Modeling the Impact of Imbalance Costs and Market Design on Generating Expansion of Stochastic Units

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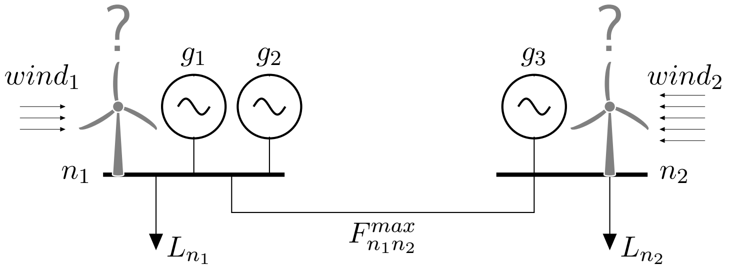
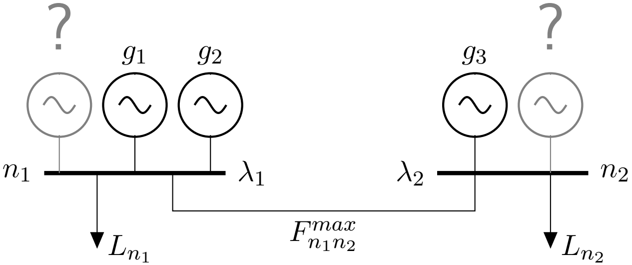
What is this presentation about?



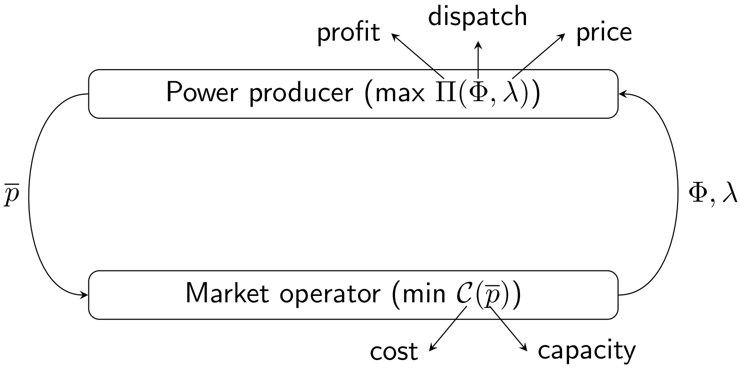
- 200 MW of wind capacity: n_1 or n_2?
  - a) Since $wind_2 > wind_1 \rightarrow \overline{w}_1 = 0$ MW and $\overline{w}_2 = 200$ MW
  - b) It depends on **forecast errors** and how these are handled by the **market**

Where should we start?



- 200 MW of conventional capacity: n_1 or n_2?
  - a) Historical data:
    - If $\lambda_1 > \lambda_2 \rightarrow 200$ MW at n_1
    - If $\lambda_2 > \lambda_1 \rightarrow 200$ MW at n_2
  - b) Not so sure since you are neglecting the **impact of your capacity** on the market outcomes

How do we model the impact of capacity on market?



- Two decision makers
- Each with their individual objectives
- Act and react in a noncooperative sequential manner
- Framework: bilevel programming

How do we formulate the GEP using bilevel programming?

$$\underset{\overline{p}}{\mathrm{Max}} \quad \Pi\left(\Phi, \lambda\right) - \mathcal{C}^{I}\left(\overline{p}\right) \tag{1a}$$

$$\text{s.t.} \quad f\left(\overline{p}\right) \leqslant 0 \tag{1b}$$

$$\left(\Phi, \lambda\right) \in \mathsf{arg}\left\{\begin{aligned} &\underset{\Phi}{\mathrm{Min}} && \mathcal{C}\left(\Phi\right) && \text{(1c)}\\ &\text{s.t.} && h\left(\Phi\right) - l = 0 : \lambda && \text{(1d)}\\ & && g\left(\overline{p}, \Phi\right) \leqslant 0 : \sigma && \text{(1e)} \end{aligned}\right\}$$

How do we solve the bilevel problem?

