Summary

Introduction
- Prudence
- Frugality
  - Production risk
  - Capacity

The model

Competitive market equilibrium

Conclusion

Precautionary Energy Storage

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Presentation

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4 Competitive market equilibrium

5 Conclusion

Summary

- energy storage technologies primarily used to take advantage of dispatchable sources and demand variability
  - the underlying economic analysis mainly on pumped hydro storage
- increasing shares of renewable energy (RE) have drawn attention to **storage technologies**
- not much consideration on energy storage due to precautionary motives
  - to what extent a convex marginal utility, **prudence**, and a convex marginal cost, **frugality**, can spur energy storage.

Summary

- a simple theoretical model
    - characterize the optimal solution
    - demonstrate how prudence and frugality induce further energy saving
    - show how the optimal allocation can be decentralized through competitive markets.
- implications of *prudence* and *frugality* in a decentralized setting
    - upward pressure on spot market energy prices
    - higher uncertainty → greater impact of prudence and frugality
    - ...

Introduction

- a number of strategies exist to deal with the challenges created by intermittent RE
    1. thermal dispatchable generation
    2. demand response
    3. energy storage
    4. ...

- the paper *embraces* the **first three**
- main contribution: **theoretical**

Introduction

- prudence w.r.t electricity consumption, $U''' \geq 0$ "*convex marginal utility*"
- frugality, $C''' \geq 0$ "*convex marginal cost*"
  - in the presence of **uncertainty**
    - endows a cost-minimizing producer with the same motivations as that of a prudent consumer

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* consuming **stored energy** is one way to increase q

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1. variations in energy demand are typically limited and more predictable
2. due to the low operating cost of intermittent RE that leads to its earlier dispatch
    - the residual load is intermittent
3. thus, a thermal dispatchable generator has to supply the **intermittent residual load**

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- A convex marginal (production) cost curve has a transparent economic interpretation
  - *it becomes increasingly expensive to make large and positive changes to meet the residual demand*

Frugality is an industrial trait

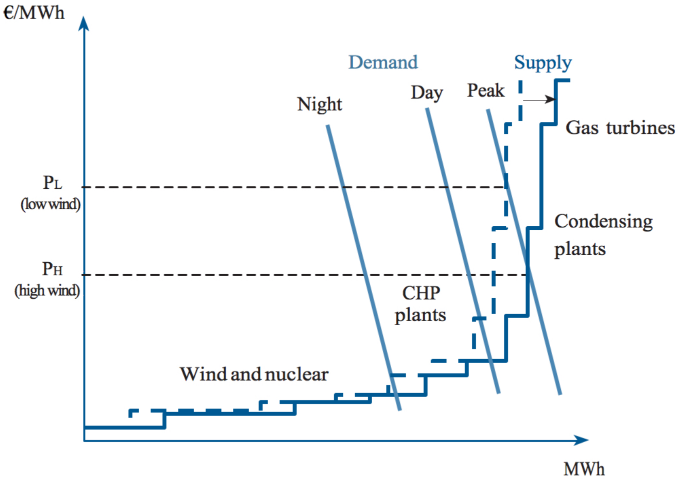

Figure : *Supply and Demand Curves for NordPool Spot*

The model

Two-period planner's problem

$$
\begin{aligned}
\max_{\{q_j, y_j, s_1\}} \quad & U(q_0) - C(y_0) + \mathbb{E}\left[U(\tilde{q}_1 - \epsilon) - C(y_1)\right] \\
\text{subject to} \quad & q_0 = y_0 + z_0 - \alpha s_1, \\
& \tilde{q}_1 = y_1 + \tilde{z}_1 + s_1, \\
& q_0 \geq 0, q_1 - \epsilon \geq 0,\ \ y_j \geq 0,\ \ j = 0, 1 \\
& \bar{s} \geq s_1,\ \ s_1 \geq 0, \\
& \alpha > 1
\end{aligned}
$$

Existing energy systems worldwide in general characterized by small shares of RE (Lund et al., 2012). Accordingly, even with very favorable weather conditions, thermal dispatchable generation generally kept active to supply the residual load.

