Transmission capacity allocation in zonal electricity markets

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Energy Day, UC Louvain,
Louvain-la-Neuve, Belgium. April 16th, 2018.

Outline

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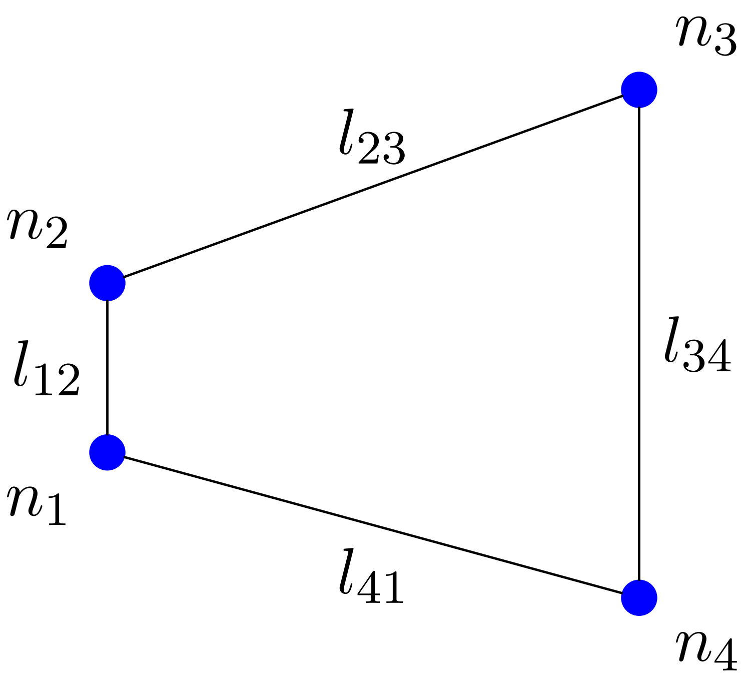
2. Day-ahead electricity market models
3. Policy analysis using 4-node, 3-zone network
4. Simulation results for the Central Western European network
5. Conclusions

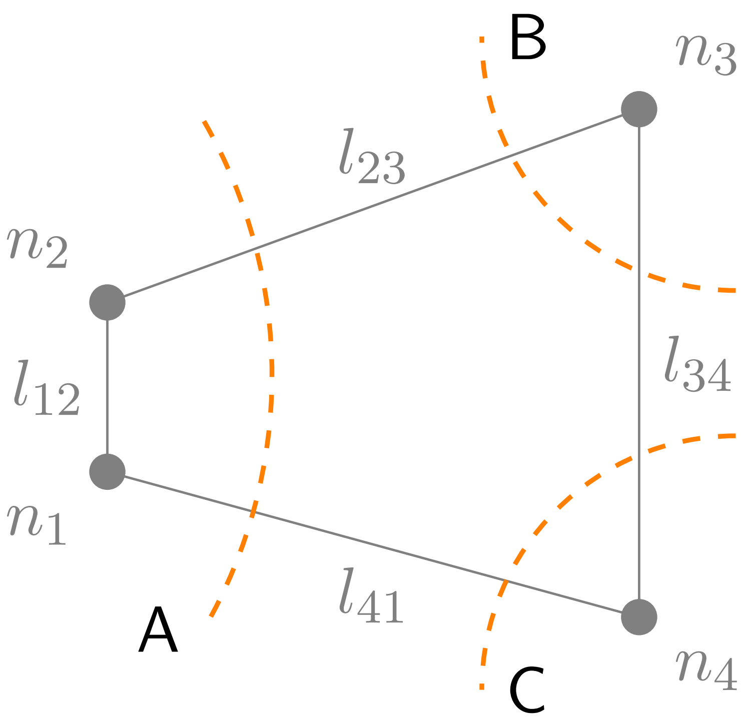
Introduction

Nodal electricity markets



- Participants can **trade freely** when located at the **same node**
- Participants in **different nodes** can trade up to **congestion** of lines
- Congestion: power flow equations, thermal limits of transmission lines, among others (**physics**)

Zonal electricity markets



- Participants **trade freely** within each **bidding zone**
- Participants in **different zones** can trade up to certain **export/import limits**
- Limits: **aggregation** of power flow equations and others

Zonal electricity markets

- European electricity market organized as a zonal market, EC 714/2009
- Two types of export/import limits:
  - Limits on the bilateral exchange between neighboring zones, Available-Transfer-Capacity Market Coupling (**ATCMC**)
  - Limits on the net position configuration of zones, Flow-Based Market Coupling (**FBMC**)
- FBMC used to clear day-ahead electricity market at the Central Western European system since May 2015
- Other markets might implement FBMC in the near future (e.g. Noord Pool, Enirginet *et al.* (2017))

Flow-Based Market Coupling (FBMC)

- Preferred methodology for electricity market operations of the EC, EU 2015/1222: "*… a method that takes into account that electricity can* **flow via different paths** *and optimises the available capacity in* **highly interdependent grids** *…*"
- Increases in day-ahead market welfare of **95M€/year** with respect to ATCMC, Amprion *et al.* (2013)
- Congestion management and balancing costs not included in studies. They amounted to **945M€** in 2015, ENTSO-E (2015).
- Questions:
  - Do FBMC or ATCMC correctly account for physical flows? Why do they/do they not?
  - Does FBMC significantly improves the overall welfare of the market with respect to ATCMC?

Literature

- Jensen *et al.* (2017), and many references therein, study ATCMC and conclude that its performance is significantly **worse than that of a nodal market**
- Waniek *et al.* (2009), Waniek *et al.* (2010) study the accuracy of the approximation of flows in FBMC at cross-border lines
- Marien *et al.* (2013) study how **discretionary aggregation parameters** (for export/import limits) affect the outcome of FBMC
- Van den Bergh *et al.* (2015) summarize the concepts and methodology used for FBMC at the Central Western European system
- Dierstein (2017) analyzes the impacts of **discretionary aggregation parameters** on welfare, exchanges, prices and counter-trading costs

Contributions

1. We propose a new framework for modeling ATCMC and FBMC in which we derive export/import limitations directly from the physics of the real network

   (the proposed models **do not depend** on discretionary aggregation parameters)

2. We develop cutting-plane algorithms to explicitly account for the N-1 security criterion on imports/exports

3. We perform numerical simulation using a 4-node network instance and an industrial-scale instance of the Central Western European system considering 88 years of operating conditions

   - Vast similarities between ATCMC and FBMC in all aspects
   - ATCMC and FBMC fail at allocating transmission capacity and are outperformed by a nodal market

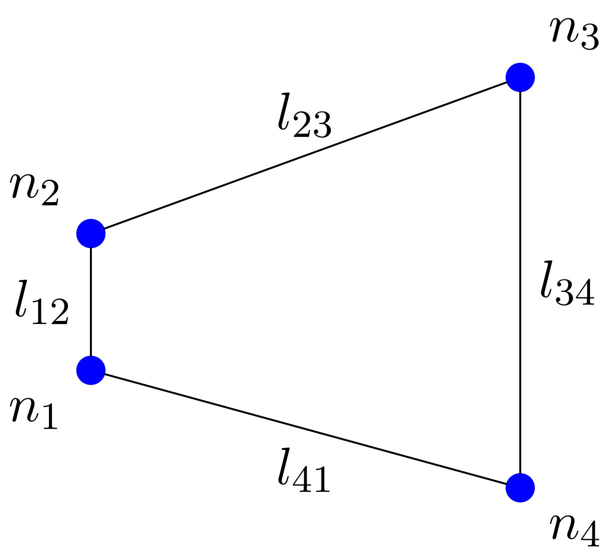
Day-ahead electricity market models

Assumptions

1. All energy trades take place at the day-ahead auction
2. Bids are price-quantity pairs, associated with a node/zone
3. Participants bid truthfully
4. System operator knows:
   - Topology of the network
   - Susceptance and thermal limits of lines
   - Installed production capacity at each node
5. Consumers have an infinite valuation (demand is fixed)

