STOCHASTIC ANALYSIS OF REAL AND VIRTUAL STORAGE IN THE SMART GRID

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ÉCOLE POLYTECHNIQUE
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joint work with

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Outline

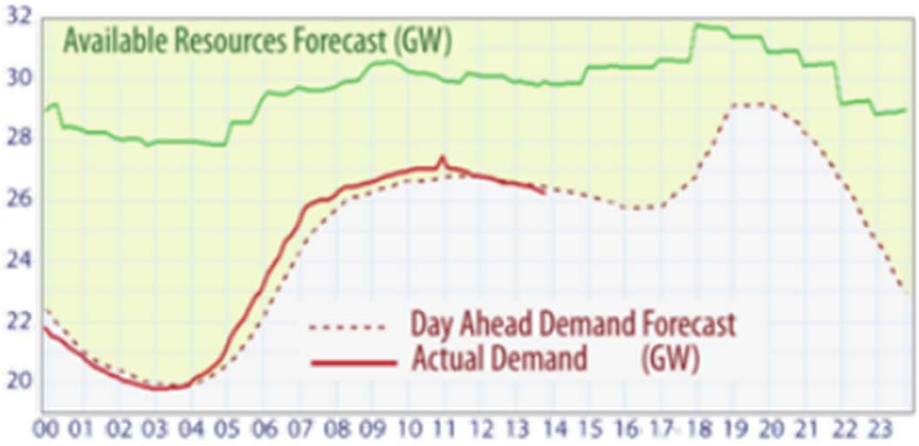
1. Introduction and motivation

2. Managing Storage

3. Impact of Storage

4. Impact of Demand Response

Wind and solar energy make the grid less predictable



Mean error: 1–2%

Mean error: 20%

Storage can mitigate volatility

- Batteries, Pump-hydro

Limberg III, switzerland

Switzerland (mountains)

Projects: artificial islands (north sea)

Belgium

Copenhagen

Green Power Island Could Power Copenhagen Sustainably

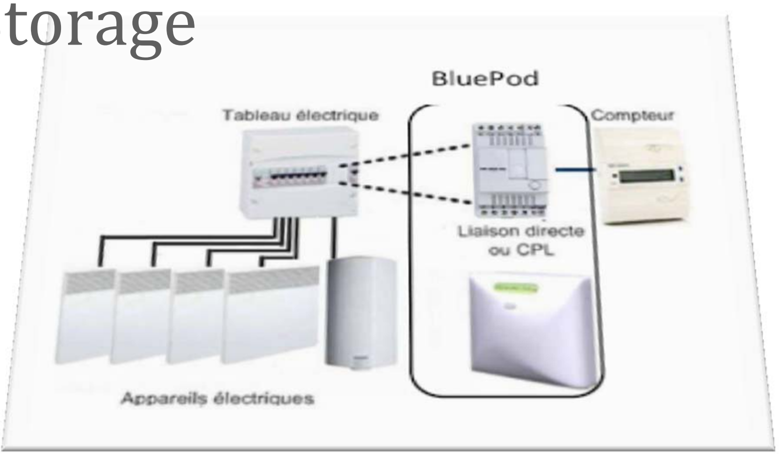
by Lori Zimmer, 06/30/11

filed under: Renewable Energy, Solar Power, Wind Power

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

Questions addressed in this talk

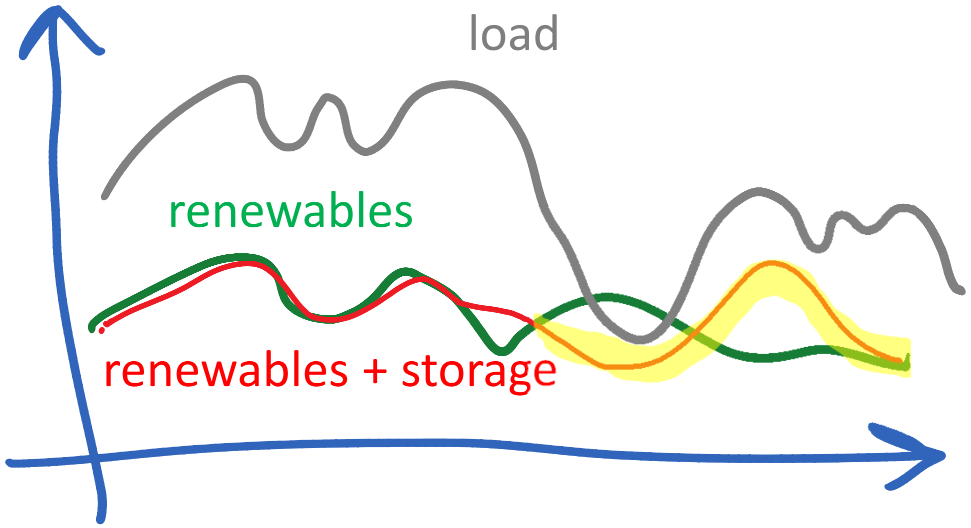
1. How to manage one piece of storage
2. Impact of storage on market and prices
3. Impact of demand response on market and prices

2.

MANAGING STORAGE

N. G. Gast, D.-C. Tomozei and J.-Y. Le Boudec. Optimal Generation and Storage Scheduling in the Presence of Renewable Forecast Uncertainties, IEEE Transactions on Smart Grid, 2014.

Storage



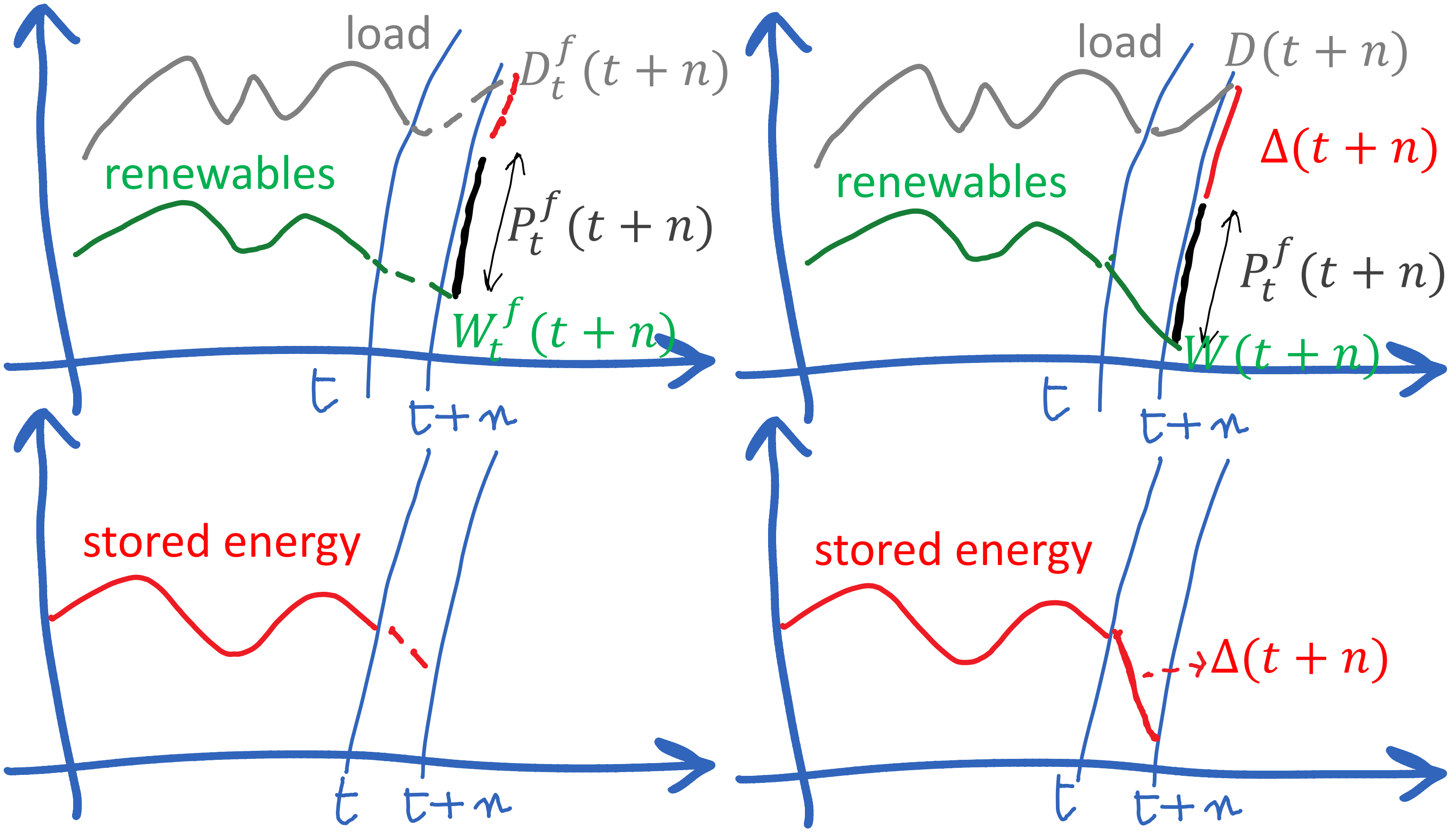
- Stationary batteries, pump hydro

  Cycle efficiency $\approx 70 - 85\%$

Operating a Grid with Storage

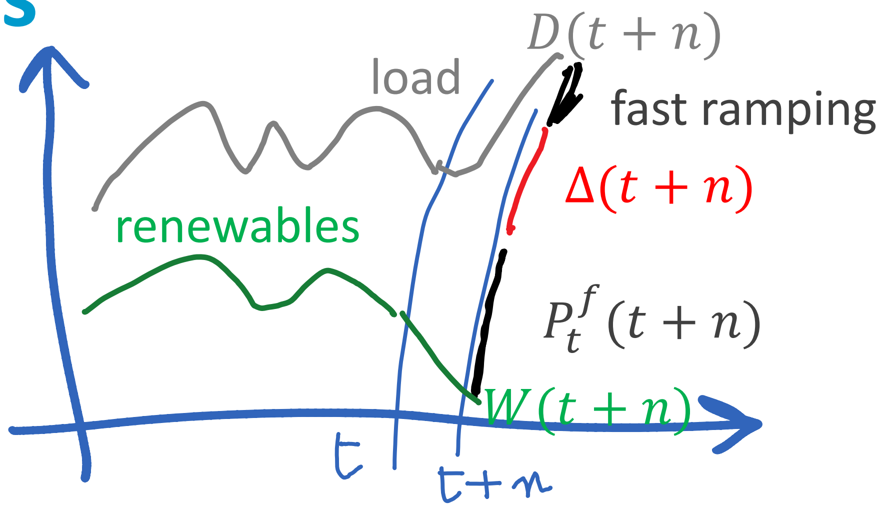
1a. Forecast load $D_t^f(t+n)$ and renewable suppy $W_t^f(t+n)$
1b. Schedule dispatchable production $P_t^f(t+n)$

