
Transmission capacity allocation in zonal electricity markets

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Outline

1. Introduction
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

Day-ahead electricity
market models

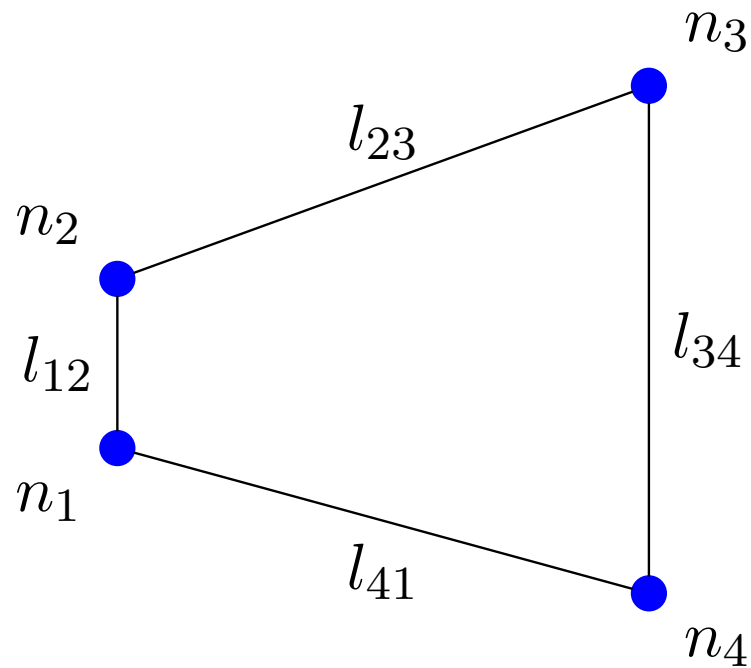
Policy analysis using
4-node, 3-zone
network

Simulation results for
the Central Western
European network

Conclusions

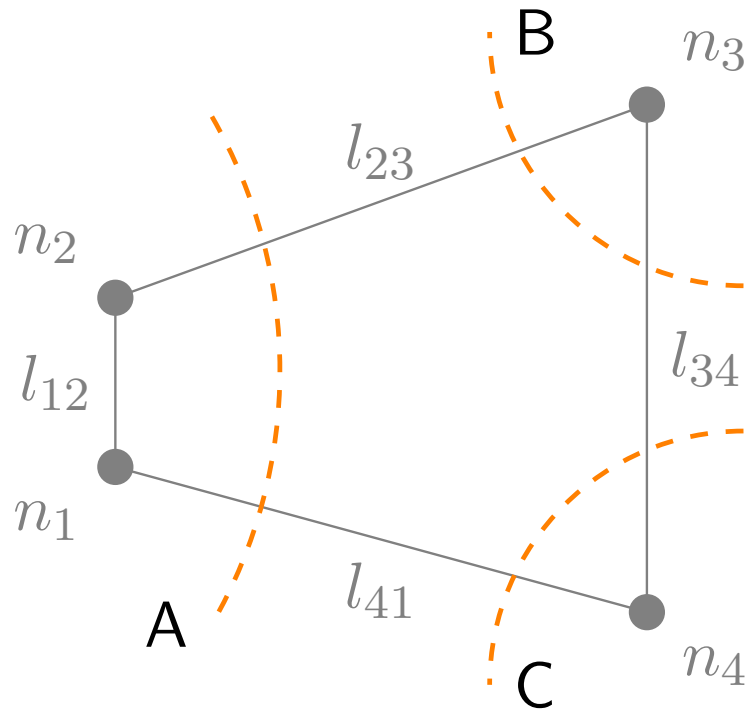
Introduction

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**

Introduction

Day-ahead
electricity market
▷ models

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Day-ahead electricity market models

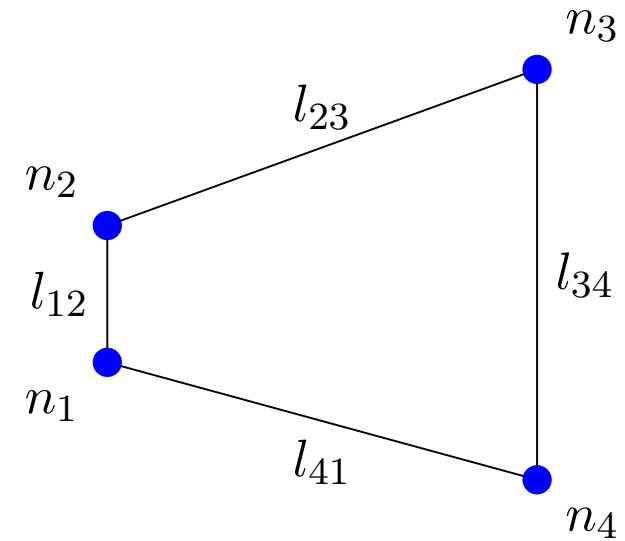
Assumptions

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

min production cost
bids,
flows

s.t. fractional bids
net production =
outgoing flows, at each node
line thermal limits
DC power flow equations



Nodal electricity market

$$\min_{v, f, \theta} \sum_{g \in G} P_g Q_g v_g$$

$$\text{s.t. } 0 \leq v_g \leq 1 \quad \forall g \in G$$

$$\sum_{g \in G(n)} Q_g v_g - Q_n =$$

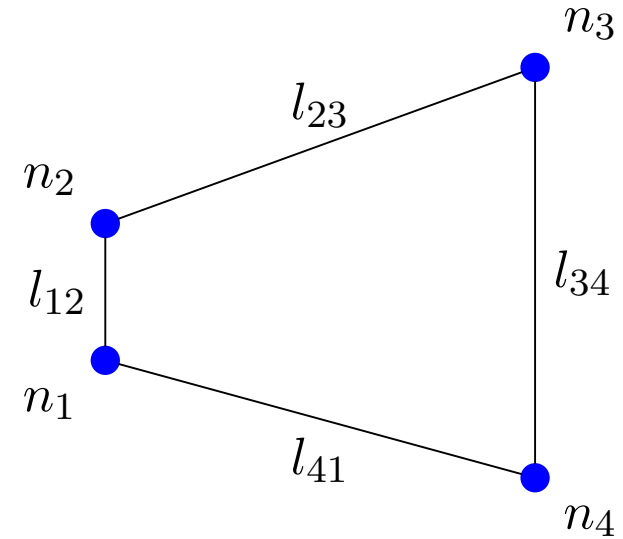
$$\sum_{l \in L(n, \cdot)} f_l - \sum_{l \in L(\cdot, n)} f_l \quad \forall n \in N \quad [\rho_n]$$