Nodal electricity market

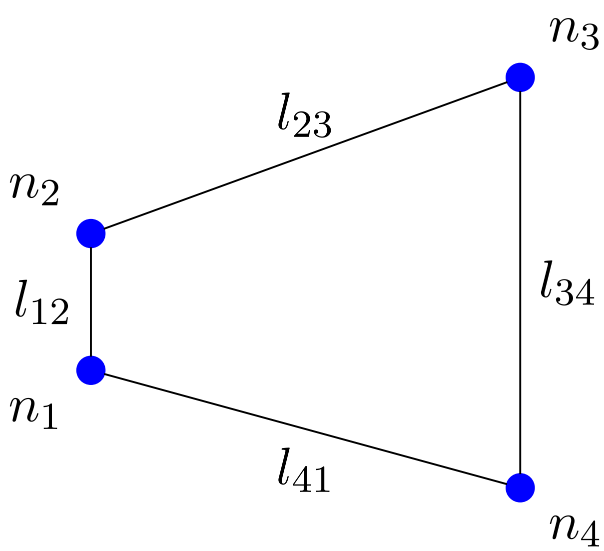
$$\begin{aligned}
\min_{\text{bids, flows}} \quad & \text{production cost} \\
\text{s.t.} \quad & \text{fractional bids} \\
& \text{net production} = \\
& \quad \text{outgoing flows, at each node} \\
& \text{line thermal limits} \\
& \text{DC power flow equations}
\end{aligned}$$



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

P, Q: price and quantity

F_l, B_l: capacity and susceptance line l



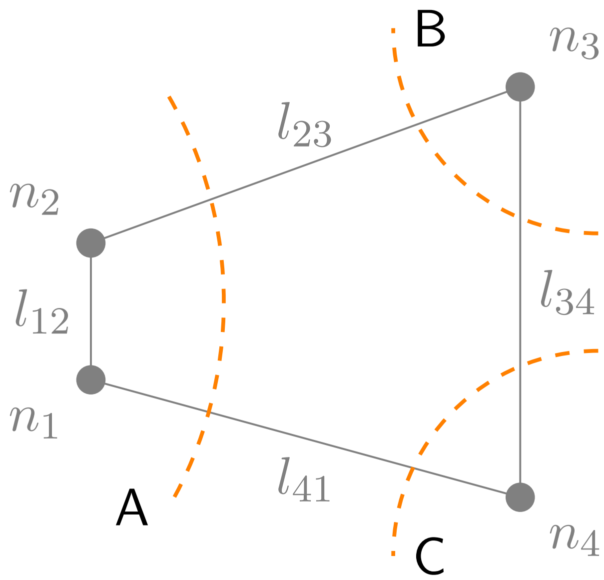
$$G = \{1, 2, 3, 4\},$$
$$G(n_1) = \{1\}, \ldots$$
$$N = \{n_1, n_2, n_3, n_4\}$$
$$L = \{l_{12}, l_{23}, l_{34}, l_{41}\},$$
$$L(n_1, n_2) = \{l_{12}\}, \ldots$$

Zonal electricity market

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

p_z: net position of zone z
$\mathcal{P}$: set of allowed net positions

$\mathcal{P}$ varies from policy to policy



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

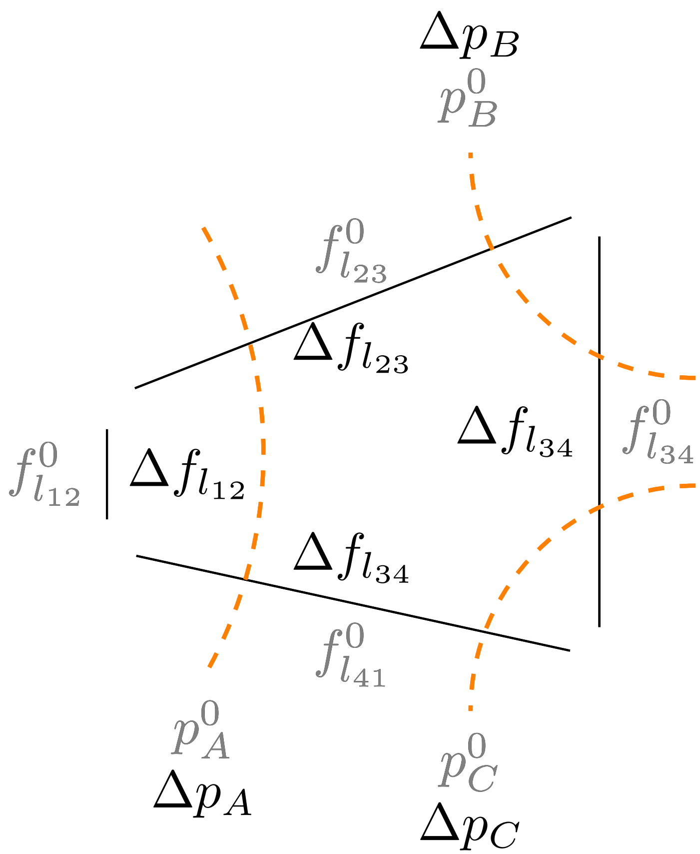
$$N = \{n_1, n_2, n_3, n_4\},$$
$$N(A) = \{n_1, n_2\}, \ldots$$

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

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

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

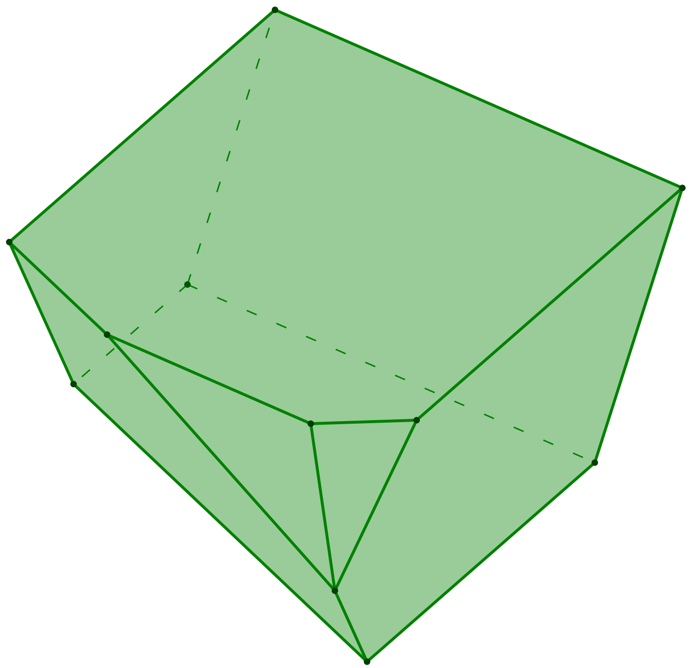
3. Define set of allowed net positions

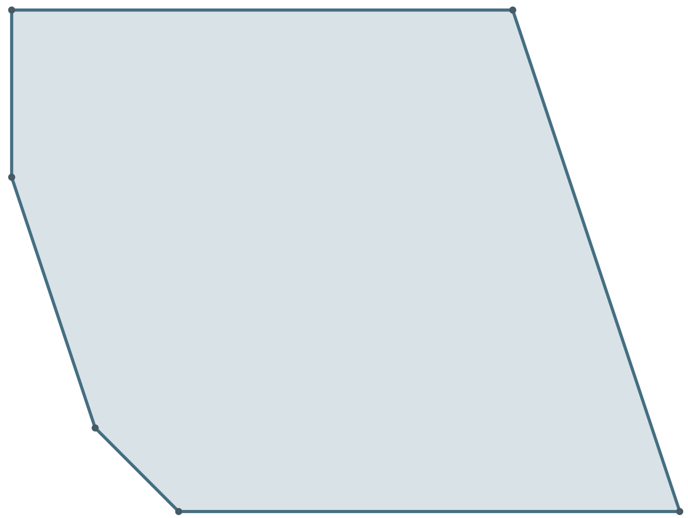


$$\mathcal{P}^{FB-A} := \left\{ p \in \mathbb{R}^{|Z|} \middle| -F_l \leq \sum_{z \in Z} PTDF_{l,z}(p_z - p_z^0) + f_l^0 \leq F_l \quad \forall l \in L \right\}$$

