Flexibility in Power System: Market Design Matters

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Motivation

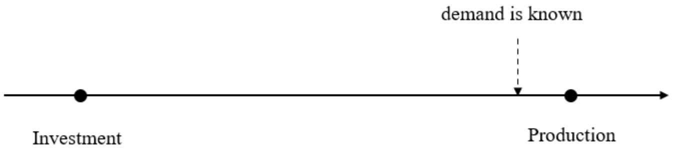
- **Intermittent renewables** will dominate (64% by 2050 according to European Parliament) future's power system.
- Balancing demand and supply with intermittent renewables **requires flexible assets**: flexible generators, batteries, demand side management.
- Does the market provide sufficient **investment incentives** for flexible technologies?
    - European commission says renewable integration requires 7 times larger flexibility by 2050 and they ask for proposal on reforms of the EU electricity market to address the flexibility needs.

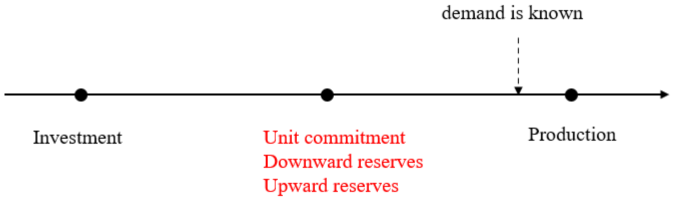
Contribution

- The standard economic tool to analyze the investment in energy sector is peak-load pricing model (Boiteux, 1949).
- However, the **peak-load pricing** model assumes perfect flexibility:
  - All generation capacity is always available
  - Production can be adjusted without costs

	Literature	**Our paper**
Demand	periodic+uncertain	periodic+uncertain
Technology	Baseload vs. Peakload	+Inflexible vs. flexible
Stage	investment+production	+unit commitment
Adjustment costs	No	Yes

Peak-load Pricing Model Timing





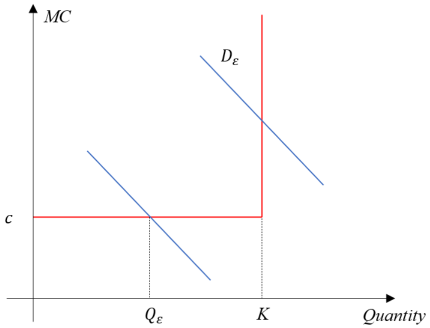
What Could we Use the Model for?

- To determine optimal generation mix and comparative statistics:
  - How much base vs peak and flexible vs. inflexible assets to invest?
  - How does the mix depend on demand elasticity?
  - How does the mix depend on uncertainty?
- Market design:
  - How can we decentralize the market outcome?
  - What is the role of reserves markets? Are the current reserves market efficient to incentive flexibility investment?
- Model extension:
  - Some assumptions such as perfect competition, risk neutrality can be further relaxed.

This Talk

- Our paper
  - A continuous set of technology, three-stage social planner optimization.
  - Two types of consumers (real-time elastic inelastic).
  - Deriving first order conditions for technology production, commitment and investment.
  - Investigating the efficiency of existing market design.
- **This talk**:
  - Give intuition from a single technology case, and understand the difference between flexible and inflexible technology.
  - Show the market design implication from a two-technology case.

Full Flexibility = Standard Peak-load Model



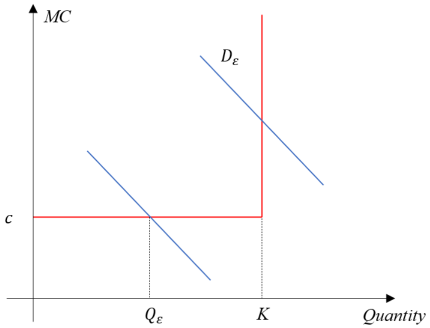
K: total capacity, D_ε: demand in state ε. Q_ε: production in state ε, p_ε: price in state ε.

- **Two**-period model.
- **Production Decision** Q_ε

$$
\begin{aligned}
Q_\varepsilon &= 0 \quad \text{if} \quad p_\varepsilon < c, \\
Q_\varepsilon &\in [0, K] \quad \text{if} \quad p_\varepsilon = c, \\
Q_\varepsilon &= K \quad \text{if} \quad p_\varepsilon > c,
\end{aligned}
$$

- Scarcity rent is earned when: $p_\varepsilon > c$.

