Capacity Expansion of Stochastic Power Generation under Two-Stage Electricity Markets

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Motivation

- Stochastic power generation (wind, solar) depends on weather
- Stochastic power generation is hard to forecast (even 24h in advance)
- Energy markets usually have two trading floors

$$\boxed{\begin{array}{c}\text{Day-ahead market}\\ \text{(24 hours before operation)}\end{array}} \longrightarrow \boxed{\begin{array}{c}\text{Balancing market}\\ \text{(30 minutes before operation)}\end{array}}$$

- Stochastic units have imbalance costs due to forecast errors
- Capacity expansion problems aim at determining the optimal type, quantity and location of power plants to be constructed
- Capacity expansion has to account for the following features of stochastic power generation:
  - Time variability ✓
  - Long-term uncertainty ✓
  - Short-term uncertainty ✗

Contribution

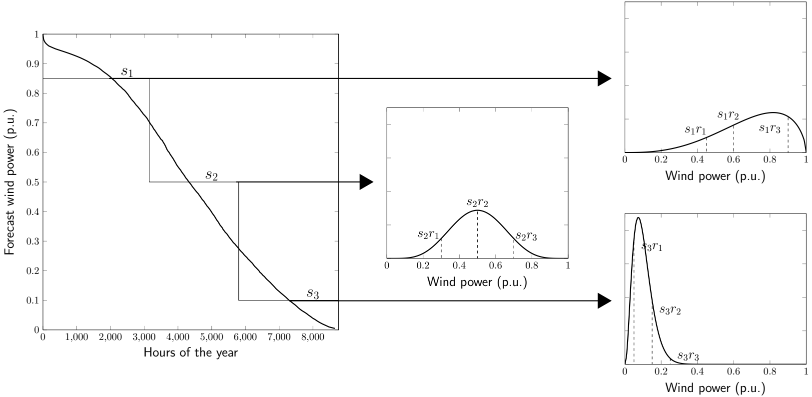
- To develop generation expansion models that explicitly account for short-term **forecast errors** of stochastic power production.
- To analyze the effect of **market design** on generation expansion by considering two paradigmatic market-clearing mechanisms.
- To investigate the impact of **competition** at the investment level in the generation expansion of stochastic power units.

Modeling overview

- Static approach with a single representative year
- Energy-only market
- Duration curves to capture time variability
- Long-term uncertainty not included
- Unit commitment constraints disregarded
- Characterization of short-term forecast errors

Characterization of short-term forecast errors

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



Modeling overview

- Static approach with a single representative year
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- Competition at the investment stage (central planner and collusion)

Competition at investment

Central planner

Investment + operation

minimize total cost

- Perfect competition
- Easier to model
- Benchmark

Collusion

Investment: maximize profit

$\downarrow \overline{p}^W$

Operation: minimize cost

- Imperfect competition
- Strategic investment
- Sequential game

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- Market design (day-ahead, efficient and inefficient)

Market design

Day-ahead market	Efficient market	Inefficient market
Day-ahead	Day-ahead + balancing	Day-ahead $\xrightarrow{\Phi^D}$ Balancing

Day-ahead market

- No balancing market
- No forecast errors
- Fully flexible
- Commonly used approach

Efficient market

- Expensive day-ahead
- Cheaper balancing
- Low total cost
- Simultaneous reserve and energy

Inefficient market

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

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- Characterization of short-term forecast errors
- Competition at the investment stage (central planner and collusion)
- Market design (day-ahead, efficient and inefficient)
- Six generation expansion models to be compared

Central planner			Collusion		
DayMC	EffMC	IneMC	DayMC	EffMC	IneMC

Central, perfect forecast, day-ahead market

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

s	System state index
τ_s	System state weight
ρ_s	System state parameters
$\overline{p}^W$	Investment decisions
$\mathcal{C}^I(\cdot)$	Investment cost
$f(\cdot)$	Investment constraints
Φ_s^D	Dispatch decisions
$\mathcal{C}^D(\cdot)$	Dispatch cost
$g(\cdot)$	Dispatch constraints

