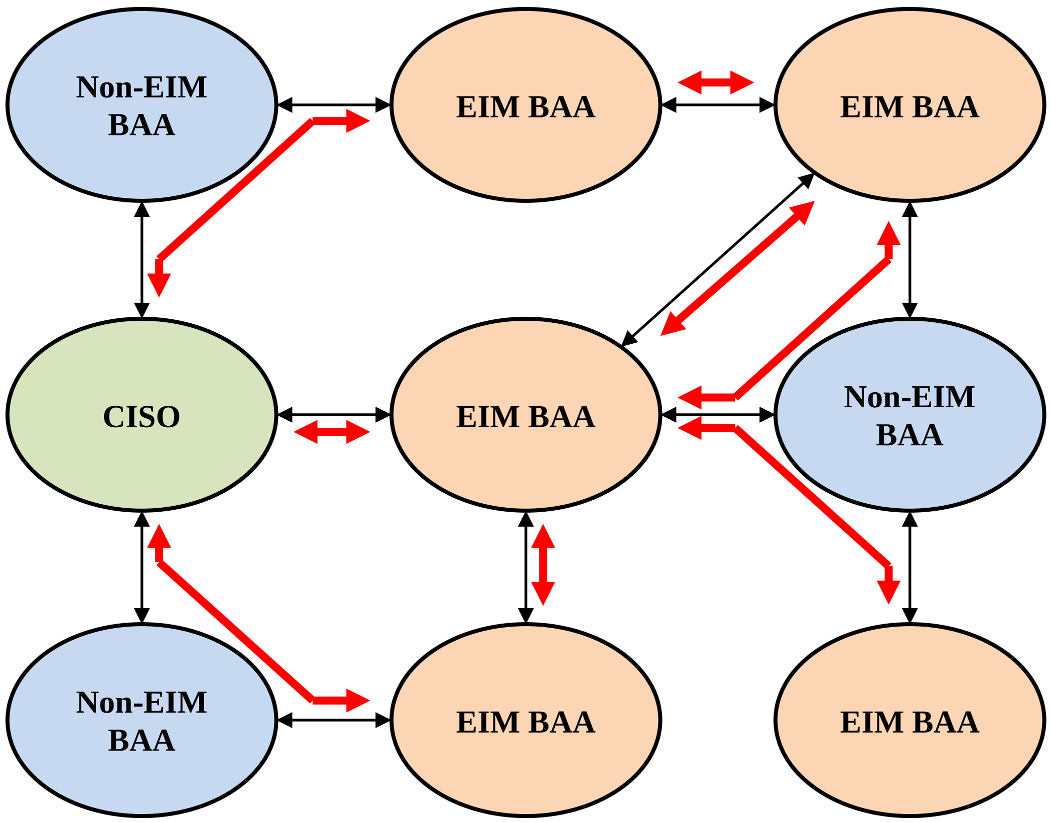
ENERGY TRANSFER SCHEDULING
IN
ENERGY IMBALANCE MARKET

1. Introduction

This technical paper describes the calculation of Energy Transfer schedules between Balancing Authority Areas (BAAs) in the Energy Imbalance Market (EIM) Area from the optimal EIM Transfer calculated for each BAA in the EIM Area by the Real-Time Unit Commitment (RTUC) and the Real-Time Dispatch (RTD) applications. The methodology in this document is general to account an arbitrary network configuration of EIM and non-EIM BAAs in the Full Network Model (FNM), such as the example shown below:



EIM BAAs may be interconnected with the CISO directly, through another EIM BAA, through a Non-EIM BAA, or a combination thereof. The EIM Entity for an EIM BAA may have made available transmission rights on a direct interconnection with the CISO, on a direct interconnection with another EIM BAA, or on an indirect interconnection with the CISO or another EIM BAA through one or more non-EIM BAAs. The red arrows in the example above illustrate such transmission rights. These transmission rights are essential to the EIM Transfers for each BAA in the EIM Area as they both allow and constrain the optimal exchange of imbalance energy among the BAAs in the EIM Area.

