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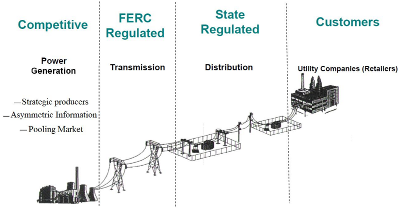
A Methodology for Generation Expansion Planning in the Restructured Electricity Industry

Mohammad Rasouli and Demosthenis Teneketzis
Dept. of Electrical Engineering & Computer Sciences,
University of Michigan, MI, USA

Berkeley UNIVERSITY OF CALIFORNIA
Massachusetts Institute of Technology
NSF
MICHIGAN
VANDERBILT UNIVERSITY

Review: From generation to investment market

Previous work on the restructured electricity industry



- **Model:** N strategic producers with private information, one elastic/inelastic demand, non-profit making system operator
- **Results:** Markets that are social welfare maximizing, budget balanced, individually rational and price efficient
- **Presentations:** Electricity pooling markets with strategic producers possessing asymmetric information [Allerton 2014, FORCES Annual Review June 14]

What about Generation Expansion Planning (Investment)?

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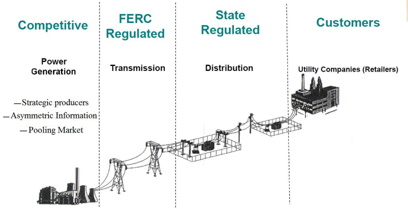

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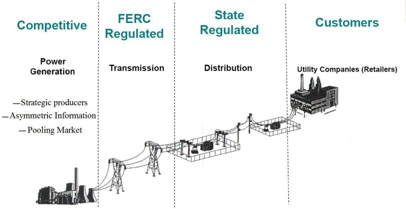

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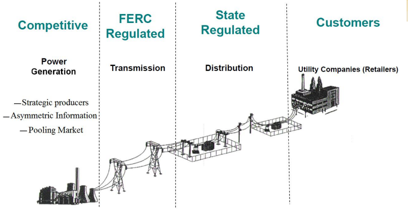

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What about Generation Expansion Planning (Investment)?

What is the Challenge in Generation Expansion Planning?

- **Generation Expansion Planning**: How much and when to invest on expanding electricity generation capacity
- **Under electricity restructuring**:
  - Profit maximizing oligopoly than cost minimizing monopoly
  - Long term planning over 10 to 20-year horizon
    - Uncertainty: future environment (technology, demand, regulations) and future preferences.
    - Gradual investment: multiple incremental investment and generation decisions over time
  - Investment (expansion) tied to generation

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GEP Challenges: Long Term Planning

- Uncertain future (different from uncertainty in stochastic systems)
  - Results in short term technologies and underinvestment
  - Requires change of plans based on new unpredictable conditions

How should generation companies gradually plan for their investment in this highly uncertain environment?

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GEP Challenges: Investment tied to Generation

- Expansions depend on market share and price in future generation markets
- Generation market price and market shares changes by the expansions

How should companies collect their cost of expansion? in separate investment markets, in generation markets or by direct subsidies?

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Contribution

- New philosophical approach to GEP
  - Forward moving approach to GEP: Adapt to the unexpected changes (uncertainty) in the future
  - Expansion block mechanism
    - uses only generation markets to incentivize efficient investment <u>**and**</u> generation
    - is social welfare maximizing, budget balanced, individually rational and price efficient.

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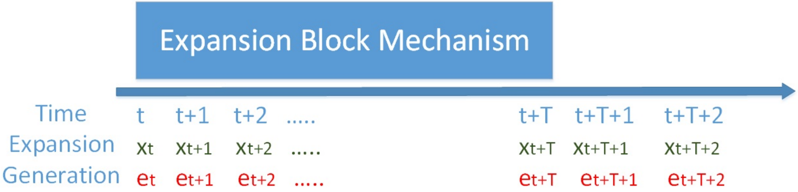

