Selling Wind: A model

Daron Acemoglu Ali Kakhbod Asuman Ozdaglar

Economics Department
Laboratory for Information and Decision Systems
Electrical Engineering and Computer Science Department
MIT

FORCES Review Meeting

May 2015

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.
- **HOWEVER**, subsidized clean energy created a **boom** in wind and solar amid slowing power demand, **decreasing spot prices** (Merit order effect).
  - For example, German electricity prices in 2015, a European benchmark, dropped to 31.15 euros a megawatt-hour on Jan. 7, a 10-year low, according to data from European Energy Exchange AG.

Motivation

Sven Becker, managing director of municipal utility Trianel GmbH, asked at the Berlin conference 2014:

> *"If we have 100 percent renewables, the market price is zero, so how can we justify new investments?"*

One feasible solution: introducing **Capacity markets**.

RWE Deputy CEO Rolf Martin Schmitz told the conference:

> *"We need a capacity market .... The true costs of a capacity market are very low."*

Plan

- We present a benchmark model for selling wind.
- Wind Producers (WPs) operate locally separate wind farms.
- d captures the extent of **heterogeneity** in terms of wind energy availability in these wind farms.
  - For example d can be represented by **distance** between wind farms, (heterogeneity $\uparrow \equiv$ distance $\uparrow$)
  - When d **grows**, **correlation** in wind energy between the wind farms **declines**.

Plan

Research Questions:

Q. How does **distance** (i.e. extent of heterogeneity in wind farms) affect **Consumer surplus, Profit** as well as **Markup**?

Q. How does **extent of dispersion** in wind farms affect **social welfare**?

Results

- Let P be the inverse demand. Then, by **increasing** d we have:

	Production	Markup	**Profit**	CS	**Welfare**
$P' < 0,\ P'' = 0$	$+$	$-$	**$+$ or $-$**	$+$	**$+$**
$P' < 0,\ P'' < 0$	$+$	$+$ or $-$	$+$ or $-$	$+$ or $-$	**$+$**

Table: The impact of **increasing heterogeneity** in wind farms locations, e.g. distance, according to the functional forms of the inverse demand P, on production, equilibrium price (markup), wind producers surplus (Profit), consumer surplus (CS) and welfare (W), where $+$ means positive effect, $-$ means negative effect and ? means ambiguous (in general).

- Is improving (public) weather forecast **socially beneficial**? **Not necessarily!!**

Intuition: Mean-effect and MisCoordination

All the results are due to interplay between **Mean effect** and **MisCoordination**.

- **Mean-effect**: when d grows production in high state of energy increases, that equivalently increases the mean of production, introducing **mean effect**.

Intuition: When d increases with a higher chance firms are different states of energy. Suppose firm i is in high state. When d increases, firm j is in low state with a higher probability. Strategic substitutability implies that best reply of firm i is decreasing in firm j's production (that is because $P' < 0, P'' \leq 0$). As a result, as d grows, the production of firm i (at high state of energy) increases.

- **MisCoordinaton (Diversification)**:

Intuition: Mean-effect and MisCoordination

All the results are due to interplay between **MisCoordination** and **Mean effect**.

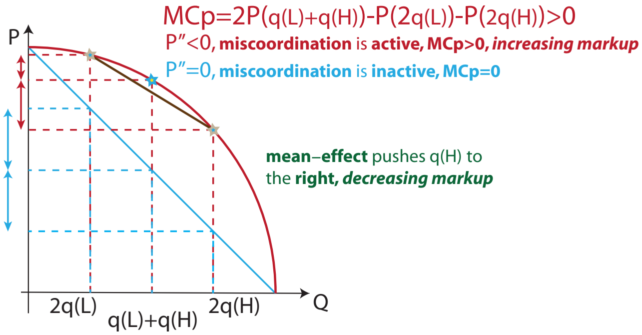
- **Mean-effect**: when d grows production in the high state of energy increases, that equivalently increases the mean of production, introducing **mean effect**.
- **MisCoordinaton (Diversification)**

Intuition: When d grows **chances** for being in different **states** increases. Consequently, with increasing d firms produce different quantities with a higher probability, introducing miscoordination effect (in short, miscoordination). Let $f : R^2 \to R$. The impact of miscoordination on f (denoted by MC_f) is given by the following expression. Let $x \neq y$ then

$$MC_f \equiv f(x,y) + f(y,x) - f(x,x) - f(y,y).$$

⋆ Sometimes the impacts of these effects are aligned with each other that result in robust predictions like what happens for welfare and some times they don't like in firms' profit and the markup.

