ARE ENERGY MARKETS EFFICIENTS?
THE CASE OF REAL AND VIRTUAL STORAGE

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joint work with
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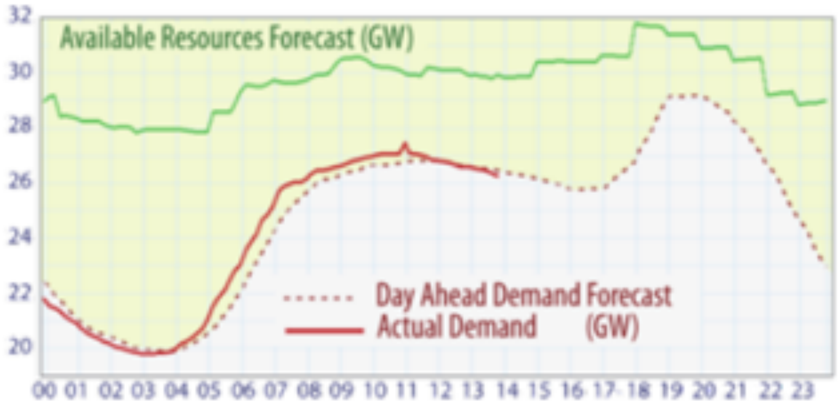
Workshop on the Mathematics of Demand Side Management and Energy Storage
1-2 June 2015

Slides adapted from Jean-Yves Le Boudec

Wind and solar energy make the grid less predictable



Mean error: 1–2%

Mean error: 20%

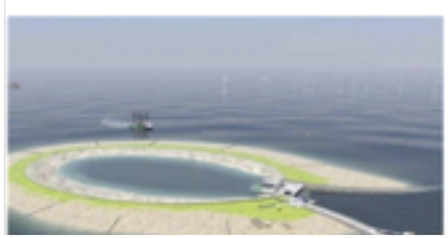
Storage can mitigate volatility

- Batteries, Pump-hydro

Projects: artificial islands (north sea)

Belgium — Copenhagen

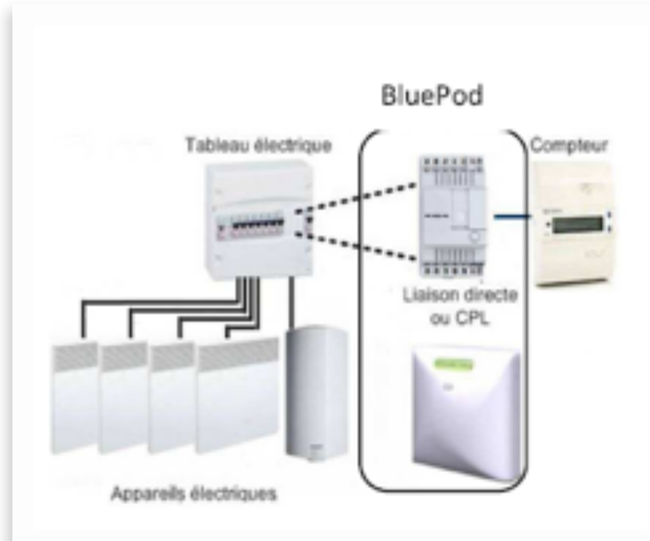
L … ll, swi …



A Manmade Island to Store Wind Energy

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

- Demand Response = Virtual Storage



Voltalis Bluepod switches off thermal load for 60 mn

A classical research question is: how to manage one piece of storage

- How to maximize profit? (optimal response to a price signal)
- What is the benefit of demand-response?
- …

In this talk, I focus on the role of Market

1. Does markets leads to a socially optimal use of storage?

   problem of coordination? over-cycling of 75% eff. storage?

2. Is there a difference between demand response and storage?

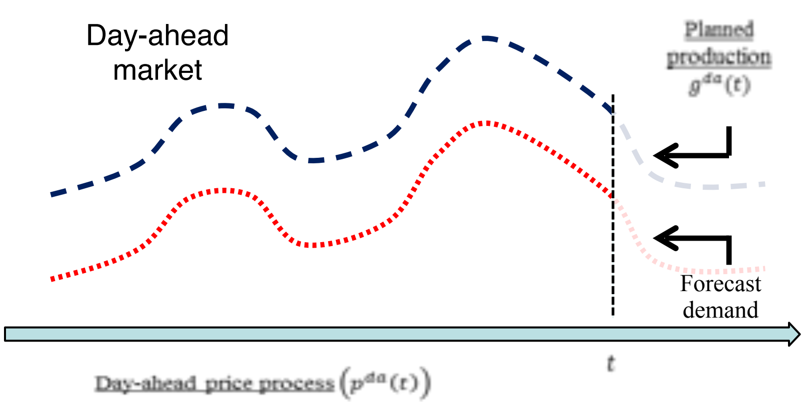
1.

