gas-burn constraints in both IFM and RUC; and
  - Minimum Online Capacity (MOC) constraints in IFM.
- Hourly intervals are used for the time horizon spanning the Trading Day in IFM.
- Hourly intervals are used for the time horizon spanning the Trading Day, and optionally additional days in RUC.

- Block hourly energy scheduling is available to hourly intertie resources in IFM.
- Hourly intertie resources, hourly Proxy Demand Resources (PDRs), and hourly Reliability Demand Response Resources (RDRRs) are not eligible for IRU/IRD awards in IFM, but they are eligible for RCU/RCD awards in RUC.
- Variable Energy Resources (VERs) are classified into two categories:
    1) CAISO-forecasted VERs with the following features:
        a) they are eligible for IRU/IRD and RCU/RCD awards;
        b) their day-ahead energy schedules and IRU awards are limited by their VER forecast in IFM; and
        c) their reliability energy schedules are limited by their VER forecast in RUC.
    2) SC-forecasted VERs with the following features:
        a) they are not eligible for ancillary services, and IRU and RCU awards, but they are eligible for IRD and RCD awards; however, no IRD or RCD is awarded above the VER forecast;
        b) their day-ahead energy schedules are limited by their bids in IFM, not by their VER forecast; the difference between the day-ahead energy schedule and the VER forecast is equivalent to virtual supply, if positive, or virtual demand, if negative; and
        c) their reliability energy schedules are limited by their VER forecast in RUC.
- The distribution of the IRU/IRD requirements in the IRU/IRD deployment scenarios in 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 IFM-MPM is a trial pass of the IFM where the following MPM principles apply:
    - the impact of resource commitment and physical and virtual energy and non-participating load schedules on network constraints is quantified;
    - network constraints are classified as competitive or uncompetitive using the Dynamic Competitive Path Assessment (DCPA) method;
    - energy and IRU/IRD bids from resources that provide counter flow on 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.
- The RUC-MPM is a trial pass of the RUC where the following MPM principles apply:
    - the impact of additional resource commitment and reliability energy schedules on network constraints is quantified;

- network constraints are classified as competitive or uncompetitive using the Dynamic Competitive Path Assessment (DCPA) method;
- RCU/RCD bids from resources that provide counter flow on 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.

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.
n	Gas-burn nomogram index.
o	Minimum Online Commitment constraint 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.
$\forall$	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_n	Set of resources bound by gas-burn nomogram n.
S_o	Set of resources bound by Minimum Online Commitment constraint o.
S_{10}	Set of Fast-Start Units ($SUT \leq$ 10min) that can be certified to provide Non-Spinning Reserve from offline status (u = 0).
S_{15}	Set of 15min-start units ($SUT \leq$ 15min) that can be certified to provide IRU from offline status (u = 0).
S_{60}	Set of 60min-start units ($SUT \leq$ 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_{VERc}	Set of CAISO-forecasted Variable Energy Resources.
S_{VERs}	Set of SC-forecasted Variable Energy Resources.
$u_{i,t}$	Binary (0/1) variable indicating commitment status (offline/online) for Resource i in time period t. For Pumped-Storage Hydro Resources, 1 indicates generating mode operation. For Limited Energy Storage Resources, 1 indicates discharging mode operation.
$v_{i,t}$	Binary (0/1) variable for Pumped-Storage Hydro Resources indicating pumping mode operation (offline/pumping).
$y_{i,t}$	Binary (0/1) variable indicating that Resource i has a start-up in time period t.
a_i	Energy-to-gas conversion factor for resource i.
$b_{i,o}$	Effectiveness factor of resource i in Minimum Online Commitment constraint o.
η_i	Pumping efficiency of Pumped-Storage Hydro Resource i, or charging efficiency of Limited Energy Storage Resource i.
C	Objective function.
$LOL_{i,t}$	Lower Operating Limit of Resource i in time period t.
$UOL_{i,t}$	Upper Operating Limit of Resource i in time period t.
$LRL_{i,t}$	Lower Regulating Limit of Resource i in time period t.
$URL_{i,t}$	Upper Regulating Limit of Resource i in time period t.
$LEL_{i,t}$	Lower Economic Limit of Resource i in time period t.
$UEL_{i,t}$	Upper Economic Limit of Resource i in time period t.
$CL_{i,t}$	Capacity Limit for Resource i in time period t; $UEL_{i,t} \leq CL_{i,t} \leq UOL_{i,t}$; it defaults to $UOL_{i,t}$; it is used to limit ancillary services awards.

