Congestion Management in a Stochastic Dispatch Model for Electricity Markets

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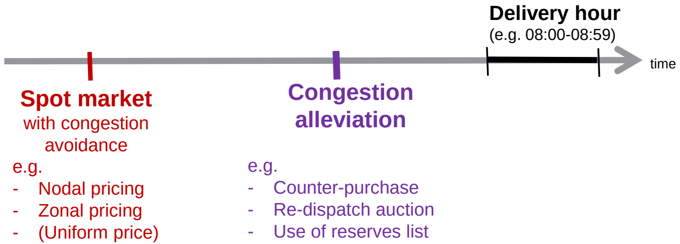
Congestion management and balancing

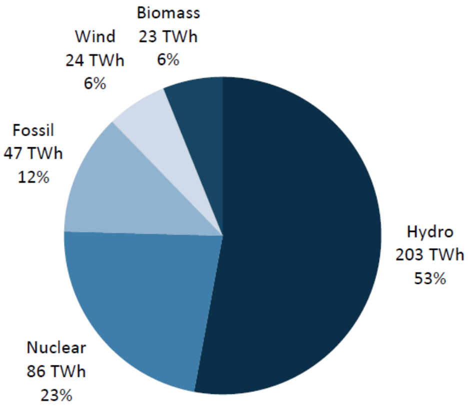


Reasons for inadequate congestion handling:

- Congestion within areas not considered (in full)
- «Loop-flow» not included in market clearing
- Inadequate representation of capacity constraints

Nordic electricity market

Figure 2. Power generation by power source in the Nordic region in 2013



Source: ENTSO-E

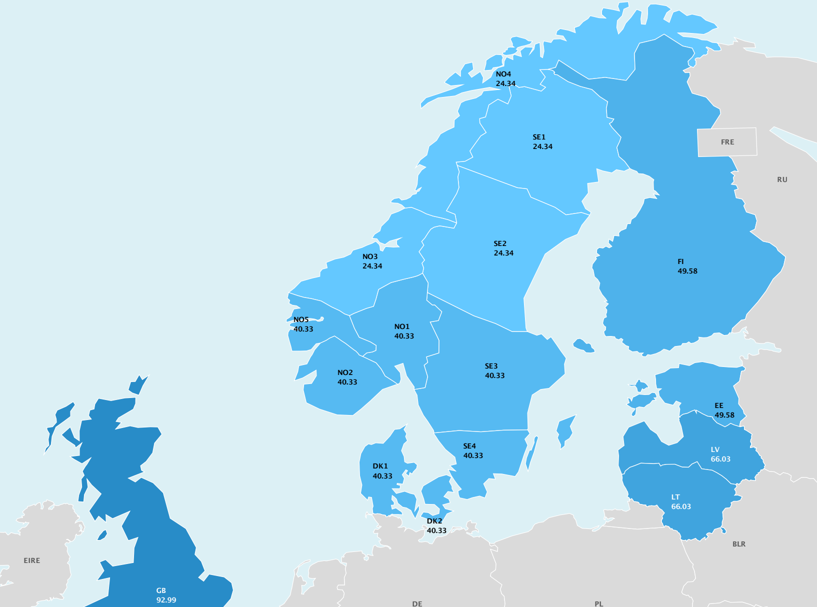
Nordic electricity market

Table 13. Nordic Generation capacity (MW) by power source, 2013

	Denmark	Finland	Norway	Sweden	Nordic region
Installed capacity (total)	14,861	17,300	32,879	38,273	103 313
Nuclear power	-	2,752	-	9,531	12 283
Other thermal power	6,989	11,135	1,040	8,079	27 243
- Condensing power	-	2,465	-	1,375	3 840
- CHP, district heating	1,929	4,375	-	3,631	9 935
- CHP, industry	562	3,180	-	1,498	5 240
- Gas turbines etc.	-	1,115	-	1,575	2 690
Hydro power	9	3,125	30,900	16,150	50 184
Wind power	4,809	288	811	3,745	9 653
Sun power	563	0	N/A	43	606

