# OPTIMAL STORAGE POLICIES WITH WIND FORCAST UNCERTAINTIES

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# EPFL «smart-grids» group

- Two EPFL labs:
  - LCA (Lab. of Communications and Applications), Prof. Jean-Yves Le Boudec
    - Communication systems / networking
    - Stochastic modeling, performance and security
  - DESL (Distributed Electrical Systems Laboratory), Prof Mario Paolone
    - Distribution networks & micro-grids / storage mechanisms
    - Real time Simulation/Emulation
- Projects: Active distribution networks
  - Installation of a smart-grid on campus (20 PMU + communication infrastructure + remote control)
    - Ex: performance and security aspects (wired/wireless network, control)
  - Generation control & Demand-response algorithms (energy balance and voltage control)

1.

# INTRODUCTION

# Renewable but non dispatchable


Source: «Battle of the grids», Greenpeace, Report 2011.

- Wind and PV require some mechanisms to compensate non dispatchability

# Renewable Methods to Compensate for Fluctuations of PV and Wind

Dispatchable renewables

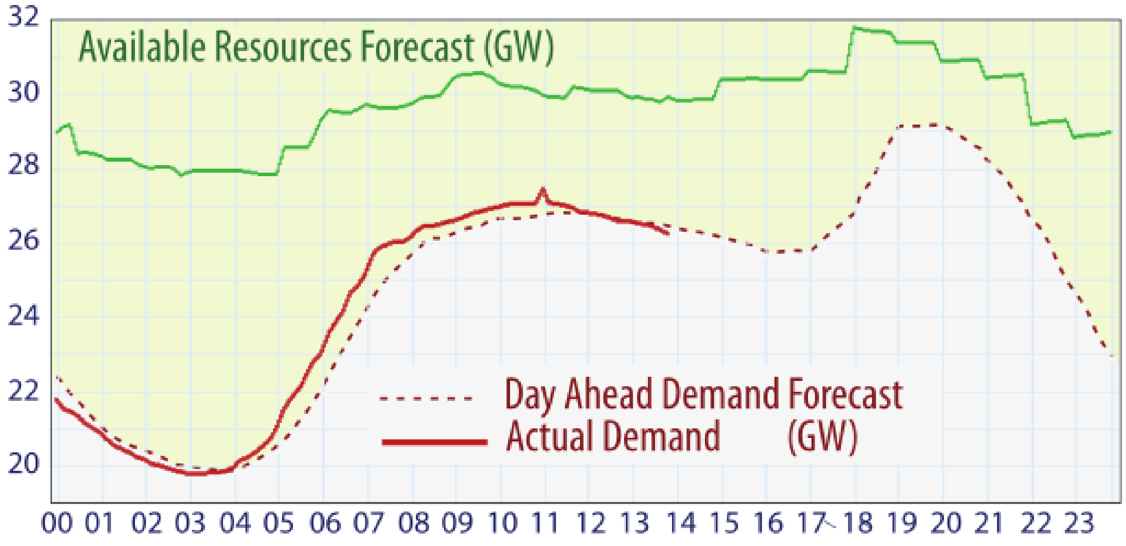
Storage
Demand Response



# Two main issues

1. Production exceeds demand
   - Long term storage

2. Deviations from forecast
   - Schedule of the rest of the production
   - Storage to compensate uncertain forecast




S. Meyn
"Dynamic Models and Dynamic Markets for Electric Power Markets"

2.

# USING STORAGE TO COPE WITH WIND VOLATILITY

Gast, Tomozei, Le Boudec. Optimal Storage Policies with Wind Forecast Uncertainties, *GreenMetrics 2012*

