Long Run Equilibrium of Zonal Pricing Followed by Market-Based Re-Dispatch

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Outline

Transmission capacity allocation in Europe: Zonal pricing

1. Market cleared with unique price per zone
2. Re-dispatching is needed to recover feasible dispatch

Figure 1: Bidding zones in Europe. Source: Meeus (2020).

The status quo is increasingly challenged

Why ? Re-dispatching costs are rising.

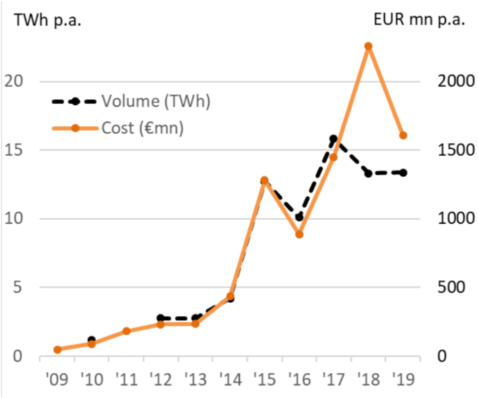


Figure 2: Increasing re-disptach costs and volume in Germany. Source: Hirth and Slecht (2020).

Cost-based vs market-based re-dispatch

Two approaches for organizing re-dispatch:

Cost-based re-dispatch

- Mandatory participation
- Compensation to get profit neutrality
- No locational signal for investment
- Default rule in most countries in Europe

Market-based re-dispatch

- Voluntary participation
- Competitive auction with nodal prices
- Leads to opportunity for arbitrage
- Used in some countries (e.g. the Netherlands)
- Favored by the EU commission

Research questions

Technical

- How to model the competitive long run equilibrium of zonal pricing followed by market-based re-dispatch ?
- How to solve the model efficiently ?

Policy

- Is the design efficient in the short run and long run ?
- What is the impact of uncertainty in re-dispatch price ?
- Can we restore the efficiency with an additional market instrument (i.e. locational capacity charge) ?

Assumptions

→ Simplifying assumptions to focus on the relationship between zonal pricing and re-dispatch.

1. 3 types of agents: Producers, a TSO and a Walrasian auctioneer
2. Inflexible demand
3. Agents are price-takers
4. All profit-maximizing problems are convex
5. No irrevocable decision are made in zonal pricing

Producers

Decision variables:

- y_{in}: production of technology i in node n in the zonal market
- $\tilde{y}_{in}$: re-dispatch amount ($+$ or $-$)

$$
\begin{aligned}
\max \; & \rho_{Z(n)} y_{in} + \tilde{\rho}_n \tilde{y}_{in} - MC_i(y_{in} + \tilde{y}_{in}) \\
(\mu_{in}) : \; & X_{in} - y_{in} \geq 0 \\
(\tilde{\mu}_{in}) : \; & X_{in} - y_{in} - \tilde{y}_{in} \geq 0 \\
(\delta_{in}) : \; & y_{in} + \tilde{y}_{in} \geq 0 \\
& y_{in} \geq 0
\end{aligned}
$$

TSO in the zonal market

Decision variables:

- p_z: net position (export - import) of zone z

$$\max -\sum_z p_z \rho_z$$
$$\text{s.t. } (\gamma_m) : p \in \mathcal{P} \Leftrightarrow W_m - \sum_z V_{mz} p_z \geq 0, m \in M$$

TSO in the re-dispatch market

Decision variables:

- $\tilde{r}_n$: amount of re-dispatch bought at node n
- r_n: net injection of node n

$$\max -\sum_n \tilde{r}_n \tilde{\rho}_n$$

$$\text{s.t. } (\nu_n): r_n - \sum_i y_{in} + D_n - \tilde{r}_n = 0, n \in N$$

$$(\tilde{\gamma}_m): r \in \mathcal{R} \Leftrightarrow \tilde{W}_m - \sum_n \tilde{V}_{mn} r_n \geq 0, m \in \tilde{M}$$

$\rightarrow$ Generalized Nash because variables y_{in} appear in the TSO's problem.

