Modeling framework and simulation results for flow-based market coupling with transmission switching and N-1 security

VITO lunch talk

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Joint work with Ignacio Aravena and Anthony Papavasiliou
Louvain Institute of Data Analysis and Modeling in economics and statistics

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Outline

Introduction and context

Modeling framework for flow-based market coupling

Modeling N-1 robustness in day-ahead

CWE case study

Conclusion

Flow-based market coupling (FBMC)

Methodology for building the network constraints in the European day-ahead market.

Motivation

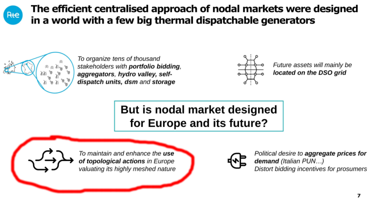
The **zonal pricing paradigm** of the European electricity is being increasingly challenged.

1. **Redispatch costs** have risen recently (from 130 M€ in 2006 to 1.000 M€ in 2016 in Germany alone).
2. Hard to implement the right **zone delimitation** (failure of the first bidding zone review).

Motivation

Arguments in favor of zonal regarding **topology control**.

1. Zonal is better suited for implementing topology control.
2. Topology control can help to decrese redispatch costs.

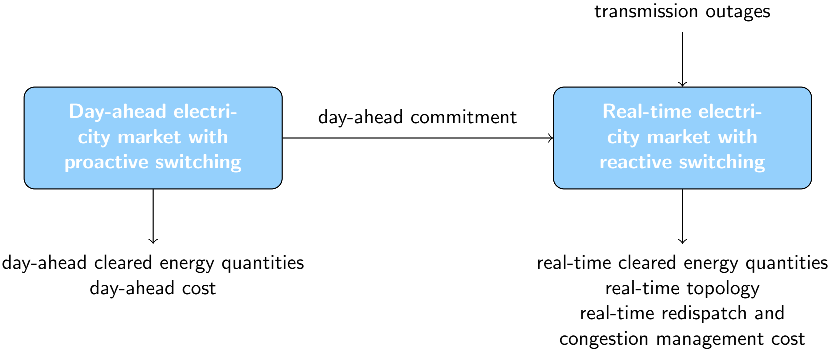


Research questions

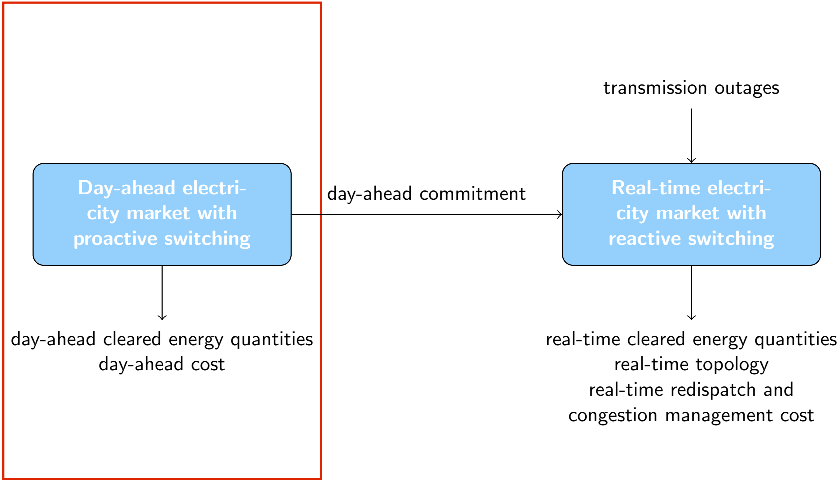
Main focus: efficiency regarding unit commitment.

- How efficient is zonal in performing unit commitment ?
- What is the differnece in performance between ATCMC and FBMC ?
- Can proactive switching help to make better unit commitment decisions ?
- Is switching more beneficial in zonal than in nodal markets ?