The EIM Transfer is an algebraic quantity (positive for export and negative for import) for the net energy exchange between a given BAA and the remaining BAAs in the EIM Area. The problem at hand is to determine the Energy Transfer schedules among the EIM BAAs and the CISO from the optimal EIM Transfers of the BAAs in the EIM Area using the available transmission rights without violating them. These Energy Transfer schedules can then be tagged to the relevant interties among the BAAs.

2. Energy Transfer System Resources

Although not necessary for implementation, it is convenient to define dedicated System Resources in each EIM BAA to anchor the Energy Transfer schedules from that BAA to other BAAs in the EIM Area for tracking, tagging, and settlement. These Energy Transfer System Resources (ETSRs) are defined as aggregate resources at the EIM BAA Default Generation Aggregation Point (DGAP), which is an aggregation of all supply resources in the BAA. Each ETSR is defined as either an import or an export resource, and it is associated with an EIM intertie with another EIM BAA, or a CISO intertie with the CISO. The associated intertie is one where the EIM Entity for the relevant EIM BAA has made transmission rights available for scheduling Energy Transfers from/to the other EIM BAA or the CISO.

At least two ETSRs must be defined in a BAA for each Energy Transfer schedule with another BAA in the EIM Area: one for import, and the other for export. An aggregate intertie may be used if there are multiple interties under the transmission rights that are made available. It may be necessary to define ETSRs for each intertie separately if the transmission rights are different for each one of them. It may also be necessary to define multiple ETSRs for each Transmission Service Provider (TSP) whose transmission rights are made available. Finally, it may be necessary to define different ETSRs for static 15min Energy Transfer schedules and dynamic 5min Energy Transfer schedules. The applicable transmission right limits can then be modeled as upper operating limits on the corresponding ETSRs.

For Energy Transfer schedules between BAAs in the EIM Area, the relevant ETSRs in these BAAs must be associated in import-export pairs since an Energy Transfer schedule between the BAAs is an import to one and an export to the other.

3. Notation

The following mathematical notation is used in this paper:

i	Node index.
j, k	BAA indexes; zero (0) is used for the CISO.
l	Intertie or Energy Transfer schedule index; in the latter case, it is the corresponding ETSR index (ETSR pair for Energy Transfers between BAAs in the EIM Area).
$\bar{\ }$	Accent denoting base schedule (RUC schedule for the ISO BAA).
$\frown$	Accent denoting gross tagged or forecasted interchange schedule between non-EIM BAAs.
$\tilde{\ }$	Accent denoting initial values from the last AC Power Flow (ACPF) solution.

Δ	Denotes incremental values from the last ACPF solution.
$\forall$	For all…
$\in$	Member of…
$\wedge$	…and…
EIM	The set of CISO and all EIM BAAs.
BAA_j	The set of nodes in BAA j.
G_i	The generation at node i.
L_i	The load at node i.
$I_{j,k,l}$	The import schedule l into EIM BAA j from BAA k.
$E_{j,k,l}$	The export schedule l from EIM BAA j to BAA k.
D_j	The demand (load plus losses) forecast in BAA j.
$Loss_j$	The transmission loss in BAA j.
LPF_i	The loss penalty factor at node i.
$LPF_{j,k,l}$	The loss penalty factor at the Scheduling Point for intertie schedule l between BAA j in the EIM Area and non-EIM BAA k.
NSI_j	The Net Scheduled Interchange of BAA j; positive for export and negative for import.
T_j	The EIM Transfer of EIM BAA j; positive for export and negative for import.
$IT_{j,k,l}$	The import Energy Transfer schedule l of EIM BAA j from BAA k in the EIM Area.
$ET_{j,k,l}$	The export Energy Transfer schedule l of EIM BAA j to BAA k in the EIM Area.
$IT_{MAXj,k,l}$	The applicable limit of the import Energy Transfer schedule l of EIM BAA j from BAA k in the EIM Area.
$ET_{MAXj,k,l}$	The applicable limit of the export Energy Transfer schedule l of EIM BAA j to BAA k in the EIM Area.
$IT_{TRj,k,l}$	The transmission right for the import Energy Transfer schedule l of EIM BAA j from BAA k in the EIM Area.
$ET_{TRj,k,l}$	The transmission right of the export Energy Transfer schedule l of EIM BAA j to BAA k in the EIM Area.
$IT_{MAX15j,k,l}$	The static limit for the import Energy Transfer schedule l of EIM BAA j from BAA k in the EIM Area.
$ET_{MAX15j,k,l}$	The static limit of the export Energy Transfer schedule l of EIM BAA j to BAA k in the EIM Area.
$IT_{MAX5j,k,l}$	The dynamic incremental limit for the import Energy Transfer schedule l of EIM BAA j from BAA k in the EIM Area.