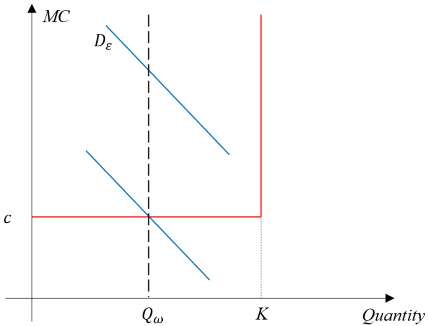
Full Flexibility = Standard Peak-load Model



K: total capacity, D_ε: demand in state ε. Q_ε: production in state ε, p_ε: price in state ε.

- **Two**-period model.
- **Investment Decision** K
  Free entry decision:
  $$E_\varepsilon\{\max(p_\varepsilon - c, 0)\} = I$$
- Capacity is a call option with strike price $= c$.

No Flexibility



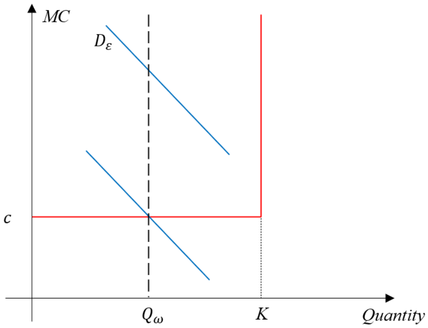
ω : period, Q_ω: production commitment for period ω.

- **Three**-period model.
- **Production Decision** Q_ε

$$Q_\varepsilon = Q_\omega$$

- Real-time supply is inelastic.

No Flexibility

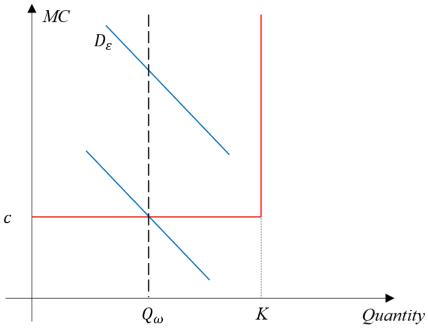


ω : period, Q_ω: production commitment for period ω.

- **Three**-period model.
- p^F_ω: $p^F_\omega = E_{\varepsilon|\omega}(p_\varepsilon)$.
- **Commitment Decision** Q_ω

$$Q_\omega = 0 \quad \text{if} \quad p^F_\omega < c,$$
$$Q_\omega \in [0, K] \quad \text{if} \quad p^F_\omega = c,$$
$$Q_\omega = K \quad \text{if} \quad p^F_\omega > c,$$

No Flexibility



ω : period, Q_ω: production commitment for period ω

- **Three**-period model.
- p^F_ω: $p^F_\omega = E_{\varepsilon|\omega}(p_\varepsilon)$
- **Investment Decision** K

  Free entry decision:

$$E_\omega\{\max(p^F_\omega - c, 0)\} = I$$

- Flexible technology is obviously more profitable.

A toy model

- Two technologies: $i \in \{1,2\}$; Tech 1 is flexible, Tech 2 is inflexible
  - production cost $c_1 = c_2 = c$;
  - Investment cost $I_1 > I_2$; Total Capacity K_1, K_2
- One period with two states:
  - low demand: $\varepsilon = L$ with probability f_L;
  - high demand: $\varepsilon = H$ with probability f_H, $f_H + f_L = 1$.
- All consumers can react to real-time prices;
- Demand: $D_\varepsilon(p)$; gross surplus: $S_\varepsilon(D_\varepsilon(p))$
- Perfect competition;
- Risk-neutral

Real-time Optimal Pricing

Social Planner Solution = Competitive Equilibrium.

$$\begin{aligned} \max_{\{K_1, K_2, Q_1^{\varepsilon}, Q_2\}} \quad & \mathbb{E}[S_{\varepsilon}(Q_1^{\varepsilon} + Q_2) - c(Q_1^{\varepsilon} + Q_2)] - I_1 K_1 - I_2 K_2 \\ s.t. \quad & Q_1^{\varepsilon} \leq K_1 \\ & Q_2^{\varepsilon} = Q_2 \leq K_2 \end{aligned} \tag{1}$$

Proposition

In the presence of demand uncertainty and an efficient real-time market:

a) *inflexible firms earn the expected price* $E_\varepsilon(p)$;
b) *flexible firms earn the high price* $p_H = \frac{I_1}{f_H} + c$;
c) *low demand price is below marginal production cost,* $p_L = c - \frac{I_1 - I_2}{f_L} < c$.

Flexible firms should earn a **flexibility premium** in order to recoup the investment cost difference.

Day-ahead Optimal Pricing

$$\begin{aligned} \max_{\{K_1,K_2,Q_1,Q_2\}} \quad & E[S_\varepsilon(Q_1+Q_2)-c(Q_1+Q_2)]-I_1K_1-I_2K_2 \\ s.t. \quad & Q_1 \leq K_1 \\ & Q_2 \leq K_2 \end{aligned} \tag{2}$$

Proposition

In the absence of real-time markets and presence of a forward market, long-term equilibrium gives:

a) **under-investment in flexible technology***;*

b) **over-investment in inflexible technology***;*

No real-time price signal distorts investment.

