Designing Markets for Reliability with Incomplete Information

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Motivations

Question

How do we choose an allocation that induces at the same time (i) an efficient consumption and (ii) a sufficient level of investment?

- Main motivation: electricity markets.
  - Consumption above available capacity and when demand is not correctly rationed $\rightarrow$ *systemic costs*.
- Since Boiteux (1949, 1951, 1956) and Vickrey (1963, 1969), efficient consumption and financing investments require specific pricing mechanisms.
  - Classic rationales: Investment as a public good / Market Power / Price regulation ...

Electricity as the main motivation

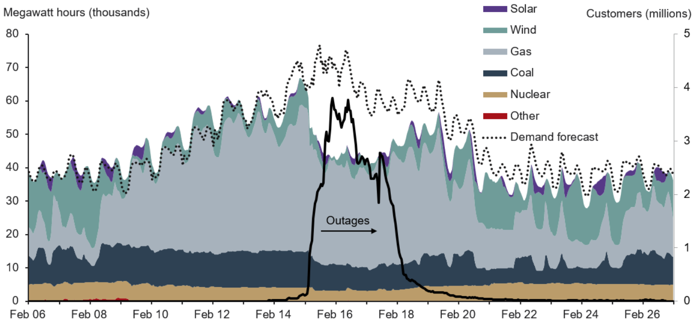


Figure: ERCOT electricity generation by source, demand, and outages during Texas Deep Freeze [DallasFed 2023]

- **Should we simply take demand as given?**

Investment is both a supply-side and demand-side problem

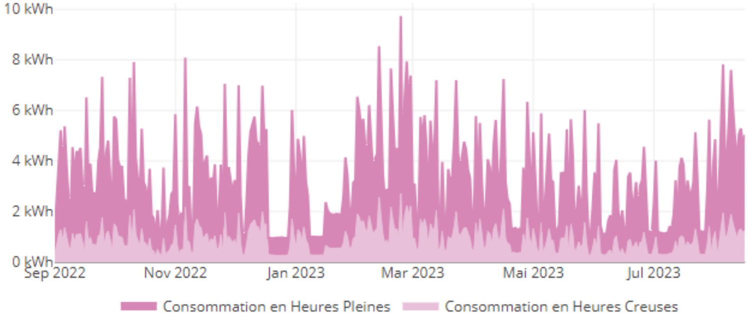


Figure: Personal consumption (https://app.lite.eco/ecoscan)

- **Can we design electricity tariffs leading to a lower need for investment?**

This paper

- Provide a **stylized theoretical framework** where a market designer has to choose the **allocation mechanism** (in price and quantity, eg. contracts) and **investment decisions**. We highlight the tension between:
  - Choosing an allocation mechanism that dictates how consumption decisions are made.
  - Generating revenue to provide sufficient available capacity.

Question

How do we choose an allocation when a market designer faces **different consumers** that vary in their **level of consumption** that will be considered **private information**.

First contribution: Peak Load Pricing Theory with Incomplete Information

Contribution 1

Link the design of an optimal allocation for the demand side under incomplete information with investment decisions.

- **Long-term supply side without incomplete information.**
  - How to make investment decisions? [Boiteux, 1949], [Crew and Kleindorfer,1976], [Crew et al., 1995], [Borenstein, 2005]. How investment decisions affect short-term equilibrium? [Zöttl, 2011], [Allcott, 2012], [Léautier, 2016], [Holmberg and Ritz, 2020].
- **Short-term demand side without investment decisions**
  - Optimal short-term pricing mechanism. [Chao and Wilson, 1987], [Chao, 2012], [Chao et al., 2022] [Spulber, 1992]. Implementation of optimal mechanism [Spulber,1992], [Spulber,1993].

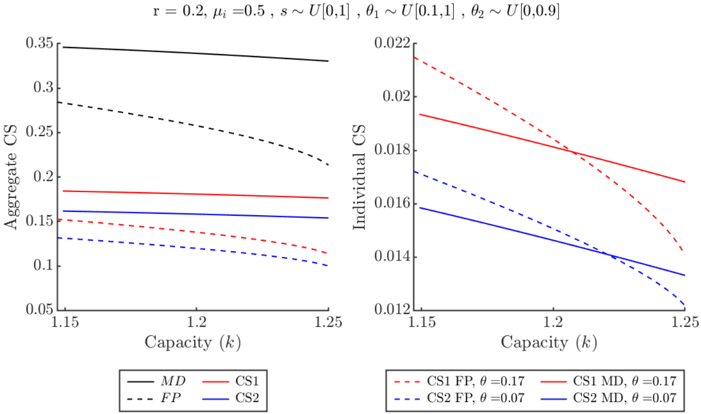
Main policy results

Contribution 2

Provide individual welfare comparisons for consumers given different environments and investment levels.