Day-ahead and real-time model

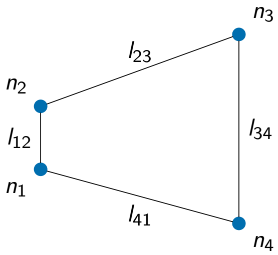


Day-ahead and real-time model



Nodal electricity market

$$\begin{aligned} \min_{\substack{\text{bids,}\\ \text{flows}}} \quad & \text{production cost} \\ \text{s.t.} \quad & \text{fractional bids} \\ & \text{net production} = \\ & \quad \text{outgoing flows, at each node} \\ & \text{line thermal limits} \\ & \text{power-angle constraints} \end{aligned}$$

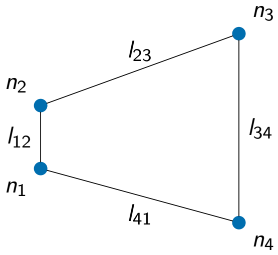


Nodal electricity market

$$
\begin{aligned}
\min_{v,f,\theta} \quad & \sum_{g\in G} P_g Q_g v_g \\
\text{s.t.} \quad & 0 \le v_g \le 1 \quad \forall g \in G \\
& \sum_{g\in G(n)} Q_g v_g - Q_n = \\
& \quad \sum_{l\in L(n,\cdot)} f_l - \sum_{l\in L(\cdot,n)} f_l \quad \forall n \in N \quad [\rho_n] \\
& -F_l \le f_l \le F_l \quad \forall l \in L \\
& f_l = B_l \left(\theta_{m(l)} - \theta_{n(l)}\right) \quad \forall l \in L
\end{aligned}
$$

P, Q: price and quantity

F_l, B_l: capacity and susceptance line l



$G = \{1, 2, 3, 4\}$,

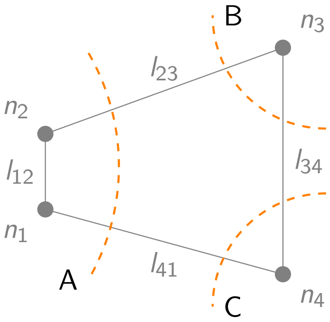
$G(n_1) = \{1\}, \dots$

$N = \{n_1, n_2, n_3, n_4\}$

$L = \{l_{12}, l_{23}, l_{34}, l_{41}\}$,

$L(n_1, n_2) = \{l_{12}\}, \dots$

Zonal network organization



$$G = \{1, 2, 3, 4\},\ G(A) = \{1, 2\}, \ldots$$

$$N = \{n_1, n_2, n_3, n_4\},\ N(A) = \{n_1, n_2\}, \ldots$$

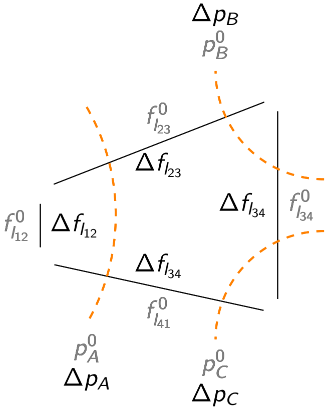
Flow-Based Market Coupling with Approximation (FBMC-A)

1. Select a base case (p^0, f^0) (net positions, flows on branches)
2. Compute zone-to-line Power-Transfer-Distribution-Factors, $PTDF_{l,z}$, so that

$$\Delta f_l \approx \sum_{z \in Z} PTDF_{l,z} \Delta p_z$$

3. Define **flow-based domain**:

$$\mathcal{P}^{FB-A} := \Big\{ p \in \mathbb{R}^{|Z|} \Big| \sum_{z \in Z} p_z = 0,$$
$$- F_l \leq \sum_{z \in Z} PTDF_{l,z}(p_z - p_z^0) + f_l^0 \leq F_l \quad \forall l \in L \Big\}$$



Flow-Based Market Coupling with Approximation (FBMC-A)

4. Clear day-ahead market by solving:

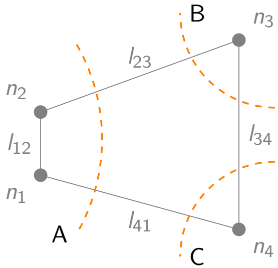
$$
\begin{aligned}
\min_{v,p} \quad & \sum_{g \in G} P_g Q_g v_g \\
\text{s.t.} \quad & 0 \leq v_g \leq 1 \quad \forall g \in G \\
& \sum_{g \in G(z)} Q_g v_g - \sum_{n \in N(z)} Q_n = p_z \quad \forall z \in Z \quad [\rho_z] \\
& \sum_{z \in Z} p_z = 0 \\
& -F_l \leq \sum_{z \in Z} PTDF_{l,z}(p_z - p_z^0) + f_l^0 \leq F_l \quad \forall l \in L
\end{aligned}
$$