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

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





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

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

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)

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

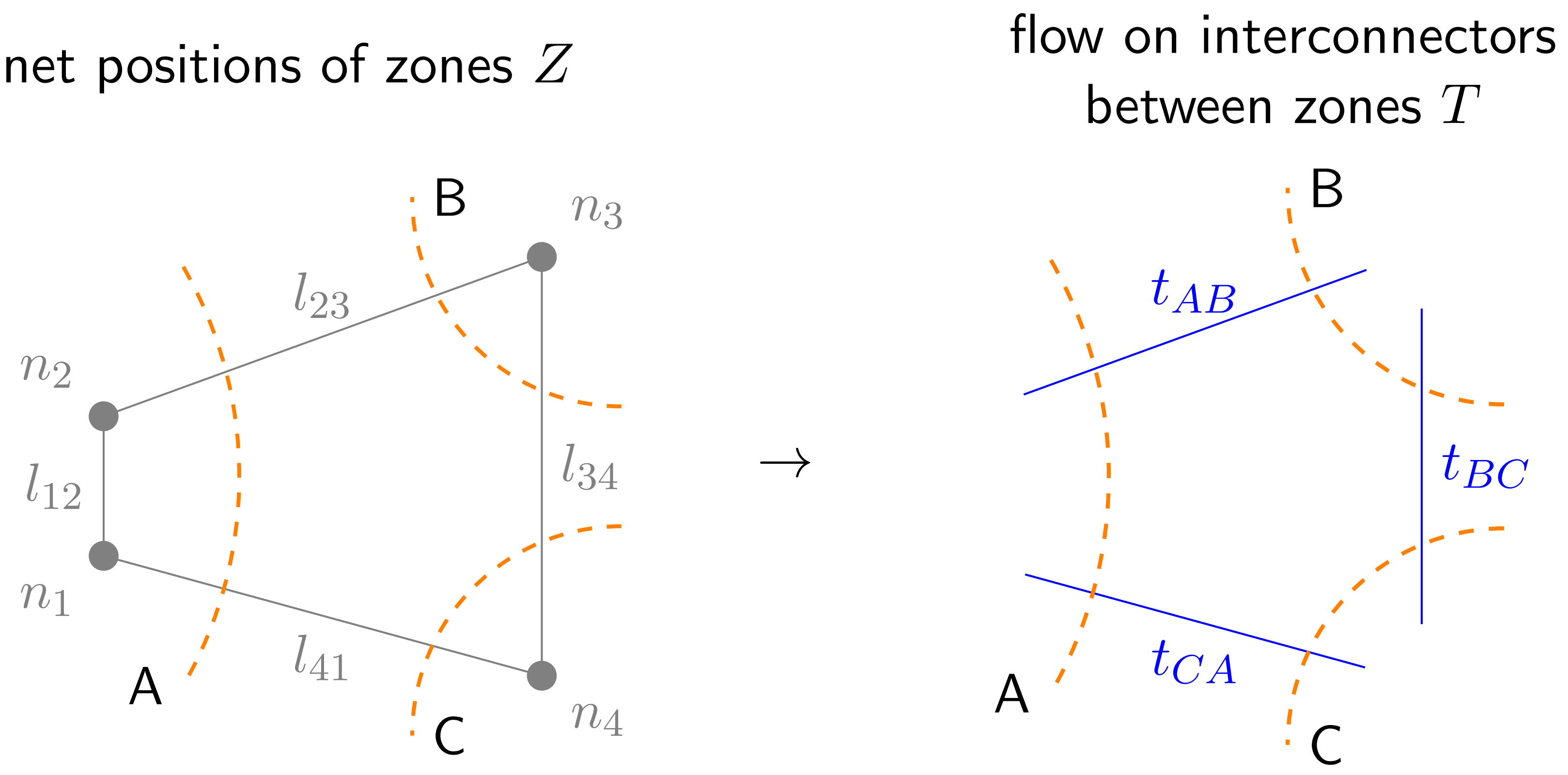
$$\sum_{g \in G(z)} Q_g \bar{v}_g - p_z = \sum_{n \in N(z)} Q_n \quad \forall z \in Z,$$

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

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

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

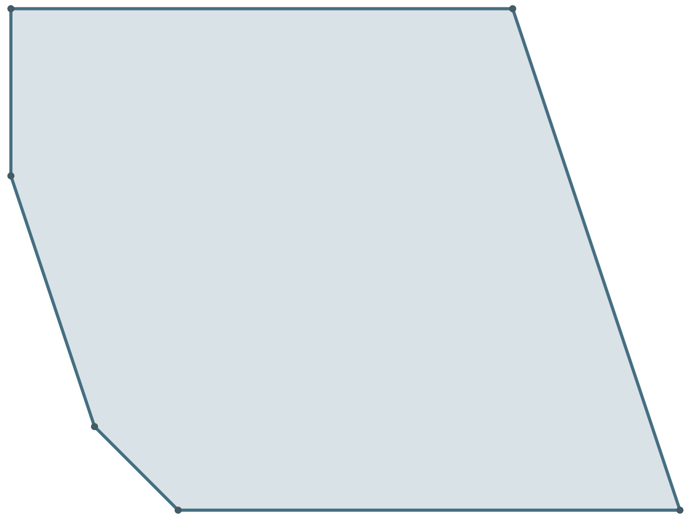
Available-Transfer-Capacity Market Coupling (ATCMC)



- ATCMC clears day-ahead market over the network $\mathcal{G}(Z, T)$
- Available-transfer-capacities (ATCs): $ATC_t^- \leq e_t \leq ATC_t^+$
- How to compute ATCs?

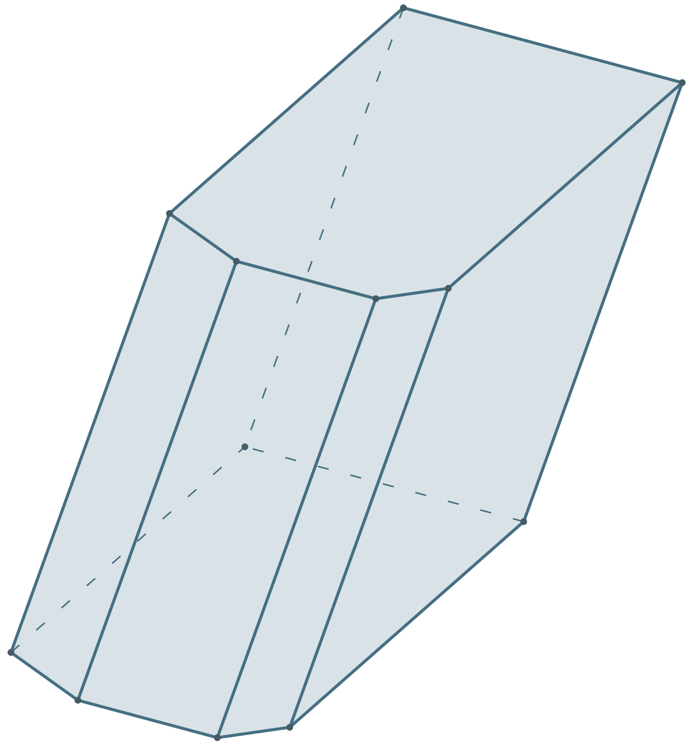
Available-Transfer-Capacity Market Coupling (ATCMC)

space of zonal net positions



$\mathcal{P}^{FB-EP}$

space of exchanges



$$\mathcal{E} := \left\{ e \in \mathbb{R}^{|T|} \,\middle|\, -\sum_{l \in L(t)} F_l \leq e_t \leq \sum_{l \in L(t)} F_l \quad \forall t \in T, \right.$$
$$\left. \exists p \in \mathcal{P} : p_z = \sum_{t \in T(z,\cdot)} e_t - \sum_{t \in T(\cdot,z)} e_t \quad \forall z \in Z \right\}$$

