Extended Day-Ahead Market

Draft Technical Description

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1 INTRODUCTION

This technical paper describes the optimization problem formulation of the Extended Day-Ahead Market (EDAM) where the California Independent System Operator (CAISO) extends its Day-Ahead Market (DAM) to other Balancing Authority Areas (BAAs) that sign the EDAM Participation Agreement, hereby referred to as EDAM BAAs. This extension is similar to the Western Energy Imbalance Market (WEIM) where the CAISO extends its Real-Time Market (RTM) to other BAAs that sign the WEIM Participation Agreement, hereby referred to as EIM BAAs.

Although an EIM BAA may not join the EDAM, because of the intertwined settlement between the DAM and the RTM, all EDAM BAAs must also be participants in the WEIM. Therefore, in this paper the following classification is used for BAAs:

1) The CAISO BAA (CISO) whose BAA Operator (CAISO) is the Market Operator (MO).
2) An EDAM BAA whose BAA Operator (EDAM Entity) has joined the EDAM and the WEIM.
3) An EIM BAA whose BAA Operator (EIM Entity) has joined the WEIM, but not necessarily the EDAM.
4) An exclusively EIM BAA whose BAA Operator (EIM Entity) has joined the WEIM, but not the EDAM.
5) A non-EIM BAA whose BAA Operator has not joined either the EDAM or the WEIM.

A general reference to an EDAM BAA or an EIM BAA collectively includes the CISO. A general reference to a non-EDAM BAA collectively includes exclusively EIM and non-EIM BAAs. Figure 1 illustrates these membership relationships with a Venn diagram.

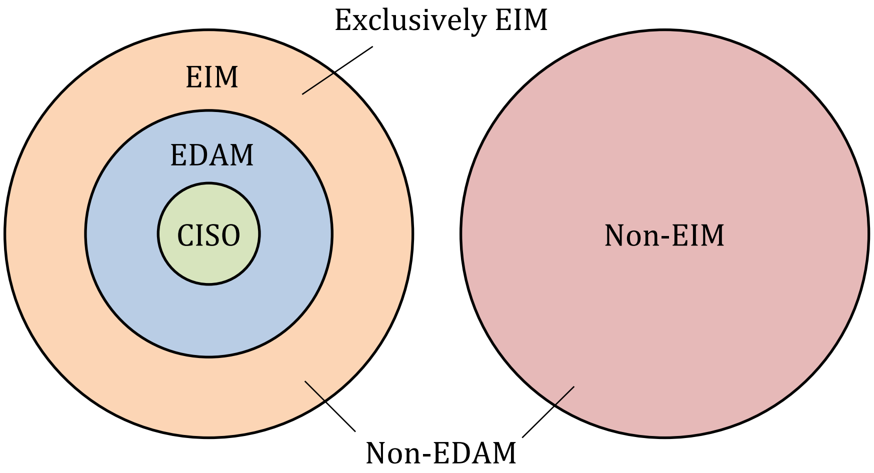

Figure 1. BAA classification

1.1 EXTENDED DAY-AHEAD MARKET FEATURES

The EDAM leverages advanced technology and many years of experience in designing and operating markets to offer an extensive set of features:

- Efficient resource commitment and scheduling using multiple-part energy bids: start-up cost, minimum load cost, state transition cost, and incremental energy cost.
- Least-cost procurement of ancillary services (regulation up/down, and spinning/non-spinning reserve) and imbalance reserve up/down, co-optimized with energy schedules to meet ancillary services and uncertainty requirements.
- Optimal Resource commitment and scheduling to balance physical and virtual supply and demand bids. In addition, reliability capacity up/down from energy schedules is reserved from physical supply and intertie resources to meet the demand forecast.
- Inter-temporal constraints, such as dynamic ramp rates, start-up and minimum up/down times, state transition times, maximum daily start-ups and transitions, and energy or state of charge limits, ensure feasible resource scheduling.
- A full network model with physical and scheduling transmission constraints ensures efficient and reliable use of available transmission within physical and scheduling limits under the base case and preventive transmission and resource contingencies.
- Market power mitigation techniques identifying uncompetitive transmission constraints and mitigating resource bids that provide congestion relief.
- Support for optimal energy, imbalance reserve, and reliability capacity transfers between EDAM BAAs.
- Resource sufficiency evaluation for each EDAM BAA to meet demand forecast, ancillary services, and uncertainty requirements, using internal resources and RSE-eligible transfers with other EDAM BAAs or intertie schedules with non-EDAM BAAs.
- A greenhouse gas (GHG) regulation model that co-optimizes GHG regulation cost and allocates GHG responsibility to resources producing energy imported to GHG regulation areas.
- Comprehensive settlement of energy schedules, imbalance reserve awards, and reliability capacity awards at locational marginal prices with bid cost recovery and cost allocation mechanisms based on cost causation principles.

2 ASSUMPTIONS

The following assumptions are made in this paper:

1. All BAAs that participate in the EDAM participate in the WEIM, too.
2. The market structure and features of the Day-Ahead Market Enhancements (DAME) are inherited by the EDAM; specifically:

  - A market power mitigation pass for mitigating energy and imbalance reserve bids, followed by the Integrated Forward Market (IFM);
  - A separate market power mitigation pass for mitigating reliability capacity bids, followed by the Residual Unit Commitment (RUC);
  - Hourly unit commitment and state transitions for Multi-State Generating (MSG) resources;
  - Hourly bids and schedules/awards for energy, ancillary services, imbalance reserve up/down, and reliability capacity up/down; ancillary services for EDAM BAAs other than the CISO are self-provided;
  - Support for hourly virtual supply, virtual demand, and load bids in the IFM;
  - Imbalance reserve up/down deployment scenarios in the IFM for locational procurement of imbalance reserves subject to transmission constraints;
  - Reliability capacity up/down awards procured in the RUC subject to transmission constraints; and
  - Resource capacity, ramp capability, and energy limit constraints.

3. Two additional passes are included at the beginning of the EDAM application sequence:
    a) The Resource Sufficiency Evaluation (RSE) pass to test that each EDAM BAA is sufficient in meeting its demand forecast, ancillary services requirements, and imbalance reserve requirements, calculating potential hourly shortfall/surplus; and
    b) The GHG Reference pass to calculate the GHG reference schedule for resources with GHG bids.

   The RSE pass also runs at specific times before the start of the EDAM sequence to produce advisory results.

   Including these two additional passes, there is a total of six sequential passes in the EDAM:

    1) RSE;
    2) GHG Reference;
    3) MPM-IFM;
    4) IFM;
    5) MPM-RUC; and
    6) RUC.

4. The WEIM GHG regulation model will be ported to the EDAM and enhanced to support multiple GHG regulation areas with boundaries that do not necessarily coincide with BAA boundaries. Resources may have distinct GHG bids and GHG attributions for each GHG regulation area.

Figure 2 shows the EDAM timeline.

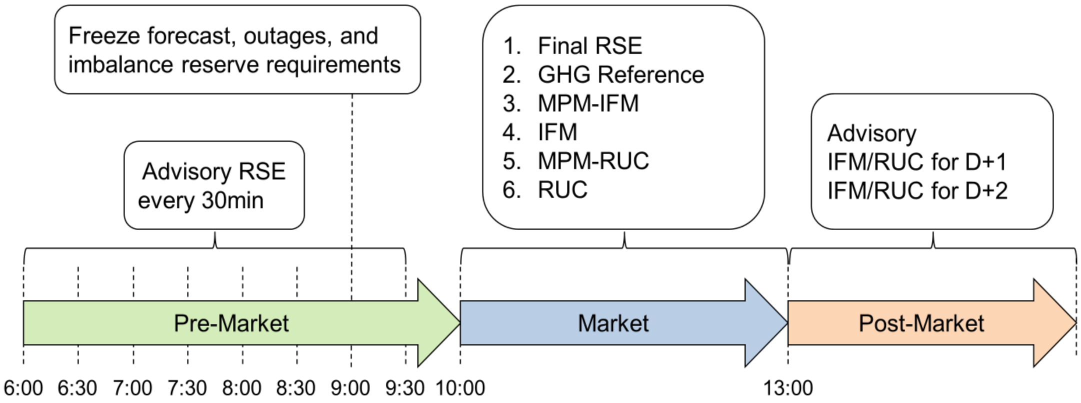

Figure 2. EDAM timeline

3 TRANSFERS

This section describes the various transfers that are supported in the EDAM. There are two different references to transfers:

1) A directional transfer between two BAAs in the market footprint. This transfer is modelled as a matching pair of export and import schedules at a pair of Transfer System Resources (TSRs) at the boundary of the two BAAs. The TSRs are associated with the intertie that is used for tagging the transfer. There may be multiple TSR pairs for multiple transfers between two BAAs at different interties, and even at the same intertie for multiple transfer types. A transfer from BAA A to BAA B is modeled as an export from BAA A to BAA B using an export TSR for BAA A, and a matching import to BAA B from BAA A using an import TSR for BAA B.

2) The algebraic net transfer of a BAA in the market footprint. This is the net of all export/import transfers from/to that BAA to/from other BAAs in the market footprint. The net transfer is algebraic, positive for export and negative for import. The sum of the net transfers of all BAAs in the market footprint nets to zero since they form a closed market system for transfers.

Figure 3 shows how transfers are modeled in EDAM.