- Circular definitions: base case (p^0, f^0), market clearing point
- Discretionary parameters: zone-to-line PTDF (among others)

Zonal electricity market

$$\min_{v,p} \sum_{g\in G} P_g Q_g v_g$$
$$\text{s.t. } 0 \le v_g \le 1 \quad \forall g \in G$$
$$\sum_{g\in G(z)} Q_g v_g - \sum_{n\in N(z)} Q_n = p_z \quad \forall z \in Z \quad [\rho_z]$$
$$p \in \mathcal{P}$$

- $\mathcal{P}$ should include all feasible cross-border trades, EC 714/2009, Annex I, Art. 1.1
- $\mathcal{P}$ should not include configurations that cannot be met by the system, EC 1222/2015, Art. 69

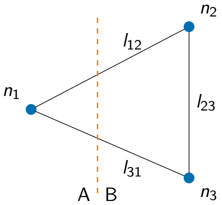


$$G = \{1,2,3,4\},$$
$$G(A) = \{1,2\}, \dots$$
$$N = \{n_1,n_2,n_3,n_4\},$$
$$N(A) = \{n_1,n_2\}, \dots$$

Deriving $\mathcal{P}$ directly from physics: an example

Physics:

$$r_1 + r_2 + r_3 = 0$$
$$-100 \leq r_1 \leq 100$$
$$-100 \leq r_2 \leq 100$$
$$-100 \leq r_3 \leq -50$$
$$-25 \leq f_{12} = 1/3\, r_1 - 1/3\, r_2 \leq 25$$



$$G = \{1, 2, 3\}$$

$$Q_1 = 200,\ Q_2 = 200,\ Q_3 = 50$$

$$N = \{n_1, n_2, n_3\}$$

$$L = \{l_{12}, l_{23}, l_{31}\},\ F_{12} = 25$$

100MW demand per node

Zonal net positions:

$$p_A = r_1$$
$$p_B = r_2 + r_3$$

Deriving $\mathcal{P}$ directly from physics: an example

Physics:

$$r_1 + r_2 + r_3 = 0$$
$$-100 \leq r_1 \leq 100$$
$$-100 \leq r_2 \leq 100$$
$$-100 \leq r_3 \leq -50$$
$$-25 \leq f_{12} = 1/3\, r_1 - 1/3\, r_2 \leq 25$$

Zonal net positions:

$$p_A = r_1$$
$$p_B = r_2 + r_3$$

Are these zonal net positions feasible?

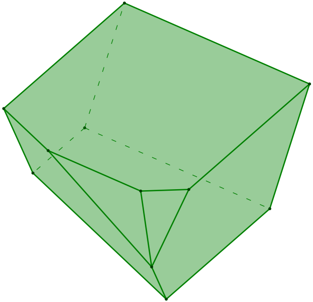
$p_A = 0$	$p_B = 0$	*Yes*
$p_A = 200$	$p_B = -200$	*No*
$p_A = -100$	$p_B = 100$	*No*
$p_A = 50$	$p_B = -50$	*Yes*

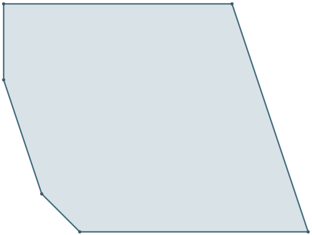
True net position feasible set $\mathcal{P}$:

$$p_A + p_B = 0$$
$$-12.5 \leq p_A \leq 87.5$$

Flow-Based Market Coupling with Exact Projection (FBMC-EP)

space of nodal injections $\rightarrow$ space of zonal net positions





$$\mathcal{R} := \left\{ r \in \mathbb{R}^{|N|} \,\middle|\, r \text{ is feasible for the real network} \right\}$$

$$\mathcal{P}^{FB-EP} := \left\{ p \in \mathbb{R}^{|Z|} \,\middle|\, \exists r \in \mathcal{R} : p_z = \sum_{n \in N(z)} r_n \ \ \forall z \in Z \right\}$$