$LCL_{i,t}$	Lower Capacity Limit of Resource *i* in time period *t*.
$UCL_{i,t}$	Upper Capacity Limit of Resource *i* in time period *t*.
$SUC_{i,t}$	Start-Up Cost for Resource *i* in time period *t*.
$SUT_{i,t}$	Start-Up Time for Resource *i* in time period *t*.
$MLC_{i,t}$	Minimum Load Cost for Resource *i* in time period *t*.
$PC_{i,t}$	Pumping cost for Pumped Storage Hydro Resource *i* in time period *t*.
$PL_{i,t}$	Pumping level for Pumped Storage Hydro Resource *i* in time period *t*.
$EN_{i,t}$	Day-ahead energy schedule of 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*.
$REN_{i,t}$	Reliability energy schedule of physical Resource *i* in time period *t*; positive for supply (generation and imports) and negative for demand (demand response and exports).
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.
$\underline{RRU}_{i,t}(\tau)$	Lowest ramp up capability within the applicable operating range of Resource i in time period t for time domain τ.
$\underline{RRD}_{i,t}(\tau)$	Lowest ramp down capability within the applicable operating range of Resource i in time period t for time domain τ.
$Loss_t$	Transmission losses in time period t.
$LPF_{i,t}$	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*.
$GL_{n,t}$	Gas limit for gas-burn nomogram *n* in time period *t*.
$MOC_{o,t}$	Minimum online capacity for Minimum Online Commitment constraint *o* in time period *t*.
α	Shared ramping coefficient for Regulation.
β	Shared ramping coefficient for Spinning Reserve.
γ	Shared ramping coefficient for Non-Spinning Reserve.
δ	Shared ramping coefficient for Imbalance Reserve.
$\overline{EN}_i$	Daily Maximum Energy Limit for Resource *i*.
$\underline{EN}_i$	Daily Minimum Energy Limit for Resource *i*.
$SOC_{i,t}$	State of Charge for Limited Energy Storage Resource *i* in time period *t*.
$\overline{SOC}_{i,t}$	Maximum State of Charge for Limited Energy Storage Resource *i* in time period *t*.
$\underline{SOC}_{i,t}$	Minimum State of Charge for Limited Energy Storage Resource *i* in time period *t*.
λ_t	Shadow price of day-ahead energy balance constraint in time period *t*.
ξ_t	Shadow price of reliability energy balance constraint in time period *t*.
ρ_t	Shadow price of 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*.

4 IFM MATHEMATICAL FORMULATION

The focus of the mathematical formulation of IFM in this technical paper is on the integration of IRU/IRD procurement with the energy scheduling and ancillary services procurement in a single optimization problem with 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.

