Re-Inventing American Infrastructure

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Distributed Control Design for Balancing the Grid Using Flexible Loads

NREL Autonomous Energy Grids Workshop

Sean Meyn

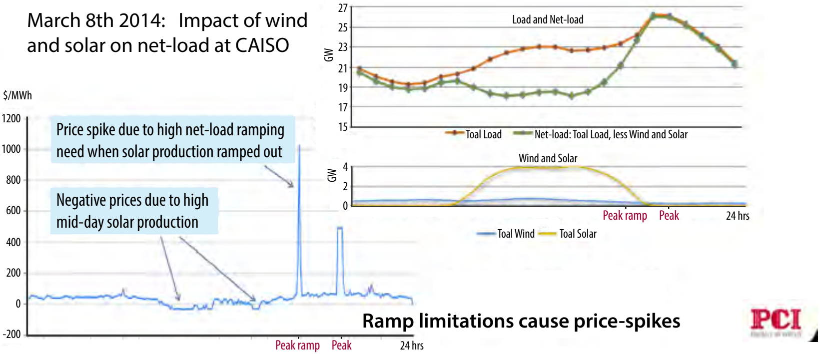
COGNITION & CONTROL
IN COMPLEX SYSTEMS

Department of Electrical and Computer Engineering — University of Florida

Based on joint research with **Dr.** Y. Chen, J. Mathias, P. Barooah, UF & A. Bušić, Inria

Thanks to to our sponsors: Google, NSF, DOE, ARPA-E

1. Challenges
2. Virtual Energy Storage
3. Demand Dispatch
4. Questions and Conclusions
5. References


March 8th 2014: Impact of wind and solar on net-load at CAISO
$/MWh
1200
1000
800
600
400
200
0
-200
Price spike due to high net-load ramping need when solar production ramped out
Negative prices due to high mid-day solar production
Peak ramp
Peak
24 hrs
Load and Net-load
GW
27
25
23
21
19
17
15
Toal Load
Net-load: Toal Load, less Wind and Solar
Wind and Solar
GW
4
2
0
Peak ramp
Peak
24 hrs
Toal Wind
Toal Solar
Ramp limitations cause price-spikes

Challenges

Some of the Challenges

1. Large sunk cost

Some of the Challenges

1. Large sunk cost
2. Engineering uncertainty

Some of the Challenges

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3. Policy uncertainty

Some of the Challenges

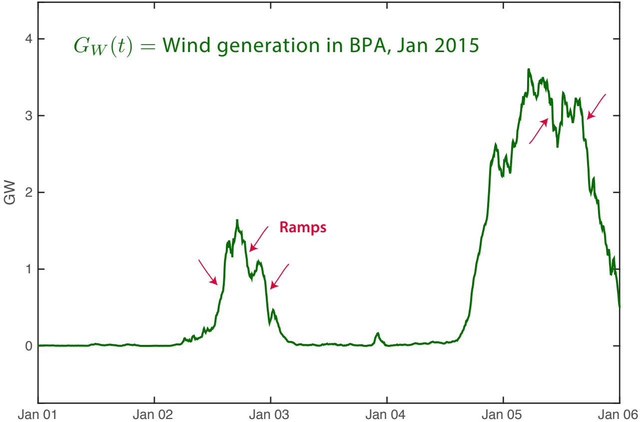
1. Large sunk cost
2. Engineering uncertainty
3. Policy uncertainty
4. Volatility

Start at the bottom...

Some of the Challenges

What's so scary about volatility?

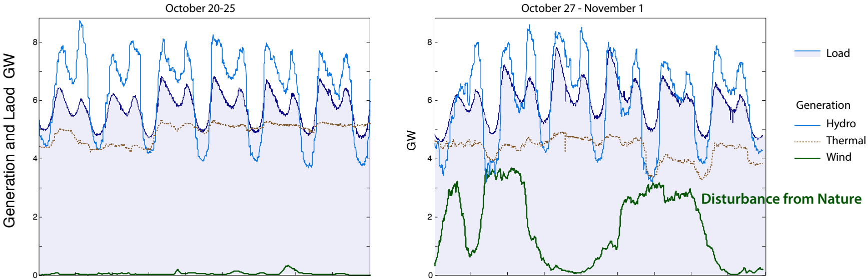
4. Volatility



Some of the Challenges

What's so scary about volatility?