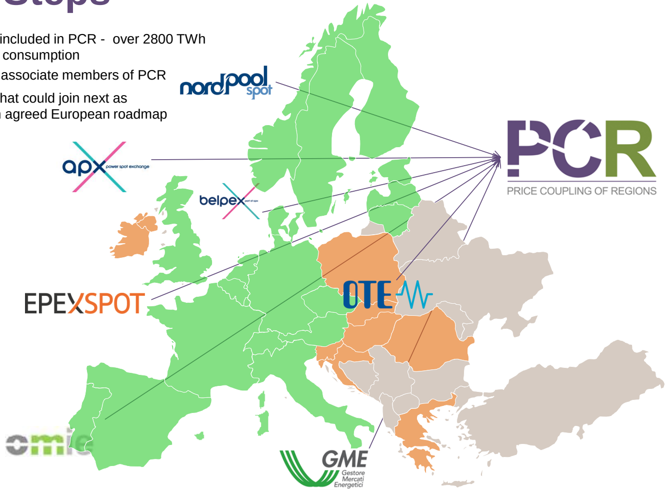
Source: Swedenergy, NVE, DERA, EMI

Nord Pool Spot - 2015/01/12, 18-19

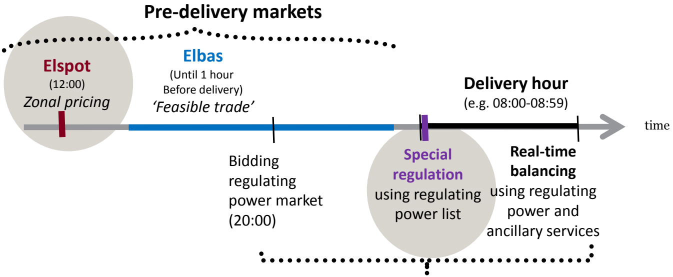


Towards Single European Market: Next Steps

- Markets included in PCR - over 2800 TWh of yearly consumption
- Markets associate members of PCR
- Markets that could join next as part of an agreed European roadmap



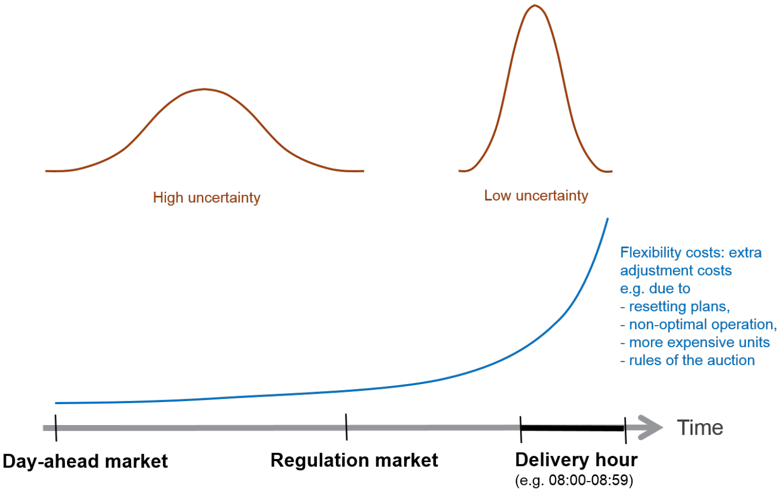
Nordic market



Markets and systems for:

- **Real-time balancing** (Regulating power market, and other ancillary services)
- **Congestion alleviation**

Flexibility costs and uncertainty



Stochastic market clearing

- Literature:
  - Wong and Fuller (2007); Bouffard et al. (2005b,a); Pritchard et al. (2010); Khazaei et al. (2012); Morales et al. (2012); Khazaei et al. (2013, 2014a,b); Morales et al. (2014); Zugno and Conejo (2013) ...
- Our paper:
  - Energy-only stochastic market clearing as in Pritchard et al. (2010)
  - How should the day-ahead part of the market be modeled?
    - Effects of day-ahead network flow and balance constraints
  - Compare to a sequential market clearing model with myopic clearing of the day-ahead part of the market

