IMPACT OF STORAGE ON THE EFFICIENCY AND PRICES IN REAL-TIME ELECTRICITY MARKETS

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Outline

1. Introduction and motivation

2. System model and dynamic competitive equilibriums

3. Social optimality and impact on investments

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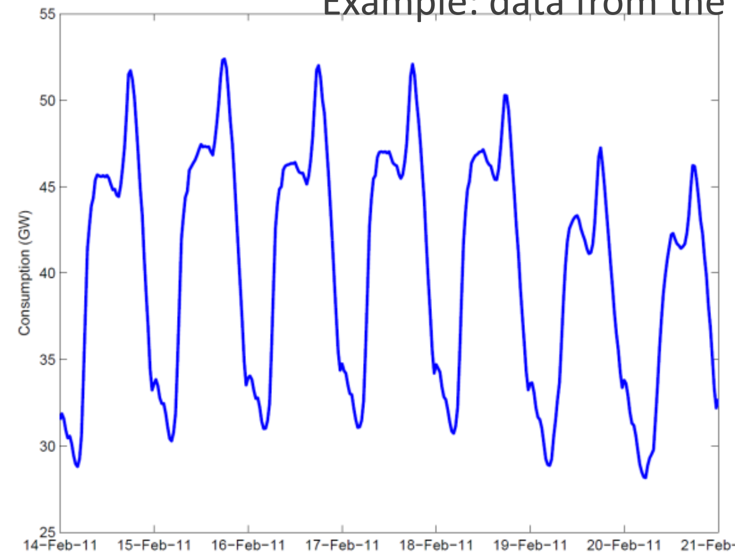
Renewables increase volatility

Example: data from the UK

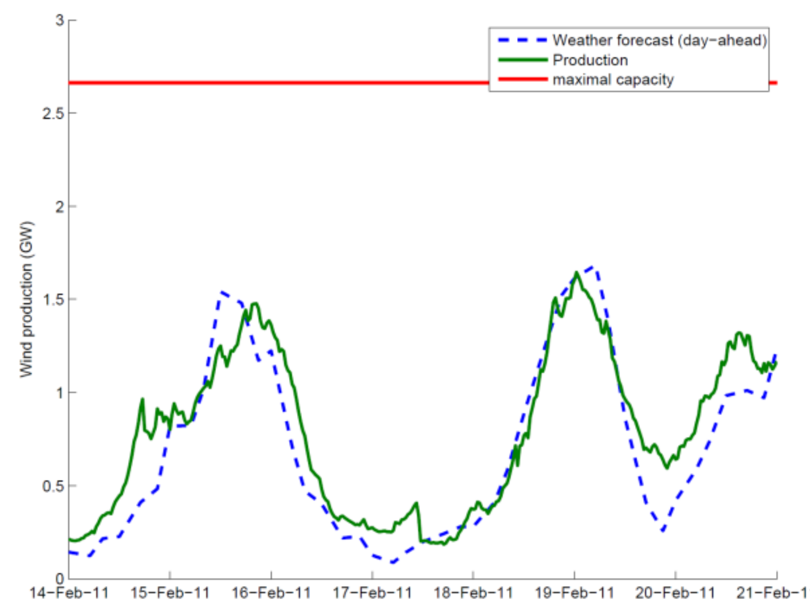
- Europe incentives the penetration of renewables
  - Target: 20% of renewable energy by 2020.



- Problem = stochasticity

Demand is predictable

Renewables are not



- Possible solutions:
  - Increase reserves
  - Use storage

Storage can mitigate volatility

- Batteries, Pump-hydro

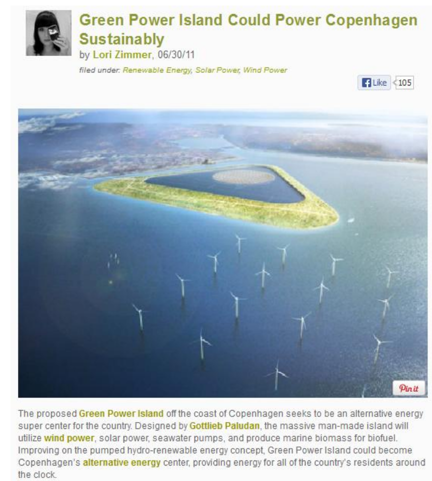
Switzerland (mountains)

Limberg III, switzerland

Projects: artificial islands (north sea)

Belgium

Copenhagen



Green Power Island Could Power Copenhagen Sustainably

by Lori Zimmer, 06/30/11

filed under: Renewable Energy, Solar Power, Wind Power

The proposed Green Power Island off the coast of Copenhagen seeks to be an alternative energy super center for the country. Designed by Gottlieb Paludan, the massive man-made island will utilize wind power, solar power, seawater pumps, and produce marine biomass for biofuel. Improving on the pumped hydro-renewable energy concept, Green Power Island could become Copenhagen's alternative energy center, providing energy for all of the country's residents around the clock.