2. Compensate deviations from forecast by charging / discharging Δ from storage

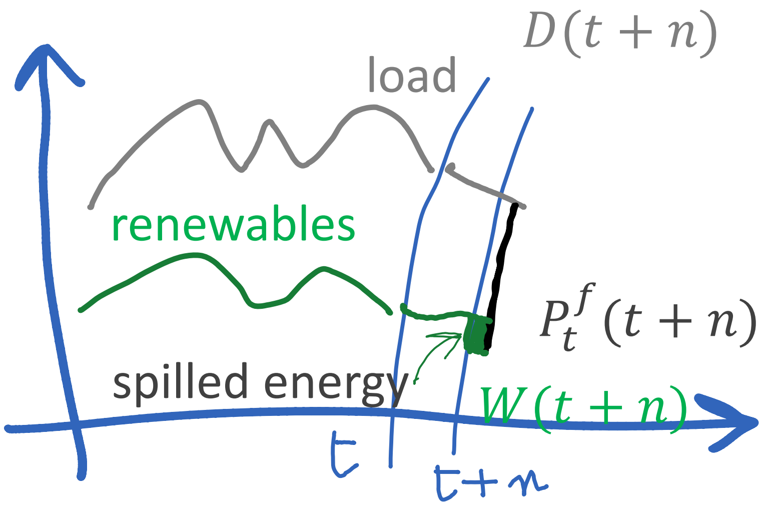


Full compensation of fluctuations by storage may not be possible due to power / energy capacity constraints

- Fast ramping energy source (CO_2 rich) is used when storage is not enough to compensate fluctuation



- Energy may be wasted when
  - Storage is full
  - Unnecessary storage (cycling efficiency < 100%)

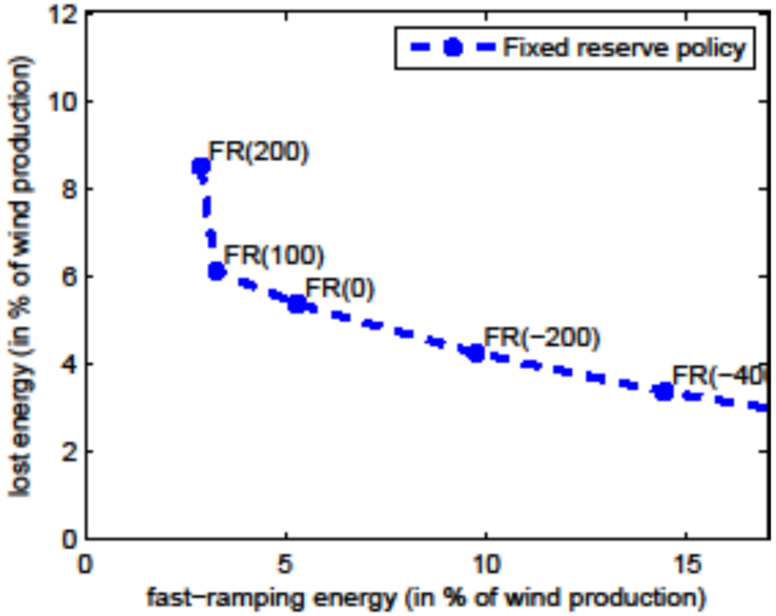


- Control problem: compute dispatched power schedule $P_t^f(t+n)$ to minimize energy waste and use of fast ramping

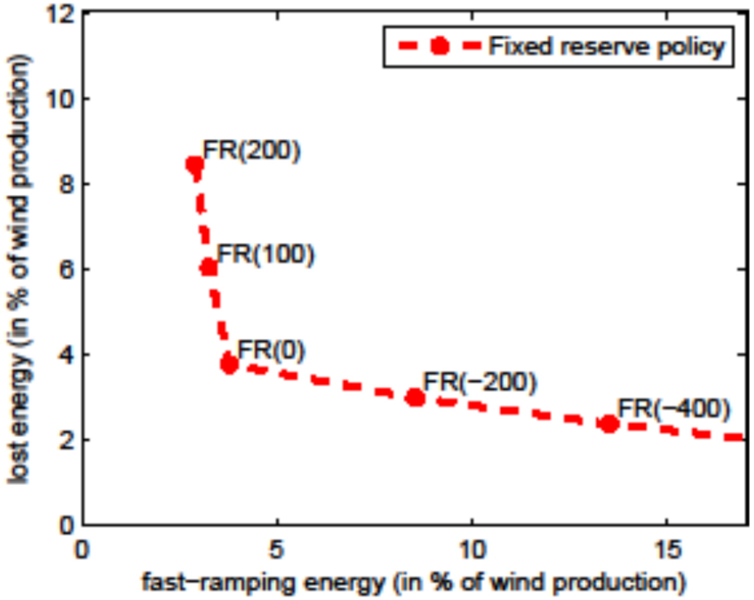
Example: The Fixed Reserve Policy

- Set $P_t^f(t+n)$ to $D_t^f(t+n) - W_t^f(t+n) + r^*$ where r^* is fixed (positive or negative)
- Metric: Fast-ramping energy used (x-axis)
  Lost energy (y-axis) = wind spill + storage inefficiencies

$B_{\max} = 100\text{GWh}, C_{\max} = D_{\max} = 2\text{GW}$



Efficiency $\eta = 0.8$



Efficiency $\eta = 1$

Aggregate data from UK (BMRA data archive https://www.elexonportal.co.uk/)
scaled wind production to 20% (max 26GW)

A lower bound

- Theorem. *Assume that the error* $e(t+n) = W(t+n) - W_t^f(t+n)$ *conditioned to* $\mathcal{F}_t$ *is distributed as* $\mathcal{E}$. *Then for any control policy:*

  (i) $\bar{G} \geq \mathbb{E}[(\varepsilon+\bar{u})^-] - \mathrm{ramp}(\bar{u})$

  $\bar{L} \geq \mathbb{E}[(\varepsilon+\bar{u})^+] - \mathrm{ramp}(\bar{u})$

  where $\mathrm{ramp}(\bar{u}) := \mathbb{E}[\min(\eta(\varepsilon+\bar{u})^+, \eta C_{\max}, (\varepsilon+\bar{u})^-, D_{\max})]$

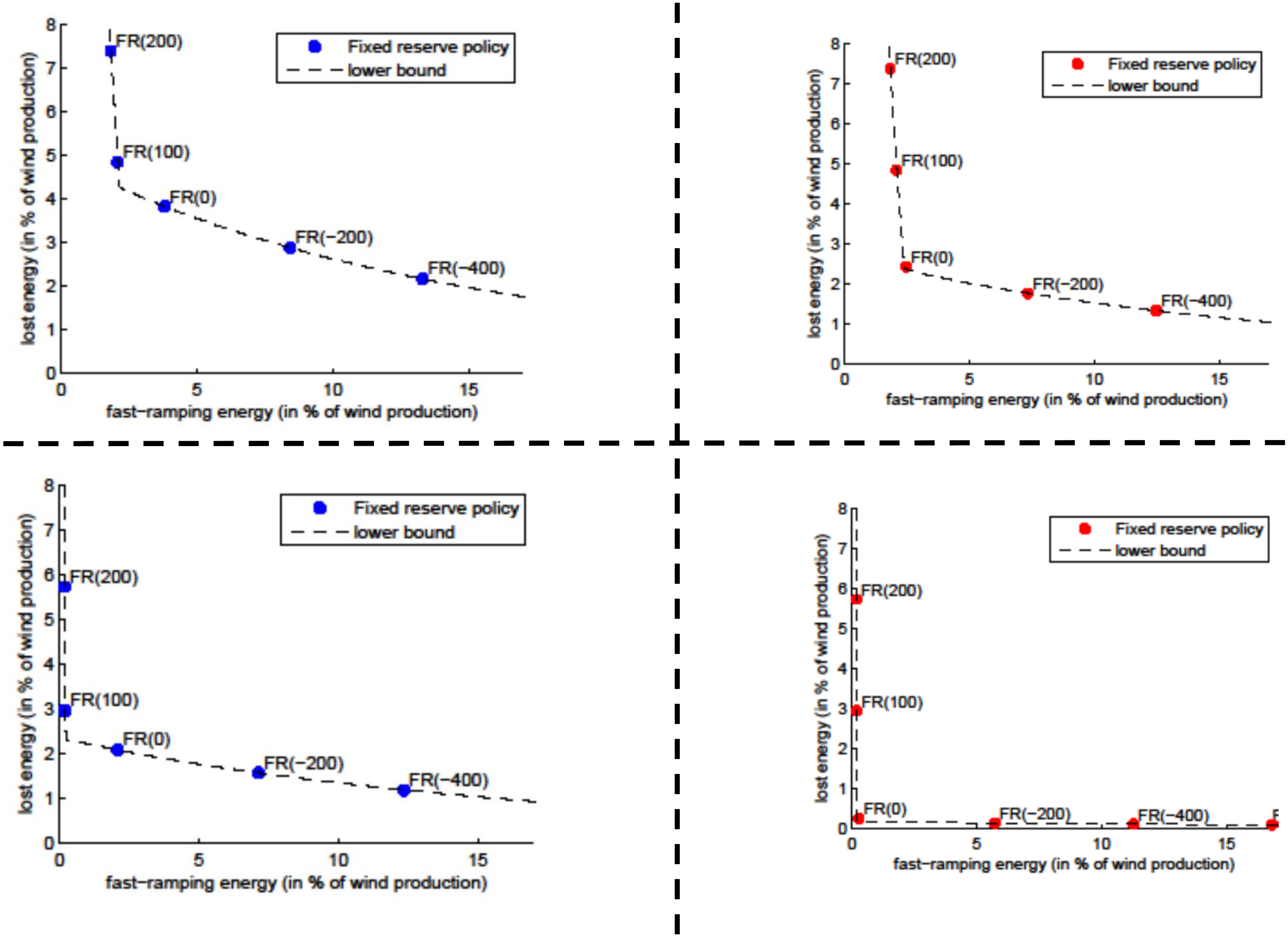
  (ii) The lower bound is achieved by the Fixed Reserve when storage capacity is infinite.