Outline

Model

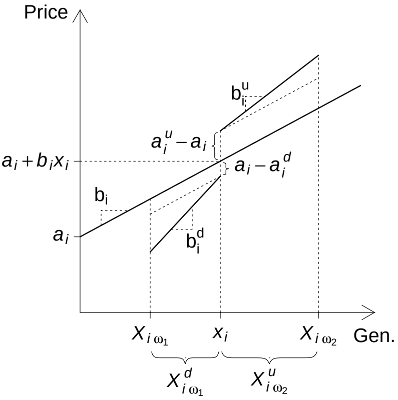
Day-ahead and real-time generation (≥ 0) and load (≤ 0) quantities:

$$x_i \in C_i^1 \qquad \forall i \in I$$

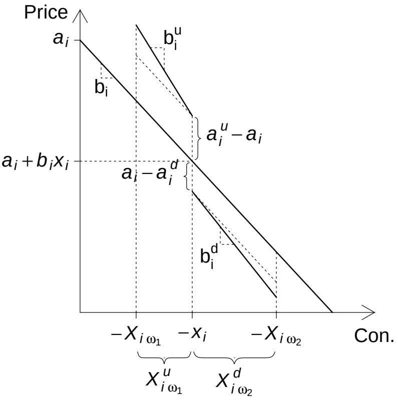
$$X_{i\omega} \in C_i^2(\omega, x_i) \qquad \forall i \in I,\ \omega \in \Omega$$

Upregulation $X_{i\omega}^u = \max\{X_{i\omega} - x_i, 0\}$ or downregulation $X_{i\omega}^d = \max\{x_i - X_{i\omega}, 0\}$ for flexible entities.

Generator cost functions



Load benefit curves



Objective function

Cost of real-time quantity at day-ahead parameters:

$$c_i(X_{i\omega}) = a_i X_{i\omega} + 0.5 b_i (X_{i\omega})^2$$

Flexibility cost:

$$\begin{aligned}\tilde{c}_i(x_i, X_{i\omega}) = &(a_i^u - a_i)X_{i\omega}^u + 0.5(b_i^u - b_i)(X_{i\omega}^u)^2 \\ &+(a_i - a_i^d)X_{i\omega}^d + 0.5(b_i^d - b_i)(X_{i\omega}^d)^2\end{aligned}$$

Stochastic market clearing model

$$\min_{x,f,X,F} \mathbb{E}\left[\sum_{i\in I}\Big(c_i(X_i)+\tilde{c}_i(x_i,X_i)\Big)\right] \tag{1a}$$

s.t.

$$x_i \in C_i^1 \qquad \forall i \in I \tag{1b}$$

$$X_{i\omega} \in C_i^2(\omega, x_i) \qquad \forall i \in I,\ \omega \in \Omega \tag{1c}$$

$$\tau_n(f) + \sum_{i\in I(n)} x_i = 0 \qquad \forall n \in N \qquad [\pi_n] \tag{1d}$$

$$\tau_n(F_\omega) - \tau_n(f) + \sum_{i\in I(n)} (X_{i\omega} - x_i) = 0 \qquad \forall n \in N,\ \omega \in \Omega \qquad [p_\omega \lambda_{n\omega}] \tag{1e}$$

$$f \in U^1 \tag{1f}$$

$$F_\omega \in U^2 \qquad \forall \omega \in \Omega \tag{1g}$$

Myopic market clearing model - day-ahead part

$$\min_{x,f} \sum_{i \in I} c_i(x_i) \tag{2a}$$

s.t.

$$x_i \in C_i^1 \qquad \forall i \in I \tag{2b}$$

$$\tau_n(f) + \sum_{i \in I(n)} x_i = 0 \qquad \forall n \in N \qquad [\pi_n] \tag{2c}$$

$$f \in U^1 \tag{2d}$$

Myopic market clearing model - real-time part, scenario ω

$$\min_{X_\omega, F_\omega} \sum_{i \in I} \Big(c_i(X_{i\omega}) + \tilde{c}_i(x_i, X_{i\omega}) \Big) \tag{3a}$$

s.t.

$$X_{i\omega} \in C_i^2(\omega, x_i) \qquad \forall i \in I \tag{3b}$$

$$\tau_n(F_\omega) - \tau_n(f) + \sum_{i \in I(n)} (X_{i\omega} - x_i) = 0 \qquad \forall n \in N \qquad [p_\omega \lambda_{n\omega}] \tag{3c}$$

$$F_\omega \in U^2 \tag{3d}$$

Day-ahead constraints

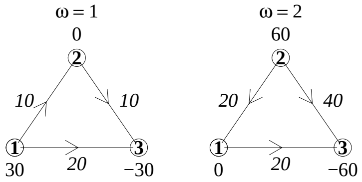
- We assume that U^2 represents the network constraints in a DC load flow model without losses
- What should U^1 represent?