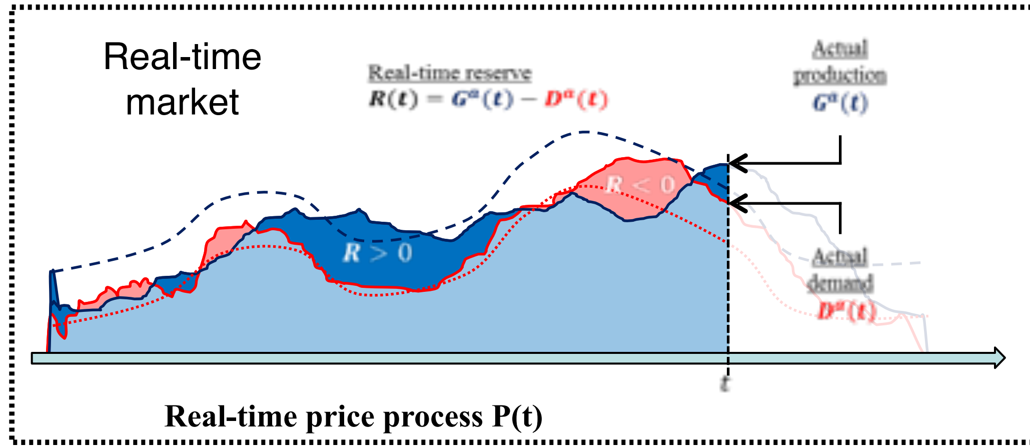
IMPACT OF STORAGE ON MARKETS

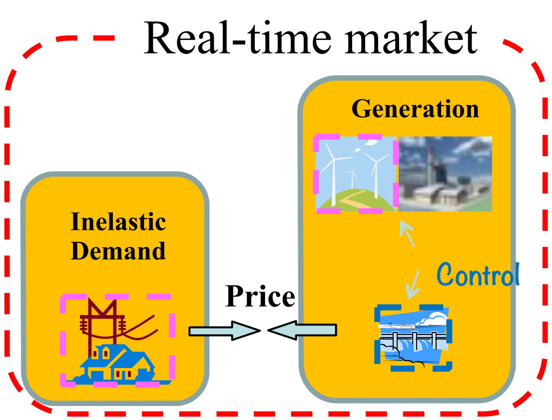
[Gast et al 2013] N. G. Gast, J.-Y. Le Boudec, A. Proutière and D.-C. Tomozei. Impact of Storage on the Efficiency and Prices in Real-Time Electricity Markets. e-Energy '13, Fourth international conference on Future energy systems, UC Berkeley, 2013.

We focus on the real-time market

- Most electricity markets are organized in two stages





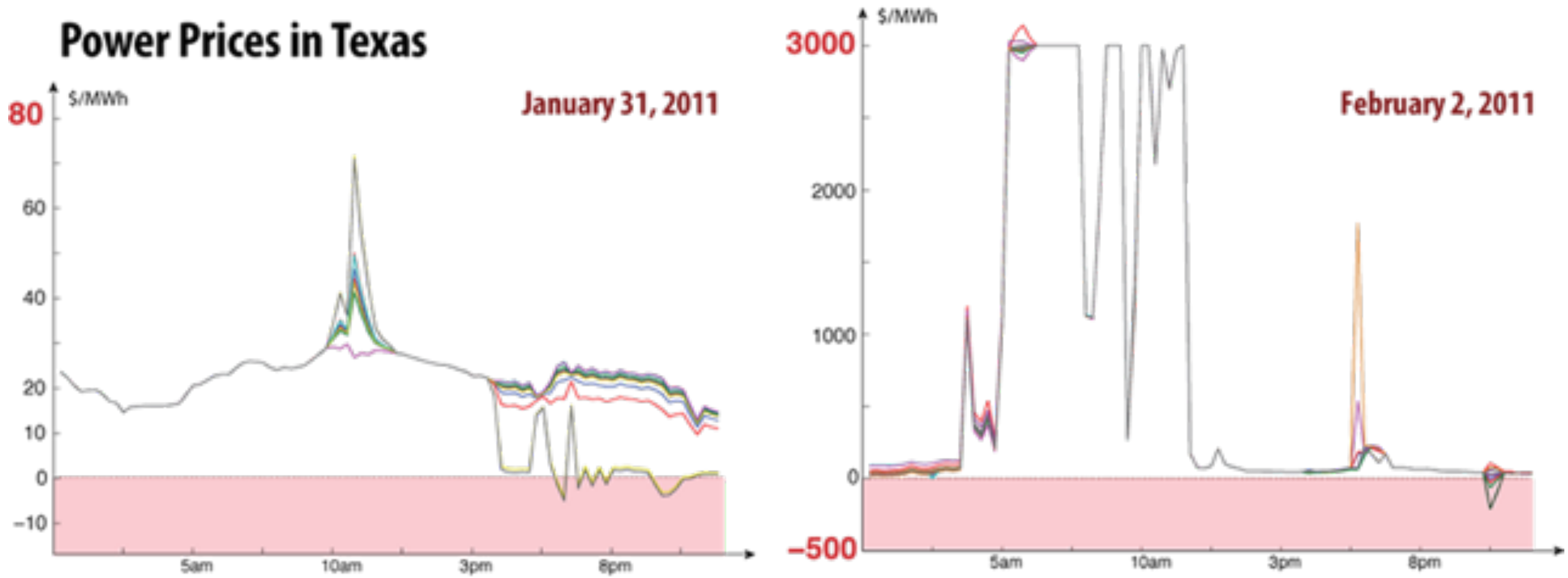


Compensate for deviations from forecast

Inelastic demand satisfied using:

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

Real-time Market exhibit highly volatile prices

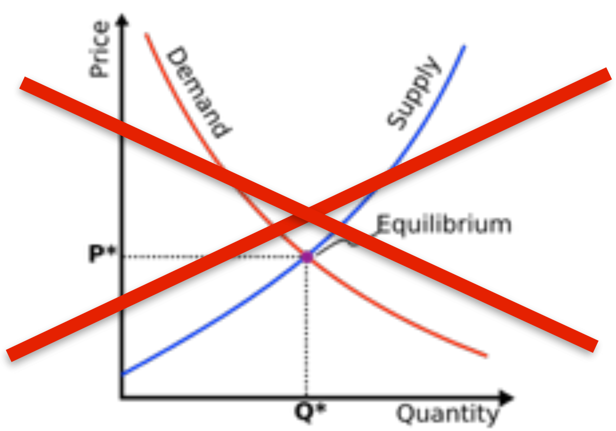


- Efficiency or Market manipulation?