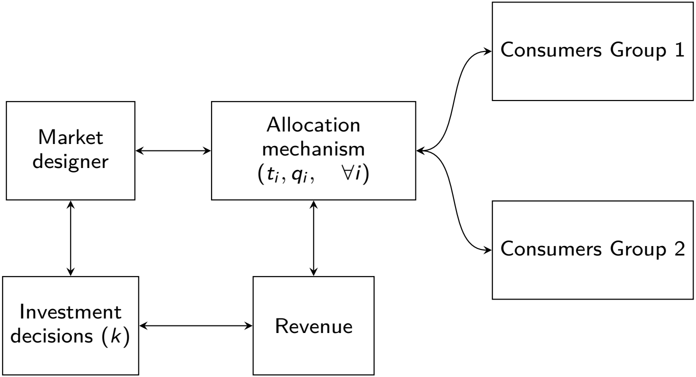
- Two main environments: (1) fixed-price allocation, (2) second-best with mechanism design.
  - We derive the set of prices/quantities that maximizes aggregate consumer surplus given investment decisions.
- Efficient investment level and corresonding allocation are not always Pareto-improving for every consumer = **distributive issues**.
  - Electricity [Cahana et al., 2022] Electricity tarifs [Burger et al., 2020] [Levinson and Silva 2022] Transport [Hall. 2021]

Optimal allocation and individual welfare



Roadmap

Agents


Consumers Group 1
Market designer
Allocation mechanism $(t_i, q_i, \quad \forall i)$
Consumers Group 2
Investment decisions (k)
Revenue

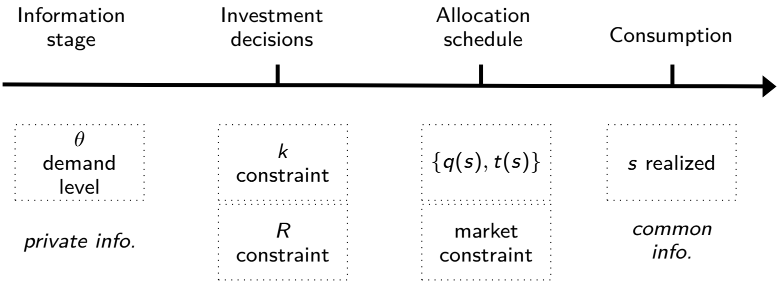
Consumers

- Unit mass of consumers :

$$u(q,\theta,s) = \overbrace{\theta + s}^{\text{agg. uncertainty}} - \underbrace{q}_{\text{qtt.}}$$

- θ: consumer type, PDF $g_i(\theta)$, CDF $G_i(\theta)$, $\theta \sim U[\underline{\theta}_i, \bar{\theta}_i]$.
  - $i \in 1, 2$: category of consumers with $\mu_i > 0$ consumers in group i.
- s: common shock, CI, PDF $f(s)$, CDF $F(s)$, $s \sim U[0, \bar{s}]$.
- With demand $d(t,\theta,s)$ and utility $U(q,\theta,s) = \int_0^q u(q,\theta,s)dq$
- **Category 1 is "bigger" than Category 2 :** $\mu_1\theta_1^{av} > \mu_2\theta_2^{av}$.

Timing - Production



Roadmap

Market designer - objective

The market designer looks for every allocation for each consumer and the level of investment that maximizes expected consumer surplus.

$$\max_{\substack{t_i^*(\theta,s)\to\mathbb{R}^+,\\ q_i^*(\theta,s)\to\mathbb{R}^+,\\ k\geq 0}} \quad \sum_i \mu_i \int_s \int_{\theta_i} U(\theta, q_i^*(\theta,s), s) \; - \; t_i^*(\theta,s) q_i^*(\theta,s) dG_i(\theta) dF(s)$$

$$\text{s.t.} \qquad I(k) \; = \; \sum_i \mu_i \int_s \int_{\theta_i} t_i^*(\theta,s) q_i^*(\theta,s) dG_i(\theta) dF(s), \qquad \text{(R)}$$

$$\sum_i \mu_i \int_{\theta_i} q_i^*(\theta,s) dG_i(\theta) \leq k, \qquad \text{(K)}$$

First-best allocation mechanism - spot market

Proposition

(i) Optimal allocation for each s:

single price *marginal cost*

$$t^*(k,s) = \begin{cases} 0 \quad \text{if} \quad s \in [0, s_1(k)) \\ p(k,s) \quad \text{if} \quad s \in [s_1(k), \bar{s}] \end{cases}$$

aggregate demand s.t. $D(p(k,s),s) = k$

$$q_i^*(k,\theta,s) = \begin{cases} d(0,\theta,s) \quad \text{if} \quad s \in [0, s_1(k)) \\ d(p(k,s),\theta,s) \quad \text{if} \quad s \in [s_1(k), \bar{s}] \end{cases}$$

(ii) Optimal mechanism design can be implemented by spot market.