Reserves Market = Options Market

Proposition

The social optimum can be attained through a forward market with forward price $p_F = E_\varepsilon(p)$ *and an option market with capacity price* p_K *and strike price* p_X *described by:*

$$p_K = f_H(p_H - p_X), \quad p_L \leq p_X \leq p_H \tag{3}$$

p^F only gives investment incentive for inflexibility, and flexible firms need two predetermined prices: one for investment, one for production.

Reserves Market: $p_X = c$

Lemma

If strike price is equal to production cost, $p_X = c$, a flexible firm should be paid a capacity payment p_K **larger than opportunity cost** *of not trading in the forward market:*

$$p_K > E_\varepsilon(p) - c \tag{4}$$

The popular idea that reserves should earn opportunity cost of not selling in day-ahead forward energy market is wrong!

Lessons to Existing Markets

Efficiency of market-based auction for reserves market?

- Integrated auction (energy+reserves): **No**, under-investement in flexibility.
- A pay-as-bid scoring auction: **Yes**, but demanding for system operator.
- Uniform pricing: **No**, under-investement in flexibility.

Conclusion

Efficient pricing and investment for (in) flexible technologies and implications for market design.

Lessons:

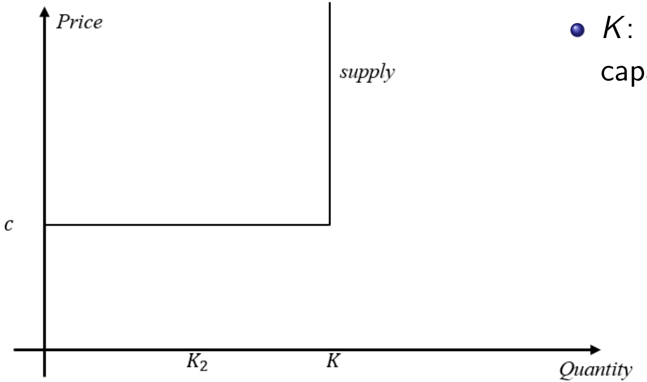
- Flexible technologies should earn flexibility premium in optimum.
- Real time market works in theory to achieve optimum.
- Only a day-ahead forward market would result in under-investment of flexible assets.
- Day-ahead market with reserve markets can implement second best, but requiring technology specific payment.
- Reserves' capacity payment based on day-ahead price as opportunity cost distorts price signal.
- Neither integrated nor separate uniform pricing auction is efficient.

Literature

- Peak load pricing
  - Different technologies: Boiteux (1949), Crew and Kleindorfer (1976)
  - With uncertainty and demand rationing: Visscher (1973), Carlton (1977), Joskow and Tirole (2007)
- Reserve Markets
  - Reserve margins prevent system wide black outs (= Public good) (Joskow & Tirole,2007)
  - Auction design for efficient activation (Bushnell & Oren, 1994; Cramton 2017, Wilson 2002, Oren & Sioshansi, 2005)
  - Reserves as financial hedge (Kleindorfer & Wu, 2005; Anderson et al. 2017)
- Adjustment cost
  - Macroeconomics (some inputs are hard to adjust): different short and long run elasticities (Lucas, 1976)
  - Electricity Markets: empirical evidence that short term supply elasticity is lower (Ito & Reguant, (2016); Hortascu & Puller (2008))

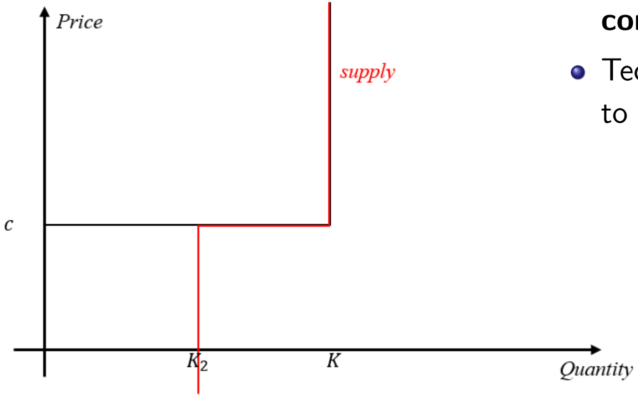
Questions?