- We replace the lower-level problem by its KKT conditions (convexity)

$$\max_{\overline{p}} \quad \Pi\left(\Phi,\lambda\right) - \mathcal{C}^{I}\left(\overline{p}\right) \tag{2a}$$

$$\text{s.t.} \quad f\left(\overline{p}\right) \leqslant 0 \tag{2b}$$

$$h\left(\Phi\right) - l = 0 \tag{2c}$$

$$g\left(\overline{p},\Phi\right) \leqslant 0 \tag{2d}$$

$$\nabla_{\Phi}\mathcal{C} + \lambda^{T}\nabla_{\Phi}h + \sigma^{T}\nabla_{\Phi}g = 0 \tag{2e}$$

$$\sigma \geqslant 0 \tag{2f}$$

$$\sigma^{T}g = 0 \tag{2g}$$

Any alternative?

- Replace the complementarity conditions by primal-dual strong duality

$$
\begin{aligned}
\underset{\overline{p}}{\text{Max}} \quad & \Pi\left(\Phi,\lambda\right) - \mathcal{C}^{I}\left(\overline{p}\right) && \text{(3a)}\\
\text{s.t.} \quad & f\left(\overline{p}\right) \leqslant 0 && \text{(3b)}\\
& h\left(\Phi\right) - l = 0 && \text{(3c)}\\
& g\left(\overline{p},\Phi\right) \leqslant 0 && \text{(3d)}\\
& \nabla_{\Phi}\mathcal{C} + \lambda^{T}\nabla_{\Phi}h + \sigma^{T}\nabla_{\Phi}g = 0 && \text{(3e)}\\
& \sigma \geqslant 0 && \text{(3f)}\\
& \mathcal{C}(\Phi) = \underset{\Phi}{\text{Min}} \quad \mathcal{C}(\Phi) + \lambda^{T}\left(h(\Phi) - l\right) + \sigma^{T}g(\Phi,\overline{p}) && \text{(3g)}
\end{aligned}
$$

How do we deal with demand variations?

- We use scenarios characterizing the demand variability throughout the planning horizon (l_s, π_s)

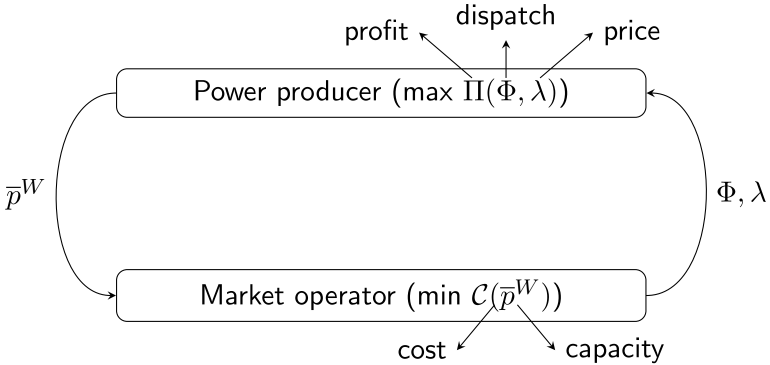
$$\underset{\overline{p}}{\text{Max}} \quad \sum_s \pi_s \Pi\left(\Phi_s, \lambda_s\right) - \mathcal{C}^I\left(\overline{p}\right) \tag{4a}$$

$$\text{s.t.} \quad f\left(\overline{p}\right) \leqslant 0 \tag{4b}$$

$$\left(\Phi_s, \lambda_s\right) \in \text{arg} \left\{ \begin{aligned} & \underset{\Phi}{\text{Min}} && \mathcal{C}\left(\Phi_s\right) && \text{(4c)} \\ & \text{s.t.} && h\left(\Phi_s\right) - l_s = 0 : \lambda_s && \text{(4d)} \\ & && g\left(\overline{p}, \Phi_s\right) \leqslant 0 : \sigma_s && \text{(4e)} \end{aligned} \right\} \forall s.$$

What stays the same for GE of stochastic units?

- We can also use bilevel programming to model the impact of new capacities on market outcomes



What is different for GE of stochastic units?

- Wind variability: the production of stochastic units depends on weather conditions
- Wind uncertainty: the production of stochastic units is difficult to forecast 24 hours ahead

How do we incorporate wind variability into the GEP?