Walrasian auctioneer

Decision variables:

- ρ_z: price in zone z in the zonal market
- $\tilde{\rho}_n$: re-dispatch price in node n

In the zonal market

$$\max \ \rho_z(p_z - \sum_{i,n \in N(z)} y_{in} + D_z)$$

In the re-disaptch market

$$\max \ \tilde{\rho}_n(\tilde{r}_n - \sum_{in} \tilde{y}_{in})$$

Formulation as an LCP

Producers

$$0 \leq y_{in} \perp MC_i + \mu_{in} + \tilde{\mu}_{in} - \rho_{Z(n)} - \delta_{in} \geq 0$$

$$\tilde{y}_{in} \text{ free } \perp MC_i + \tilde{\mu}_{in} - \tilde{\rho}_n - \delta_{in} = 0$$

$$0 \leq \mu_{in} \perp X_{in} - y_{in} \geq 0$$

$$0 \leq \tilde{\mu}_{in} \perp X_{in} - y_{in} - \tilde{y}_{in} \geq 0$$

$$0 \leq \delta_{in} \perp y_{in} + \tilde{y}_{in} \geq 0$$

TSO

$$p_z \text{ free } \perp \rho_z + \sum_m V_{mz}\gamma_m = 0$$

$$0 \leq \gamma_m \perp W_m - \sum_z V_{mz} p_z \geq 0$$

$$\tilde{r}_n \text{ free } \perp \tilde{\rho}_n + \nu_n = 0$$

$$r_n \text{ free } \perp -\nu_n + \sum_m \tilde{V}_{mn}\tilde{\gamma}_m = 0$$

$$\nu_n \text{ free } \perp r_n - \sum_i y_{in} + D_n - \tilde{r}_n = 0$$

$$0 \leq \tilde{\gamma}_m \perp \tilde{W}_m - \sum_n \tilde{V}_{mn} r_n \geq 0$$

Market clearing

$$\rho_z \text{ free } \perp p_z - \sum_{i,n \in N(z)} y_{in} + D_z = 0$$

$$\tilde{\rho}_n \text{ free } \perp \tilde{r}_n - \sum_{in} \tilde{y}_{in} = 0$$

Re-dispatch equations in the LCP

Producers

$$0 \le y_{in} \perp MC_i + \mu_{in} + \tilde{\mu}_{in} - \rho_{Z(n)} - \delta_{in} \ge 0$$

$$\tilde{y}_{in} \text{ free} \perp MC_i + \tilde{\mu}_{in} - \tilde{\rho}_n - \delta_{in} = 0$$

$$0 \le \mu_{in} \perp X_{in} - y_{in} \ge 0$$

$$0 \le \tilde{\mu}_{in} \perp X_{in} - y_{in} - \tilde{y}_{in} \ge 0$$

$$0 \le \delta_{in} \perp y_{in} + \tilde{y}_{in} \ge 0$$

TSO

$$p_z \text{ free } \perp \rho_z + \sum_m V_{mz}\gamma_m = 0$$

$$0 \le \gamma_m \perp W_m - \sum_z V_{mz} p_z \ge 0$$

$$\tilde{r}_n \text{ free} \perp \tilde{\rho}_n + \nu_n = 0$$

$$r_n \text{ free } \perp -\nu_n + \sum_m \tilde{V}_{mn}\tilde{\gamma}_m = 0$$

$$\nu_n \text{ free } \perp r_n - \sum_i y_{in} + D_n - \tilde{r}_n = 0$$

$$0 \le \tilde{\gamma}_m \perp \tilde{W}_m - \sum_n \tilde{V}_{mn} r_n \ge 0$$

Market clearing

$$\rho_z \text{ free } \perp p_z - \sum_{i,n \in N(z)} y_{in} + D_z = 0$$

$$\tilde{\rho}_n \text{ free } \perp \tilde{r}_n - \sum_{in} \tilde{y}_{in} = 0$$

Re-dispatch equations in the LCP

We observe that the re-dispatch equations in the LCP correspond to the KKT conditions of the nodal economic dispatch problem:

$$\begin{aligned} \min \ & \sum_{in} MC_i \bar{y}_{in} \\ \text{s.t. } & X_{in} - \bar{y}_{in} \geq 0, i \in I, n \in N \\ & r_n - \sum_{in} \bar{y}_{in} + D_n = 0, n \in N \\ & r \in \mathcal{R} \end{aligned}$$