4-node, 3-zone network: $p_A = r_1 + r_2,\ p_B = r_3,\ p_C = r_4$

Flow-Based Market Coupling with Exact Projection (FBMC-EP)

$$\mathcal{P}^{FB-EP} = \Bigg\{ p \in \mathbb{R}^{|Z|} \,\Bigg|\, \exists(\bar{v}, f, \theta) \in [0,1]^{|G|} \times \mathbb{R}^{|L|} \times \mathbb{R}^{|N|} :$$

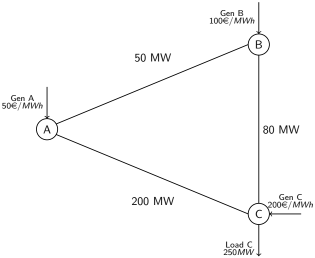
$$\sum_{g \in G(z)} Q_g \bar{v}_g - p_z = \sum_{n \in N(z)} Q_n \quad \forall z \in Z,$$

$$\sum_{g \in G(n)} Q_g \bar{v}_g - \sum_{l \in L(n,\cdot)} f_l + \sum_{l \in L(\cdot,n)} f_l = Q_n \quad \forall n \in N,$$

$$-F_l \leq f_l \leq F_l, \; f_l = B_l \left(\theta_{m(l)} - \theta_{n(l)}\right) \quad \forall l \in L \Bigg\}$$

- $\mathcal{P}^{FB-EP}$ **allows for all trades that are feasible** with respect to the real network and **bans only trades that can be proven to be infeasible** for the real network
- $\mathcal{P}^{FB-A}$ provides no guarantees: might ban feasible trades and, also, allow infeasible trades

Acceptable set of net positions with switching

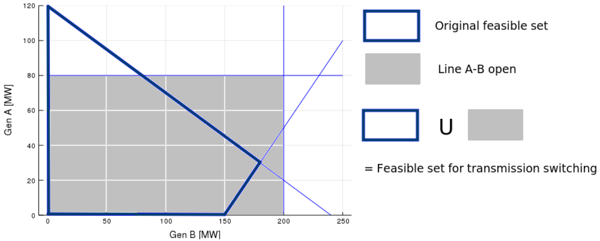


$p \in \mathcal{P}_t$

$$-50 \leq \frac{1}{3}\mathrm{GEN_A} - \frac{1}{3}\mathrm{GEN_B} \leq 50$$

$$-80 \leq \frac{1}{3}\mathrm{GEN_A} + \frac{2}{3}\mathrm{GEN_B} \leq 80$$

$$-200 \leq \frac{2}{3}\mathrm{GEN_A} + \frac{1}{3}\mathrm{GEN_B} \leq 200$$



→ solve on the union of polytopes

Day-ahead market clearing with proactive switching

$$\min_{v \in [0,1], p, t} \sum_{g \in G} P_g Q_g v_g$$

$$\text{s.t.} \sum_{g \in G(z)} Q_g v_g - p_z = \sum_{n \in N(z)} Q_n \qquad \forall z \in Z$$

$$p \in \mathcal{P}_t$$

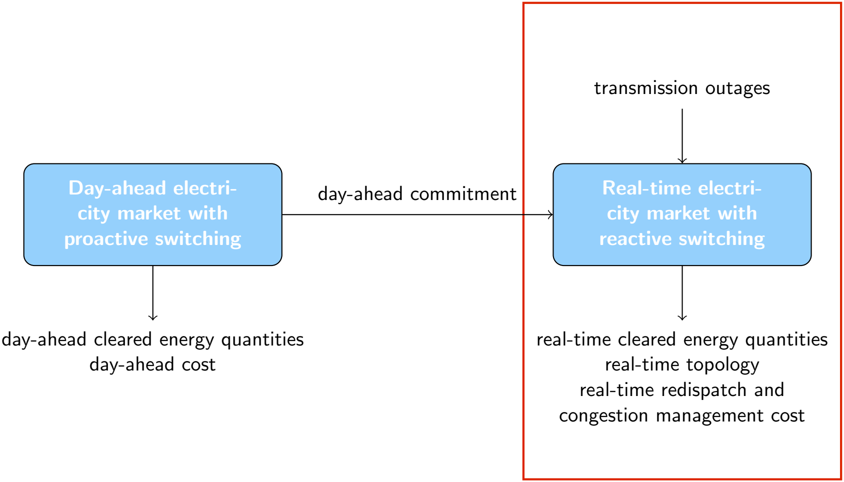
- (P_g, Q_g) is the price quantity bid of generator g
- v_g is the acceptance of the bid of generator g
- p_z is the net position of zone z
- $\mathcal{P}$ is the acceptable set of net positions, which depends on the topology (t).