4. Volatility $\Longrightarrow$ greater regulation needs



Some of the Challenges

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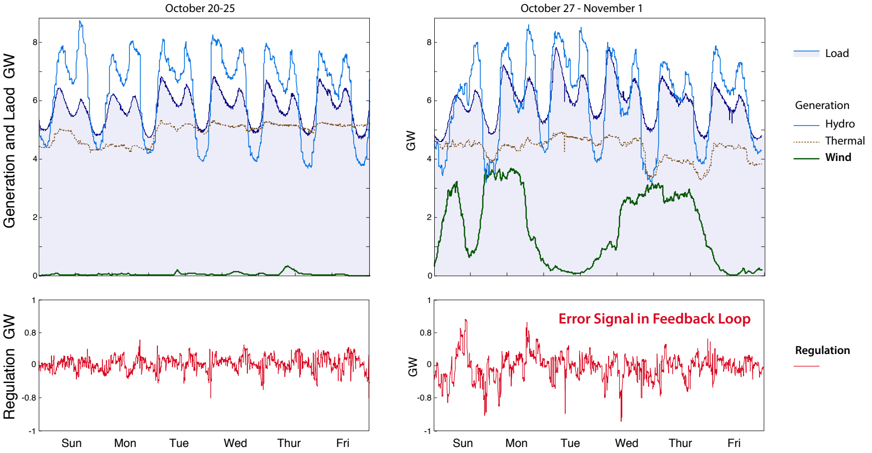
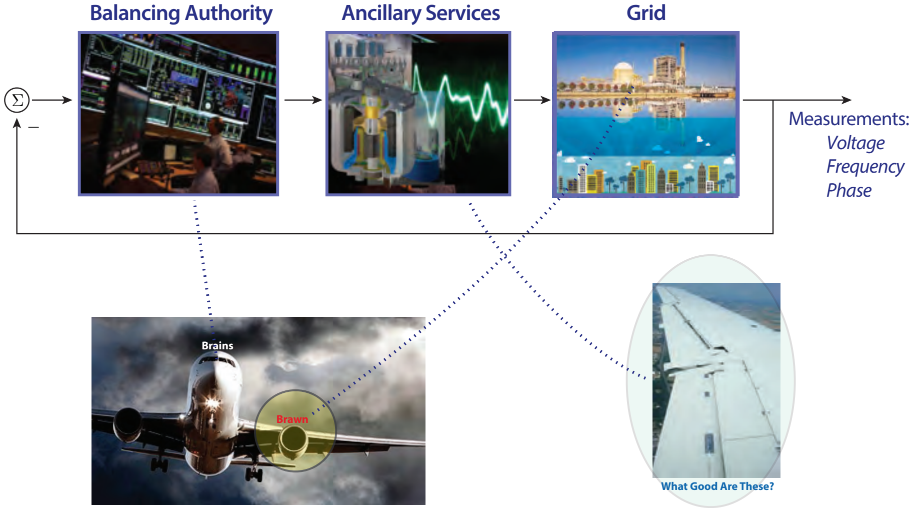


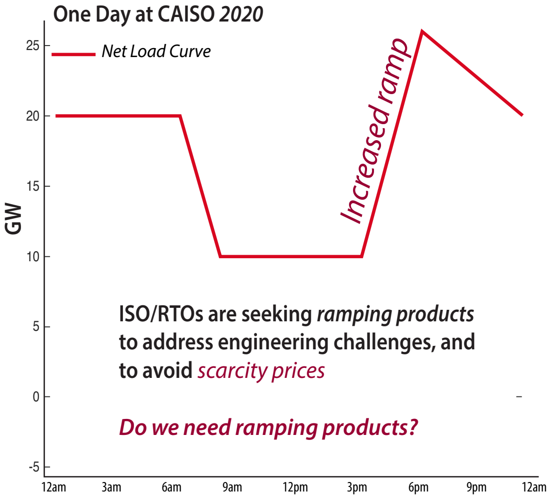
Comparison: Flight control

How do we operate the grid in a storm?



