Investing in inflexible generation capacity

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Overview

Motivation

- Higher penetration of RES requires **more flexibility in electricity systems**
- Will an energy-only market provide the right incentives for investments in flexibility,
  - Storage operators
  - Demand response
  - Sufficiently flexible thermal generation
- Or should we create long-term markets for flexibility (similar to the capacity markets)?
- **Market failures** could be similar as for capacity markets
  - Missing long-term hedging markets for flexibility (forward contracts are not a good hedge)
  - Market power at investment stage
  - Inefficiencies in spot market “under-price” flexibility

Goal of this paper

- Understand how short-term market design affects long term investment strategies
  - Compare two short-term market models (US vs EU)
  - Focus on (in)flexible thermal generation (no storage or demand response)
    - Adjustment costs + on / off decision
  - Identify possible market failures / externalities
  - Not: market power / risk aversion / storage / investment in demand response

Two market designs for dealing with start-up

US-Model: One complex auction for several periods

- Firms submit all relevant information into auction (marginal cost and start-up costs).
- Auctioneer minimizes overall system cost, and decides about firm's scheduling decisions
- Firms receive an **energy price** (reward for variable costs) and **an up-lift payment** (which pays for start-up costs, if necessary).
  - No unique market design to determine energy prices and the up-lift payment
- Up-lift payments are often collected in a lump-sum way from consumers (e.g. through connection charge).

Two market designs for dealing with start-up

EU-Model: Several simple auctions, one for each period

- Firms submit separate bids for each period
- Auctioneer clears each market separately
- The firm receives the market clearing price for energy in each market (no up-lift payment)
- The firm self schedules, and has to internalize start-up costs in its bid

Conjectures

- US-model
  - Short-term auction leads to efficient production scheduling (with perfect competition)
  - Might lead to optimal short run consumption (if energy prices are set correctly)
  - Up-lift payments could lead to over-investments, because they do not correctly reflect consumers' Willingness To Pay
- EU-model
  - Short-term auction might lead to inefficient scheduling within firm
  - Coordination failures across firms (if adjustment cost differ across firms)
  - Existing capacity is used inefficiently, investments below social optimum

Overview

Model

Demand

- **Two demand periods** $(1, 2)$
- Elastic and stochastic demand with additive price shocks

$$p_i = p_i(q) + \varepsilon_i$$

  - Demand is symmetric $p_i() = p()$
  - Shocks are independent with identical cdf. $H(\varepsilon_i)$ on $[\underline{\varepsilon}, \bar{\varepsilon}]$.
- Continuum of production technologies (base load - peak load)

Model

Production cost

- **Total cost for two periods:**

$$\underbrace{\underbrace{c \cdot (q_1 + q_2)}_{\text{Fuel Cost}} + \underbrace{\alpha \cdot (q_1 - q_2)^2}_{\text{Adjustment Cost}}}_{C(q_1, q_2)} - \underbrace{2 \cdot k(c)}_{\text{Investment cost}}$$

- Each power plant has a capacity of 1 unit. A power plant is either on or off. $q_i \in \{0, 1\}$
- **Opportunity cost** for producing one unit in period 1
  - If already producing in period 2 for sure $(q_2 = 1)$: $c - \alpha$
  - If not producing in period 2 for sure $(q_2 = 0)$: $c + \alpha$

Model

Continuum of technologies

- Continuum of technologies with different marginal cost c on $[\underline{c}, \bar{c}]$
- Annualized per period **investment cost** $k(c)$ for technology c
  - Investment cost increases for more efficient technology ($\mathrm{d}k/\,\mathrm{d}c < 0$)
  - No investment cost for marginal cost $\bar{c}$ (= Value of Lost Load)

$$k(\bar{c}) = \frac{dk(\bar{c})}{dc} = 0$$

  - Pure baseload technology $\underline{c}$:

$$\frac{dk(\underline{c})}{dc} = 1$$

- All technologies have identical adjustment cost $\alpha(c) = \alpha$

Model

Market equilibrium

- **Long run:** no entry barriers and risk neutral firms
  - Many potential firms with technology c decide on whether to enter the market
  - Long term expected profit is zero for all firms & technologies
  - Aggregate market supply curve $G(c)$ represents those entry decision.
- **Short run:** Competitive bidding
  - Firms are price takers in the spot market
    ($\neq$ naive bidding in spot market, e.g. price $\neq$ fuel cost)