A Manmade Island to St Wind Energy

MIT Technolog Review

Belgium has plans for an artificial "energy atoll" to store excess wind power in the North Sea.

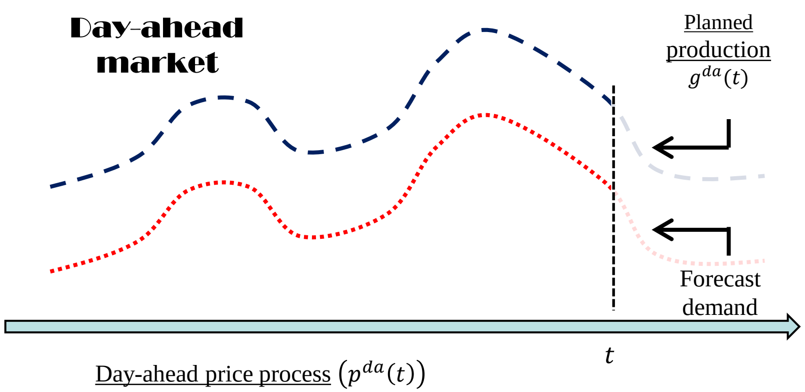
This illustration shows how the artificial island would use pumped hydro energy storage where water is pumped to a reservoir during off-peak times and released to a lower reservoir later to generate electricity.

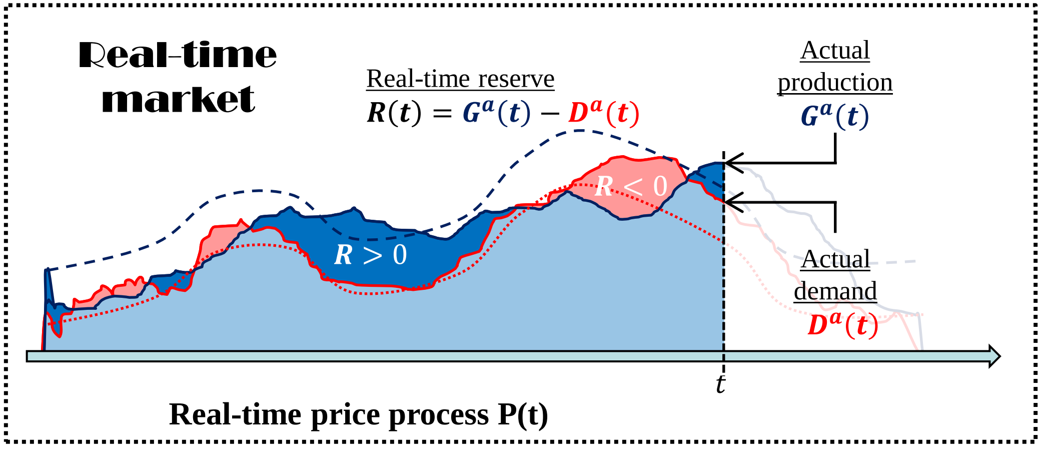
- Business model:
  - Pump when energy is cheap, release when energy is expensive

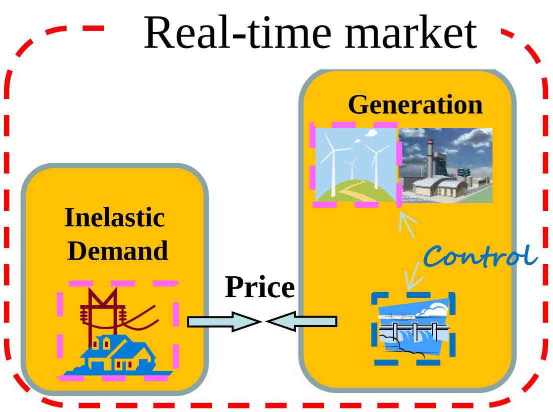
- **Main question of this paper:**
  - Is it efficient?