  - Assumption valid if prediction is best possible

Lower bound is attained for $B_{\max} = 100\text{GWh}$

$C_{\max} = D_{\max} = 2\text{GW}$

$C_{\max} = D_{\max} = 6\text{GW}$

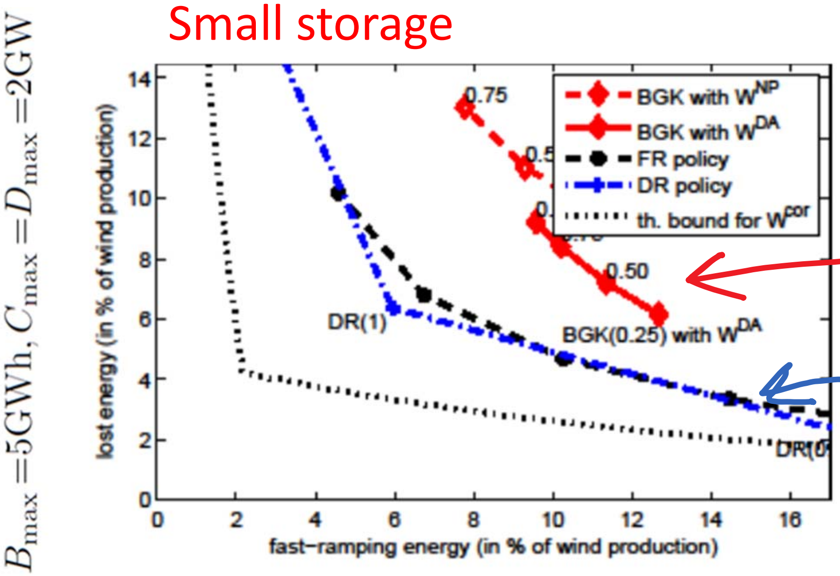


Efficiency $\eta = 0.8$

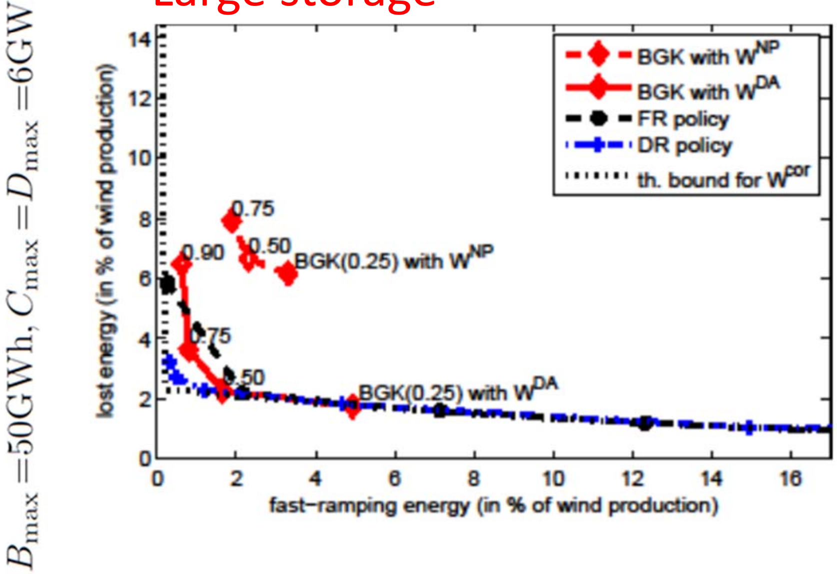
Efficiency $\eta = 1$

Concrete Policies

Small storage



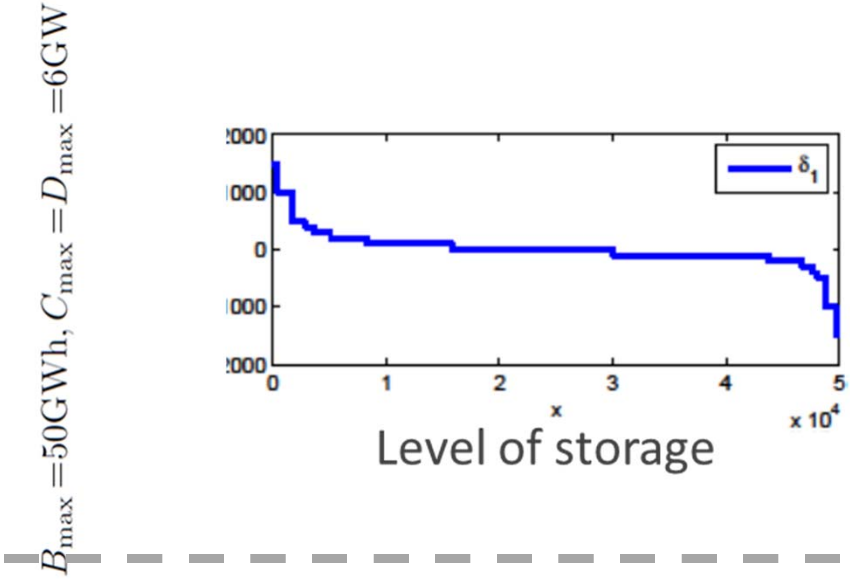
Large storage



Efficiency $\eta = 0.8$

BGK policy [Bejan et al, 2012]
= targets fixed storage level

Dynamic Policy (Gast, Tomozei, L. 2014) minimizes average anticipated cost using policy iteration



Level of storage

[Bejan et al, 2012] Bejan, Gibbens, Kelly, *Statistical Aspects of Storage Systems Modelling in Energy Networks.* 46th Annual Conference on Information Sciences and Systems, 2012, Princeton University, USA.

What this suggests about Storage

- A lower bound exists for any type of policy
  - Tight for large capacity (>50GWh)
  - Open issue: bridge gap for small capacity

- (BGK policy:) Maintain storage at fixed level: not optimal
  - Worse for low capacity
  - There exist better heuristics, which use error statistics

- Can be used for sizing

  UK 2020: 50GWh and 6GW is enough for 26GW of wind

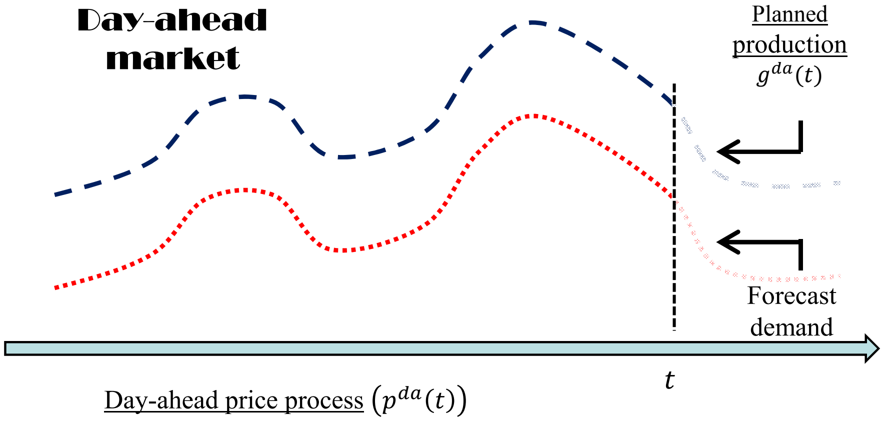
3.