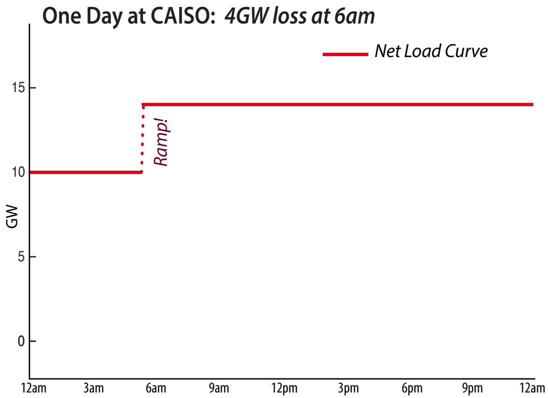
Frequency Decomposition

Taming the Duck



Frequency Decomposition

Smoothing Contingencies



Demand Response the Answer?

CPUC Decision 14-03-026 March 27, 2014

BEFORE THE PUBLIC UTILITIES COMMISSION OF THE STATE OF CALIFORNIA

... to Enhance the Role of Demand Response in Meeting the State's Resource Planning Needs and Operational Requirements.

Bidding demand response into the CAISO energy markets has been an objective of the Commission since the initiation of R.07-01-041 in 2007.[81] The Commission has moved forward with directing the utilities to revise their tariffs to allow retail customers to bid demand response into the CAISO energy markets[82] and authorized the utilities to bid demand response into the market.[83] To our dismay, very little demand response capacity has been integrated into the CAISO's markets to date.[84] But how much demand response should be bid into the CAISO market? What are our goals for either side of bifurcation and, how do we get there from here?

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Need to rethink role of demand-side resources

Demand Response the Answer?

Audrey Zibelman's bold plan to transform New York's electricity market

Utility DIVE TOPICS FEATURES

What's most critical to Zibelman is the creation of liquidity and transparency in the marketplace, as well as erasing barriers to entry. "Regardless of whether it's one distributed platform provider or multiple utilities," she said, "I want—from the customer-facing and market-facing approach—for everything to be very consistent."

Unpacking the value of demand

One of the most radical ideas in the REV is that New York is having demand—as opposed to generation—be the state's primary energy resource.

"Rather than demand being the last resource you manage in the system, it's the first resource," Zibelman said. "Demand can respond much more quickly than any other resource."

Like many other regions in the country, New York has slowing overall demand for electricity, but a growing gap between peaks and non-peaks, which diminishes the overall efficiency of the electricity system.

Need to rethink role of demand-side resources

Virtual Energy Storage

Capacity of Virtual Energy Storage

Buildings as Batteries

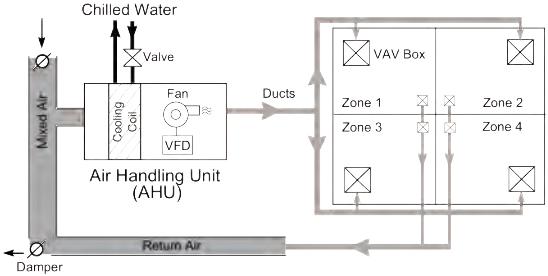
HVAC flexibility to provide additional ancillary service

- Buildings consume 70% of electricity in the US
- Buildings have large thermal capacity