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

$$f_l = B_l (\theta_{m(l)} - \theta_{n(l)}) \quad \forall l \in L$$

P, Q : price and quantity

F_l, B_l : capacity and susceptance line l



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

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

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

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

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

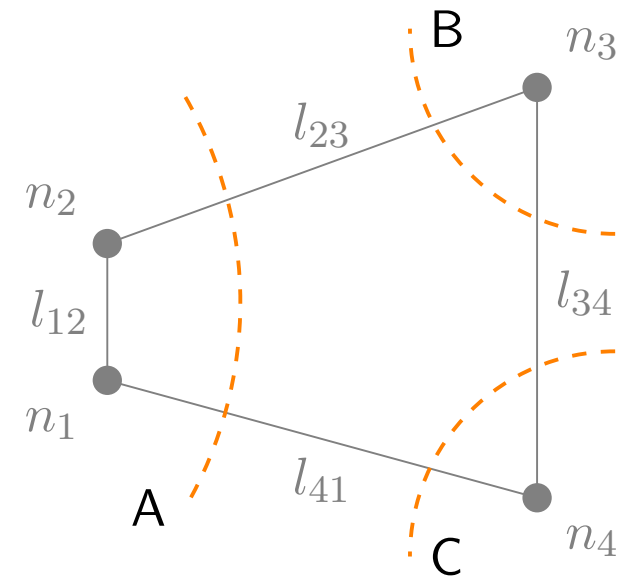
Zonal electricity market

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

p_z : net position of zone z

\mathcal{P} : set of allowed net positions

\mathcal{P} varies from policy to policy



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

$$G(A) = \{1, 2\}, \dots$$

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

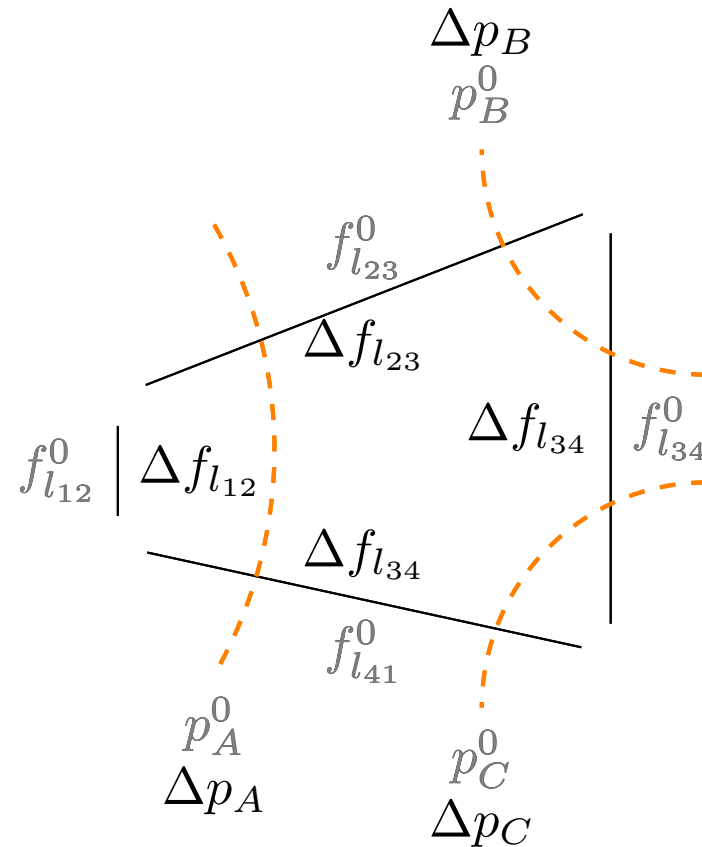
$$N(A) = \{n_1, n_2\}, \dots$$

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

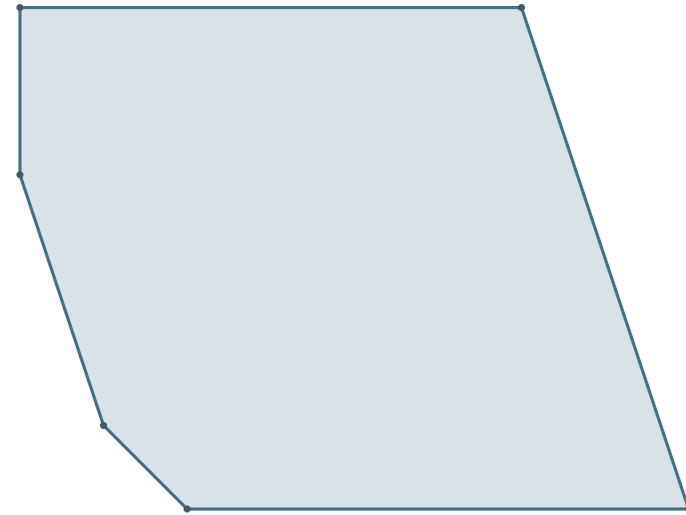
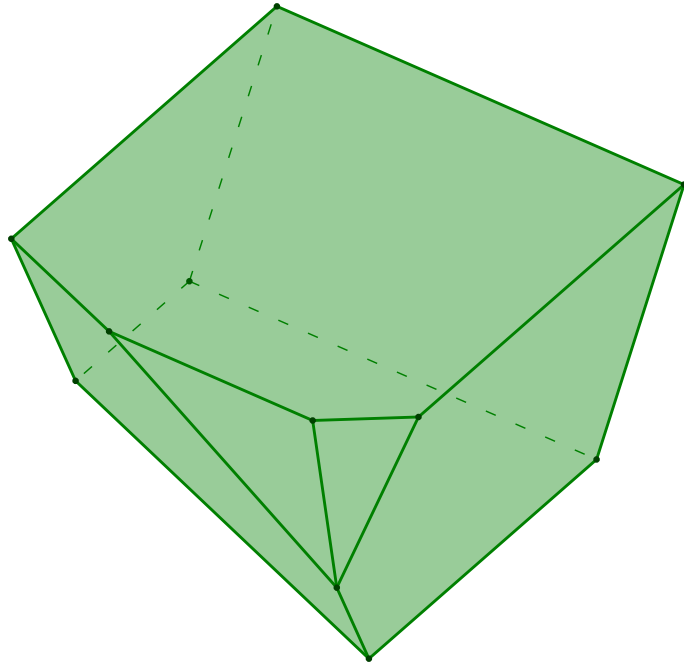


$$\mathcal{P}^{FB-A} := \left\{ p \in \mathbb{R}^{|Z|} \mid -F_l \leq \sum_{z \in Z} PTDF_{l,z} (p_z - p_z^0) + f_l^0 \leq F_l \quad \forall l \in L \right\}$$

