Competition in Electricity Markets with Renewable Sources

Ali Kakhbod and Asu Ozdaglar

Laboratory for Information and Decision Systems
Electrical Engineering and Computer Science Department
Massachusetts Institute of Technology

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Introduction

- Our earlier work [Wei, Malekian, Ozdaglar 14] focused on demand management under competitive markets with rich heterogeneity on the demand side and production and ramp up/ramp down costs on the production side.
- Two important elements missing from this picture:
    - Market power of several generators in deregulated wholesale markets → oligopolistic rather than competitive modeling.
    - Increasing importance of renewables.

Motivation

- Concerns about climate change have led both to an expansion in renewable energy investments and the establishment of ambitious targets for the share of future renewable energy sources.
- At least 67 countries, including 27 EU countries have renewable energy targets of some type.
    - The EU baseline target is to have 20% of electricity provided by renewables by year 2020.
- This motivates many conventional (thermal) energy companies to diversify their energy portfolio and increase their investments in renewable plants, e.g. Xcel Energy in US, Alstom Energy in Europe:

    "A diverse energy portfolio is the only sound business and policy strategy able to address any Energy & Climate scenario", says Alstom at World Energy Congress (WEC 2013).

Merit Order Effect

- Because marginal cost of wind and solar is negligible, expansion of their supply reduces spot prices (the so called “merit order" effect).

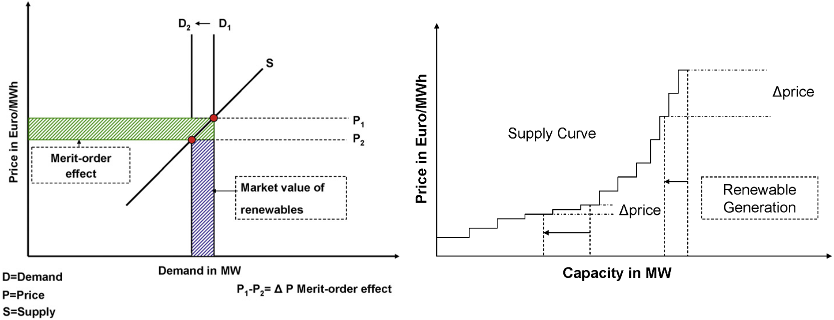

Figure: Source: [Sensfuss et al. 2008]

Merit Order Effect

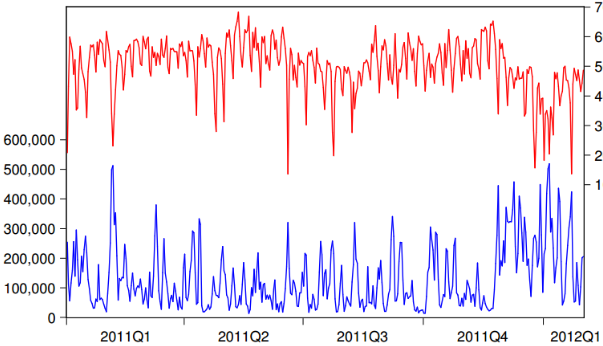

Figure: Relation between prices in red ($/MWh) and renewable energy output in blue (MWh) in Germany. Source: European Energy Exchange (EEX).

- Based on this evidence and theoretical expectation, it is generally forecast that merit order effect will continue to reduce prices in the future.

Our Contribution

- The fact that much of wind power may come to be supplied by conventional energy companies (which rely on thermal generators) may neutralize the merit order effect.
- In an oligopolistic market, firms may strategically reduce their conventional supply exactly to offset the increase in wind output.
- This effect crucially depends on conventional energy companies being the suppliers of wind power.
    - Otherwise they would not internalize the increase in profits in wind supply from reducing conventional energy supply.
- This suggests that the diversification of conventional energy companies and their potential dominance over wind power may need to be regulated.

Plan

- We illustrate the merit order neutralization using a simple oligopoly model with conventional and wind energy.
- We show that strategic supply choices creates an offset on the impact of wind supply.
- If all wind is owned by conventional suppliers, then this offset is complete and there is no impact from wind power penetration on prices.
- If there are forward contracts (a common feature of energy markets), then prices are uniformly lower but neutralization of merit order effect still applies.
- We will also consider the incomplete information case when the wind availability is stochastic, heterogeneous and not commonly known.