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.

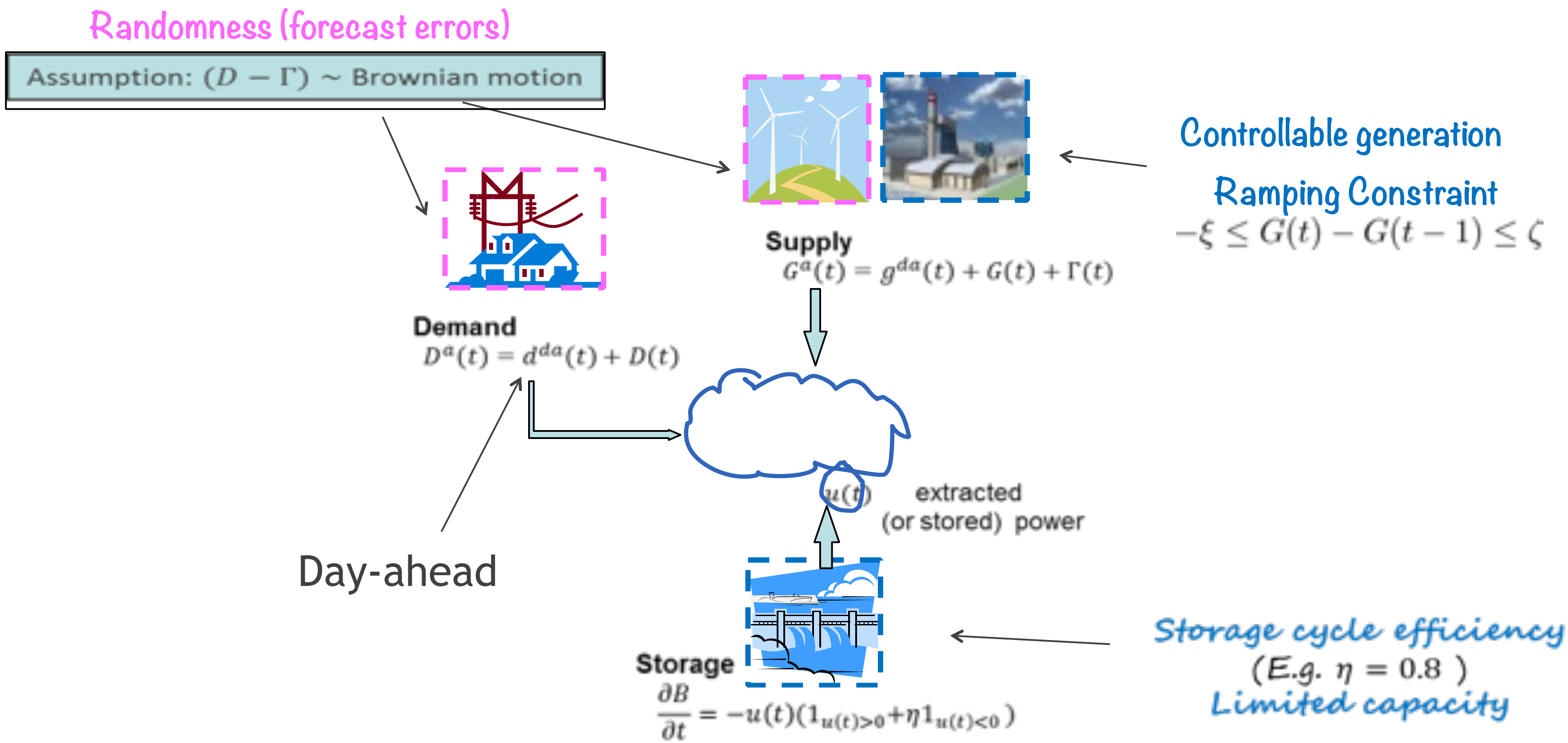


[Cho and Meyn, 2010] I. Cho and S. Meyn *Efficiency and marginal cost pricing in dynamic competitive markets with friction,* Theoretical Economics, 2010

What happens when we add storage to the picture ?

Does the market work, i.e. does the invisible hand of the market control storage in the socially optimal way ?

