Flow-Based Market Coupling in the European Electricity Market

Endre Bjørndal
Mette Bjørndal
Hong Cai

NHH Norwegian School of Economics
Department of Business and Management Science

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Background and outline

- European market integration
  - Target model
    - Energy only regional markets
    - Market coupling between regional markets
- Locational pricing variants
  - Nodal pricing - Benchmark
  - Zonal pricing – Available Transfer Capacity (ATC) model
  - Zonal pricing – Flow-based Market Coupling (FBMC) model
- Examples
- Conclusions

Europe 2007

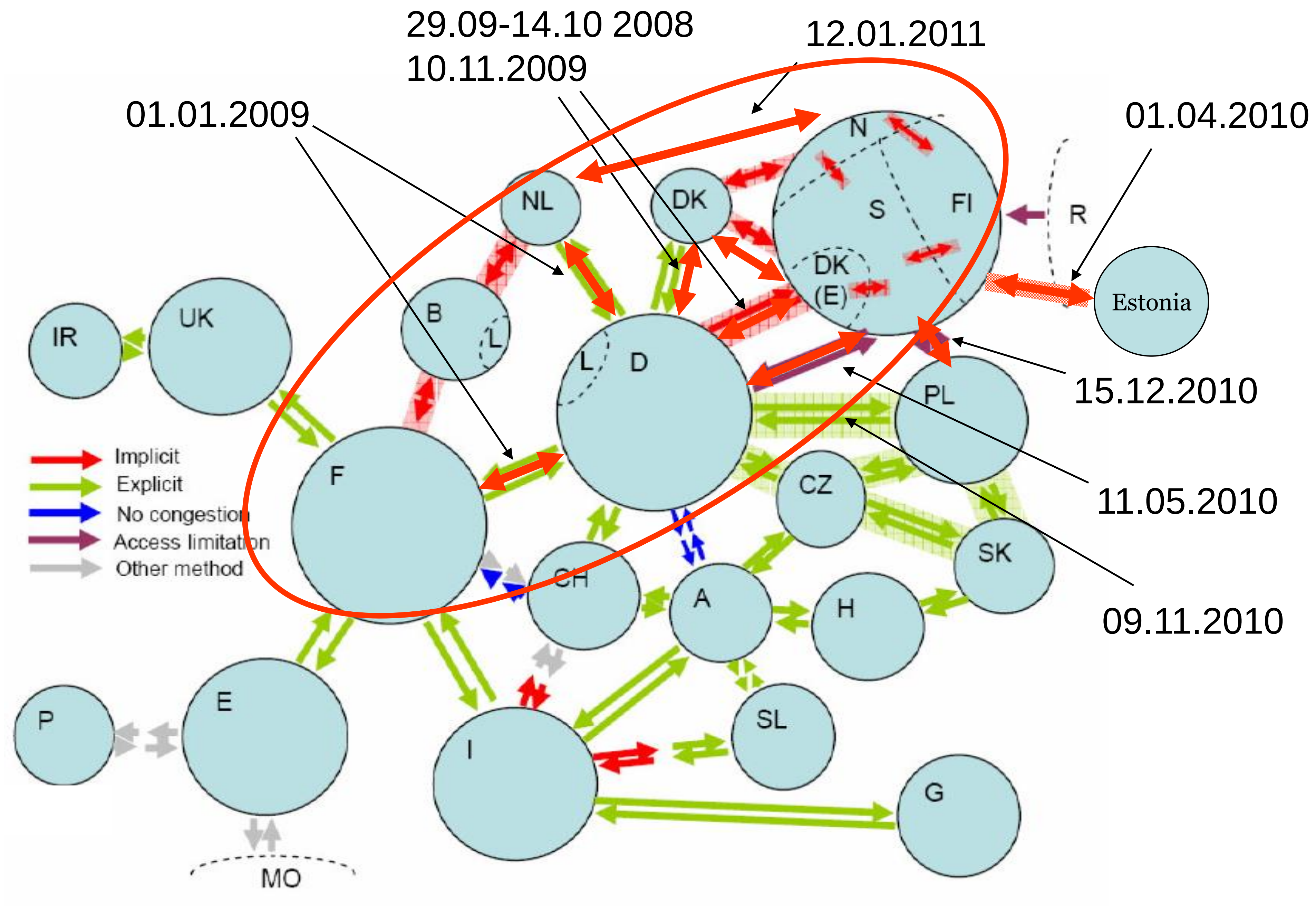


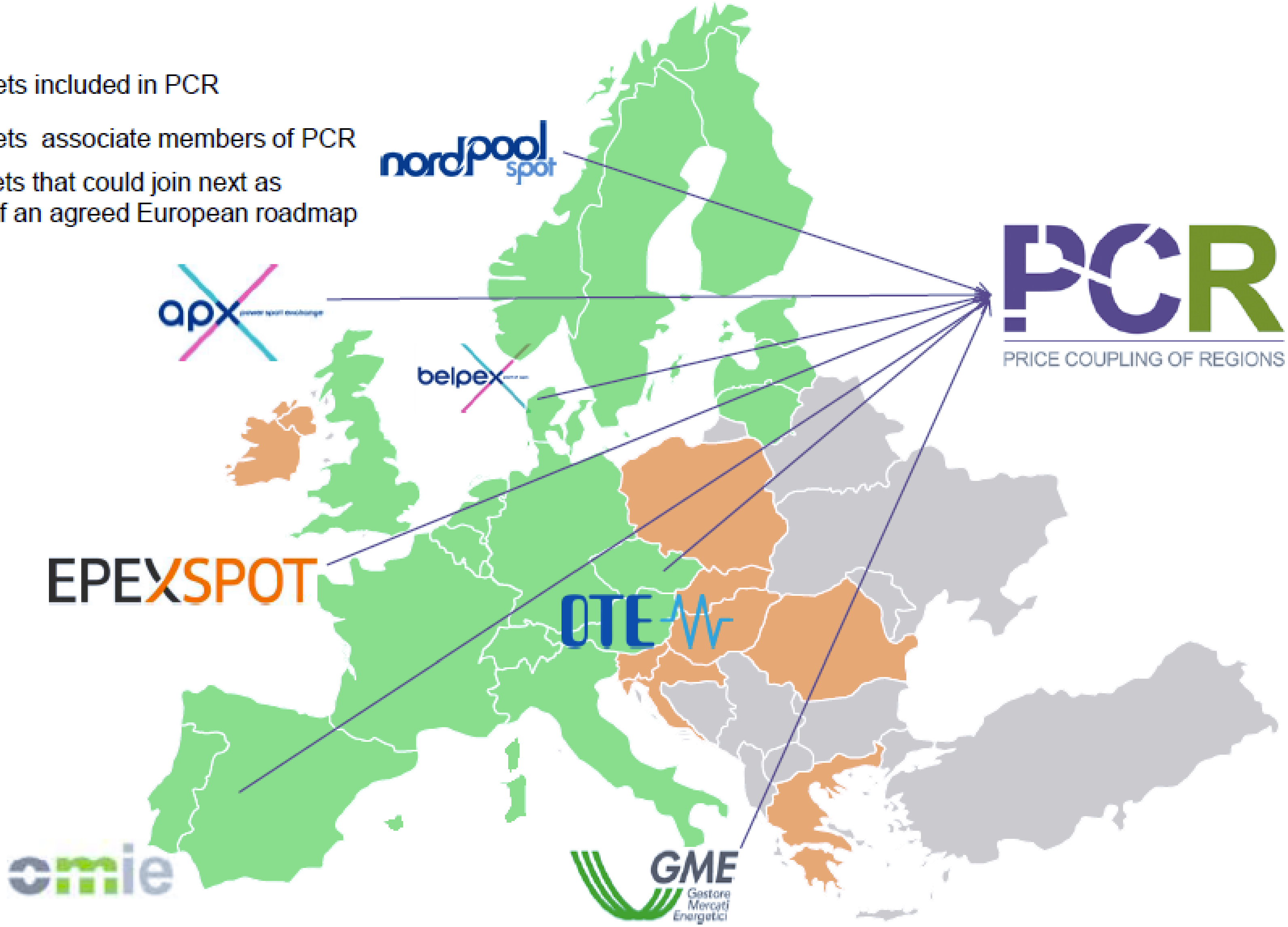
Figure 4.1 – Day-ahead transmission capacity allocations across Europe (updated June 2007)