Alternative day-ahead network representations

1. Nodal model, i.e., $U^1 = U^2$
2. Zonal model
   - No loop flow
   - Aggregate flow capacities set by system operator(s)
3. Unconstrained flow, i.e., $U^1 = \mathbb{R}^{|L|}$
4. Unconstrained flow and balance

$$\min[v^{stoch}_{nodal}, v^{stoch}_{zonal}] \geq v^{stoch}_{bal} \geq v^{stoch}_{unc}$$

Example 1

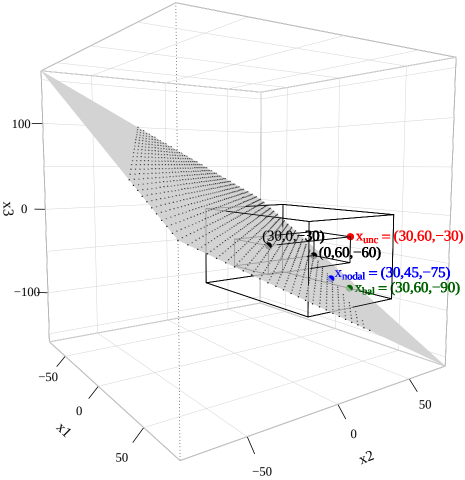


- $P(1) = P(2) = 0.5$
- Real-time quantities X_ω are given above
- All cost parameters equal zero, except $a_1^u = a_2^u = 1$ and $a_3^u = 0.25$
- All lines have identical impedances
- Capacity of line (2,3) is 40

Example 1 - stochastic model

$$
\begin{aligned}
\min\ & 0.5 \cdot 1 \cdot \left([30 - x_1]^+ + [0 - x_1]^+ + [0 - x_3]^+ + [60 - x_3]^+\right) \\
& + 0.5 \cdot 0.25 \cdot \left([-30 - x_3]^+ + [-60 - x_3]^+\right) \\
\text{s.t.} & \\
& x_1 + x_2 + x_3 = 0 \\
& -40 \leq \frac{x_2 - x_3}{3} \leq 40
\end{aligned}
$$

Example 1 - optimal day-ahead schedules

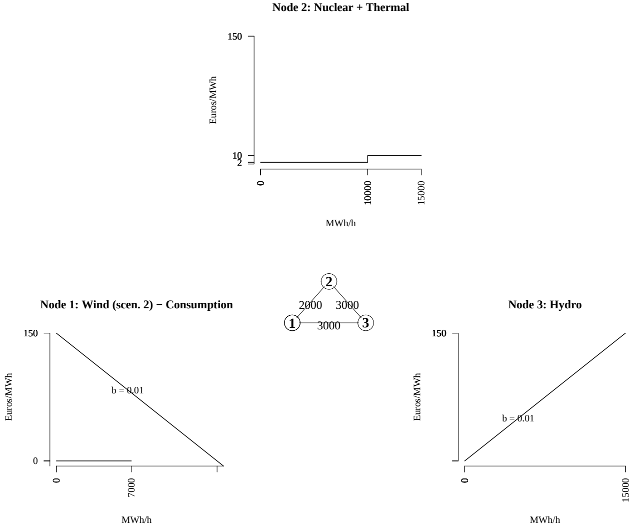


$$v_{unc}^{stoch} = 0$$

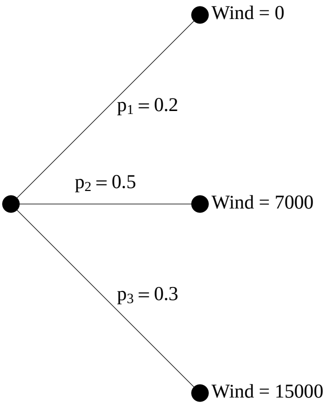
$$v_{bal}^{stoch} = 0.5 \cdot (-30 - (-90)) \cdot 0.25 + 0.5 \cdot (-60 - (-90)) \cdot 0.25 = 11.25$$