Acceptable set of net positions

- Put the two together

$$
\begin{aligned}
\mathcal{P}_t = \Big\{ & p \in \mathbb{R}^{|Z|} : \exists(\bar{v}, f, \theta, t) \in [0,1]^{|\mathcal{G}|} \times \mathbb{R}^{|L|} \times \mathbb{R}^{|N|} \times \{0,1\}^{|L|} : \\
& \sum_{g \in \mathcal{G}(z)} Q_g \bar{v}_g - p_z = \sum_{n \in N(z)} Q_n, \quad \forall z \in Z \\
& \sum_{g \in \mathcal{G}(n)} Q_g \bar{v}_g - \sum_{l \in L(n,\cdot)} f_l + \sum_{l \in L(\cdot,n)} f_l = Q_n, \quad \forall n \in N \\
& - t_l F_l \leq f_l \leq t_l F_l, \quad \forall l \in L \\
& f_l \leq B_l(\theta_{m(l)} - \theta_{n(l)}) + M(1 - t_l), \quad \forall l \in L \\
& f_l \geq B_l(\theta_{m(l)} - \theta_{n(l)}) - M(1 - t_l), \quad \forall l \in L \Big\}
\end{aligned}
$$

Day-ahead and real-time model



Cost-based redispatch

Goal

Minimize the **cost** while respecting the constraints of the nodal grid

$$
\begin{aligned}
\min_{\substack{v\in[0,1],f,\theta \\ t\in\{0,1\}}} \sum_{g\in G} P_g Q_g v_g & \\
\text{s.t.} \quad \sum_{g\in G(n)} Q_g v_g - \sum_{l\in L(n,\cdot)} f_l + \sum_{l\in L(\cdot,n)} f_l = Q_n, & \quad n \in N \\
-F_l t_l \leq f_l \leq F_l t_l, & \quad \forall l \in L \\
f_l \leq B_l(\theta_{m(l)} - \theta_{n(l)}) + M(1 - t_l), & \quad \forall l \in L \\
f_l \geq B_l(\theta_{m(l)} - \theta_{n(l)}) - M(1 - t_l), & \quad \forall l \in L
\end{aligned}
$$

Preventive vs curative remedial actions

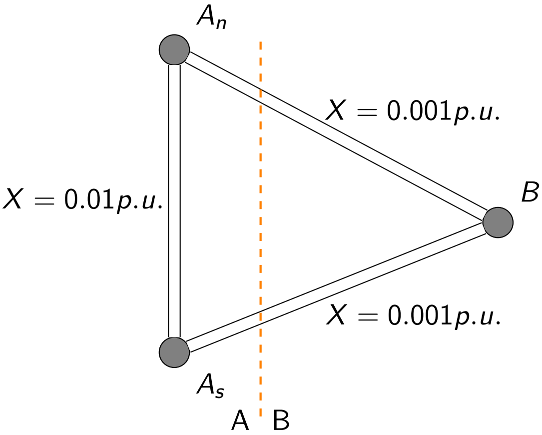
Central distinction in N-1 modeling.

- **Preventive:** Performed before the realization of a contingency.
- **Curative:** Performed in reaction to the contingency.

TSO practices:

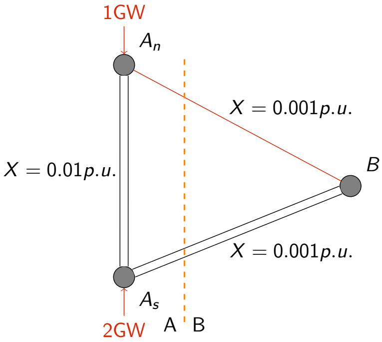
- Topological changes (PST settings, line switching, ...) can be curative.
- **Most** redispatching is preventive.