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

space of nodal injections

→ space of zonal net positions



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

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

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

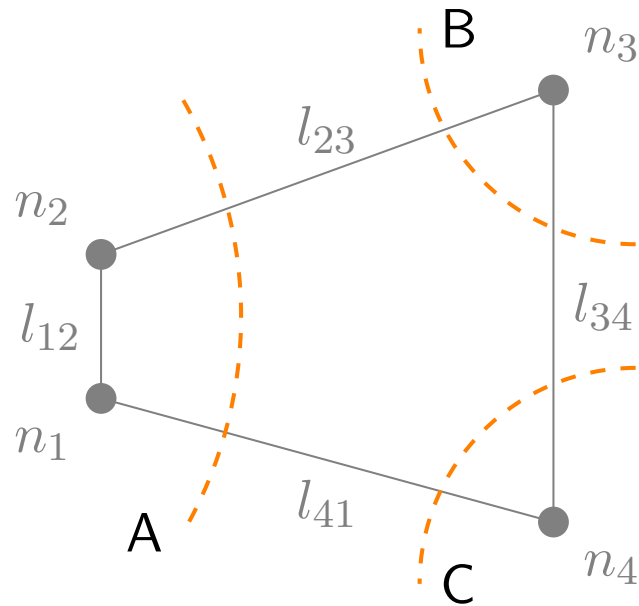
Flow-Based Market Coupling with Exact Projection (FBMC-EP)

$$\mathcal{P}^{FB-EP} = \left\{ p \in \mathbb{R}^{|Z|} \left| \begin{array}{l} \exists (\bar{v}, f, \theta) \in [0, 1]^{|G|} \times \mathbb{R}^{|L|} \times \mathbb{R}^{|N|} : \\ \sum_{g \in G(z)} Q_g \bar{v}_g - p_z = \sum_{n \in N(z)} Q_n \quad \forall z \in Z, \\ \sum_{g \in G(n)} Q_g \bar{v}_g - \sum_{l \in L(n, \cdot)} f_l + \sum_{l \in L(\cdot, n)} f_l = Q_n \quad \forall n \in N, \\ -F_l \leq f_l \leq F_l, \quad f_l = B_l (\theta_{m(l)} - \theta_{n(l)}) \quad \forall l \in L \end{array} \right. \right\}$$

- \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

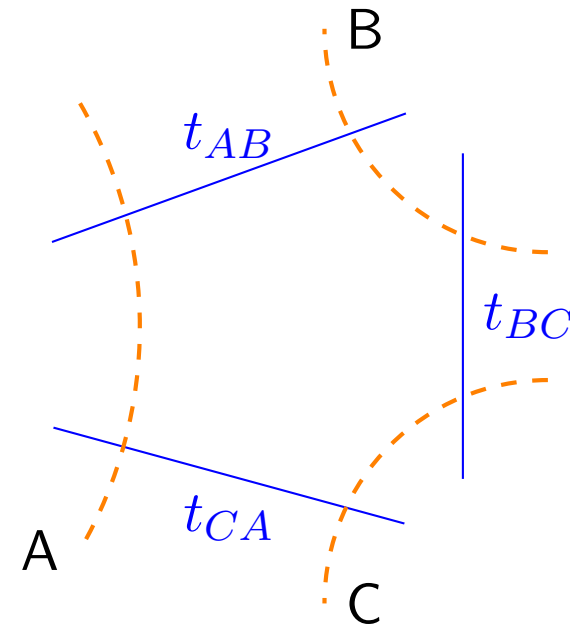
Available-Transfer-Capacity Market Coupling (ATCMC)

net positions of zones Z



→

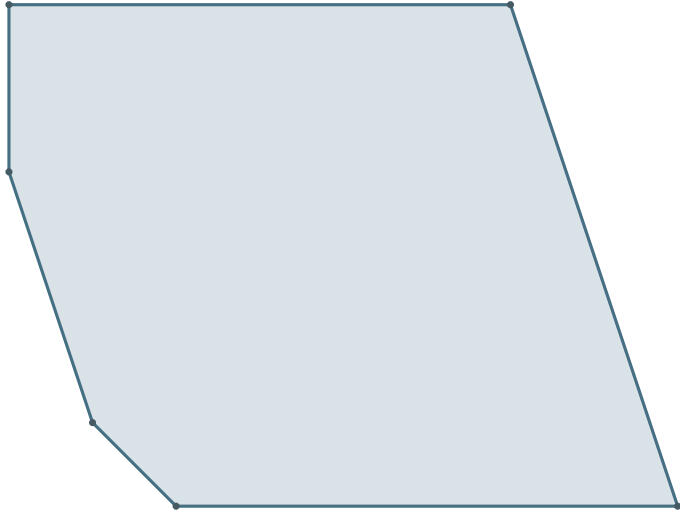
flow on interconnectors
between zones T



- 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?

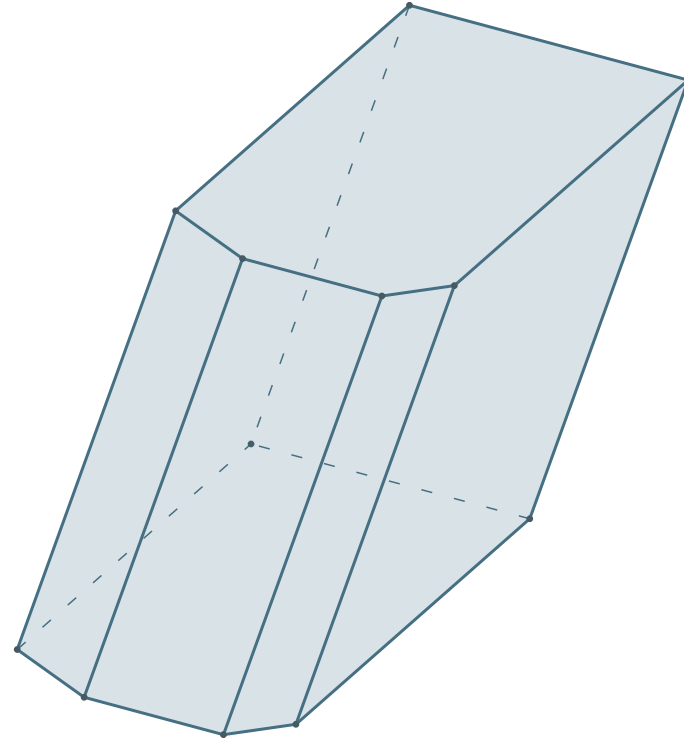
Available-Transfer-Capacity Market Coupling (ATCMC)

space of zonal net positions



\mathcal{P}^{FB-EP}

space of exchanges



$$\mathcal{E} := \left\{ e \in \mathbb{R}^{|T|} \mid - \sum_{l \in L(t)} F_l \leq e_t \leq \sum_{l \in L(t)} F_l \quad \forall t \in T, \right.$$

$$\left. \exists p \in \mathcal{P} : p_z = \sum_{t \in T(z, \cdot)} e_t - \sum_{t \in T(\cdot, z)} e_t \quad \forall z \in Z \right\}$$

