Grid-aware Flexibility Aggregation for Zonal Balancing Markets

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Cross-border integration for electricity balancing

Source: ENTSO-e website

AI generated image
How is the grid represented?

- Balancing market clears at the zonal resolution.
Intra-area **congestion** to be managed by respective TSO.
Available tools to manage intra-area congestion

**Ex-ante Bid Filtering**

- TSO can filter any intra-area bid that is anticipated to cause congestion.
  - How to do this?
  - Intra-zonal grid constraints hidden from the market?
  - TSO risk aversion also hidden from the market?

**Ex-post Bid Blocking**

- TSO can block & replace any activated intra-area bid to resolve congestion.
  - Only replacing within the same zone causes inefficiencies?
Aggregation/disaggregation approach [1, 2, 3]

- Aggregate intra-zonal resources into a price – quantity curve (ex-ante).
  ✓ Communicate both resource & intra-zonal congestion mgmt costs.

- Dispatch & settle intra-zonal resources s.t. grid constraints (ex-post).
Residual Supply Function (RSF) \textit{ex-ante} approximation

► Given an export volume, minimize intra-area cost s.t. grid constraints.
  Ø over an export volume range:

► Resulting price – quantity curve can be submitted in the zonal market.
Aggregation/disaggregation approach [1, 2, 3]

Residual Supply Function (RSF) *ex-ante* approximation

- Given an export volume, minimize intra-area costs s.t. grid constraints.
  - to construct a price – quantity curve.

Why revisit?

- Incremental export cost depends on uncertain & unobservable factors:
  - realization of imbalances all over the multi-area grid.
  - activation of balancing bids in external control-areas.
  - detailed topologies of external control-areas.

- Represented by a single "best-guess" in [2, 3]:
  $\star$ comes with the risk that the disaggregation cost may be greater than approximated by the RSF (a.k.a., disaggregation risk).
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Residual Supply Function (RSF) \textit{ex-ante} approximation

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1. Proposal
Introducing boundary injection changes

The changes in the interconnector power flows, after the balancing market activations.

For any given export volume:
– depend on the unobservable state of external control-areas,
– also on the precise location of the demand for balancing power,
– translate into intra-area power flows,
– also into the minimum cost of exporting the considered volume.

We consider these a proxy of the external balancing demand.
Introducing boundary injection changes

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- We consider these a **proxy** of the external balancing demand.
Worst-Case RSF approximation

- Assume a range of boundary injection changes, caused by the balancing market.
- Given any export volume, compute the upper bound of the intra-area minimum export cost within this assumed range.
  - to construct a price – quantity curve.
Intuition

Worst-Case RSF approximation

- A larger (smaller) range of boundary injection changes implies...
  - a larger (smaller) upper bound on the intra-area minimum export cost,
  - a smaller (larger) disaggregation risk.

✓ WcRSF also communicates the disaggregation risk aversion with the balancing market.
2. Mathematical formulation & solution approach
How to compute the WcRSF approximation?

For any market zone $\bar{z}$ and export volume $e_z$

$$\max \{ \text{Operating Cost(Zonal Flexibility)} \};$$

s.t.

Boundary Injection Changes $\in$ Plausible Range;

$$\min \{ \text{Operating Cost(Zonal Flexibility)} \};$$

s.t.

Nodal Balance(Boundary Injection Changes, Zonal Flexibility);

Zonal Flexibility $\in$ Limits of Zonal Resources;

Intra-area power flows $\in$ Branch Capacity Limits.
Defining a plausible range of boundary injection changes

- For any market zone $\bar{z} \in \mathcal{Z}$

  $\mathcal{N}_{a(\bar{z})}$: nodes with interconnectors outside the respective control area.

  $\phi_{nx}$: is the boundary injection change towards external node $x \in \mathcal{X}_{n}^{a(\bar{z})}$.
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  $\phi_{nx}$: is the boundary injection change towards external node $x \in \mathcal{X}_{n}^{a(\bar{z})}$.

- For any given target export quantity $e_{\bar{z}}$

  $$\phi_{nx}^{\min} \leq \phi_{nx} \leq \phi_{nx}^{\max}, \quad \forall n \in \mathcal{N}_{a(\bar{z})}, x \in \mathcal{X}_{n}^{a(\bar{z})}, \quad \# \text{lower/upper bounds} \quad (1)$$

  $$\sum_{n \in \mathcal{N}_{a(\bar{z})}} \sum_{x \in \mathcal{X}_{n}^{a(\bar{z})}} \phi_{nx} = e_{\bar{z}}. \quad \# \text{net change balances export quantity} \quad (2)$$

  
  
  
  
  
  
  
  
  
  N.b.: definition of boundary injection bounds to be discussed …
Minimizing the Intra-area Operating Cost

\[
\min_{p, \theta, s} \sum_{b \in B_\bar{z}} c_b \cdot p_b + \sum_{n \in \mathcal{N}_{a(\bar{z})}} pen \cdot (s_n^+ + s^-_n),
\]

(3)

subject to:

\[
\sum_{b \in B_n} p_b = \sum_{j \in \mathcal{N}_n} \frac{\theta_n - \theta_j}{X_{nj}} + \sum_{x \in \mathcal{X}_{n}^{a(\bar{z})}} \phi_{nx} + (s_n^+ - s_n^-), \quad \forall n \in \mathcal{N}_{a(\bar{z})},
\]

(4)

\[
p_{b}^{\text{min}} \leq p_b \leq p_{b}^{\text{max}}, \quad \forall b \in B_{\bar{z}},
\]

(5)

\[
p_b = 0, \quad \forall b \in B_{\bar{z}}, \forall z \in \mathcal{Z} \setminus \bar{z} : a(z) = a(\bar{z}),
\]

(6)

\[
- \bar{f}_{nj} \leq \frac{\theta_n - \theta_j}{X_{nj}} + f_{nj}^0 \leq \bar{f}_{nj}, \quad \forall n, j \in \mathcal{N}_{a(\bar{z})}
\]

(7)

\[
s_n^+, s_n^- \geq 0, \quad \forall n \in \mathcal{N}_{a(\bar{z})}.
\]

(8)
How do we solve the Bi-Level Optimization Problem?

