Impact of Forecast errors on Generation and Transmission Expansion Planning

Workshop on Mathematical Models and Methods for Energy Optimization (Budapest)

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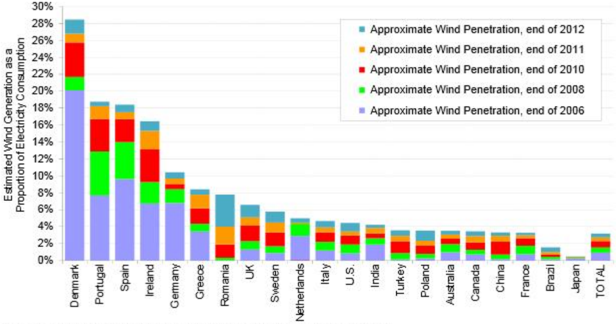
Energy systems

- A **power system** is a network of electrical components used to supply, transmit and use electric power
- Electricity cannot be **stored**: generation = demand
- Increase in production by **renewable** sources: new challenges

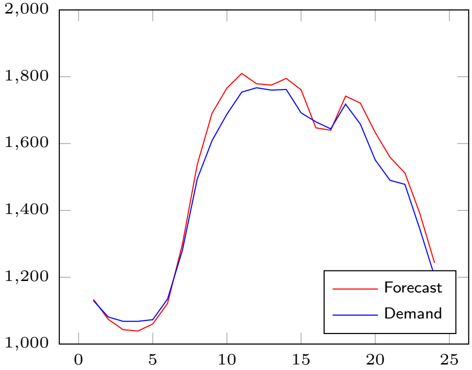


Source: Berkeley Lab estimates based on data from Navigant, EIA, and elsewhere

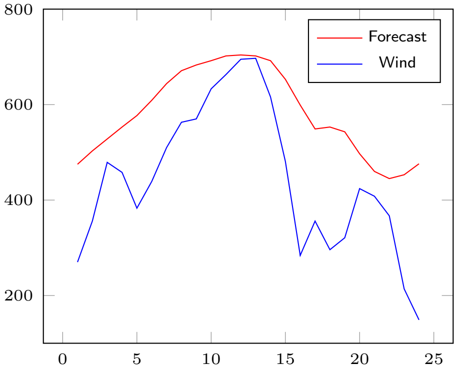
Wind power production

- Wind power production **varies** through time
- Wind power production is **hard to predict** in advance

Demand DK2 (12/08/14)



Wind DK2 (12/08/14)



We were wondering...

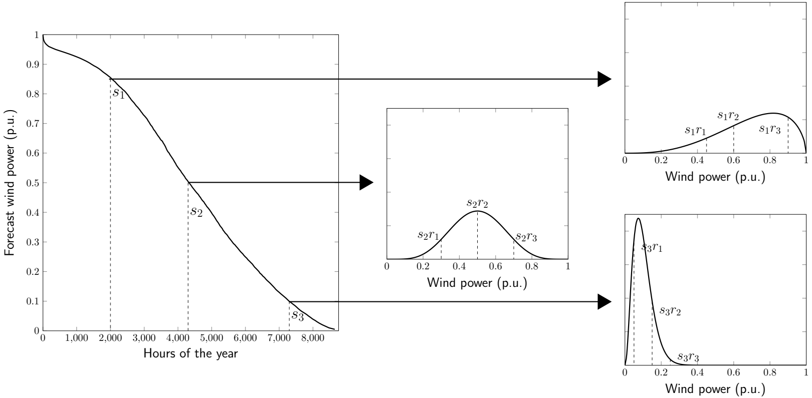
- How can we account for forecast errors within current generation and transmission capacity expansion models?
- What is the impact of these forecast errors on generation and transmission capacity expansion planning?
- What is the impact of the market design on generation and transmission capacity expansion planning?