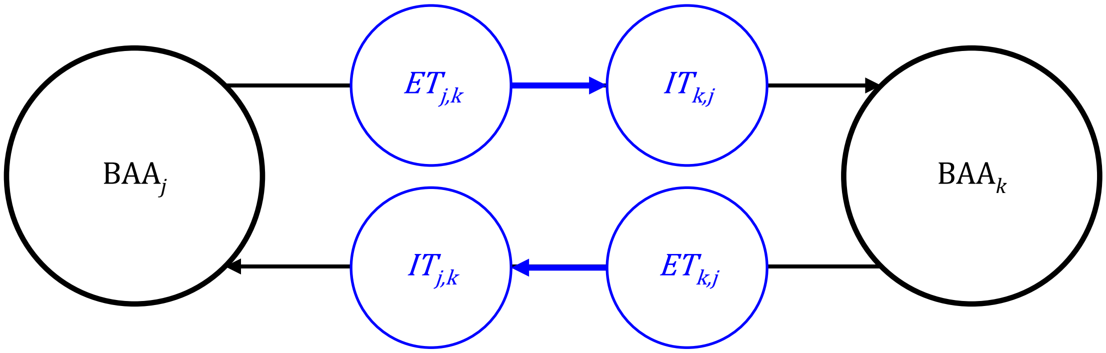

Figure 3. Transfer modeling

3.1 ENERGY TRANSFERS

In the WEIM, an energy transfer is an energy exchange between two BAAs in the WEIM footprint. There are three different types of energy transfers and associated TSRs:

1) Base transfer, which is a fixed transfer that has an hourly base energy schedule that is not optimized in the market. This transfer represents bilateral energy transactions between the relevant BAAs.
2) Static transfer, which is a transfer that is optimally scheduled in the Fifteen-Minute Market (FMM) for each 15min interval. These transfers are fixed in the Real-Time Dispatch (RTD) for each of the 5min intervals that span that 15min interval.
3) Dynamic transfer, which is a transfer that is optimally scheduled in the FMM for each 15min interval, and then in the RTD for each 5min interval, unless there is a corresponding static transfer, in which case the dynamic transfer is zero in the FMM and it is only optimally scheduled in the RTD.

In the EDAM, since there are no resource base schedules and the scheduling interval is 1hr, there is no reason for such distinction among transfers and associated TSRs; all transfers are optimally scheduled in the EDAM. The exception are transfers associated with transmission contracts that can be self-scheduled to exercise the respective scheduling right. Transfers and associated TSRs that are designated as RSE-eligible have a special meaning in the RSE, but other than that, all transfers are optimally scheduled in the IFM and RUC with no distinction. Self-scheduled transfers are considered RSE-eligible.

3.2 CAPACITY TRANSFERS

The concept of energy transfers is expanded in the EDAM to capacity transfers. As such, a capacity transfer from EDAM BAA A to EDAM BAA B is the transfer of capacity requirement from BAA B to BAA A, and a reservation of transfer capacity to dispatch it as energy in the WEIM from BAA A to BAA B, optimally or when needed. There are different capacity transfers for different capacity services:

1) A regulation up/down transfer from BAA A to BAA B is the export of regulation up/down from BAA A to BAA B. This is achieved by transferring an equal amount of regulation up/down requirement from BAA B to BAA A. Transmission capacity is reserved for this transfer on the associated intertie so that the Automatic Generation Control (AGC) of BAA A can provide a dynamic export/import to/from BAA B in the WEIM to regulate a negative/positive Area Control Error (ACE) in BAA B as if it occurred in BAA A. Note that an export regulation down transfer requires an equal amount of export energy transfer because it is dispatched as a dynamic import.
2) A contingency reserve (spinning or non-spinning reserve) transfer from BAA A to BAA B is the export of contingency reserve from BAA A to BAA B. This is achieved by transferring an equal amount of contingency reserve requirement from BAA B to BAA A. Transmission capacity is reserved for this transfer on the associated intertie so that contingency reserve in BAA A can be dispatched to provide a dynamic export to BAA B in the WEIM to assist BAA B in a contingency as if the contingency occurred in BAA A.
3) An imbalance reserve up/down transfer from BAA A to BAA B is the export of imbalance reserve up/down from BAA A to BAA B. This is achieved by transferring an equal amount of imbalance reserve up/down requirement from BAA B to BAA A. Transmission capacity is reserved for this transfer on the associated intertie so that imbalance reserve up/down awards in BAA A can be dispatched optimally to provide a dynamic export/import transfer to/from BAA B in the WEIM to meet positive/negative uncertainty materializing in BAA B as if it were materialized in BAA A. Note that an export imbalance reserve down transfer requires an equal amount of export energy transfer because it is dispatched as a dynamic import.
4) A reliability capacity up/down transfer from BAA A to BAA B is the export of reliability capacity up/down from BAA A to BAA B. Transmission capacity is reserved for this transfer on the associated intertie so that reliability capacity up/down awards in BAA A can be dispatched optimally to provide a dynamic export/import transfer to/from BAA B in the WEIM to assist BAA B in meeting its demand forecast. Because there is a single deployment scenario in RUC where reliability capacity up and down awards are simultaneously dispatched, there is no reason to distinguish between reliability capacity up and down transfers; an export reliability capacity down transfer is equivalent to an import reliability capacity up transfer. Consequently, only reliability capacity up transfers are included in the mathematical formulation in this paper for simplicity, and they are generically referred to as reliability capacity transfers.

Energy and capacity transfers may coexist on the same transfer (TSR pair) defined between two BAAs in the market footprint because the associated TSRs may have both energy schedules and capacity awards, like any other resource. This is particularly true for energy and imbalance reserves because they are co-optimized in the IFM. However, the scope of the first implementation of the EDAM does not include the co-optimization of ancillary services, i.e., regulation up/down and spinning/non-spinning reserves, in EDAM BAAs other than the CISO. Therefore, ancillary services in EDAM BAAs other than the CISO, are self-provided and not optimized. The ancillary services transfers are RSE-eligible and they are used in the RSE to support bilateral contracts, on demand obligations, and reserve group agreements.

3.3 TRANSFER SCHEDULES AND SCHEDULING LIMITS

The scheduling limit on a transfer indicates the amount of transfer capacity that is released in the EDAM for optimal scheduling. This is specified as an upper capacity limit for the relevant TSR by the relevant EDAM Entity. TSRs used for ancillary services transfers have a self-provision for the relevant service. Any remaining transfer capacity under the scheduling limit is used in the IFM to co-optimize energy and imbalance reserve transfers. Furthermore, any transfer capacity that remains available after the IFM is used in the RUC to schedule optimally reliability capacity transfers. The optimal transfer schedules are the energy schedule and capacity awards of the associated TSRs.

This design leverages the existing functionality for resource registration, bid submission and validation, outage/derate management, optimal scheduling and reporting, and settlement, to implement transfers in the EDAM. Capacity constraints are enforced for TSRs, like all resources, so that even when the underlying transfer capacity is made available for co-optimization among different market commodities, the optimal schedules and awards are feasible under the relevant scheduling limit. There is no overlap among energy and upward capacity transfers; however, downward capacity transfers overlap with energy transfers.

4 NOTATION

The following notation is used in the mathematical formulation for the market applications in this technical paper:

i	Resource/node index.
j	BAA index.
l	Transfer index; there may be multiple transfers at an intertie between BAAs.
g	GHG regulation area index.
k	Alternate BAA or GHG regulation area index.
m	Generalized network constraint index, including intertie scheduling limits.
t	Time period (hour) index (zero for initial condition).
(EN)	Superscript denoting energy transfers.
(IRU)	Superscript denoting imbalance reserve up values and transfers.
(IRD)	Superscript denoting imbalance reserve down values and transfers.
(RCU)	Superscript denoting reliability capacity (up) transfers.
(RUC)	Superscript denoting RUC values.
(RSE)	Superscript denoting RSE schedules/awards and RSE-eligible transfers for energy and imbalance reserves.
(RU)	Superscript denoting regulation up transfers.
(RD)	Superscript denoting regulation down transfers.
(SR)	Superscript denoting spinning reserve transfers.
(NR)	Superscript denoting non-spinning reserve transfers.
(GHG)	Superscript denoting GHG reference schedules.
(DA)	Superscript denoting day-ahead schedules in RTM.
$(BASE)$	Superscript denoting base schedules and base transfers in FMM and RTD.
$(STAT)$	Superscript denoting static transfers in the FMM and RTD.

T	The number of time periods in the time horizon, considering the short and long days due to daylight savings changes.
$\forall$	For all…
$\in$	Member of…
$\notin$	Not member of…
$\not\ni$	Does not contain…
$\wedge$	Logical and…
$\cup$	Union…
$\cap$	Intersection…
$\emptyset$	Empty set.
$\Longrightarrow$	Leads to…
Δ	Denotes incremental values from the previous iteration.
$\tilde{\square}$	Accent denoting initial value from an AC power flow solution.
$\hat{\square}$	Accent denoting GHG attribution.
$\bar{\square}$	Accent denoting reference value.
$\overline{\square}$	Overbar denoting maximum value.
$\underline{\square}$	Underbar denoting minimum value.
$'$	Prime denoting adjusted quantity.
$EDAM$	Set of BAAs in the EDAM (CISO and EDAM BAAs).
EIM	Set of BAAs in the WEIM (CISO and EIM BAAs).
BAA_j	Set of resources in BAA j.
GHG_g	Set of resources in GHG regulation area g.
GHG	Set of resources in all GHG regulation areas: $GHG = \bigcup\{GHG_g, \forall g\}$.
S_{RSE}	Set of RSE-eligible resources.
S_I	Set of intertie (import/export) resources.
I_m	Set of import resources associated with ITC/ISL m.
E_m	Set of export resources associated with ITC/ISL m.
$u_{i,t}$	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.
C	Objective function.
$DFIRU$	Deployment factor of imbalance reserve up.
$DFIRD$	Deployment factor of imbalance reserve down.
$UOL_{i,t}$	Upper operating limit of resource i in time period t.
$URL_{i,t}$	Upper regulating 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 of 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. For a TSR, it is the released transfer capacity.
$UCL_{i,t}$	Upper capacity limit of resource i in time period t.
$EN_{i,t}$	Energy schedule of physical resource i in time period t; positive for supply and negative for demand.
$I_{i,t}$	Energy schedule of import resource i in time period t from a non-EDAM BAA.

