A Demand Response Calculus with Perfect Batteries

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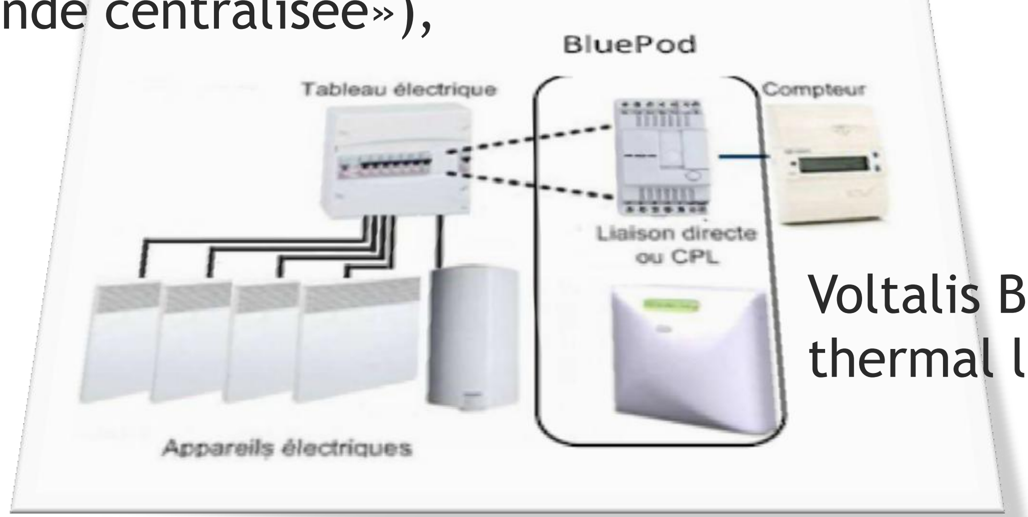
Joint work with Jean-Yves Le Boudec

CCW, Sedona AZ, 07/11/2012

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

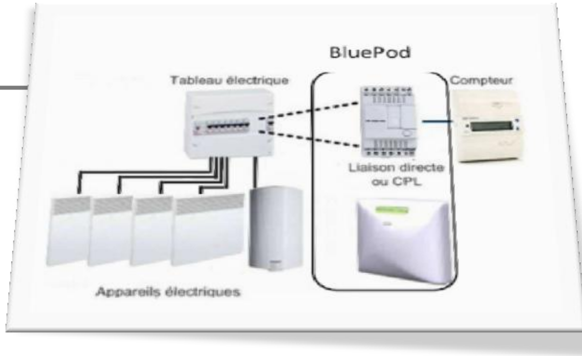
Demand Response by Quantity

- = distribution network operator may interrupt / modulate power
- elastic loads support graceful degradation
- Thermal load (Voltalis),
  water heaters (Romande Energie «commande centralisée»),
  e-cars



Voltalis Bluepod switches off thermal load for 60 mn

Network Calculus? Service curve?



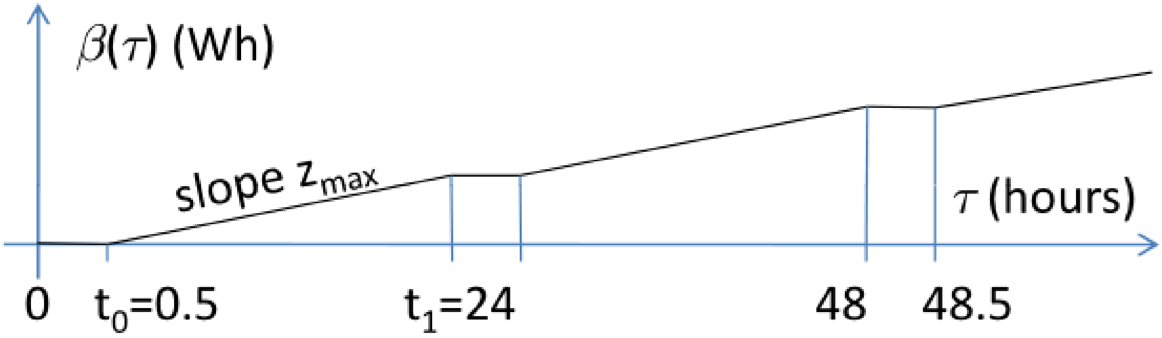
Voltalis:

- At most 30 mn of interruption total per day

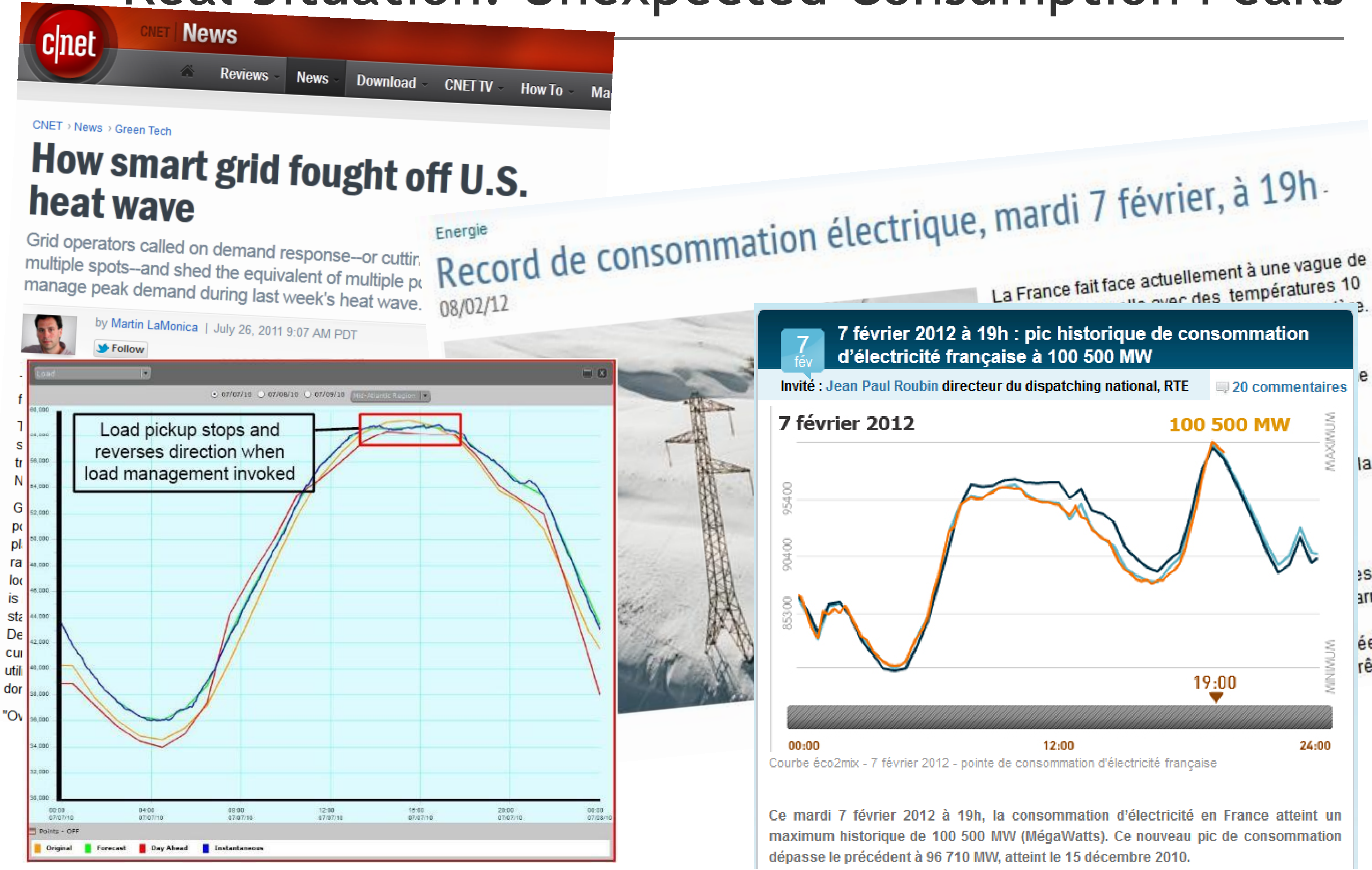
“Service curve” contract

$$\text{Guaranteed energy delivered in } (s,t) \geq \beta(t-s), \qquad \forall 0 \leq s \leq t$$

$\beta(t)$ = superadditive function.



Real Situation: Unexpected Consumption Peaks



How smart grid fought off U.S. heat wave

Grid operators called on demand response--or cuttin
multiple spots--and shed the equivalent of multiple p
manage peak demand during last week's heat wave.

by Martin LaMonica | July 26, 2011 9:07 AM PDT

Load pickup stops and reverses direction when load management invoked

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Energie

Record de consommation électrique, mardi 7 février, à 19h

08/02/12

La France fait face actuellement à une vague de
... avec des températures 10

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7 février 2012 à 19h : pic historique de consommation d'électricité française à 100 500 MW

Invité : Jean Paul Roubin directeur du dispatching national, RTE

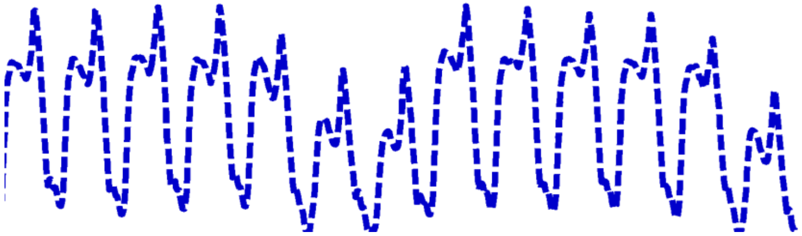
Courbe éco2mix - 7 février 2012 - pointe de consommation d'électricité française