Maximum-volume Available-Transfer-Capacities (ATCs)

- ATC limits, $ATC_t^- \leq e_t \leq ATC_t^+ \ \forall t \in T$, are a box in the space of exchanges

- Compute ATCs as a maximum volume box inside $\mathcal{E}$,

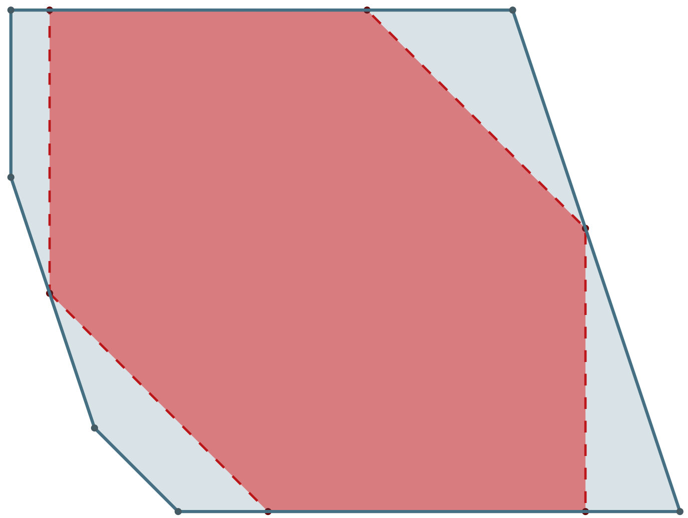
$$\begin{aligned} \max_{ATC} \quad & \prod_{t \in T} (ATC_t^- + ATC_t^+) \\ \text{s.t.} \quad & [-ATC^-, ATC^+] \subseteq \mathcal{E} \end{aligned}$$

- $\mathcal{E}^{ATC} := [-ATC^{-,*}, ATC^{+,*}]$ allows for the **largest subset of bilateral exchanges** that can be accommodated using a box and it **bans** all trades that would result in **infeasible zonal net positions**

- Implemented methodology for computing ATCs provides no guarantees

Maximum-volume Available-Transfer-Capacities (ATCs)

space of zonal net positions

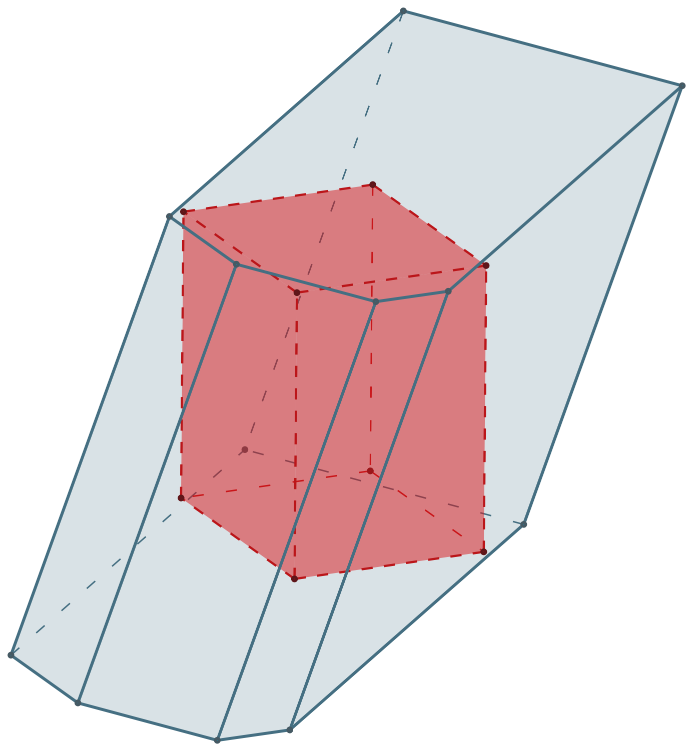


$\mathcal{P}$

$\rightarrow$

$\leftarrow$

space of exchanges



$$\mathcal{P}^{ATC} := \left\{ p \in \mathbb{R}^{|Z|} \middle| \exists e \in \mathcal{E}^{ATC} : \right.$$

$$\left. p_z = \sum_{t \in T(z,\cdot)} e_t - \sum_{t \in T(\cdot,z)} e_t \; \forall z \in Z \right\}$$

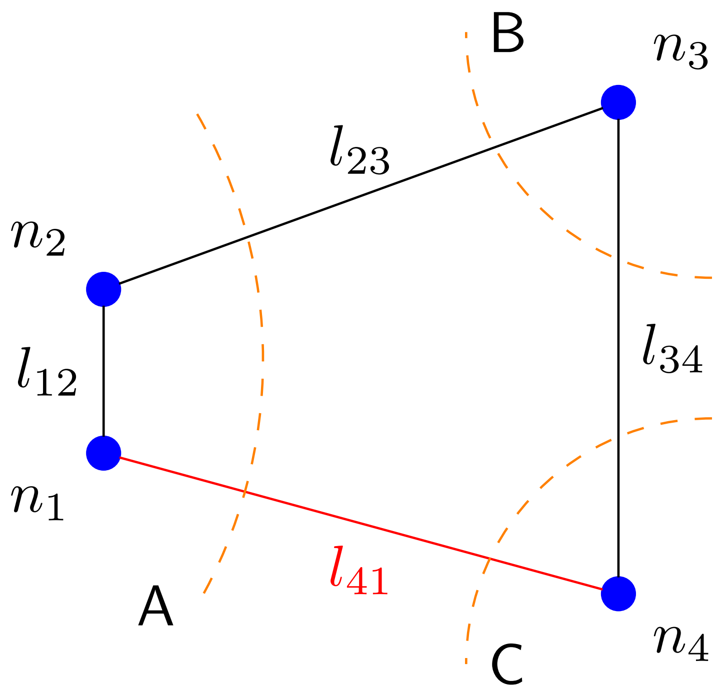
$$\mathcal{E},\; \mathcal{E}^{ATC} = [-ATC^{-,*}, ATC^{+,*}]$$

Policy analysis using 4-node, 3-zone network

Recap: 4 policies

- **LMP**: Minimizes cost over nodal model
- **FBMC-A**: Minimizes cost over zonal model with $\mathcal{P} = \mathcal{P}^{FB-A}$
- **FBMC-EP**: Minimizes cost over zonal model with $\mathcal{P} = \mathcal{P}^{FB-EP}$
- **ATCMC**: Minimizes cost over zonal model with $\mathcal{P} = \mathcal{P}^{ATC}$

Inter-zonal congestion case study



$$B_l = 1\text{pu}\ \forall l \in L$$

Generators

g	$n(g)$	Q_g [MW]	P_g [\$/MWh]
1	n_1	500	8
2	n_2	200	45
3	n_3	300	18
4	n_4	500	200

Consumers

n	Q_n [MW]
n_2	300
n_4	300

$$F_{l_{41}} = 100\text{MW}, F_l = +\infty\ \forall l \in L \setminus \{l_{41}\}$$