Some assumptions

- Static expansion models (single target year)
- Focus on short-term uncertainties (scenarios)
- No inter-temporal constraints (stationary process)
- Energy-only market with marginal pricing
- Perfect competitive market
- Convex production cost functions
- Inelastic demand
- DC representation of the network

Two markets floors

Day-ahead market (24 hours before operation) → **Balancing market** (30 minutes before operation)



Coordination between the two market floors

Inefficient market

Day-ahead: min $\mathcal{C}^D(\Phi^D)$

$\downarrow \Phi^D$

Balancing: min $\mathcal{C}^B(\Phi^D, \Phi^B)$

- Cheapest day-ahead
- Expensive balancing
- High total cost
- Reserves after energy

Efficient market

Day-ahead + balancing

min $\mathcal{C}^D(\Phi^D) + \sum_r \pi_r \mathcal{C}^B(\Phi^D, \Phi^B)$

- More expensive day-ahead
- Cheaper balancing
- Minimum total cost
- Simultaneous reserve and energy

We have investigated

- The impact of forecast errors on GE of stochastic units by a central planner:
  - Central GEP without forecast errors
  - Central GEP with forecast errors under efficient market
  - Central GEP with forecast errors under inefficient market
- How a collusion of producers affects the GE of stochastic units:
  - Collusion GEP without forecast errors
  - Collusion GEP with forecast errors under efficient market
  - Collusion GEP with forecast errors under inefficient market
- The impact of forecast errors on G&T expansion by a central planner:
  - G&TEP without forecast errors
  - G&TEP with forecast errors under efficient market
  - G&TEP with forecast errors under inefficient market

Central GEP without forecast errors

$$
\begin{aligned}
\underset{\overline{p}^W, \Phi_s^D}{\text{Min}} \quad & \sum_s \tau_s \mathcal{C}^D\left(\Phi_s^D\right) + \mathcal{C}^I\left(\overline{p}^W\right) \\
\text{s.t.} \quad & f\left(\overline{p}^W\right) \leqslant 0 \\
& h^D\left(\Phi_s^D; l_s\right) = 0, \quad \forall s \\
& g^D\left(\overline{p}^W, \Phi_s^D; \rho_s\right) \leqslant 0, \quad \forall s.
\end{aligned}
$$

$\overline{p}^W$ capacity to be installed

Φ_s^D dispatch decisions

ρ_s capacity factor of stochastic units

Central GEP with forecast errors under efficient market

$$\begin{aligned}\underset{\overline{p}^W,\Phi_s^D,\Phi_{sr}^B}{\text{Min}} \quad & \sum_s \tau_s \left(\mathcal{C}^D\left(\Phi_s^D\right) + \sum_r \pi_{sr} \mathcal{C}^B\left(\Phi_{sr}^B\right)\right) + \mathcal{C}^I\left(\overline{p}^W\right) \\ \text{s.t.} \quad & f\left(\overline{p}^W\right) \leqslant 0 \\ & h^D\left(\Phi_s^D; l_s\right) = 0, \quad \forall s \\ & g^D\left(\overline{p}^W, \Phi_s^D; \rho_s\right) \leqslant 0, \quad \forall s \\ & h^B\left(\Phi_{sr}^B\right) = 0, \quad \forall s, \forall r \\ & g^B\left(\overline{p}^W, \Phi_s^D, \Phi_{sr}^B; \rho_s, \Delta\rho_{sr}\right) \leqslant 0, \quad \forall s, \forall r.\end{aligned}$$

Φ_{sr}^B re-dispatch decisions

$\Delta\rho_{sr}$ variation of capacity factor

Central GEP with forecast errors under inefficient market

$$\begin{aligned}
\underset{\overline{p}^W, \Phi_s^D, \Phi_{sr}^B}{\text{Min}} \quad & \sum_s \tau_s \left(\mathcal{C}^D \left(\Phi_s^D \right) + \sum_r \pi_{sr} \mathcal{C}^B \left(\Phi_{sr}^B \right) \right) + \mathcal{C}^I \left(\overline{p}^W \right) \\
\text{s.t.} \quad & f\left(\overline{p}^W \right) \leqslant 0 \\
& h^B \left(\Phi_{sr}^B \right) = 0, \quad \forall s, \forall r \\
& g^B \left(\overline{p}^W, \Phi_s^D, \Phi_{sr}^B; \rho_s, \Delta\rho_{sr} \right) \leqslant 0, \quad \forall s, \forall r
\end{aligned}$$

$$\Phi_s^D \in \text{arg} \left\{ \begin{aligned} \underset{\Phi_s^D}{\text{Min}} \quad & \mathcal{C}^D \left(\Phi_s^D \right) \\ \text{s.t.} \quad & h^D \left(\Phi_s^D; l_s \right) = 0 \\ & g^D \left(\overline{p}^W, \Phi_s^D; \rho_s \right) \leqslant 0. \end{aligned} \right\} \forall s.$$