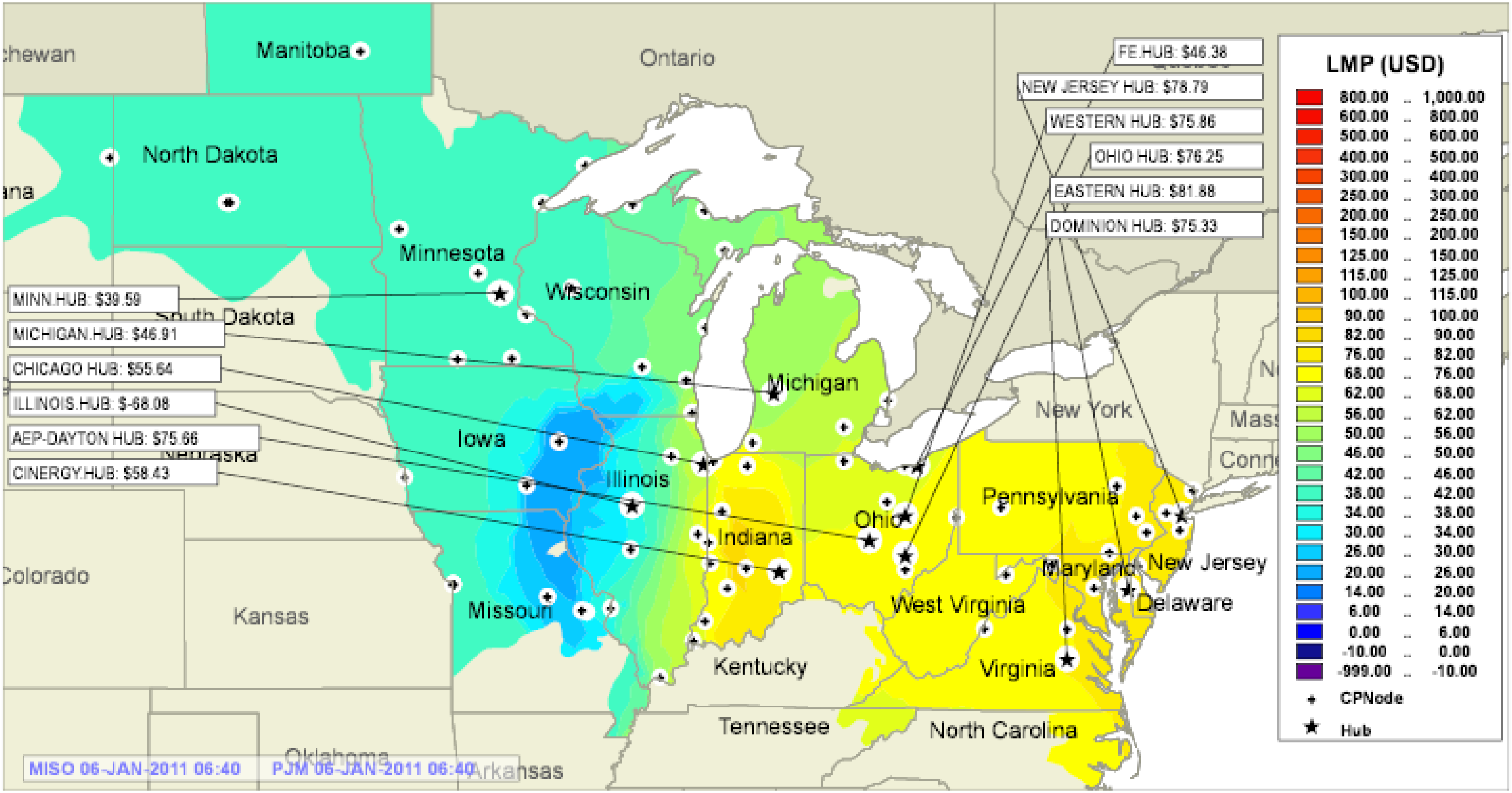
Towards the Single European Market: Next Steps

Markets included in PCR

Markets associate members of PCR

Markets that could join next as part of an agreed European roadmap





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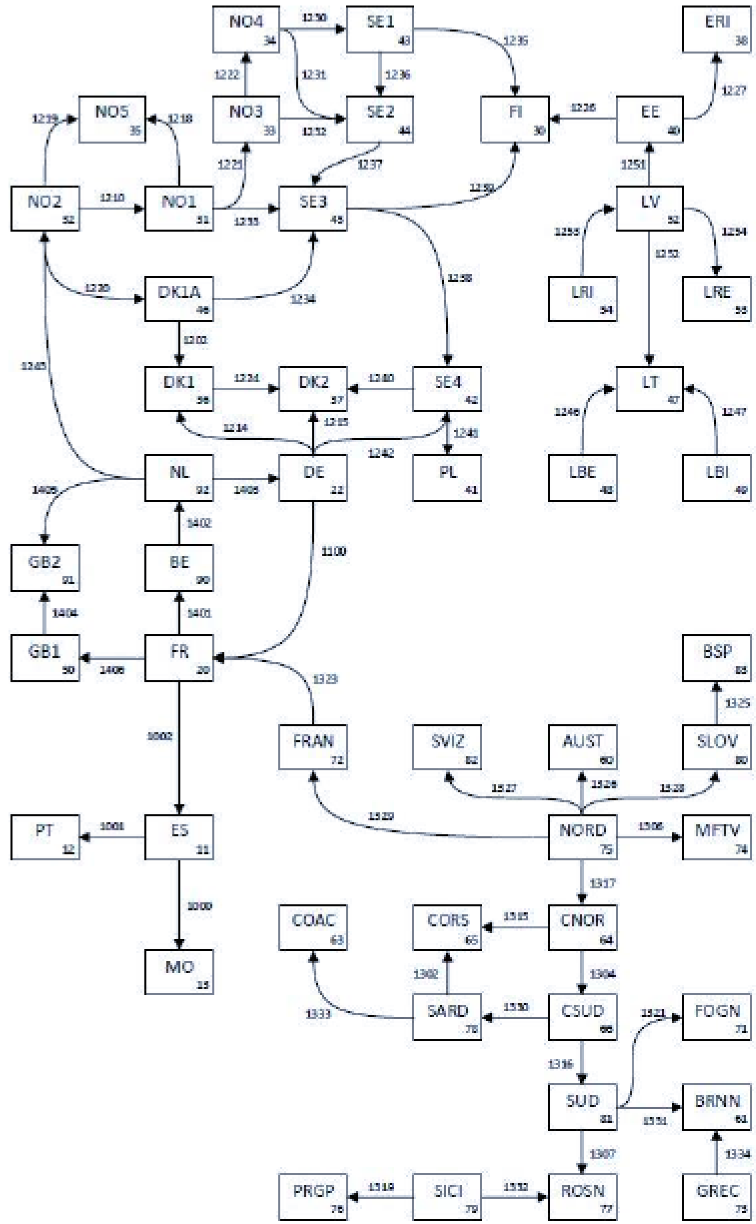
Midwest ISO Market data is based on Eastern Standard Time (EST) while PJM Market data is based on Eastern Prevailing Time.