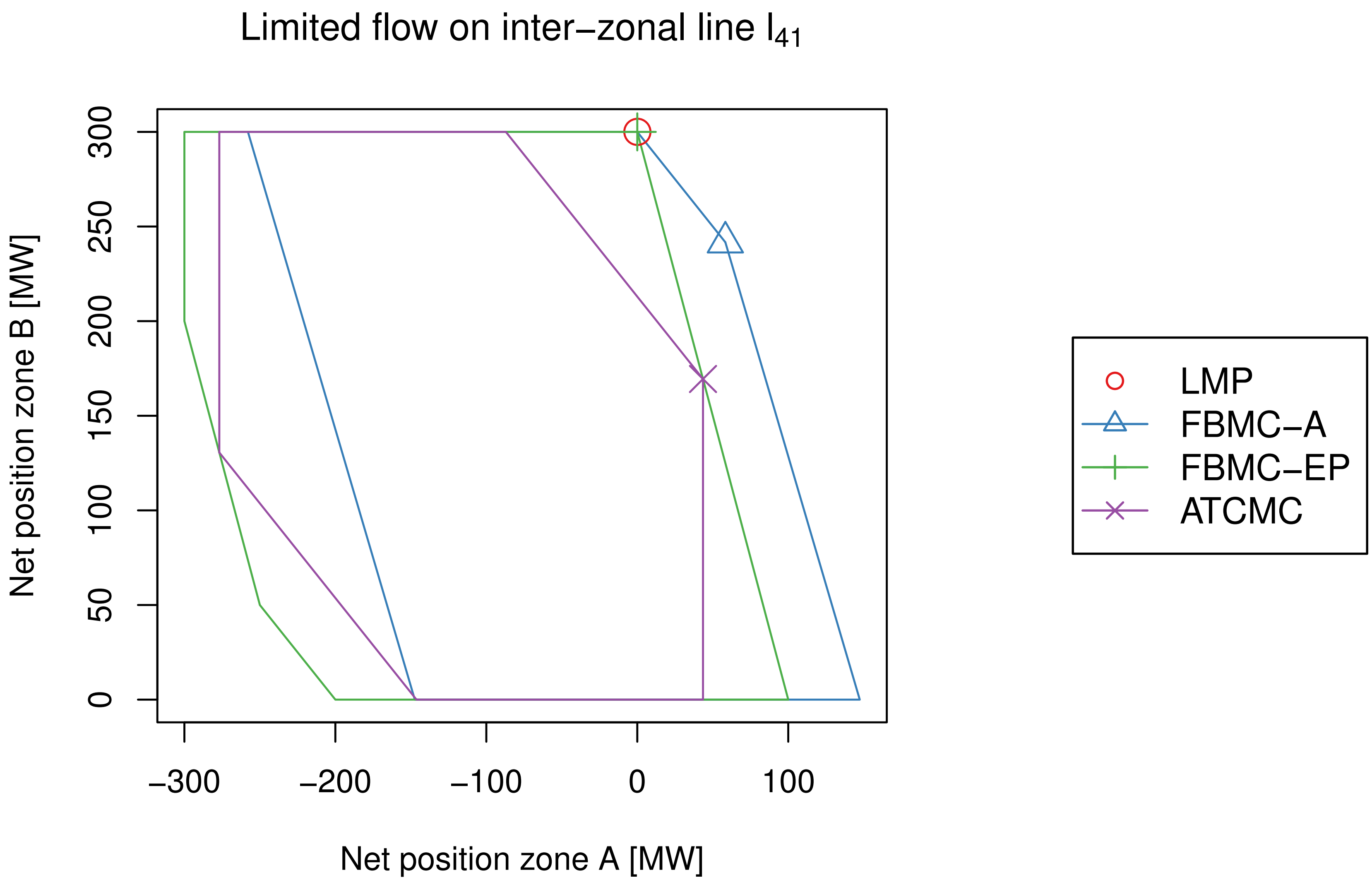
Inter-zonal congestion: results

Summary of clearing quantities and prices for a case of inter-zonal congestion (l_{41} limited to 100MW)

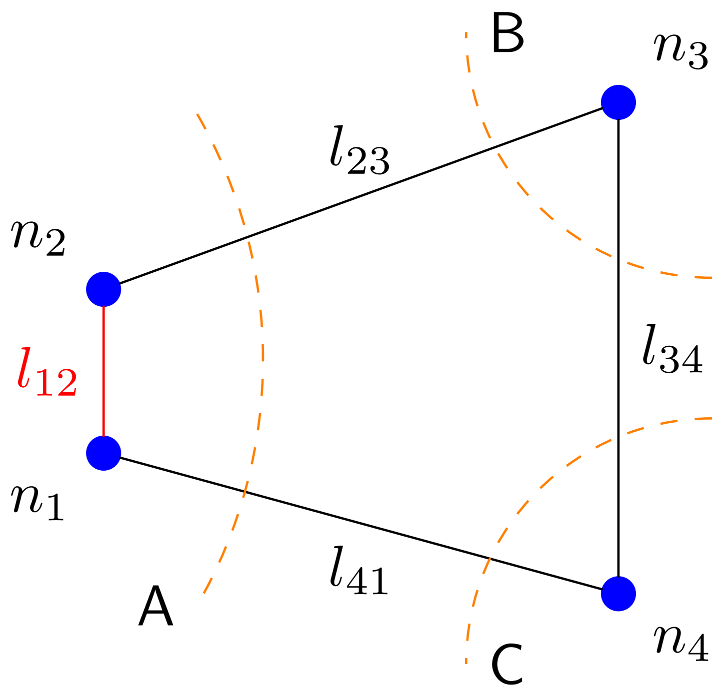
Policy	Total cost [$]	ρ [$/MWh] Min.	ρ [$/MWh] Max.	Abs. error flow approx. [MW]	Overload l_{41} [MW]
LMP	15 200	8	119	0	0
FBMC-A	7 217	8	200	475	79
FBMC-EP	7 800	8	23	300	50
ATCMC	23 208	8	200	–	50

- Cleared quantities on all zonal markets overload line l_{41}: **failure to account for inter-zonal congestion**
- Flow approximation error and overload larger in FBMC-A than in FBMC-EP
- Cost of ATCMC larger than cost of LMP, ATCMC clears at an infeasible point

Inter-zonal congestion: space of zonal net positions



Intra-zonal congestion case study



$B_l = 1\text{pu } \forall l \in L$

Generators

g	$n(g)$	Q_g [MW]	P_g [$/MWh]
1	n_1	500	8
2	n_2	200	45
3	n_3	300	18
4	n_4	500	200

Consumers

n	Q_n [MW]
n_2	300
n_4	300

$$F_{l_{12}} = 100\text{MW}, F_l = +\infty \ \forall l \in L \setminus \{l_{12}\}$$