Impose cost merit-order at the day-ahead

Data of illustrative example

- Four 100-MW inflexible blocks with marginal costs 20, 21, 22, 23
- Two 100-MW flexible blocks with marginal costs 24, 25
- A constant load of 400 MW and no network
- Expansion of one hundred 5-MW units with a cost of $430000
- Two time segments: $\rho_{s1} = 0.2$ and $\rho_{s2} = 0.8$
- Four equiprobable scenarios for forecast errors:

$\Delta\rho_{s1r1} = -0.07$	$\Delta\rho_{s1r2} = -0.02$	$\Delta\rho_{s1r3} = 0.02$	$\Delta\rho_{s1r4} = 0.08$
$\Delta\rho_{s2r1} = -0.26$	$\Delta\rho_{s2r2} = -0.02$	$\Delta\rho_{s2r3} = 0.10$	$\Delta\rho_{s2r4} = 0.18$

Generation expansion under perfect competition

	$\overline{p}$ (MW)	$\mathcal{C}^I$ (\$M)	$\overline{\mathcal{C}}^D$ (\$M)	$\overline{\mathcal{C}}^B$ (\$M)	$\overline{\mathcal{C}}$ (\$M)	ψ (%)
No errors	410	35.26	35.82	0.00	71.08	51.25
Efficient	360	30.96	42.35	-0.83	72.48	45.02
Inefficient	250	21.50	50.58	2.45	74.54	28.34

- Without forecast errors we get the highest capacity and wind share
- Forecast errors reduce the installed capacity and the wind share
- An efficient market designs soften the adverse effects of forecast errors

Collusion GEP without forecast errors

$$
\begin{aligned}
\underset{\overline{p}^W}{\text{Max}} \quad & \sum_s \tau_s \Pi^D \left(\Phi_s^D, \lambda_s^D\right) - \mathcal{C}^I \left(\overline{p}^W\right) \\
\text{s.t.} \quad & f\left(\overline{p}^W\right) \leqslant 0 \\
& \left(\Phi_s^D, \lambda_s^D\right) \in \text{arg} \left\{ \begin{aligned} \underset{\Phi_s^D}{\text{Min}} \quad & \mathcal{C}^D\left(\Phi_s^D\right) \\ \text{s.t.} \quad & h^D\left(\Phi_s^D; l_s\right) = 0 : \lambda_s^D \\ & g^D\left(\overline{p}^W, \Phi_s^D; \rho_s\right) \leqslant 0 \end{aligned} \right\} \forall s
\end{aligned}
$$

Π^D revenue in the day-ahead market

λ_s^D day-ahead price

Collusion GEP with forecast errors under efficient market

$$\begin{aligned} \underset{\overline{p}^W}{\text{Max}} \quad & \sum_s \tau_s \left(\Pi^D\left(\Phi_s^D, \lambda_s^D\right) + \sum_r \pi_{sr} \Pi^B \left(\Phi_{sr}^B, \lambda_{sr}^B\right) \right) - \mathcal{C}^I\left(\overline{p}^W\right) \\ \text{s.t.} \quad & f\left(\overline{p}^W\right) \leqslant 0 \end{aligned}$$