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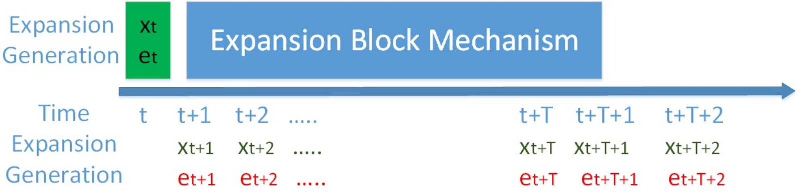

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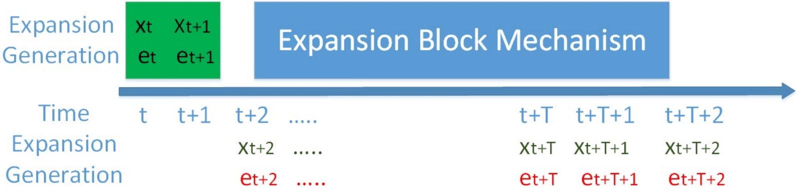

Expansion Block Mechanism

Generation Companies' (GenCos') Model

- Strategic and self-profit maximizers
- Fixed initial capacity, $X_{0,i} > 0$, and expansion limits $x_{i,t} \leq \bar{x}_{i,t}$, $i = 1, 2, ..., N$
- Private production and expansion cost functions, $C_{i,t}(e_{i,t})$, $\hat{C}_{i,t}(x_{i,t})$, $i = 1, 2, ..., N$, with

$$C_{i,t}(0) = 0, \quad \hat{C}_{i,t}(0) = 0 \tag{1}$$

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- Producer i's utility function over planning horizon $\mathcal{T}$

$$-\sum_{\tau \in \mathcal{T}} \hat{C}_{i,\tau}(x_{i,\tau}) - \sum_{\tau \in \mathcal{T}} C_i(e_{i,\tau}) + \sum_{\tau \in \mathcal{T}} \Delta_{i,\tau} \tag{4}$$

Cost of Expansion Cost of Generation Subsidy

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Demand Model

- Non-strategic **elastic** demand due to restructuring of the electricity industry

  "an important change in the traditional production cost model (in Generation Expansion Planning) is the introduction of elasticity of the demand. In classic production cost models the demand was inelastic and had to be met (subject to a penalty for unserved load). Now, the equilibrium quantity is obtained by maximizing the total surplus, defined as the sum of consumer's and producer's surplus"- D. Th. Askounis et al.

- Utility $U_t(d)$: the benefit of the consumers' society from consuming energy d, as common knowledge

$$U_t(0) = 0, \quad U_t^{'}(d) > 0, \quad U_t^{''}(d) < 0$$

- The consumers' total utility

$$\sum_{\tau \in \mathcal{T}} U_\tau(d_\tau) - \sum_{i \in \mathcal{I}} \sum_{\tau \in \mathcal{T}} \Delta_{i,\tau}$$

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Independent System Operator (ISO)

- Non-profit making and Social welfare maximizer
- Centralized problem

$$\max_{x_{i,t}, e_{i,t}, i \in \mathcal{I}, \tau \in \mathcal{T}} \quad \sum_{t \in \mathcal{T}} U_d\Big(\sum_{i \in \mathcal{I}} e_{i,\tau}\Big) - \sum_{i \in \mathcal{I}, \tau \in \mathcal{T}} [\hat{C}_{i,\tau}(x_{i,\tau}) + C_{i,\tau}(e_{i,\tau})]$$
$$s.t. \quad 0 \leq x_{i,t} \leq \overline{x}_{i,t}$$
$$0 \leq e_{i,t} \leq X_{0,i} + \sum_{\tau \in \{1,2,\ldots,t\}} x_{i,\tau} \qquad (5)$$

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Expansion Block Mechanism

- For ease of notation assume $\mathcal{T} = \{1, 2, ..., T\}$.
- <u>GenCos' bids</u>

$$
\begin{aligned}
m_i &= (\{\hat{x}_{i,t}\}_{t\in\mathcal{T}}, \{\hat{e}_{i,t}\}_{t\in\mathcal{T}}, \{\hat{p}_{i,t}\}_{t\in\mathcal{T}}) \\
0 &\leq \hat{x}_{i,t} \leq \overline{x}_{i,t} \\
0 &\leq \hat{e}_{i,t} \leq X_0 + \sum_{k=1}^{t} \hat{x}_{i,t} \\
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- <u>Allocations</u> Every producer is allocated T production amounts, $e_{i,t}$, T expansion amounts, $x_{i,t}$ and T subsidies to receive, $\Delta_{i,t}$.