$\rightarrow$ This shows that zonal pricing followed by market-based re-dispatch is efficient in the short run

Solution methodology

The full solution to the short run equilibrium can be obtained as follows:

1. Solve the nodal economic dispatch problem.
2. Denote by $\tilde{\rho}^*_n$ the nodal prices.
3. Solve the following zonal economic dispatch problem:

$$
\begin{aligned}
\min\ & \sum_{in} \tilde{\rho}^*_n y_{in} \\
\text{s.t. } & X_{in} - y_{in} \geq 0, i \in I, n \in N \ \ [\mu_{in}] \\
& p_z - \sum_{i,n \in N(z)} y_{in} + D_z = 0, z \in Z \ \ [\rho_z] \\
& W_m - \sum_z V_{mz} p_z \geq 0 \ \ [\gamma_m]
\end{aligned}
$$

Producers/Investors

Additional decision variable:

- x_{in}: capacity invested in technology i in node n

$$\max \sum_{t \in T} \Big(\rho_{Z(n)t} y_{int} + \tilde{\rho}_{nt} \tilde{y}_{int} - MC_i (y_{int} + \tilde{y}_{int}) \Big) - IC_i x_{in}$$

$$(\mu_{int}) : X_{in} + x_{in} - y_{int} \geq 0$$

$$(\tilde{\mu}_{int}) : X_{in} + x_{in} - y_{int} - \tilde{y}_{int} \geq 0$$

$$(\delta_{int}) : y_{int} + \tilde{y}_{int} \geq 0$$

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

Long run equilibrium

→ Introducing investment completely modifies the nature of the problem !

- The investment condition links both problems together:

$$0 \leq x_{in} \perp IC_i - \sum_{t \in T} \mu_{int} - \sum_{t \in T} \tilde{\mu}_{int} \geq 0$$

with $\sum_{t \in T} \mu_{int}$ = zonal rent
$\sum_{t \in T} \tilde{\mu}_{int}$ = re-dispatch rent

- Cannot be solved as two sequential optimization problems
- Correspond to a large LCP with special structure
- Existence and unicity must be checked

Existence

Proposition

If the marginal costs, the investment costs and the demand in all nodes are non-negative, then the investment problem with zonal pricing followed by market-based re-dispatch has a solution.

Proof.

M is copositive and

$$[v \geq 0, Mv \geq 0, v^\top Mv = 0] \Rightarrow v^\top q \geq 0$$

□

Solution methodology

$\rightarrow$ Use the basic linear splitting algorithm for solving LCPs:
$M = B + C$

1. *Initialization.* Let z_0 be an arbitrary nonnegative vector, set $\nu = 0$.
2. *General iteration.* Given $z^\nu \geq 0$, solve the $LCP(q^\nu, B)$ where

$$q^\nu = q + Cz^\nu$$

   and let $z^{\nu+1}$ be an arbitrary solution.
3. *Test for termination.* If $z^{\nu+1}$ satisfies a prescribed stopping rule, terminate. Otherwise, return to Step 1 with ν replaced by $\nu + 1$.

Solution methodology: splitting

→ This takes advantage of the special structure of the problem:

- Almost an optimization problem
- Just one variable has been dropped in producers problem
- $LCP(q, B)$ is a linear optimization problem if the market was complete

B = skew-symmetrix matrix and

$$C = \begin{array}{c} \\ y_{int} \\ \\ \\ \\ \end{array} \begin{array}{c} \qquad\quad \tilde{\rho}_{nt} \\ \begin{pmatrix} 0 & \dots & I & \dots & 0 \\ 0 & 0 & \dots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \dots & 0 & 0 \end{pmatrix} \end{array}$$

Solution methodology: iterations

At iteration ν, solve

$$
\begin{aligned}
\min \;& \sum_{int} MC_i \bar{y}_{int} + \sum_{in} IC_i x_{in} + \sum_{int} \tilde{\rho}^{\nu}_{nt} y_{int} \\
\text{s.t. } & X_{in} + x_{in} - \bar{y}_{int} \geq 0 \\
& r_{nt} - \sum_{int} \bar{y}_{int} + D_{nt} = 0 \;\; [\tilde{\rho}^{\nu+1}_{nt}] \\
& r_{:t} \in \mathcal{R} \\
& X_{in} + x_{in} - y_{int} \geq 0 \\
& p_{zt} - \sum_{i,n \in N(z),t} y_{int} + D_{zt} = 0 \\
& p_{:t} \in \mathcal{P}
\end{aligned}
$$