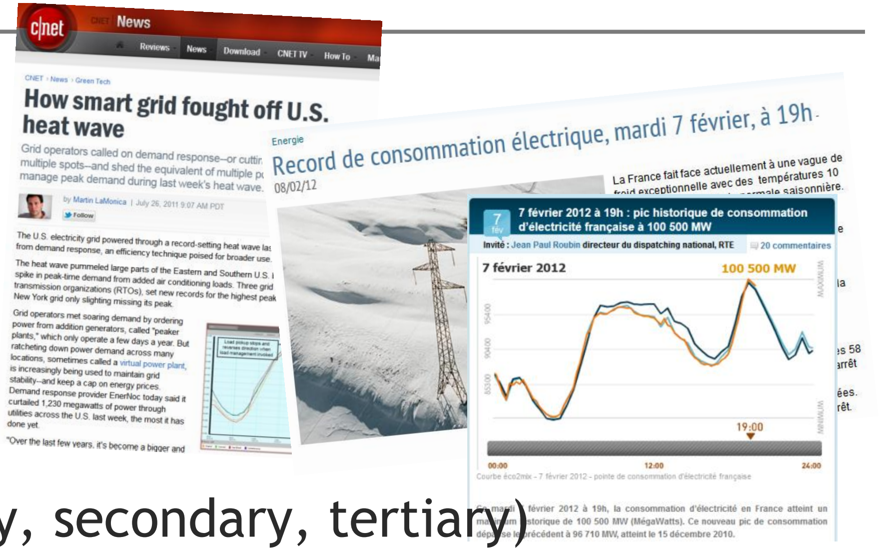
Ce mardi 7 février 2012 à 19h, la consommation d'électricité en France atteint un maximum historique de 100 500 MW (MégaWatts). Ce nouveau pic de consommation dépasse le précédent à 96 710 MW, atteint le 15 décembre 2010.

Is Demand Response a good solution?

Today

- Aggregate demand is **predictable**





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How smart grid fought off U.S. heat wave

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Follow

The U.S. electricity grid powered through a record-setting heat wave las
from demand response, an efficiency technique poised for broader use.

The heat wave pummeled large parts of the Eastern and Southern U.S. i
spike in peak-time demand from added air conditioning loads. Three grid
transmission organizations (RTOs), set new records for the highest peak
New York grid only slighting missing its peak.

Grid operators met soaring demand by ordering power from addition generators, called "peaker plants," which only operate a few days a year. But ratcheting down power demand across many locations, sometimes called a virtual power plant, is increasingly being used to maintain grid stability--and keep a cap on energy prices. Demand response provider EnerNoc today said it curtailed 1,230 megawatts of power through utilities across the U.S. last week, the most it has done yet.

"Over the last few years, it's become a bigger and

Energie

Record de consommation électrique, mardi 7 février, à 19h

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La France fait face actuellement à une vague de
froid exceptionnelle avec des températures 10
normale saisonnière.

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20 commentaires

Courbe éco2mix - 7 février 2012 - pointe de consommation d'électricité française

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- Operators foresee "**reserve**" (primary, secondary, tertiary)
  - E.g., gas turbines
- Reserve is expensive (capacity) / rare event → demand response
  - Delay ("**buffer**") demand until the peak has passed ~ **virtual energy storage**

Tomorrow?

- High penetration of renewables →
  Large (unaffordable) reserve requirements
- E.g., fleet of e-cars → DR exploits load flexibility

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Demand Response by Quantity

Formally:

- Consumption:

“energy” (Watt-hours) “power” (Watts)

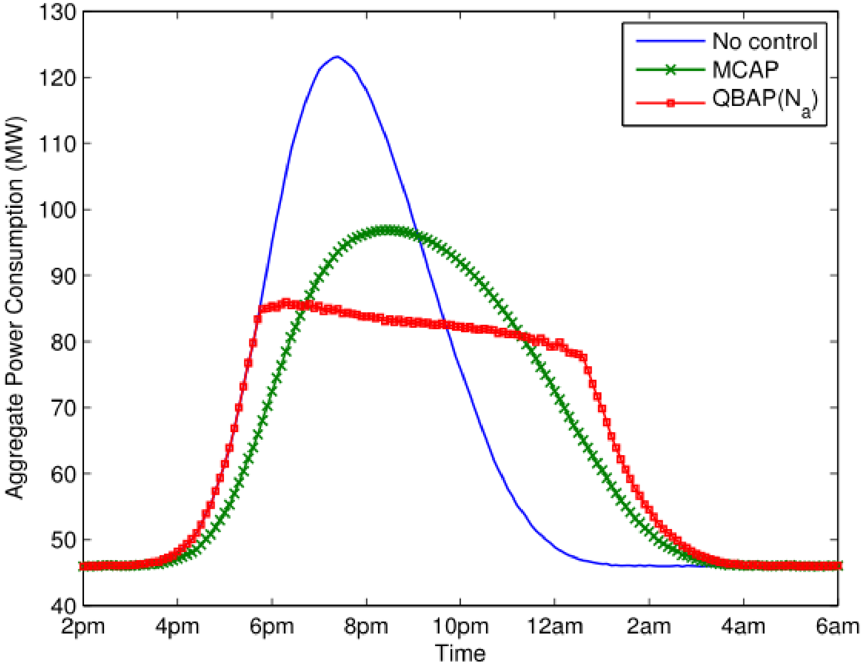
$$U(t) = \int_0^t u(s)ds$$

- Allowed consumption (control):