We focus on the real-time market

- Most electricity markets are organized in two stages





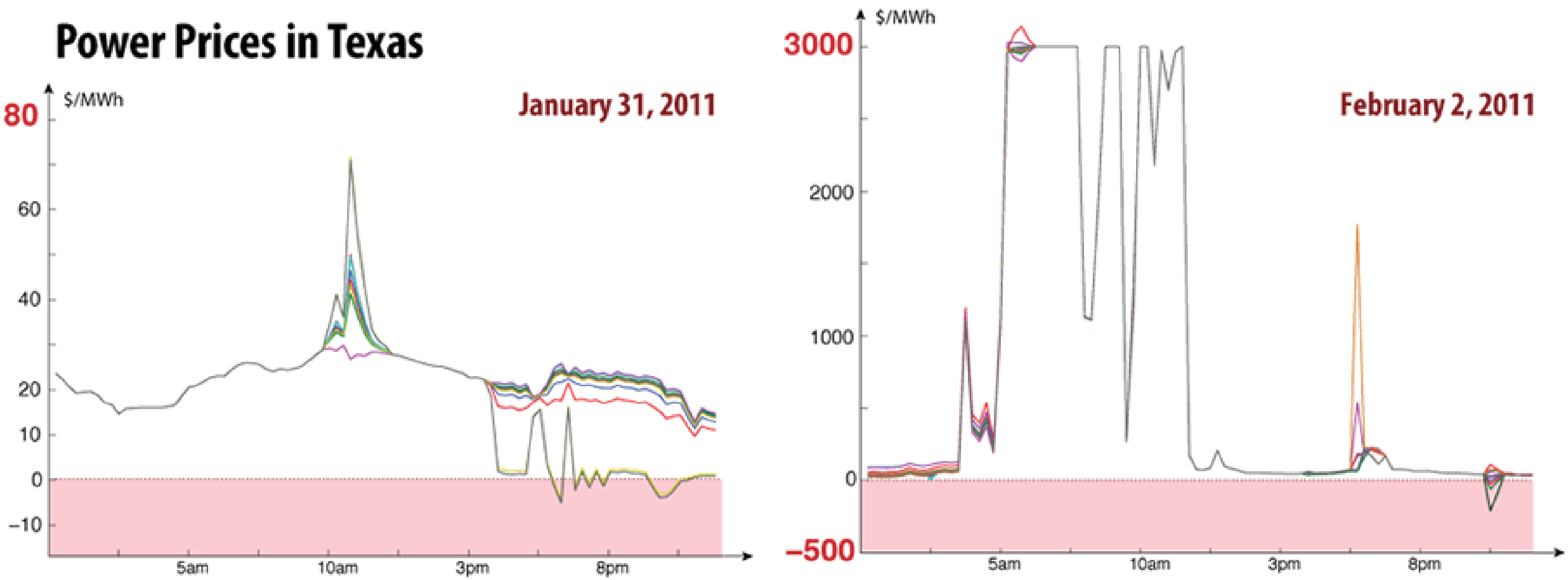


Compensate for deviations from forecast

Inelastic demand satisfied using:

- Thermal generation (ramping constraints)
- Storage (capacity constraints)

Real-time Market exhibit highly volatile prices



- Efficiency or Market manipulation?

The first welfare theorem

- Impact of volatility on prices in real time market is studied by Meyn and co-authors: price volatility is expected

> Theorem (Cho and Meyn 2010). When generation constraints (ramping capabilities) are taken into account:
> - Markets are efficient
> - Prices are never equal to marginal production costs.

We add storage to the model

- Q1: Still efficiency?
- Q2: Effects on prices?
- Q3: Investments strategies?

[Cho and Meyn, 2010] I. Cho and S. Meyn *Efficiency and marginal cost pricing in dynamic competitive markets with friction*, Theoretical Economics, 2010

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A Macroscopic Model of Real-time generation and Storage

Randomness (forecast errors)

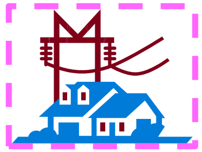
Assumption: $(D - \Gamma) \sim$ Brownian motion

Supply
$$G^a(t) = g^{da}(t) + G(t) + \Gamma(t)$$

Controllable generation

Ramping Constraint

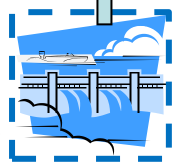
$$-\xi \leq G(t) - G(t-1) \leq \zeta$$



Demand
$$D^a(t) = d^{da}(t) + D(t)$$

Day-ahead

$u(t)$ extracted (or stored) power



Storage
$$\frac{\partial B}{\partial t} = -u(t)(1_{u(t)>0} + \eta 1_{u(t)<0})$$

Storage cycle efficiency

(E.g. $\eta = 0.8$)