$E_{i,t}$	Energy schedule of export resource *i* in time period *t* to a non-EDAM BAA.
$VS_{i,t}$	Energy schedule of virtual supply resource *i* in time period *t*.
$VD_{i,t}$	Energy schedule of virtual demand resource *i* in time period *t*.
$L_{i,t}$	Energy schedule of non-participating load 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*.
$IRU_{i,t}$	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*.
$RCU_{i,t}$	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*.
$ABCU_{i,t}$	Available balancing capacity up of resource *i* in time period *t*.
$ABCD_{i,t}$	Available balancing capacity down of resource *i* in time period *t*.
$ENUS_{j,t}$	Energy surplus in BAA *j* in time period *t*.
$ENDS_{j,t}$	Energy shortfall in BAA *j* in time period *t*.
$RUS_{j,t}$	Regulation up shortfall in BAA *j* in time period *t*.
$RDS_{j,t}$	Regulation down shortfall in BAA *j* in time period *t*.
$SRS_{j,t}$	Spinning reserve shortfall in BAA *j* in time period *t*.
$NRS_{j,t}$	Non-spinning reserve shortfall in BAA *j* in time period *t*.
$IRUS_{j,t}$	Imbalance reserve up shortfall in BAA *j* in time period *t*.
$IRDS_{j,t}$	Imbalance reserve down shortfall in BAA *j* in time period *t*.
$RCUS_{j,t}$	Reliability capacity up shortfall in BAA *j* in time period *t*.
$RCDS_{j,t}$	Reliability capacity down surplus in BAA *j* in time period *t*.
$US_{j,t}$	Energy and imbalance reserve up shortfall in BAA *j* in time period *t*.
$DS_{j,t}$	Energy and imbalance reserve down surplus in BAA *j* in time period *t*.
$D_{j,t}$	Demand forecast for BAA *j* in time period *t*.
$RUR_{j,t}$	Regulation up requirement in BAA *j* and time period *t*.
$RDR_{j,t}$	Regulation down requirement in BAA *j* and time period *t*.
$SRR_{j,t}$	Spinning reserve requirement in BAA *j* and time period *t*.
$NRR_{j,t}$	Non-spinning reserve requirement in BAA *j* and time period *t*.
$IRUR_{t}$	Imbalance reserve up requirement in time period *t*.
$IRDR_{t}$	Imbalance reserve down requirement in time period *t*.
$T_{j,t}$	Net transfer of BAA *j* in time period *t*; positive for export and negative for import.
$T_{g,t}$	Net GHG transfer of GHG regulation area *g* in time period *t*; positive for export and negative for import.
$ET_{j,k,l,t}$	Export transfer *l* from BAA *j* to BAA *k* in time period *t*.
$IT_{j,k,l,t}$	Import transfer *l* to BAA *j* from BAA *k* in time period *t*.
$\overline{ET}_{j,k,l,t}$	Scheduling limit of the export transfer *l* of BAA *j* to BAA *k* in time period *t*.
$\overline{IT}_{j,k,l,t}$	Scheduling limit of the import transfer *l* of BAA *j* from BAA *k* in time period *t*.
$Loss_{j,t}$	Transmission loss in BAA *j* and time period *t*.

$Loss_{g,t}$	Transmission loss in GHG regulation area *g* and time period *t*.
$LPF_{i,t}$	Loss penalty factor for resource *i* in time period *t*.
$SF_{i,m,t}$	Shift factor for resource *i* on network constraint *m* in time period *t*.
$SF_{j,m,t}$	Shift factor for imbalance reserve requirement distribution in BAA *j* on network constraint *m* in time period *t*.
$AC_{i,t}$	Available capacity from resource *i* in time period *t*.
$CF_{j,t}$	Confidence factor for non-RSE-eligible resources of BAA *j* in time period *t*.
$RM_{j,t}$	Reliability margin of BAA *j* in time period *t*.
$UFL_{m,t}$	Upper limit on network constraint *m* in time period *t*.
$LFL_{m,t}$	Lower limit on network constraint *m* in time period *t*.
$F_{m,t}$	Active power flow or schedule on network constraint *m* in time period *t*.
$GHGBC_{i,g,t}$	GHG bid capacity of resource *i* for GHG regulation area *g* in time period *t*.
$GHGBP_{i,g,t}$	GHG bid price of resource *i* for GHG regulation area *g* in time period *t*.
$ALF_{g,t}$	Average loss factor for GHG regulation area *g* in time period *t*.
$CO_{i,g,t}$	Capacity obligation of resource *i* for GHG regulation area *g* in time period *t*.
$\lambda_{j,t}$	Shadow price of energy balance constraint of BAA *j* in time period *t*.
$\rho_{j,t}$	Shadow price of imbalance reserve up balance constraint of BAA *j* in time period *t*.
$\sigma_{j,t}$	Shadow price of imbalance reserve down balance constraint of BAA *j* in time period *t*.
$\xi_{j,t}$	Shadow price of reliability capacity balance constraint of BAA *j* in time period *t*.
$\psi_{g,t}$	Shadow price of GHG import allocation constraint for GHG regulation area *g* in time period *t*.
$\mu_{m,t}$	Shadow price of network constraint *m* in time period *t*.

Note: quantities in the downward direction (*RD*, *IRD*, and *RCD*) are non-negative. Moreover, all requirements and surplus variables are also non-negative.

5 INTEGRATED FORWARD MARKET

The mathematical formulation for the IFM is fully described in the DAME Technical Description.[1] In this paper, the focus is on the additional elements introduced by the EDAM, namely the transfers for energy and imbalance reserves, the procurement of imbalance reserves, the power balance relaxation constraints, the net export transfer constraints, the resource sufficiency evaluation, and the GHG regulation cost model.

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[1] https://projectserverpmo.oa.caiso.com/PWA/DAME/Project%20Documents/03%20-%20Design%20Phase/Day-Ahead%20Market%20Enhancements%20Draft%20Technical%20Description%20(v9.5).docx

5.1 OBJECTIVE FUNCTION

The objective function in the IFM includes the additional cost of GHG attributions, as described in §9.1.

5.2 ENERGY TRANSFERS

The net energy transfer for each BAA in the EDAM is included in the power balance constraint for that BAA, as follows:

$$\sum_{i \in BAA_j} \left(EN_{i,t} + I_{i,t} - E_{i,t} + VS_{i,t} - VD_{i,t} - L_{i,t} \right) - T_{j,t}^{(EN)} - Loss_{j,t} = 0,$$
$$\forall j \in EDAM \wedge t = 1,2, \dots, T$$

The net energy transfer is an algebraic quantity, positive for net export and negative for net import.

The transmission loss (*Loss*) in the BAA is linearized using loss penalty factors obtained from the Jacobian of the AC power flow solution in the previous iteration; the linearized power balance constraints are as follows:

$$\sum_{i \in BAA_j} \frac{\left(\Delta EN_{i,t} + \Delta I_{i,t} - \Delta E_{i,t} + \Delta VS_{i,t} - \Delta VD_{i,t} - \Delta L_{i,t} \right)}{LPF_{i,t}} - \Delta T_{j,t}^{(EN)} = 0,$$
$$\forall j \in EDAM \wedge t = 1,2, \dots, T$$

The net energy transfer of an EDAM BAA is distributed optimally over the various energy transfers on different interties between that BAA and other BAAs in the EDAM, as follows:

$$T_{j,t}^{(EN)} = \sum_{\substack{k \in EDAM \\ k \neq j}} \sum_{l} \left(ET_{j,k,l,t}^{(EN)} - IT_{j,k,l,t}^{(EN)} \right), \forall j \in EDAM \wedge t = 1,2, \dots, T$$

Where each energy transfer is directional and modeled as a pair of an export energy transfer (*ET*) and a matching import energy transfer (*IT*) at TSRs on each side of the relevant intertie, as follows:

$$0 \leq ET_{j,k,l,t}^{(EN)} = IT_{k,j,l,t}^{(EN)}, \forall l \wedge \forall \{j,k\} \in EDAM \wedge j \neq k \wedge t = 1,2, \dots, T$$

An immaterial transfer cost is assigned to each transfer in the objective function to yield a robust net transfer distribution observing scheduling priorities among parallel transfers and preventing omnidirectional transfer schedules at any given intertie as well as circular transfers.

Since the BAAs in EDAM form a closed system for energy transfers, the net of all energy transfers is zero:

$$\sum_{j \in EDAM} T_{j,t}^{(EN)} = 0, t = 1,2, \dots, T$$

5.3 ANCILLARY SERVICE TRANSFERS

Ancillary service transfers are not optimized in the EDAM, but they are considered in the RSE to transfer the corresponding ancillary service requirement from the sink BAA to the source BAA. Dedicated transfer capacity for ancillary service transfers is reserved from the transfer capacity released for energy, imbalance reserves, and reliability capacity.

For CISO where ancillary services are co-optimized with energy and imbalance reserves, the ancillary service transfers adjust the ancillary service requirements of the super region, as follows:

$$\left.\begin{aligned}
\sum_{i \in BAA_j} RD_{i,t} &\geq RDR_{j,t} + T_{j,t}^{(RD)} \\
\sum_{i \in BAA_j} RU_{i,t} &\geq RUR_{j,t} + T_{j,t}^{(RU)} \\
\sum_{i \in BAA_j} \left(RU_{i,t} + SR_{i,t} \right) &\geq RUR_{j,t} + T_{j,t}^{(RU)} + SRR_{j,t} + T_{j,t}^{(SR)} \\
\sum_{i \in BAA_j} \left(RU_{i,t} + SR_{i,t} + NR_{i,t} \right) &\geq RUR_{j,t} + T_{j,t}^{(RU)} + SRR_{j,t} + T_{j,t}^{(SR)} + NRR_{j,t} + T_{j,t}^{(NR)} \\
j = CISO \wedge t = 1,2, \ldots, T &
\end{aligned}\right\},$$

The sum of the nested ancillary service requirements for inner regions must not exceed the ancillary service requirement for the higher-level region that includes them, and ultimately the adjusted ancillary service requirement for the super region.