A Note on Modeling

- Electricity market competition (on generation) modeled using two approaches.
- Supply Function Competition:
  - Firms (or generators) compete by choosing supply functions specifying power supply as a function of price. ([Klemperer, Meyer 89], [Green, Newbery 92], [Rudkevich et al. 98], [Baldick, Hogan 02], [Baldick et al. 04]).
  - Appealing due to its similarity to how markets operate in practice where generators submit step-wise increasing offer function.
- Cournot Competition:
  - Firms compete by choosing their power supply (price determined by market clearing) ([Borenstein et al. 95], [Borenstein, Bushnell 99], [Hogan 97], [Oren 97], [Yao et al. 08]).
  - Appealing due to its analytical tractability.
  - Cournot model often provides a good explanation of observed price variations ([Baldick 02], [Willems et al. 09])
- We will use Cournot model in representing the strategic interactions between generators (we ignore transmission constraints for now).

Simplified Model

- Two conventional generators each producing q_i units of thermal energy (from gas or fuel) at cost

$$c_i(q_i) = \gamma q_i, \qquad \text{where } \gamma > 0 \text{ is a scalar.}$$

- We assume there are wind farms producing a total amount of R units of wind energy (with zero marginal cost of production).
- Inverse demand function (specifying market price as a function of total amount) is given by

$$P(q) = \alpha - (q + R), \qquad \text{where } \alpha > 0 \text{ is a scalar.}$$

Case 0: Merit Order Effect (MoE) with Nonstrategic Suppliers

- As a benchmark, suppose that the two conventional generators supply some amount q_1 and q_2 to the market regardless of wind availability.
- We can see the starkest form of merit order effect:

  $$p^{\mathrm{C0}} = P(q_1 + q_2) = \alpha - (q_1 + q_2 + R),$$

  implying that $\frac{dp}{dR} = -1$.
- In this case, when R increases, price goes down one for one.

Case 1: MoE with Strategic Suppliers

- Now suppose that supply is determined by Cournot competition by two conventional generators that do not own wind farms.
- Each generator i is interested in maximizing his profit given by

$$\Pi_i^{\mathrm{C1}}(q_1, q_2) = P(q_1 + q_2)q_i - \gamma q_i = (\alpha - (q_1 + q_2 + R))q_i - \gamma q_i.$$

- The price at the Nash equilibrium of the resulting game is given by

$$p^{\mathrm{C1}} = \frac{1}{3}(\alpha - R + 2\gamma),$$

  implying that $\frac{dp}{dR} = -\frac{1}{3}$, an offset relative to full MoE.
- This is due to strategic substitutes in Cournot competition (when one player increases its strategy, other player's best response declines).
- Here strategic substitutes entails that when R increases, both q_1 and q_2 decreases accounting for partial offset of MoE.

Case 2: Neutralization of MoE

- Suppose that each conventional generator owns $\delta \frac{R}{2}$ units of wind, $\delta \in [0, 1]$.
    - When $\delta = 1$, all wind is supplied by conventional power generators.
- Generator i's profit is now given by

$$\Pi_i^{\mathrm{C2}}(q_1, q_2) = P(q_1 + q_2)\left(q_i + \delta \frac{R}{2}\right) - \gamma q_i = (\alpha - (q_1 + q_2 + R))\left(q_i + \delta \frac{R}{2}\right) - \gamma q_i.$$

- The price at the Nash equilibrium of the resulting game is given by

$$p^{\mathrm{C2}} = \frac{1}{3}(\alpha - R + \delta R + 2\gamma).$$

- When $\delta \to 1$, $\frac{dp}{dR} = 0$, thus MoE is fully neutralized.
- What explains this paradoxical result?
    - When $\delta \to 1$, all wind supply generates profits for conventional power generators. Incentive to hold back on conventional supply to keep prices higher and protect their profits from wind.

Case 3: Forward Contracts

- We now consider the same economy, but allow conventional generators to sign forward contracts.
- Forward contracts have become increasingly important in electricity markets. They are sometimes argued to:
    - reduce price by creating a precommitted supply in the market,
    - reduce volatility by making certain quantity available before cost and wind power availability is realized.
- We will now see that introducing forward contracts indeed reduce prices, but MoE is still neutralized in the presence of diversified producers.

Case 3: Forward Contracts (Continued)

- Economy has two dates, $t = 1, 2$.
- At $t = 1$, each conventional generator i signs a contract (q_i^f, p_i^f), promising to generate q_i^f units of (thermal) energy at price p_i^f for delivery at $t = 2$ (similar to the model in [Allaz, Vila 93]).[1]
- The price at the (subgame perfect) Nash equilibrium of the resulting game is given by

$$p^{\mathrm{C3}} = \frac{1}{5}(\alpha - R + \delta R + 4\gamma) < p^{\mathrm{C2}}.$$

- With forward contracts, prices are uniformly lower because forward commitments make each Cournot oligopolists act partially as a Stackleberg leader (since they first choose their forward contract and this forces other producer to cut back on his production).
- Therefore forward contracts make competition fiercer pushing prices down.