- We use scenarios characterizing the wind and demand variability throughout the planning horizon (ρ_s, l_s, π_s)
- $\rho_s \in [0,1]$ is the capacity factor of wind

$$\underset{\overline{p}^W}{\text{Max}} \quad \sum_s \pi_s \Pi\left(\Phi_s, \lambda_s\right) - \mathcal{C}^I\left(\overline{p}^W\right) \tag{5a}$$

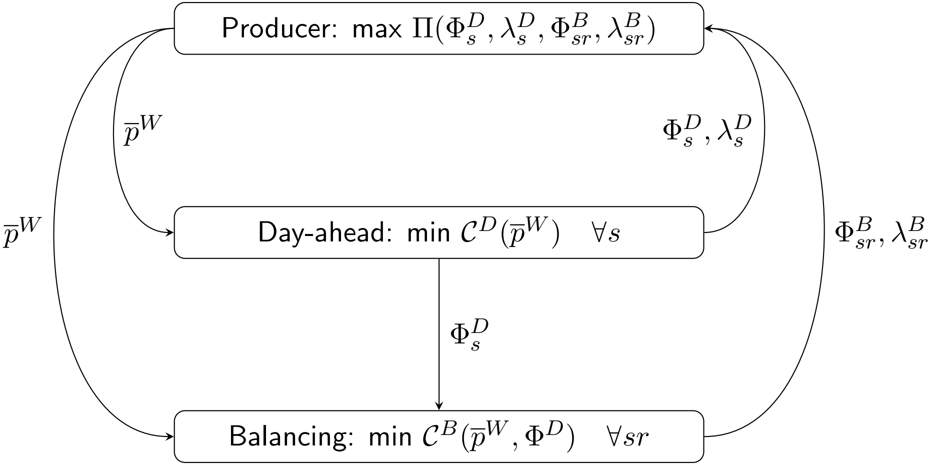
$$\text{s.t.} \quad f\left(\overline{p}^W\right) \leqslant 0 \tag{5b}$$

$$\left(\Phi_s, \lambda_s\right) \in \text{arg} \left\{ \begin{array}{ll} \underset{\Phi}{\text{Min}} & \mathcal{C}\left(\Phi_s\right) \qquad (5c) \\ \text{s.t.} & h\left(\Phi_s\right) - l_s = 0 : \lambda_s \qquad (5d) \\ & g\left(\overline{p}^W, \Phi_s; \rho_s\right) \leqslant 0 : \sigma_s \qquad (5e) \end{array} \right\} \forall s.$$

How do we incorporate wind uncertainty into the GEP?

- We need to model two markets:
  - Day-ahead market
  - Balancing market
- We need to include more uncertain parameters:
  - Production forecast: ρ_s
  - Forecast errors: $\Delta\rho_{sr}$

How do we model the two markets?



What if the two markets are coordinated?

Producer: max $\Pi(\Phi_s^D, \lambda_s^D, \Phi_{sr}^B, \lambda_{sr}^B)$

$\overline{p}^W$

Φ_s^D, λ_s^D
$\Phi_{sr}^B, \lambda_{sr}^B$

min $\mathcal{C}^D(\overline{p}^W) + \sum_r \pi_{sr}\mathcal{C}^B(\overline{p}^W, \Phi^D) \quad \forall s$

What are the differences between the market design?

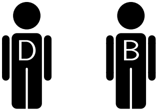
Inefficient market

Day-ahead: min $\mathcal{C}^D(\overline{p}^W)$

$\downarrow \Phi_s^D$

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

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

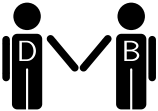


Efficient market

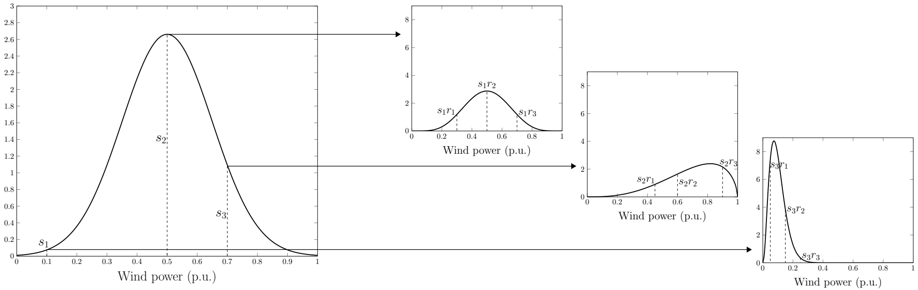
Day-ahead + balancing

min $\mathcal{C}^D(\overline{p}^W) + \sum_r \pi_{sr}\mathcal{C}^B(\overline{p}^W, \Phi^D)$

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



How do we characterize the uncertain parameters?



s → scenarios in the day-ahead market
r → scenarios in the balancing market

How do we incorporate scenarios into the GEPs?