$ET_{MAX5j,k,l}$ The dynamic incremental limit of the export Energy Transfer schedule *l* of EIM BAA *j* to BAA *k* in the EIM Area.

$C_{j,k}$ The transmission cost of the Energy Transfer scheduless of EIM BAA *j* from/to BAA *k* in the EIM Area.

4. Mathematical Formulation

This section describes the relevant calculations and mathematical formulae.

4.1. Base Schedules

The base Energy Transfer schedules between EIM BAAs are submitted along with the generation and intertie base schedules ahead of the market run. The base Energy Transfer schedules between EIM BAAs and the CISO are the corresponding intertie schedules from the Residual Unit Commitment (RUC)[1] and need not be submitted since they are known:

$$\left.\begin{aligned} \overline{IT}_{j,0,l} &= \bar{E}_{0,j,l} \\ \overline{ET}_{j,0,l} &= \bar{I}_{0,j,l} \end{aligned}\right\} \; \forall j \in EIM \land j > 0$$

For accounting and validation purposes, base Energy Transfer schedules between EIM BAAs must be submitted for both BAAs and must be matching:

$$\overline{IT}_{j,k,l} = \overline{ET}_{k,j,l} \;\; \forall j,k \in EIM \land j \neq k \land j,k > 0$$

It is assumed that the base Energy Transfer schedules are feasible:

$$\left.\begin{aligned} 0 \leq \overline{IT}_{j,k,l} \leq IT_{MAX\,j,k,l} \\ 0 \leq \overline{ET}_{j,k,l} \leq ET_{MAX\,j,k,l} \end{aligned}\right\} \; \forall j,k \in EIM \land j \neq k \land j > 0$$

For efficiency, there should not be both an import and an export base Energy Transfer schedule on a given intertie; at least one of them ought to be zero.

The base EIM Transfer for each EIM BAA is the net of all base Energy Transfer schedules:

$$\bar{T}_j = \sum_{\substack{k \in EIM \\ k \neq j}} \sum_{l} \left(\overline{ET}_{j,k,l} - \overline{IT}_{j,k,l} \right) \;\; \forall j \in EIM \land j > 0$$

The base EIM Transfer for the CISO is simply the negative sum of the base EIM Transfers of all EIM BAAs:[1]

$$\bar{T}_0 = -\sum_{\substack{j \in EIM \\ j > 0}} \bar{T}_j$$

1 Currently, RUC intertie schedules are not part of the base EIM Transfer because no scheduling is allowed from EIM BAA Scheduling Hubs in the Day-Ahead Market, and intertie schedules from existing CISO Scheduling Points in EIM BAAs are not considered EIM transactions; hence the base Energy Transfer schedules with the CISO and the base EIM Transfer for the CISO are all zero.

The base NSI for each EIM BAA is the net of the EIM Transfer and the submitted base intertie schedules with non-EIM BAAs:

$$\overline{NSI}_j = \bar{T}_j + \sum_{k \notin EIM} \sum_{l} \left(\bar{E}_{j,k,l} - \bar{I}_{j,k,l} \right) \;\; \forall j \in EIM \wedge j > 0$$

The base demand in each EIM BAA is derived to achieve power balance with the submitted base generation schedules and the base NSI:

$$\bar{D}_j = \sum_{i \in BAA_j} \bar{G}_i - \overline{NSI}_j \;\; \forall j \in EIM \wedge j > 0$$

The base load in each EIM BAA is obtained initially by reducing the base demand with an assumed initial transmission loss and then distributing it to the load nodes in the BAA using Load Distribution Factors (LDFs); the base load is then adjusted to absorb the loss error by an ACPF using distributed load slack and Area Interchange Control (AIC) to maintain the base NSI:

$$\bar{D}_j = \sum_{i \in BAA_j} \bar{L}_i + \overline{Loss}_j \;\; \forall j \in EIM \wedge j > 0$$

The base generation and load for the CISO are initialized at the RUC schedules; the CISO base load is also adjusted in the ACPF to account for generation and transmission outages occurred after RUC, and to absorb loss error as the CISO base NSI is maintained.