# Schedule production and use storage

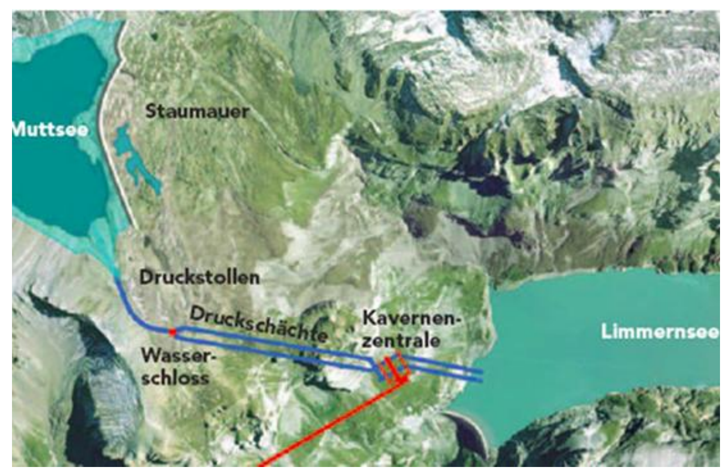
load

renewables

renewables + storage

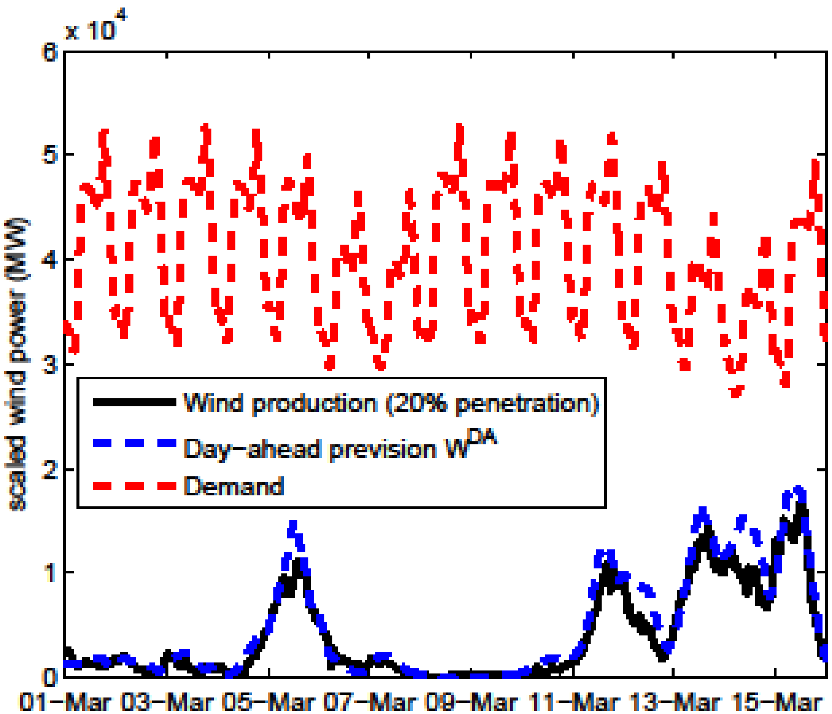

- Stationary batteries, pump hydro

  Cycle efficiency $\approx 70 - 80\%$



# We evaluate on data from the UK

- Aggregate data from UK (BMRA data archive https://www.elexonportal.co.uk/)




- National data (wind production and demand)
- 3 years data

- Demand close to perfectly predicted
- We normalized the wind production

- Day ahead forecast = 24%
- Corrected day ahead forecast = 19%

# Model: Schedule energy=dispatch storage

1. Schedule dispatchable production using forecast

2. In real time: compensate deviations from forecast by charging / discharging $\Delta$ from storage

We plan to use u from storage

load $D_t^f(t+n)$

renewables

$P_t^f(t+n)$

$W_t^f(t+n)$

stored energy

Typically, n=6h
(up to n=18h)