Inefficient market

Maximize GENCO's profit

- DA market (s1)
- B market (s1,r1)
- B market (s1,r2)
- DA market (s2)
- B market (s2,r1)
- B market (s2,r2)
- DA market (s3)
- B market (s3,r1)
- B market (s3,r2)
- DA market (s4)
- B market (s4,r1)
- B market (s4,r2)

Efficient market

Maximize GENCO's profit

- DA market (s1)
  - B market (s1,r1)
  - B market (s1,r2)
- DA market (s2)
  - B market (s2,r1)
  - B market (s2,r2)
- DA market (s3)
  - B market (s3,r1)
  - B market (s3,r2)
- DA market (s4)
  - B market (s4,r1)
  - B market (s4,r2)

How do we formulate a GEP under the efficient market?

$$\underset{\overline{p}^W}{\text{Max}} \quad \sum_s \pi_s \left(\Pi^D \left(\Phi_s^D, \lambda_s^D \right) + \sum_r \pi_{sr} \Pi^B \left(\Phi_{sr}^B, \lambda_{sr}^B \right) \right) - \mathcal{C}^I \left(\overline{p}^W \right) \tag{6a}$$

$$\text{s.t.} \quad f\left(\overline{p}^W \right) \leqslant 0 \tag{6b}$$

$$\begin{pmatrix} \Phi_s^D, \lambda_s^D \\ \Phi_{sr}^B, \lambda_{sr}^B \end{pmatrix} \in \text{arg} \left\{ \begin{array}{rll} \underset{\Phi_s^D, \Phi_{sr}^B}{\text{Min}} & \mathcal{C}^D\left(\Phi_s^D\right) + \sum_r \pi_{sr} \mathcal{C}^B\left(\Phi_{sr}^B\right) & (6c) \\ \text{s.t.} & h^D\left(\Phi_s^D\right) - l_s = 0 : \lambda_s^D & (6d) \\ & g^D\left(\overline{p}^W, \Phi_s^D; \rho_s\right) \leqslant 0 & (6e) \\ & h^B\left(\Phi_{sr}^B\right) = 0 : \pi_{sr}\lambda_{sr}^B & (6f) \\ & g^B\left(\overline{p}^W, \Phi_s^D, \Phi_{sr}^B; \rho_s, \Delta\rho_{sr}\right) \leqslant 0 & (6g) \end{array} \right\} \forall s.$$

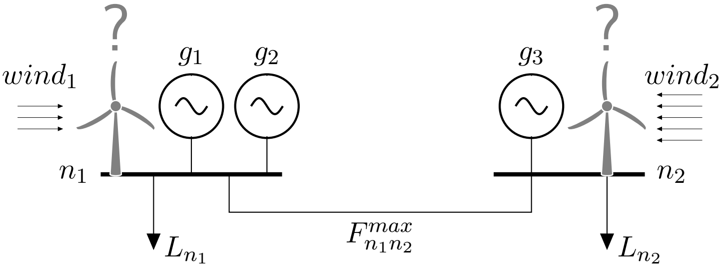
How do we formulate a GEP under the inefficient market?

$$\underset{\overline{p}^W}{\text{Max}} \quad \sum_s \pi_s \left(\Pi^D \left(\Phi_s^D, \widehat{\lambda}_s^D \right) + \sum_r \pi_{sr} \Pi^B \left(\Phi_{sr}^B, \lambda_{sr}^B \right) \right) - \mathcal{C}^I \left(\overline{p}^W \right) \qquad \text{(7a)}$$

$$\text{s.t.} \quad f \left(\overline{p}^W \right) \leqslant 0 \qquad \text{(7b)}$$