Buildings as Batteries

HVAC flexibility to provide additional ancillary service

- Buildings consume 70% of electricity in the US
- Buildings have large thermal capacity
- Modern buildings have fast-responding equipment:
  VFDs (variable frequency drive)



Buildings as Batteries

Tracking RegD at Pugh Hall

In one sentence: *Ramp up and down power consumption, just 10%, to track regulation signal.*

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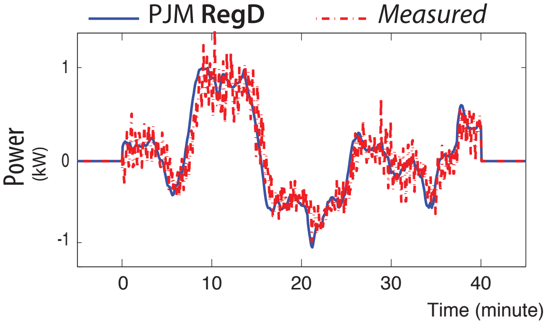
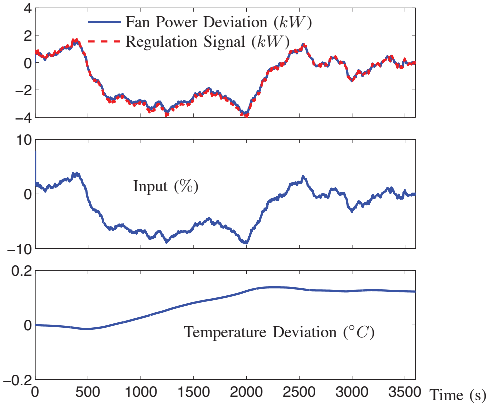


ignore the measurement noise

How demand response from commercial buildings will provide the regulation ..., Allerton, 2012

Pugh Hall @ UF

How much?

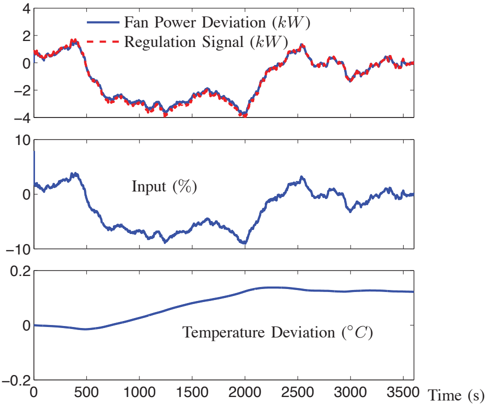


- One AHU fan with 25 kW motor:
  > 3 kW of regulation reserve
- Pugh Hall (40k sq ft, 3 AHUs):
  > 10 kW

Indoor air quality is not affected

Pugh Hall @ UF

How much?



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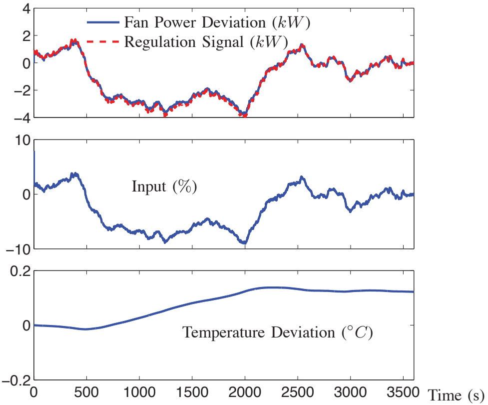

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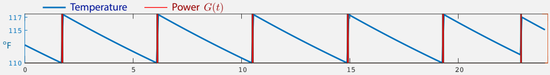
just using 10% of the fans

Capacity

100,000 residential water heaters



Residential Water Heater: *Consumer Wants Hot Water*

Question: What is the capacity in terms of

- Virtual energy storage (MWh)
- Virtual power (MW)

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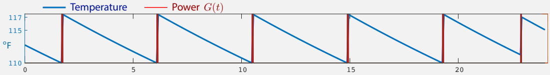