Storage compensates for u + forecast error

load $D(t+n)$

Forecast error

u

renewables

$P_t^f(t+n)$

$\Delta(t+n)$

$W(t+n)$

stored energy

$\Delta(t+n)$

# 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

load $D(t+n)$

fast ramping $\Delta(t+n)$

renewables

$P_t^f(t+n)$

$W(t+n)$

load $D(t+n)$

renewables

$P_t^f(t+n)$

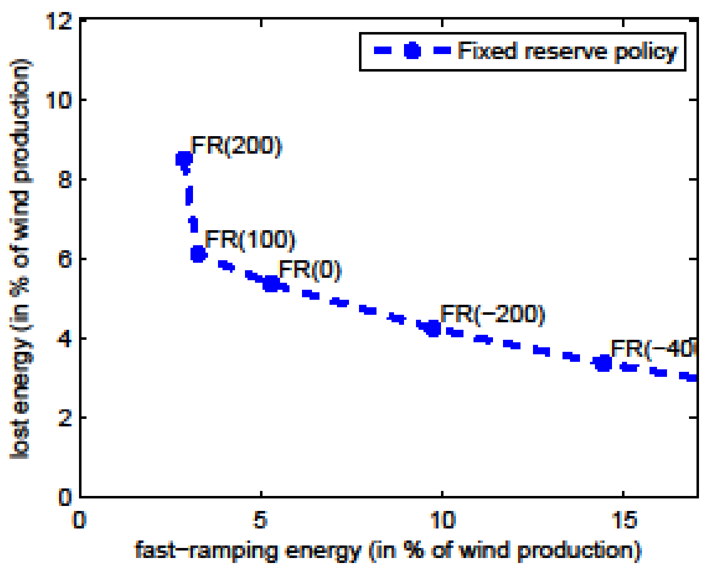
spilled energy

$W(t+n)$

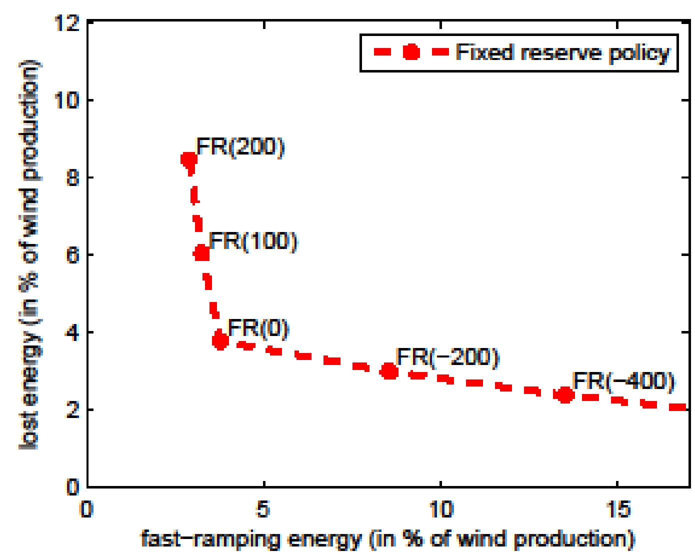
# Policy 1: The Fixed Reserve Policy

- Set $P_t^f(t+n) = D_t^f(t+n) - W_t^f(t+n) + r^*$ → Charge or discharge a fixed quantity
  - $r^*$ 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 $\eta = 1$

# Policy 2: BGK policy [Bejan, Gibbens, Kelly 2012]

- aims at keeping a constant level of stored energy

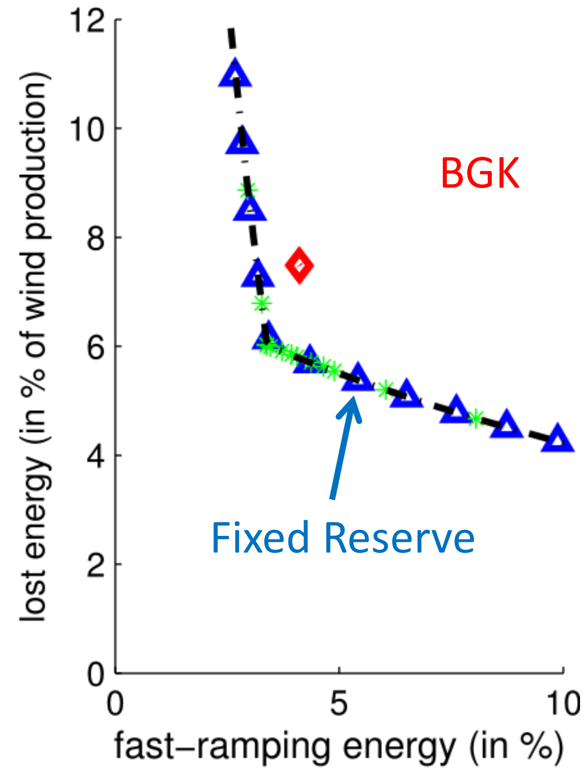
load $D_t^f(t+n)$

renewables $P_t^f(t+n)$

$W_t^f(t+n)$

stored energy

target level $\lambda$




- Sub-optimal for large energy storage capacity

# Fixed Reserve is asymptotically optimal

Let $\ell(u) := \mathbb{E}\left[(\varepsilon+u)^+\right] - f(u)$ with $f(u) := \min\left(\eta\mathbb{E}\left[\min\left((\varepsilon+u)^+, C_{\max}\right)\right], \mathbb{E}\left[\min\left((\varepsilon+u)^-, D_{\max}\right)\right]\right)$