Limited capacity

Macroscopic model

- At each time: generation = consumption

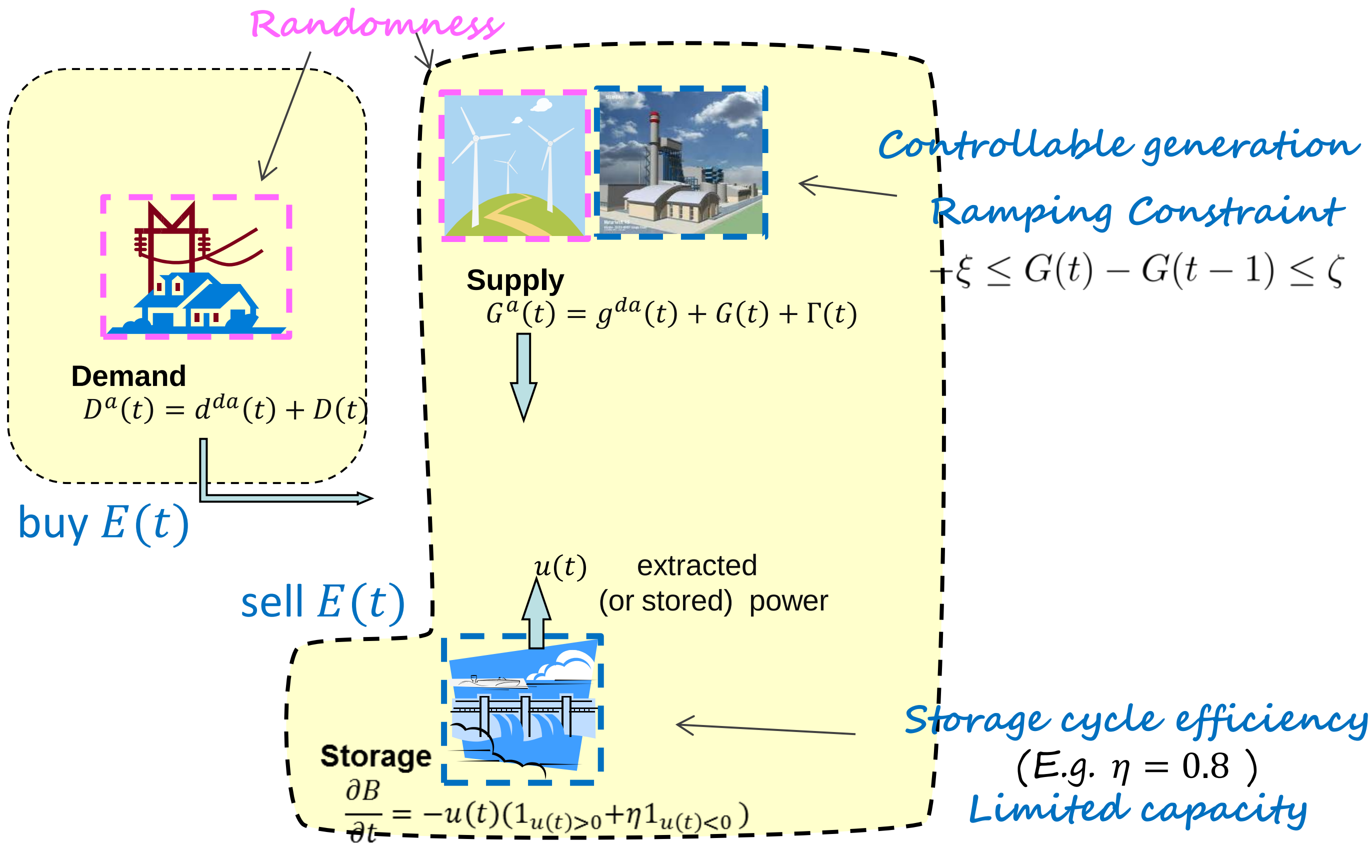
$$G^a(t) + u(t) = D^a(t)$$

A Macroscopic Model of Real-time generation and Storage

In the paper, we consider 3 scenarios for storage ownership:

1. Storage ∈ Supplier (this slide)
2. Storage ∈ Consumer
3. Independent storage

(ownership does mostly not affect the results)