Maximum-volume Available-Transfer-Capacities (ATCs)

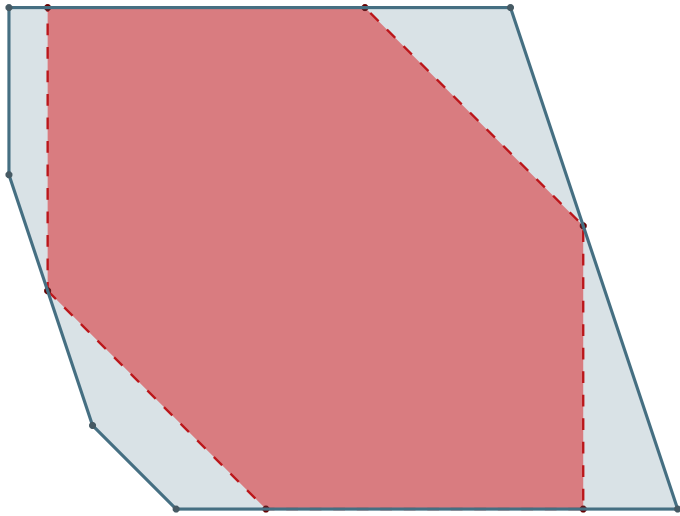
- ATC limits, $ATC_t^- \leq e_t \leq ATC_t^+ \quad \forall t \in T$, are a box in the space of exchanges
- Compute ATCs as a maximum volume box inside \mathcal{E} ,

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

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

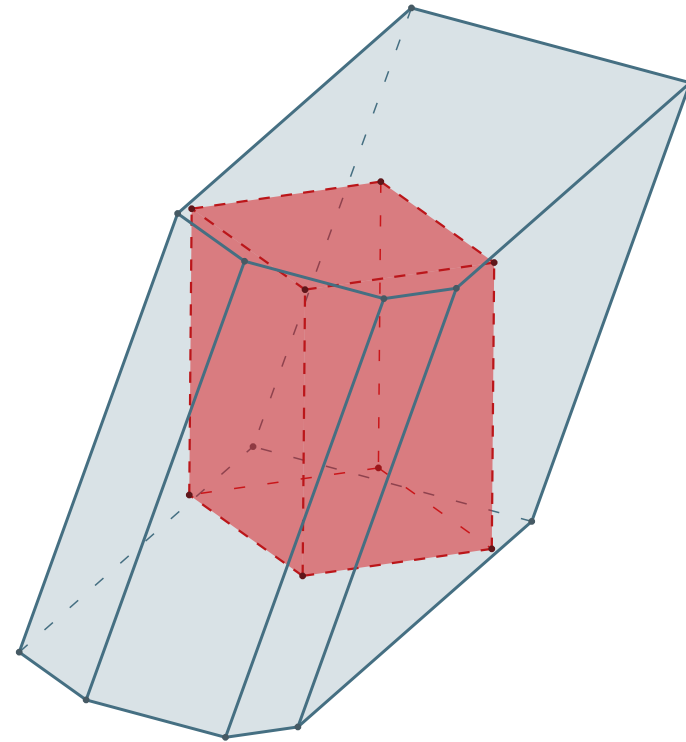
Maximum-volume Available-Transfer-Capacities (ATCs)

space of zonal net positions



\mathcal{P}

space of exchanges



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

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

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

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Day-ahead electricity
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Policy analysis
using 4-node,
▷ 3-zone network

Simulation results for
the Central Western
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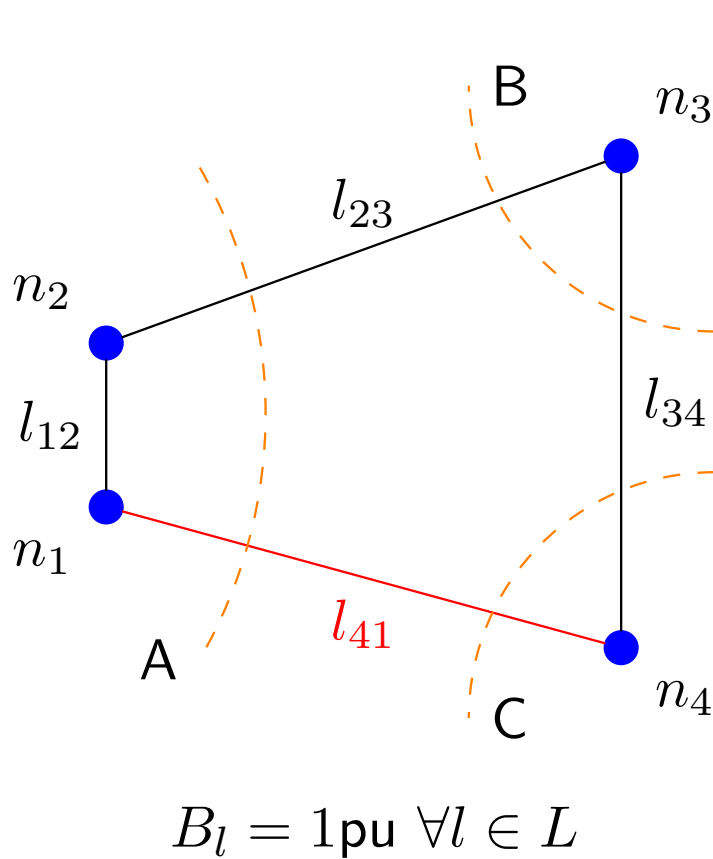
Conclusions