5.4 IMBALANCE RESERVE TRANSFERS

The imbalance reserve up/down procurement constraints become the power balance constraints in the IRU/IRD deployment scenarios by introducing net imbalance reserve transfers, as follows:

$$\left.\begin{aligned}
&\sum_{i \in BAA_j} \sum_{i} IRU_{i,t} + IRUS_{j,t} - T_{j,t}^{(IRU)} = IRUR_{j,t} \\
&\sum_{i \in BAA_j} \sum_{i} IRD_{i,t} + IRDS_{j,t} - T_{j,t}^{(IRD)} = IRDR_{j,t} \\
&0 \leq IRUS_{j,t} \leq IRUR_{j,t} \\
&0 \leq IRDS_{j,t} \leq IRDR_{j,t}
\end{aligned}\right\}, \forall j \in EDAM \wedge t = 1,2, \ldots, T$$

The net imbalance reserve transfer is an algebraic quantity, positive for net export and negative for net import.

Similarly to the net energy transfer, the net imbalance reserve transfer of an EDAM BAA is distributed optimally over the various imbalance reserve transfers on different interties between that BAA and other BAAs in the EDAM, as follows:

$$\left.\begin{array}{l} T_{j,t}^{(IRU)} = \displaystyle\sum_{\substack{k \in EDAM \\ k \neq j}} \sum_{l} \left(ET_{j,k,l,t}^{(IRU)} - IT_{j,k,l,t}^{(IRU)} \right) \\ T_{j,t}^{(IRD)} = \displaystyle\sum_{\substack{k \in EDAM \\ k \neq j}} \sum_{l} \left(ET_{j,k,l,t}^{(IRD)} - IT_{j,k,l,t}^{(IRD)} \right) \end{array}\right\}, \forall j \in EDAM \wedge t = 1,2,\dots,T$$

Where each imbalance reserve transfer is directional and modeled as a pair of an export imbalance reserve transfer and a matching import imbalance reserve transfer at TSRs on each side of the relevant intertie, as follows:

$$\left.\begin{array}{l} 0 \leq ET_{j,k,l,t}^{(IRU)} = IT_{k,j,l,t}^{(IRU)} \\ 0 \leq ET_{j,k,l,t}^{(IRD)} = IT_{k,j,l,t}^{(IRD)} \end{array}\right\}, \forall l \wedge \forall \{j,k\} \in EDAM \wedge j \neq k \wedge t = 1,2,\dots,T$$

Since the BAAs in EDAM form a closed system for imbalance reserve transfers, the net of all imbalance reserve transfers in EDAM is zero:

$$\left.\begin{array}{l} \displaystyle\sum_{j \in EDAM} T_{j,t}^{(IRU)} = 0 \\ \displaystyle\sum_{j \in EDAM} T_{j,t}^{(IRD)} = 0 \end{array}\right\}, t = 1,2,\dots,T$$

The same TSRs are used to model energy and imbalance reserve transfers, and ancillary services transfers when applicable. All transfers are limited by the respective TSR scheduling limits, as follows:

$$\left.\begin{array}{c} ET_{j,k,l,t}^{(EN)} + ET_{j,k,l,t}^{(RU)} + ET_{j,k,l,t}^{(SR)} + ET_{j,k,l,t}^{(NR)} + ET_{j,k,l,t}^{(IRU)} \leq \overline{ET}_{j,k,l,t} \\ 0 \leq ET_{j,k,l,t}^{(EN)} - ET_{j,k,l,t}^{(RD)} - ET_{j,k,l,t}^{(IRD)} \\ IT_{j,k,l,t}^{(EN)} + IT_{j,k,l,t}^{(RU)} + IT_{j,k,l,t}^{(SR)} + IT_{j,k,l,t}^{(NR)} + IT_{j,k,l,t}^{(IRU)} \leq \overline{IT}_{j,k,l,t} \\ 0 \leq IT_{j,k,l,t}^{(EN)} - IT_{j,k,l,t}^{(RD)} - IT_{j,k,l,t}^{(IRD)} \\ \overline{ET}_{j,k,l,t} = \overline{IT}_{k,j,l,t} \end{array}\right\},$$
$$\forall l \wedge \forall \{j,k\} \in EDAM \wedge j \neq k \wedge t = 1,2,\dots,T$$

Note that IRU and IRD transfers do not net in reserving transfer capacity because the IRU and IRD awards are not deployed simultaneously, but in different deployment scenarios in the IFM. An export IRU transfer reserves transfer capacity in the export direction, whereas an export IRD transfer reserves transfer capacity in the import direction.

5.5 POWER BALANCE RELAXATION CONSTRAINTS

The EDAM BAA power balance constraints in the IFM can be relaxed at a penalty by including energy supply shortfall and surplus variables as follows:

$$\sum_{i \in BAA_j} \frac{\left(\Delta EN_{i,t} + \Delta I_{i,t} - \Delta E_{i,t} + \Delta VS_{i,t} - \Delta L_{i,t} - \Delta VD_{i,t}\right)}{LPF_{i,t}} - \Delta T_{j,t}^{(EN)} + ENUS_{j,t} - ENDS_{j,t} = 0,$$
$$\forall j \in EDAM \wedge t = 1,2, \ldots , T$$

Where the energy supply shortfall (*ENUS*) and surplus (*ENDS*) variables are assigned penalty costs in the objective function. To prevent transfers causing a power balance constraint relaxation in an EDAM BAA, the following constraints are enforced in the IFM:

$$\left.\begin{array}{l} ENUS_{j,t}\left(T_{j,t}^{(EN)} - \bar{T}_{j,t}\right) \leq 0 \\ ENDS_{j,t}\left(T_{j,t}^{(EN)} - \bar{T}_{j,t}\right) \geq 0 \end{array}\right\}, \forall j \in EDAM \wedge t = 1,2, \ldots , T$$

These constraints will not allow a net export energy transfer above a reference to cause power balance shortfall, or a net import energy transfer below a reference to cause power balance surplus. The net transfer reference is the RSE-eligible net transfer, as follows:

$$\bar{T}_{j,t} = T_{j,t}^{(RSE)}, \forall j \in EDAM \wedge t = 1,2, \ldots , T$$

Similar imbalance reserve balance relaxation constraints are not required in the IRU/IRD deployment scenarios because of the economic relaxation of the IRU/IRD requirements provided by the IRU/IRD surplus.

5.6 NET EXPORT TRANSFER CONSTRAINTS

Because of the economic relaxation of the imbalance reserve requirements via the imbalance reserve demand price curve, an EDAM BAA may come out of the EDAM being sort in meeting its uncertainty requirements, even if it passes the RSE. To preserve available supply capacity for meeting the balance of uncertainty requirements in the WEIM, instead of overly committing export transfers to other EDAM BAAs, the net export transfer may be limited in the IFM by a volumetric constraint. At a conceptual level, the net export transfer, beyond the committed net RSE-eligible transfer, is limited to the available supply capacity in excess of the sum of the RSE requirements and a configurable reliability margin. Furthermore, the available supply capacity from non-RSE-eligible resources is discounted by a confidence factor that reflects the confidence in these resources being available in the RTM.

The implementation of this constraint is very complex. The actual available supply capacity is limited by resource constraints, including intertemporal constraints like ramping capability and energy limitations. The effect of intertemporal constraints cannot be captured in independent hourly constraints. Furthermore, even the hourly resource capacity constraints are not straightforward because although imbalance reserve awards overlap with the energy bid range, ancillary services awards may overlap with resource capacity above the energy bid range. To capture the effect of these constraints, the net export transfer constraint is formulated in terms of the RSE schedules because all these constraints are enforced in the RSE.

To facilitate the calculation of available supply capacity, it is convenient to define upper and lower capacity limits as follows:

$$\left.\begin{array}{l}
RU_{i,t}^{(RSE)} + RD_{i,t}^{(RSE)} > 0 \Longrightarrow UCL_{i,t} = \min\left(UOL_{i,t}, URL_{i,t}, CL_{i,t}\right) \\
\left.\begin{array}{l} RU_{i,t}^{(RSE)} + RD_{i,t}^{(RSE)} = 0 \\ SR_{i,t}^{(RSE)} + NR_{i,t}^{(RSE)} > 0 \end{array}\right\} \Longrightarrow UCL_{i,t} = \min\left(UOL_{i,t}, CL_{i,t}\right) \\
RU_{i,t}^{(RSE)} + RD_{i,t}^{(RSE)} + SR_{i,t}^{(RSE)} + NR_{i,t}^{(RSE)} = 0 \Longrightarrow UCL_{i,t} = UOL_{i,t} \\
UEL'_{i,t} = \min\left(UCL_{i,t}, UEL_{i,t}\right)
\end{array}\right\}, \\
\forall i \in BAA_j \wedge j \in EDAM \wedge t = 1,2,\ldots,T$$

Then, ignoring intertemporal constraints, the available supply capacity is calculated as follows:

$$AC_{i,t} = u_{i,t}^{(RSE)} \min\left(UCL_{i,t} - RU_{i,t}^{(RSE)} - SR_{i,t}^{(RSE)} - NR_{i,t}^{(RSE)}, UEL'_{i,t}\right) - IRU_{i,t}^{(RSE)} - EN_{i,t}^{(RSE)}, \\
\forall i \in BAA_j \wedge j \in EDAM \wedge t = 1,2,\ldots,T$$