$$\begin{pmatrix} \Phi_s^D, \lambda_s^D \\ \Phi_{sr}^B, \lambda_{sr}^B \end{pmatrix} \in \text{arg} \left\{ \begin{array}{ll} \underset{\Phi_s^D, \Phi_{sr}^B}{\text{Min}} & \mathcal{C}^D \left(\Phi_s^D \right) + \sum_r \pi_{sr} \mathcal{C}^B \left(\Phi_{sr}^B \right) \qquad \text{(7c)} \\ \text{s.t.} & h^B \left(\Phi_{sr}^B \right) = 0 : \pi_{sr} \lambda_{sr}^B \qquad \text{(7d)} \\ & g^B \left(\overline{p}^W, \Phi_s^D, \Phi_{sr}^B ; \rho_s, \Delta\rho_{sr} \right) \leqslant 0 \\ \Phi_s^D \in \text{arg} & \left\{ \begin{array}{ll} \underset{\Phi_s^D}{\text{Min}} & \mathcal{C}^D \left(\Phi_s^D \right) \qquad \text{(7e)} \\ \text{s.t.} & h^D \left(\Phi_s^D \right) - l_s = 0 : \widehat{\lambda}_s^D \qquad \text{(7f)} \\ & g^D \left(\overline{p}^W, \Phi_s^D ; \rho_s \right) \leqslant 0 \qquad \text{(7g)} \end{array} \right\} \end{array} \right\} \forall s.$$

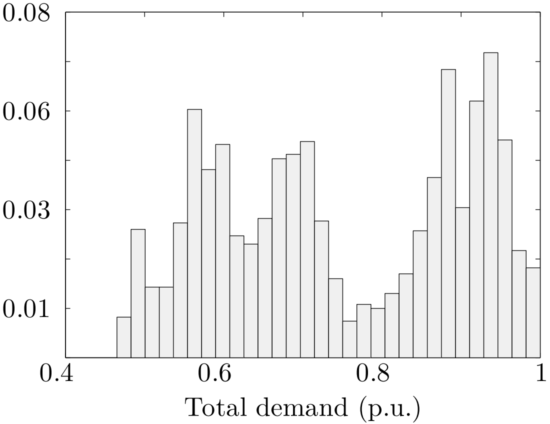
Should we try with some numbers?



Unit	P_g^{max}	C_g	$P_g^{max,u}$	C_g^u	$P_g^{max,d}$	C_g^d
g_1	400	20	-	-	-	-
g_2	400	30	50	35	50	29
g_3	600	22	-	-	-	-

$$F_{n_1 n_2}^{max} = 200\text{MW}$$

How is the variability of the load?

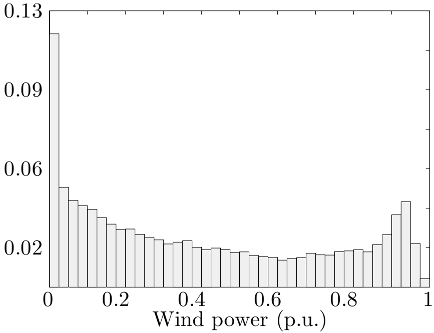


Peak load = 660 MW

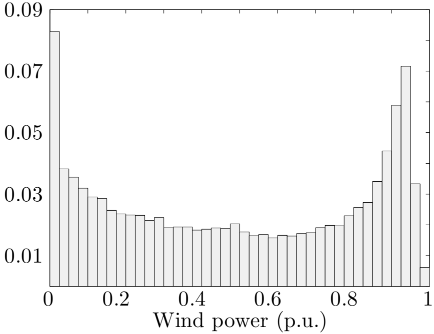
$L_{n_2} = 10 \cdot L_{n_1}$

Load forecast errors disregarded

How is the variability of the wind?



(a) Node n_1

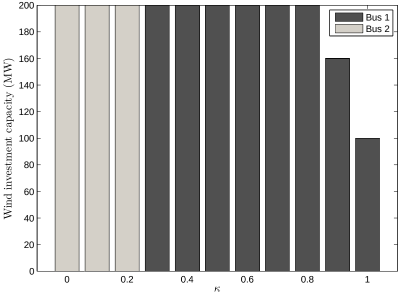


(b) Node n_2

$$wind_1 = 0.3960 < 0.4899 = wind_2$$

How much should we invest under the inefficient market?

Inefficient market



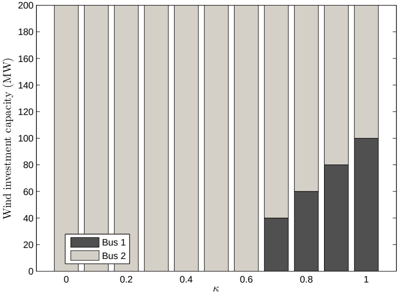
- Total capacity of 200 MW
- $n_1 = \downarrow$ wind $\uparrow$ balancing
- $n_2 = \uparrow$ wind $\downarrow$ balancing
- $\kappa = 0 \rightarrow$ Wind predictable
- $\kappa = 1 \rightarrow$ Forecast errors

- For low forecast errors ($\kappa = [0, 0.2]$) $\rightarrow$ 200 MW at n_2
- For medium forecast errors ($\kappa = [0.3, 0.8]$) $\rightarrow$ 200 MW at n_1
- For high forecast errors ($\kappa = 1$) $\rightarrow$ 100 MW at n_1

How much should we invest under the efficient market?