$$\begin{pmatrix} \Phi_s^D, \lambda_s^D \\ \Phi_{sr}^B, \lambda_{sr}^B \end{pmatrix} \in \arg \left\{ \begin{aligned} \underset{\Phi_s^D, \Phi_{sr}^B}{\text{Min}} \quad & \mathcal{C}^D\left(\Phi_s^D\right) + \sum_r \pi_{sr} \mathcal{C}^B\left(\Phi_{sr}^B\right) \\ \text{s.t.} \quad & h^D\left(\Phi_s^D; l_s\right) = 0 : \lambda_s^D \\ & g^D\left(\overline{p}^W, \Phi_s^D; \rho_s\right) \leqslant 0 \\ & h^B\left(\Phi_{sr}^B\right) = 0 : \pi_{sr}\lambda_{sr}^B, \quad \forall r \\ & g^B\left(\overline{p}^W, \Phi_s^D, \Phi_{sr}^B; \rho_s, \Delta\rho_{sr}\right) \leqslant 0, \quad \forall r \end{aligned} \right\} \forall s$$

Π^B revenue in the balancing market

λ_{sr}^B balancing price

Collusion GEP with forecast errors under inefficient market

$$\begin{aligned} \underset{\overline{p}^W}{\text{Max}} \quad & \sum_s \tau_s \left(\Pi^D \left(\Phi_s^D, \lambda_s^D \right) + \sum_r \pi_{sr} \Pi^B \left(\Phi_{sr}^B, \lambda_{sr}^B \right) \right) - \mathcal{C}^I \left(\overline{p}^W \right) \\ \text{s.t.} \quad & f \left(\overline{p}^W \right) \leqslant 0 \end{aligned}$$

$$\left(\Phi_s^D, \lambda_s^D \right) \in \arg \left\{ \begin{aligned} \underset{\Phi_s^D}{\text{Min}} \quad & \mathcal{C}^D \left(\Phi_s^D \right) \\ \text{s.t.} \quad & h^D \left(\Phi_s^D; l_s \right) = 0 : \lambda_s^D \\ & g^D \left(\overline{p}^W, \Phi_s^D; \rho_s \right) \leqslant 0 \end{aligned} \right\} \forall s$$

$$\left(\Phi_{sr}^B, \lambda_{sr}^B \right) \in \arg \left\{ \begin{aligned} \underset{\Phi_{sr}^B}{\text{Min}} \quad & \mathcal{C}^B \left(\Phi_{sr}^B \right) \\ \text{s.t.} \quad & h^B \left(\Phi_{sr}^B \right) = 0 : \lambda_{sr}^B \\ & g^B \left(\overline{p}^W, \Phi_s^D, \Phi_{sr}^B; \rho_s, \Delta\rho_{sr} \right) \leqslant 0 \end{aligned} \right\} \forall sr.$$

Collusion GEP with forecast errors under inefficient market

$$\underset{\overline{p}^W}{\text{Max}} \quad \sum_s \pi_s \left(\Pi^D \left(\Phi_s^D, \widehat{\lambda}_s^D \right) + \sum_r \pi_{sr} \Pi^B \left(\Phi_{sr}^B, \lambda_{sr}^B \right) \right) - \mathcal{C}^I \left(\overline{p}^W \right)$$

$$\text{s.t.} \quad f\left(\overline{p}^W\right) \leqslant 0$$

$$\begin{pmatrix} \Phi_s^D, \lambda_s^D \\ \Phi_{sr}^B, \lambda_{sr}^B \end{pmatrix} \in \text{arg} \left\{ \begin{array}{ll} \underset{\Phi_s^D, \Phi_{sr}^B}{\text{Min}} & \mathcal{C}^D \left(\Phi_s^D \right) + \sum_r \pi_{sr} \mathcal{C}^B \left(\Phi_{sr}^B \right) \\ \text{s.t.} & h^B \left(\Phi_{sr}^B \right) = 0 : \pi_{sr} \lambda_{sr}^B \\ & g^B \left(\overline{p}^W, \Phi_s^D, \Phi_{sr}^B; \rho_s, \Delta\rho_{sr} \right) \leqslant 0 \\ \Phi_s^D \in \text{arg} & \left\{ \begin{array}{ll} \underset{\Phi_s^D}{\text{Min}} & \mathcal{C}^D \left(\Phi_s^D \right) \\ \text{s.t.} & h^D \left(\Phi_s^D; l_s \right) = 0 : \widehat{\lambda}_s^D \\ & g^D \left(\overline{p}^W, \Phi_s^D; \rho_s \right) \leqslant 0 \end{array} \right\} \end{array} \right\} \forall s$$