$$G(t) = \int_0^t g(s)ds$$

- Demand Response imposes:

$$0 \le U(t) - U(s) \le G(t) - G(s), \\ \forall 0 \le s \le t$$



(b) $t_0 = 3\text{h}$, quota $N_a = 3500$.

[Le Boudec, Tomozei – ISGT-EU’11]

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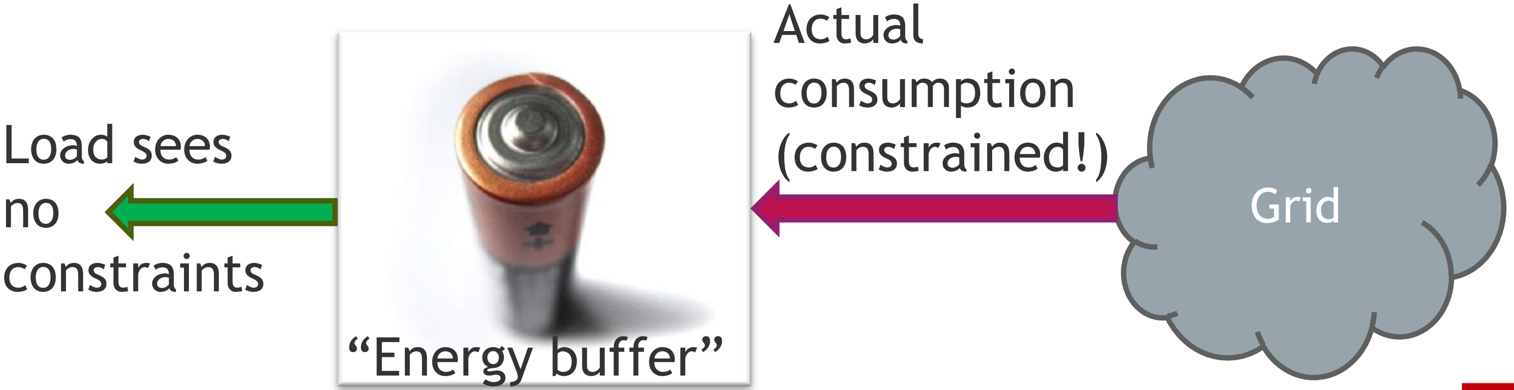
Inelastic load = lights out?

- Inelastic (non-dispatchable) loads
  - Lamps, TVs, Microwaves, …
- Elastic (dispatchable) loads
  - Heating, A/C (TCLs)
- *Make it* dispatchable!
  - Inelastic load $L(t) = \int_0^t \ell(s)ds$
  - Use a large enough battery!

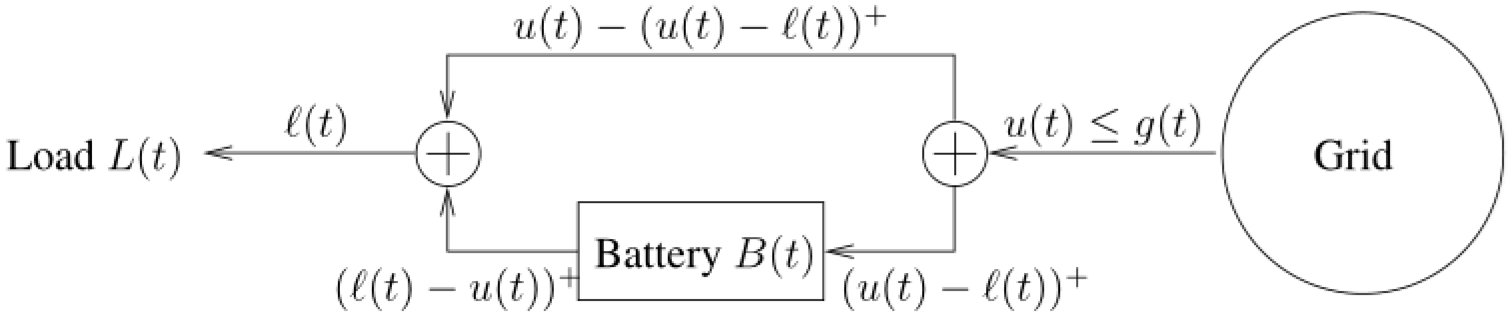


Load sees no constraints

“Energy buffer”

Actual consumption (constrained!)

