An analysis of zonal electricity markets from a long-term perspective

ESIM seminar - Leuven

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Outline

Motivation

Capacity expansion in transmission-constrained markets

Capacity expansion with FBMC

Case study on CWE

Research questions

What are the impacts of zonal pricing on investment ?

- Zonal distorts the price → cash flows to producers → investment
- In the energy transition era, this may be important

To what extend does it depend on the model of zonal constraints ?

- No unique way of organizing a zonal market
- In Europe, **flow-based market coupling (FBMC)**

How to model capacity expansion with FBMC ?

- Nodal and well-defined zonal: single optimization problem
- FBMC: no equivalence between centralized and decentralized
- Generalized Nash equilibrium

Motivation

Capacity expansion in transmission-constrained markets

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Capacity expansion in a decentralized market

"The goal of a well functioning market should be to reproduce the ideal central planning results"[1]

Boiteux (1960):

1. Consistent with marginal pricing
2. The marginal cost ($\neq$ variable cost) has to include a scarcity premium
3. Short-run and long-run marginal costs are equal in optimally designed systems

Does it extend to **transmission-constrained** markets ?

[1] Paul Joskow, "The new energy paradigm", 2007.

Nodal pricing: optimal long term solution

Transmission constraints

Assume that the central planner considers all transmission constraints via the DC approximation

Feasible set of nodal net injections:

$$\mathcal{R} = \Big\{ r \in \mathbb{R}^{|N|} \,\Big|\, \exists f \in \mathbb{R}^{|K|} : \\ f_k = \sum_{n \in N} PTDF_{kn} \cdot r_n, k \in K \\ \sum_{n \in N} r_n = 0, -TC_k \leq f_k \leq TC_k, k \in K \Big\}$$

This set completely defines the network constraints.

Nodal pricing: optimal long term solution (2)

Capacity expansion

Minimize	the cost of production
s.t.	generators operational constraints
	transmission constraints
	the market clears

$$\min_{x,y,s,r} \sum_{i \in I, n \in N} IC_i \cdot x_{in} + \sum_{i \in I, n \in N, t \in T} MC_i \cdot y_{int} + \sum_{n \in N, t \in T} VOLL \cdot s_{nt}$$

$$(\mu_{int}) : y_{int} \leq x_{in} + X_{in}, i \in I, n \in N, t \in T$$

$$(\rho_{nt}) : r_{nt} = \sum_{i \in I} y_{int} + s_{nt} - D_{nt}, n \in N, t \in T$$

$$r_{:t} \in \mathcal{R}, t \in T$$

$$x \geq 0, y \geq 0, s \geq 0$$

Nodal pricing: Equivalence to decentralized solution

Producers:

$$\max_{x_{in}} \sum_{t \in T} \Big((\rho_{nt} - MC_i) y_{int} \Big) - IC_i x_{in}$$

$$\text{s.t. } X_{in} + x_{in} - y_{int} \geq 0$$

$$x_{in} \geq 0, y_{int} \geq 0$$

TSO:

$$\max_{r_{nt}} - \sum_{n \in N, t \in T} r_{nt} \rho_{nt}$$

$$\text{s.t. } r_{:t} \in \mathcal{R}, t \in T$$

Consumers:

$$\max_{s_{nt}} \sum_{t \in T} VOLL(D_{nt} - s_{nt}) - \rho_{nt}(D_{nt} - s_{nt})$$

$$\text{s.t. } D_{nt} - s_{nt} \geq 0, t \in T$$

$$s_{nt} \geq 0$$

Auctioneer:

$$\max_{\rho_{nt}} \ \rho_{nt}(r_{nt} + D_{nt} - \sum_i y_{int} - s_{zt})$$

What about in zonal pricing ?

Our claims:

- It depends on how you define the transmission constraints
- It could hold in well defined zonal system
- **It does not hold in FBMC**
- It has a consequence in terms of efficiency

Zonal pricing: optimal long term solution

Transmission constraints ?

- Unique price per zone
- nodal primal $\rightarrow$ nodal dual $\xrightarrow{\text{prices } =}$ zonal dual $\rightarrow$ zonal primal

Feasible set of **zonal** net injections:

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

$$\left. r \in \mathcal{R} \right\}$$

Zonal pricing: Equivalence to decentralized solution

Producers:

$$\max_{x_{iz}} \sum_{t\in T} \Big((\rho_{zt} - MC_i) y_{izt}\Big) - IC_i x_{iz}$$

$$\text{s.t. } X_{iz} + x_{iz} - y_{izt} \geq 0$$

$$x_{iz} \geq 0, y_{izt} \geq 0$$

TSO:

$$\max_{p_{zt}} - \sum_{z\in Z, t\in T} p_{zt} \rho_{zt}$$

$$\text{s.t. } p_{:t} \in \mathcal{P}^{\text{PA}}, t \in T$$

Consumers:

$$\max_{s_{zt}} \sum_{t\in T} VOLL(D_{zt} - s_{zt}) - \rho_{zt}(D_{zt} - s_{zt})$$

$$\text{s.t. } D_{zt} - s_{zt} \geq 0, t \in T$$

$$s_{zt} \geq 0$$

Auctioneer:

$$\max_{\rho_{zt}} \rho_{zt}(p_{zt} + D_{zt} - \sum_i y_{izt} - s_{zt})$$

Motivation

Capacity expansion in transmission-constrained markets

Capacity expansion with FBMC

Case study on CWE

FBMC: set of feasible net injections ?