Illustrative example: Preventive vs curative

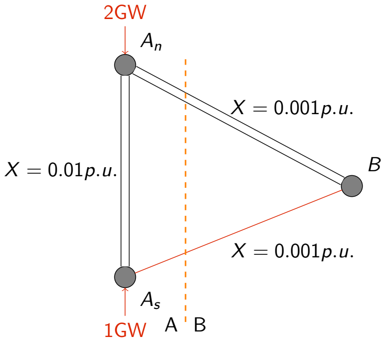


What is the largest acceptable net position of zone A in a N-1 setting ?

Illustrative example: curative

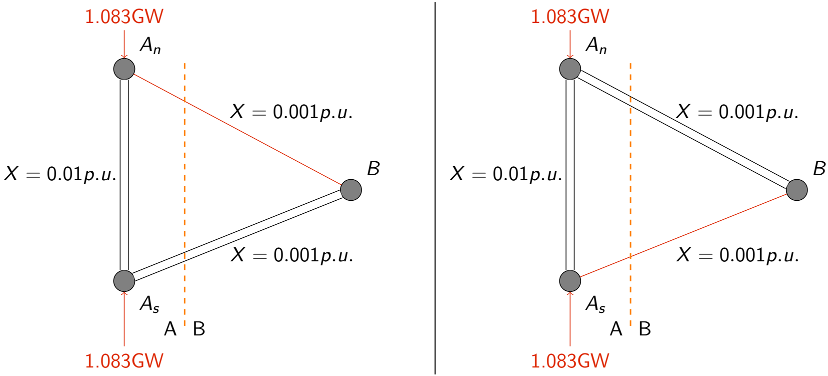


$$p_A = 3GW$$



$$p_A = 3GW$$

Illustrative example: preventive



$$p_A = 2.17GW$$

Curative redispatching

$$p \in \bigcap_{\|u\|_1 \le 1} \mathcal{P}_t^{\text{cur}}(u)$$

with

$$\begin{aligned}
\mathcal{P}_t^{\text{cur}}(u) = \Big\{ & p \in \mathbb{R}^{|Z|} : \\
& \exists (\bar{v}, f, \theta, t) \in [0,1]^{|G|} \times \mathbb{R}^{|L|} \times \mathbb{R}^{|N|} \times \{0,1\}^{|L|} : \\
& \sum_{g \in G(z)} Q_g \bar{v}_g - p_z = \sum_{n \in N(z)} Q_n, \ \ \forall z \in Z \\
& \sum_{g \in G(n)} Q_g \bar{v}_g - \sum_{l \in L(n,\cdot)} f_l + \sum_{l \in L(\cdot,n)} f_l = Q_n, \ \ \forall n \in N \\
& - t_l F_l \le f_l \le t_l F_l, \ \ \forall l \in L \\
& f_l \le (1 - u_l) B_l (\theta_{m(l)} - \theta_{n(l)}) + M(1 - t_l), \ \ \forall l \in L \\
& f_l \ge (1 - u_l) B_l (\theta_{m(l)} - \theta_{n(l)}) - M(1 - t_l), \ \ \forall l \in L \Big\}
\end{aligned}$$

Preventive redispatching

$$\mathcal{P}_t^{\text{prev}} = \Big\{ p \in \mathbb{R}^{|Z|} : \exists\ \bar{v} \in [0,1]^{|G|} :$$

$$\sum_{g \in G(z)} Q_g \bar{v}_g - p_z = \sum_{n \in N(z)} Q_n, \quad \forall z \in Z$$

$$\bar{v} \in \bigcap_{\|u\|_1 \leq 1} \mathcal{V}_t(u) \Big\}$$

with

$$\mathcal{V}_t(u) = \Big\{ v \in [0,1]^{|G|} :$$

$$\exists (f, \theta, t) \in \mathbb{R}^{|L|} \times \mathbb{R}^{|N|} \times \{0,1\}^{|L|} :$$

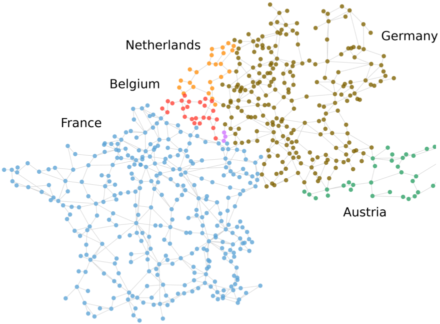
$$\sum_{g \in G(n)} Q_g v_g - \sum_{l \in L(n,\cdot)} f_l + \sum_{l \in L(\cdot,n)} f_l = Q_n, \quad \forall n \in N$$