Overview

Goal

- This section looks at the optimal bidding strategy of a single, price taking firm
- For this firm the price p_i is stochastic and distributed over $[\underline{p}, \bar{p}]$ with cumulative density function $F_i(p)$
- We compare the US and EU market designs

US Market

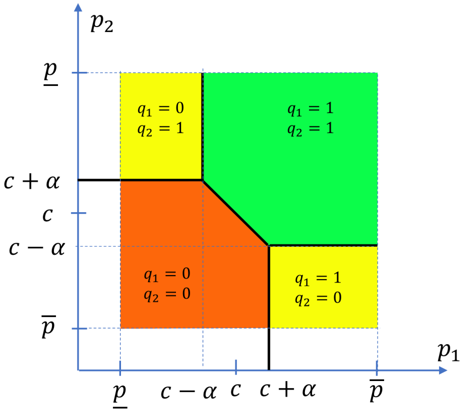
- Firms submit marginal cost c and start up cost α to the system operator / auctioneer
- Auctioneer observes all bids and demand shocks and collects all information
- For each realized price (p_1, p_2) the auctioneer sets the production output (q_1, q_2) of a firm such that

$$\max_{q_1,q_2}(p_1 - c)q_1 + (p_2 - c)q_2 - \alpha(q_1 - q_2)^2 \text{ with } q_1, q_2 \in \{0, 1\}$$

- If the firm does not cover its costs, the auctioneer pays an uplift payment.

US Market

- The firm's output depends on the realized price (p_1, p_2):



US Market: Discussion

- A small firm does not change “market prices”, so they are assumed to be given
- In my set-up with small firms: no need for up-lift payments. Prices are sufficient.
- Prices p_1 and p_2 reflect the consumers willingness to pay for the goods in market 1 and 2. They represent the social value of additional electricity
- Social welfare is optimized in the US market design

EU Market

- For a single firm the price p_i is stochastic and distributed over $[\underline{p}, \bar{p}]$ with cumulative density function $F_i(p)$
- The firm makes a bid b_i into the market, and produces when $b_i < p_i$
- Firm's maximizes expected profit taking into account adjustment costs:

$$\int_{b_1}^{\bar{p}} (p_1 - c) dF_1(p_1) + \int_{b_2}^{\bar{p}} (p_2 - c) dF_2(p_2)$$
$$-\alpha \left[F_1(b_1)\left(1 - F_2(b_2)\right) + F_2(b_2)\left(1 - F_1(b_1)\right)\right]$$

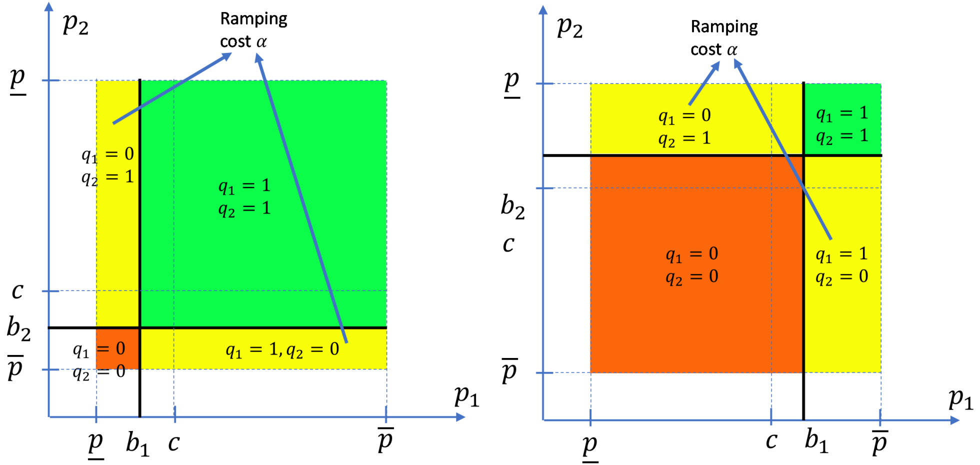
- Firm bids the expected opportunity cost in market 1

$$b_1(c) = c - \alpha \cdot (1 - 2F_2(b_2(c)))$$

which depends on the likelihood of producing in market 2

EU-Market

Trade-off: minimize ramping cost vs (selling at loss or insufficient selling)



EU Market

- Discussion:
  - Optimal bids depend on price distribution
  - The distribution function $F(p)$ depends on the availability / actions of other firms
  - Firm needs to have a lot of information
- For a given distribution $F(p)$
  - High cost firm (peaker): Not likely to produce: so $b > c$
  - Low cost firm (baseload): Likely to produce, so $b < c$
- Production decisions are inefficient as they depend only on price of one good (not of both).
- Firm sometimes sells at a loss (if $b < c$): EU-market design seems to be at least as risky as the US one