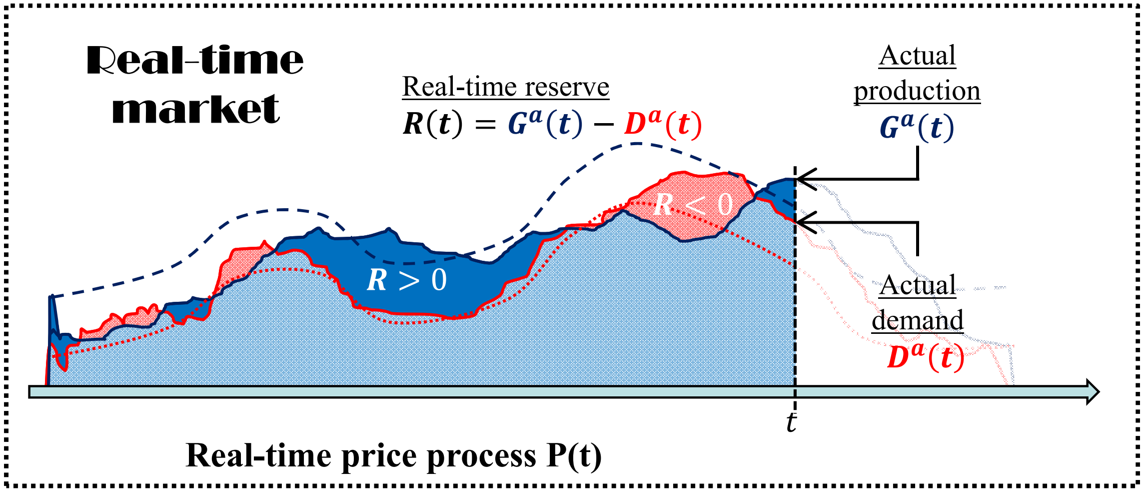
IMPACT OF STORAGE ON MARKETS AND PRICES

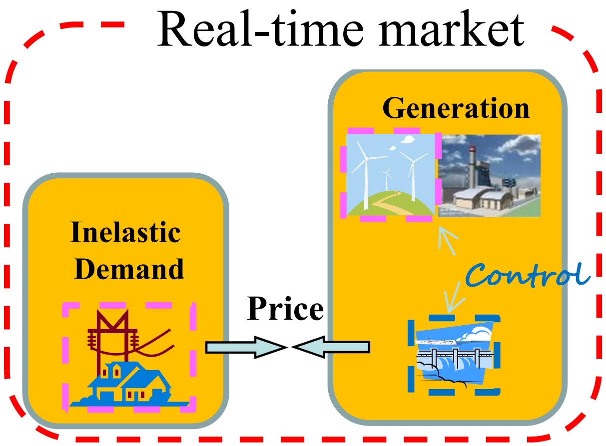
[Gast et al 2013] N. G. Gast, J.-Y. Le Boudec, A. Proutière and D.-C. Tomozei. Impact of Storage on the Efficiency and Prices in Real-Time Electricity Markets. e-Energy '13, Fourth international conference on Future energy systems, UC Berkeley, 2013.

We focus on the real-time market

- Most electricity markets are organized in two stages





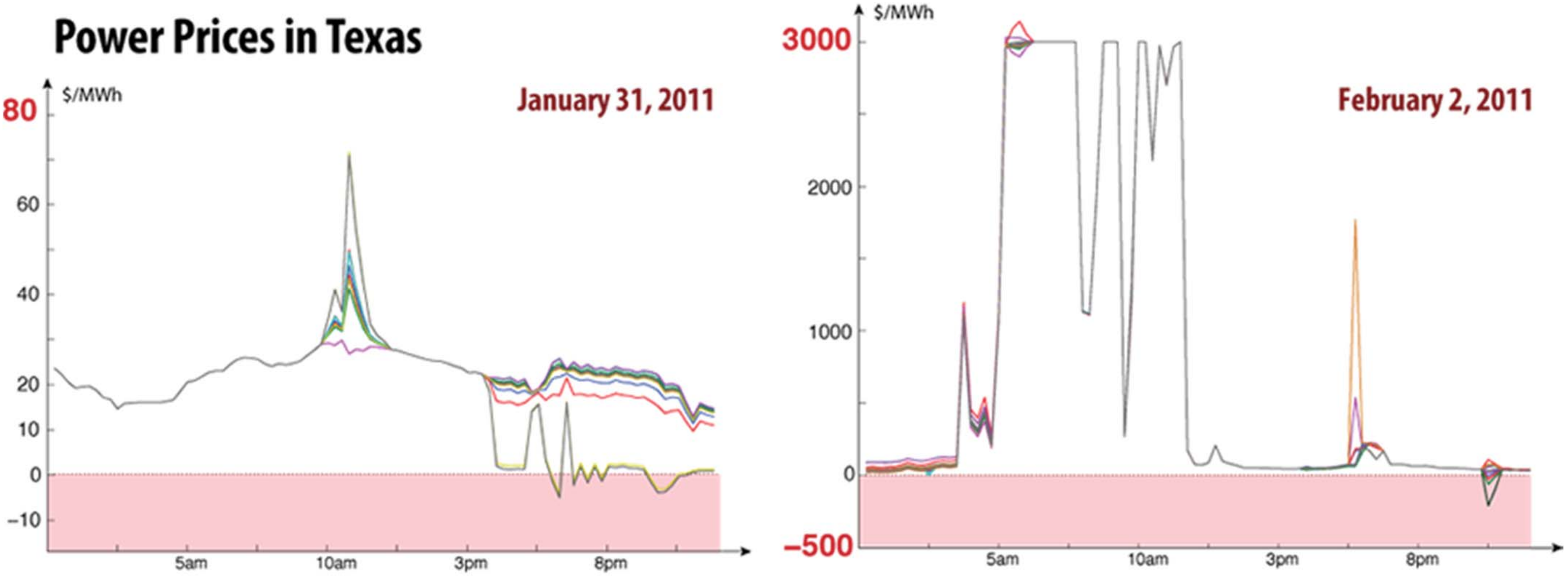


Compensate for deviations from forecast

Inelastic demand satisfied using:

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

Real-time Market exhibit highly volatile prices



Power Prices in Texas

- 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:

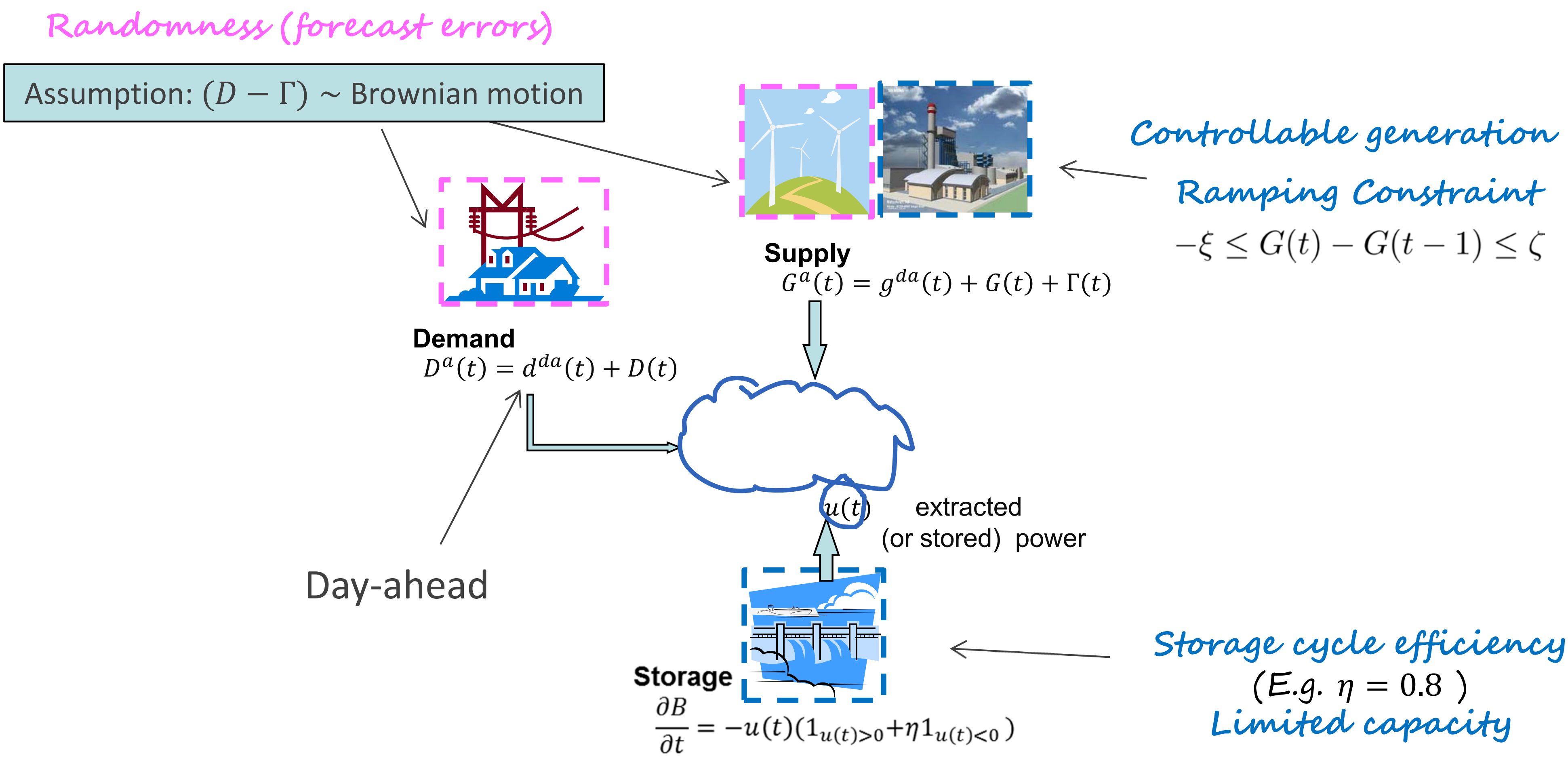
- Markets are efficient
- Prices are never equal to marginal production costs.