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Average power consumption: $P_{\mathsf{avg}} = 8$ MW (*without usage*)
Peak power: $P_{\mathsf{peak}} = 200$ MW

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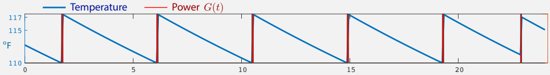

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Answer: $P_{+} = P_{\text{avg}}$ and $P_{-} = P_{\text{peak}} - P_{\text{avg}}$

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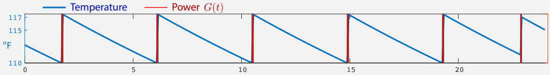

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Suppose system is *fully charged* at time $t = 0$.

$T =$ time to *discharge: All units off for* $0 \leq t \leq T$

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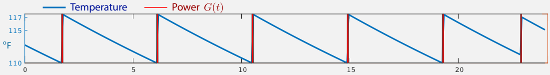

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Answer: $E = T \times P_{\text{avg}}$

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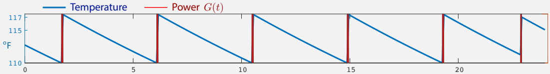

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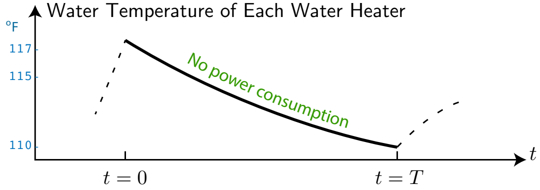

∼ agrees with H. Hao et. al., Aggregate flexibility of thermostatically controlled loads, 2015

Capacity

100,000 residential water heaters

Capacity

$$P_+ = P_{\text{avg}}$$

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For a *single high-end unit*:
$E_1 = 6 \text{ hrs} \times 100 \text{ Watts}$

$\approx$ 10 MW, 60 MWh
battery system

Capacity

100,000 residential water heaters

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How do we compare?

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How do we compare?

$\approx$ 30 MW, 120 MWh battery system

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100,000 residential water heaters

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$\approx$ 10 MW, 60 MWh battery system

$\approx$ 30 MW, 120 MWh battery system

The Escondido system consists of 24 containers hiding nearly 20,000 modules that hold 20 batteries each ... 10% round-trip energy loss, cooling required, ... $P_+ \neq P_- \neq 30$ MW ...

Capacity

100,000 residential water heaters

Capacity

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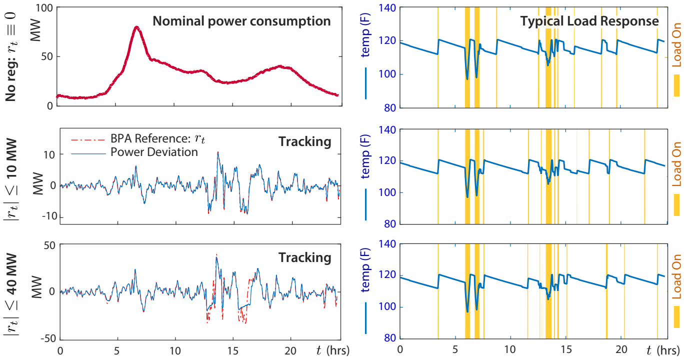
The population of California is 40 million,
and the electricity doesn't just go into the hot tubs

Tracking with 100,000 Water Heaters

Power Limits – Regulation



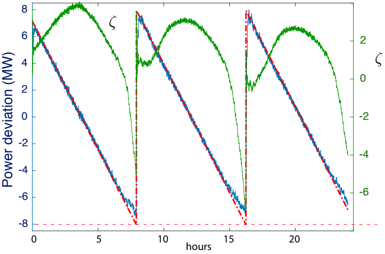
Tracking results with 100,000 water heaters, and the behavior of a single water heater in three cases, distinguished by the reference signal [1].