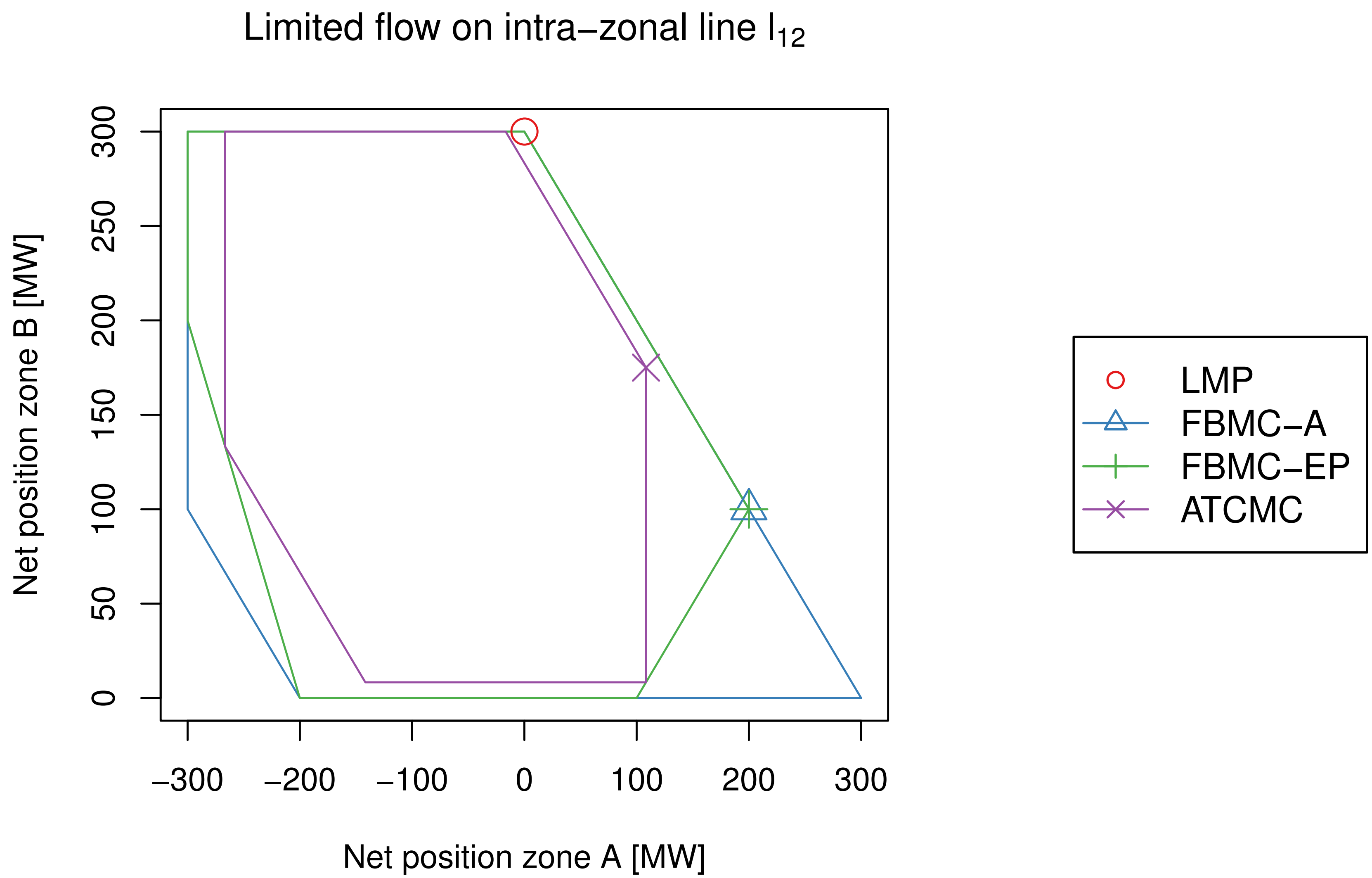
Intra-zonal congestion: results

Summary of clearing quantities and prices for a case of inter-zonal congestion (l_{12} limited to 100MW)

Policy	Total cost [$]	ρ [$/MWh] Min.	ρ [$/MWh] Max.	Abs. error flow approx. [MW]	Overload l_{12} [MW]
LMP	10 267	8	45	0	0
FBMC-A	5 800	18	18	536	150
FBMC-EP	5 800	18	18	300	150
ATCMC	9 750	8	200	–	108

- Cleared quantities on all zonal markets overload line l_{12}: **failure to account for intra-zonal congestion**
- Flow approximation error larger in FBMC-A than in FBMC-EP

Intra-zonal congestion: space of zonal net positions



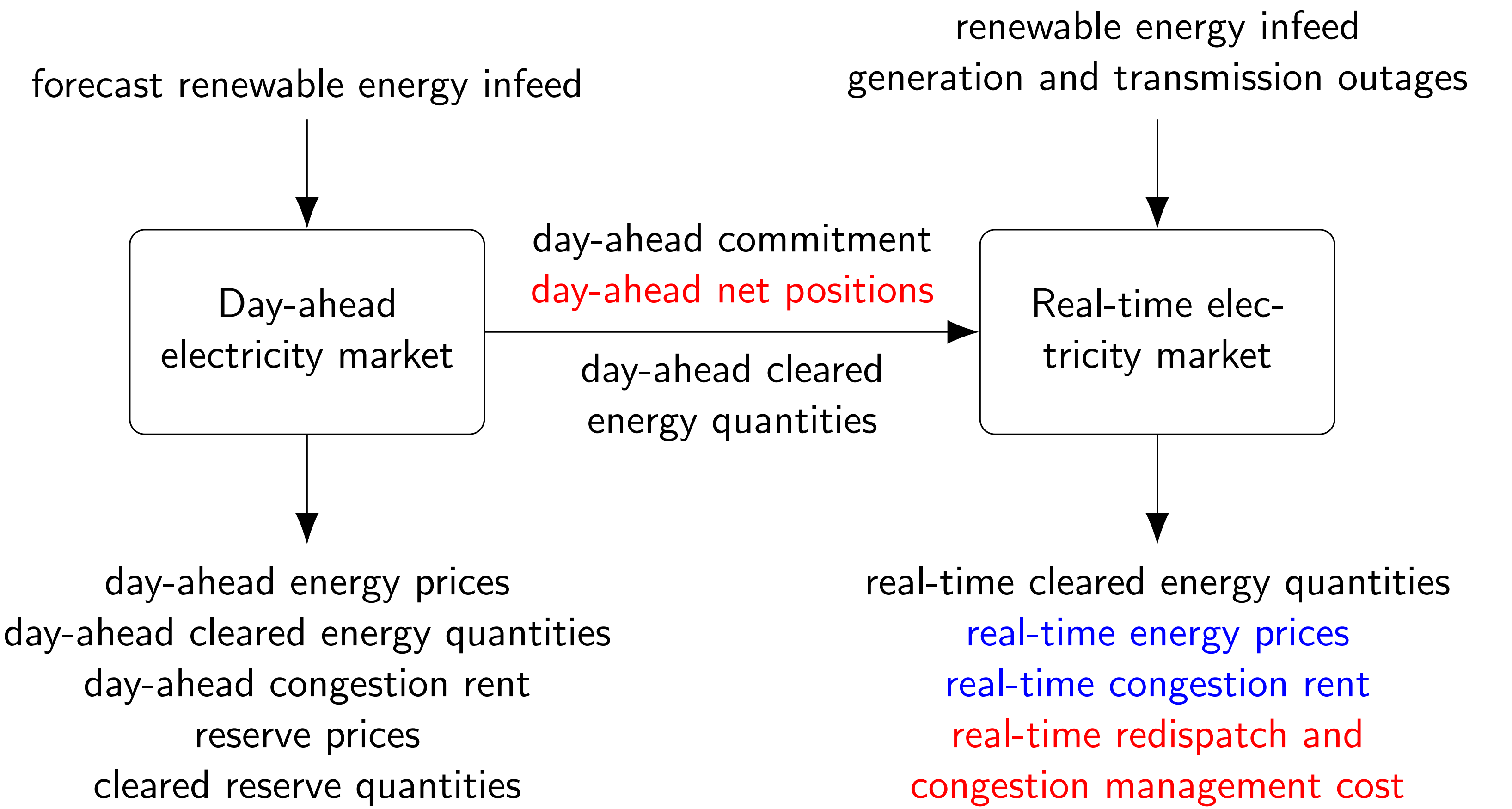
Discussion

- FBMC-A, FBMC-EP, ATCMC led to clearing quantities that would overload the transmission system
- FBMC-A cleared with infeasible net positions and can prevent feasible trades from being accepted

  This in conflict with EC 714/2009, Annex I, Art. 1.1
- **All zonal market designs suffer the same problem** for inter- and intra-zonal transmission capacity allocation: losing track of nodal injections leads to **inaccurate physical flow estimations**
- Given these results, in what follows, we only simulate FBMC-EP and refer to it as FBMC