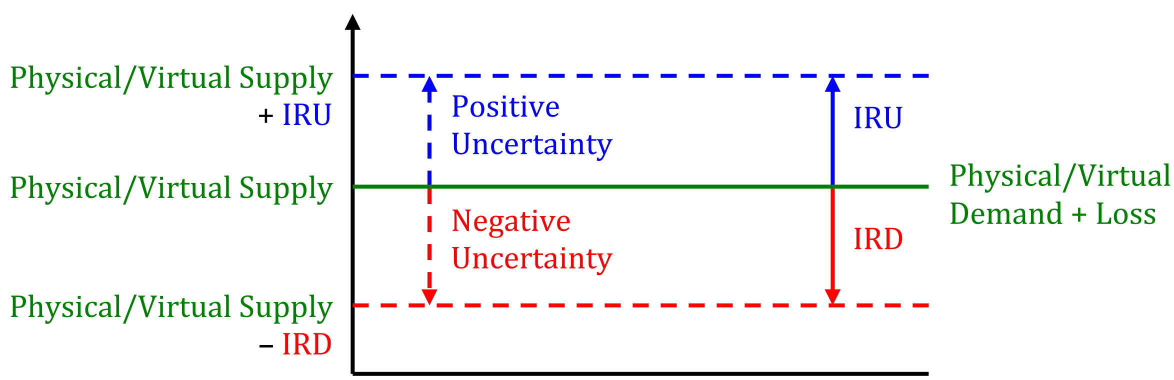

Figure 1. IFM targets for energy and imbalance reserves

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

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

CAISO-forecasted VERs are eligible for both IRU and IRD awards, but their energy and upward capacity awards are limited by their VER forecast. SC-forecasted VERs are not eligible for IRU awards, but they are eligible for IRD awards and their day-ahead energy schedules are limited by their bids, not by their VER forecast; however, no IRD is awarded above the 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%). 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.

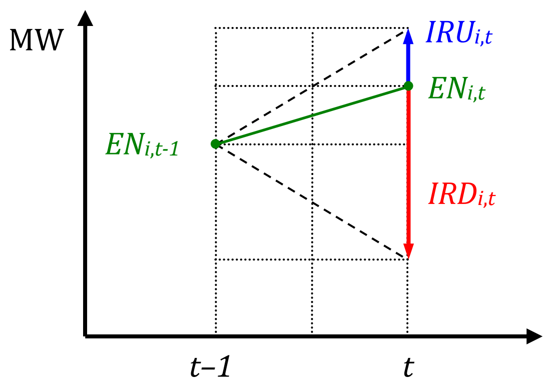

Figure 2. Imbalance reserve up and down awards

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):

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

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 and Import/Export System Resource can be certified to provide IRU/IRD, except for non-participating load resources, hourly intertie resources, and hourly PDRs and RDRRs. In addition, SC-forecasted VERs are not eligible for IRU awards. 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:

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

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 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:

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

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 the 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:

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

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

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

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

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:

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

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:

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

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

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

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:

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

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:

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

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:

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

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:

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

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

$$\left.\begin{array}{l} SDF_{i,t} = \dfrac{FS_{i,t}}{\sum_i FS_{i,t}}, \forall i \in S_{SVER} \\ WDF_{i,t} = \dfrac{FW_{i,t}}{\sum_i FW_{i,t}}, \forall i \in S_{WVER} \end{array}\right\}, t = 1,2, \dots, N$$

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:

$$\left.\begin{aligned}
\widetilde{LFL}_{m,t}^{(u)} \le \tilde{F}_{m,t}^{(u)} + \sum_i \left(\Delta EN_{i,t} + \Delta IRU_{i,t} + \Delta VS_{i,t} - \Delta VD_{i,t} - \Delta L_{i,t}\right) SF_{i,m,t} \le \widetilde{UFL}_{m,t}^{(u)} \\
\widetilde{LFL}_{m,t}^{(d)} \le \tilde{F}_{m,t}^{(d)} + \sum_i \left(\Delta EN_{i,t} - \Delta IRD_{i,t} + \Delta VS_{i,t} - \Delta VD_{i,t} - \Delta L_{i,t}\right) SF_{i,m,t} \le \widetilde{UFL}_{m,t}^{(d)}
\end{aligned}\right\},$$

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

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.

In the IRU deployment scenarios, the SC-forecasted VERs are considered fixed at their VER forecast, whereas in the IRD deployment scenarios their IRD awards are fully deployed.