PJM – 51 mill people/max load 145 000 MW/730 TWh/650 members/8700 nodes

MARKET DATA

- Each PX (Market) operates several bidding areas
- All bidding areas are matched at the same time
- A different price can be obtained for each bidding area
- The price for the bidding area must respect maximum and minimum price market boundaries



NETWORK DATA AND BALANCE CONSTRAINTS

The energy balance concept is defined as: The global supply minus the losses must be equal to the global demand of all markets involved. Depending on the manner the interconnections are modeled, there are the following:

- ***ATC network model:*** The network is described as a set of lines interconnecting bidding areas. The nomination of the line can be made up to its Available Transfer Capacity (ATC)

- ***Flow-based network model:*** Also known as PTDF model, with all bidding areas connected in a meshed network. It expresses the constraints arising from Kirchhoff's laws and physical elements of the network in the different contingency scenarios considered by the TSOs. It translates into linear constraints on the net positions of the different bidding areas

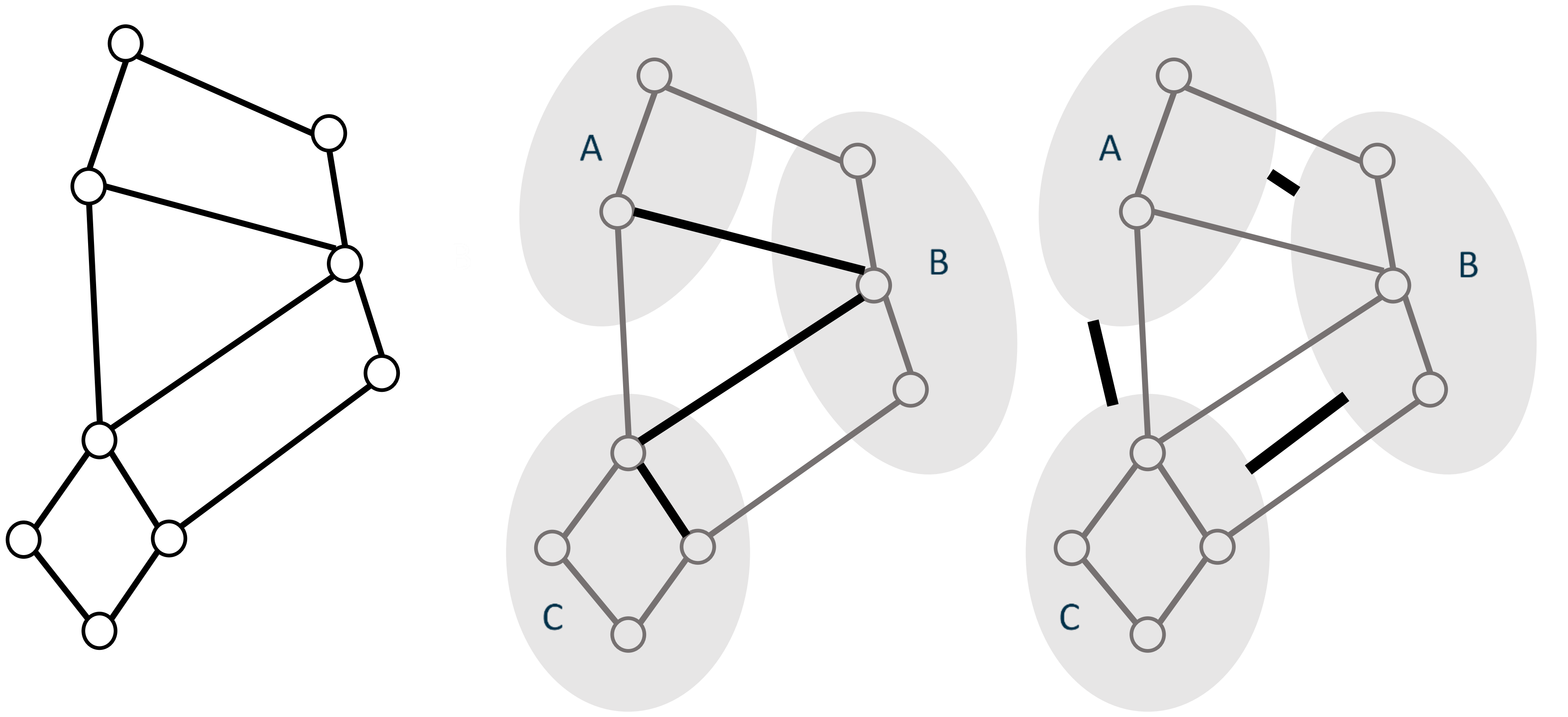
- ***Hybrid network model:*** Some bidding areas are connected using the Flow-based network model; the remaining using the ATC network model

PRICE COUPLING OF REGIONS

Literature – Flow-based market coupling

- Amprion et al. (2011, 2013, 2014)
- Aguado et al. (2012)
- de Maere d'Aertrycke and Smeers (2013)
- Marien et al. (2013)
- Boury (2015)
- Van den Bergh et al. (2016)
- Nordeng (2016)
- …