Illustration of Proposition



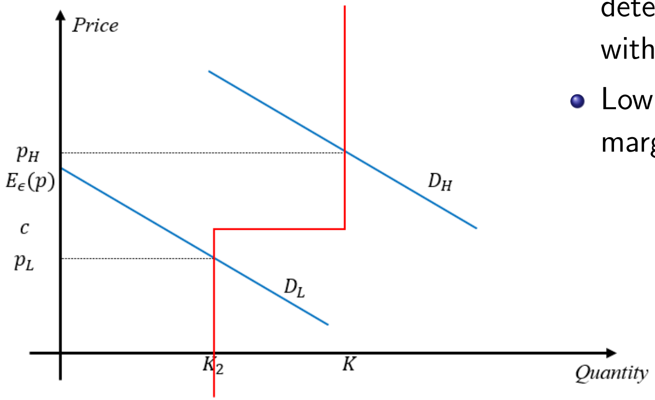
- Supply curve with **total capacity**.
- K: total capacity, K_2: inflexible capacity.

Illustration of Proposition



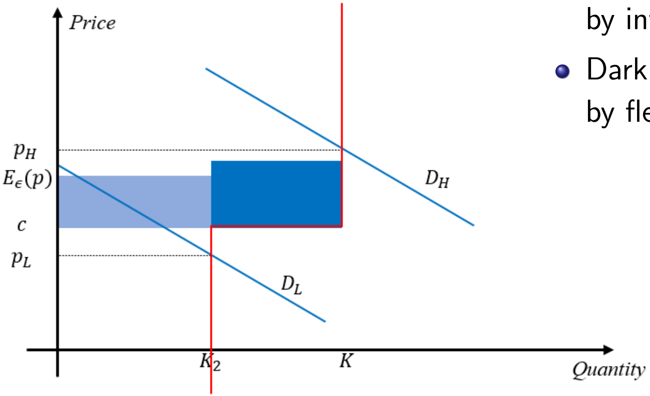
- Supply curve with **production commitment**.
- Technology 2 is inflexible, so has to commit its production.

Illustration of Proposition



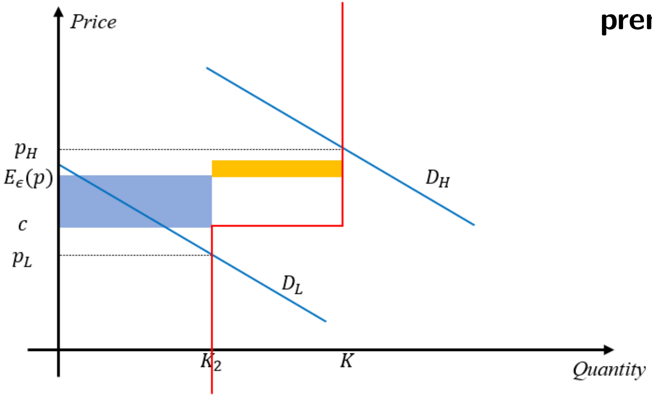
- Price and actual production are determined by demand and supply with commitment.
- Low demand price is lower than marginal production cost.

Illustration of Proposition



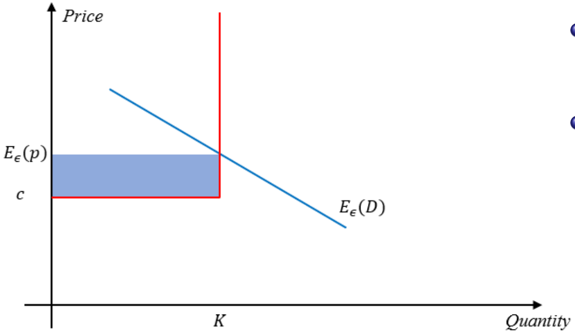
- Light blue part is the profit earned by inflexible technology 2.
- Dark blue part is the profit earned by flexible technology 1.

Illustration of Proposition



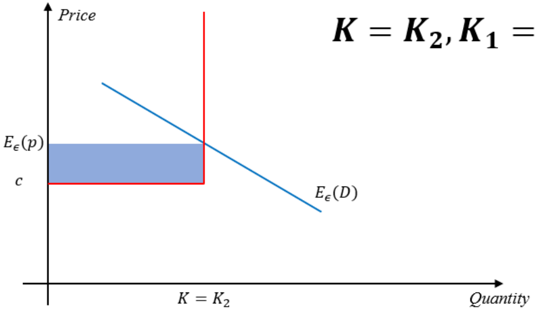
- Yellow part is the **flexibility premium**.

Illustration of Proposition



- No real-time adjustment.
- Supply curve with total capacity.
  Commitment = Production.
- Same profit for both technologies.

Illustration of Proposition



$$K = K_2, K_1 = 0!$$

- No flexibility premium earned.
- No flexible technology invested.