▶ “The global maximum of a convex function over a closed bounded convex set is an extreme point.”
  - The optimal value of the lower level (3–8) is piece-wise convex in the upper level decision variable.
  ✓ The upper level maximizes a convex function in a closed bounded set (1–2).

▶ We can just exhaustively evaluate the lower level problem (3–8) over all corner points of (1–2):
  - the number of corner points depends on the number of interconnectors,
  - this is not prohibitively large for typical power grids,
  - it is also trivial to parallelize the solution of the respective linear programs.
The Non-convexity Issue

- The Worst-Case resource aggregation cost (i.e., the optimal value of the Bi-Level problem) is **non-convex in the target export quantity**.

![Graph showing non-convex behavior](image)

- In the PSCC paper, we added logical constraints in the balancing market clearing problem to represent price – quantity **ordered bids**.

- Since then, we also developed a translation into **exclusive block bids**.
3. Results & discussion
The test systems

The Chao-Peck example

The Nordic System (N44 BC) case
Chao-Peck example: intra-zonal resource aggregation

Northern-Zone WcRSF

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Chao-Peck example: intra-zonal resource aggregation

Northern-Zone WcRSF

Alternative Corner Points
Chao-Peck example: Plausible Boundary Injection Range

Too narrow: WcRSF touches the resource cost curve (a.k.a. merit order).

Too wide: Sharing balancing resources looks infeasible!

Just-right: Recovering the eventual delivery cost for the Activated Quantity.
How to evaluate the WcRSF?

The process (_circle over 1000 samples):

0. Generate nodal imbalance sample.
1. Clear Zonal Balancing Market given the WcRSF for a zone of study.
2. Disaggregate Activated Balancing Quantity s.t. intra-area grid constrains.

The metrics (average values):

- \( Q_a \): the Activated Balancing Quantity (in MWh).
- \( CD_a \): the Disaggregation Cost (in money).
- \( CO_a \): the Activated Offer Cost as per the aggregated offer (in money).

The alternative: All bids from the zone of study sent to the market (merit order aggregation).

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How to evaluate the WCRSF?

The process (₽ over 1000 samples):

0. Generate nodal imbalance sample.
1. Clear Zonal Balancing Market given the WCRSF for a zone of study.
2. Disaggregate Activated Balancing Quantity s.t. intra-area grid constrains.

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Chao-Peck example – simulation results overview

Average values over 1000 imbalance samples

- A moderate boundary injection range \( \pm 0.25 \bar{f} \) sufficient to recover the disaggregation cost.

- Too much risk aversion reduces the competitiveness of the balancing resources.
Nordic test case – simulation results overview

Even at a very conservative range ($\pm \bar{f}$) there is a negative gap between the average Disaggregation Cost and Aggregated Offer Cost!
Modified Nordic test case

- without imbalance realizations within aggregation area

- Grid congestion still possible while sharing balancing resources.

✓ the WcRSF hedges correctly against this risk.
Round-up & conclusions

- Flexibility resource aggregation in the context of zonal balancing markets.
- Proposal to evaluate the worst-case intra-area congestion cost over a plausible range of interconnection power flow changes.
- Purpose is to communicate intra-area grid constraints and congestion risk aversion with the market.
Round-up & conclusions

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  - Given a suitable range, hedging vs the risk of costly intra-area congestion.
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- Purpose is to communicate intra-area grid constraints and congestion risk aversion with the market.
- Given a suitable range, hedging vs the risk of costly intra-area congestion.
  - further work on defining the range from historical data.
  - also on accounting for intra-area uncertainties.


Case studies – results over importing samples
Logical Constraints for Ordered (price, quantity) Bids

\[ q_{k,z} = u_{k,z} \cdot dq_{k,z}^{\text{max}} + dq_{k,z}, \quad \forall k \in K_z, \forall z \in Z_{\tilde{a}}, \]  
\[ 0 \leq dq_{k,z} \leq v_{k,z} \cdot dq_{k,z}^{\text{max}}, \forall k \in K_z, \forall z \in Z_{\tilde{a}}, \]  
\[ v_{k,z} + u_{k,z} \leq u_{k-1,z}, \quad \forall k \in K^+_z, \forall z \in Z_{\tilde{a}}, \]  
\[ v_{k,z} + u_{k,z} \leq u_{k+1,z}, \quad \forall k \in K^-_z, \forall z \in Z_{\tilde{a}}, \]  
\[ \sum_{k \in K_z} v_{k,z} \leq 1, \forall z \in Z_{\tilde{a}}, \]  
\[ u_{-1,z} + u_{1,z} \leq 1, \quad \forall z \in Z_{\tilde{a}}, \]  
\[ v_{k,z}, u_{k,z} \in \{0; 1\}, \quad \forall k \in K_z, z \in Z_{\tilde{a}}. \]