The base load for EIM BAAs is significant because it is used as a reference for imbalance energy settlement; however, the base load for the CISO is not important since for the CISO the reference for imbalance energy settlement is the day-ahead schedules from the Integrated Forward Market (IFM); nevertheless, it is used in the ACPF to balance the CISO, and the FNM overall, for calculating the power flows on EIM BAA transmission branches to identify any transmission limit violations for the feasibility test.

For the same reason, base schedules are also calculated for non-EIM BAAs to model unscheduled loop flow through the EIM Area. The approach for the non-EIM BAA base schedules is somewhat different because they are not submitted; instead, the demand forecast and the tagged or forecasted interchange schedules with other non-EIM BAAs are used to supplement the information available for the EIM BAAs and the CISO. Specifically, the base NSI for non-EIM BAAs is derived as follows:

$$\overline{NSI}_j = \sum_{\substack{k \notin EIM \\ k \neq j}} \sum_{l} \left(\hat{E}_{j,k,l} - \hat{I}_{j,k,l} \right) - \sum_{k \in EIM} \left(\bar{E}_{k,j,l} - \bar{I}_{k,j,l} \right) \;\; \forall j \notin EIM$$

The base generation in each non-EIM BAA is derived as the sum of the demand forecast and the base NSI, and it is distributed to the generating resources in the BAA using Generation Distribution Factors (GDFs), renormalized for generation outages:

$$\sum_{i \in BAA_j} \bar{G}_i = \bar{D}_j + \overline{NSI}_j \;\; \forall j \notin EIM$$

The base load in each non-EIM BAA is calculated similarly to the base load in EIM BAAs.

The base NSI for the CISO is simply the negative sum of the base NSIs of all BAAs in the FNM:

$$\overline{NSI}_0 = -\sum_{j>0} \overline{NSI}_j$$

4.2. Optimal NSI and EIM Transfers

The optimal NSI for each BAA in the EIM Area, as calculated by RTUC and RTD, is the result of the optimal dispatch of resources within the BAA:

$$NSI_j = \sum_{i \in BAA_j} (G_i - L_i) - Loss_j \ \ \forall j \in EIM \wedge j > 0$$

Linearizing from the previous ACPF solution:

$$\left.\begin{aligned} NSI_j &= \widetilde{NSI}_j + \Delta NSI_j \\ \widetilde{NSI}_j &= \sum_{i \in BAA_j} \left(\tilde{G}_i - \tilde{L}_i\right) - \widetilde{Loss}_j \\ \Delta NSI_j &= \sum_{i \in BAA_j} \frac{(\Delta G_i - \Delta L_i)}{LPF_i} \end{aligned}\right\} \forall j \in EIM$$

Where the optimal changes in generation and load are adjusted for marginal losses. Note that the load is not dispatched unless there is an outage or it is a dispatchable load, e.g., a hydro pump.

The optimal EIM Transfer for each EIM BAA is derived from the optimal NSI by subtracting the next export interchange with non-EIM BAAs:

$$T_j = NSI_j - \sum_{k \notin EIM} \sum_l \left(E_{j,k,l} - I_{j,k,l}\right) \ \ \forall j \in EIM \wedge j > 0$$

Linearizing from the previous ACPF solution:

$$\left.\begin{aligned} T_j &= \tilde{T}_j + \Delta T_j \\ \tilde{T}_j &= \widetilde{NSI}_j - \sum_{k \notin EIM} \sum_l \left(\tilde{E}_{j,k,l} - \tilde{I}_{j,k,l}\right) \\ \Delta T_j &= \sum_{i \in BAA_j} \frac{(\Delta G_i - \Delta L_i)}{LPF_i} - \sum_{k \notin EIM} \sum_l \frac{\left(\Delta E_{j,k,l} - \Delta I_{j,k,l}\right)}{LPF_{j,k,l}} \end{aligned}\right\} \forall j \in EIM \wedge j > 0$$

Note that marginal loss contributions from network branches external to the EIM Area are ignored in the Loss Penalty Factors; consequently, the effect of intertie schedules between non-EIM BAAs and BAAs in the EIM Area on the EIM Area losses is the same as if the energy was generated or consumed at the EIM Area boundary.