Generation expansion under imperfect competition

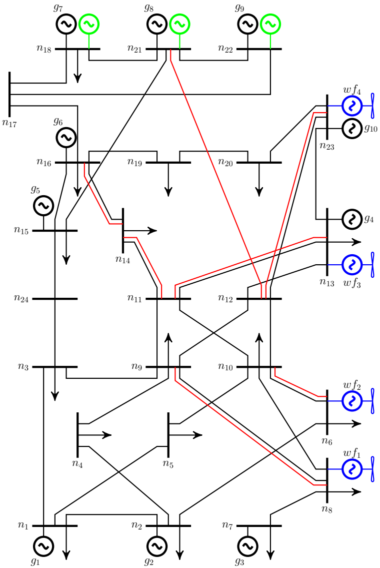
	Perfect competition			Collusion		
	$\overline{p}$ (MW)	$\overline{\mathcal{C}}$ ($M)	ψ (%)	$\overline{p}$ (MW)	$\overline{\mathcal{C}}$ ($M)	ψ (%)
No errors	410	71.08	51.25	305	71.69	38.14
Efficient	360	72.48	45.02	200	73.84	25.01
Inefficient	250	74.54	28.34	120	74.99	13.60

- Under a collusion the installed capacities decrease
- Forecast errors reduce the capacity and the wind share
- An efficient market designs soften the adverse effects of forecast errors

Generation and transmission expansion models

- Investment decisions made by a central planner
- New stochastic and conventional generation
- New transmission lines
- Day-ahead and a balancing market
- Forecast errors of load and wind production
- Efficient and inefficient market design

Generation and transmission expansion models



- 24-bus system (IEEE)
- 10 existing conventional units
- 3 flexible generating units
- Variable demand
- 4 projects of stochastic units
- 3 new flexible generating units
- 7 new transmission lines
- Renewable target of 20/30/40%

G&T expansion for 20% renewable target

		No errors	Efficient	Inefficient
Wind capacity	n_6	-	-	50
	n_8	950	1000	900
	n_{13}	-	-	-
	n_{23}	400	350	450
Flexible Generation	n_{18}	-	-	-
	n_{21}	-	80	-
	n_{22}	-	-	160
Line capacity	n_6n_{10}	-	-	-
	n_8n_9	-	-	-
	$n_{11}n_{13}$	175	175	175
	$n_{11}n_{14}$	-	-	175
	$n_{12}n_{21}$	-	350	-
	$n_{12}n_{23}$	-	-	-
	$n_{14}n_{16}$	-	-	175
Investment cost		162.6	165.1	172.8

Impact of forecast errors on G&T expansion

		Renewable target		
Market	Expansion	20%	30%	40%
Efficient	Errors	474.8(20)	527.8(30)	589.2(40)
	No errors	475.5(19.2)	530.7(26.5)	587.7(31.5)
Inefficient	Errors	484.2(20)	543.6(30)	607.8(40)
	No errors	526.5(19.3)	631.7(28.7)	728.2(36.1)

- Under an efficient market, disregarding the errors will entail a reduction of the renewable target
- Under an inefficient market, disregarding the errors will entail a significant increase of the cost

Conclusions

- We have presented a set of generation and transmission expansion models that account for the forecast errors of stochastic production
- These models can be reformulated as single-level mixed-integer linear or non-linear programming problems
- Considering production forecast errors impacts the expansion plans for the generation and transmission of power systems
- An efficient market design softens the negative effects of forecast errors and leads to cheaper expansion plans and higher penetration levels of renewable production
- The consequences of an expansion plan determined under an error-free assumption highly depend on the market design

Future research

- Model intermediate situations at the investment level between perfect competition and collusion
- Model intermediate market designs between the paradigmatic efficient and inefficient
- Model the exercise of market power by the producers when offering in the electricity market
- Apply dedicated computational methods to improve tractability of the multi-year case

Thanks for the attention!

Questions?

Website: https://sites.google.com/site/slv2pm/