Difficulty: based on a set of paramters that depend on

1. Expected state of the grid
2. **Installed capacity**

We use a model that internalizes these dependences (Aravena et al. 2021):

$$\mathcal{PX}^{\text{FBMC}}(x_{in}) = \Bigg\{ p \in \mathbb{R}^{|Z|} \,\Bigg|\, \exists (r, \tilde{y}) : p_z = \sum_{n \in N(z)} r_n \;\; \forall z \in Z, \\ r \in \mathcal{R}, \\ r_n = \tilde{y}_{int} - D_{nt} \;\; \forall n \in N, \\ 0 \leq \tilde{y}_{int} \leq x_{in} + X_{in} \;\; \forall i \in I, n \in N \Bigg\}$$

Equivalence to decentralized solution is broken

Producers:

$$\max_{x_{iz}} \sum_{t\in T} \Big((\rho_{zt} - MC_i) y_{izt} \Big) - IC_i x_{iz}$$

$$\text{s.t. } X_{iz} + x_{iz} - y_{izt} \geq 0$$

$$x_{iz} \geq 0, y_{izt} \geq 0$$

TSO:

$$\max_{p_{zt}} - \sum_{z\in Z, t\in T} p_{zt}\rho_{zt}$$

$$\text{s.t. } p_{:t} \in \mathcal{PX}^{\text{FBMC}}(x_{in}), t \in T$$

Consumers:

$$\max_{s_{zt}} \sum_{t\in T} VOLL(D_{zt} - s_{zt}) - \rho_{zt}(D_{zt} - s_{zt})$$

$$\text{s.t. } D_{zt} - s_{zt} \geq 0, t \in T$$

$$s_{zt} \geq 0$$

Auctioneer:

$$\max_{\rho_{zt}} \; \rho_{zt}(p_{zt} + D_{zt} - \sum_i y_{izt} - s_{zt})$$

Investment conditions

Nodal:

$$0 \leq x_{in} \perp IC_i - \sum_{t \in T} \mu_{int} \geq 0 \;\; \forall i \in I, n \in N$$

Zonal PA:

$$0 \leq x_{iz} \perp IC_i - \sum_{t \in T} \mu_{izt} \geq 0 \;\; \forall i \in I, z \in Z$$

FBMC-C:

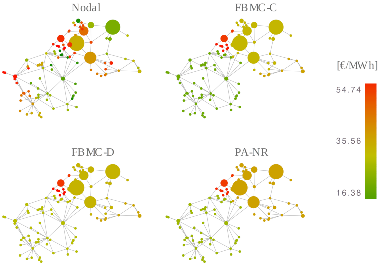
$$0 \leq x_{iz} \perp IC_i - \sum_{t \in T} \mu_{izt} - \sum_{m \in \{1,\ldots,M\}} U_{miz}\gamma_m \geq 0 \;\; \forall i \in I, z \in Z$$

FBMC-D:

$$0 \leq x_{iz} \perp IC_i - \sum_{t \in T} \mu_{izt} \geq 0 \;\; \forall i \in I, z \in Z$$

Results: case study on the Central Western European network

- 100 nodes and 20 time periods
- Based on realistic data of CWE
- Splitting based algorithm to solve the FBMC-D



Results

Policy	OC	IC	TC	Losses
		[M€/yr]		[%]
Nodal	15,855	10,432	26,287	-
FBMC-C	16,314	10,221	26,535	0.94
FBMC-D	16,368	10,700	27,068	3.0
PA	16,835	10,909	27,744	5.5

Table 1: Performance comparison of the different policies.

- Large efficiency gaps between the four designs
- Influence on decommissioning of hard coal and lignite in Germany
- Reallocation of technologies in different locations of the same zone cannot occur in decentralized FBMC and PA

Conclusion

Equivalence between central planner and decentralized solution is broken in FBMC.

Consequences:

- Multiple equilibria: not clear what the output will be
- Intervention from the TSO is necessary (network reserve)
- Market efficiency is degraded:
  Nodal $>$ FBMC-C $>$ FBMC-D $>$ Zonal-PA

Thank you

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