For discrete investment decisions and linear functions $\Longrightarrow$ MIP

Central, imperfect forecast, efficient two-stage market

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

r	Balancing scenario index	Φ_{sr}^B	Redispatch decisions
π_{sr}	Balancing scenario probability	$\mathcal{C}^B\left(\cdot\right)$	Redispatch cost
$\Delta\rho_{sr}$	Parameter variations	$h\left(\cdot\right)$	Redispatch constraints

For discrete investment decisions and linear functions $\Longrightarrow$ MIP

Central, imperfect forecast, inefficient two-stage market

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

- Particular use of bilevel programming to impose day-ahead merit order
- Discrete investment decisions and linear functions
- Replace the lower-level problem by its primal-dual formulation
- Linearize the products of continuous and binary variables
- We obtain a single-level mixed-integer linear programming problem

Collusion, perfect forecast, day-ahead market

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

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

Π^D Day-ahead profit
λ_s^D Day-ahead price

- Discrete investment decisions and linear functions
- Replace the lower-level problem by its primal-dual formulation
- Linearize profit expression using KKT conditions
- Linearize the products of continuous and binary variables
- We obtain a single-level mixed-integer linear programming problem

Collusion, imperfect forecast, efficient two-stage market

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

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

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

- Discrete investment decisions and linear functions
- Replace the lower-level problem by its primal-dual formulation
- Linearize profit expression using KKT conditions
- Linearize the products of continuous and binary variables
- We obtain a single-level mixed-integer linear programming problem

Collusion, imperfect forecast, inefficient two-stage market

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

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

- Three-level optimization problem with particular structure since second-level variables $\left(\Phi_{sr}^B \right)$ do not enter the third-level problem.

Collusion, imperfect forecast, inefficient two-stage market

- Discrete investment decisions and linear functions
- Replace the third-level problem by its primal-dual formulation.
- For fix upper-level decisions, the resulting lower-level problem still satisfies the linearity constraint qualification.
- Replace the lower-level problem by its primal-dual formulation.
- Linearize the products of continuous and binary variables.
- The profit expression cannot be linearized.
- We obtain a single-level mixed-integer non-linear programming problem.
- We use an heuristic procedure to find a solution close to the optimal one and provide it as an initial point to the non-linear solver.

Danish case study

- 2 bus system (DK1, DK2) with 600MW transmission line
- Hourly demand and wind capacity factor of 2012
- Approximated supply cost function using aggregated conventional production and prices of 2012
- 25 system states (demand and wind variability)
- 10 balancing scenarios for each state (short-term wind uncertainty)
- Wind investment blocks of 50 MW
- No existing wind generating capacity

Danish case study

Table: Central-planner

	$\overline{p}_{DK1}$	$\overline{p}_{DK2}$	$\overline{\mathcal{C}}$	ψ
DayMC	3500	2500	6834	42.9
EffMC	3500	2250	6999	40.2
IneMC	3450	2350	7067	39.4

Table: Collusion

	$\overline{p}_{DK1}$	$\overline{p}_{DK2}$	$\overline{\Pi}$	ψ
DayMC	2150	1950	612	29.4
EffMC	1300	1600	475	20.6
IneMC	300	2550	277	19.3

- Forecast errors reduce investments, cost, profit and renewable share
- An efficient market clearing reduces the impact of forecast errors
- Impact of forecast errors is larger for imperfect competition
- Forecast errors and market design also affects investment locations

Conclusions

- We have presented a family of generation expansion models for stochastic generating plants that account for the impact of short-term forecast errors. The models differ in the market design and competitiveness at the investment level.
- We have formulated some of these models as multi-level optimization problems and shown how to recast them, under certain assumptions, as single-level linear and non-linear optimization problems that can be solved using commercial software.
- We have provided the results of a case study based on the danish power system to show that forecast errors affect the install capacity of stochastic power plants and that an efficient short-term market can lead to higher investment in renewable power generation.

All details in...

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Thanks for the attention!

Questions???

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