$g(u) := \mathbb{E}\left[(\varepsilon+u)^-\right] - f(u)$

**Theorem.** *Assume that the forecast error conditioned to $\mathcal{F}_t$ is distributed as $\varepsilon$. Then:*

1. (l,g) is a lower bound: for any policy $\pi$, there exists $u$ such that:

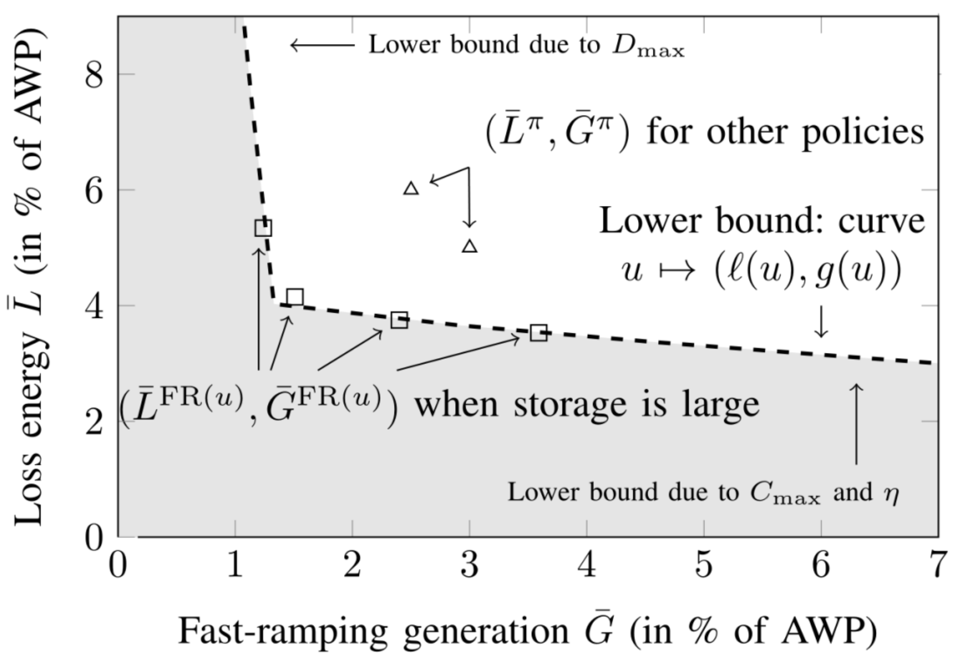
$$\bar{G}^{\pi}(T) \geq g(u) - \frac{B_{\max}}{T}$$