Overview

Optimal generation mix formula

- Define $h_i(c)$ as the c.d.f. of the marginal power plant in market i.
- With symmetric markets $h = h_i$
- Well known optimal generation mix formula

$$\underbrace{(h(c)-1)}_{\substack{\text{Prob. that firm } c \\ \text{is producing} \\ = \\ \text{Prob. firm with MC} > c \\ \text{is marginal}}} \cdot \underbrace{\mathrm{d}c}_{\substack{\text{Production cost} \\ \text{advantage}}} = \underbrace{\mathrm{d}k(c)}_{\substack{\text{Capital cost of reducing} \\ \text{marginal cost with } \mathrm{d}c \\ \text{(per period)}}}$$

- This expression is also valid in our setting for US and EU market designs
- *The next slides provide insights why this is so for the US market design*

Optimal Generation mix formula: US market: Intuition

- The expected short-term per period profit of a firm with marginal cost c is equal to

$$\pi(c) = \frac{1}{2}\int_{\underline{c}}^{\bar{c}}\int_{\underline{c}}^{\bar{c}} (p_1(t_1,t_2) - c)\cdot q_1(t_1,t_2)\, \mathrm{d}h_1(t_1|t_2)\, \mathrm{d}h_2(t_2)$$
$$+ \frac{1}{2}\int_{\underline{c}}^{\bar{c}}\int_{\underline{c}}^{\bar{c}} (p_2(t_1,t_2) - c)\cdot q_2(t_1,t_2)\, \mathrm{d}h_2(t_2|t_1)\, \mathrm{d}h_2(t_2)$$
$$+ \text{Uplift} - \text{Adjustment costs}$$

- By bidding in the spot market a firm influences when it is producing (q_1, q_2).

Optimal Generation mix formula: US market: Intuition

- We can use **the envelope theorem** to derive the total derivative of profit with respect to c (and monoticity)

$$\frac{\mathrm{d}\pi(c)}{\mathrm{d}c} = -\frac{1}{2}\left(\int_{c}^{\bar{c}} \mathrm{d}h_1(t_1) + \int_{c}^{\bar{c}} \mathrm{d}h_2(t_2)\right) = h(c) - 1 \tag{1}$$

  - Note, if adjustment costs would directly depend on c, there would be an additional term $\alpha'(c) \cdot \text{AdjustmentProb.}(c)$

- The first derivatives of the free entry condition $\pi(c) = k(c)$ w.r.t. c gives:

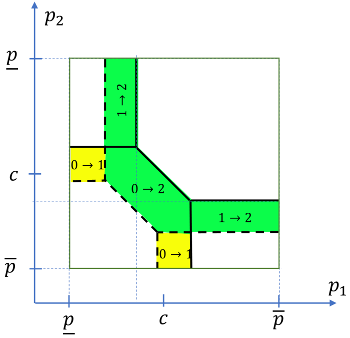
$$\frac{\mathrm{d}\pi(c)}{\mathrm{d}c} = \frac{\mathrm{d}k(c)}{\mathrm{d}c} \tag{2}$$

- Combining both equations we find:

$$h(c) - 1 = \frac{\mathrm{d}k(c)}{\mathrm{d}c}$$

Technical requirements: Existence of a marginal firm

- **As a side note**: The **production level** in market i for a given state $(\varepsilon_1, \varepsilon_2)$ **is (weakly) monotonic decreasing in** c
- Illustrated in the graph US market design: lowering c will weakly increase production (given our assumption of constant α).



Overview

Main idea

- Optimal generation mix formula

$$h(c) - 1 = \frac{\mathrm{d}k(c)}{\mathrm{d}c}$$

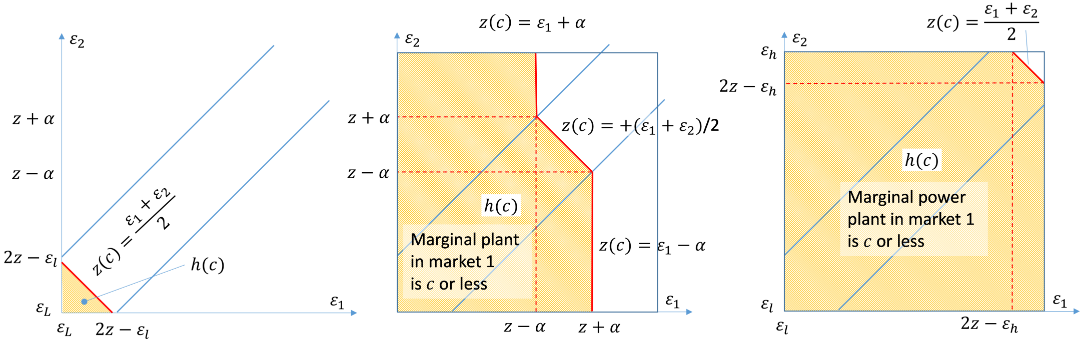
- For a given aggregate investment strategy $G(c)$ we can determine the cdf $h(c)$of the marginal firm:

$$G(c) \xrightarrow[\text{Spot market}]{\text{Optimal Bidding}} h(c)$$

- Inverting the last expression gives us $G(c)$.

Deriving $h(c)$ for the US Market

- Set of shocks $[\varepsilon_1, \varepsilon_2]$ for with only power plants with production costs $\leq c$ run in market 1
- Set depends on $z(c) = c - p(G(c))$ (demand and supply conditions)



Deriving $h(c)$ for US market

- Integrating probabilities provides the cdf $h(c)$:

$$h(c) = \begin{cases} \int_{\varepsilon_L}^{2z(c)-\varepsilon_L} H(2z(c) - \varepsilon_1)\, dH(\varepsilon_1) & \text{if } z(c) < \alpha + \varepsilon_L \\ H(z(c) - \alpha) + \int_{z(c)-\alpha}^{z(c)+\alpha} H(2z(c) - \varepsilon_1) dH(\varepsilon_1) & \text{if } \alpha + \varepsilon_L \leq z(c) \leq \alpha + \varepsilon_H \\ H(2z(c) - \varepsilon_H) + \int_{2z(c)-\varepsilon_H}^{\varepsilon_H} H(2z(c) - \varepsilon_1) dH(\varepsilon_1) & \text{if } \alpha + \varepsilon_H \leq z(c) \end{cases}$$

- The shock distribution $H(\cdot)$ is known, so this results in

$$h(c) = F(z(c)) = F(c - p(G(c)))$$

- The optimal generation mix formula fixes $h(c)$
- Equilibrium generation mix can be derived
  - $z(c)$ can be calculated $\rightarrow$ Optimal generation mix $G(c)$

Deriving $h(c)$: European market

- For the European design, market do not interact so, $h(c)$ is follows a simple expression

$$h(c) = H(\varepsilon(c))$$

- Optimal bid shading depends on the distribution $h(c)$:

$$p(G(c)) + \varepsilon(c) = c - \alpha(1 - 2h(c))$$

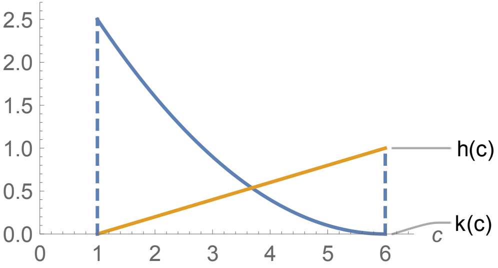
- The shock distribution $H(\cdot)$ is known
- The optimal generation mix formula determines $h(c)$
    - $\varepsilon(c)$ can be calculated $\rightarrow$ Optimal generation mix $G(c)$

Overview

Functional form

- Available technologies / Technology Mix

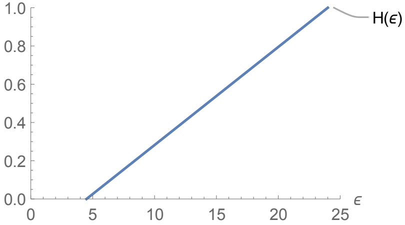
$$k(c) = \frac{1}{2}\frac{(\bar{c}-c)^2}{\bar{c}-\underline{c}} \qquad h(c) = \frac{c-\underline{c}}{\bar{c}-\underline{c}}$$



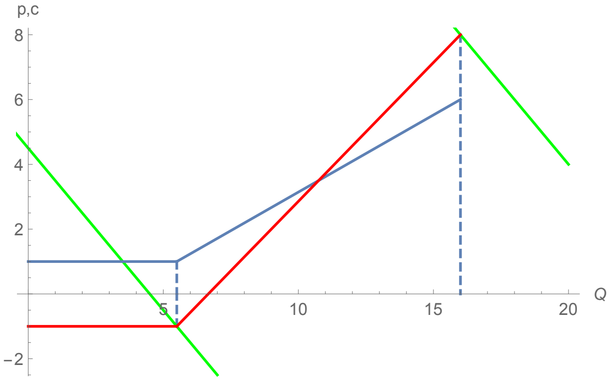
- Inverse linear demand function

$$p = \varepsilon + p(q) = \varepsilon - \beta \cdot q$$

- Uniform Distribution
  $\varepsilon \backsim U[\varepsilon_L, \varepsilon_H]$ with cdf $H(\varepsilon)$