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 ?

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

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

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

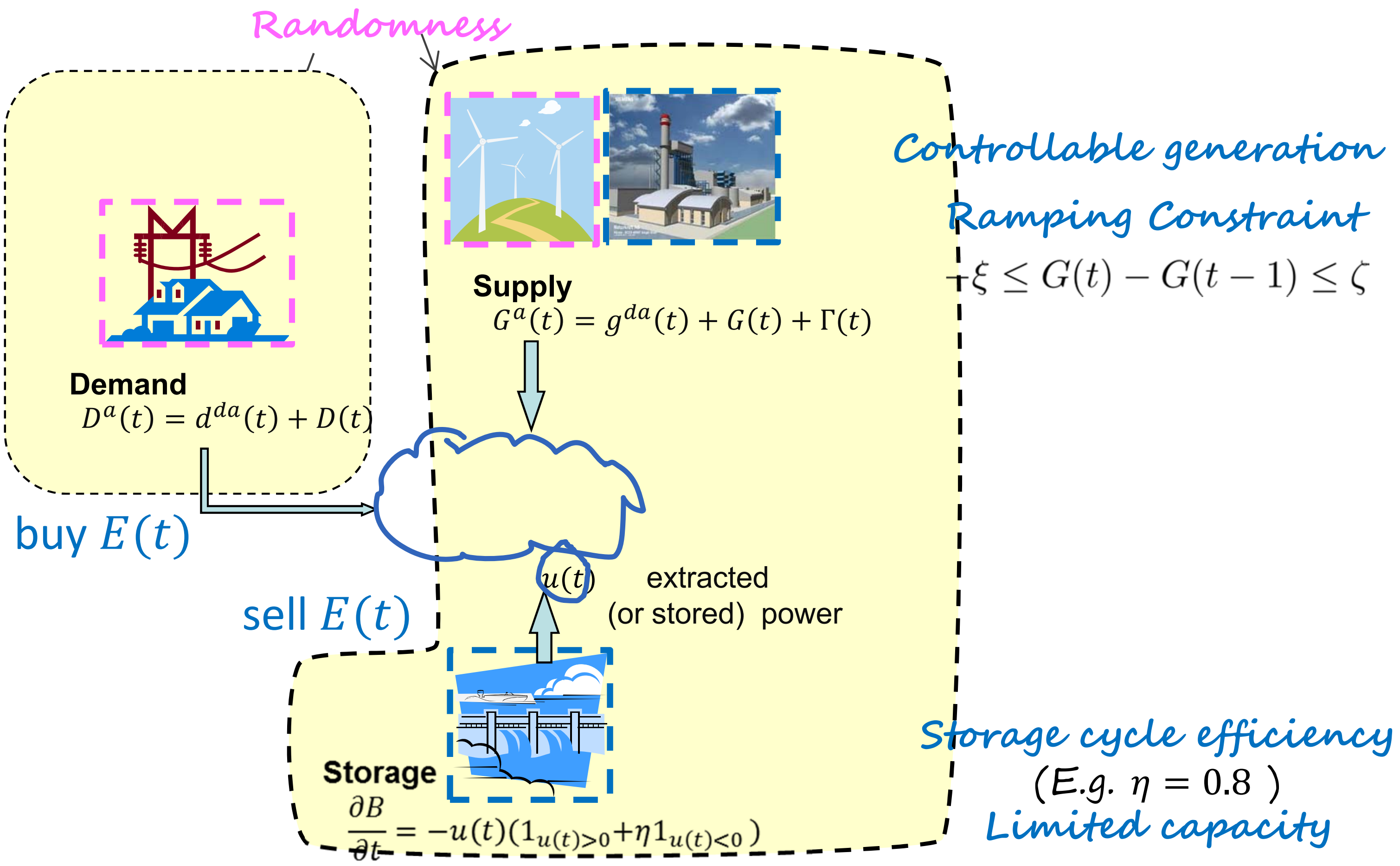
A Macroscopic Model of Real-time generation and Storage

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



Randomness

Demand

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

Supply

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

Controllable generation

Ramping Constraint

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

buy $E(t)$

sell $E(t)$

$u(t)$ 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

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

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

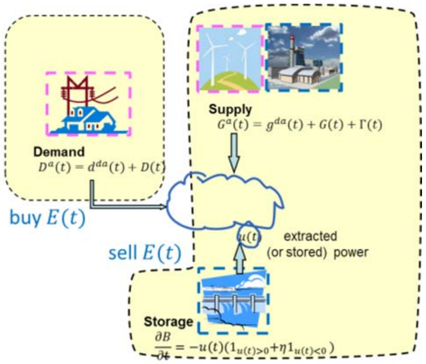
- Supplier's payoff: $W_S(t)$

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

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

- 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 $\eta < 1$

Cycle efficiency

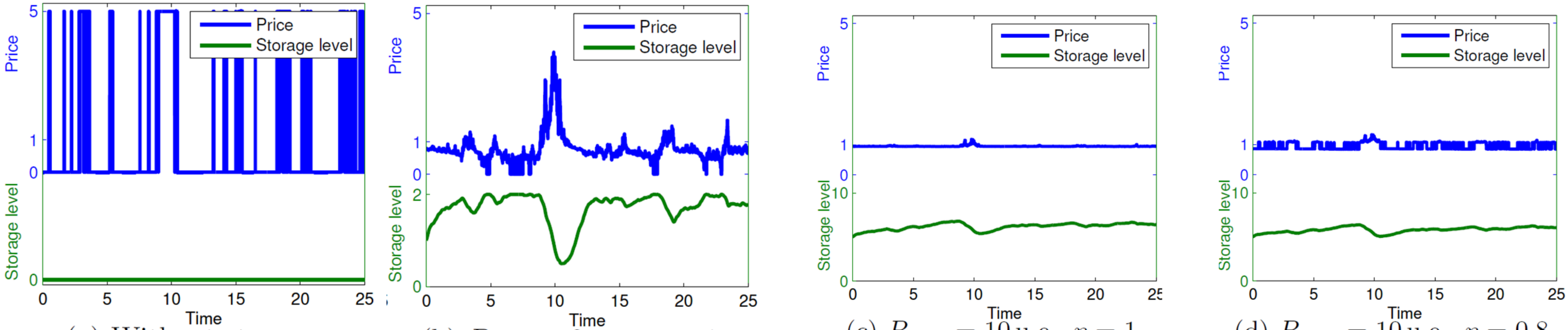
Overproduction that storage cannot store

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

Storage compensates fluctuations

Underproduction that storage cannot satisfy

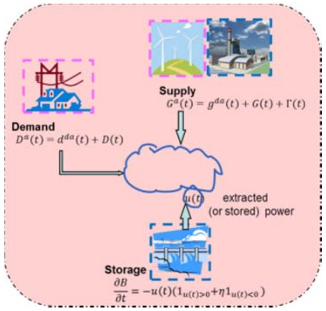
No storage | Small storage | Large storage, $\eta = 1$ | Large storage, η =0.8



(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.

The social planner problem



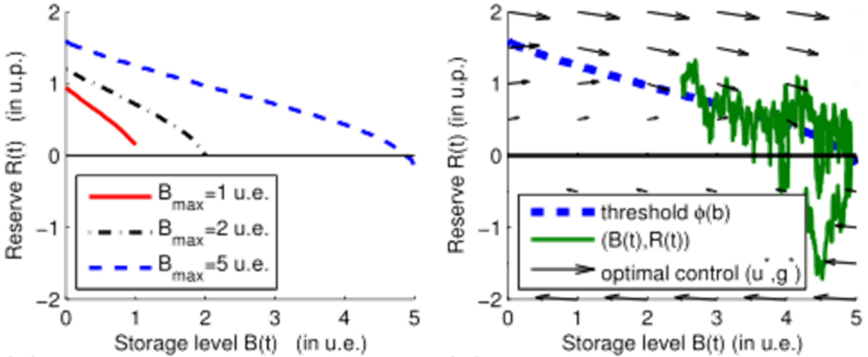
- The social planner wants to find G and u to maximize total expected discounted payoff

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

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

- 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)

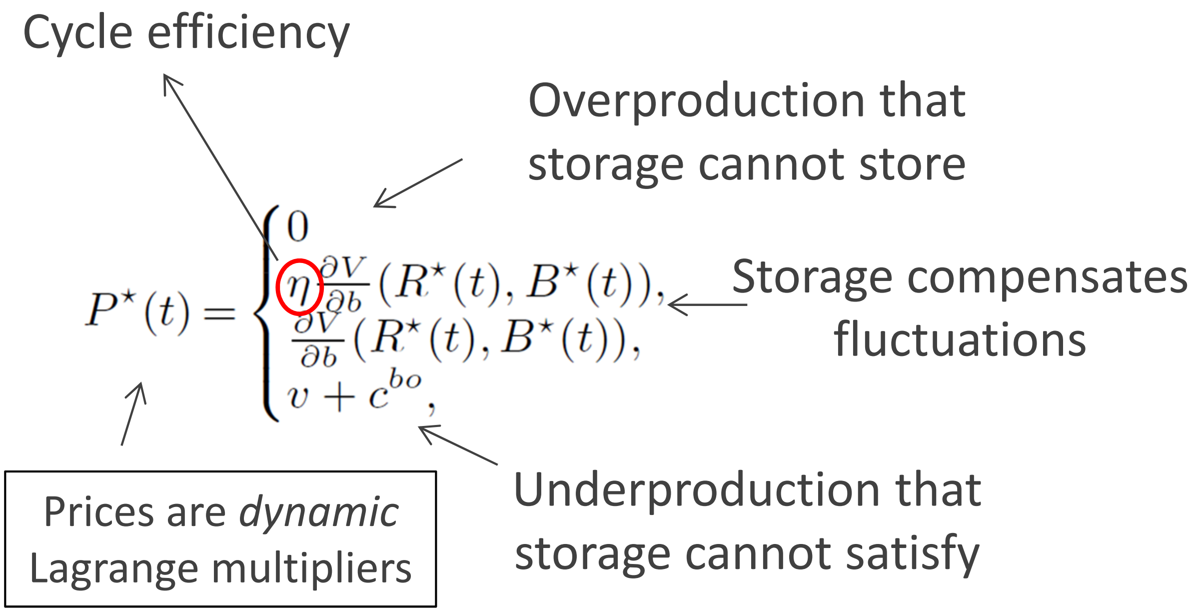


(a) Function $b \mapsto \phi(b)$ for various values of the storage energy capacity $B_{\max}$.