$P(t) =$ stochastic price process on real time market

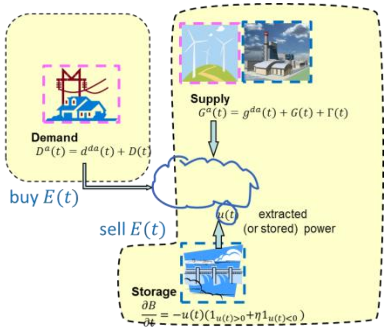
- Consumer's payoff: $W_D(t)$

$$= \underbrace{v\min(D^a(t), E(t) + g^{da}(t))}_{\text{satisfied demand}} - \underbrace{c^{bo}\left(D^a(t) - G^{da}(t) - -u(t)\right)^+}_{\text{Frustrated demand}} - \underbrace{P(t)E(t) - p^{da}(t)g^{da}(t)}_{\text{Price paid}}$$

- Supplier's payoff: $W_S(t)$

$$= P(t)E(t) + p^{da}(t)g^{da}(t) - cG(t) - c^{da}g^{da}(t)$$

Definition of a competitive equilibrium



Assumption: agents are price takers

$P(t)$ does not depend on players' actions

- Both users want to maximize their average expected payoff:
  - Consumer: find E such that
    $$E_D \in \text{argmax}_E \ \mathbb{E}\left[\int W_D(t) e^{-\gamma t} dt\right]$$
  - Supplier: find E, G, u such that
    - G and u satify generation constraints and
      $$E_S, G, u \in \text{argmax}_E \ \mathbb{E}\left[\int W_S(t) e^{-\gamma t} dt\right]$$

- Question: does there exists a price process Psuch that consumer and supplier aggree on the production: $E_S(t) = E_D(t)$

  (P,E,G,u) is called a *dynamic competitive equilibrium*

Dynamic Competitive Equilibria

Theorem. Dynamic competitive equilibria exist and are essentially independent of storage owner [Theorem 3]

For all 3 scenarios, the price and the use of generation and storage is the same.

Prices ≈ marginal value of storage

- Concentrate on marginal production cost when $\eta = 1$
- Oscillate for $\eta < 1$

Cycle efficiency

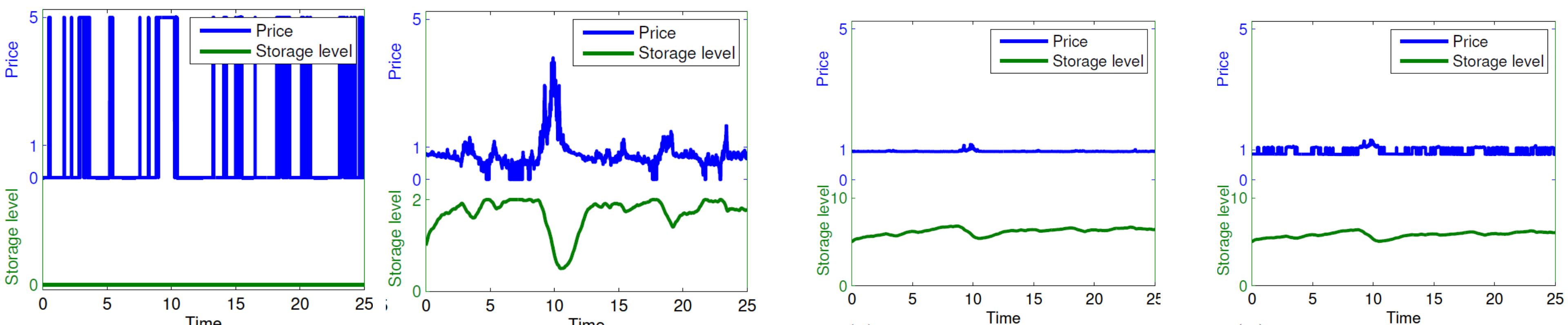
Overproduction that storage cannot store

$$P^\star(t) = \begin{cases} 0 \\ \eta \frac{\partial V}{\partial b}(R^\star(t), B^\star(t)), \\ \frac{\partial V}{\partial b}(R^\star(t), B^\star(t)), \\ v + c^{bo} \end{cases}$$

Storage compensates fluctuations

Underproduction that storage cannot satisfy

No storage | Small storage | Large storage, $\eta = 1$ | Large storage, η =0.8



(a) Without storage (b) $B_{\max} = 2$ u.e., $\eta = 1$. (c) $B_{\max} = 10$ u.e., $\eta = 1$ (d) $B_{\max} = 10$ u.e., $\eta = 0.8$

Parameters based on UK data: 1 u.e. = 360 MWh, 1 u.p .= 600 MW, σ^2= 0.6 GW2/h, ζ = 2GW/h, Cmax=Dmax= 3 u.p.