Long-term vs short-term allocation

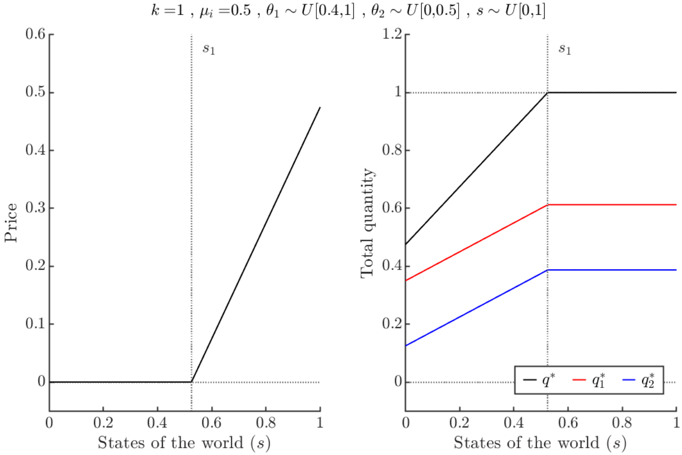
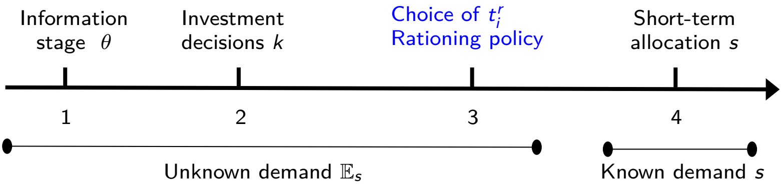


Figure: Surplus-maximizing allocations

Roadmap

Second-Best 2: current market design

- Consumers' type is **private information**.
- The market designer can only set a **fixed and unique price per category**. *Third-degree price discrimination*
- The market designer **cannot extract any information**.
- Consumers **adjust their consumption**.



Rationing policy

- Fixed-price + K Constraint + Incomplete Info. : **Inefficient rationing**.
- Given t:
  - If Demand(t) $<$ K, no intervention (but welfare loss due to fixed prices).
  - If Demand(t) $>$ K, **random allocation** within each group.
- **Main ingredients**: Group Discrimination + Asymmetry between off-peak and on-peak periods.

Proposition - main result

$$\max_{\substack{t_i^r \to \mathbb{R}^+, \\ k \geq 0}} \quad CS^r(t_i^r, k)$$

$$\text{s.t.} \quad (R^r)$$

Proposition

Suppose that category 1 is bigger than category 2, then:

- $t_1^r(k)$ *is increasing with* k
- $t_2^r(k)$ *is first decreasing, then increasing with* k.

Proposition - main result

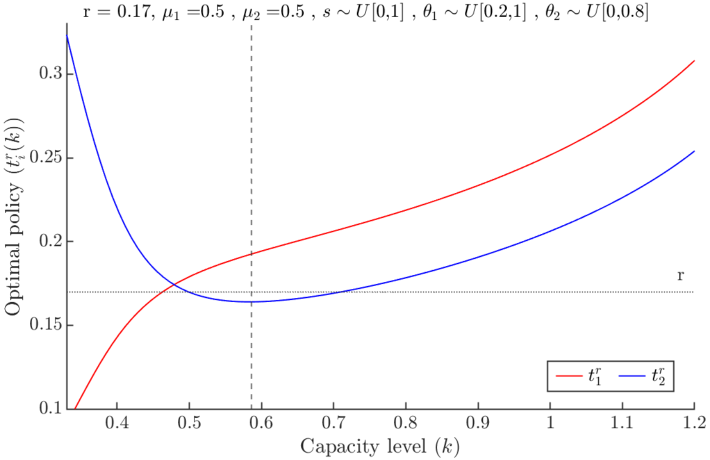


Figure: Evolution of optimal prices t_i^r with respect to investment level k

Intuitions

- Consumer surplus effect:
  - Preference for lower prices: $t_i^r \downarrow$
  - Preference for discrimination of lower types: $t_1^r \downarrow \quad t_2^r \uparrow$
- Revenue effect:
  - Preference for higher prices: $t_i^r \uparrow$
  - Preference for discrimination of higher types: $t_1^r \uparrow \quad t_2^r \downarrow$

Consumer vs revenue effect with respect to k

- Net effect:
  - Consumer effect $>$ Revenue effect for low values of k
  - Consumer effect $<$ Revenue effect for high values of k
- Marginal CS decreases in k because the capacity binds less often.