The optimal EIM Transfer for the CISO is simply the negative sum of the optimal EIM Transfers of all EIM BAAs:

$$T_0 = -\sum_{\substack{j \in EIM \\ j>0}} T_j$$

The aggregate interchange dispatch at non-EIM BAA Scheduling Points/Hubs determines the NSI deviation (from the base NSI) of non-EIM BAAs and it is distributed to the generating resources of the relevant Generation Aggregation Point (GAP) using the applicable GDFs:

$$NSI_j - \overline{NSI}_j = -\sum_{k \in EIM} \sum_{l} \left(\Delta E_{k,j,l} - \Delta I_{k,j,l} \right) = \sum_{i \in BAA_j} \left(G_i - \bar{G}_i \right) \quad \forall j \notin EIM$$

The NSI is maintained for each BAA in the ACPF by adjusting the load using distributed load slack and AIC. Therefore, the NSI, EIM Transfer, and generation for EIM BAAs in the ACPF solution are always equal to the optimal solution in the last iteration.

4.3. Energy Transfer Schedules

The EIM Transfer for each EIM BAA is distributed optimally to the applicable Energy Transfer Schedules:

$$\sum_{\substack{k \in EIM \\ k \neq j}} \sum_{l} \left(ET_{j,k,l} - IT_{j,k,l} \right) = T_j \quad \forall j \in EIM \wedge j > 0$$

Where:

$$IT_{j,k,l} = ET_{k,j,l} \quad \forall j,k \in EIM \wedge j \neq k \wedge j,k > 0$$

Without violating the applicable transmission right limits:

$$\left. \begin{array}{l} 0 \leq IT_{j,k,l} \leq IT_{MAX\,j,k,l} \\ 0 \leq ET_{j,k,l} \leq ET_{MAX\,j,k,l} \end{array} \right\} \quad \forall j,k \in EIM \wedge j \neq k \wedge j > 0$$

For efficiency, there should not be both an import and an export Energy Transfer schedule on a given intertie; at least one of them should be zero.

It is assumed that the transmission limits are symmetric:

$$IT_{MAX\,j,k,l} = ET_{MAX\,k,j,l} \quad \forall j,k \in EIM \wedge j \neq k \wedge j,k > 0$$

To clarify, Energy Transfer schedules are variables in the market optimization calculated optimally subject to the above constraints. The base Energy Transfer schedule is included in the optimal Energy Transfer schedule; in other words, the optimal Energy Transfer schedule on any given intertie may completely back down a base Energy Transfer schedule and the energy transfer may reverse, resulting in efficient use of interconnecting transmission capacity.

The CISO is used as a reference, hence no constraints are formulated for the CISO Energy Transfer or Energy Transfer schedules from CISO ETSRs. Furthermore, to reduce the problem dimensionality, only the export ETSRs are included in the problem formulation; their import ETSR counterparts can be eliminated; the exception is the CISO export ETSRs, for which their import ETSR counterparts in EIM BAAs are used instead, for reasons explained in §4.5.

4.4. Energy Transfer Schedule Limits

Normally, Energy Transfer schedules are dynamic and the same ETSRs and transmission limits are used in both RTUC and RTD. However, if some Energy Transfer schedules must be differentiated between RTUC and RTD, static ETSRs will be used for the 15min Energy