Locational pricing variants



Nodal FB model

Zonal FB model

ATC model

Nodal pricing

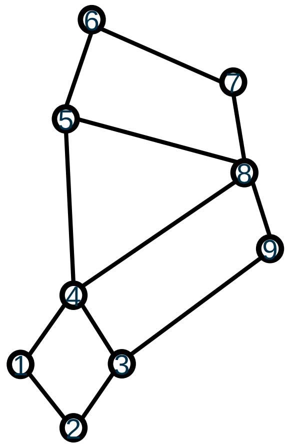
$$\max_{Q^d,Q^s,FL,\theta} \quad \sum_{i\in N}\left[\int_0^{Q_i^d} P_i^d(Q)dQ - \int_0^{Q_i^s} P_i^s(Q)dQ\right]$$

s.t. $$Q_i^s - Q_i^d = \sum_{j:(i,j)\in L} FL_{ij} - \sum_{j:(j,i)\in L} FL_{ji} \qquad i\in N$$

$$FL_{ij} = H_{ij}(\theta_i - \theta_j) \qquad (i,j)\in L\setminus L^{DC}$$

$$\theta_1 = 0$$

$$-CAP_{ji} \le FL_{ij} \le CAP_{ij} \qquad (i,j)\in L$$



Nodal pricing – flow-based model

$$\max \sum_i \int_0^{Q_i^d} P_i^d(Q)dQ - \int_0^{Q_i^s} P_i^s(Q)dQ \quad (1)$$

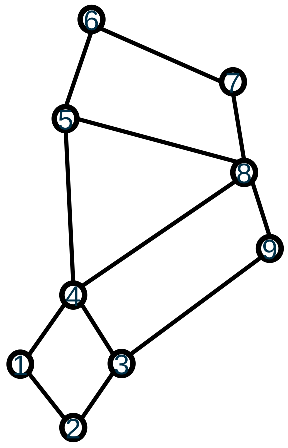
Subject to:

$$NI_i = Q_i^s - Q_i^d, \forall i \in N \quad (2)$$

$$\sum_i NI_i = 0 \quad (3)$$

$$FL_l{}^N = \sum_i nptdf_{l,i} * NI_i, \forall l \in L \quad (4)$$

$$\left|FL_l{}^N\right| \leq cap_l, \forall l \in L \quad (5)$$



Zonal pricing – ATC market coupling model

$$\max \sum_i \int_0^{Q_i^d} P_i^d(Q)dQ - \int_0^{Q_i^s} P_i^s(Q)dQ \quad (1)$$

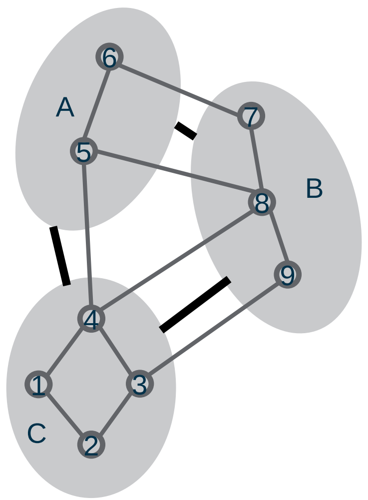
Subject to:

$$NEX_z = \sum_{i \in N_z} Q_i^s - Q_i^d, \forall z \in Z \quad (2)$$

$$\sum_{z \in Z} NEX_z = 0 \quad (3)$$

$$\mathrm{NEX}_z = \sum_{zz} (BEX_{z,zz} - BEX_{zz,z}), \forall z \in Z \quad (4)$$

$$0 \leq BEX_{z,zz} \leq atc_{z,zz}, \forall z, zz \quad (5)$$



Nodal pricing versus ATC zonal pricing

- If adding individual link capacities to set ATC
  - The model is a relaxation of the nodal price model
  - Will typically result in infeasible solutions
- Restrictions are added, i.e., ATC capacities are lower
- Trade-off
  - Too loose restrictions lead to costly re-dispatch
  - Too tight restrictions lead to too constrained market clearing
  - Nord Pool last 15-20 years

FBMC – Generation shift keys (GSKs)

- A GSK gives the change in net injection at a node relative to a change in the net position of the zone it belongs to
- Is determined before market clearing, but cannot be known accurately until after
- TSOs calculate GSKs by using a Base Case, anticipating grid topology, net positions, and corresponding power flows for each hour of the day of delivery
- We define GSKs as the nodal weight of the net position within each zone:

$$gsk_{i,z} = \frac{Q_i^s - Q_i^d}{\sum_{i \in N_z}(Q_i^s - Q_i^d)}, \forall i, z, i \in N_z$$

- The GSKs cannot be defined in a balanced pricing area, i.e. where

$$\sum_{i \in Z}(Q_i^{s^*} - Q_i^{d^*}) = 0$$

FBMC – Zonal PTDFs

- TSOs use GSKs and nodal PTDF matrices to calculate zonal PTDF matrices
- Zonal PTDF matrices are used to estimate the influence of the net position of any zone on the lines in the FBMC model

$$zptdf_{l,z} = \sum_{i \in N_z} nptdf_{l,i} * gsk_{i,z}, \forall l \in L$$

$$zptdf_l^{z,zz} = zptdf_{l,z} - zptdf_{l,zz}$$

- In the nodal model physical limitations are typically applied to the whole network
- In the FBMC model physical restrictions are imposed on the selected critical branches (CBs)

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FBMC – Critical branches (CBs)

- A CB is a transmission line that is significantly impacted by cross-border trading
  - In CWE a transmission line is critical if its maximum zone-to-zone PTDF is larger than a fixed threshold value
- The TSOs publish CBs and their corresponding Remaining Available Margin (RAM) before market clearing

FBMC – Remaining Available Margin (RAM)

- The RAM is the line capacity that can be used by the day-ahead market, and is calculated as

$$ram_l = cap_l - F_l'$$

- where cap_l is the thermal capacity limit and F_l' includes:
  - flows caused by transactions outside the day-ahead market, e.g. re-dispatching, bilateral trades, forward market,…
  - an adjustment value based on TSO knowledge, and
  - a safety margin that is needed to compensate for the approximations and simplifications made by the FBMC model
- For simplicity we assume $ram_l = cap_l$

Zonal pricing – Flow based market coupling (FBMC)

$$\max \sum_i \int_0^{Q_i^d} P_i^d(Q)dQ - \int_0^{Q_i^s} P_i^s(Q)dQ \quad (1)$$

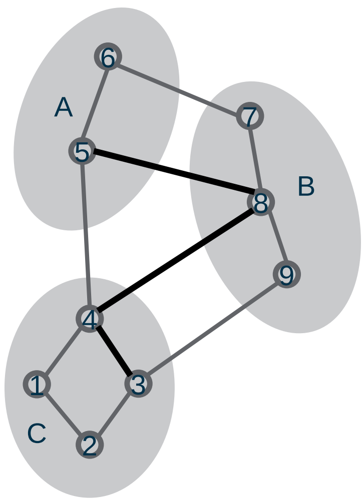
Subject to:

$$NEX_z = \sum_{i \in N_z} (Q_i^s - Q_i^d), \forall z \in Z \quad (2)$$

$$\sum_{z \in Z} NEX_z = 0 \quad (3)$$

$$FL_l{}^{FBMC} = \sum_z zptdf_{l,z} * NEX_z, \forall l \in CB \quad (4)$$

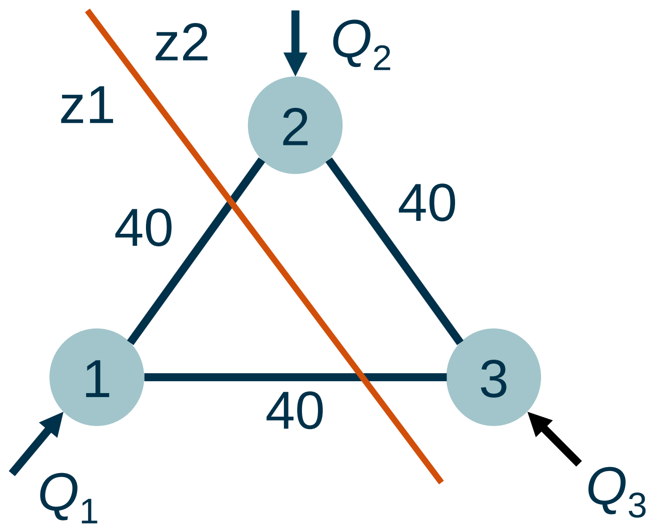
$$\left| FL_l{}^{FBMC} \right| \leq cap_l, \forall l \in CB \quad (5)$$



