Grid-aware Flexibility Aggregation for Zonal Balancing Markets

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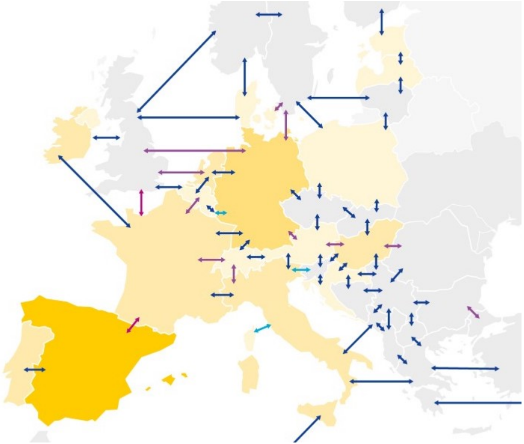
Cross-border integration for electricity balancing

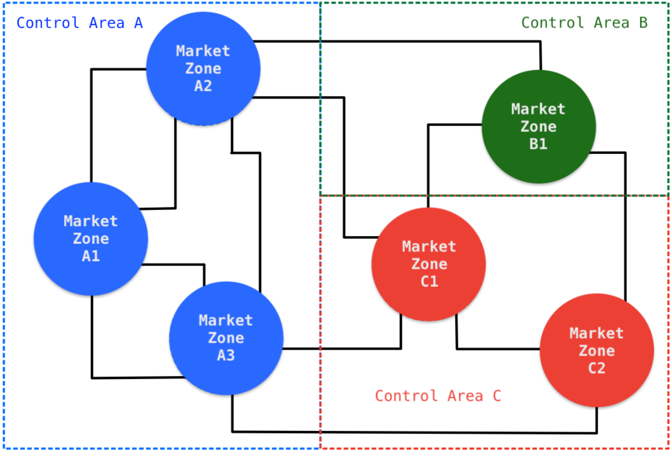


Source: ENTSO-e website

AI generated image

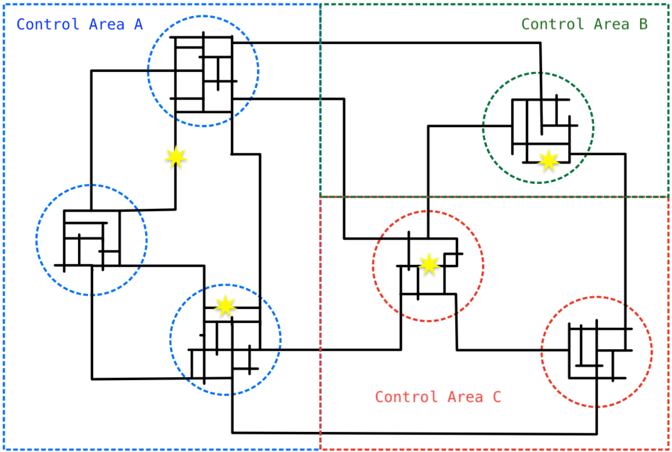
How is the grid represented?

- Balancing market clears at the zonal resolution.



How is the grid represented?

- Intra-area **congestion** to be managed by respective TSO.



Available tools to manage intra-area congestion

Ex-ante Bid Filtering

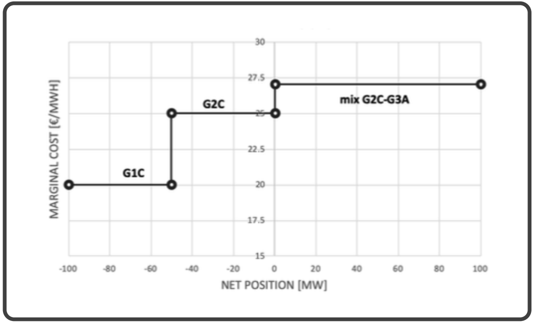
- TSO can filter any intra-area bid that is anticipated to cause congestion.
  - ✗ How to do this?
  - ✗ Intra-zonal grid constraints hidden from the market?
  - ✗ TSO risk aversion also hidden from the market?