The Perfect Battery

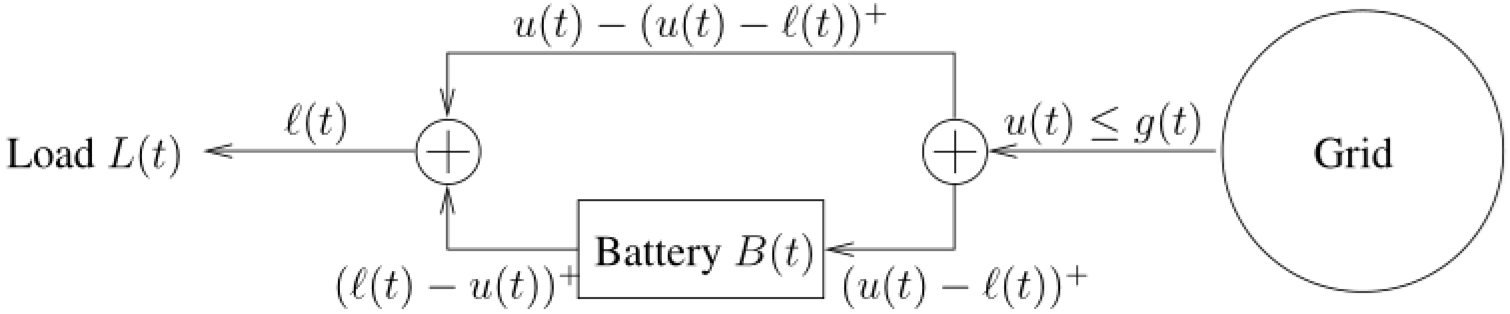


Battery may be charged ($u(t) > \ell(t)$) or discharged ($u(t) < \ell(t)$)

Load $\ell(t)$ is given

Problem is to determine a power schedule $u(t)$, subject to $0 \le u(t) \le g(t)$ and within battery constraints

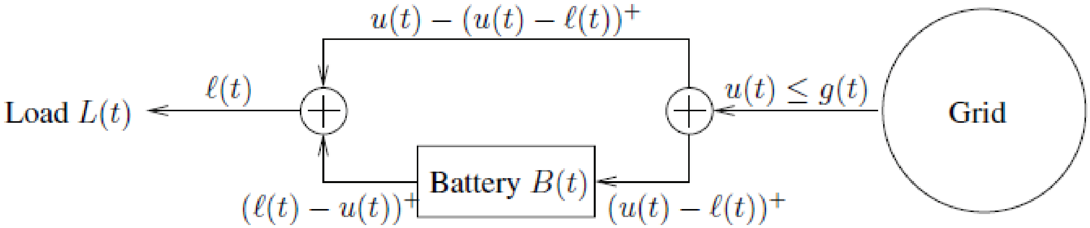
System Equations for the Perfect Battery



1. $L(t) \leq B_0 + U(t)$ no underflow
2. $U(t) - L(t) + B_0 \leq B$ no overflow
3. $U(t) - U(s) \leq G(t) - G(s), \forall s \leq t$ power constraint

where $U(t), L(t), G(t)$ are cumulative functions such as $U(t) = \int_0^t u(s)ds$

Omniscient Problem



Given (known) signals:

- The load

$$L(t) = \int_0^t \ell(s)ds$$

- Allowed consumption

$$G(t) = \int_0^t g(s)ds$$

To be determined:

- Battery initial charge B_0
- Max battery capacity B
- Schedule (consumption from grid)

$$U(t) = \int_0^t u(s)ds$$

Constraints:

- Demand Response: $0 \le U(t) - U(s) \le G(t) - G(s), \forall s \le t$
- Perfect battery constraints: $L(t) \le B_0 + U(t)$

$$U(t) - L(t) + B_0 \le B$$

Main Result

Theorem

- There exists a feasible schedule if and only if

$$\begin{cases} B_0 \geq \sup_t \left(L(t) - G(t)\right) \\ B \geq \sup_{0 \leq s \leq t} \left(L(t) - L(s) - G(t) + G(s)\right) \end{cases}$$

- Moreover, if this is the case, then there exist a "minimal" and a "maximal" schedule:

$$U_*(t) = 0 \vee \sup_{\tau \geq t}(G(t) - G(\tau) + L(\tau) - B_0)$$

$$U^*(t) = G(t) \wedge \inf_{s \leq t}(G(t) - G(s) + L(s) + B - B_0)$$

$$U_*(t) \leq U(t) \leq U^*(t), \qquad \forall t \geq 0$$

- The maximal schedule is causal & corresponds to the greedy policy (maximizes battery charge)