Nodal pricing versus FBMC

- If the base case that defines the GSKs is feasible in the nodal model, it is also feasible in the FBMC model
- If the optimal nodal price solution is used to set GSKs, then the optimal nodal price solution is feasible in FBMC and the objective function value is ≥ the objective function value of the nodal price solution
- The FBMC solution might not be feasible in the original problem, implying a need for re-dispatching
- A lot of discretion
  - Generation shift keys, GSKs
  - Critical branches, CBs
  - Capacity on critical branches, RAM

Example: 3 nodes



GSKs:

Zone 2:

Node 2: $\frac{Q_2'}{Q_2'+Q_3'} = \alpha$

Node 3: $\frac{Q_3'}{Q_2'+Q_3'} = 1 - \alpha$

Nodal ptdfs:

Line	21	31	23
β^1	0	0	0
β^2	$\frac{2}{3}$	$\frac{1}{3}$	$\frac{1}{3}$
β^3	$\frac{1}{3}$	$\frac{2}{3}$	$-\frac{1}{3}$

Zonal ptdfs:

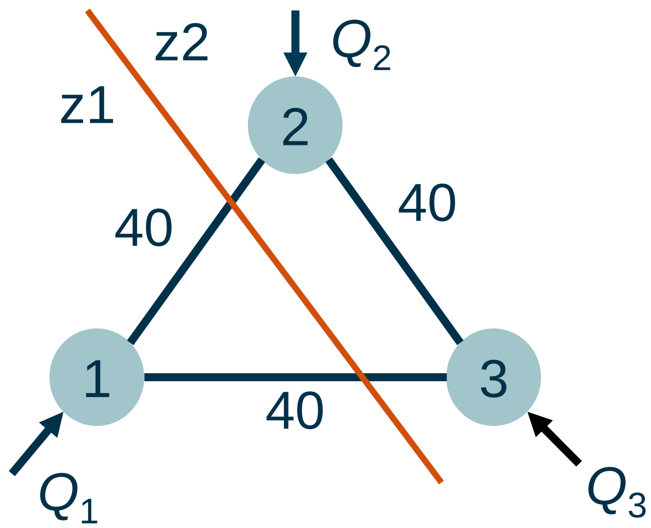
$$zptdf_{ij}^{z2} = \alpha \cdot \beta_{ij}^2 + (1-\alpha) \cdot \beta_{ij}^3$$

$$zptdf_{21}^{z2} = \frac{1}{3} \cdot \alpha + \frac{1}{3}$$

$$zptdf_{31}^{z2} = -\frac{1}{3} \cdot \alpha + \frac{2}{3}$$

$$zptdf_{23}^{z2} = \frac{2}{3} \cdot \alpha - \frac{1}{3}$$

Example: 3 nodes - Constraints



Zonal ATC model:

$$-ATC \leq Q_2 + Q_3 \leq ATC$$

$$-80 \leq Q_2 + Q_3 \leq 80$$ Sum of individual capacities

$$-60 \leq Q_2 + Q_3 \leq 60$$ «Worst case»

Zonal FBMC model:

$$-RAM_{21} \leq \left(\tfrac{1}{3}\alpha + \tfrac{1}{3}\right) \cdot (Q_2 + Q_3) \leq RAM_{21}$$

$$-RAM_{31} \leq \left(-\tfrac{1}{3}\alpha + \tfrac{2}{3}\right) \cdot (Q_2 + Q_3) \leq RAM_{31}$$

$$-RAM_{23} \leq \left(\tfrac{2}{3}\alpha - \tfrac{1}{3}\right) \cdot (Q_2 + Q_3) \leq RAM_{23}$$

Nodal model:

$$-40 \leq \tfrac{2}{3}Q_2 + \tfrac{1}{3}Q_3 \leq 40$$

$$-40 \leq \tfrac{1}{3}Q_2 + \tfrac{2}{3}Q_3 \leq 40$$

$$-40 \leq \tfrac{1}{3}Q_2 - \tfrac{1}{3}Q_3 \leq 40$$

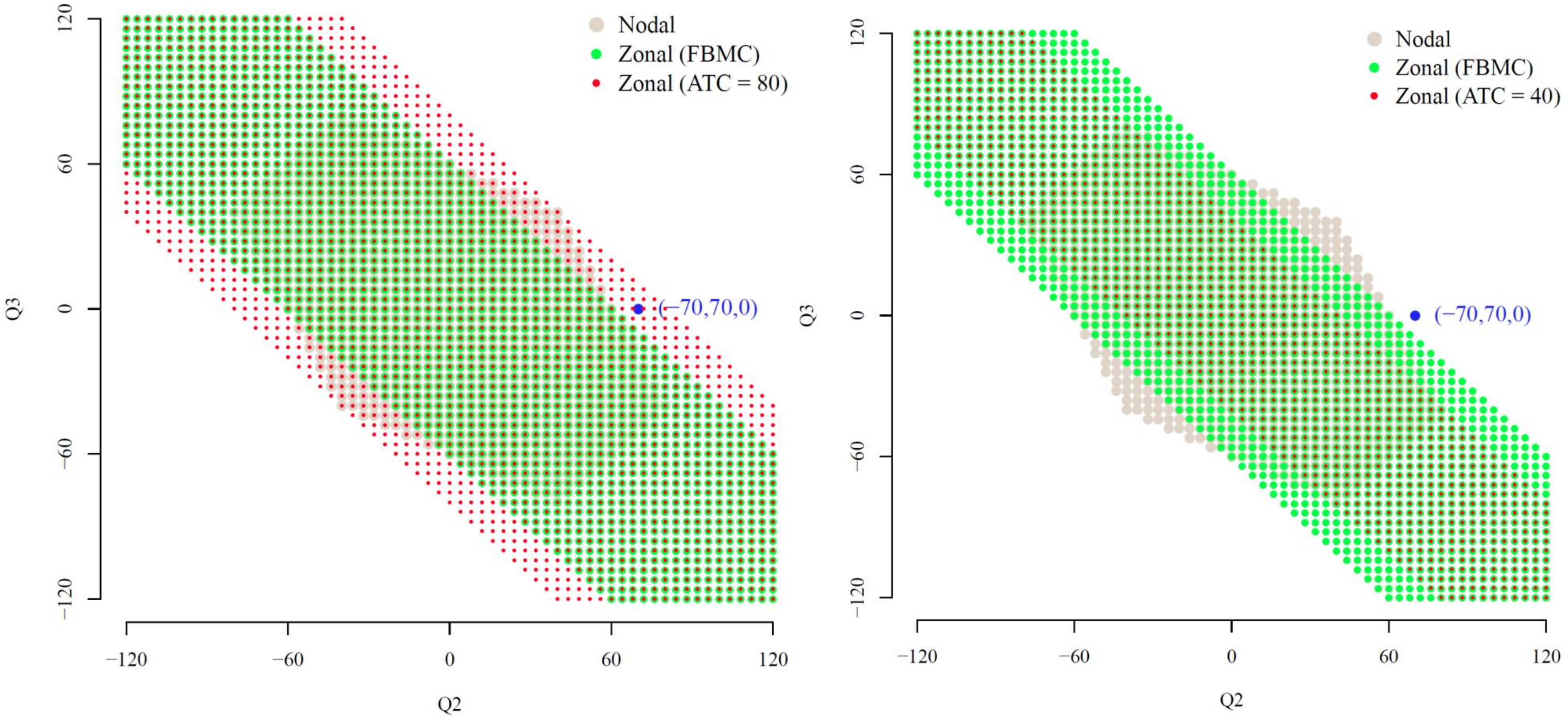
If $\alpha = \frac{1}{2}$ and $ram_l = cap_l$:

$$-40 \leq \tfrac{1}{2} \cdot Q_2 + \tfrac{1}{2} \cdot Q_3 \leq 40$$

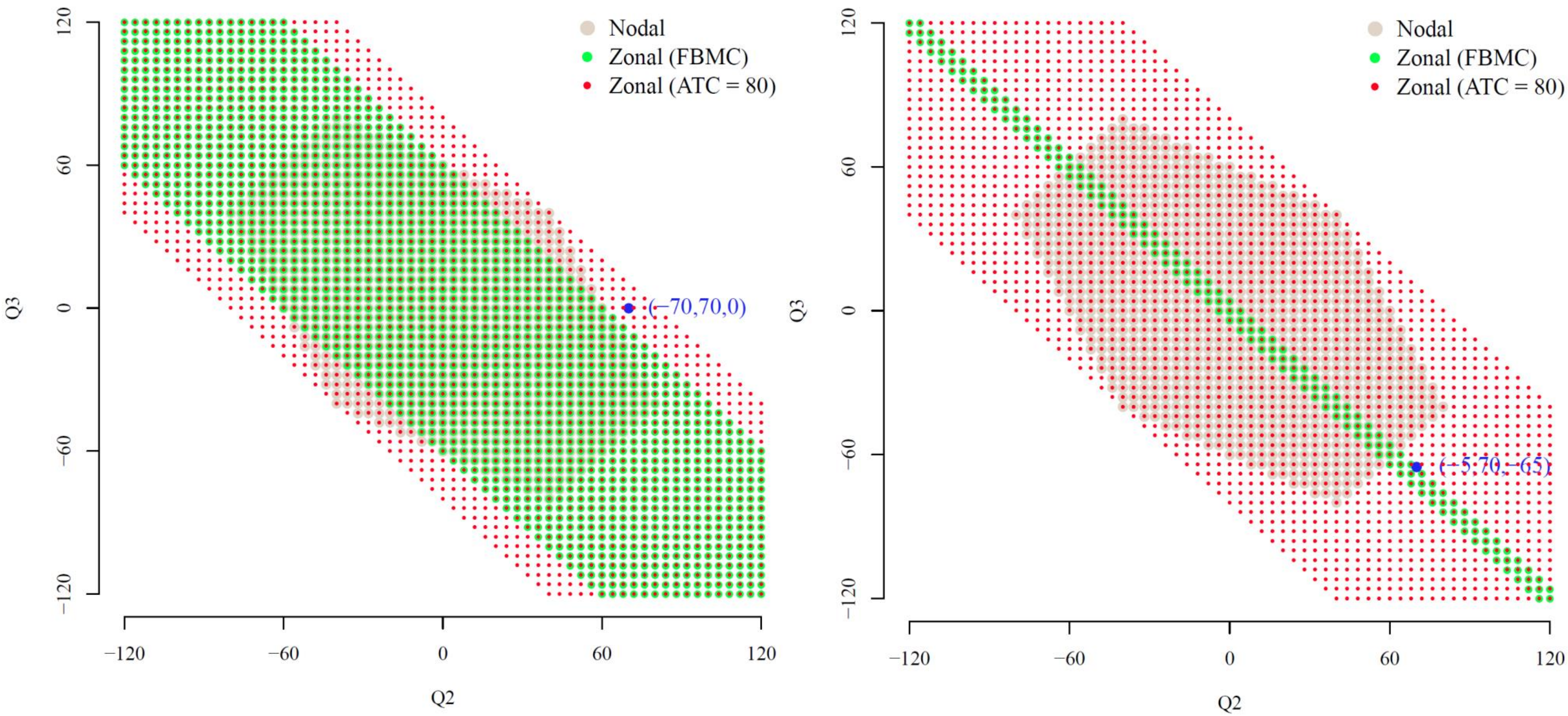
$$-40 \leq \tfrac{1}{2} \cdot Q_2 + \tfrac{1}{2} \cdot Q_3 \leq 40$$