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



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

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

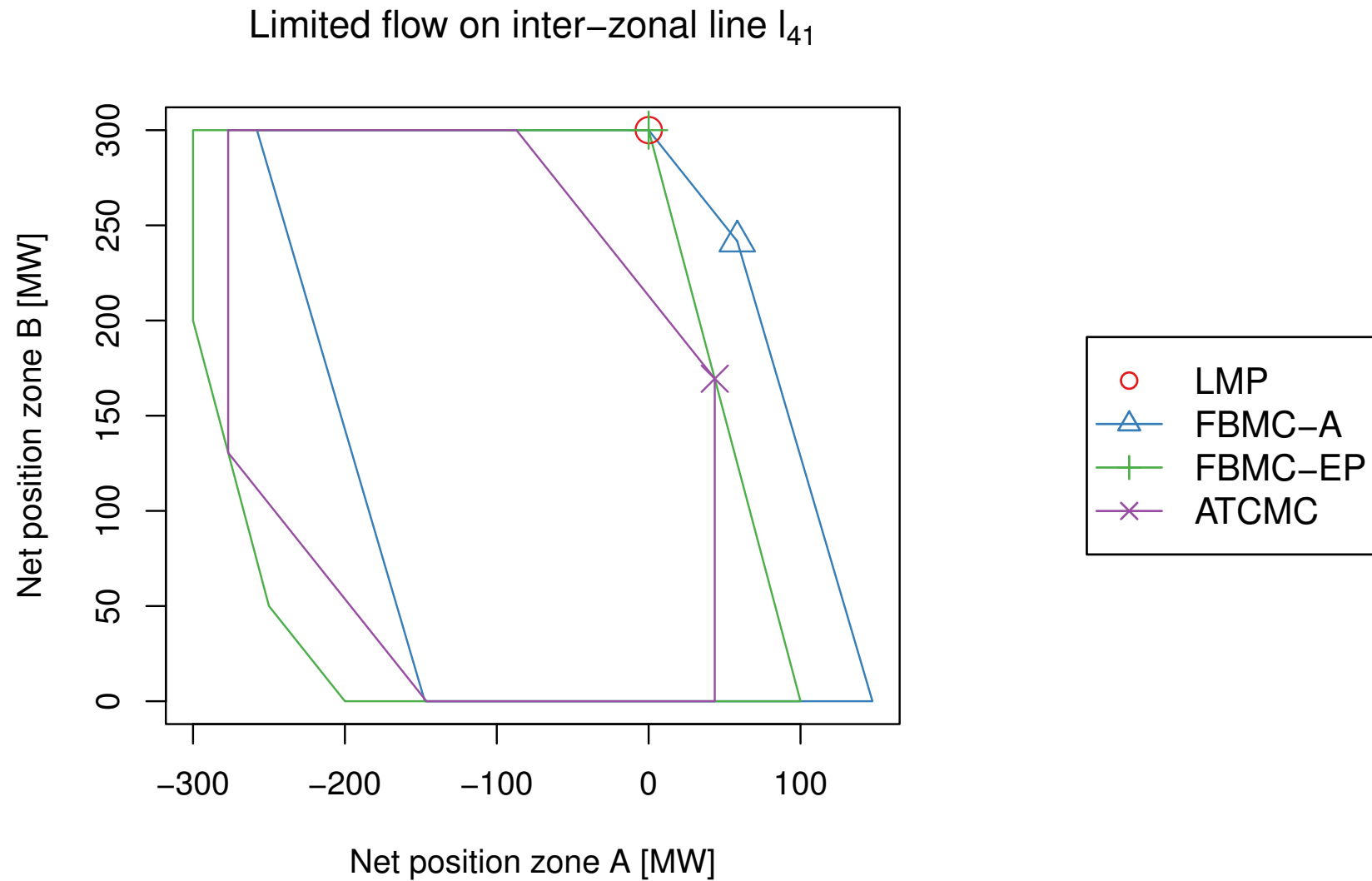
Inter-zonal congestion: results

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

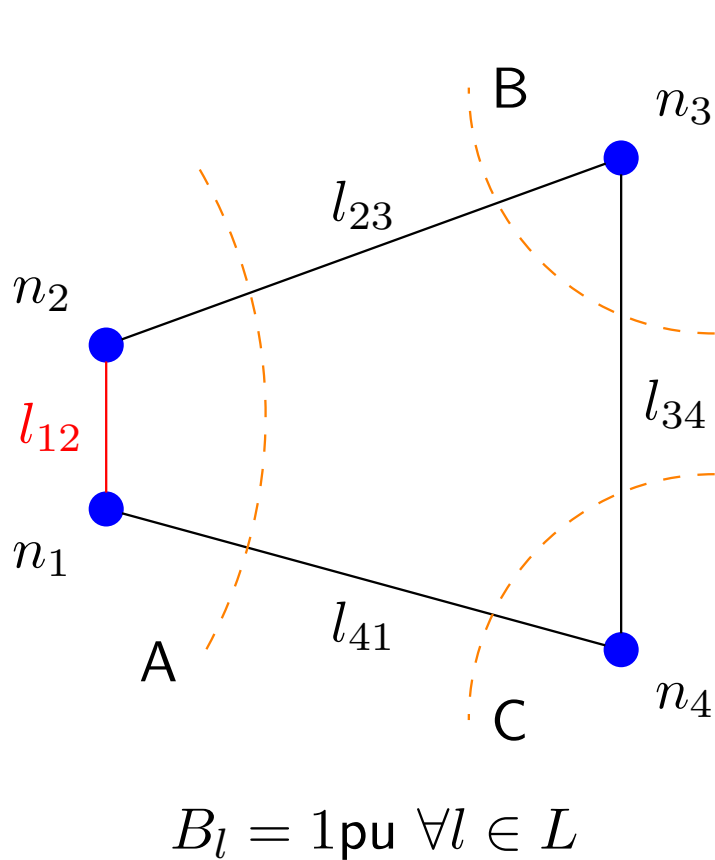
Policy	Total cost [\$]	ρ [\$/MWh]		Abs. error flow approx. [MW]	Overload l_{41} [MW]
		Min.	Max.		
LMP	15 200	8	119	0	0
FBMC-A	7 217	8	200	475	79
FBMC-EP	7 800	8	23	300	50
ATCMC	23 208	8	200	—	50