Intuition: Distance vs. Markup



With increasing dispersion

- Miscoordination is active when $P'' < 0$ increasing markup (because $MC_P = 2P(q(L) + q(H)) - P(2q(L)) - P(2q(H)) > 0$). However, mean-effect decreases markup.
- When $P'' = 0$, miscoordination is inactive, thus markup decreases only by mean-effect with increasing dispersion.

Intuition: **Distance** vs. **Profit**

With increasing dispersion:

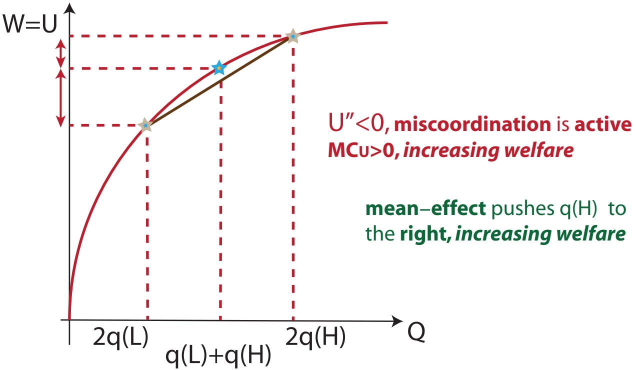
- **Miscoordination** increases markup ⇒ **Profit goes up**
- **Mean-effect** decreases markup ⇒ **Profit goes down**

Extent of energy at low sate is important because:

⋆ The impact of Miscoordination on profit gets **stronger** when extent of energy at low state is sufficiently *limited*. Therefore, when energy at low state is insufficient, profit **increases** with increasing dispersion (by Miscoordination effect).
Thus, firms would prefer to place their plants **far** from each other.

⋆⋆ In contrast, when energy at low state is *sufficiently available*, impact of Miscoordnation on profit gets **weaker** so that profit becomes **decreasing** with increasing dispersion (by Mean-effect).
Therefore, firms would prefer to place their plants **close** to each other.

Intuition: Distance vs. Welfare



With increasing dispersion:

- Mean-effect increases welfare because $U' = p > 0$.
- Miscoordination is also active when $U'' < 0$, increasing welfare because

$MC_U = 2U(q(H) + q(L)) - U(2q(L)) - U(2q(H)) > 0.$

Intuition: Distance vs. Welfare vs. Profit

Increasing dispersion (e.g. distance) in wind farm locations:

→ **Always** increases **welfare**.

However,

→ Sometimes, it's **more beneficial** for wind energy producers to be **close** to each other.

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 how much power it is willing to supply at each 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 amount (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 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).

Model: Wind producers

- Two wind energy producers (WPs), denoted by 1 and 2, operate two locally separate wind farms.
- At wind farm $i \in \{1, 2\}$ the maximum wind realization, denoted by w_i, is **stochastic** and might be either H (high) or L (low), where $H > L$ with prior probability $\Pr\{w_i = H\} = \beta = 1 - \Pr\{w_i = L\}$.
- Let $d \in [0, 1]$ be the distance between the wind farms, where the maximum distance is normalized to 1.
    - Importantly, d measures the extent of **heterogeneity** in terms of wind energy availability in theses wind farms.

Model: Effects of d on the posteriors

- Precisely for $i, j \in \{1, 2\}$

$$\Pr\{w_i = H | w_j = H\} = \frac{\beta}{\beta + d(1-\beta)} \quad \text{(decreasing in } d\text{)}$$

$$\Pr\{w_i = H | w_j = L\} = \frac{d\beta}{\beta + d(1-\beta)} \quad \text{(increasing in } d\text{)}$$

  - Thus, when $d = 0$, we are in the *full information* case and when $d = 1$, we are in the *independent value* case.

- As d **grows** the possibilities for having different quantities increases.

Model: WP's problem and Inverse demand

- We assume the inverse demand $P(\cdot)$ is **decreasing and concave**, i.e. $P' < 0, P'' \leq 0$ and the marginal cost of production via wind is **negligible**.

- Let q_i denote amount of wind energy produced by WP $i \in \{1, 2\}$.

- Each producer i according to its maximum available wind $w_i \in \{L, H\}$, finds $q_i(w_i)$ maximizing her profit:

$$\begin{aligned} &\mathbb{E}[\pi_i|w_i] = \mathbb{E}[\ q_i\ P\big(q_1(w_1) + q_2(w_2)\big)\ |w_i] \\ &\text{s.t.} \qquad q_i(w_i) \in [0, w_i] \quad \text{(capacity constraint)} \end{aligned}$$

- Importantly, w_i may **release some information** about w_j, according to extent of d.