For imports from non-EDAM BAAs, the available supply capacity is further constrained by the applicable intertie scheduling limit, considering high priority (price-taker) exports to non-EDAM BAAs. Low priority and economic exports are ignored, as they are also ignored in the RSE because they are not RSE-eligible. Then, the net export transfer constraints are as follows:

$$T_{j,t}^{(EN)} + T_{j,t}^{(IRU)} - T_{j,t}^{(IRD)} \le T_{j,t}^{(RSE)} + \\
\max\left(\begin{array}{l}
0, \sum_{i \in BAA_j \cap S_{RSE} - S_I} AC_{i,t} + CF_{j,t} \sum_{i \in BAA_j - S_{RSE} - S_I} AC_{i,t} + \\
\sum_m \min\left(\begin{array}{c} UFL_{m,t} + \sum_{i \in BAA_j \cap E_m} E_{i,t}^{(RSE)}, \\ \sum_{i \in BAA_j \cap I_m \cap S_{RSE}} AC_{i,t} + CF_{j,t} \sum_{i \in BAA_j \cap I_m - S_{RSE}} AC_{i,t} \end{array}\right) - \\
US_{j,t}^{(RSE)} - RUS_{j,t}^{(RSE)} - SRS_{j,t}^{(RSE)} - NRS_{j,t}^{(RSE)} - RM_{j,t}
\end{array}\right), \\
\forall j \in EDAM \wedge t = 1,2,\ldots,T$$

Note that if there are multiple overlapping intertie scheduling limits, only the set of outermost limits are included in these constraints for simplicity. Furthermore, if the BAA has failed the upward RSE, the RSE upward shortfalls must be subtracted from the available supply capacity.

6 RESIDUAL UNIT COMMITMENT

The mathematical formulation for the RUC is fully described in the DAME Technical Description.[1] In this paper, the focus is on the additional elements introduced by the EDAM, namely the transfers for reliability capacity.

6.1 RELIABILITY CAPACITY TRANSFERS

The net reliability capacity transfer for each BAA in the EDAM is included in the power balance constraint for that BAA, as follows:

$$\sum_{i\in BAA_j}\left(EN_{i,t}+RCU_{i,t}-RCD_{i,t}\right)-T_{j,t}^{(RCU)}=D_{j,t},\forall j\in EDAM\wedge t=1,2,\dots,T$$

Where the energy schedules (EN) are fixed from the IFM. The net reliability capacity transfer is an algebraic quantity, positive for net export and negative for net import.

The linearized power balance constraints are as follows:

$$\sum_{i\in BAA_j}\frac{\left(\Delta RCU_{i,t}-\Delta RCD_{i,t}\right)}{LPF_{i,t}^{(RUC)}}-\Delta T_{j,t}^{(RCU)}=0,\forall j\in EDAM\wedge t=1,2,\dots,T$$

Similarly to the net energy transfers, the net reliability capacity transfer of an EDAM BAA is distributed optimally over the various reliability capacity transfers on different interties between that BAA and other BAAs in the EDAM, as follows:

$$T_{j,t}^{(RCU)}=\sum_{\substack{k\in EDAM\\ k\neq j}}\sum_{l}\left(ET_{j,k,l,t}^{(RCU)}-IT_{j,k,l,t}^{(RCU)}\right),\forall j\in EDAM\wedge t=1,2,\dots,T$$

Where each reliability capacity transfer is directional and modeled as a pair of an export reliability capacity transfer and a matching import reliability capacity transfer at TSRs on each side of the relevant intertie, as follows:

$$0\le ET_{j,k,l,t}^{(RCU)}=IT_{k,j,l,t}^{(RCU)},\forall l\wedge\forall\{j,k\}\in EDAM\wedge j\neq k\wedge t=1,2,\dots,T$$

Since the BAAs in EDAM form a closed system for reliability capacity transfers, the net of all reliability capacity transfers in EDAM is zero:

$$\sum_{j\in EDAM}T_{j,t}^{(RCU)}=0,t=1,2,\dots,T$$

The same TSRs are used to model energy, imbalance reserve, and reliability capacity transfers, and ancillary services transfers when applicable. The energy, imbalance reserve, and ancillary services transfers are fixed from the IFM. All transfers are limited by the respective TSR scheduling limits, as follows:

$$\left.\begin{array}{c}
ET_{j,k,l,t}^{(EN)}+ET_{j,k,l,t}^{(RU)}+ET_{j,k,l,t}^{(SR)}+ET_{j,k,l,t}^{(NR)}+ET_{j,k,l,t}^{(IRU)}+ET_{j,k,l,t}^{(RCU)}\le\overline{ET}_{j,k,l,t}\\
0\le ET_{j,k,l,t}^{(EN)}-ET_{j,k,l,t}^{(RD)}-ET_{j,k,l,t}^{(IRD)}-IT_{j,k,l,t}^{(RCU)}\\
IT_{j,k,l,t}^{(EN)}+IT_{j,k,l,t}^{(RU)}+IT_{j,k,l,t}^{(SR)}+IT_{j,k,l,t}^{(NR)}+IT_{j,k,l,t}^{(IRU)}+IT_{j,k,l,t}^{(RCU)}\le\overline{IT}_{j,k,l,t}\\
0\le IT_{j,k,l,t}^{(EN)}-IT_{j,k,l,t}^{(RD)}-IT_{j,k,l,t}^{(IRD)}-ET_{j,k,l,t}^{(RCU)}\\
\overline{ET}_{j,k,l,t}=\overline{IT}_{k,j,l,t}
\end{array}\right\},$$

$$\forall l\wedge\forall\{j,k\}\in EDAM\wedge j\neq k\wedge t=1,2,\dots,T$$

These constraints are enforced as normal capacity limits on TSRs since they are treated like regular resources. Note that IRU, IRD, and RCU transfers do not net in reserving transfer capacity because they are deployed in different deployment scenarios in the IFM and RUC.

6.2 POWER BALANCE RELAXATION CONSTRAINTS IN THE RUC

The EDAM BAA power balance constraints in the RUC can be relaxed at a penalty by including reliability capacity shortfall and surplus variables as follows:

$$\sum_{i \in BAA_j} \frac{\left(\Delta RCU_{i,t} - \Delta RCD_{i,t}\right)}{LPF_{i,t}^{(RUC)}} + \Delta T_{j,t}^{(RCU)} + RCUS_{j,t} - RCDS_{j,t} = 0, \forall j \in EDAM \wedge t = 1,2, \dots, T$$

Where the reliability capacity shortfall (*RCUS*) and surplus (*RCDS*) variables are assigned penalty costs in the objective function. To prevent transfers causing a power balance constraint relaxation in an EDAM BAA, the following constraints are enforced in the RUC:

$$\left.\begin{matrix} RCUS_{j,t}\left(T_{j,t}^{(RCU)} - \bar{T}_{j,t}\right) \leq 0 \\ RCDS_{j,t}\left(T_{j,t}^{(RCU)} - \bar{T}_{j,t}\right) \geq 0 \end{matrix}\right\}, \forall j \in EDAM \wedge t = 1,2, \dots, T$$

These constraints will not allow a net export reliability capacity transfer above a reference to cause power balance shortfall, or a net import reliability capacity transfer below a reference to cause power balance surplus. The net transfer reference includes the energy and IRU/IRD net transfers from the IFM, as follows:

$$\bar{T}_{j,t} = T_{j,t}^{(EN)} + T_{j,t}^{(IRU)} - T_{j,t}^{(IRD)}, \forall j \in EDAM \wedge t = 1,2, \dots, T$$

Where positive IRD transfers reserve transfer capacity in the import direction.

6.3 NET EXPORT TRANSFER CONSTRAINTS

Net export transfer constraints may also be enforced in the RUC to prevent overly committing reliability capacity export transfers to other EDAM BAAs. These constraints are as follows:

$$\begin{gathered} T_{j,t}^{(EN)} + T_{j,t}^{(IRU)} - T_{j,t}^{(IRD)} + T_{j,t}^{(RCU)} \leq T_{j,t}^{(RSE)} + \\ \max\left(\begin{matrix} 0, \sum\limits_{i \in BAA_j \cap S_{RSE} - S_I} AC_{i,t} + CF_{j,t} \sum\limits_{i \in BAA_j - S_{RSE} - S_I} AC_{i,t} + \\ \sum\limits_{m} \min\left(\begin{matrix} UFL_{m,t} + \sum\limits_{i \in BAA_j \cap E_m} E_{i,t}^{(RSE)}, \\ \sum\limits_{i \in BAA_j \cap I_m \cap S_{RSE}} AC_{i,t} + CF_{j,t} \sum\limits_{i \in BAA_j \cap I_m - S_{RSE}} AC_{i,t} \end{matrix}\right) - \\ US_{j,t}^{(RSE)} - RUS_{j,t}^{(RSE)} - SRS_{j,t}^{(RSE)} - NRS_{j,t}^{(RSE)} - RM_{j,t} \end{matrix}\right), \\ \forall j \in EDAM \wedge t = 1,2, \dots, T \end{gathered}$$

Where the energy and IRU/IRD transfers are fixed from the IFM. Note that if there are multiple overlapping intertie scheduling limits, only the set of outermost limits are included in these constraints for simplicity. Furthermore, if the BAA has failed the upward RSE, the RSE upward shortfalls must be subtracted from the available supply capacity.

7 MARKET POWER MITIGATION

The market power mitigation for the MPM-IFM and the MPM-RUC are fully described in the DAME Technical Description.[1] There are no additional elements introduced by the EDAM except that scheduled transfers are considered fringe competitive supply.