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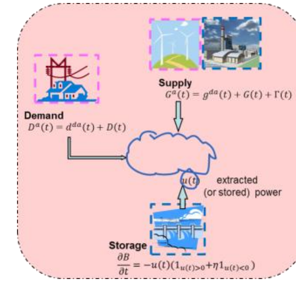
The social planner problem



- The social planner wants to find G and u to maximize total expected discounted payoff

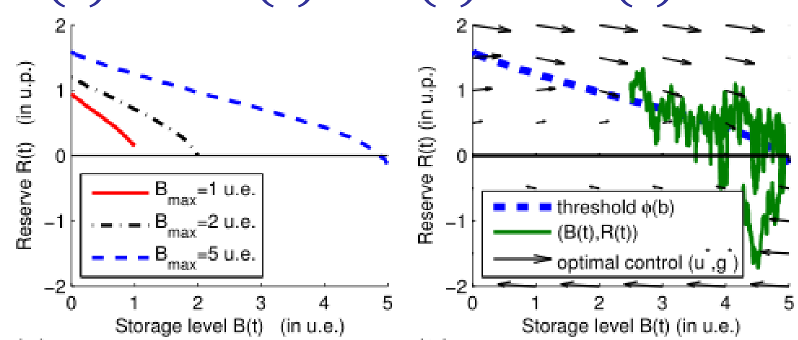
$$\max_{G,u} \mathbb{E}\int (W_S(t) + W_D(t))e^{-\gamma t}dt$$

$$\underbrace{v\min(D^a(t), E(t) + g^{da}(t))}_{\text{satisfied demand}} - \underbrace{c^{bo}\left(D^a(t) - G^{da}(t) - -u(t)\right)^+}_{\text{Frustrated demand}} \underbrace{-cG(t) - c^{da}g^{da}(t)}_{\text{Cost of generation}}$$

- Does not depend on storage owner

- Let $R(t)$ be the excess of production: $R(t) := G^a(t) + u(t) - D^a(t)$

> Theorem. The optimal control is s.t.:
> if $R(t) < \Phi(B(t))$ increase G(t)
> if $R(t) > \Phi(B(t))$ decrease G(t)



(a) Function $b \mapsto \phi(b)$ for various values of the storage energy capacity $B_{\max}$.

(b) Sample of a trajectory of the optimal reserve and storage processes. $B_{\max} = 5$ u.e.

The Social Welfare Theorem [Gast et al., 2013]

- Any dynamic competitive equilibrium for any of the three scenarios maximizes social welfare
  - The same price process controls optimally both the storage AND the production

- As storage grows, prices concentrate on the marginal production cost if $\eta = 1$

- If $\eta < 1$: discontinuity in R(t)=0
  - Bad for decentralized control

Cycle efficiency

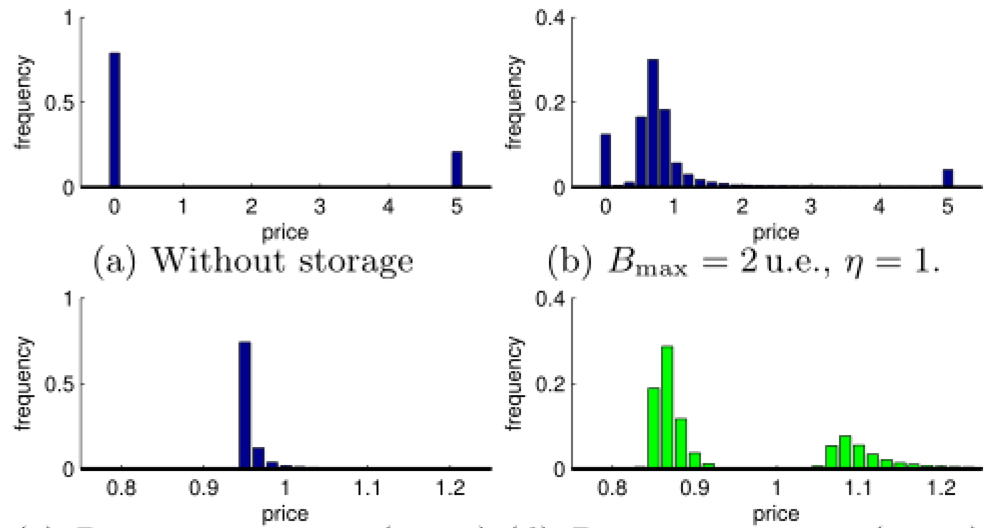
Overproduction that storage cannot store

$$P^\star(t) = \begin{cases} 0 \\ \eta \frac{\partial V}{\partial b}(R^\star(t), B^\star(t)), \\ \frac{\partial V}{\partial b}(R^\star(t), B^\star(t)), \\ v + c^{bo}, \end{cases}$$