Service Curve Approach to Demand Response

Assume we do not know the control signal $G(t)$

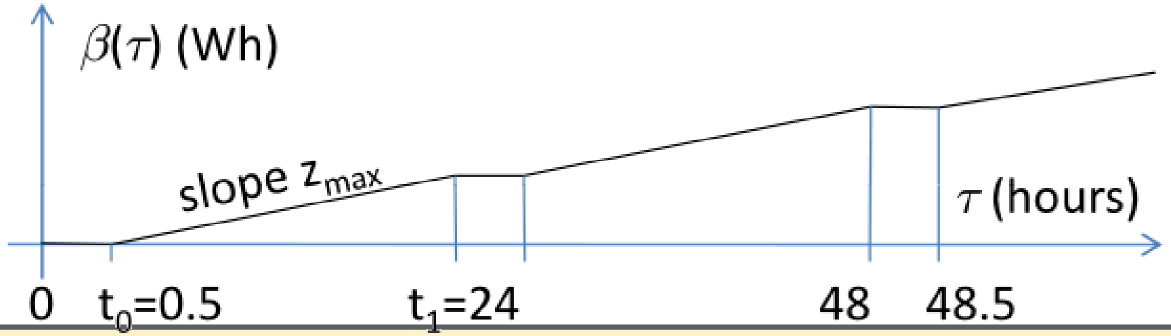
Instead: service curve contract [Le Boudec, Tomozei, ISGT-EU'11]

$$G(t) - G(s) \geq \beta(t-s), \qquad \forall 0 \leq s \leq t$$

$\beta(t)$ = superadditive function.

Example:

- At most 30 mn of interruption total per day
- Or reduction to $\frac{z_{max}}{2}$ for 60mn total per day



- Similar theorem → closed form condition on B, B_0 + min/max schedule

Service Curve + Arrival Curve

Assume we don't know the load $L(t)$ either!

Instead, $L(t)$ is constrained by a subadditive arrival curve:

$$L(t) - L(s) \leq \alpha(t-s), \qquad \forall 0 \leq s \leq t$$

Smallest arrival curve – obtained via min-plus deconvolution:

$$\alpha(t) \coloneqq \sup_{s \geq 0} \{L(s+t) - L(s)\}$$

$G(t)$ is well behaved (according to superadditive service curve):

$$G(t) - G(s) \geq \beta(t-s), \qquad \forall 0 \leq s \leq t$$

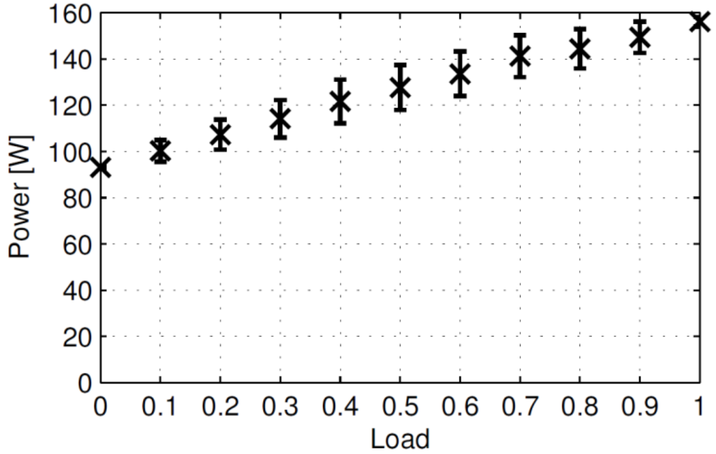
Theorem

For all $(\mathrm{B} \geq) B_0 \geq B^* \coloneqq \sup_s \{\alpha(s) - \beta(s)\}$, there exists a feasible online (causal) schedule, valid for all loads and control signal compatible with $\alpha(\cdot)$ and $\beta(\cdot)$ respectively.

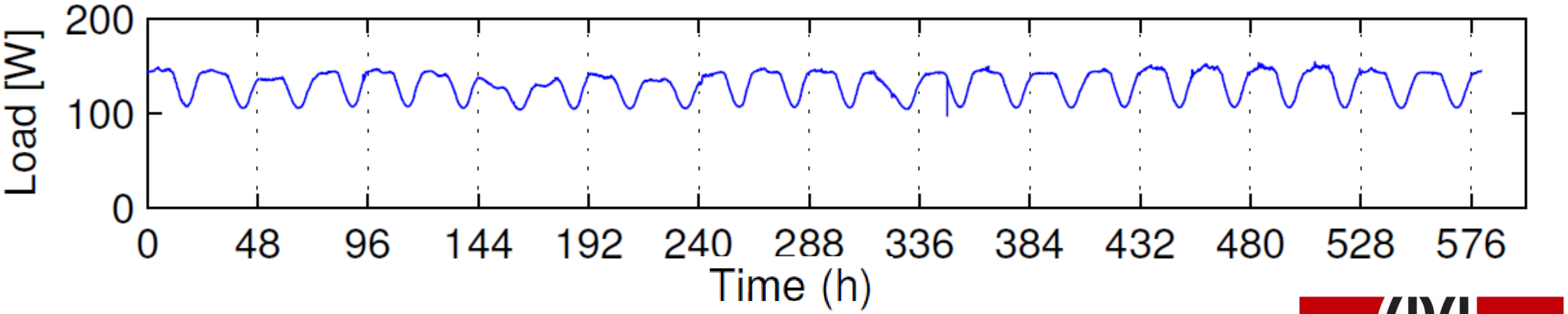
Application: Transparent DR for data centers