8 RESOURCE SUFFICIENCY EVALUATION

This section describes the resource sufficiency evaluation in the EDAM. Unlike the resource sufficiency evaluation in the WEIM, there is no balancing test, but a combined capacity and flexibility test simultaneously for all hours in the time horizon. The objective of the resource sufficiency evaluation is for each EDAM BAA to demonstrate sufficiency in resource capacity and flexibility before the EDAM to meet the BAA demand forecast, ancillary service requirements, and uncertainty requirements, collectively referred to as the RSE requirements. Only RSE-eligible resources are considered in the RSE. Transfers between EDAM BAAs are ignored with the exception of RSE-eligible transfers that are used to transfer requirements from the sink BAA to the source BAA. Transmission constraints are ignored, but all resource constraints, including inter-temporal constraints, are enforced. The mathematical formulation of the RSE problem is as follows:

$$\min \sum_{t=1}^{T} \sum_{j \in EDAM} \left(US_{j,t} + DS_{j,t} + RUS_{j,t} + SRS_{j,t} + NRS_{j,t} + RDS_{j,t} \right)$$

$$\left.\begin{aligned}
&\sum_{i \in BAA_j \cap S_{RSE}} \left(EN_{i,t} + I_{i,t} - E_{i,t} + IRU_{i,t} \right) + US_{j,t} \geq D_{j,t} + T_{j,t}^{(RSE)} + T_{j,t}^{(RD)} + IRUR_{j,t} \\
&\sum_{i \in BAA_j \cap S_{RSE}} \left(EN_{i,t} + I_{i,t} - E_{i,t} - IRD_{i,t} \right) - DS_{j,t} \leq D_{j,t} + T_{j,t}^{(RSE)} + T_{j,t}^{(RD)} - IRDR_{j,t} \\
&\sum_{i \in BAA_j \cap S_{RSE}} RU_{i,t} + RUS_{j,t} \geq RUR_{j,t} + T_{j,t}^{(RU)} \\
&\sum_{i \in BAA_j \cap S_{RSE}} \left(RU_{i,t} + SR_{i,t} \right) + RUS_{j,t} + SRS_{j,t} \geq RUR_{j,t} + T_{j,t}^{(RU)} + SRR_{j,t} + T_{j,t}^{(SR)} \\
&\sum_{i \in BAA_j \cap S_{RSE}} \left(RU_{i,t} + SR_{i,t} + NR_{i,t} \right) + RUS_{j,t} + SRS_{j,t} + NRS_{j,t} \geq \\
&\qquad RUR_{j,t} + T_{j,t}^{(RU)} + SRR_{j,t} + T_{j,t}^{(SR)} + NRR_{j,t} + T_{j,t}^{(NR)} \\
&\sum_{i \in BAA_j \cap S_{RSE}} RD_{i,t} + RDS_{j,t} \geq RDR_{j,t} + T_{j,t}^{(RD)}
\end{aligned}\right\},$$

$$t = 1, 2, \ldots, T$$

Where the resource constraints are not shown for simplicity. The objective is to find a feasible solution where all RSE shortfalls for each EDAM BAA are zero, i.e., all RSE requirements (demand forecast, ancillary services, and uncertainty), as adjusted by RSE-eligible transfers, are met. The optimality of the solution is not important, thus bid prices are not used at all. If all shortfalls for an EDAM BAA in an hour are zero, that BAA passes the RSE in that hour. Otherwise, if any upward shortfall (*US*, *RUS*, *SRS*, or *NRS*) takes value, the BAA fails the RSE in the upward direction, or if any downward shortfall (*DS* or *RDS*) takes value, the BAA fails the RSE in the downward direction, in the respective hour. An EDAM BAA may fail the RSE in both directions in a given hour. Note that a regulation down self-provided transfer forces an equal amount of an energy transfer in the same direction, hence it must be included in the RSE adjustment for the demand forecast and imbalance reserve requirements.

9 GREEN HOUSE GAS REGULATION

This section describes the greenhouse gas (GHG) regulation model in the EDAM. The objective of the model is to reflect the GHG regulation cost for net import into a GHG regulation area in the optimal market solution. This is accomplished by introducing GHG attributions as control variables for physical supply resources outside a GHG regulation area and tying them to the net import into that area. The cost of the GHG attribution in the objective function is determined by the GHG bid that is voluntarily submitted by supply resources outside a GHG regulation area for serving demand in that area. The GHG bid acts as a bid adder to the energy bid for the GHG attribution that serves demand in a GHG regulation area and reflects the GHG regulation cost that is imposed for imports into that area.

Because GHG regulation is state-mandated regulation and state boundaries do not align with BAA boundaries, the GHG regulation model supports GHG regulation areas that are not aligned with BAAs. Furthermore, as more states adopt GHG regulation policies that may be diverse, the GHG regulation model supports multiple non-overlapping GHG regulation areas. Supply resources outside of GHG regulation areas can have multiple GHG bids, one for each GHG regulation area, and as a result, potentially multiple non-overlapping GHG attributions, one for each GHG regulation area. Furthermore, the GHG model supports multiple GHG bids and multiple non-overlapping GHG attributions for resources in a GHG regulation area attributed to other GHG regulation areas.

The GHG attribution is linked with the net import into a GHG regulation area via the GHG import allocation constraint for that GHG regulation area. The shadow price of that constraint is the marginal GHG cost for that GHG regulation area, which is the marginal GHG cost component of the LMP for all nodes in that area. The marginal GHG cost is zero for nodes outside all GHG regulation areas. The GHG attributions for a GHG regulation area receive a payment at the corresponding marginal GHG cost; this payment is in addition to the regular energy schedule settlement and it provides a mechanism to recover the GHG regulation cost imposed on imports into that GHG regulation area.

The GHG regulation model is required to reflect the GHG regulation cost in the market solution; otherwise, emitting resources outside a GHG regulation area may displace economically resources with lower emissions within that area disregarding the emission cost associated with the import, thus resulting in a non-optimal solution.

Figure 4 illustrates the basic principle of the GHG regulation model where GHG bid adders augment the energy bids of external supply resources for their GHG attributions to a GHG regulation area; these GHG attributions comprise the net import into that area.

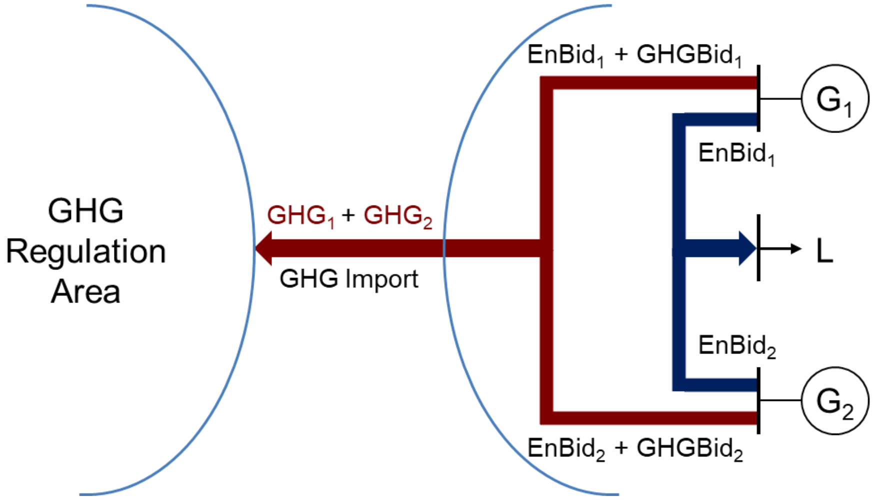

Figure 4. GHG regulation model

To avoid an outcome where lower emitting resources that would serve demand outside GHG regulation areas are attributed instead to imports into a GHG regulation area while higher emitting resources backfill to serve demand outside GHG regulation areas, a phenomenon referred to as “secondary dispatch,” the GHG attributions are limited by certain constraints in the GHG model. One constraint limits the GHG attribution to a specific resource based on its schedule in a counterfactual market solution where no net import is allowed into GHG regulation areas. Another constraint limits the gross GHG attribution to resources in a BAA outside of GHG regulation areas to the net export transfer from that BAA, adjusted to support RSE-eligible export transfers and contractual obligations for imports into GHG regulation areas. A similar constraint limits the gross GHG attribution to resources in a GHG regulation area for other GHG regulation areas to the net export from that GHG regulation area, adjusted to support contractual obligations for exports to these other GHG regulation areas. In these last two constraints, the net export transfer from the BAA and the net export from the GHG regulation area are obtained from the optimal solution in the previous iteration to sever the dynamic dependency on transfers and maintain the convexity of the problem.

Considering all the above, the mathematical formulation of the GHG regulation model for the EDAM is an expansion to the IFM problem as described in the following sections.

9.1 OBJECTIVE FUNCTION

The objective function includes the additional GHG regulation cost of the GHG attributions, as follows:

$$\min \left(C + \sum_{t=1}^{T} \sum_{i} \sum_{g} \widehat{EN}_{i,g,t}\, GHGBP_{i,g,t} \right)$$

9.2 GHG ATTRIBUTION LIMITS

The GHG attributions are limited by the GHG bid capacity, the energy schedule, and the GHG reference, as follows:

$$\left. \begin{array}{c} 0 \le \widehat{EN}_{i,g,t} \le GHGBC_{i,g,t}, \forall g \\ \sum_{g} \widehat{EN}_{i,g,t} \le EN_{i,t} \\ \sum_{g} \widehat{EN}_{i,g,t} \le UEL'_{i,t} - EN_{i,t}^{(GHG)} \end{array} \right\} , \forall i \wedge t = 1,2, \dots, T$$

Note that a resource in a GHG regulation area may not have a GHG bid for that GHG regulation area, i.e., the corresponding GHG bid capacity is zero. The GHG regulation cost of the GHG regulation area that a resource resides in is included in its energy bid. This assumes that all energy produced by such resource is subject to the GHG regulation of its GHG regulation area, even if it is attributed to another GHG regulation area. Nevertheless, such resource may have a GHG bid and a resulting GHG attribution for another GHG regulation area; in this case, the GHG bid represents additional GHG regulation cost imposed by the GHG regulation area for that GHG attribution, which could be zero.