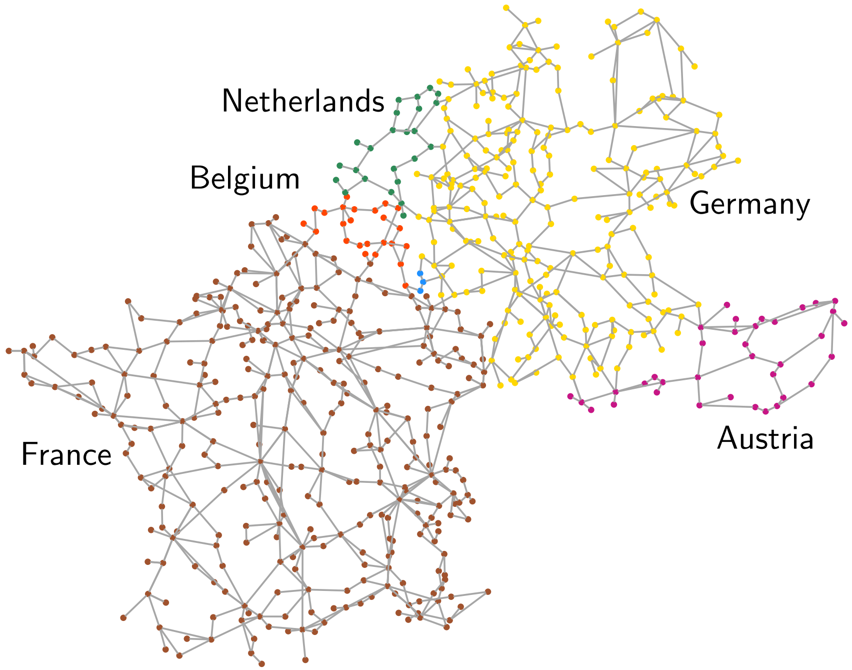
Simulation results for the Central Western European network

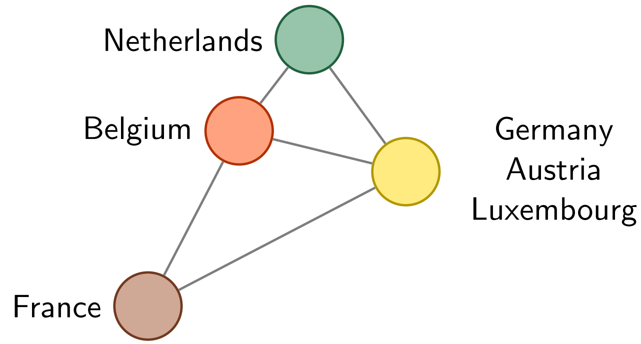
Two-settlement system



- Commitment refers to $\{0, 1\}$ (on-off) decisions $\rightarrow$ European rules for integer pricing
- N-1 security criterion for exports/imports $\rightarrow$ **cutting-plane algorithms**

Central Western European network





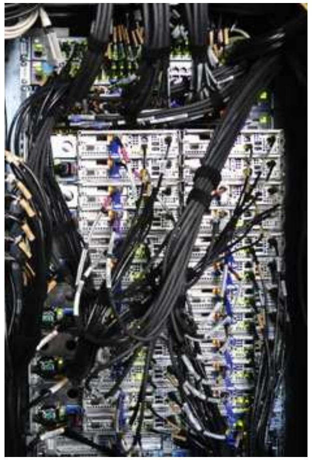
- 632 buses, 945 branches, 346 slow thermal generators (154GW), 301 fast thermal generators (89GW) and 1 312 renewable generators (149GW)
- 768 typical snapshots $\times$ 1 000 random uncertainty realizations $\rightarrow$ $\sim$88 years of operation

Implementation and deployment on HPC infrastructure

- Implementation in Julia/JuMP, using Cplex, Ipopt compiled with HSL and Xpress as mathematical programming solvers
- High-performance computing (HPC) deployment using Julia's built-in parallel computing capabilities
- Total simulation time: ~48 CPU-days