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:

$$\left.\begin{aligned}
\widetilde{LFL}_{m,t}^{(k,u)} \le \tilde{F}_{m,t}^{(k,u)} + \sum_i \left(\Delta EN_{i,t} + \Delta IRU_{i,t} + \Delta VS_{i,t} - \Delta VD_{i,t} - \Delta L_{i,t}\right) SF_{i,m,t}^{(k)} \le \widetilde{UFL}_{m,t}^{(k,u)} \\
\widetilde{LFL}_{m,t}^{(k,d)} \le \tilde{F}_{m,t}^{(k,d)} + \sum_i \left(\Delta EN_{i,t} - \Delta IRD_{i,t} + \Delta VS_{i,t} - \Delta VD_{i,t} - \Delta L_{i,t}\right) SF_{i,m,t}^{(k)} \le \widetilde{UFL}_{m,t}^{(k,d)}
\end{aligned}\right\},$$

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

$$\left.\begin{aligned}
\widetilde{LFL}_{m,t}^{(g,u)} \le \tilde{F}_{m,t}^{(g,u)} + \sum_i \left(\Delta EN_{i,t} + \Delta IRU_{i,t} + \Delta VS_{i,t} - \Delta VD_{i,t} - \Delta L_{i,t}\right) SF'^{(g)}_{i,m,t} \le \widetilde{UFL}_{m,t}^{(g,u)} \\
\widetilde{LFL}_{m,t}^{(g,d)} \le \tilde{F}_{m,t}^{(g,d)} + \sum_i \left(\Delta EN_{i,t} - \Delta IRD_{i,t} + \Delta VS_{i,t} - \Delta VD_{i,t} - \Delta L_{i,t}\right) SF'^{(g)}_{i,m,t} \le \widetilde{UFL}_{m,t}^{(g,d)}
\end{aligned}\right\},$$

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

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.

In the IRU deployment scenarios, the SC-forecasted VERs are considered fixed at their VER forecast, whereas in the IRD deployment scenarios their IRD awards are fully deployed below their VER forecast.

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:

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

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:

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

4.12 CAPACITY CONSTRAINTS

This section describes the resource capacity constraints. In the 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:

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

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

The LEL is either zero or equal to the energy self-schedule, if submitted.

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:

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

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

The capacity constraints for virtual and non-participating load resources are as follows:

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

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

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

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

The IRD award for SC-forecasted VERs is limited by their VER forecast:

$$\left.\begin{array}{l} LCL_{i,t} + IRD_{i,t} \leq FV_{i,t} \\ LEL'_{i,t} + IRD_{i,t} \leq FV_{i,t} \end{array}\right\}, \forall i \in S_{VERs} \wedge u_{i,t} = 1 \wedge t = 1,2, \dots, T$$

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:

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

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

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

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

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

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

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

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

$$\left.\begin{array}{l}\underline{RRU}_{i,t}(T_{10}) = \min\left(RRU(p_i, T_{10})\big|_{p_i=LCL_{i,t}}^{p_i=UCL_{i,t}-RRD(UCL_{i,t},T_{10})}\right) \\ \underline{RRD}_{i,t}(T_{10}) = \min\left(RRD(p_i, T_{10})\big|_{p_i=LCL_{i,t}+RRU(LCL_{i,t},T_{10})}^{p_i=UCL_{i,t}}\right)\end{array}\right\}, \forall i \wedge u_{i,t} = 1 \wedge t = 1,2,\ldots,T$$

Although ancillary services can be dispatched at any time, IRU/IRD awards are dispatched simultaneously with the energy schedules in RTM; hence, the dynamic ramp capability should be used for ramp capability constraints on IRU/IRD awards. Capacity awards and day-ahead energy schedule changes across hours share the resource dynamic ramp capability. For resources that remain online across hours, these constraints are as follows:

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

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:

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

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 from the beginning of the hour.

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

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

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:

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

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:

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

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

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

5 RUC MATHEMATICAL FORMULATION

The focus of the mathematical formulation of RUC in this technical paper is on 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:

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

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 scenarios for the reliability energy and reliability capacity up and down targets in a given time interval.