- 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



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

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

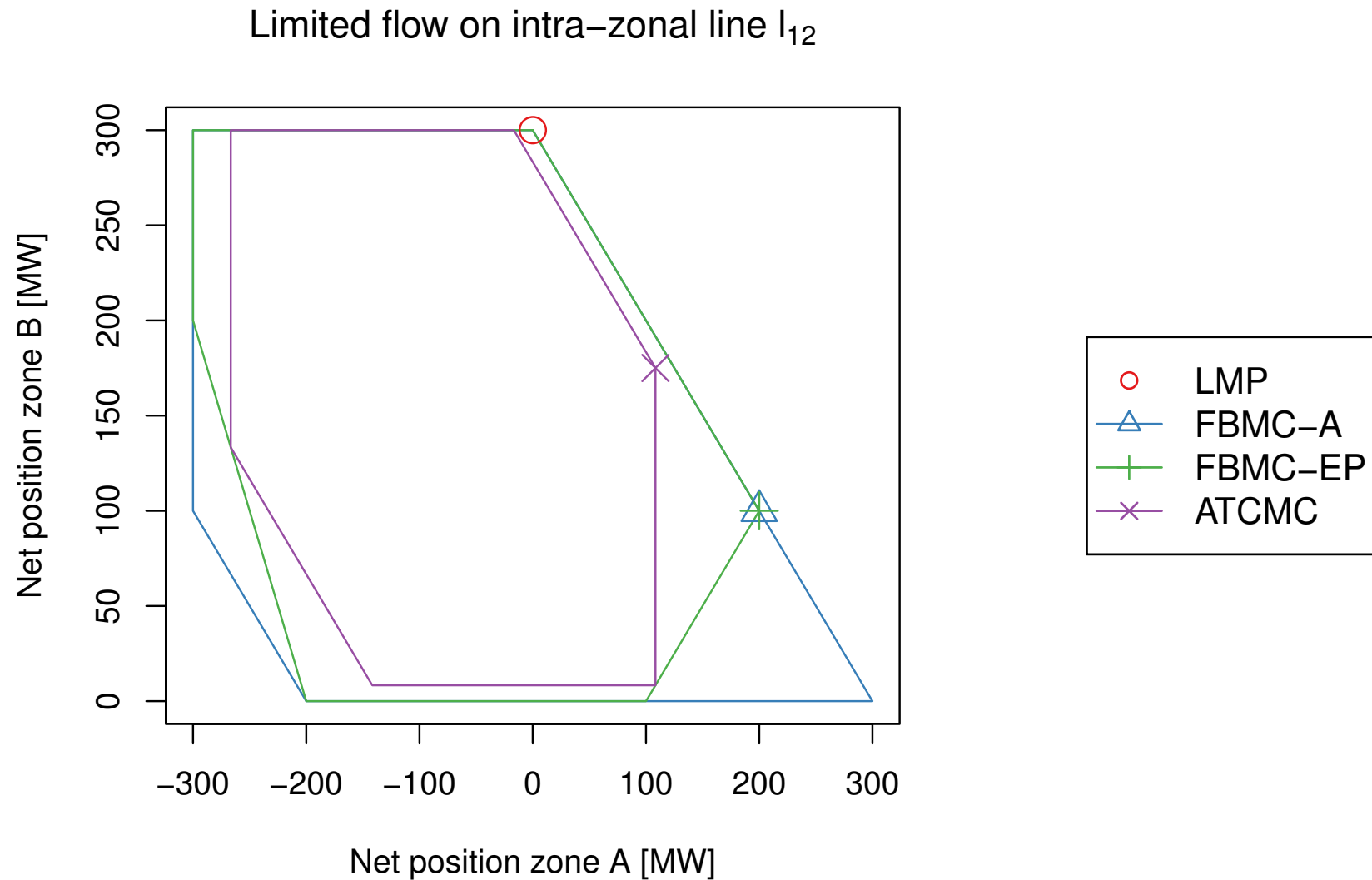
Intra-zonal congestion: results

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

Policy	Total cost [\$]	ρ [\$/MWh]		Abs. error flow approx. [MW]	Overload l_{12} [MW]