$$\bar{L}^{\pi}(T) \geq \ell(u) - \frac{B_{\max}}{T}$$

2. For any $\delta$, there exists $B_\delta$ such that if $B_{max} > B_\delta$ :

$$\bar{G}^{\mathrm{FR}(u)} \leq g(u) + \delta$$

$$\bar{L}^{\mathrm{FR}(u)} \leq \ell(u) + \delta$$



# Scheduling Policies for Small Storage

load

$D_t^f(t+n)$

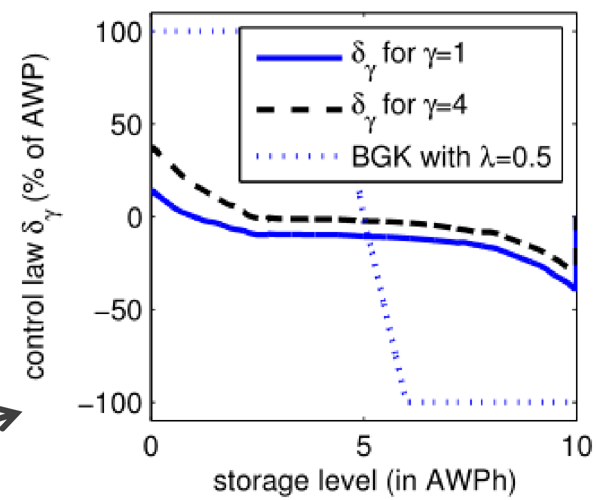
$-u$

renewables

$P_t^f(t+n)$

$W_t^f(t+n)$

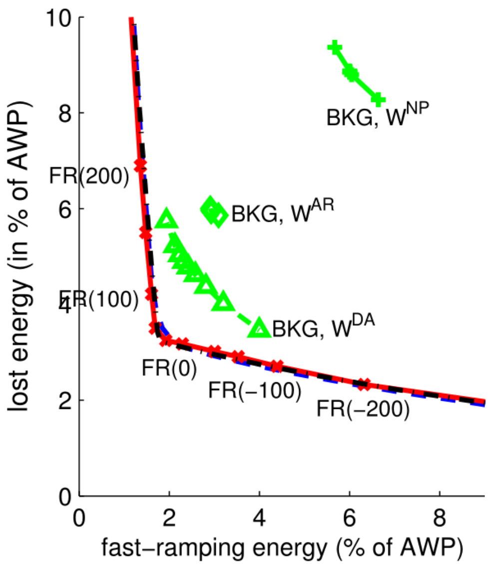
- Fixed Reserve: $u = r^*$
- BGK: compute $u$ so as to let storage level be close to nominal value $\lambda$
- Dynamic Reserve: compute $u$ so as to minimize average anticipated cost
  - Solved using an MDP model and policy iteration
  - Schedule reserve as a function of current storage level




(a) $\eta = 0.8$

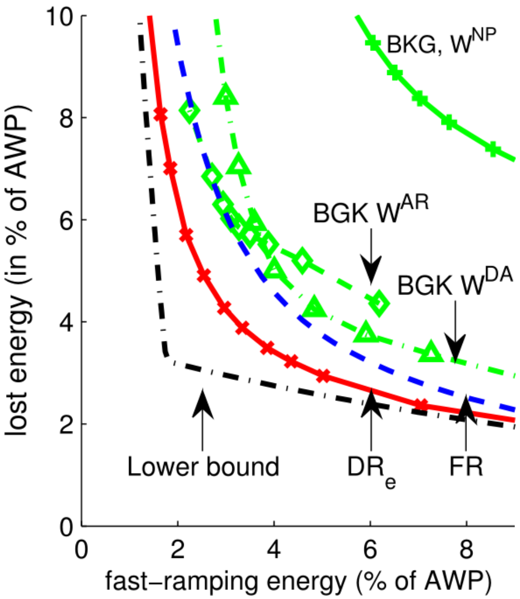
# DR outperforms other heuristics

- Large storage capacity




- FR & DR optimal

- Small storage capacity



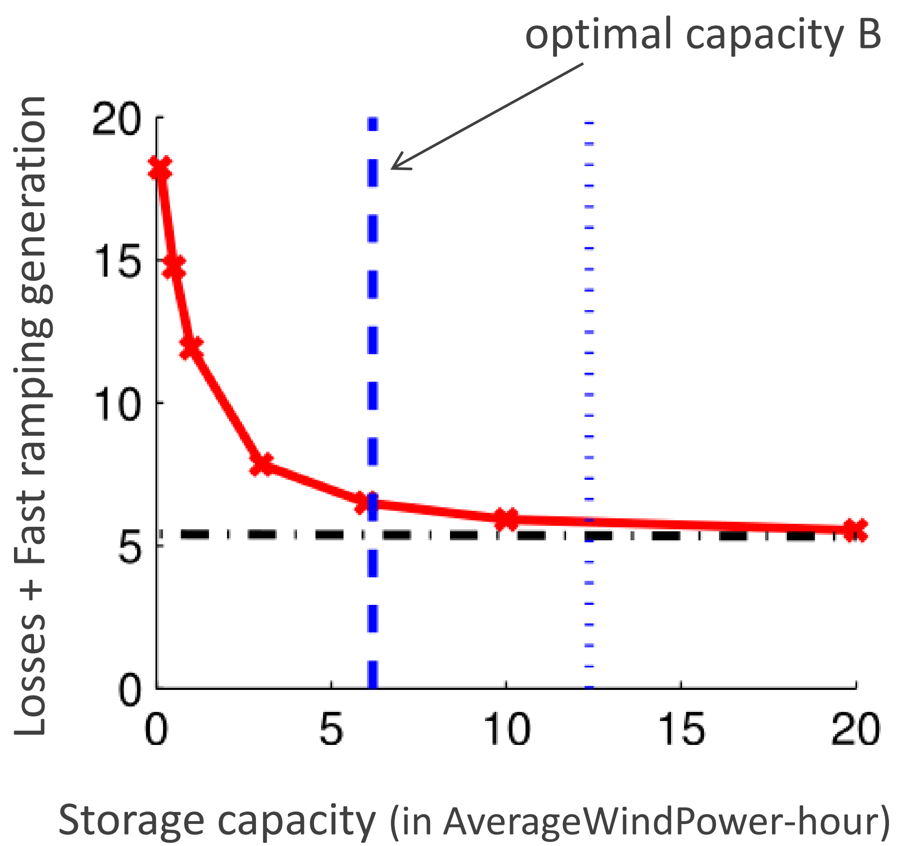

- DR is the best heuristic

Maintaining storage at fixed level: not optimal

There exist better heuristics

# Computing the optimal storage

- Losses & Gaz used decreases
  - As capacity increases
  - As maximum power increases