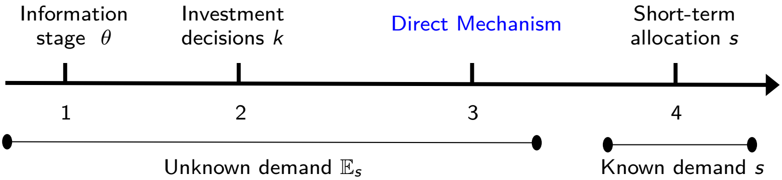
$$\sum_i \mu_i \int_{s^r(k,t_i^r)}^{\bar{s}} \int_{\theta_i} u(\alpha_i k, \theta, s) - t_i^r dG_i(\theta) dF(s)$$

- Revenue is more constraining with high values of k.

Roadmap

Second-best 3: theoretical upper bound

- We make three assumptions:
  - Consumers' type is private information.
  - The market designer can extract consumer information (Revelation Principle).
  - The market designer ask consumers to report their type θ, then assign quantity $q_i(\theta, s)$ and charge $t_i(\theta, s)$.



Market designer - objective

$$\max_{\substack{t_i^m(\theta,s)\to\mathbb{R}^+,\\ q_i^m(\theta,s)\to\mathbb{R}^+,\\ k\geq 0}} \sum_i \mu_i \int_s \int_{\theta_i} U(q_i^m(\theta,s),\theta,s) - t_i^m(\theta,s) q_i^m(\theta,s) dG_i(\theta) dF(s)$$

(K)

(R)

$$0 \leq \int_s U(q_i^m(\theta,s),\theta,s) \; - \; t_i^m(\theta,s) q_i^m(\theta,s) \; dF(s) \qquad (IR)$$

$$\theta = \arg\max_{\tilde{\theta}} \int_s U(q_i^m(\hat{\theta},s),\theta,s) - t_i^m(\hat{\theta},s) q_i^m(\hat{\theta},s) \; dF(s) \qquad (IC)$$

Revenue constraint + Participation constraint

- We define the inverse hazard rate $\Gamma_i(\theta) = \frac{1-G_i(\theta)}{g_i(\theta)}$ $(\downarrow)$.
- New constraint $(R - IR)$:

$$\sum_i \mu_i \int_s \int_{\theta_i} U(q_i^m(\theta, s), \theta, s) - \Gamma(\theta) q_i^m(\theta, s) dG_i(\theta) dF(s) \quad - \quad I(k) \quad \text{(R-IR)}$$

- Interpretation:
  - After paying for truthful behavior, the market designer is left with a net utility.
  - Virtual utility = utility net of information rent = maximum revenue the market designer can extract to finance investments.

First result

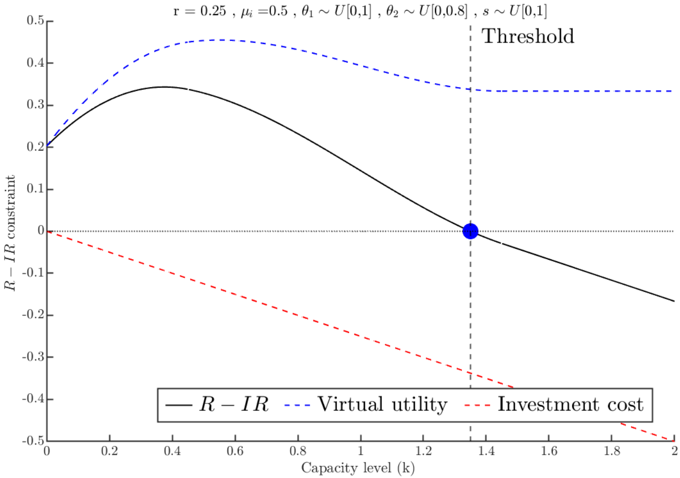


Figure: Change in the R-RI constraint with respect to investment level.

Second result

The effect of k on the individual optimal allocation depends on the consumer's type.