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]

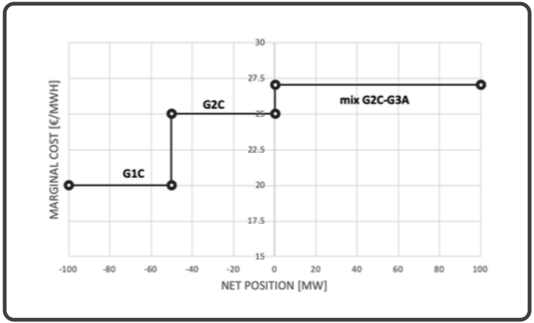
- Aggregate intra-zonal resources into a price – quantity curve (*ex-ante*).
  - ✓ Communicate both resource & intra-zonal congestion mgmt costs.



- Dispatch & settle intra-zonal resources s.t. grid constraints (*ex-post*).

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

- Given an export volume, minimize intra-area cost s.t. grid constraints.
  - 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.

Aggregation/disaggregation approach [1, 2, 3]

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

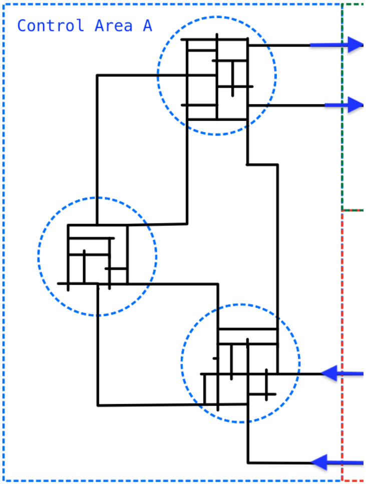
- Given an export volume, minimize intra-area costs s.t. grid constraints.
  - to construct a price – quantity curve.

Why revisit?

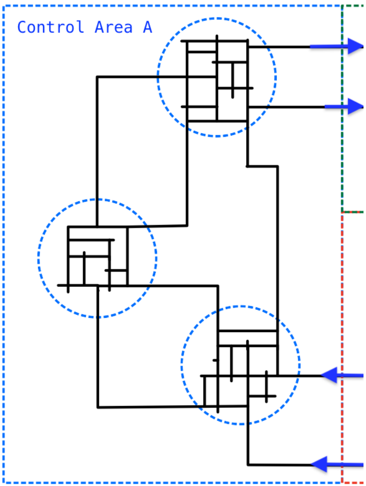
- Incremental export cost depends on uncertain & unobservable factors:
  - realization of imbalances all over the multi-area grid.
  - activation of balancing bids in external control-areas.
  - detailed topologies of external control-areas.
- Represented by a single *"best-guess"* in [2, 3]:
  - ⋆ comes with the **risk** that the **disaggregation cost** may be greater than approximated by the RSF (a.k.a., disaggregation risk).

1. Proposal

Introducing boundary injection changes

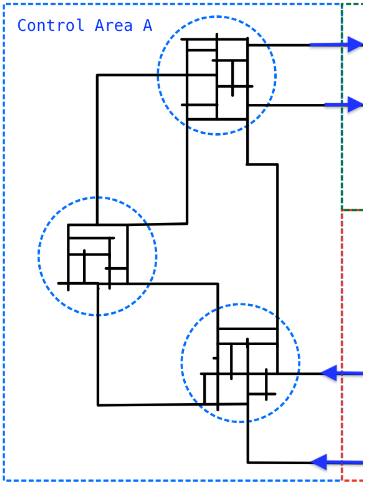


Introducing boundary injection changes



- 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.

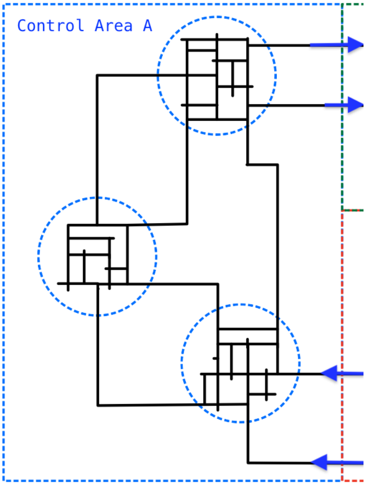
Proposal



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 $e_{\bar{z}}$

max {Operating Cost(Zonal Flexibility)};

s.t.

Boundary Injection Changes ∈ Plausible Range;

min {Operating Cost(Zonal Flexibility)};

s.t.

Nodal Balance(Boundary Injection Changes, Zonal Flexibility);

Zonal Flexibility ∈ Limits of Zonal Resources;

Intra-area power flows ∈ 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.

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

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

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

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

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

N.b.: definition of boundary injection bounds to be discussed ...