A Macroscopic Model of Real-time generation and Storage



Macroscopic model

- At each time: generation = consumption

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

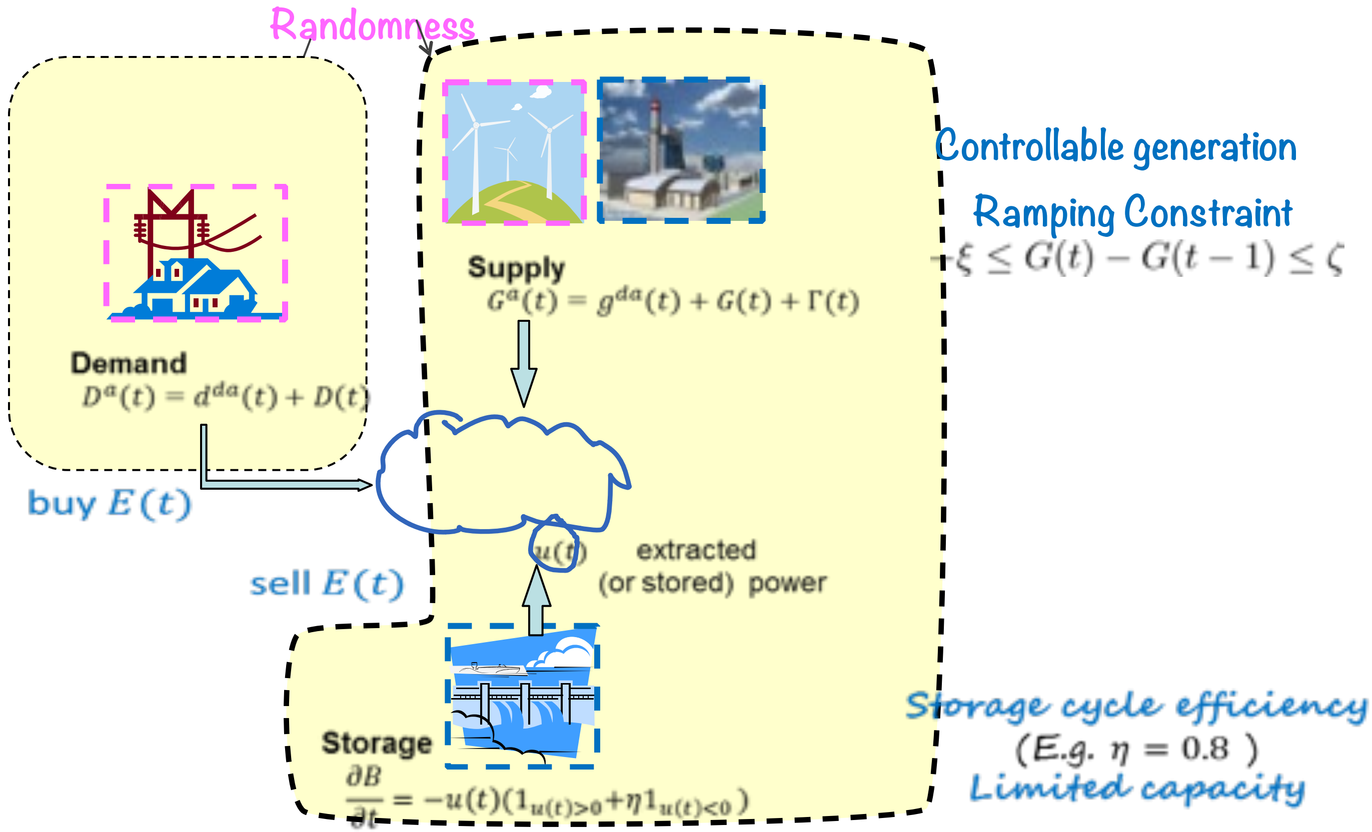
A Macroscopic Model of Real-time generation and Storage

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: $W_D(t)$

$$= v \min(D^a(t), E(t) + g^{da}(t)) - c^{bo}\left(D^a(t) - G^{da}(t) - u(t)\right)^+ - P(t)E(t) - p^{da}(t)g^{da}(t)$$

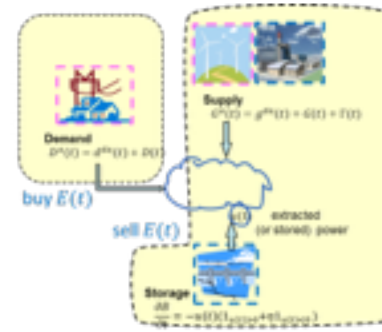
satisfied demand | Frustrated demand | Price paid

- 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
    $$E \in \text{argmax}_E \, \mathbb{E}\left[\int W_D(t)e^{-\gamma t}dt\right]$$
  - Supplier: find E, G, u such that
    - G and u satisfy generation constraints and
    $$E, G, u \in \text{argmax}_E \, \mathbb{E}\left[\int W_S(t)e^{-\gamma t}dt\right]$$

- Question: does there exists a price process Psuch that consumer and supplier agree on the production ?

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

Dynamic Competitive Equilibria

Theorem. Dynamic competitive equilibria exist and are essentially independent of who is storage owner [Gast et al, 2013]