$$v_{nodal}^{stoch} = 0.5 \cdot (-30 - (-75)) \cdot 0.25 + 0.5 \cdot \Big[(60 - 45) \cdot 1 + (-60 - (-75)) \cdot 0.25\Big] = 15$$

Example 2


Node 2: Nuclear + Thermal
150
10
2
Euros/MWh
0
10000
15000
MWh/h
2
2000
3000
1
3000
3
Node 1: Wind (scen. 2) − Consumption
150
0
Euros/MWh
b = 0.01
0
7000
MWh/h
Node 3: Hydro
150
Euros/MWh
b = 0.01
0
15000
MWh/h

Wind scenarios



Cost and benefit parameters

Entity	Node	Intercept (a)	Slope (b)	Flexible?	Flex. cost up	Flex. cost down
Wind	1	0	0	Partly	-	-
Load	1	150	0.01	Yes	$b^u = 30b$	-
Nucl.	2	2	0	No	-	-
Therm.	2	10	0	Yes	$a^u - a = 6$	-
Hydro	3	0	0.01	Yes	$b^u = 10b$	-

Example 2 - optimal values, stochastic model

Model	Value (1000 €s)
Wait-and-see	956.620
Unconstrained	952.500
Balanced	950.808
Nodal	950.542
Zonal ($cap_{\{1\},\{2,3\}} = 3000$)	938.986
Zonal ($cap_{\{1\},\{2,3\}} = 5000$)	950.808

Example 2 - optimal schedules, stochastic model

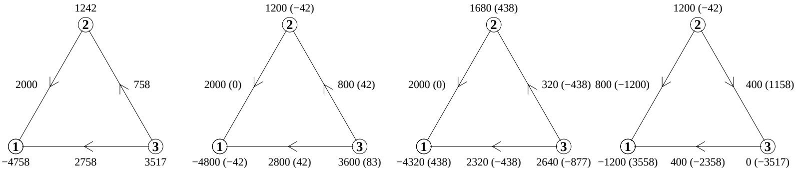
Nodal model

Entity	Day-head	Real-time adj. Low	Medium	High
Wind	0		7000	13800
Nucl.	1200			
Therm.	42	-42	438	-42
Hydro	3517	83	-877	-3517
Load	-4758	-42	-6562	-10242
Total	0	0	0	0

Unconstrained model

Entity	Day-head	Real-time adj. Low	Medium	High
Wind	0		7000	14000
Nucl.	1000			
Therm.	800	-800		-800
Hydro	4000		-1600	-4000
Load	-5000		-6200	-10000
Total	800	-800	-800	-800

Power flow - nodal model



Example 2 - cost and benefit effects, stochastic model

Nodal model

Entity	$\mathbb{E}[-c]$	Flex. costs $(-\tilde{c})$ Low	Medium	High	$\mathbb{E}[-c-\tilde{c}]$
Wind	0.000				0.000
Nucl.	-2.400				-2.400
Therm.	-2.400		-2.630		-3.715
Hydro	-30.384	-0.313			-30.447
Load	987.104				987.104
Total	951.920	-0.313	-2.630	-0.000	950.542