Minimizing the Intra-area Operating Cost

$$\min_{p,\theta,s} \sum_{b\in\mathcal{B}_{\bar{z}}} c_b \cdot p_b + \sum_{n\in\mathcal{N}_{a(\bar{z})}} pen \cdot (s_n^+ + s_n^-) \ , \tag{3}$$

subject to:

$$\sum_{b\in\mathcal{B}_n} p_b = \sum_{j\in\mathcal{N}_n} \frac{\theta_n - \theta_j}{X_{nj}} + \sum_{x\in\mathcal{X}_n^{a(\bar{z})}} \phi_{nx} + (s_n^+ - s_n^-), \ \ \forall n \in \mathcal{N}_{a(\bar{z})}, \tag{4}$$

$$p_b^{\min} \leq p_b \leq p_b^{\max}, \ \ \forall b \in \mathcal{B}_{\bar{z}}, \tag{5}$$

$$p_b = 0, \ \ \forall b \in \mathcal{B}_z, \forall z \in \mathcal{Z} \setminus \bar{z} : a(z) = a(\bar{z}), \tag{6}$$

$$-\bar{f}_{nj} \leq \frac{\theta_n - \theta_j}{X_{nj}} + f_{nj}^0 \leq \bar{f}_{nj}, \forall n, j \in \mathcal{N}_{a(\bar{z})} \tag{7}$$

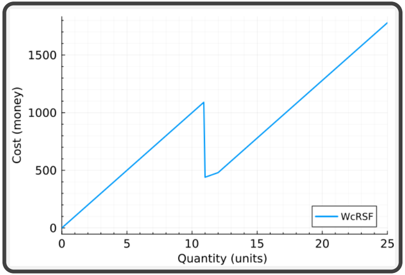
$$s_n^+, s_n^- \geq 0, \forall n \in \mathcal{N}_{a(\bar{z})}. \tag{8}$$

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

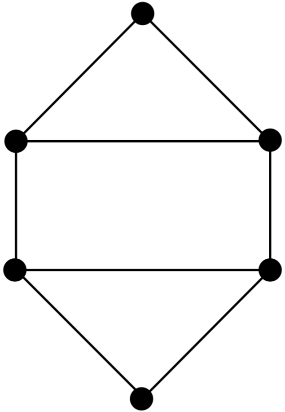
- The Worst-Case resource aggregation cost (*i.e.*, the optimal value of the Bi-Level problem) is **non-convex in the target export quantity**.



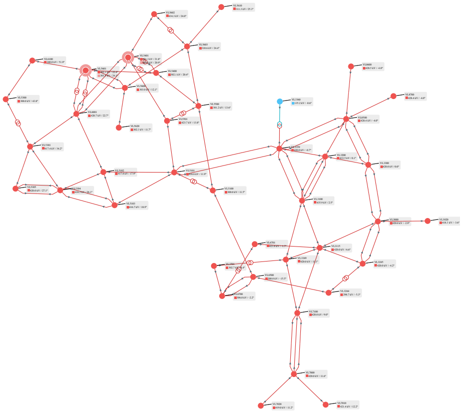
- In the PSCC paper, we added logical constraints in the balancing market clearing problem to represent price – quantity **ordered bids**.
- Since then, we also developed a translation into **exclusive block bids**.