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 $\eta < 1$

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

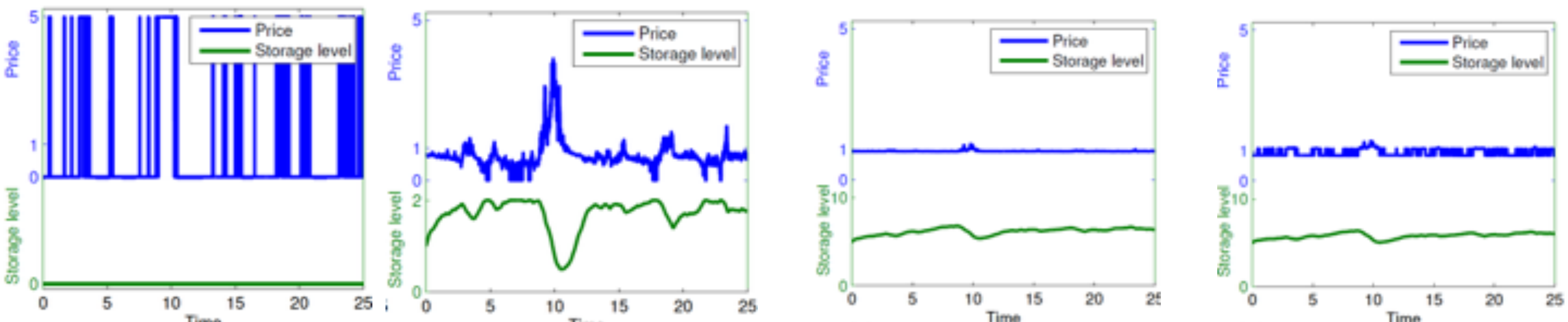
Cycle efficiency

Overproduction that storage cannot store

Storage compensates fluctuations

Underproduction that storage cannot satisfy

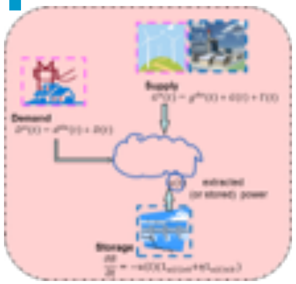
No storage | Small storage | Large storage, $\eta = 1$ | Large storage, $\eta = 0.8$



(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.

The social planner problem



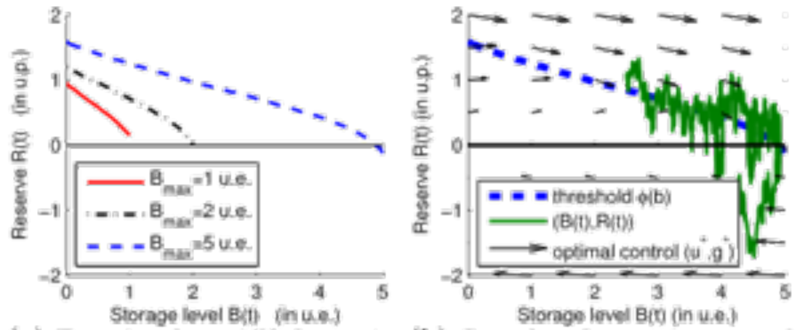
- The social planner wants to find G and u to maximize total expected discounted payoff

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

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

- The solution does not depend on storage owner, and depends on the relation between the reserve $R(t)$ and the storage level $B(t)$ (where reserve = generation – demand : $R(t) := G^a(t) + u(t) - D^a(t)$)

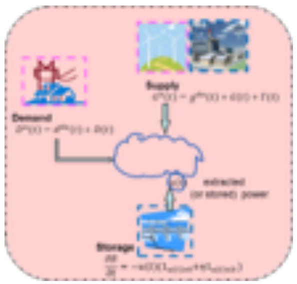
> Theorem [Gast et al 2013] The optimal control is s.t.:
> if $R(t) < \Phi(B(t))$ increase $G(t)$
> if $R(t) > \Phi(B(t))$ decrease $G(t)$



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

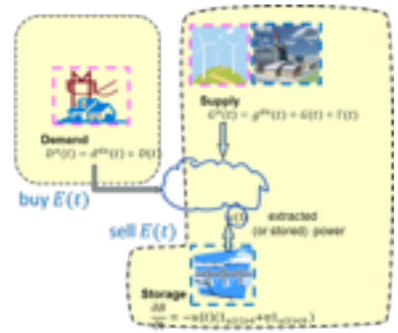
(b) Sample of a trajectory of the optimal reserve and storage processes. $B_{\max} = 5$ u.e.

Theorem: the market is efficient



- Social planner's problem:

Maximizes the sum of the utility



- Competitive equilibrium:

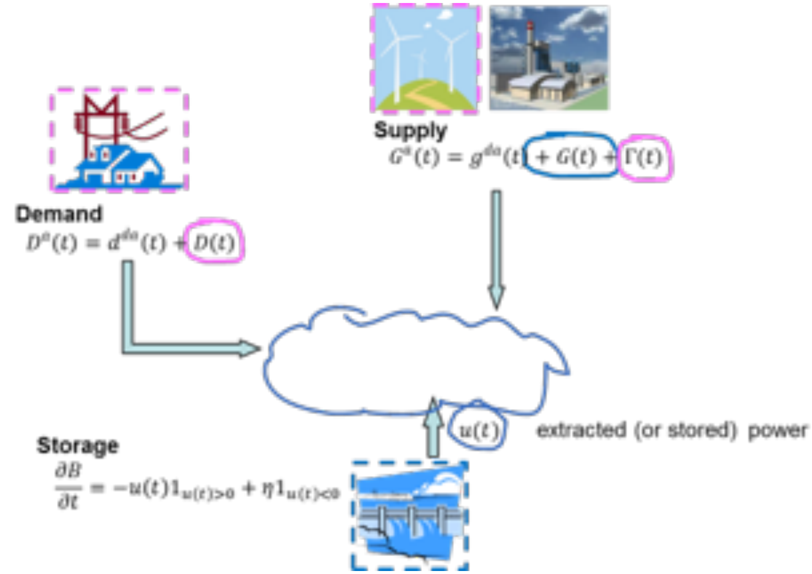
Users are selfish

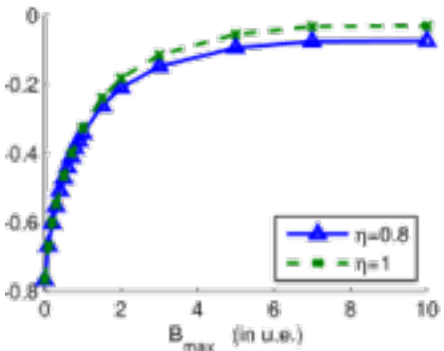
Users are price-takers

Theorem [G et al. 2013].
- Dynamic competitive equilibria exist and are essentially independent of who is storage owner
- Any dynamic competitive equilibrium for any of the three scenarios maximizes social welfare