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Expansion Block Mechanism

The outcome function is

$$h(m) = (\{x_{i,t}\}_{i\in I, t\in \mathcal{T}}, \{e_{i,t}\}_{i\in I, t\in \mathcal{T}}, \{\Delta_i, t\}_{i\in I, t\in \mathcal{T}}) \tag{7}$$

where

$$\begin{aligned}
x_{i,t} &= \hat{x}_{i,t} && (8)\\
e_{i,t} &= \hat{e}_{i,t} && (9)\\
\Delta_{i,t} &= p_{i+1,t} e_{i,t} - p_{i,t}^{-0.5} \zeta_{i,t}^2 && (10)\\
\zeta_{i,t} &= D(p_{i+1,t}) - \sum_{i\in I} e_{i,t} && (11)\\
D_t(p) &= U_t'^{-1}(p) && (12)\\
p_{N+1,t} &:= p_{1,t}. && (13)
\end{aligned}$$

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Mechanism Properties at Equilibrium

At every Nash Equilibrium (NE) of the game induced by the mechanism

- (FEASIBILITY) The allocation are feasible solution of centralized problem

$$D(p^*_{i+1,t}) - \sum_{i \in I} e^*_{i,t} = 0. \quad (14)$$

- (STRONG NASH IMPLEMENTATION) Any outcome corresponding to a NE of the game induced by the mechanism has an expansion and generation profile that is equal to the solution of the ISO's centralized problem.
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- (PRICE EFFICIENCY) The price at equilibrium is the marginal utility of demand and marginal cost of production of the producers with free capacity

$$p^*_t = U'_t(\sum_{i \in \mathcal{I}} e^*_{i,t}) \quad (15)$$

$$p^*_t = C'_i(e^*_{i,t}) \quad \text{if } 0 < e^*_{i,t} < X_{i,0} + \sum_{\tau=1,\ldots,t} x^*_{i,\tau}. \quad (16)$$

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- Any solution of the ISO's centralized problem is equal to an expansion and generation profile corresponding to the outcome of a NE of the game induced by the mechanism.
- (PRICE EFFICIENCY) The price at equilibrium is the marginal utility of demand and marginal cost of production of the producers with free capacity

$$p^*_t = U^{'}_t(\sum_{i \in \mathcal{I}} e^*_{i,t}) \tag{15}$$

$$p^*_t = C^{'}_i(e^*_{i,t}) \quad \text{if } 0 < e^*_{i,t} < X_{i,0} + \sum_{\tau=1,\dots,t} x^*_{i,\tau}. \tag{16}$$

Mechanism Properties at Equilibrium

At every Nash Equilibrium (NE) of the game induced by the mechanism

- (INDIVIDUAL RATIONALITY) Every NE of the game induced by the mechanism is individually rational.
- (BUDGET BALANCE) At equilibrium, the sum of the payments to the producers and the demand at any $t \in T$ is equal to zero
- (SATURATION) At equilibrium, for any GenCo $i \in I$, and any time t such that $x_{i,t} > 0$, there exists at least one future time $t' \in t, t+1, ..., T$ such that GenCo i is saturated, i.e.

$$\hat{e}^*_{i,t'} = X_0 + \sum_{k=1}^{t'} x^*_{i,k}. \tag{17}$$

Interpretation:

- **Expansion block mechanism only uses generation markets to cover cost of expansion and generation.**
  - GenCos cover their cost of expansion at t, in corresponding saturation times, $t' \geq t$.
- The game induced by the mechanism has a unique NE which is efficient in expansions and generations, budget balanced, individually rational and price efficient.

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- Expansion block mechanism for ISO to Incentivize sufficient expansion and generation using generation markets (without introducing separate investment markets, or extra subsidy tools)

Future directions

- Mechanism is easily extensible to portfolio of technologies
- Bayesian framework
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Thanks. Questions?