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- larger shares of RE considered in the appendices

Intertemporal efficiency condition

$$\overbrace{U'(y_0^* + z_0 - \alpha s_1^*)}^{\text{MC of energy storage}} = \overbrace{\phi \mathbb{E}\left[U'(\tilde{y}_1^* + \tilde{z}_1 + s_1^* - \epsilon)\right]}^{\text{Net expected MB of energy storage}}$$

$$\text{if} \quad \bar{s} > s_1^* > 0,$$

where $\tilde{z}_1 = \mu + \tilde{x}$, $\mathbb{E}[\tilde{x}] = 0$, $\mathbb{E}[\tilde{x}^2] = \sigma^2$ and $\phi = 1/\alpha$

Main result

Theorem

for every μ *and* $\tilde{x}$ *with* $\mathbb{E}[\tilde{x}] = 0$, $s_1^* \geq s_1^+$ *iff*

$$\psi_U U''' + \psi_C C''' \geq 0,$$

where $\psi_U \equiv (C''^3)/(C'' - U'')^3$, $\psi_C \equiv (-U''^3)/(C'' - U'')^3$.

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Corollary

$U''' \geq 0$ *and* $C''' \geq 0$ *are sufficient for* $s_1^* \geq s_1^+$.

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$s_1^* \geq s_1^+$ *implies* $y_0^* \geq y_0^+$ *and* $q_0^* \leq q_0^+$.

Further use of our main result (i.e., Theorem 1)

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second-order Taylor approximation

$$U'\left(q_0^*\right) \simeq \phi\left[U'\left(q_1^* - \epsilon\right) + \frac{1}{2}\sigma^2\left(\psi_U U'''(q_1^* - \epsilon) + \psi_C C'''\left(y_1^*\right)\right)\right]$$

Competitive market equilibrium with energy storage

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- the planner solution can be decentralized through competitive markets
- enables us to see the role of prices in coordinating the energy market
- no externalities in the model
    - the planner solution will coincide with the competitive rational expectations equilibrium (REE).

Competitive market equilibrium with energy storage

- optimization problem of a representative consumer with quasilinear preferences.

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first-order necessary conditions for the consumer problem

$$U'(q_0^*) = P_0^*,$$
$$U'(q_1^* - \epsilon) = P_1^*$$

- $q_t^* \equiv q(P_t^*)$ is the **aggregate demand function** for energy given the market price.

Competitive market equilibrium with energy storage

Intertemporal efficiency condition in a competitive market

$$P_0 \simeq \phi \left[1 + \frac{1}{2}\sigma^2 \left(\psi_U \frac{U'''}{U'} + \psi_C \frac{C'''}{C'} \right) \right] P_1,$$

Assume $U''' > 0$ and $C''' = 0$

Assume that the consumers are prudent, $U''' > 0$, but capacity constraint is less of an issue, $C''' = 0$:

Proposition

If $U''' > 0$ and $C''' = 0$, then P_0 is augmented by a lower η_d and a higher ϕ, ξ_r^p, σ and ψ_U.

$$P_0 \simeq \phi \left[1 + \frac{1}{2} \left(\frac{\sigma}{\bar{q}_1} \right)^2 \psi_U \frac{\xi_r^p}{\eta_d} \right] P_1,$$

Assume $U''' = 0$ and $C''' > 0$

Assume that the consumers are not prudent, $U''' = 0$, but producers are capacity constrained, $C''' > 0$:

Proposition

If $U''' = 0$ and $C''' > 0$, then P_0 is augmented by a lower η_s, and a higher ϕ, ξ_r^f, σ and ψ_c.

$$P_0 \simeq \phi \left[1 + \frac{1}{2} \left(\frac{\sigma}{\bar{y}_1} \right)^2 \psi_c \frac{\xi_r^f}{\eta_s} \right] P_1$$

General case: $U''' > 0$ and $C''' > 0$:

$$P_0 \simeq \phi \left[1 + \frac{1}{2} \left(\left(\frac{\sigma}{\bar{q}_1} \right)^2 \psi_U \frac{\xi_r^p}{\eta_d} + \left(\frac{\sigma}{\bar{y}_1} \right)^2 \psi_C \frac{\xi_r^f}{\eta_s} \right) \right] P_1$$

Conclusion

- even though energy storage is addressed in many studies, the extent to which precautionary motives can spur energy storage is not well known.
- in designing coherent energy policies and making utility planning decisions, both governments and power utilities can benefit from knowledge regarding the impacts of precautionary motives on electricity prices, and electricity generation and storage decisions.
- the model provides a simple setup to assess these impacts

Thank you for your attention

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Cecchetti, S. G., A. K. Kashyap, and D. W. Wilcox (1997). Interactions between the seasonal and business cycles in production and inventories. *American Economic Review 87*(5), 884–892.

Lund, H., A. N. Andersen, P. A. Østergaard, B. V. Mathiesen, and D. Connolly (2012). From electricity smart grids to smart energy systems–a market operation based approach and understanding. *Energy 42*(1), 96–102.