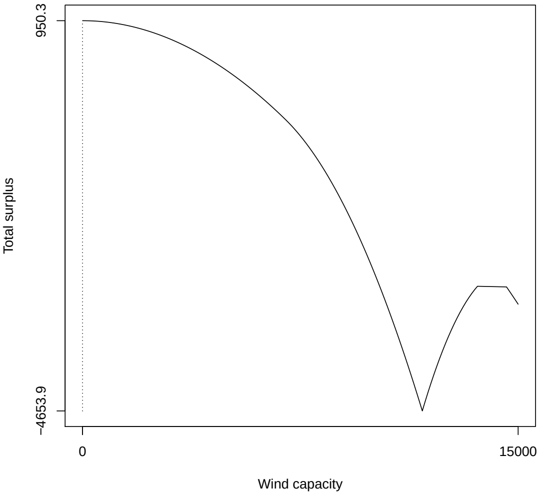
Unconstrained model

$\mathbb{E}[-c]$	Flex. costs $(-\tilde{c})$ Low	Medium	High	$\mathbb{E}[-c-\tilde{c}]$
0.000				0.000
-2.000				-2.000
-4.000				-4.000
-30.400				-30.400
988.900				988.900
952.500	0.000	0.000	0.000	952.500

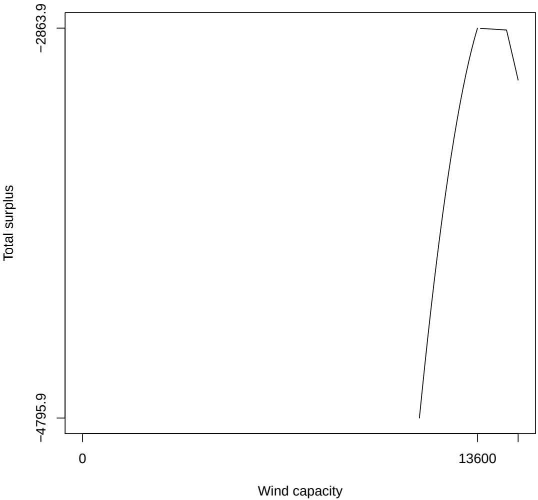
Myopic model

- Infeasibility issue, e.g. due to scheduling of non-flexible nuclear in day-ahead market

Myopic / nodal model - effect of day-ahead wind capacity



Myopic / balanced model - effect of day-ahead wind capacity



Conclusions and further research

- Too restrictive constraints in the day-ahead stage of a stochastic market clearing model may hinder flexibility and yield sub-optimal solutions
- Examples of such constraints are DC load flow capacitites, European-style zonal capacities, and even nodal balance constraints
- Further research:
  - Pricing
  - Investigate relevance for deterministic (sequential) market clearing models

References

Bouffard, F., Galiana, F. D., and Conejo, A. J. (2005a). Market-clearing with stochastic security-part i: formulation. *Power Systems, IEEE Transactions on*, 20(4):1818–1826.

Bouffard, F., Galiana, F. D., and Conejo, A. J. (2005b). Market-clearing with stochastic security-part ii: Case studies. *Power Systems, IEEE Transactions on*, 20(4):1827–1835.

Khazaei, J., Zakeri, G., and Oren, S. (2012). Single and multi-settlement approaches to market clearing mechanisms under demand uncertainty.

Khazaei, J., Zakeri, G., and Oren, S. (2013). Deterministic vs. stochastic settlement approaches to market clearing mechanisms under demand uncertainty.

Khazaei, J., Zakeri, G., and Oren, S. S. (2014a). Market clearing mechanisms under uncertainty.

Khazaei, J., Zakeri, G., and Pritchard, G. (2014b). The effects of stochastic market clearing on the cost of wind integration: a case of new zealand electricity market. *Energy Systems*, 5(4):657–675.

Morales, J., Conejo, A., Liu, K., and Zhong, J. (2012). Pricing electricity in pools with wind producers. *Power Systems, IEEE Transactions on*, 27(3):1366–1376.

Morales, J. M., Zugno, M., Pineda, S., and Pinson, P. (2014). Electricity market clearing with improved scheduling of stochastic production. *European Journal of Operational Research*, 235(3):765 – 774.

Pritchard, G., Zakeri, G., and Philpott, A. (2010). A single-settlement, energy-only electric power market for unpredictable and intermittent participants. *Operations Research*, 58(4-part-2):1210–1219.

Wong, S. and Fuller, J. D. (2007). Pricing energy and reserves using stochastic optimization in an alternative electricity market. *Power Systems, IEEE Transactions on*, 22(2):631–638.

Zugno, M. and Conejo, A. J. (2013). A robust optimization approach to energy and reserve dispatch in electricity markets. Technical report, Technical University of Denmark.