Akamai data set [Qureshi et al, SIGCOMM 2009]

- Traffic at Akamai (millions of hits over 24 days)
- Measured power consumption of a desktop (SPEC)

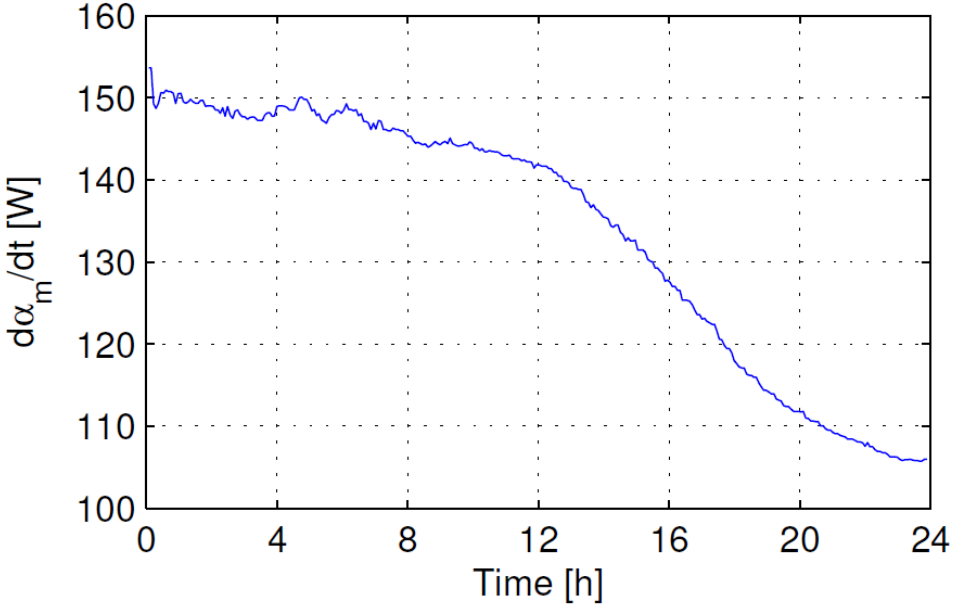


- Uniform repartition of tasks => consumption of one server



Empirical arrival curve

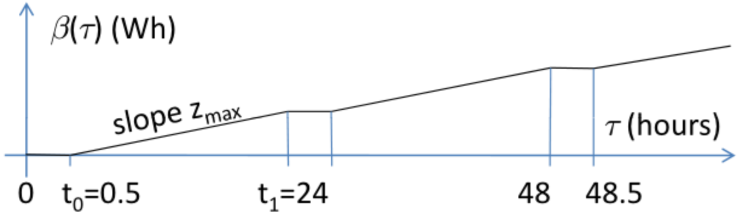
$$\alpha_m(t) \coloneqq \sup_{0 \le s \le T_{max} - t} \{L(s+t) - L(s)\}$$