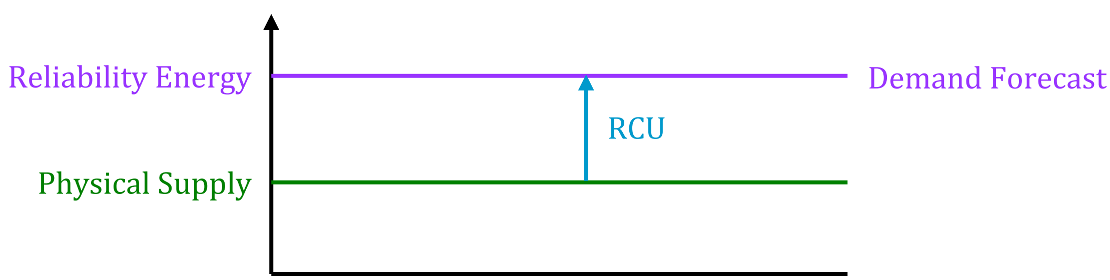

Figure 3. RUC target when physical supply clears in IFM below the demand forecast

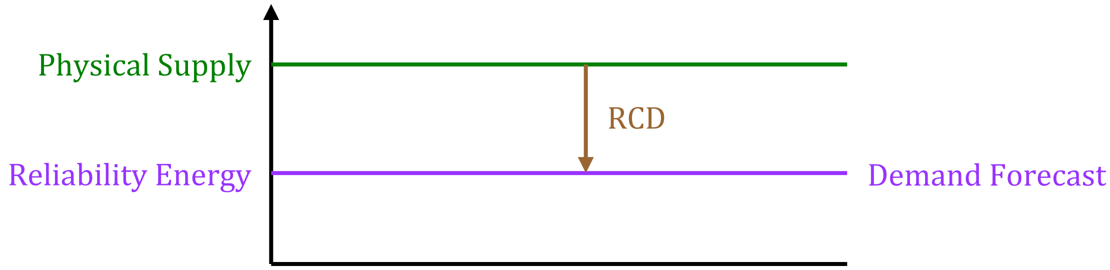

Figure 4. RUC target when physical supply clears in IFM above the demand forecast

Although the net system reliability capacity from all physical resources in the system is either upward (in the scenario shown in Figure 3) or downward (in the scenario shown in Figure 4), individual resources may have either a RCU or a RCD award in either scenario due to binding transmission constraints.

The reliability energy schedules and RCU/RCD awards are related to the day-ahead energy schedules as follows:

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

For a given resource, these constraints allow either RCU to take value, resulting in a reliability energy schedule higher than the day-ahead energy schedule, or RCD to take value, resulting in a reliability energy schedule lower than the day-ahead energy schedule.

The following constraint is enforced in RUC to meet the RUC target:

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

The day-ahead energy schedules are fixed in RUC at the IFM solution. CAISO-forecasted VERs are eligible for both RCU and RCD awards, but their reliability energy schedules are limited by their VER forecast. SC-forecasted VERs are not eligible for RCU awards, but they are eligible for RCD awards and their reliability energy schedules are limited by their VER forecast; however, no RCD is awarded above the VER forecast.

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.

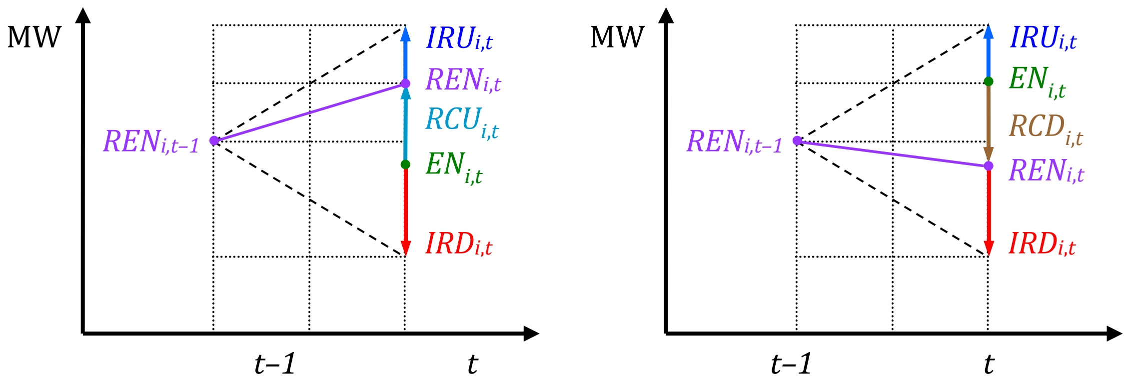

Figure 5. Reliability capacity up or down awards

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

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

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 ramp capability and capacity 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:

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

Resources that are committed in IFM are modeled as must run in RUC, i.e., they are kept online. However, all feasible MSG online transitions are allowed. RCU and RCD are zero when the resource is offline, except for RCU that can be provided by offline resources that can start within 60min ($SUT \le 60$min):

$$u_{i,t} = 0 \rightarrow \left\{\begin{array}{l} REN_{i,t} = RCD_{i,t} = 0 \\ RCU_{i,t} = 0, \forall i \notin S_{60} \end{array}\right\}, \forall i \wedge t = 1,2,\ldots,T$$

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 and Import/Export System Resource can be certified to provide RCU/RCD. The exception is SC-forecasted VERs that are not eligible for RCU awards and their reliability energy schedules are limited by their VER forecast. An energy bid is required for RCU/RCD awards.

5.4 POWER BALANCE CONSTRAINTS

The power balance constraints for the reliability energy schedules are as follows:

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

The demand forecast is distributed to the load nodes in the market footprint using load distribution factors that are adopted from the State Estimator solution for the relevant season, type of day, and time of day. The distributed load, accounting for transmission losses, is adjusted by the distributed load slack in the AC power flow solution, but it is not a variable in the SCUC, hence the linearized power balance constraint for the reliability energy schedules is as follows:

$$\sum_i \frac{\Delta REN_{i,t}}{LPF_{i,t}^{(r)}} = 0, t = 1,2, \dots, T$$

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 the 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 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 RUC are the same as those enforced in IFM.

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

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

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 critical constraints are 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:

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

The ITC/ISL constraints are linearized as follows:

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

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:

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

No additional control variables are introduced. The difference is that the upper/lower flow limits are emergency limits and the shift factors reflect the changed network topology in the post-contingency case after the loss of the associated transmission element. Different AC power flow solutions 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:

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

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

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

The difference is that the constraints are formulated for the post-contingency reliability 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.

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

$$\widetilde{LFL}_{m,t}^{(g,r)} \leq \tilde{F}_{m,t}^{(g,r)} + \sum_{i} \Delta REN_{i,t}\, SF'^{(g)}_{i,m,t} \leq \widetilde{UFL}_{m,t}^{(g,r)}, \forall g, m \wedge t = 1,2, \ldots, T$$

Where:

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

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:

$$\sum_{i \in S_n} a_i \left(REN_{i,t} + RCU_{i,t} + IRU_{i,t} \right) \leq GL_{n,t}, \forall n, t = 1,2, \ldots, T$$

5.10 CAPACITY CONSTRAINTS

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

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

The capacity constraints for offline physical resources are as follows:

$$\left. \begin{array}{l} NR_{i,t} + RCU_{i,t} + IRU_{i,t} \leq UCL_{i,t} \\ RCU_{i,t} + IRU_{i,t} \leq UEL'_{i,t} \end{array} \right\}, \forall i \in S_{60} \wedge i \wedge u_{i,t} = 0 \wedge t = 1,2, \ldots, T$$

The RCD award for SC-forecasted VERs is limited by their VER forecast:

$$\left. \begin{array}{l} LCL_{i,t} + RCD_{i,t} + IRD_{i,t} \leq FV_{i,t} \\ LEL'_{i,t} + RCD_{i,t} + IRD_{i,t} \leq FV_{i,t} \end{array} \right\}, \forall i \in S_{VERs} \wedge u_{i,t} = 1 \wedge t = 1,2, \ldots, T$$

5.11 RAMP CAPABILITY CONSTRAINTS

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

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

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:

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

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.

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

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

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:

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

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:

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

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

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

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

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 SOC for a LESR is calculated as follows:

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

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

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

6 PRICE FORMATION

This section presents the price formation for the day-ahead energy schedules, the RCU/RCD awards, and the IRU/IRD awards in the DAME. 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 and reliability energy schedules, and the IRU/IRD procurement constraints:

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

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 in the DAME are calculated as follows:

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

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