		Min.	Max.		
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

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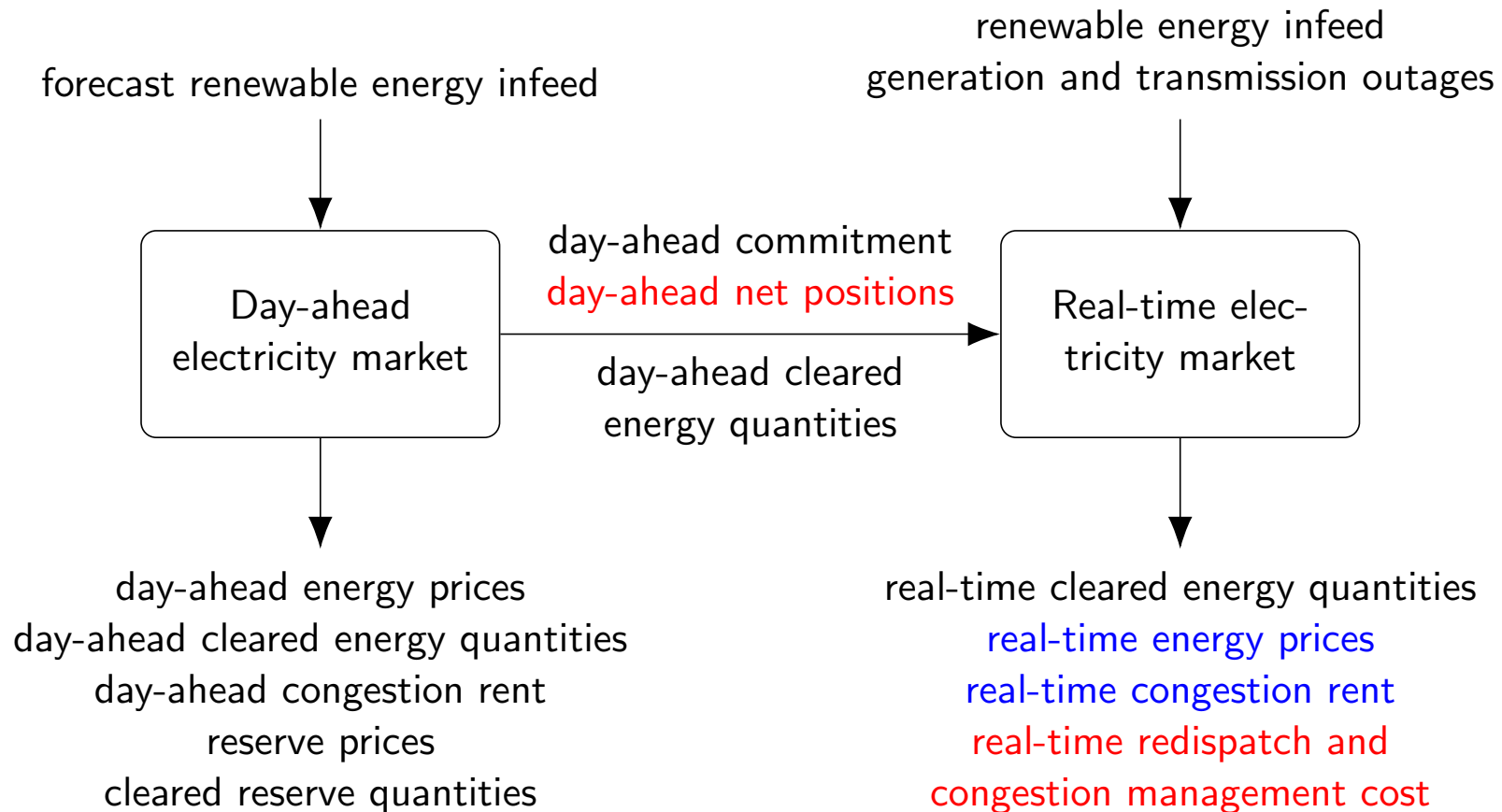
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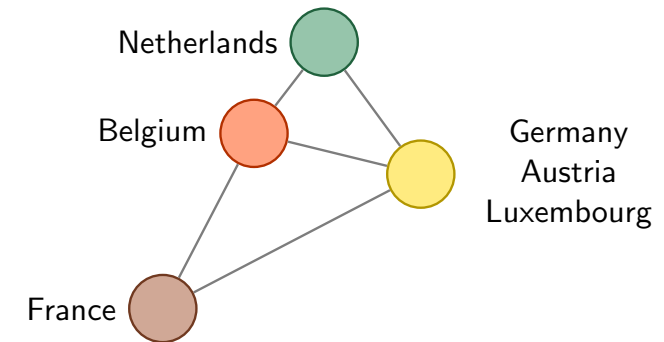
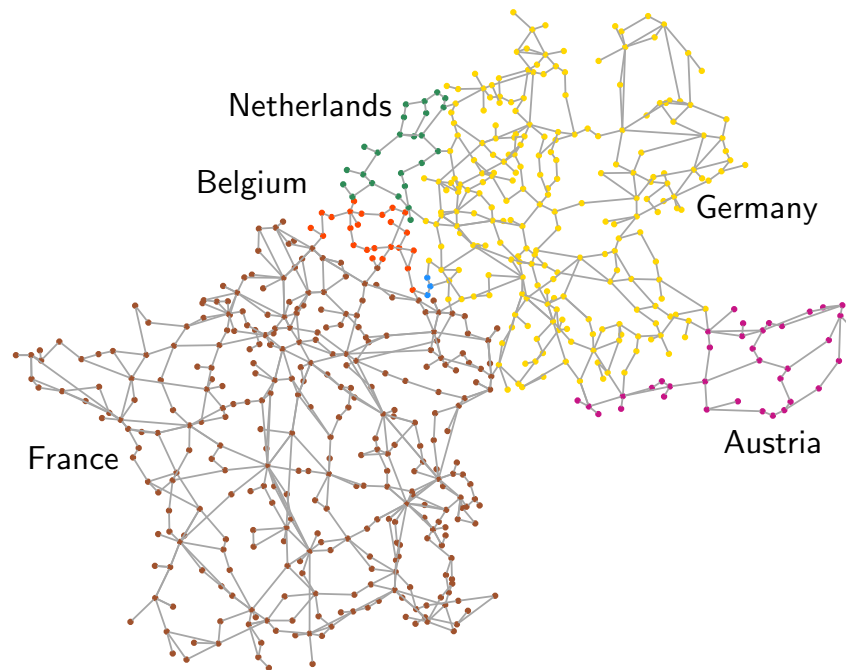
Simulation results for the Central Western European network