In the WEIM, the GHG reference is the base schedule for exclusively EIM BAAs and the day-ahead schedule for EDAM BAAs:

$$\sum_{g} \widehat{EN}_{i,g,t} \leq UEL'_{i,t} - EN_{i,t}^{(BASE)}, \forall i \in BAA_j \wedge \forall j \in EIM - EDAM \wedge t = 1,2, \dots, T$$

$$\sum_{g} \widehat{EN}_{i,g,t} \leq UEL'_{i,t} - EN_{i,t}^{(DA)} - \sum_{g} \widehat{EN}_{i,g,t}^{(DA)}, \forall i \in BAA_j \wedge \forall j \in EDAM \wedge t = 1,2, \dots, T$$

To permit the DA GHG attributions to be optimally re-attributed in the WEIM, since they are subject to a deviation settlement, they are subtracted from the GHG reference in the constraint above.

9.3 GHG IMPORT ALLOCATION CONSTRAINT

The physical GHG transfer for each GHG regulation area is calculated as follows:

$$T_{g,t} \equiv \sum_{i \in GHG_g} \left(EN_{i,t} + I_{i,t} - E_{i,t} - L_{i,t}\right) - Loss_{g,t}, \forall g \wedge t = 1,2 \dots., T$$

Where only physical supply and demand are considered, ignoring virtual supply and demand schedules. The objective is to allocate the GHG import to GHG attributions; since the latter exist only for physical supply resources, the GHG import should also be physical for consistency. Physical transmission losses in the GHG regulation area cannot be derived from the ACPF solution due to loss contributions from virtual supply and demand. However, they can be approximated by using an average loss factor applied to the scheduled physical demand, as follows:

$$Loss_{g,t} \cong ALF_{g,t} \sum_{i \in GHG_g} \tilde{L}_{i,t}, \forall g \wedge t = 1,2 \dots., T$$

The load schedules from the previous iteration are used in this approximation to sever the dynamic dependency between transmission losses and GHG attributions so that the marginal GHG price is uniform and free from marginal loss contributions in a GHG regulation area. This approach is not unlike the use of lossless shift factors to separate the marginal loss and congestion components of the LMP.

The GHG import allocation constraint is formulated in the IFM as follows:

$$-T_{g,t} \cong - \sum_{i \in GHG_g} \left(EN_{i,t} + I_{i,t} - E_{i,t} - L_{i,t}\right) + ALF_{g,t} \sum_{i \in GHG_g} \tilde{L}_{i,t} \leq \sum_{i \notin GHG_g} \widehat{EN}_{i,g,t},$$
$$\forall g \wedge t = 1,2 \dots., T$$

The formulation of the constraint in the WEIM is similar, but L is the delivered load, i.e., the distributed demand forecast in the relevant GHG regulation area. Furthermore, there is no virtual supply and demand in the WEIM, thus the losses in a GHG regulation area can be derived from the ACPF, as follows:

$$-T_{g,t} \cong -\sum_{i\in GHG_g}\left(EN_{i,t}+I_{i,t}-E_{i,t}-L_{i,t}\right)+\widetilde{Loss}_{g,t}- \sum_{\substack{j\in EIM-EDAM\wedge BAA_j\cap GHG_g\neq\emptyset\\ k\in EIM-EDAM\wedge BAA_k\cap GHG=\emptyset}}\sum_{l} IT^{(BASE)}_{j,k,l,t} \le \sum_{i\notin GHG_g}\widehat{EN}_{i,g,t}\,, \forall g\wedge t=1,2\ldots,T$$

Note that in the WEIM, the net GHG import to a GHG regulation area must be reduced by the import base transfers from exclusively EIM BAAs outside GHG regulation areas to exclusively EIM BAAs that overlap with the GHG regulation area. This is because these base imports to the GHG regulation area have a separate GHG regulation mechanism, like imports from non-EIM BAAs, thus they should not be attributed.

9.4 GROSS GHG ATTRIBUTION CONSTRAINTS

For EDAM BAAs that do not overlap with any GHG regulation area, the following gross GHG attribution constraints are enforced:

$$\sum_{i\in BAA_j}\sum_{g}\widehat{EN}_{i,g,t} \le \max\left(\sum_{i\in BAA_j}\sum_{g} CO_{i,g,t}\,, \sum_{BAA_k\cap GHG\neq\emptyset}\sum_{l} ET^{(RSE)}_{j,k,l,t}\,, \tilde{T}_{j,t}\right),$$
$$\forall j\in EDAM\wedge BAA_j\cap GHG=\emptyset\wedge t=1,2\ldots,T$$

Where the first term in the max() function is the total resource capacity in the EDAM BAA that is contractually obligated to serve demand in GHG regulation areas, the second term is the gross RSE-eligible export transfers from the EDAM BAA to other EDAM BAAs that overlap with GHG regulation areas, and the third term is the net transfer of the BAA at the optimal solution of the previous iteration. The constraint is not enforced in the first iteration to initialize this value for the second iteration. Note that the constraint is linear because all the terms in the max() function are constant in any given iteration where the constraint is enforced.

A similar constraint limits the gross GHG attribution in each GHG regulation area for other GHG regulation areas, as follows:

$$\sum_{i\in GHG_g}\widehat{EN}_{i,g,t} \le \max\left(\sum_{i\in GHG_g}\sum_{k\neq g} CO_{i,k,t}\,, \tilde{T}_{g,t}\right), \forall g\wedge t=1,2\ldots,T$$

Where the first term in the max() function is the total resource capacity that is contractually obligated to serve demand in other GHG regulation areas and the second term is the GHG transfer of the GHG regulation area at the optimal solution of the previous iteration. The constraint is not enforced in the first iteration to initialize this value for the second iteration. Note that the constraint is linear because all the terms in the max() function are constant in any given iteration where the constraint is enforced.

The gross GHG attribution constraints for EDAM BAAs and GHG regulation areas are conditionally enforced in an hour in the IFM, only if all EDAM BAAs that overlap with GHG regulation areas have passed the upward RSE test in that hour. This condition is required to prevent net import limitations into these BAAs when they fail the upward RSE.

The gross GHG attribution constraints for BAAs in the WEIM are as follows:

$$\sum_{i\in BAA_j}\sum_{g}\widehat{EN}_{i,g,t} \le \max\left(\sum_{i\in BAA_j}\sum_{g} CO_{i,g,t}\,,\ \sum_{BAA_k\cap GHG\neq\emptyset}\ \sum_{l}\overline{ET}_{j,k,l,t}\,,\tilde{T}_{j,t}-\bar{T}_{j,t}\right),$$
$$\forall j\in EDAM \wedge BAA_j\cap GHG=\emptyset \wedge t=1,2\,\ldots.,T$$

The net base transfer is excluded from the right-hand side because it is reflected in the base supply schedules, which are the GHG reference in the WEIM:

$$\bar{T}_{j,t} = T_{j,t}^{(BASE)}, \forall j\in EIM-EDAM \wedge t=1,2,\ldots,T$$
$$\bar{T}_{j,t} = 0, \forall j\in EDAM \wedge t=1,2,\ldots,T$$

The export transfer reference for exclusively EIM BAAs is zero in the FMM and the net static transfer in the RTD because static transfers are fixed in the RTD:

$$\left.\begin{array}{ll} FMM: & \overline{ET}_{j,k,l,t}=0 \\ RTD: & \overline{ET}_{j,k,l,t}=ET_{j,k,l,t}^{(STAT)} \end{array}\right\}, \forall j\in EIM-EDAM \wedge t=1,2,\ldots,T$$

Base transfers are not included in that reference because they are excluded from the GHG import allocation constraint.

The export transfer reference for EDAM BAAs includes additionally the day-ahead export transfer position (day-ahead energy and IRU/IRD export transfers):

$$\left.\begin{array}{ll} FMM: & \overline{ET}_{j,k,l,t}=ET_{j,k,l,t}^{(EN)}+ET_{j,k,l,t}^{(IRU)}+IT_{j,k,l,t}^{(IRD)}+ET_{j,k,l,t}^{(RCU)} \\ RTD: & \overline{ET}_{j,k,l,t}=ET_{j,k,l,t}^{(EN)}+ET_{j,k,l,t}^{(IRU)}+IT_{j,k,l,t}^{(IRD)}+ET_{j,k,l,t}^{(RCU)}+ET_{j,k,l,t}^{(STAT)} \end{array}\right\},$$
$$\forall j\in EDAM \wedge t=1,2,\ldots,T$$

The gross GHG attribution constraints for GHG regulation areas in the WEIM are the same as in the EDAM.

The gross GHG attribution constraints for EIM BAAs and GHG regulation areas in the WEIM are conditionally enforced in an hour, only if all EIM BAAs that overlap with GHG regulation areas have passed the upward RSE test in that hour. This condition is required to prevent net import limitations into these BAAs when they fail the upward RSE.

9.5 GHG REFERENCE

This section describes the GHG reference pass in the EDAM. The GHG reference pass is a counterfactual of the IFM where there are no GHG attributions, and thus no GHG regulation cost. The important outcome of the GHG reference pass is the optimal counterfactual schedules of physical supply resources, which are used to limit the respective GHG attributions in the IFM (and the MPM-IFM). The counterfactual schedules reflect the optimal solution without net import into GHG regulation areas, hence no GHG regulation cost.