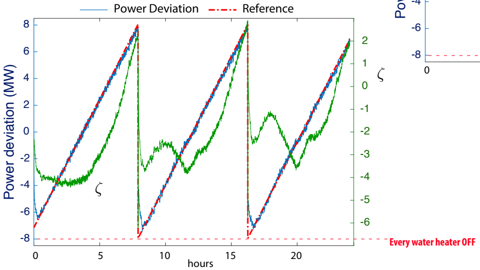
Tracking with 100,000 Water Heaters

Energy Limits – Ramps and Contingencies

Tracking a sawtooth wave with 100,000 water heaters:

Average power consumption = 8MW





Quality of Service = temperature limits

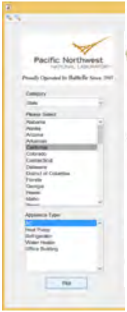
By design, QoS violation is not possible

Distributed Control Design for Balancing the Grid Using Flexible Loads, Springer 2018

DER Flexibility Assessment & Valuation

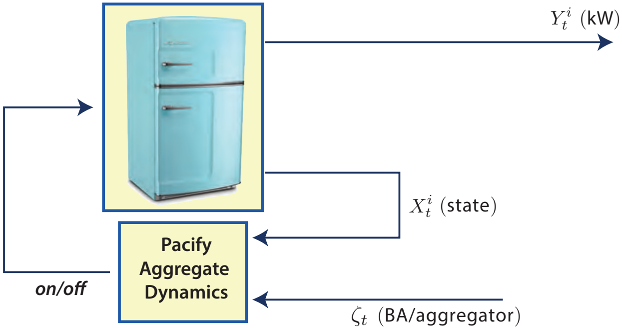
Ongoing GMLC project – PNNL/ORNL/UF

Virtual Battery-Based Characterization and Control of Flexible Building Loads Using VOLTTRON



	Energy Arbitrage $/year	Regulation Up $/year	Regulation Down $/year	Spinning Reserve $/year	Total $/year
Siskiyou	10,983	150,501	25,651	2,559	189,696
San Diego	1,534	11,764	42,447	0	55,746

Value in Siskiyou vs San Diego



Demand Dispatch Design

Balancing the Grid

Demand Dispatch the Answer?

Players:
Grid operator = Balancing Authority, or BA
Consumers (residential in this lecture)

A partial list of the needs of the grid operator, and each consumer:

Balancing the Grid

Demand Dispatch the Answer?

A partial list of the needs of the grid operator, and each consumer:

- High quality AS? (Ancillary Service)

Balancing the Grid

Demand Dispatch the Answer?

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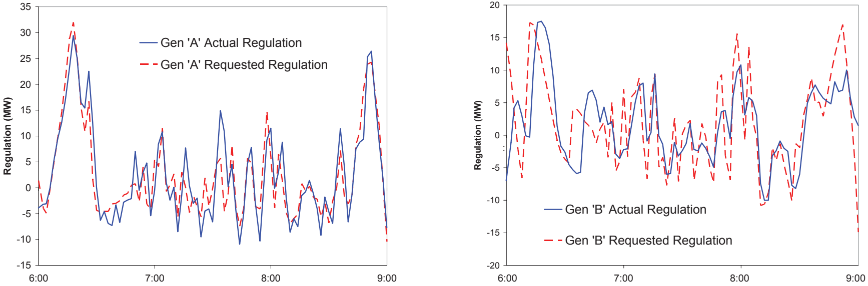
Fig. 10. Coal-fired generators do not follow regulation signals precisely....
Some do better than others



Regulation service from generators is not perfect

Frequency Regulation Basics and Trends — Brendan J. Kirby, December 2004

Balancing the Grid

Demand Dispatch the Answer?

A partial list of the needs of the grid operator, and each consumer:

- High quality AS?
- Reliable?
  Will AS be available each day?
  It may vary with time, but capacity must be predictable.

Balancing the Grid

Demand Dispatch the Answer?

A partial list of the needs of the grid operator, and each consumer:

- High quality AS?
- Reliable?
- Cost effective?