Equilibrium

Assumption (1)

Let $P(\cdot)$ be the inverse demand. Then $P(2L)+LP'(2L)>0$ and $P(H)+HP'(H)<0$.

Proposition (Equilibrium: General inverse demand)

The exists a unique symmetric BNE such that

$$q_i(w_i)=q(w_i)=\min\{w_i,\phi\} \qquad w_i\in\{L,H\},\ i=1,2$$

where $\phi>L$ is the unique root of the following equation

$$\Pr\{L|H\}\left[P(L+\phi)+\phi P'(\phi+L)\right]+\Pr\{H|H\}\left[P(2\phi)+\phi P'(2\phi)\right]=0.$$

Example: Linear inverse demand

- Let the inverse demand be **linear**, i.e. $P(q_1 + q_2) = s - q_1 - q_2$.
- Assumption (1) with linear inverse demand translates into the following *nontrivial* case:

$$L < \mathbf{q_C} = \frac{\mathbf{s}}{\mathbf{3}} < \mathbf{q_M} = \frac{\mathbf{s}}{\mathbf{2}} < H.$$

where $\mathbf{q_C}$ and $\mathbf{q_M}$ read as Cournot and Monopoly levels, respectively.

Proposition (Equilibrium: Linear inverse demand)

The exists a unique symmetric BNE such that

$$q_i(w_i) = q(w_i) = \min\{w_i, \phi\} \qquad w_i \in \{L, H\},\ i = 1, 2$$

where

$$\phi = \frac{s\beta + (s-L)(1-\beta)d}{3\beta + 2(1-\beta)d}.$$

Distance vs. Quantity

Proposition (distance vs. quantity)

For any concave and downward inverse demand $P(\cdot)$, the **production** *at the H (high) state* **increases** *in d. That is $\frac{\partial \phi}{\partial d} > 0$.*

Example: Let $P(q_1 + q_2) = s - q_1 - q_2$. Then

$$q(H, d = \mathbf{0}) = \mathbf{q_C} = \frac{\mathbf{s}}{\mathbf{3}} < q(H, d = \mathbf{1}) = \frac{s\beta + (1-L)(1-\beta)}{\beta + 2}$$

- When d grows chances for having different quantities **increases**, increasing production at the H state, given that best replies are decreasing.

Distance vs. Markup

Proposition (**distance vs. markup**)

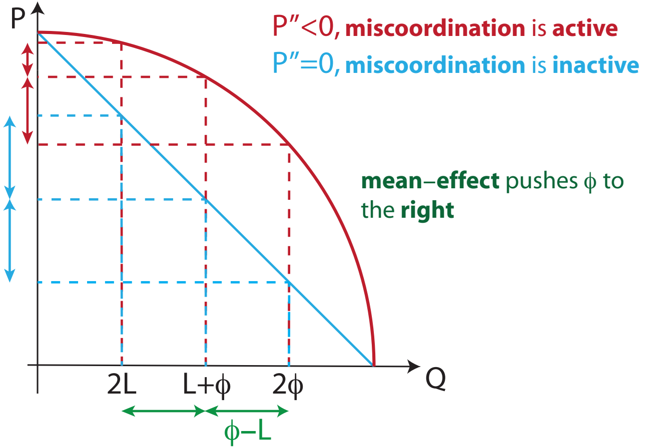
For any linear inverse demand $P(\cdot)$, the **average markup price decreases** *in d. That is* $\frac{\partial}{\partial d}\,\mathbb{E}_{w_1,w_2}[P(q_1(w_1)+q_2(w_2))] < 0$.

- When d grows two effects are in play: (i) increasing quantity at the H state (in short, **mean-effect**) and increasing chances for having different quantities (in short **miscoordination**).
- **mean-effect reduces the price** because inverse demand is decreasing, i.e. $P' < 0$.
- However, **miscoordination** that kicks in when $P'' < 0$ **increases the price** because $P'' < 0$. Precisely, the effect of having different quantities is

$$\text{miscoordination effect } \equiv 2P(L+\phi) - P(2L) - P(2\phi) > 0$$

- Importantly, **miscoordination** is **inactive** when $P'' = 0$.

Distance vs. Markup



The LH-effect is active when $P'' < 0$, pushing the price up:
$P(2L) - P(L + \phi) < P(L + \phi) - P(2\phi)$.