Transfer schedules in RTUC and dynamic ETSRs will be used for the incremental 5min Energy Transfer schedules in RTD. In this case, the base Energy Transfer schedule is included in the 15min Energy Transfer schedule, and the transmission limit for the 5min Energy Transfer schedule is zero in RTUC and incremental (from the optimal 15min Energy Transfer schedule) in RTD. For a uniform treatment of all ETSRs to simplify implementation, the applicable Energy Transfer schedule limits in RTUC and RTD can be derived from the transmission right, static limit, and incremental dynamic limit, as follows:

$$\text{RTUC: } \left.\begin{cases} IT_{MAX\,j,k,l} = \min\left(IT_{TR\,j,k,l}, IT_{MAX15\,j,k,l}\right) \\ ET_{MAX\,j,k,l} = \min\left(ET_{TR\,j,k,l}, ET_{MAX15\,j,k,l}\right) \end{cases}\right\} \forall j,k \in EIM \wedge j \neq k \wedge j > 0$$

$$\text{RTD: } \left.\begin{cases} IT_{MAX\,j,k,l} = \min\left(IT_{TR\,j,k,l}, IT_{j,k,l} + IT_{MAX5\,j,k,l}\right) \\ ET_{MAX\,j,k,l} = \min\left(ET_{TR\,j,k,l}, ET_{j,k,l} + ET_{MAX5\,j,k,l}\right) \end{cases}\right\} \forall j,k \in EIM \wedge j \neq k \wedge j > 0$$

Where the Energy Transfer schedules used in the calculation of the applicable Energy Transfer schedule limit in RTD are the optimal 15min Energy Transfer schedules from RTUC. With these generic formulae, the static limit is what is made available from the transmission right in RTUC, and the dynamic limit is additional transmission capacity that can be used in RTD. If there is no distinction between static and dynamic Energy Transfer schedules, both static and dynamic limits should be equal to the transmission right to maximize transmission capacity use across RTUC and RTD.

4.5. Energy Transfer Tags

The optimal Energy Transfer schedules are assigned to the corresponding ETSRs and are tagged to the associated intertie using the corresponding ETSR identification. For static ETSRs, the tag is a static 15min tag that includes the base Energy Transfer. For dynamic ETSRs, the tag is a dynamic 5min tag; if there is no distinction between static and dynamic Energy Transfers on a given intertie, there is no static tag and the base Energy Transfer schedule is included in the dynamic 5min tag. Because the Energy transfer schedules between two BAAs are duplicated as import and export counterparts seen from each BAA, by convention only the export ETSRs will be tagged between the two BAAs. As an exception, because the CAISO as a Market Operator is not authorized to submit tags, both import and export ETSRs at EIM BAAs with CISO interties will be tagged.

4.6. Intertie Transmission Cost

The distribution of the Energy Transfer for a BAA over the various interties to adjacent BAAs in the EIM Area is not influenced by network impedance or transmission losses, and as such it does not represent actual power flows on these interties; it resembles the classical problem of transferring goods from supply centers to demand centers over a road network. The Energy Transfer schedule limits are scheduling limits and they resemble road throughput capacity. Physical intertie limits need to be enforced separately to constrain actual power flows on the interties, including loop flow contributions from base schedules in non-EIM BAAs.

In a problem like that, there is often not a unique solution, particularly if many intertie scheduling limits are not binding, i.e., there may be multiple ways to transfer the goods from the supply centers to the demand centers without violating any road constraints. To obtain a robust and efficient solution without circulating Energy Transfer schedules, a small nominal cost should be included in the objective function for each ETSR, as follows:

$$\min\left(\dots + \sum_{\substack{j,k\in EIM \\ k\neq j \\ j>0}} C_{j,k} \sum_{l} \left(ET_{j,k,l} + IT_{j,k,l} \right) \right)$$

This cost resembles tolls paid on the roads connecting the supply and demand centers. Introducing this cost will also guarantee that Energy Transfer schedules between two BAAs in the EIM Area will always be unidirectional, i.e., either the export or the import will take value, but never both. This cost may ultimately reflect applicable wheeling or transmission access fees depending on agreed transmission pricing methods among the BAAs in the EIM Area.

4.7. Energy Transfer Economic Value

In calculating real-time neutrality by BAA, an economic value is required for the Energy Transfer, which must be considered to balance the BAA. Currently, the economic value is determined by pricing the EIM Transfer at the LMP of the metered end of the intertie used for tagging the relevant EIM Transfer schedule. With the introduction of multiple interties (multiple ETSRs) for a given BAA where the Energy Transfer can be optimally distributed based on the presented methodology, a more robust price would be the LMP of the DGAP of the BAA where the ETSR resides. This is a more appropriate price since the location of the ETSR is the DGAP of its BAA, which is deemed to be the source of the Energy Transfer anyway.