Balancing the Grid

Demand Dispatch the Answer?

A partial list of the needs of the grid operator, and each consumer:

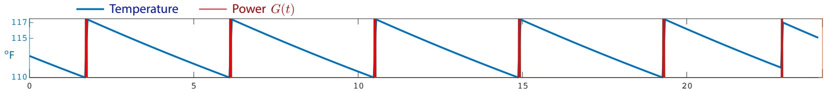
- High quality AS?
- Reliable?
- Cost effective?
- Is the incentive to the consumer reliable?

Balancing the Grid

Demand Dispatch the Answer?

A partial list of the needs of the grid operator, and each consumer:

- High quality AS?
- Reliable?
- Cost effective?
- Is the incentive to the consumer reliable?
- Customer QoS constraints satisfied?
  Fresh fish, comfy house, clean pool, hot water, cool data centers, happy farmers, ...



Residential Water Heater: *Consumer Wants Hot Water* $\mathcal{U}(G(t))$??

Balancing the Grid

Demand Dispatch the Answer?

A partial list of the needs of the grid operator, and each consumer:

- High quality AS?
- Reliable?
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- Is the incentive to the consumer reliable?
- Customer QoS constraints satisfied?

Demand dispatch can do all of this (by design)

Demand Dispatch the Answer?

Related Prior Research

- Schweppe's FAPER Concept

Frequency adaptive, power-energy re-scheduler

US 4317049 A

ABSTRACT

A frequency adaptive, power-energy re-scheduler (FAPER) that includes a frequency transducer that notes frequency or frequency deviations of an electrical system and logic means which controls and re-schedules power flow to a load unit in part on the basis of the deviations in frequency from a nominal frequency and in part on the needs to the load unit as expressed by an external sensor signal obtained from the physical system affected by the load unit.

Publication number	US4317049 A
Publication type	Grant
Application number	US 06/076,019
Publication date	Feb 23, 1982
Filing date	Sep 17, 1979
Priority date	Sep 17, 1979
Inventors	Fred C. Schweppe
Original Assignee	Massachusetts Institute Of Technology
Export Citation	BiBTeX, EndNote, RefMan

Patent Citations (4), Referenced by (69), Classifications (10)

External Links: USPTO, USPTO Assignment, Espacenet

Demand Dispatch the Answer?

Related Prior Research

- Schweppe's FAPER Concept
- Mathematical foundations: Malhamé et. al. in 80s [Mean-Field Model]

Demand Dispatch the Answer?

Related Prior Research

- Schweppe's FAPER Concept
- Mathematical foundations: Malhamé et. al. in 80s [Mean-Field Model]
- Randomized control:
  Callaway, Hiskens, Mathieu, Kizilkale, Malhamé, Strbac, Almassalkhi, Hines
  Often system inversion to obtain linear MFM

Demand Dispatch the Answer?

Related Prior Research

- *Industry now recognizes the value of randomization for distributed control*

Demand Dispatch the Answer?

Related Prior Research

- *Industry now recognizes the value of randomization for distributed control*

Electrical load disconnect device with electronic control

US 8328110 B2

ABSTRACT

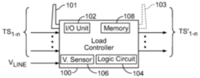
Electrical load spreading arrangements reduce peak power demand. An enclosure houses an electronic circuit board, which receives at a first input terminal a first thermostat control signal from a thermostat intended to control a first air conditioning unit and at a second input terminal a second thermostat control signal from a thermostat intended to control a second AC unit. A controller on the circuit board is programmed with instructions stored in a memory coupled to the controller causing the controller to monitor the first and second input terminals to determine the timing and duration of the thermostat control signals passed to the output terminals for activating or deactivating the AC units such that overlapping operation of the AC units is reduced particularly during peak demand periods. A similar arrangement may be applied to a broader class of HVAC equipment, including water heaters, for example.