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

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 i.e. the invisible hand of the market works



Cycle efficiency

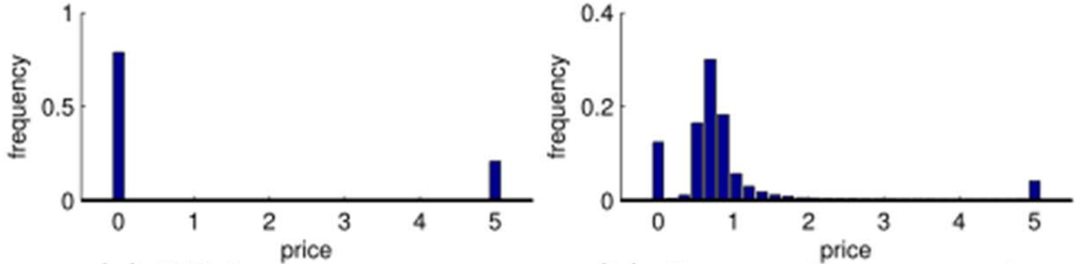
Overproduction that storage cannot store

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

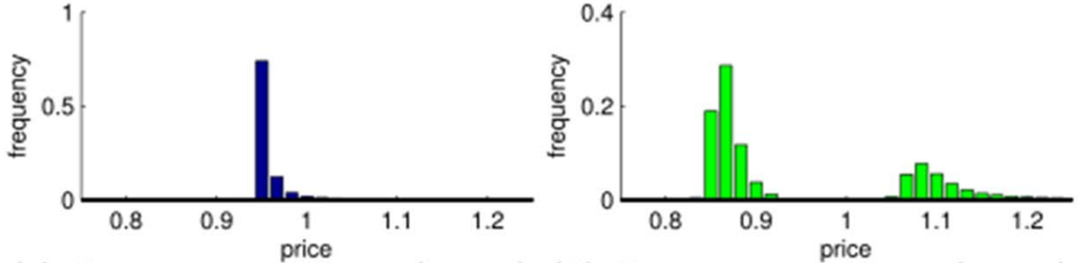
Storage compensates fluctuations

Prices are *dynamic* Lagrange multipliers

Underproduction that storage cannot satisfy



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

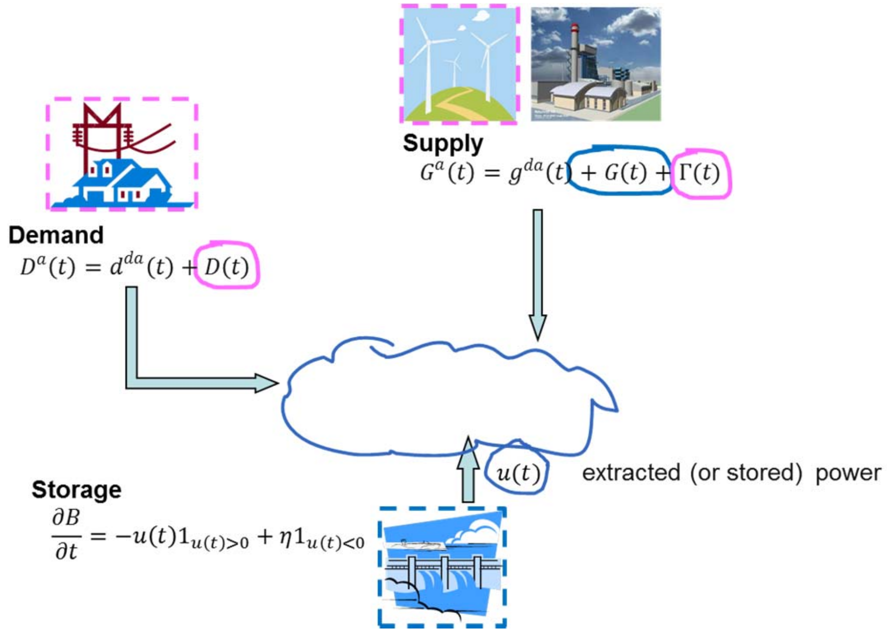


(c) $B_{\max}$=10 u.e., η=1 (zoom) (d) $B_{\max}$=10ue, η=0.8(zoom)

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

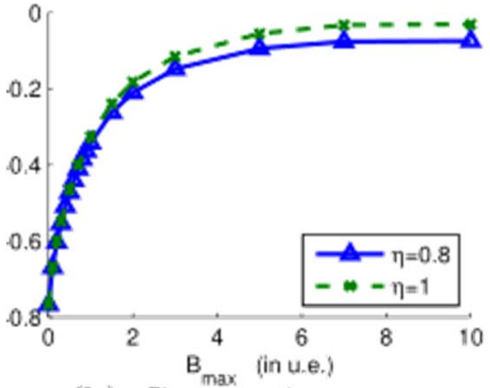


Supply
$G^a(t) = g^{da}(t) + \boxed{G(t)} + \boxed{\Gamma(t)}$

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

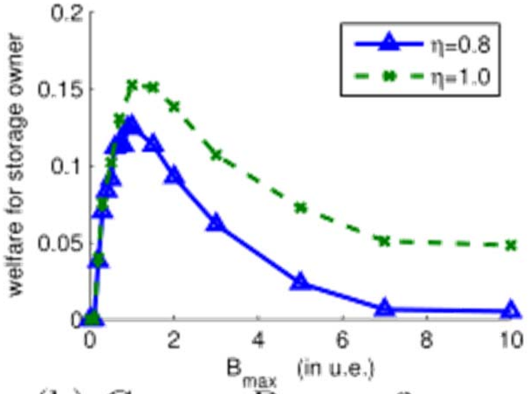
Storage
$\frac{\partial B}{\partial t} = -u(t)1_{u(t)>0} + \eta 1_{u(t)<0}$

$\boxed{u(t)}$ extracted (or stored) power



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

Expected social welfare



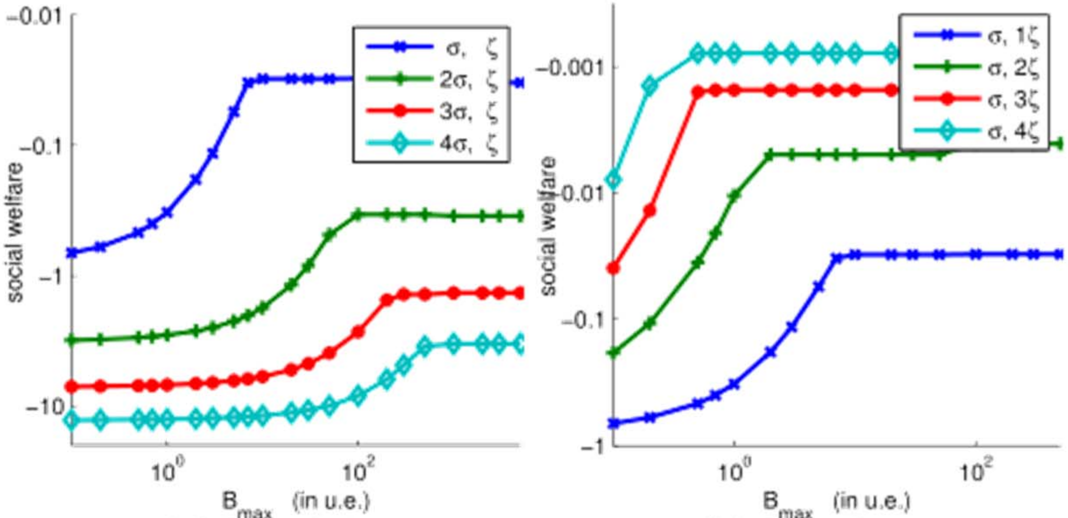
(b) $C_{\max} = D_{\max} = 3\,\mathrm{u.p.}$

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 $\frac{\sigma^4}{\zeta^3}$!

proportional to installed renewable capacity

ζ proportional to ramp-up capacity of traditional generators

- increase volatility and ramp-up capacity by x
  = increase storage by x

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 linearly with amount of renewables

4.

IMPACT OF DEMAND-RESPONSE ON MARKETS 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.