Lemaitre2

Consortium des Équipements de Calcul Intensif



Cab

Lawrence Livermore National Laboratory

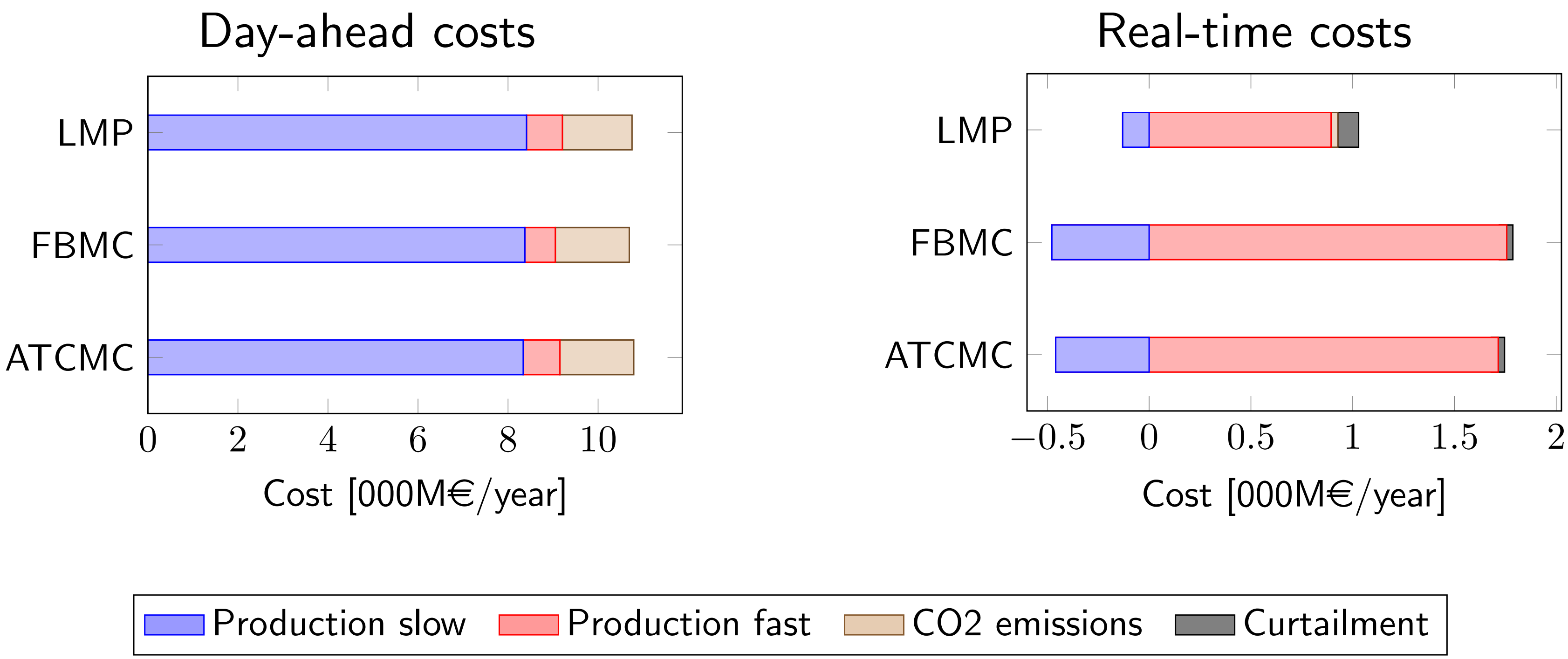
CWE results: total cost perfomance

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%

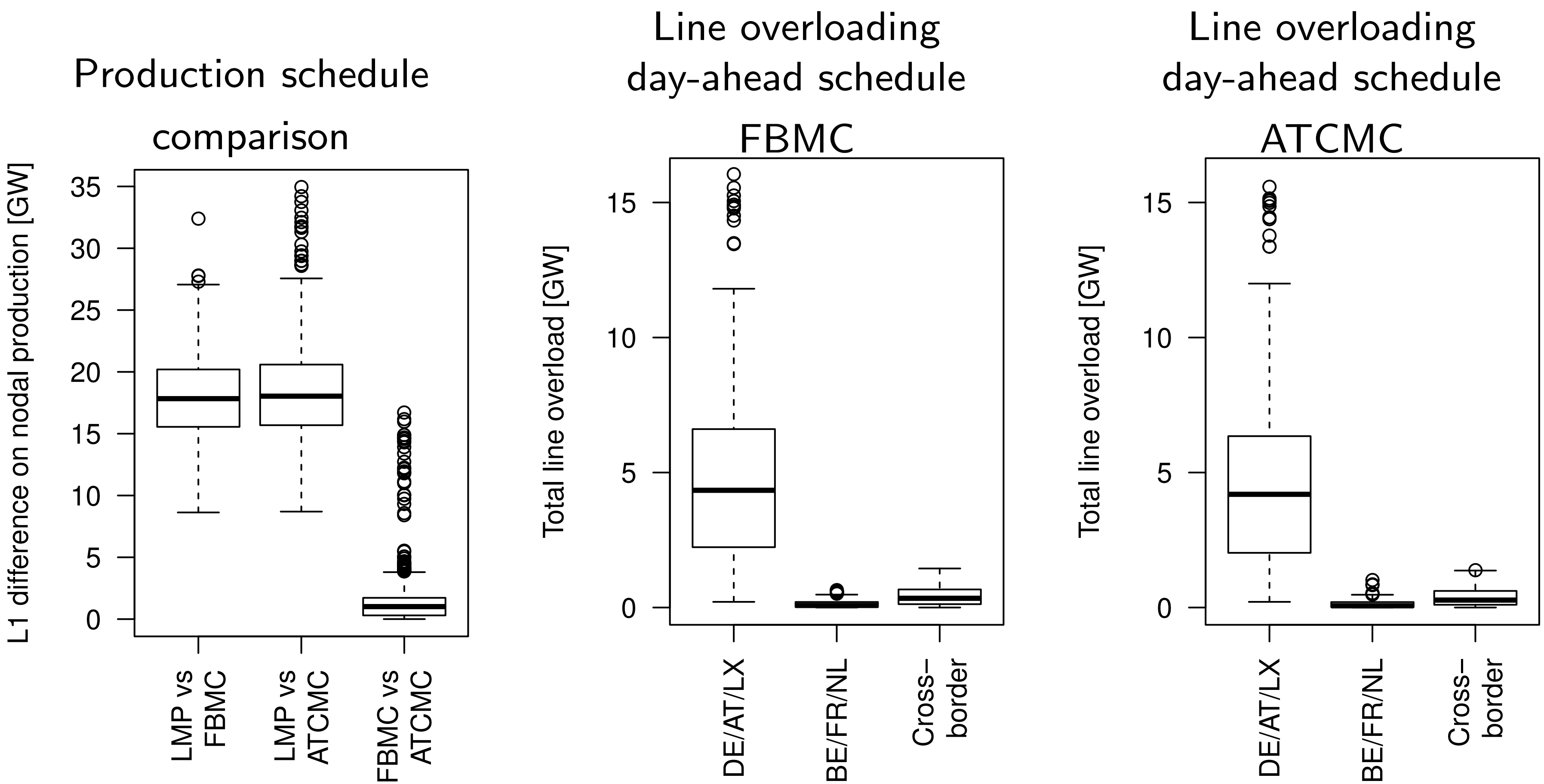
- PF: Perfect Foresight benchmark
- FBMC outperforms ATCMC by ∼**100M€/year in day ahead** (parallel run, Amprion *et al.* (2013), estimated 95M€/year) but only by ∼**60M€/year in total**
- Efficiency losses of zonal markets amount to about 6% of total costs, ∼**720M€/year**

CWE results: costs composition



- Day-ahead cost similar for all policies, cost differences concentrate on production costs of fast thermal generators in real time
- Zonal policies: re-dispatching slow (cheap) generators down and re-dispatching fast (expensive) generators up in real time

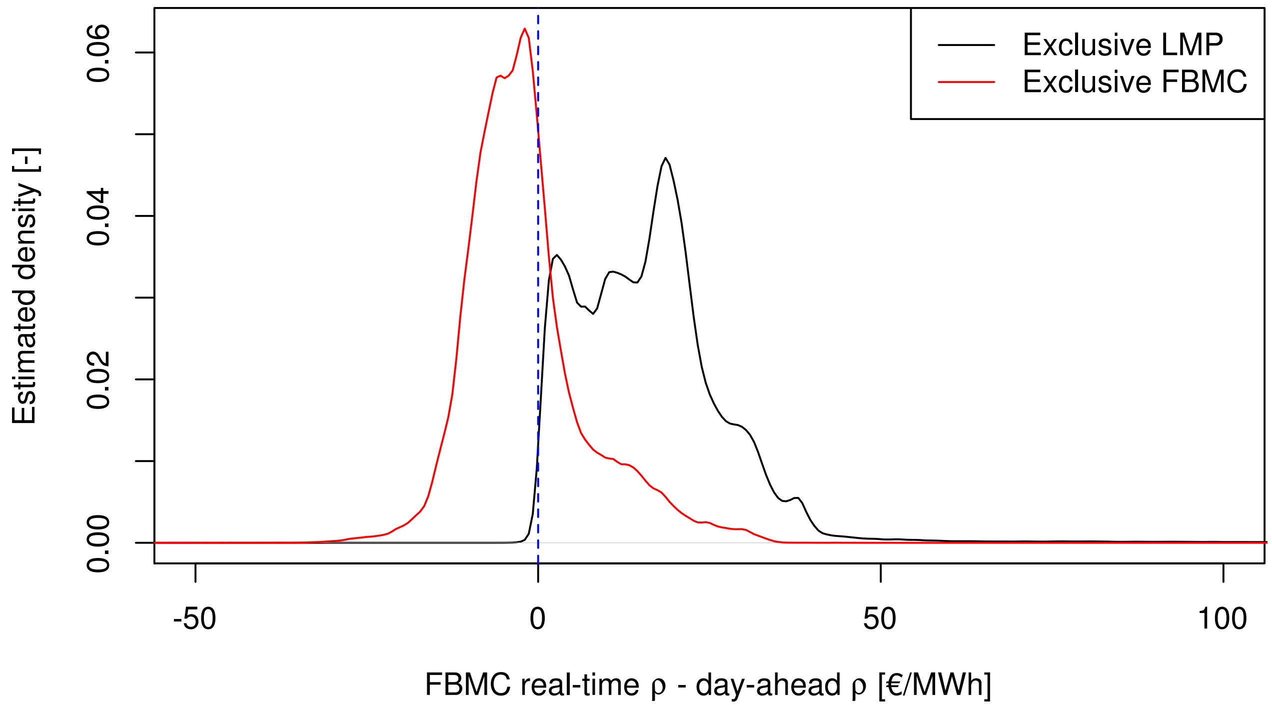
CWE results: production schedules and line overloading



- **Large differences** between day-ahead schedules of **nodal and zonal** policies, **small differences** between **FBMC and ATCMC**
- Zonal policies lead to decisions **overloading inter- and intra-zonal transmission lines**

CWE results: difference on commitment decisions

Price change in FBMC at nodes where $\text{UC}^{\text{FBMC}} \neq \text{UC}^{\text{LMP}}$



- "Exclusive LMP": weighted average change $\rho_n^{RT} - \rho_{z(n)}^{DA}$ over all nodes where LMP committed slow units and FBMC did not commit units. "Exclusive FBMC" series computed analogously.
- LMP commits capacity where it is needed. FBMC suffers from suboptimal commitment.

Conclusions

Conclusions

- New framework for modeling zonal electricity markets:
  - Projecting network constraints onto space of exports/imports
  - Free from discretionary parameters (base case, flow approximation)
- ATCMC and FBMC fail at allocating inter- and intra-zonal transmission capacity
- CWE: **FBMC outperforms ATCMC** by ∼100M€/year on day ahead, but only by ∼**60M€/year** in total
- CWE: **Nodal design outperforms FBMC and ATCMC** by ∼**720M€/year**

Future extensions

- Application of the developed framework to answer policy questions in European electricity markets via simulation
- Extensions of the proposed framework:
  - Pricing AC power flow constraints implicitly on active power
  - TSO-DSO coordination

Thank you

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