The Invisible Hand of the Market may not be optimal

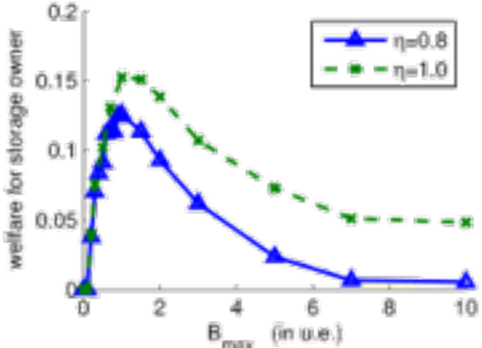
- Any dynamic competitive equilibrium for any of the three scenarios maximizes social welfare
- However, this assumes a given storage capacity.
- Is there an incentive to install storage ?
  - No, stand alone operators or consumers have no incentive to install the optimal storage





(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)

What this suggests about storage :

- With a free and honest market, storage can be operated by prices
- 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
- Storage requirement scales super-linearly with amount of renewables

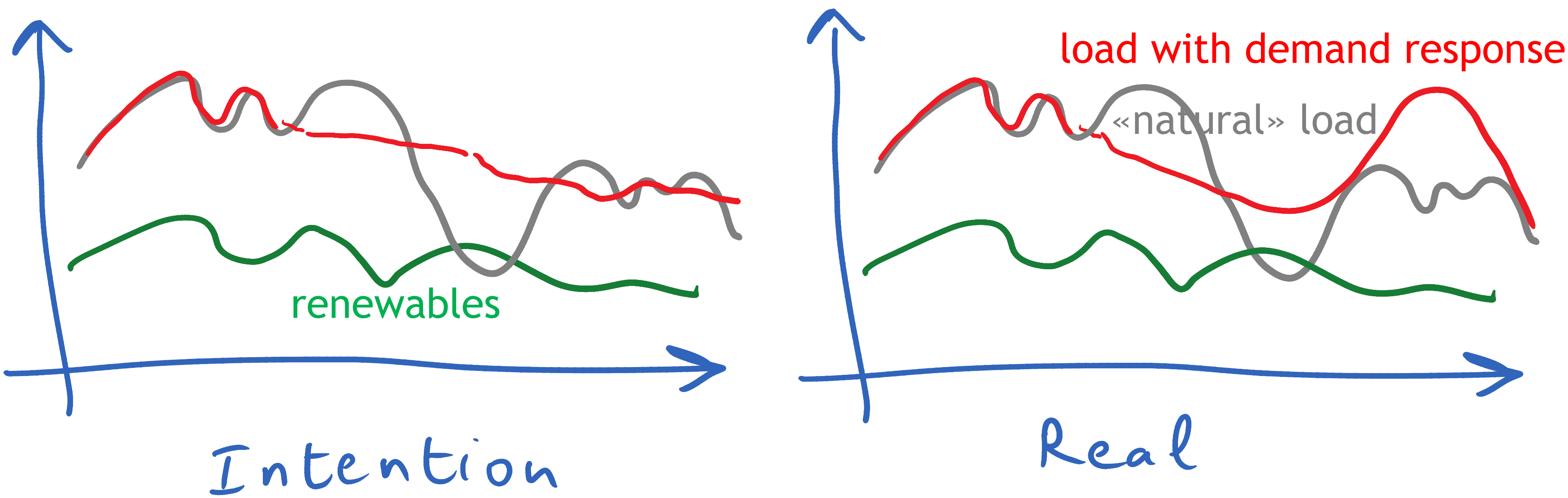
2.

DEMAND-RESPONSE AND PRICES

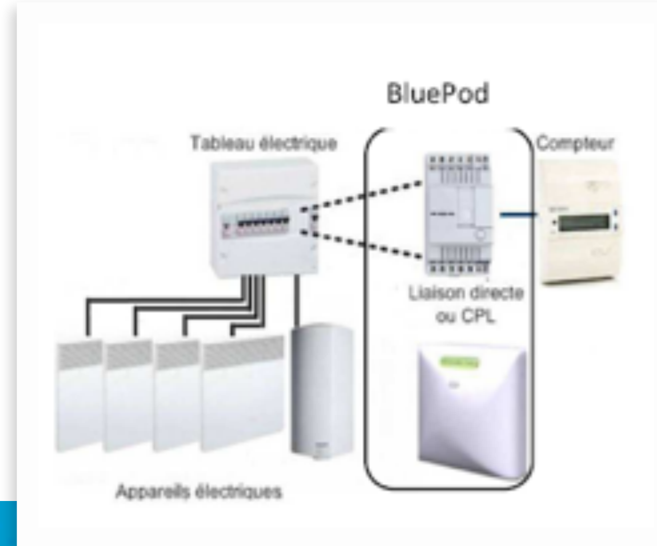
[Gast et al 2014] N. Gast, J.-Y. Le Boudec and D.-C. Tomozei. Impact of demand-response on the efficiency and prices in real-time electricity markets. e-Energy '14, Cambridge, United Kingdom, 2014.

Issue with Demand Response: Non Observability

- Widespread demand response may make load hard to predict



Demand Response



- = distribution network operator may interrupt / modulate power

  = virtual storage

- elastic loads support graceful degradation

- Thermal load (Voltalis), washing machines (Romande Energie«commande centralisée»)
  e-cars

boilers / heating for ≤60 mn

Our Problem Statement

Does it really work as virtual storage ?