Stop when $\tilde{\rho}^{\nu+1}_{nt} = \tilde{\rho}^{\nu}_{nt}$

Introduction

Short run competitive equilibrium

Long run competitive equilibrium

Results: case study on Central Western Europe

Conclusion and perspectives

Central Western Europe network

- 632 buses and 945 branches
- Hourly time series data for net demand
- 892 existing units

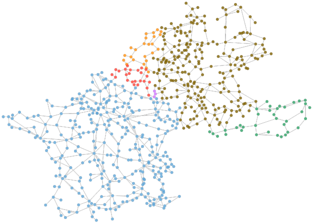
Type	Number of units	Total installed capacity [GW]
Nuclear	73	77.67
Natural gas	403	56.38
Coal	93	30.7
Lignite	59	20.82
Oil	75	6.37
Other	189	6.08

- 3 types of candidate units

Type	IC [k€/MW yr]	FC [k€/MW yr]	MC [€/MWh]
CCGT	80.1	16.5	61.29
OCGT	56.33	9.33	100.4
CCGT&CHP	94.39	16.5	41.37

Data reduction

Network



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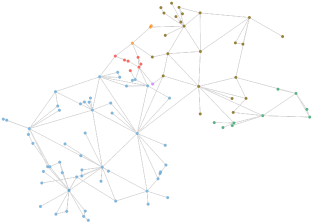
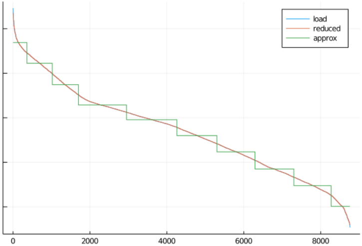


Periods



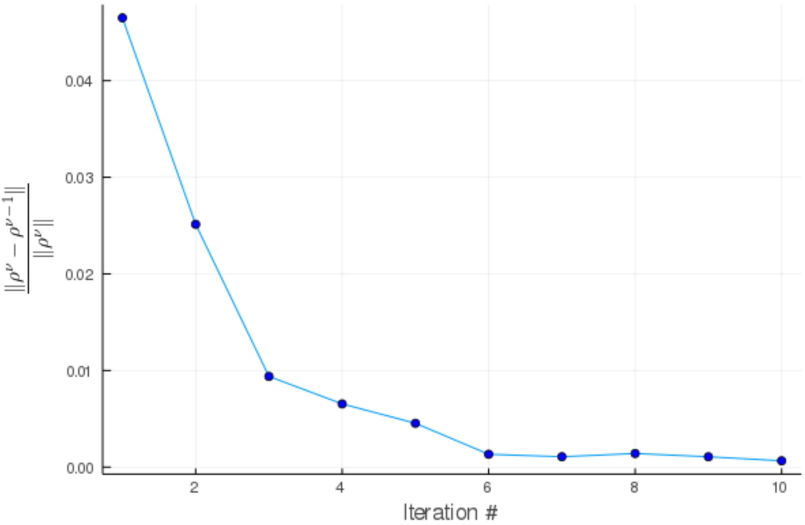
Results

Policy	Op. cost	Inv. cost [M€/yr]	Total cost
Nodal	15,810	10,433	26,243
Cost-based re-dispatch	16,835	10,909	27,744
Market-based re-dispatch	15,867	19,057	34,924

Table 1: Performance comparison of the different policies.

- Important losses of efficiency compared to nodal and const-based re-dispatch
- Due to much higher investment cost
- Operational costs are indeed very similar

Convergence



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Conclusion and perspectives

Summary

- Model of zonal pricing followed by market-based re-dispatch as Generalized Nash
- Efficient in the short run (under simplifying assumptions which do not hold in practice)
- Large losses of efficiency in the long-term
- Splitting algorithm leveraging special structure

Model enhancements

- Uncertainty in the re-dispatch price
- Additional market instruments to recover efficiency

Remaining questions

- Unicity ?
- Convergent algorithm ?

Thank you

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