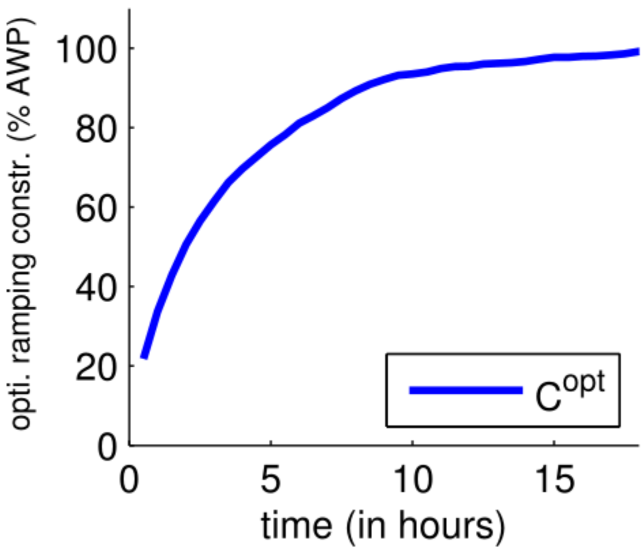



- Develop two rules-of-thumb to compute optimal storage characteristics:
  - Optimal power C is when P(forecast error >= C) < 1%.
  - Optimal capacity B, when

P(sum of errors over n slots >= B/2) < 1%.

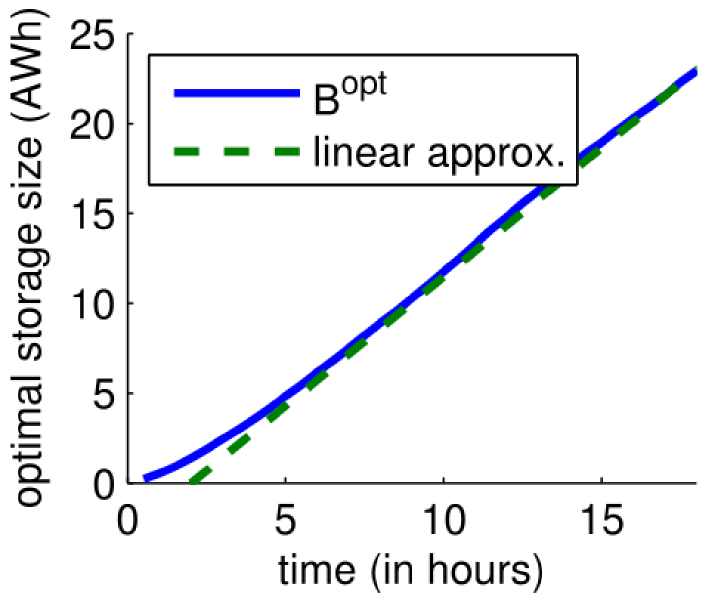
# Optimal storage and time horizon

- Optimal storage power




(a) $C^{opt}$ as a function of $n$

- Optimal storage capacity




(b) $B^{opt}$ as a function of $n$

We schedule the base production **n hours** in advance

# Conclusion

- Mantain storage at fixed level is not optimal
  - Statistics of forecast error are important
  - We propose a close to optimal heuristics
- Rule of thumb to compute optimal storage capacities
- Future Work:
  - Economic implications of storage
  - Distributed storage systems in distribution networks (location, usage)

# Questions ?


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

[2] David MacKay, *Sustainable Energy – Without the Hot Air,* UIT Cambridge, 2009

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

[4] Nicolas Gast, Dan-Christian Tomozei, Jean-Yves Le Boudec. *Optimal Storage Policies with Wind Forecast Uncertainties.* Greenmetrics 2012, London, UK.

[5] Le Boudec, Tomozei, *Satisfiability of Elastic Demand in the Smart Grid,* Energy 2011 and ArXiv.1011.5606