The GHG reference pass is identical to the MPM-IFM pass, i.e., essentially, the same problem is solved as in the IFM, but using submitted bids, and with the following important differences:

- GHG bids are ignored, thus there is no GHG transfer in the import direction:

$$T_{g,t} \cong \sum_{i\in GHG_g} \left(EN_{i,t} + I_{i,t} - E_{i,t} - L_{i,t}\right) - ALF_{g,t} \sum_{i\in GHG_g} \tilde{L}_{i,t} \geq 0, \forall g \wedge t = 1,2 \ldots.,T$$

- There are additional constraints that limit the counterfactual supply schedules for resources with contractual obligations to serve demand in GHG regulation areas:

$$EN_{i,t}^{(GHG)} \leq \max\left(0, UEL'_{i,t} - \sum_{GHG_g \not\ni i} CO_{i,g,t}\right), \forall i \wedge t = 1,2 \ldots.,T$$

  This constraint reserves the contractually obligated capacity to serve demand in GHG regulation areas from receiving a counterfactual schedule so that it will be available for GHG attributions in the IFM. Contractual obligations from a resource to its own GHG regulation area, e.g., RA capacity from CISO resources, are ignored in this constraint because they are not eligible for GHG attributions for other GHG regulation areas anyway.

10 PRICE FORMATION

The marginal prices for the various commodities in EDAM are derived from the shadow prices of binding constraints. The set of balancing area and GHG regulation area constraints and their respective shadow prices are as follows:

$$\left.\begin{array}{lr}
\sum_{i\in BAA_j} \frac{\left(\Delta EN_{i,t} + \Delta I_{i,t} - \Delta E_{i,t} + \Delta VS_{i,t} - \Delta VD_{i,t} - \Delta L_{i,t}\right)}{LPF_{i,t}} - \Delta T_{j,t}^{(EN)} = 0 & \lambda_{j,t} \\
\sum_{i\in BAA_j} \sum_{i} IRU_{i,t} + IRUS_{j,t} - T_{j,t}^{(IRU)} = IRUR_{j,t} & \rho_{j,t} \\
\sum_{i\in BAA_j} \sum_{i} IRD_{i,t} + IRDS_{j,t} - T_{j,t}^{(IRD)} = IRDR_{j,t} & \sigma_{j,t} \\
\sum_{i\in BAA_j} \frac{\left(\Delta RCU_{i,t} - \Delta RCD_{i,t}\right)}{LPF_{i,t}^{(RUC)}} - \Delta T_{j,t}^{(RCU)} = 0 & \xi_{j,t}
\end{array}\right\},$$

$$\forall j \in EDAM \wedge t = 1,2, \ldots, T$$

$$\left.-\sum_{i\in GHG_g} \left(EN_{i,t} + I_{i,t} - E_{i,t} - L_{i,t}\right) - ALF_{g,t} \sum_{i\in GHG_g} \tilde{L}_{i,t} - \sum_{i\notin GHG_g} \widehat{EN}_{i,g,t} \leq 0 \quad \psi_{g,t}\right\},$$

$$\forall g \wedge t = 1,2 \ldots.,T$$

The generalized network constraints in the IFM, the IRU/IRD deployment scenarios, and the RUC are as follows:

$$\left.\begin{array}{lr}
\widetilde{LFL}_{m,t} \le \tilde{F}_{m,t} + \sum_{i} \left(\Delta EN_{i,t} + \Delta VS_{i,t} - \Delta VD_{i,t} - \Delta L_{i,t} \right) SF_{i,m,t} \le \widetilde{UFL}_{m,t} & \mu_{m,t} \\
\begin{aligned} \widetilde{LFL}_{m,t} \le \tilde{F}_{m,t} + \sum_{i} \left(\Delta EN_{i,t} + DFIRU\ IRU_{i,t} + \Delta VS_{i,t} - \Delta VD_{i,t} - \Delta L_{i,t} \right) SF_{i,m,t} - \\ DFIRU \sum_{j \in EDAM} \left(IRUR_{j,t} - IRUS_{j,t} \right) SF_{j,m,t}^{(IRU)} \le \widetilde{UFL}_{m,t} \end{aligned} & \mu_{m,t}^{(IRU)} \\
\begin{aligned} \widetilde{LFL}_{m,t} \le \tilde{F}_{m,t} + \sum_{i} \left(\Delta EN_{i,t} - DFIRD\ IRD_{i,t} + \Delta VS_{i,t} - \Delta VD_{i,t} - \Delta L_{i,t} \right) SF_{i,m,t} + \\ DFIRD \sum_{j \in EDAM} \left(IRDR_{j,t} - IRDS_{j,t} \right) SF_{j,m,t}^{(IRD)} \le \widetilde{UFL}_{m,t} \end{aligned} & \mu_{m,t}^{(IRD)} \\
\widetilde{LFL}_{m,t}^{(RUC)} \le \tilde{F}_{m,t}^{(RUC)} + \sum_{i} \left(\Delta RCU_{i,t} - \Delta RCD_{i,t} \right) SF_{i,m,t} \le \widetilde{UFL}_{m,t}^{(RUC)} & \mu_{m,t}^{(RUC)}
\end{array}\right\},$$

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

Therefore, the marginal prices are derived as follows:

$$\left.\begin{array}{c}
LMP_{i,t} = \dfrac{\lambda_{j,t}}{LPF_{i,t}} - \sum_{m} SF_{i,m,t} \left(\mu_{m,t} + \mu_{m,t}^{(IRU)} + \mu_{m,t}^{(IRD)} \right) + \psi_{g,t} \\
IRUMP_{i,t} = \rho_{j,t} - DFIRU \sum_{m} SF_{i,m,t}\, \mu_{m,t}^{(IRU)} \\
IRDMP_{i,t} = \sigma_{j,t} + DFIRD \sum_{m} SF_{i,m,t}\, \mu_{m,t}^{(IRD)} \\
RCUMP_{i,t} = -RCDMP_{i,t} = \dfrac{\xi_{j,t}}{LPF_{i,t}^{(RUC)}} - \sum_{m} SF_{i,m,t}\, \mu_{m,t}^{(RUC)} \\
\widehat{LMP}_{i,g,t} = \psi_{g,t}
\end{array}\right\},$$

$$\forall i \in BAA_j \wedge j \in EDAM \wedge i \in GHG_g \wedge \forall g \wedge t = 1,2, \dots, T$$

For resources outside of GHG regulation areas, the marginal GHG price is zero.

11 POWER BALANCE RELAXATION CONSTRAINTS IN THE WEIM

The EIM BAA power balance constraints in the WEIM can be relaxed at a penalty by including energy supply shortfall and surplus variables as follows:

$$\sum_{i \in BAA_j} \frac{\left(\Delta EN_{i,t} + \Delta I_{i,t} - \Delta E_{i,t} \right)}{LPF_{i,t}} - \Delta T_{j,t} + ENUS_{j,t} - ENDS_{j,t} = 0, \forall j \in EIM \wedge t = 1,2, \dots, T$$

Where the energy supply shortfall (*ENUS*) and surplus (*ENDS*) variables are assigned penalty costs in the objective function. To prevent transfers causing a power balance constraint relaxation in a BAA, the following constraints are enforced in the WEIM:

$$\left.\begin{array}{l}\left(ENUS_{j,t}+\sum_{i\epsilon BAA_j} ABCU_{i,t}\right)\left(T_{j,t}-\bar{T}_{j,t}\right)\leq 0\\ \left(ENDS_{j,t}+\sum_{i\epsilon BAA_j} ABCD_{i,t}\right)\left(T_{j,t}-\bar{T}_{j,t}\right)\geq 0\end{array}\right\},\forall j\in EIM\wedge t=1,2,\dots,T$$

These constraints will not allow a net export energy transfer above a reference to cause power balance shortfall or upward available balancing capacity dispatch, or a net import energy transfer below a reference to cause power balance surplus or downward available balancing capacity dispatch. The net transfer reference for exclusively EIM BAAs is the net base transfer in FMM, because base transfers are fixed. The net transfer reference in RTD also includes the net static transfer because static transfers are fixed in RTD:

$$\left.\begin{array}{ll}FMM: & \bar{T}_{j,t}=T_{j,t}^{(BASE)}\\ RTD: & \bar{T}_{j,t}=T_{j,t}^{(BASE)}+T_{j,t}^{(STAT)}\end{array}\right\},\forall j\in EIM-EDAM\wedge t=1,2,\dots,T$$

The net transfer reference for EDAM BAAs includes additionally the net day-ahead transfer position (day-ahead energy and IRU/IRD net transfers):

$$\left.\begin{array}{ll}FMM: & \bar{T}_{j,t}=T_{j,t}^{(EN)}+T_{j,t}^{(IRU)}-T_{j,t}^{(IRD)}+T_{j,t}^{(RCU)}\\ RTD: & \bar{T}_{j,t}=T_{j,t}^{(EN)}+T_{j,t}^{(IRU)}-T_{j,t}^{(IRD)}+T_{j,t}^{(RCU)}+T_{j,t}^{(STAT)}\end{array}\right\},\forall j\in EDAM\wedge t=1,2,\dots,T$$

Where positive IRD net transfers reserve transfer capacity in the import direction. Although IRU/IRD and RCU/RCD are procured in the EDAM using different scenarios and market passes, the energy bids for the dispatch of these capacity awards in the RTM are available for optimal dispatch under all scenarios. Including both energy and capacity transfers in the net reference transfer, locks in the RTM the transfer capacity commitment from the DAM and provides a high confidence in the delivery of EDAM transfers, if needed. There are no base transfers between EDAM BAAs, including the CISO, and exclusively EIM BAAs, only static and dynamic transfers.