Storage compensates fluctuations

Prices are *dynamic* Lagrange multipliers

Underproduction that storage cannot satisfy



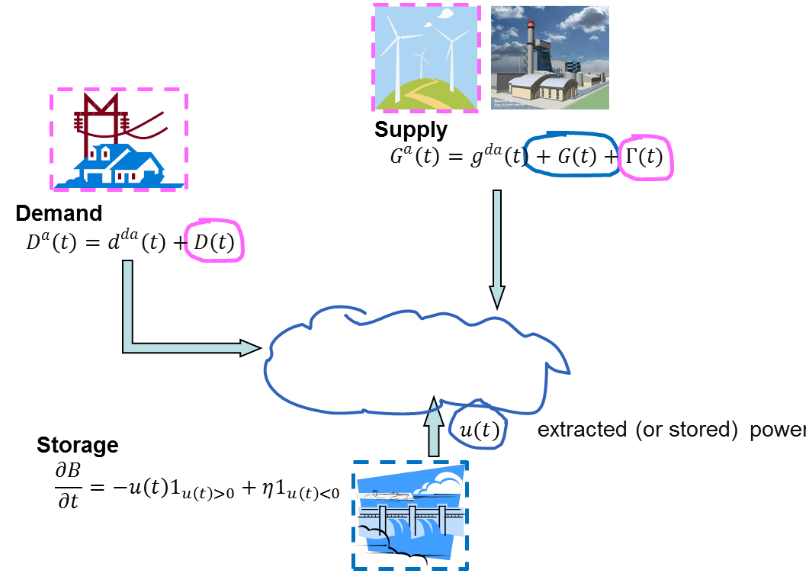
(a) Without storage (b) $B_{\max} = 2$ u.e., $\eta = 1$.

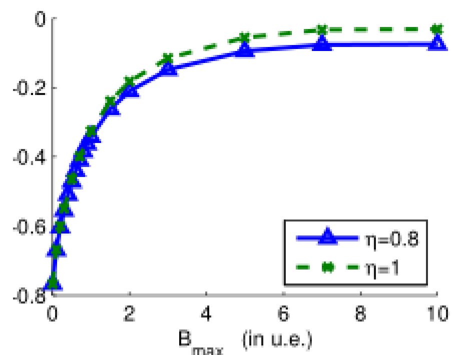
(c) $B_{\max}$=10 u.e., η=1 (zoom) (d) $B_{\max}$=10ue, η=0.8(zoom)

Figure 6: Steady-state distribution of prices for various storage energy capacities $B_{\max}$. For $B_{\max}$ = 10 u.e., we zoom on c=1 to compare $\eta = 0.8$ and $\eta = 1$.

The Invisible Hand of the Market may not be optimal

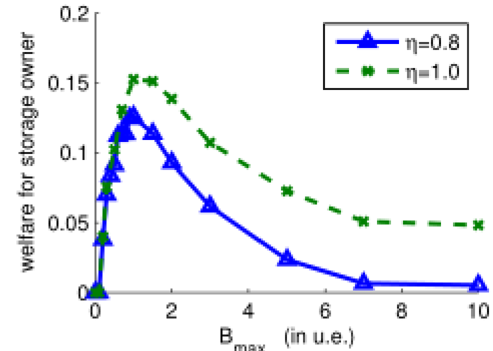
- Any dynamic competitive equilibrium for any of the three scenarios maximizes social welfare
- However, this assumes a given storage capacity.
- Is there an incentive to install storage ?
  - No, stand alone operators or consumers have no incentive to install the optimal storage