Distance vs. Profit

An implementation question: Markup decreases in d for *linear inverse demands*. So, is it then more beneficial for WPs to place their plants *close* to each other??
Answer: Not necessarily!

Proposition (**distance vs. profit**)

Let $P(q_1 + q_2) = s - q_1 - q_2$. *There exist* $0 < L_1 < L_2 < \frac{s}{3}$ *for which when* $L < L_1$ *then is beneficial for wind producers to place their wind farms* **far** *from each other, i.e.*

$$\arg\max_{d \in [0,1]} E_{w_1,w_2}[\pi_i] = 1.$$

However, when $L > L_2$ *then is beneficial for WPs to place their plants* **close** *to each other, i.e.*

$$\arg\max_{d \in [0,1]} E_{w_1,w_2}[\pi_i] = 0.$$

MAIN RESULT: Distance vs. Welfare

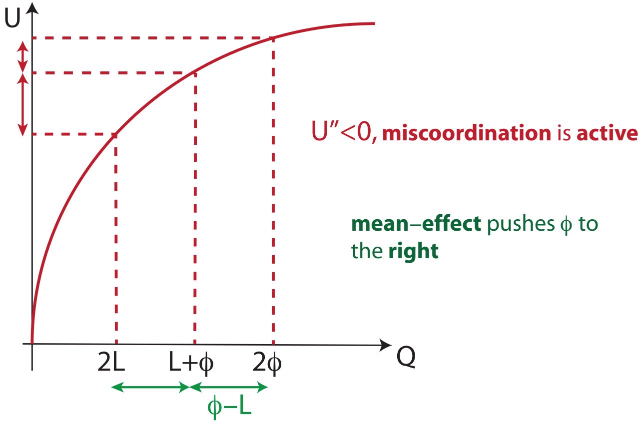
Suppose the demand arises from an aggregate consumer whose gross surplus $U(q) \geq 0$ is concave (we assume $U(0) = 0$).

Proposition (distance vs. welfare)

Let the inverse demand be any concave and downward function, i.e. $P' < 0, P'' \leq 0$. *Then,* **increasing** *heterogeneity in wind farm locations, i.e.* d, *is* **socially beneficial**, *that is* $\frac{\partial}{\partial d}\, \mathbb{E}_{w_1,w_2}[welfare] = \frac{\partial}{\partial d}\, \mathbb{E}_{w_1,w_2}[U(q_1(w_1) + q_2(w_2))] > 0$.

- When d grows two effects are in play: (i) increasing quantity at the H state (in short, **mean-effect**) and increasing chances for having different quantities (in short **miscoordination**). Here, in contrast to the markup analysis the impacts of these effects are aligned.
- **mean-effect** increases the quantity, increasing the **welfare**, since $U' = P > 0$ and $P' < 0, P'' < 0$
- **miscoordination** that kicks in when $U'' < 0$ also **increases the welfare** because $U' > 0, U'' < 0$.

Distance vs. Welfare



The miscoordination is active when $U'' < 0$, pushing the welfare up: $U(2\phi) - U(L+\phi) < U(L+\phi) - U(2L)$.

Public information vs. Welfare

A policy question: Is improving public information about weather forecast **socially** beneficial??

- We assume public information about weather forecast is precise so that w_j becomes observable for WP i after realizing the public information.

Proposition (public information vs. welfare)

The impact of having a better **public** *weather forecast on welfare is* **ambiguous**.

The proof is by construction. Let $L = 0$, $\beta = \frac{1}{2}$ and the inverse demand be any linear function, $P = s - q_1 - q_2$. Then:

- Releasing the public information is always beneficial for WPs.
- There exists a unique $s_1(d)$, i.e. a function of d, such that releasing the public information becomes beneficial for consumers if and only if $s < s_1(d)$.
- Importantly, the later effect dominates the former. That is, there exists a unique $s_2(d)$ such that releasing the public information is socially beneficial if and only if $s < s_2(d)$.

Conclusions

- We presented a benchmark model for selling wind.
- We studied the effect of heterogeneity in wind farms locations (in terms of wind energy realizations) on social welfare, CS, WPS, mark up and average production.
- We studied the effect of improving weather forecast on the social welfare.
- Ongoing Work and Extensions:
    - Effect of “network structure" of wind farms on price volatility.
    - Optimal pricing when renewable generators compete with thermal producers:
        - Market design to help reduce price volatility.
    - Transmission constraints:
        - Introduce power flow constraints and treat each bus separately.
        - Price will be location dependent: Locational Marginal Pricing (LMP).