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[1] We assume no arbitrage. Forward price must be equal to spot price given forward positions.

Case 4: Incomplete Information

- Now imagine incomplete information where the availability of wind at generator i is given by $R_i = R/2 + \theta_i$, where $\theta_i \sim \mathcal{N}(0, \sigma^2)$ (each generator owns δR_i units of wind).
- θ_i is private information of generator i: each generator knows his own realized wind.
- We assume θ_1 and θ_2 are correlated capturing the geographic proximity of the wind farms of the generators affected by some local condition.
    - $\mathrm{Cov}(\theta_1, \theta_2) = \kappa\sigma^2$, where κ is inversely proportional to the distance between the wind farms.

Equilibrium

Proposition

There exists a unique pure-strategy perfect Bayesian equilibrium (PBE) in linear strategies in which each generator i produces

$$\begin{aligned} q_i(\theta_i) &= q_i^{\textit{complete information}} - \left(\frac{1+\delta+\kappa}{2+\kappa}\right)\theta_i \\ &= \frac{2}{5}(\alpha - R - \delta R/4 - \gamma) - \left(\frac{1+\delta+\kappa}{2+\kappa}\right)\theta_i, \end{aligned}$$

and the resulting price satisfies

$$E[p^{C4}] = p^{C3},$$

$$Var(p^{C4}) = 2\left(\frac{1-\delta}{2+\kappa}\right)^2 (1+\kappa)\sigma^2.$$

Intuition

- Each generator cuts back on supply (relative to complete information) as a function of their wind availability for the same reason as before.
- This effect is now modulated because θ_i also gives information about wind availability of competitor:
    - When κ high, wind availability more correlated and greater holding back.
- When $\delta = 1$: this effect disappears, production does not depend on κ!
    - With $\delta = 1$, there is complete neutralization of MoE, i.e., total production of each producer (conventional +wind) is independent of θ.
- Volatility of prices is decreasing in κ, because lower κ creates more miscoordination in supplies across competitors.
- When $\delta = 1$, total supply of each producer independent of θ, hence price volatility disappears.

General Model

- Suppose we have n conventional generators.
- The availability of wind at generator i is given by $R_i = R/n + \theta_i$, where $\theta_i \sim \mathcal{N}(0, \sigma^2)$ (each generator owns δR_i units of wind).
- The covariance matrix of $(\theta_1, \ldots, \theta_n)$ is given by

$$\Sigma \equiv \sigma^2 \begin{pmatrix} 1 & \kappa_{1,2} & \cdots & \kappa_{1,n} \\ \kappa_{2,1} & 1 & \cdots & \kappa_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ \kappa_{n,1} & \kappa_{n,2} & \cdots & 1 \end{pmatrix}$$

where $\kappa_{i,j}$ is inversely proportional to the distance between wind farms of generators i and j.

Equilibrium

Proposition

There exists a unique pure-strategy perfect Bayesian equilibrium (PBE) in linear strategies in which each generator i produces

$$q_i(\theta_i) = \frac{n}{n^2+1}\left(\alpha - R - \frac{\delta R}{n^2} - \gamma\right) - a_i\theta_i$$

where $\boldsymbol{a} = A^{-1}\boldsymbol{v}$, $A = \frac{1}{\sigma^2}\Sigma + I$, I *is the identity matrix, and each element of the vector* $\boldsymbol{v} = (v_1, v_2, \cdots, v_n)^T$ *is given by* $v_i = 1 + \delta + \sum_{j \neq i} \kappa_{i,j}$. *The resulting price satisfies*

$$E[p] = \frac{1}{n^2+1}(\alpha - R + \delta R + n^2\gamma),$$

$$Var(p) = \boldsymbol{a}^T\Sigma\boldsymbol{a} - 2\boldsymbol{a}^T\Sigma\boldsymbol{1} + \boldsymbol{1}^T\Sigma\boldsymbol{1}$$

Conclusions

- We presented an oligopoly model with conventional and wind energy.
- We studied the effect of diversification of energy portfolio of conventional generators on spot market prices.
- Ongoing Work and Extensions:
    - Effect of “network structure" of wind farms on price volatility.
    - Optimal pricing when renewable generators have incentive to hold back their supply:
        - Oligopoly pricing with stochastic and correlated capacity constraints.
        - Market design to reduce prices and price volatility.
    - Transmission constraints:
        - Introduce power flow constraints and treat each bus separately.
        - Price will be location dependent: Locational Marginal Pricing (LMP).