$$-40 \leq 0 \cdot (Q_2 + Q_3) \leq 40$$ Always fulfilled

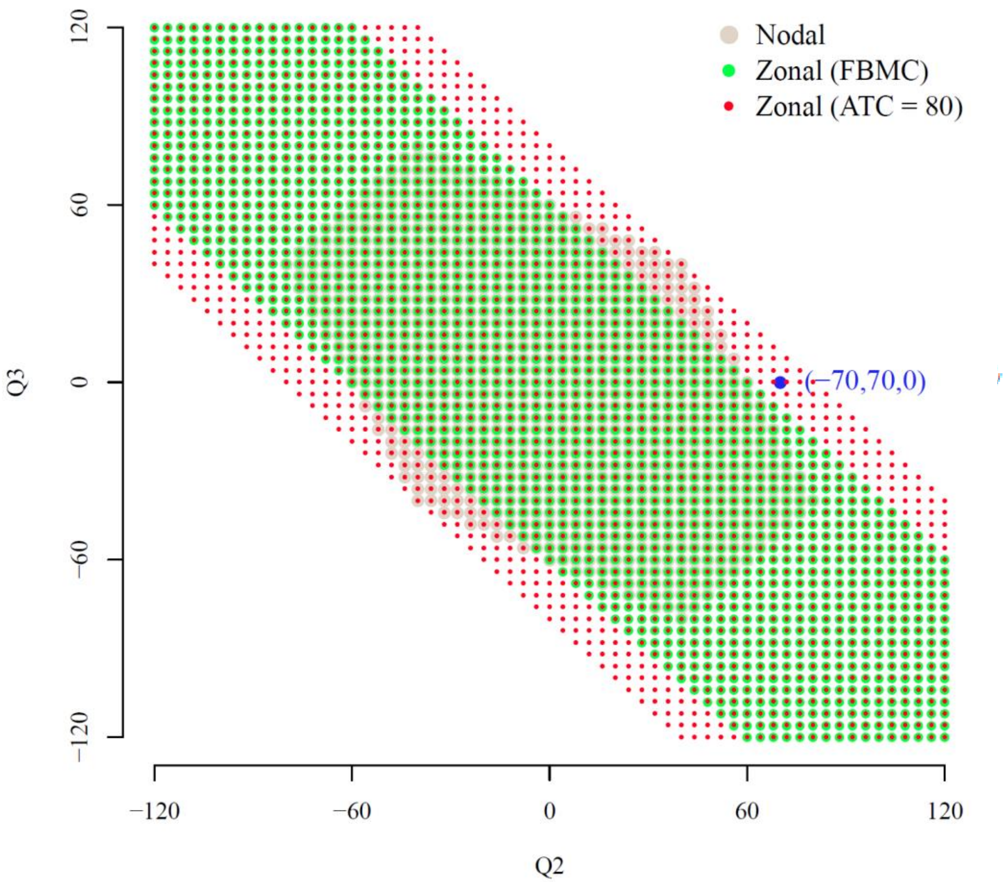
Feasible area

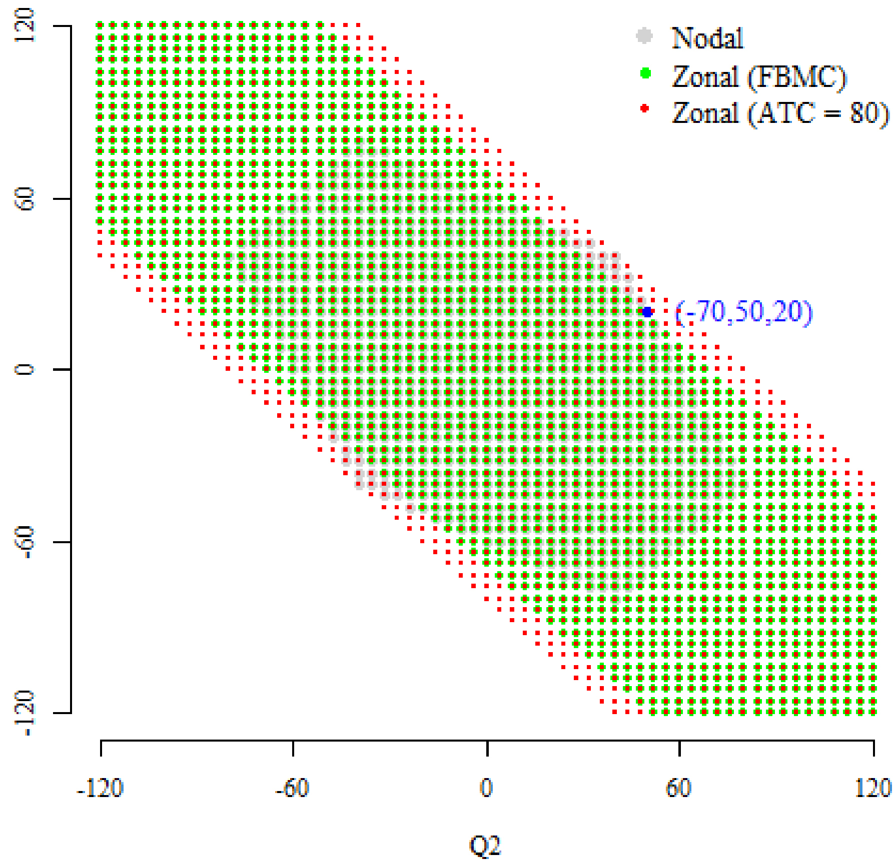


Feasible area

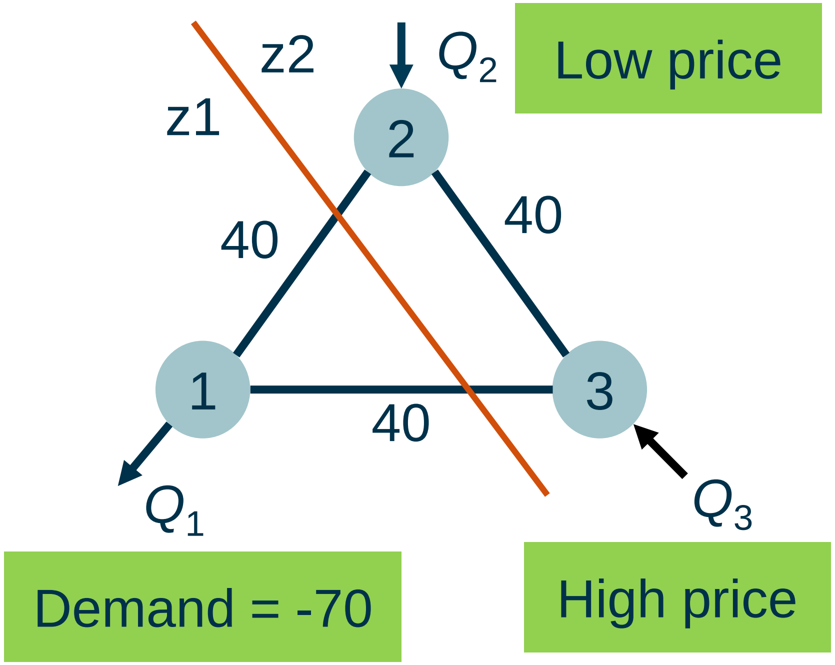


Feasible area





Example: 3 nodes - Solutions



Nodal model:

$$-40 \le \tfrac{2}{3}Q_2 + \tfrac{1}{3}Q_3 \le 40$$

$$-40 \le \tfrac{1}{3}Q_2 + \tfrac{2}{3}Q_3 \le 40$$

$$-40 \le \tfrac{1}{3}Q_2 - \tfrac{1}{3}Q_3 \le 40$$

(-70, 50, 20)

Zonal ATC model:

$$-ATC \le Q_2 + Q_3 \le ATC$$

(-70, 70, 0)

$$-80 \le Q_2 + Q_3 \le 80$$ Sum of individual capacities

$$-60 \le Q_2 + Q_3 \le 60$$ «Worst case»

No solution

Zonal FBMC model:

$$-RAM_{21} \le (\tfrac{1}{3}\alpha + \tfrac{1}{3}) \cdot (Q_2 + Q_3) \le RAM_{21}$$

$$-RAM_{31} \le (-\tfrac{1}{3}\alpha + \tfrac{2}{3}) \cdot (Q_2 + Q_3) \le RAM_{31}$$

$$-RAM_{23} \le (\tfrac{2}{3}\alpha - \tfrac{1}{3}) \cdot (Q_2 + Q_3) \le RAM_{23}$$