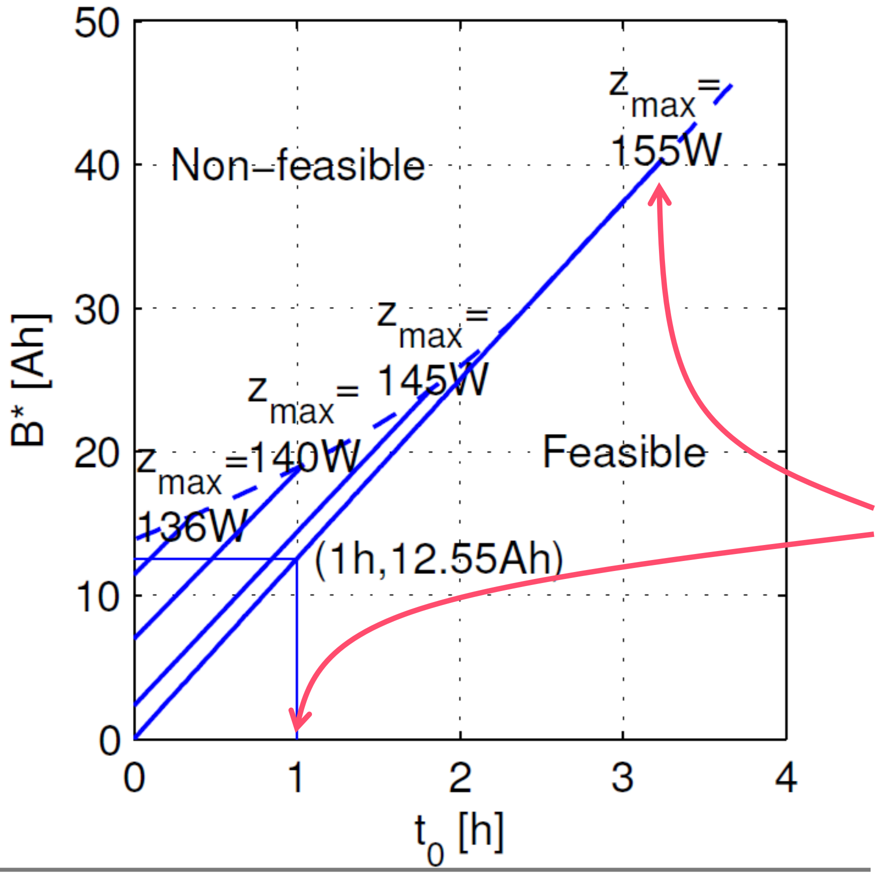


- Intuitively = worst observed day

Choosing a SC contract and a battery

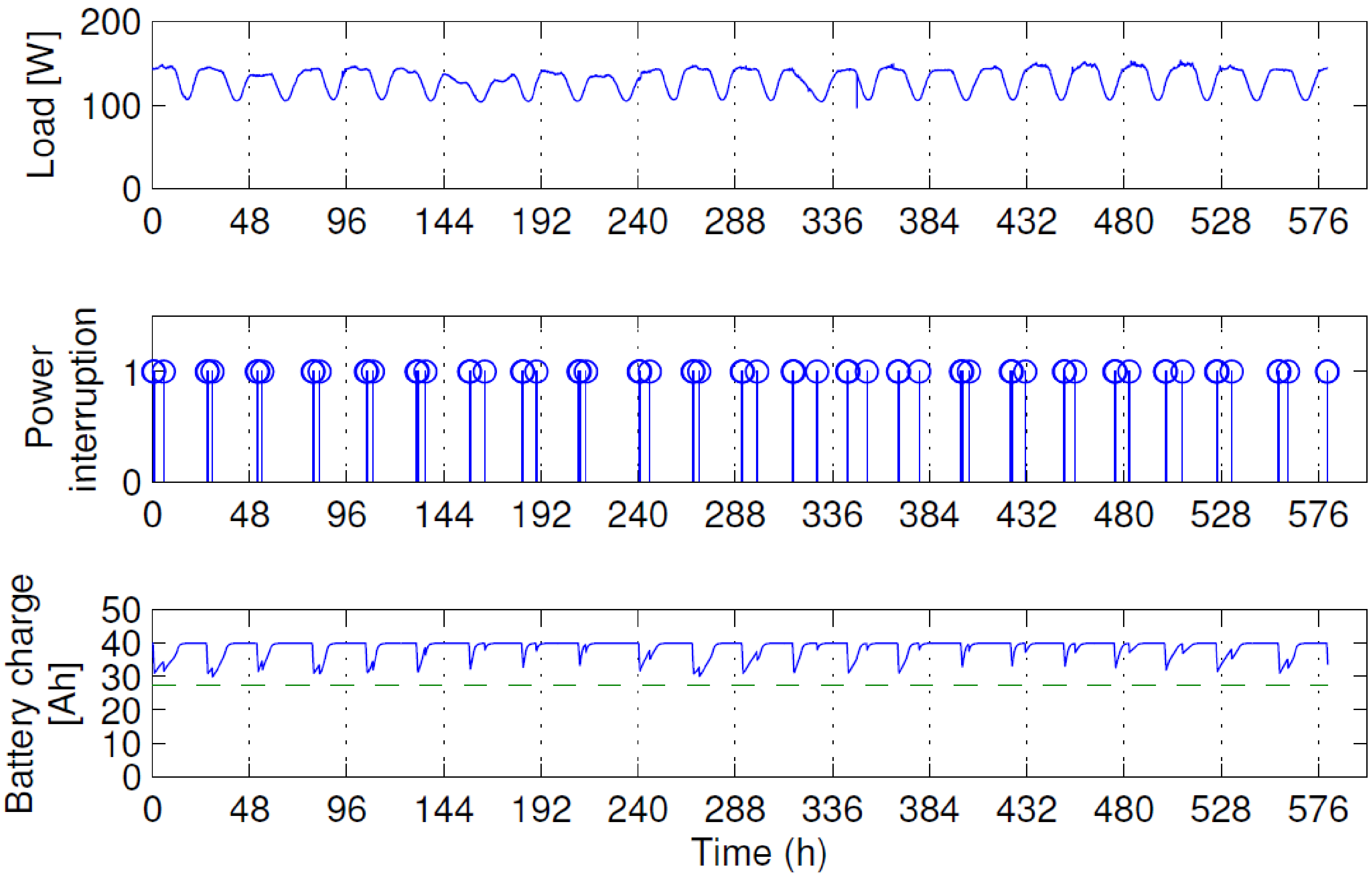
- Interruption time = t_0
- Maximum power = z_{max}
- Required battery charge = B^*





1h/24h
Service
interruption

A run of the system using the greedy policy



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Conclusion

Another application of Network Calculus: Smart Grids

- Theoretical results for perfect battery

Practical battery sizing problem

- Easy to compute

Ongoing work

- Realistic battery model (losses, aging, …)