Two-settlement system



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



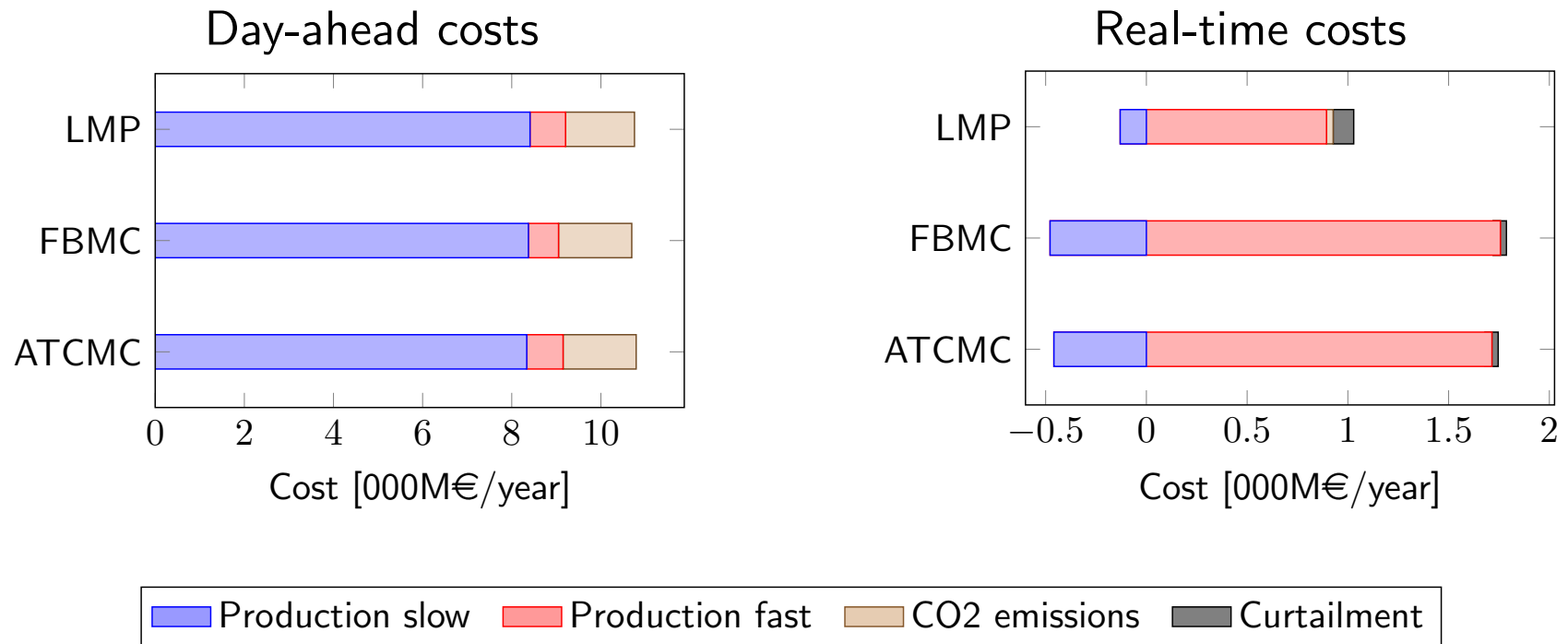
CWE results: total cost performance

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%

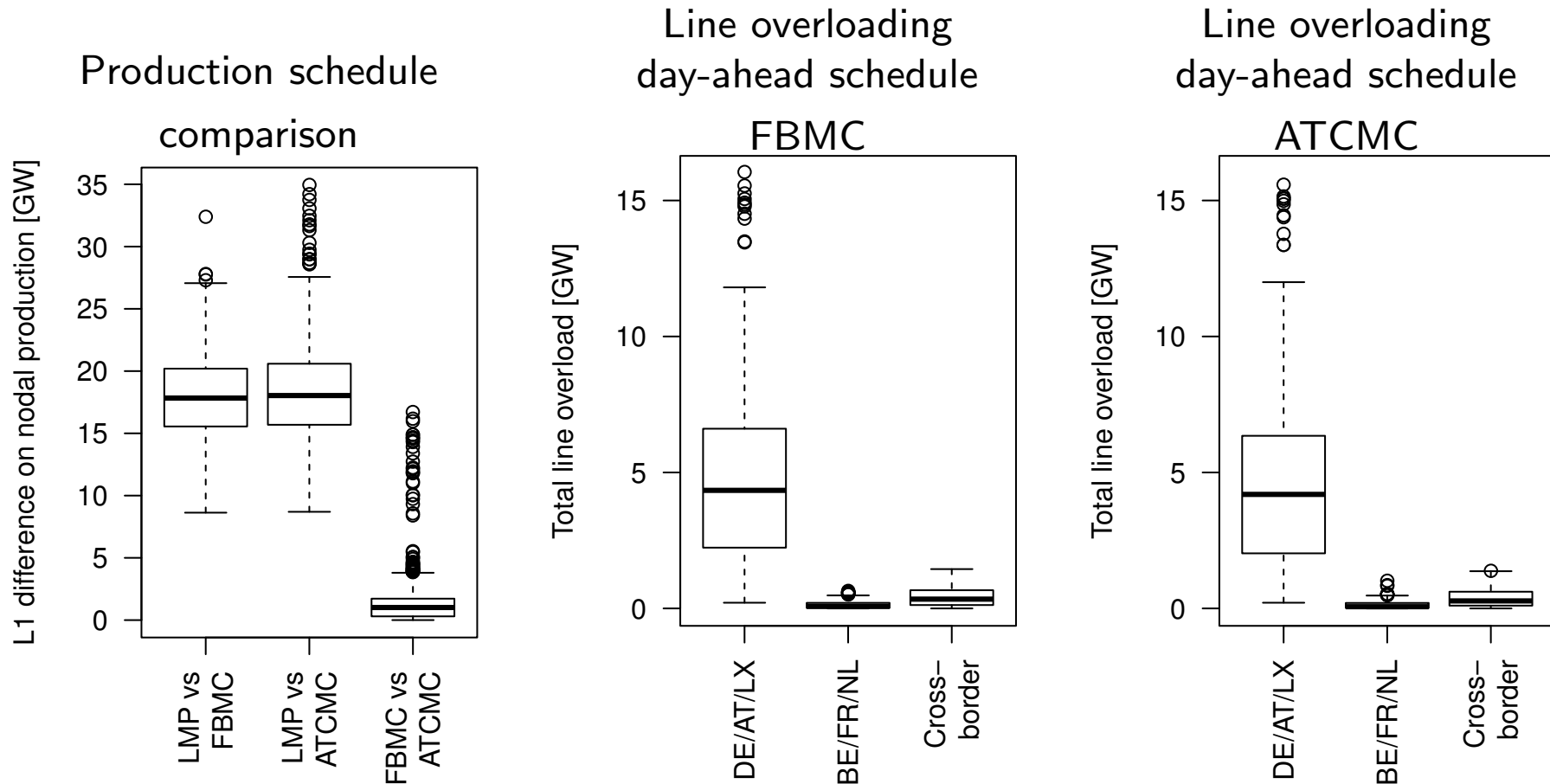
- PF: Perfect Foresight benchmark
- FBMC outperforms ATCMC by **~100M€/year in day ahead** (parallel run, *Amprion et al. (2013)*, estimated 95M€/year) but only by **~60M€/year in total**
- Efficiency losses of zonal markets amount to about 6% of total costs, **~720M€/year**

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

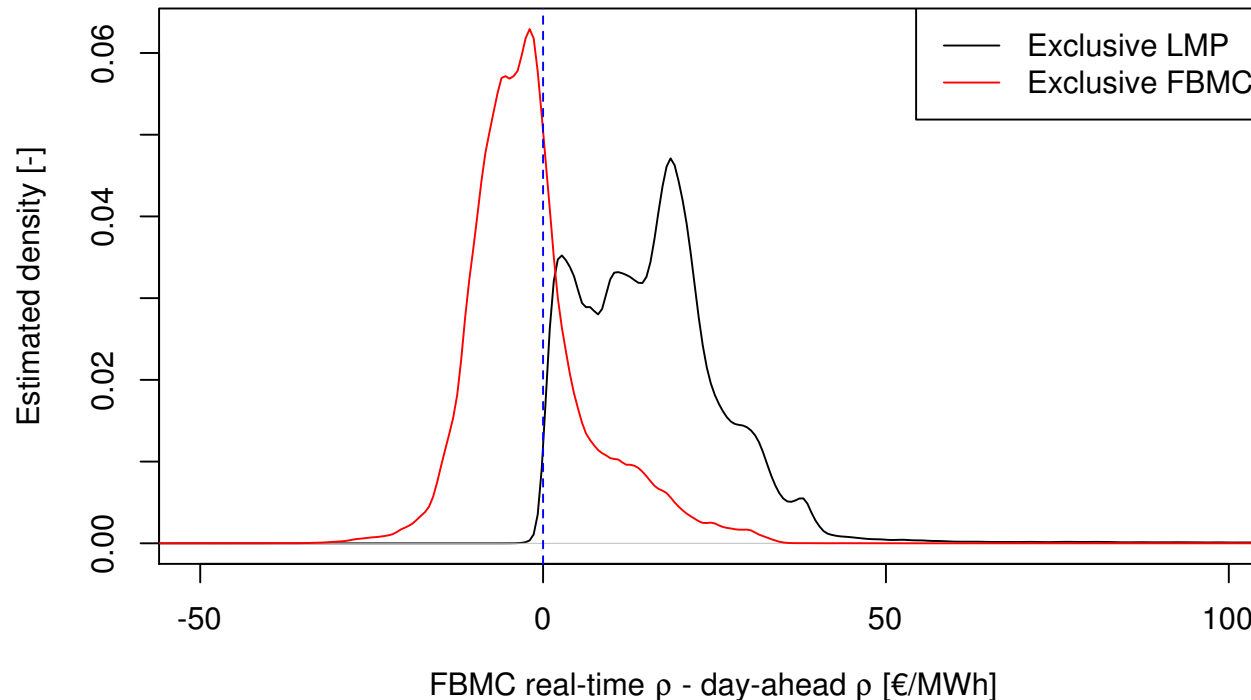
CWE results: production schedules and line overloading



- 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 $UC^{FBMC} \neq UC^{LMP}$



- “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.

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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 $\sim 100\text{M€}/\text{year}$ on day ahead, but only by $\sim 60\text{M€}/\text{year}$ in total
- CWE: **Nodal design outperforms FBMC and ATCMC** by $\sim 720\text{M€}/\text{year}$

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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