3. Results & discussion

The test systems

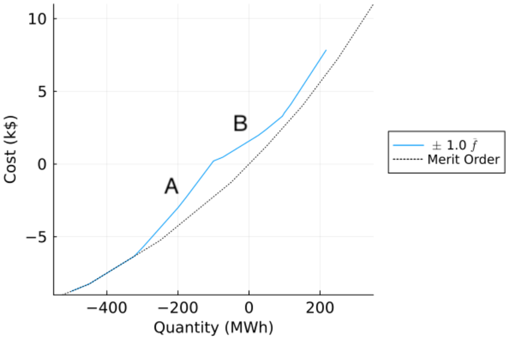


The Chao-Peck example



The Nordic System (N44 BC) case

Chao-Peck example: intra-zonal resource aggregation



Northern-Zone WcRSF

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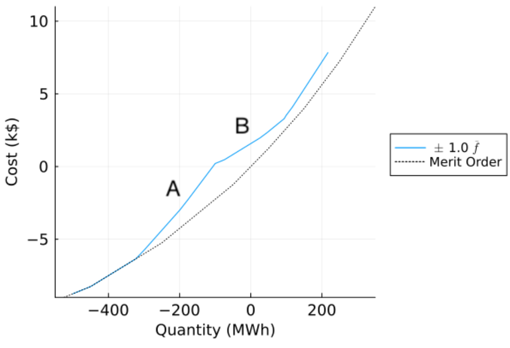
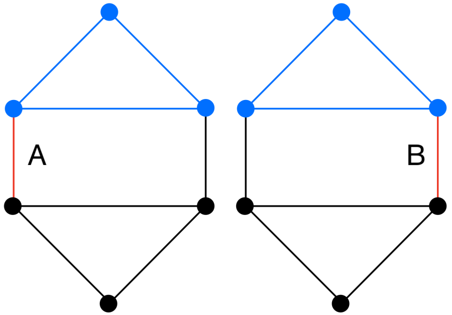


Northern-Zone WcRSF



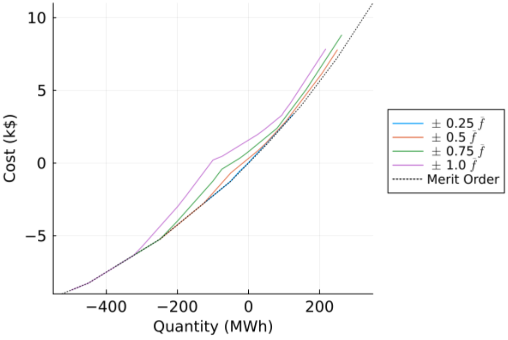
Alternative Corner Points

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.



Northern-Zone WcRSF

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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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).

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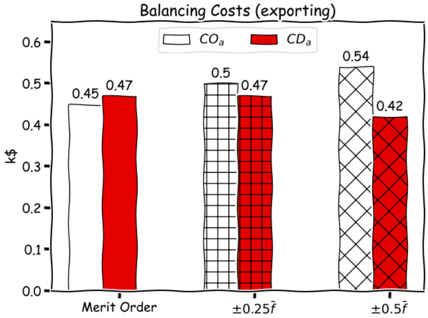
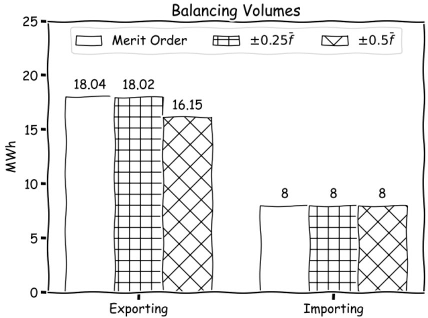
The alternative: All bids from the zone of study sent to the market (merit order aggregation).

Chao-Peck example – simulation results overview

Average values over 1000 imbalance samples

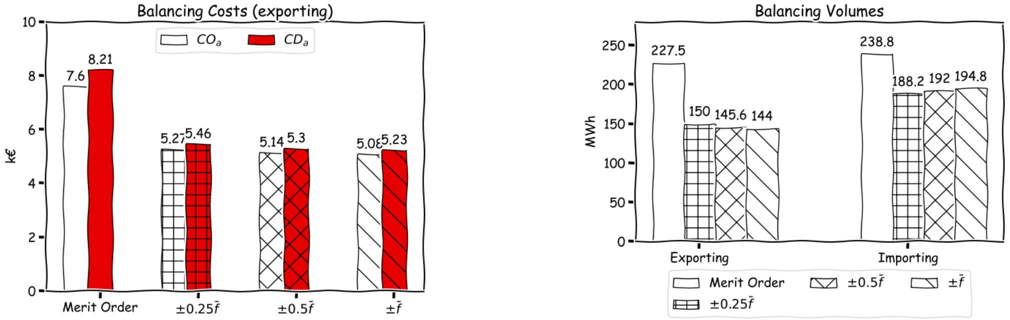




- A moderate boundary injection range $\pm 0.25\bar{f}$ sufficient to recover the disaggregation cost.
- Too much risk aversion reduces the competitiveness of the balancing resources.