Proposition

- *(Optimal off-peak)* $q^m_{i,3}$ *is always decreasing with* k *for every values of* k *and for every type.*
- *(Optimal on-peak) if*
  - $J_{i,4} > \mathbb{E}J_4 - \frac{1}{\mathbb{B}}$ $q^m_{i,4}$ is always increasing with k.
  - $J_{i,4} < \mathbb{E}J_4 - \frac{1}{\mathbb{B}}$ $q^m_{i,4}$ is always decreasing with k.

With $\mathbb{E}J_4 = \sum_i \mu_i \int_{\theta_i} J_{i,4} dG_i(\theta)$, the expected virtual marginal utility across all types and categories. $\mathbb{B}$ encompasses aggregate consumer surplus and revenue effect.

Second result

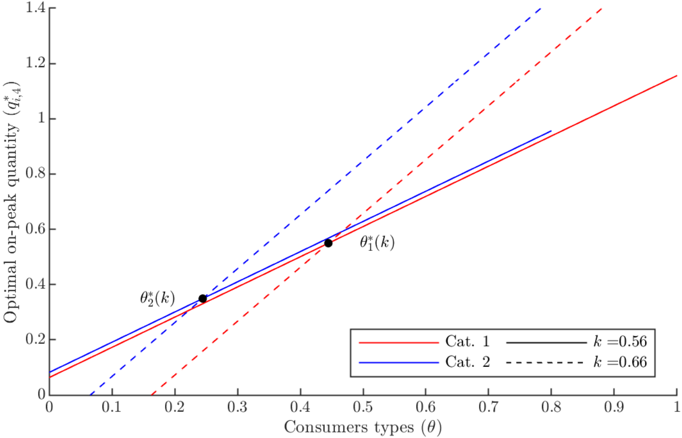


Figure: Optimal on-peak allocation for different consumers with respect to k

From quantity to welfare

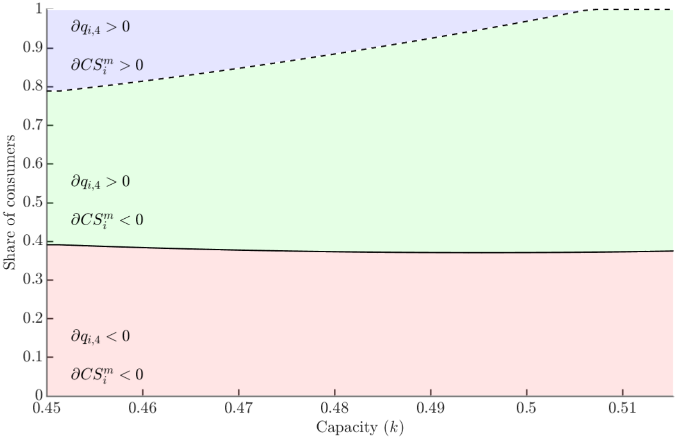
Consumer surplus is the information rent:

$$CS^m(\theta, s) = \int_s \int_{\underline{\theta}}^{\theta} q_i(\hat{\theta}, s) dF(s) d\hat{\theta}$$

How the information rent changes with respect to k gives the individual welfare:

$$\frac{\partial CS^m}{\partial k} = \int_0^{s^m(k)} \underbrace{\int_{\underline{\theta}}^{\theta} \frac{\partial q^m_{i,3}}{\partial k} d\hat{\theta}}_{\text{off-peak information rent} < 0} dF(s) + \int_{s^m(k)}^{\bar{s}} \underbrace{\int_{\underline{\theta}}^{\theta} \frac{\partial q^m_{i,4}}{\partial k} d\hat{\theta}}_{\text{on-peak information rent} \gtrless 0} dF(s)$$

Implication for the welfare



Roadmap

Conclusion

We build a framework unifying surplus-maximizing investment decisions with optimal short-term allocations under incomplete information.

Under a set of constraints, we described the pair of quantity and prices that a market designer should implement and the consequences in terms of investment level.

(i) revenue constraints (ii) implementation constraints, and (iii) heterogeneity between consumers implies non-intuitive relationship between the short-term mechanism and investment level.

Extensions

I - We derive the current second-best and the theoretical second-best, representing a market designer's lower and upper bound in terms of possible mechanisms.

How do some practical contractual frameworks (ie. long-term arrangements) that allow consumers to partially reveal information to the market designer behave with respect to the two boundaries?

II - In a framework with some redistributive preferences, the non-monotonicity of the allocations could contradict the optimal policies.

How does redistributive preferences changes the optimal allocation mechanism?

Thank you !

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