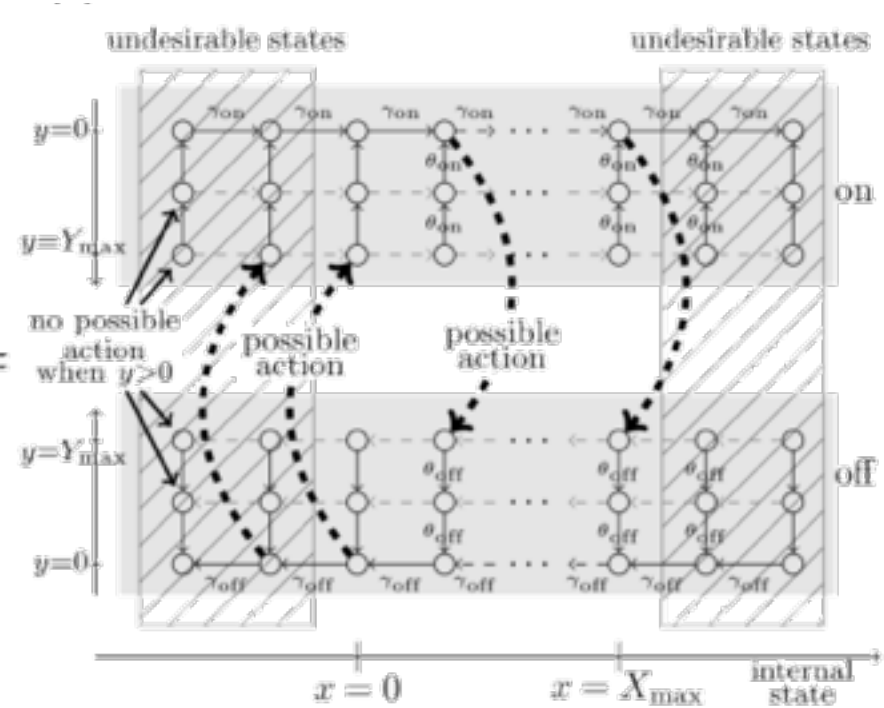
Side effect with load prediction ?

To this end we add demand response to the previous model

Mean-field game model of Flexible Loads

- Population of N on-off appliances (fridges, building,pool,…)
- Without control: behavior = Markov chain (normal cycle)

=



- Demand-response action may force an on/off transition
- Mini-cycles are avoided

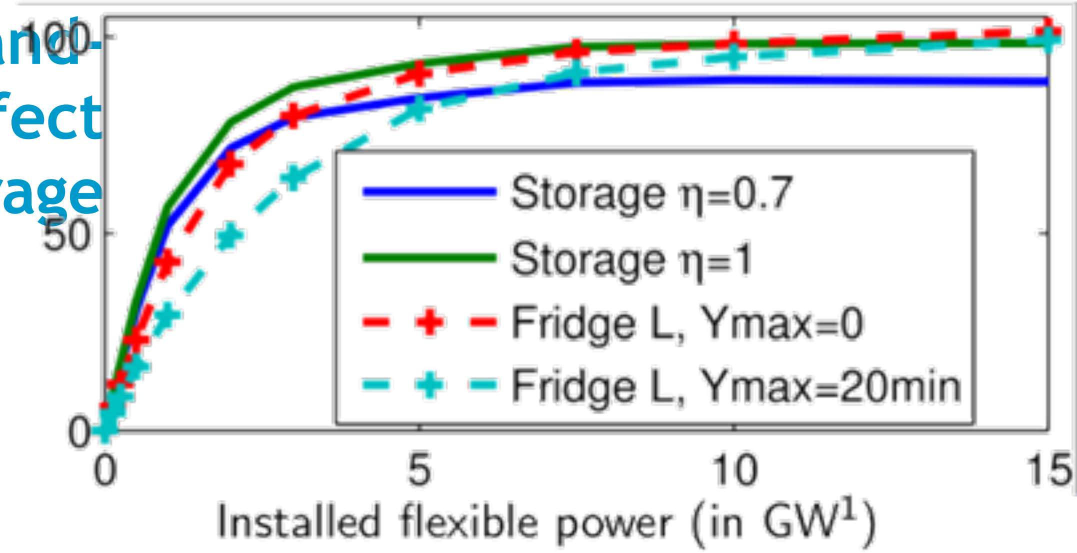
- **Consumer game: anticipate or delay power consumption**

Results of this model with Demand Response

- Social welfare theorem continues to hold, i.e. demand response can be controlled by price and this is socially optimal, given an installed base
- We numerically compute the optimum using
  - A mean field approximation for a homogeneous population of N appliances
  - Branching trajectory model for renewable production [Pinson et al 2009]
  - ADMM for solution of the optimization problem
  - We assume all actors do not know the future but know the stochastic model

[Pinson et al 2009] P. Pinson, H. Madsen, H. A. Nielsen, G. Papaefthymiou and B. Klöckl. “From probabilistic forecasts to statistical scenarios of short-term wind power production”. Wind energy, 12(1):51–62, 2009.