Nordic test case – simulation results overview

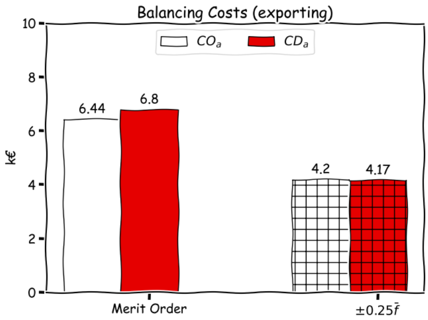
Average values over 1000 imbalance samples

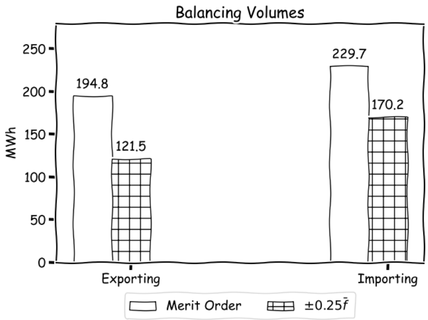


✗ Even at a very conservative range ($\pm\bar{f}$) there is a negative gap between the average Disaggregation Cost and Aggregated Offer Cost!

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.

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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.

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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.

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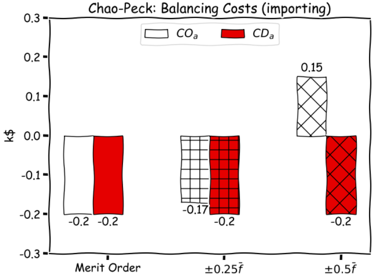
References

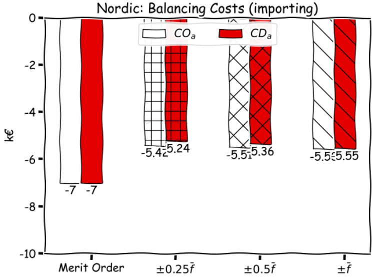
[1] I. Mezghani, N. Stevens, A. Papavasiliou, and D. I. Chatzigiannis, "Hierarchical coordination of transmission and distribution system operations in European balancing markets," IEEE Transactions on Power Systems, 2022.

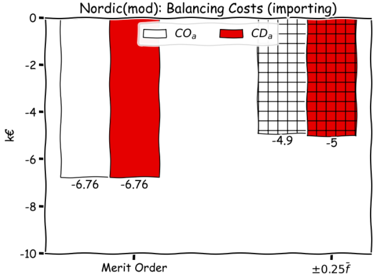
[2] A. Papavasiliou, M. Bjørndal, G. Doorman, and N. Stevens, "Hierarchical balancing in zonal markets," in 2020 17th International Conference on the European Energy Market (EEM). IEEE, 2020, pp. 1–6.

[3] A. Papavasiliou, G. Doorman, M. Bjørndal, Y. Langer, G. Leclercq, and P. Crucifix, "Interconnection of Norway to European balancing platforms using hierarchical balancing," in 2022 18th International Conference on the European Energy Market (EEM), 2022, pp. 1–7.

Case studies – results over importing samples







Logical Constraints for Ordered (price, quantity) Bids

$$q_{k,z} = u_{k,z} \cdot dq^{\max}_{k,z} + dq_{k,z}, \;\; \forall k \in \mathcal{K}_z, \forall z \in \mathcal{Z}_{\bar{a}}, \tag{9}$$

$$0 \leq dq_{k,z} \leq v_{k,z} \cdot dq^{\max}_{k,z}, \forall k \in \mathcal{K}_z, \forall z \in \mathcal{Z}_{\bar{a}}, \tag{10}$$

$$v_{k,z} + u_{k,z} \leq u_{k-1,z}, \;\; \forall k \in \mathcal{K}^{+}_z, \forall z \in \mathcal{Z}_{\bar{a}}, \tag{11}$$

$$v_{k,z} + u_{k,z} \leq u_{k+1,z}, \;\; \forall k \in \mathcal{K}^{-}_z, \forall z \in \mathcal{Z}_{\bar{a}}, \tag{12}$$

$$\sum_{k \in \mathcal{K}_z} v_{k,z} \leq 1, \forall z \in \mathcal{Z}_{\bar{a}}, \tag{13}$$

$$u_{-1,z} + u_{1,z} \leq 1, \;\; \forall z \in \mathcal{Z}_{\bar{a}}, \tag{14}$$

$$v_{k,z}, u_{k,z} \in \{0; 1\}, \;\; \forall k \in \mathcal{K}_z, z \in \mathcal{Z}_{\bar{a}}. \tag{15}$$