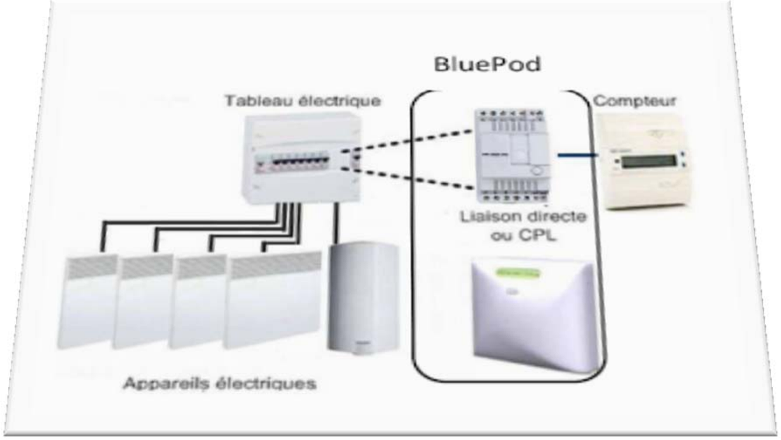
Demand Response

- = distribution network operator may interrupt / modulate power

  = virtual storage

- elastic loads support graceful degradation

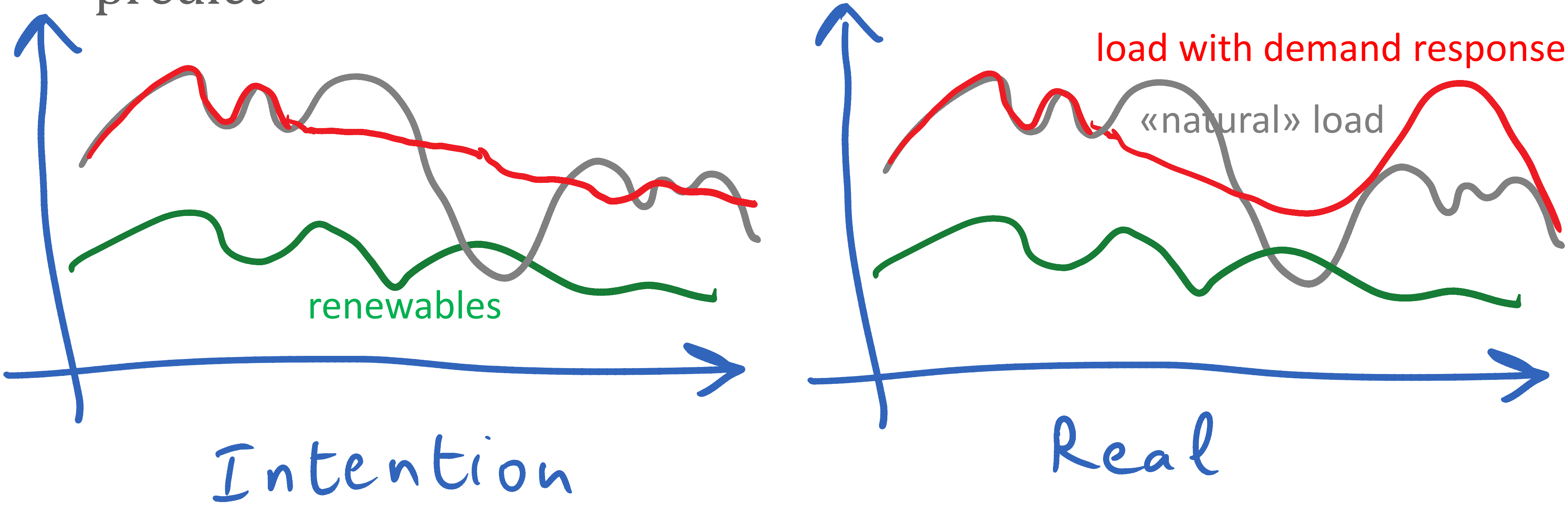
- Thermal load (Voltalis), washing machines (Romande Energie«commande centralisée»)
  e-cars



Voltalis Bluepod switches off boilers / heating for ≤60 mn

Issue with Demand Response: Non Observability

- Widespread demand response may make load hard to predict



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

Our Problem Statement

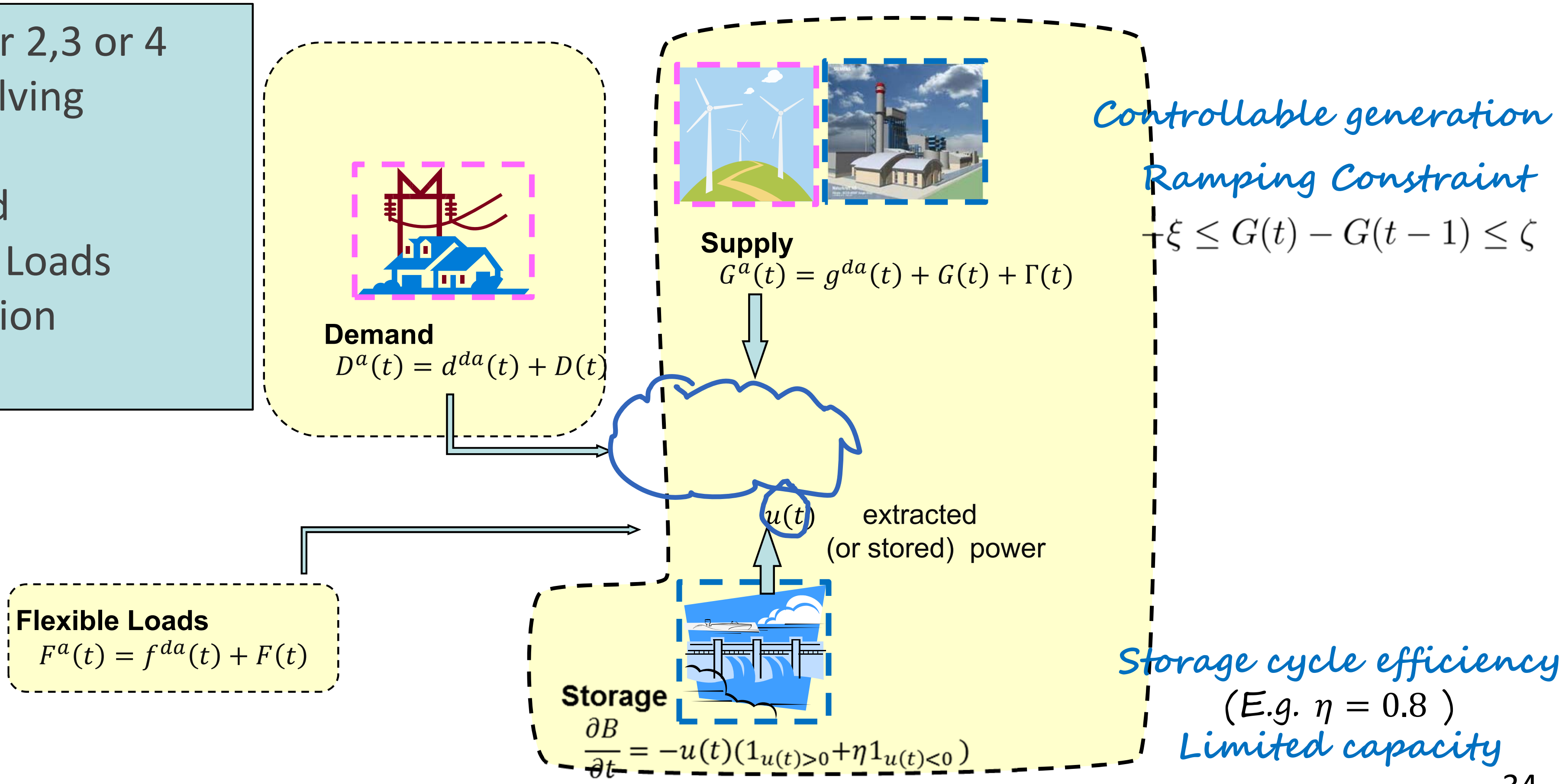
Does it really work as virtual storage ?