- Total capacity of 200 MW
- $n_1 = \downarrow$ wind $\uparrow$ balancing
- $n_2 = \uparrow$ wind $\downarrow$ balancing
- $\kappa = 0 \rightarrow$ Wind predictable
- $\kappa = 1 \rightarrow$ Forecast errors

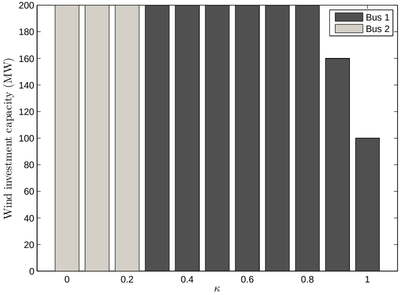
Efficient market



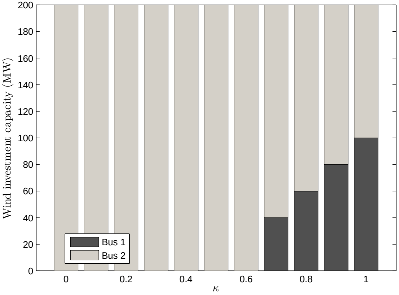
- For low forecast errors ($\kappa = [0, 0.6]$) $\rightarrow$ 200 MW at n_2
- For medium errors ($\kappa = 0.8$) $\rightarrow$ 60 MW at n_1 and 140 MW at n_2
- For high forecast errors ($\kappa = 1$) $\rightarrow$ 100 MW at n_1 and 100 MW at n_2

What is the impact of market design on the investment?

Inefficient market



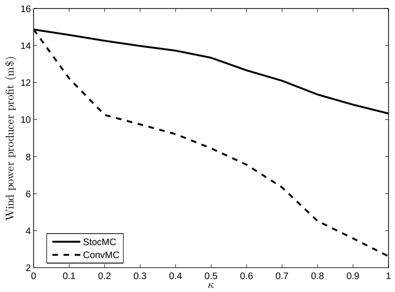
Efficient market



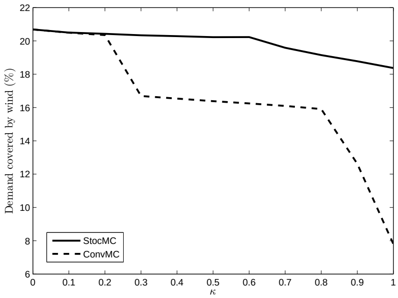
- $\downarrow \kappa \rightarrow$ 200 MW at n_2 for both markets
- $\uparrow \kappa \rightarrow \begin{cases} \text{100 MW at } n_1 \text{ for the inefficient} \\ \text{100 MW at } n_1 \text{ and 100 MW at } n_2 \text{ for the efficient} \end{cases}$

What about the producer's profit and the renewable share?

Profit of wind producer



Demand covered by wind



- Higher profits for the wind producer with effective market
- Higher wind penetration levels with effective market

What have I learned from this presentation?

- GEP are formulated as bilevel optimization problems.
- Wind variability easy to incorporate into GEP models.
- To incorporate wind uncertainty: day-ahead and balancing markets.
- Forecast errors may significantly affect investment decisions.
- An efficient market design encourages investment of stochastic units.

What is left for future research?

- Model competition among investors
- Compare with investments by central planner
- Obtain investment for intermediate market designs
- Apply dedicated computational methods to improve tractability

Where can I get further details?

Modeling the Impact of Imbalance Costs on Generating Expansion of Stochastic Units

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The imbalance costs incurred by a stochastic power producer due to forecast production errors have a significant impact on its total profit and therefore, such an impact needs to be taken into account when evaluating investment decisions. In this paper, we propose a modeling framework to analyze the effect of these imbalance costs on optimal generating expansion decisions of stochastic units. The proposed model is cast as a mathematical program with equilibrium constraints, which allows the explicit representation of both the day-ahead and balancing market-clearing mechanisms. We use the proposed framework to investigate the effect

Thanks for the attention!

More questions?

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