(b) $C_{\max} = 3\,\mathrm{u.p.}$

Expected social welfare



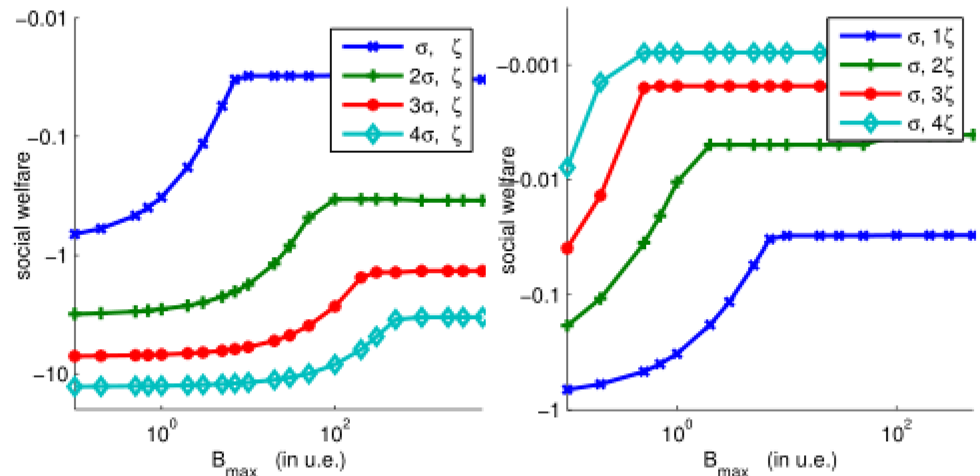
(b) $C_{\max} = D_{\max} = 3\,\mathrm{u.p.}$

Expected welfare of stand alone operator

Can lead to market manipulation
(undersize storage and generators)

Scaling laws and optimal storage sizing

- (steepness) being close to social welfare requires the optimal storage capacity



(a) Fixed ζ (b) Fixed σ

- optimal storage capacity scales like $\frac{\sigma^4}{\zeta^3}$!

(σ is ≈proportional to the installed renewable capacity)

Bad news for renewables

(similar situation in Spain: for each 1MW of wind turbines, 1MW of gaz turbines in build!)

- increase volatility and rampup capacity by x = increase storage by x

What this suggests about storage :

- With a free and honest market, storage can be operated by prices
  - But prices are still discontinuous when $\eta < 1$
- However:
  - there may not be enough incentive for storage operators to install the optimal storage size
  - perhaps preferential pricing should be directed towards storage as much as towards PV
- Multi temporal-scales are inherent to electricity networks
  - Joint scheduling is essential
- Limitation of the model / future work
  - Oligopolistic setting
  - Network constraints and distributed storage

Thank You !

- [Cho and Meyn, 2010] I. Cho and S. Meyn *Efficiency and marginal cost pricing in dynamic competitive markets with friction*, Theoretical Economics, 2010
- [Gast et al 2012] Gast, Tomozei, Le Boudec. "Optimal Storage Policies with Wind Forecast Uncertainties", *GreenMetrics 2012.* *https://infoscience.epfl.ch/record/178202*
- [Gast et al 2013] Gast, Tomozei, Le Boudec. "Optimal Generation and Storage Scheduling in the presence of Renewable Forecast Uncertainties", *submitted, 2013*. *https://infoscience.epfl.ch/record/183046*
- [Gast et al 2013] Gast, Le Boudec, Proutière, Tomozei, "Impact of Storage on the Efficiency and Prices in Real-Time Electricity Markets", ACM e-Energy 2013, Berkeley, May 2013. https://infoscience.epfl.ch/record/183149

Vue d'ensemble de mes contributions

Théorie (modèles mathématiques)

Champs moyen et contrôle optimal

- Contrôle optimal d'un système stochastique à l'aide d'une approximation fluide [ValueTools 2009] **best student paper award,** [TAC 2011,JDEDS 2011]

- Dynamiques discontinues et inclusions différentielles [PeVa 2012, Mama 2010]

Applications

Calcul distribué et équilibrage de charge

- Ordonnancement centralisé [ValueTools 2009]
- Équilibrage de charge décentralisé [Sigmetrics 2010, ISAAC 2010, Anor 2012]

Réseaux de communication

- MPTCP [Conext 2012] **best paper award**
- Contrôle de Puissance [ToN 2011, brevet]

Réseaux électrique: contrôle multi-échelle de la génération et du stockage

- Niveau national [GreenMetrics 2012]
- Gestion décentralisé (théorie des jeux) [e-Energy 2013]

Véhicules en libre service

- Garantie de performance et redistribution optimale [AofA 2012]

Séminaire d'aujourd'hui

Collaborations possibles?