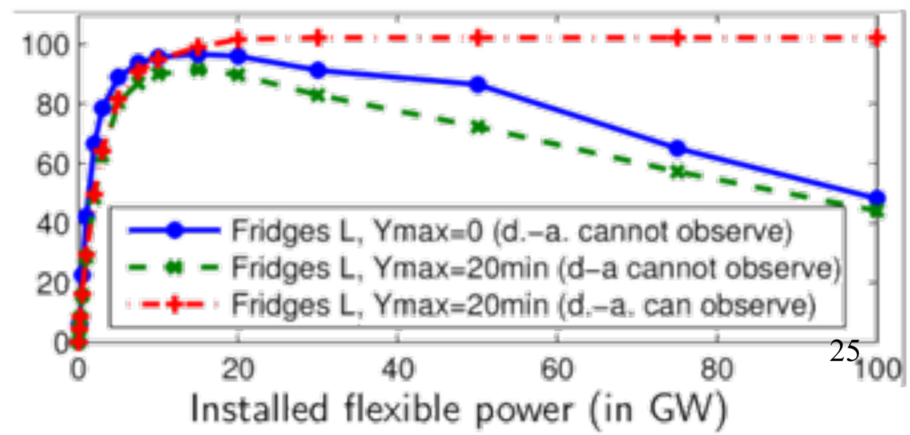
The Benefit of demand-response is similar to perfect storage



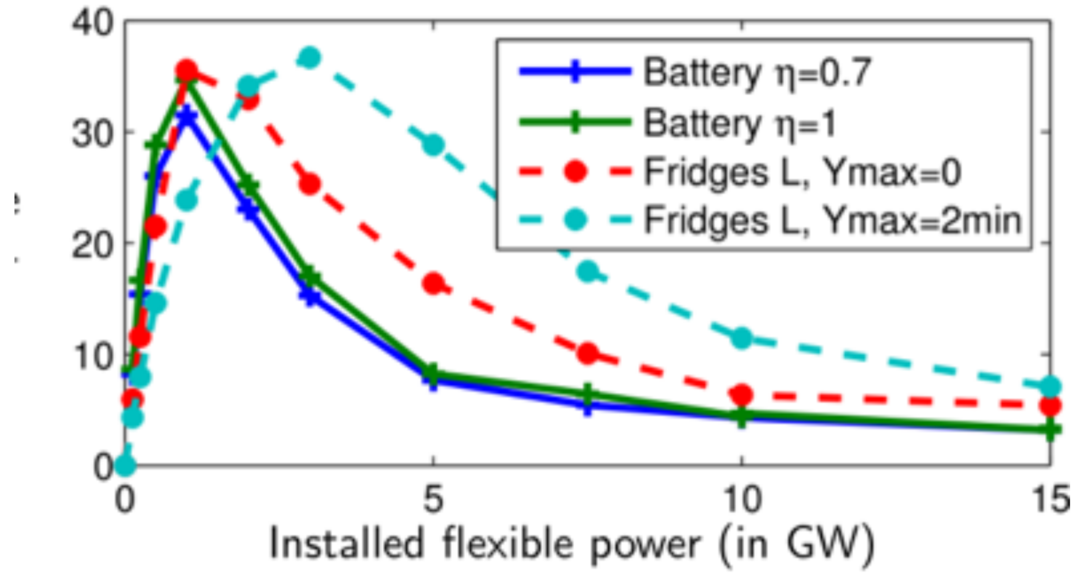
Non-Observability Significantly Reduces Benefit of Demand-Response

We assume that:

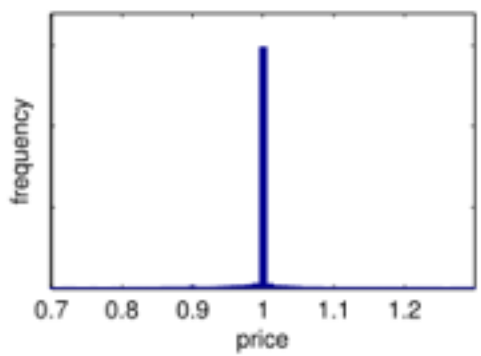
- The demand-response operator knows the state of its fridges
- The day-ahead forecast does not.



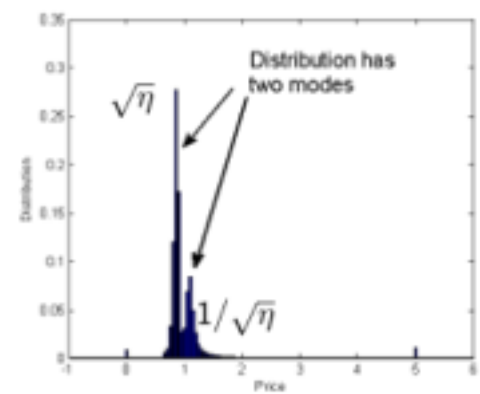
The Invisible Hand of the Market may not be optimal



Demand Response stabilizes prices more than storage



Large amount of 100% efficient storage or demand-response



Storage with efficiency $\eta < 1$

CONCLUSIONS

Where is the catch?

- The efficiency of the equilibrium is a property of the market structure: price-taker + common knowledge (it does not depend on the assumption about storage/DR characteristics)
  - Prices are Lagrange multipliers

- The existence of an equilibrium does depend on storage/DR/ generation characteristics (here: convex).
  - can be computed by primal/dual iterations (distributed)

What this suggests :

- With a free and honest market, storage and demand response can be operated by prices
- However there may not be enough incentive for storage operators to install the optimal storage size / demand response infrastructure

- Demand Response is similar to an ideal storage that would have close to perfect efficiency
- However it is essential to be able to estimate the state of loads subject to demand response (observability)

- Market can be used for decentralized optimization (Lagrangian decomposition / ADMM)

Thank You !

- slides available:
  http://mescal.imag.fr/membres/nicolas.gast/research/