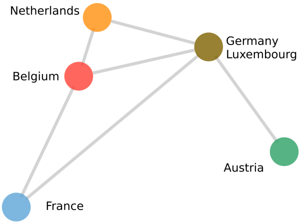
$$-t_l F_l \leq f_l \leq t_l F_l, \quad \forall l \in L$$

$$f_l \leq (1 - u_l) B_l (\theta_{m(l)} - \theta_{n(l)}) + M(1 - t_l), \quad \forall l \in L$$

$$f_l \geq (1 - u_l) B_l (\theta_{m(l)} - \theta_{n(l)}) - M(1 - t_l), \quad \forall l \in L \Big\}$$

Central Western European network





- 632 buses, 945 branches, 346 slow thermal generators (154GW), 301 fast thermal generators (89GW) and 1 312 renewable generators (149GW)
- 768 typical snapshots $\times$ 1 000 random uncertainty realizations $\rightarrow \sim$88 years of operation

CWE results: total cost performance

Total costs and efficiency of different policies

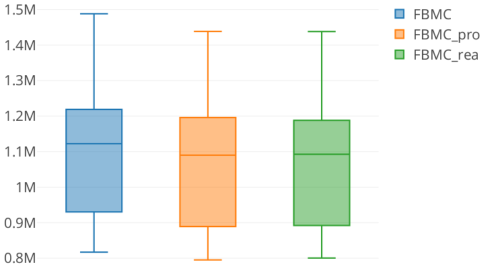
Policy	Day-ahead [M€/year]	Real-time [M€/year]	Total [M€/year]	Efficiency losses
PF	–	11 677	11 677	-0.93%
LMP	10 758	1 029	11 787	–
FBMC	10 693	1 787	12 480	5.88%
ATCMC	10 793	1 746	12 539	6.38%

- PF: Perfect Foresight benchmark
- FBMC outperforms ATCMC by ∼**100M€/year in day ahead** (parallel run, Amprion *et al.* (2013), estimated 95M€/year) but only by ∼**60M€/year in total**
- Efficiency losses of zonal markets amount to about 6% of total costs, ∼**720M€/year**

Benefits of switching on FBMC

Setting:

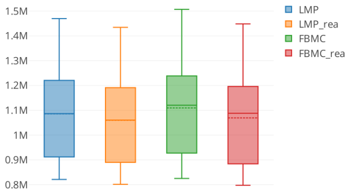
- Switching budget of 6 lines
- Smaller number of snapshots (32)



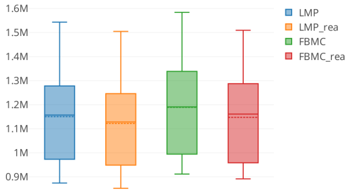
- No significant improvement with proactive switching.
- Benefits of switching $\sim 3\%$

Comparison with a nodal market

Base case situation



Hard contingency situation



Benefits of switching

- FBMC: 3%
- LMP: 1.8%

- FBMC: 3.5%
- LMP: 2.5%

Simulation results

Main results

- Difference between ATCMC and FBMC is negligible.
- Considering switching in the market coupling methodology has a negligable effect. Nodal remains more efficient.
- Reactive transmission switching has considerable value.
- Transmission switching benefits more to FBMC than to LMP.

Discussion and conclusion

Answer to pro-zonal arguments:

1. Is zonal better suited for topology control ?
   - Yes: Zonal $\rightarrow$ less price variability $\rightarrow$ more acceptable to have a sub-optimal solution
   - No: Proactive switching does not help much

2. Topology control is more beneficial to zonal ?
   - True for reactive switching

Further research directions: Impacts in terms of pricing

Thank you

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https://qlete.github.io/

More details :

- I. Aravena, Q. Lété, A. Papavasiliou, Y. Smeers, Transmission Capacity Allocation in Zonal Electricity Markets, Operations Research, forthcoming
- Q. Lété, A. Papavasiliou, Impacts of Transmission Switching in Zonal Electricity Markets - Part I, IEEE Transactions on Power Systems, forthcoming
- Q. Lété, A. Papavasiliou, Impacts of Transmission Switching in Zonal Electricity Markets - Part II, IEEE Transactions on Power Systems, forthcoming