EU Market design

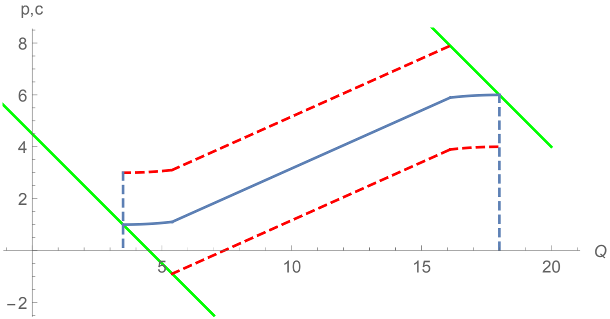


- **Blue Line**: Aggregate supply curve
- **Red Line**: Bid curve
- **Green lines**: highest and lowest demand functions

- Peaker: bids above cost
- Baseload: bids below cost

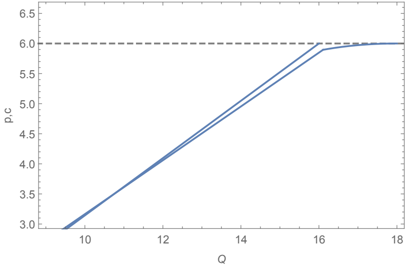
- Sometimes firms sell below cost → risky

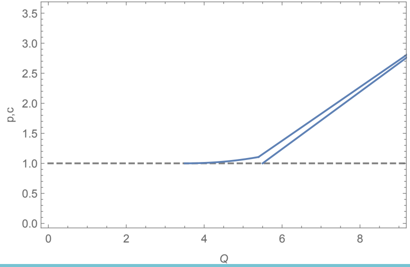
US Market design



- **Blue Line**: Aggregate supply curve
- **Red lines:** Range of prices (price depends on other market)

Comparison US Vs EU





- EU & US market very similar investments
- US-market
  - Slightly more investment in peak technology (close to VOLL)
  - Slightly less investments in baseload investments
- Welfare effects: (still guesses)
  - Long-term: similar investment patterns, relatively small effects (on average EU price reflects more or less value capacity)
  - Short-term: price distortions have larger effects (prices can be wrong up to 4$/unit)

Overview

Conclusion

- **Complex auction**
  - allows for better inter-temporal decisions in short run
  - bidding requires less information about the market conditions (only own production cost)
  - less risky for bidders (not selling below marginal cost)
  - difference in technology mix is limited
- **Ass: Very small firms**
  - Uplift payments are not necessary (?)
  - Market achieves welfare optimum (?)
  - Ideally existing market designs converge to model presented here as firm size decreases

Conclusion

- **Ass: Uncorrelated demand shocks / bidding only once**
  - Adjustment costs are more important in model than in practice
  - Larger bid shading for EU. (red line further from blue line)
  - Adjustment costs matter more US (higher probability price is away from blue line)
  - Multiple subsequent / parallel markets in EU: firms might learn over time
- **Ass: Adjustment cost is same for all firms**
  - monoticity: baseload starts up before peaker
  - all technologies are built
  - In practice: Adjustment costs decrease with marginal costs: results may no longer hold
- **Investing in flexibility (important limitation of model)**
  - A more flexible power plant: benefits from price differences between periods
  - Price variation is larger in US market than EU market
    - US market provide more incentives to invest in flexibility
  - EU market: flexible investment lowers risk for selling below cost

Modeling adjustment costs

- General model **fully endogenizes adjustment costs** α
  - Investment costs k depend on flexibility and adjustment cost α

$$k(\alpha, c)$$

  - This would cause problems similar to the **multi-dimensional screening literature** (monoticity assumptions are no longer satisfied)
  - We will probably be unable to solve this.
- Alternatively we could assume a fixed technology relationship $\alpha(c)$
  - Similar to a one-dimensional screening model with an endogenous participation constraint
  - Non-monotonic production: power plant with higher marginal costs operates before power plant with lower marginal cost
  - Bunching of technologies: not all technologies are used in equilibrium
  - Might be solvable in subset of cases?