Side effect with load prediction

To analyze this we add demand response to the previous model

We consider 2,3 or 4 actors, involving

1. Demand
2. Flexible Loads
3. Production
4. Storage



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

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

$$F^a(t) = f^{da}(t) + F(t)$$

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

Controllable generation

Ramping Constraint

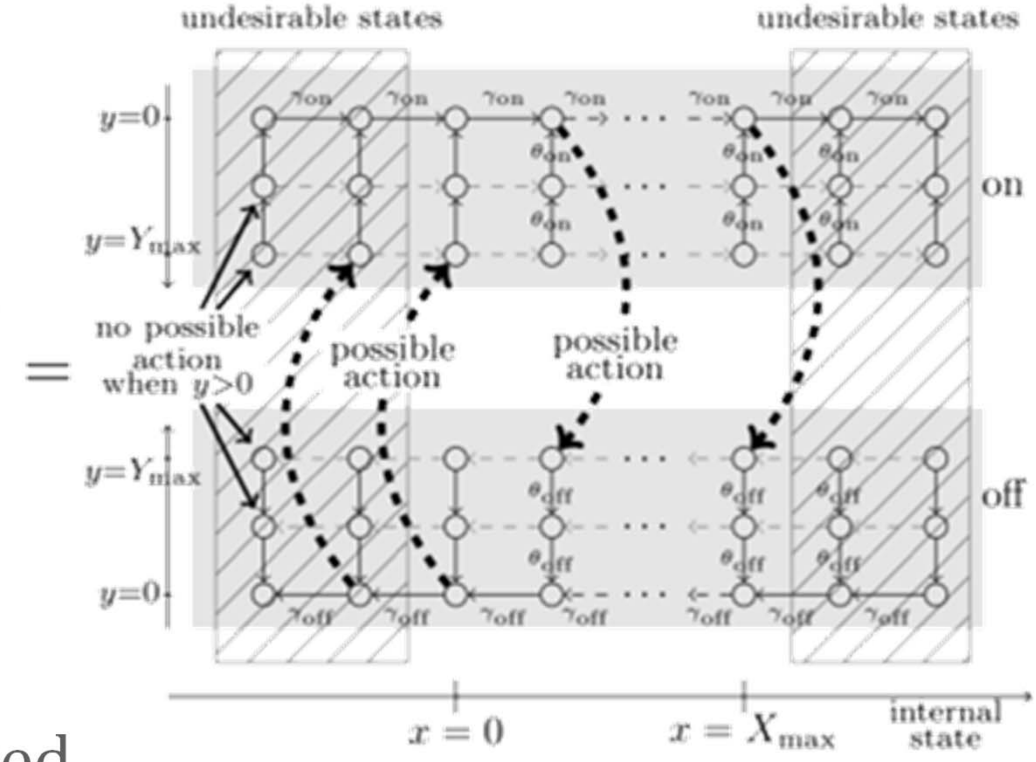
$$-\xi \leq G(t) - G(t-1) \leq \zeta$$

Storage cycle efficiency

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

Limited capacity

Model of Flexible Loads



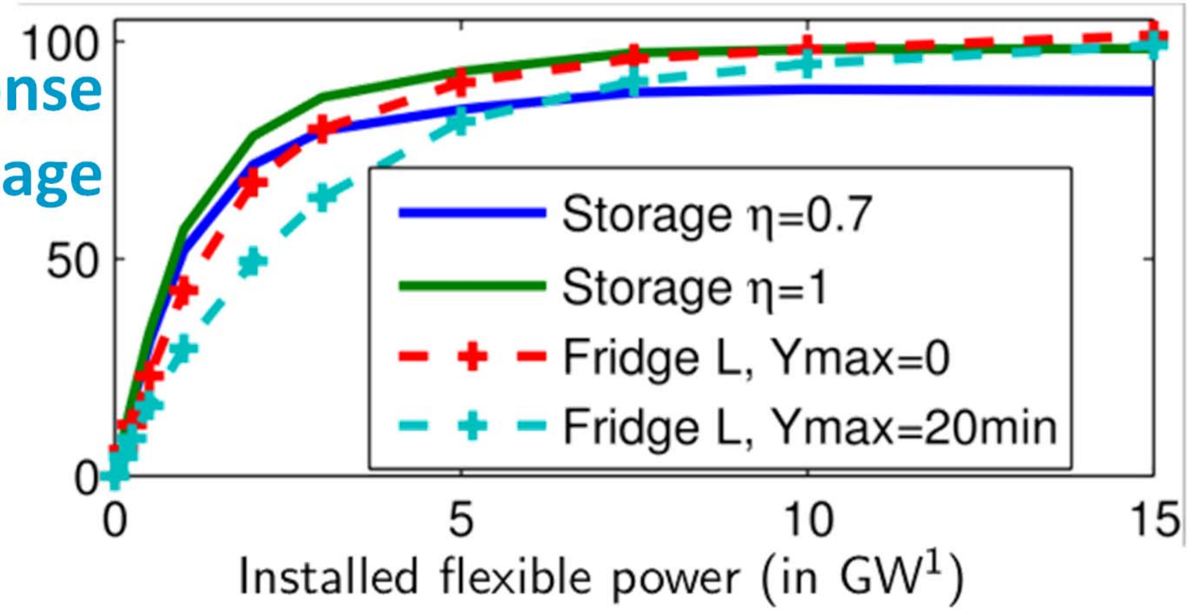
- Population of *N* On-Off appliances (fridges, buildings, pools)
- Without demand response, appliance switches on/off based on internal state (e.g. temperature) driven by a Markov chain
- Demand response action may force an off/off transition but mini-cycles are avoided
- Consumer game: anticipate or delay power consumption to reduce cost while avoiding undesirable states

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.

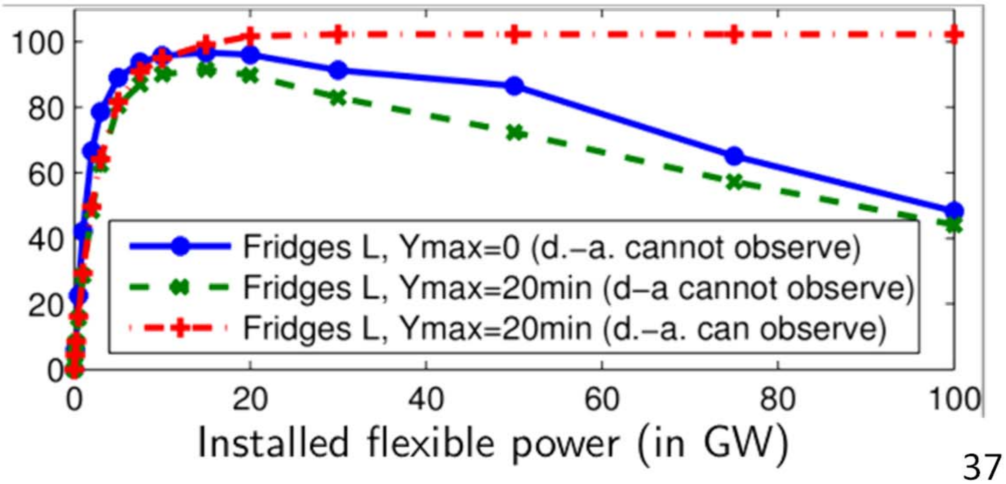
The Benefit of demand-response is similar to perfect storage



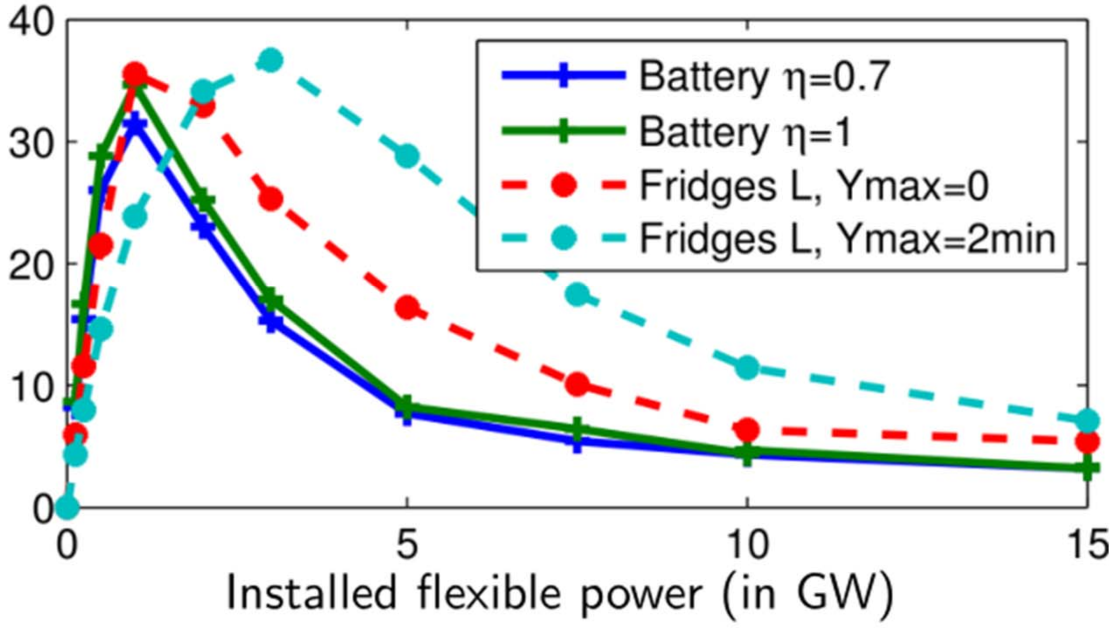
Non-Observability Significantly Reduces Benefit of Demand-Response

We assume that:

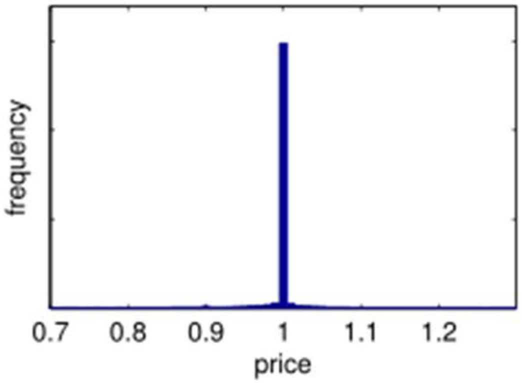
- The demand-response operator knows the state of its fridges
- The day-ahead forecast does not.



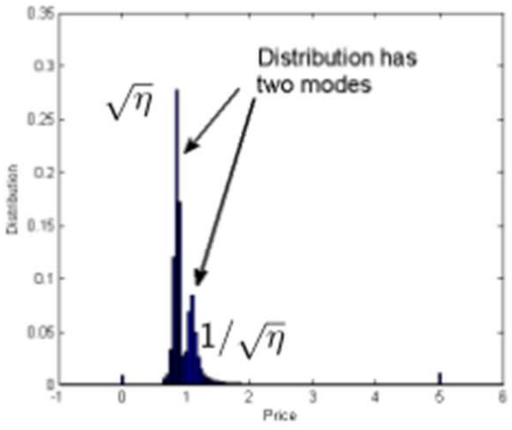
The Invisible Hand of the Market may not be optimal



Demand Response stabilizes prices more than storage



Large amount of 100% efficient storage or demand-response



Storage with efficiency $\eta < 1$

What this suggests about Demand Response :

- 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)

Thank You !

- More details on smartgrid.epfl.ch