If $\alpha = \frac{1}{2}$ and $ram_l = cap_l$:

$$-40 \le \tfrac{1}{2} \cdot Q_2 + \tfrac{1}{2} \cdot Q_3 \le 40$$

$$-40 \le \tfrac{1}{2} \cdot Q_2 + \tfrac{1}{2} \cdot Q_3 \le 40$$

(-70, 70, 0)

$$-40 \le 0 \cdot (Q_2 + Q_3) \le 40$$ Always fulfilled

Re-dispatch model

$$\min_{GUP_i, GDN_i} \sum_i \int_{Q_i^{s'}}^{Q_i^{s'} + GUP_i + GDN_i} P_i^s(Q)dQ + \sum_i voll * LOADSHED_i \quad (1)$$

Subject to:

$$NI_i = \left(Q_i^{s'} + GUP_i - GDN_i\right) - (Q_i^{d'} - LOADSHED_i), \forall i \in N \quad (2)$$

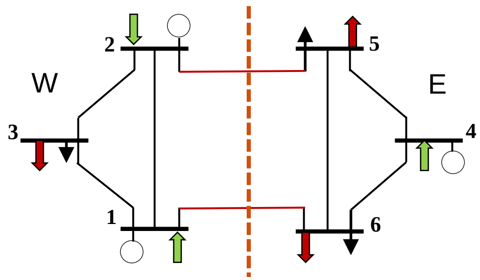
$$\sum_i NI_i = 0 \quad (3)$$

$$FL_l{}^N = \sum_i nptdf_{l,i} * NI_i, \forall l \in L \quad (4)$$

$$\left|FL_l{}^N\right| \leq CAP_l, \forall l \in L \quad (5)$$

$$GUP_i, GDN_i, LOADSHED_i \geq 0, \forall i \in N \quad (6)$$

Example: 6-bus test system (Chao and Peck, 1998)



	Node 1	Node2	Node3	Node4	Node5	Node6
Line1	0	-0.583	-0.292	-0.292	-0.333	-0.250
Line2	0	-0.292	-0.646	-0.146	-0.167	-0.125
Line3	0	-0.125	-0.063	-0.563	-0.500	-0.625
Line4	0	0.292	-0.354	0.146	0.167	0.125
Line5	0	0.125	0.063	-0.438	-0.500	-0.375
Line6	0	-0.042	-0.021	0.479	-0.167	0.125
Line7	0	0.042	0.021	0.521	0.167	-0.125
Line8	0	0.083	0.042	0.042	0.333	-0.250

Table 1: Node-to-branch PTDF matrix (Node 1 is set to be the reference node)

Bus-ID		*Net Input (nodal FB)*	*Price (nodal FB)*		*GSKs*
1	W	300	25	$gsk_{1,N}$	0.75
2		300	30	$gsk_{2,N}$	0.75
3		-200	27.5	$gsk_{3,N}$	-0.5
4	E	200	47.5	$gsk_{4,S}$	-0.5
5		-300	45	$gsk_{5,S}$	0.75
6		-300	50	$gsk_{6,S}$	0.75

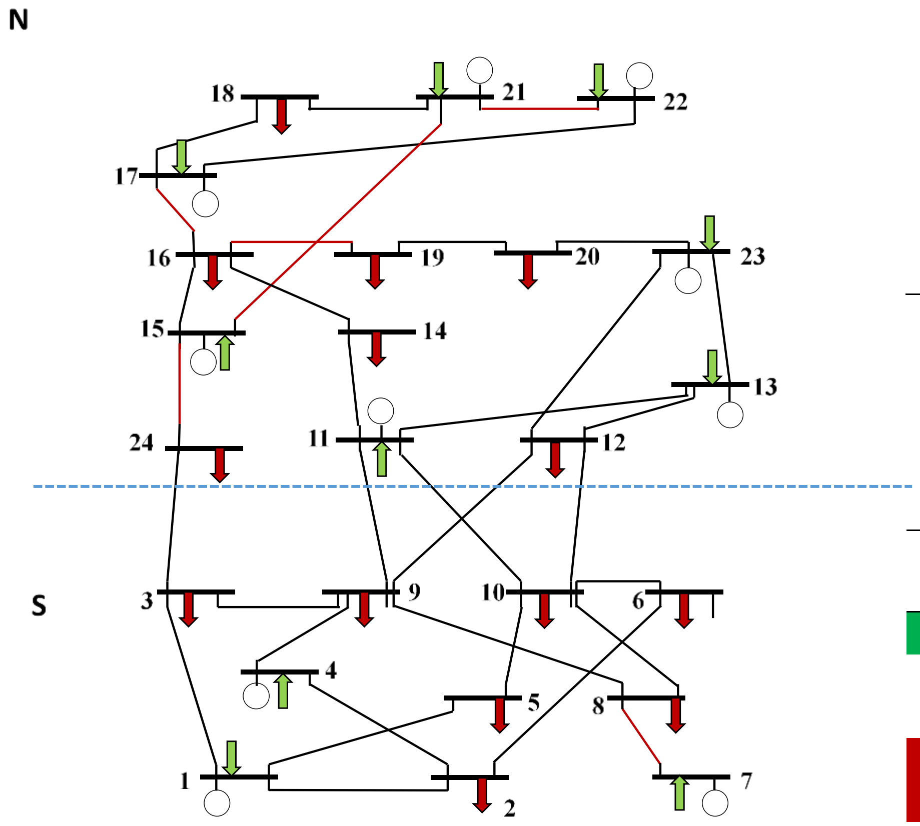
Table 1: Generation shift keys

	CB=3	*CB=5*	*CB=3,5*	*Nodal FB*
Price (W)	27.5	29.17	27.5	27.5*
Price (E)	47.5	45.83	47.5	47.5*
Social Surplus①	23187.50	25020.83	23187.50	23000
Re-dispatching cost②	250.95	2176.87	250.95	0
① -②	22936.55	22843.96	22936.55	23000
W→E(power exchange)	400	500	400	400
Total generation	800	800	800	800

* Supply volume weighted average price

Table 1: Results for 6-bus system

Example: IEEE 24 network (Deng et al., 2010)



	ATC	FBMC	Nodal FB
Price (N)	34.205	33.994	24.313*
Price (S)	37.314	37.444	38.941*
Social Surplus($)	104165	104044	90273
Re-dispatching cost($) (Generation part)	14353	14099	0
Load shedding(MW)	202	207	0
N→S(power exchange)(MW)	380	343	-343
Unit cost	32.229	32.232	28.464

** Supply volume weighted average price*

Table 1: Results for IEEE24 system

	From	To	Line Capacity	Actual Flow (ATC)	Actual Flow (FBMC)
CB 1	7	8	350	615	609
CB 2	15	21	1000	-353	-360
CB 3	15	24	500	392	400
CB 4	16	17	500	-510	-519
CB 5	16	19	500	537	543
CB 6	21	22	500	-366	-369

Conclusions and future research

- Not necessarily clear that FBMC model is an improvement, neither when it comes to efficiency nor transparency
- Still many choices that affect prices in own and other regions (GSKs, CBs, RAM)

- More systematic simulation study to get a better understanding of how the method works
- Consider definition of regions
- Study hybrid systems, i.e. systems where ATC and FBMC models are used simultaneously