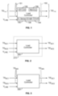
Publication number	US8328110 B2
Publication type	Grant
Application number	US 12/499,347
Publication date	11 Dec 2012
Filing date	8 Jul 2009
Priority date	8 Jul 2009
Fee status	Paid
Also published as	US20110006123
Inventors	Jeffrey O. Sharp
Original Assignee	Schneider Electric USA, Inc.
Export Citation	BiBTeX, EndNote, RefMan

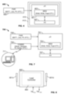
Patent Citations (5), Classifications (8), Legal Events (3)

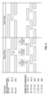
External Links: USPTO, USPTO Assignment, Espacenet

IMAGES (5)









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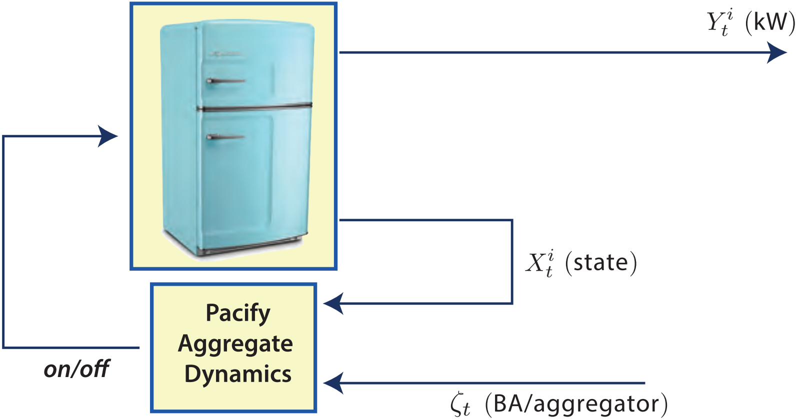
Control Architecture

Intelligence at the Load *distinguishes our work from others*

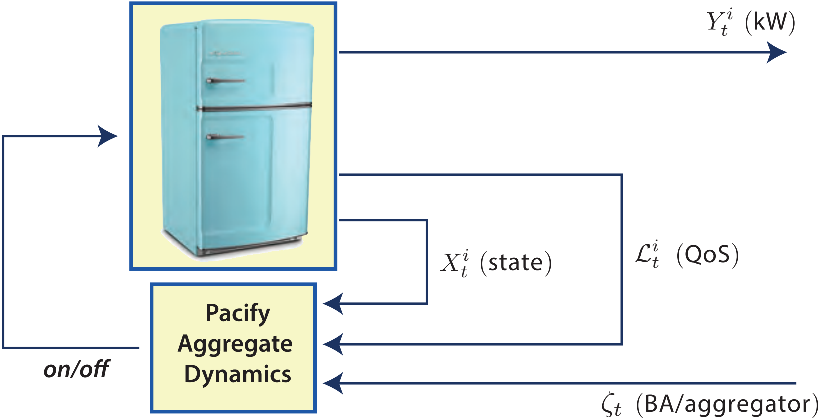
Step 1: Load-level Feedback Loops



Control Architecture

Intelligence at the Load *distinguishes our work from others*

Step 1: Load-level Feedback Loops



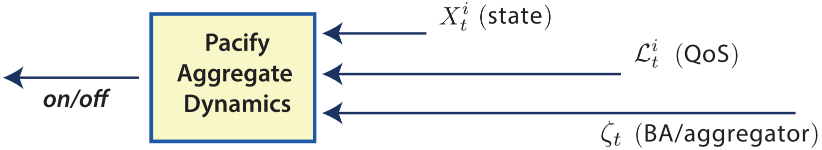
Control Architecture

Intelligence at the Load *distinguishes our work from others*

Step 1: Load-level Feedback Loops

Basic Ingredients:

1. Randomized decision rule design.
   Maps (X, ζ) to a probability of on/off
2. Secondary control monitors QoS,
   on slower time-scale



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Step 1: Load-level Feedback Loops

Basic Ingredients:

1. Randomized decision rule design.
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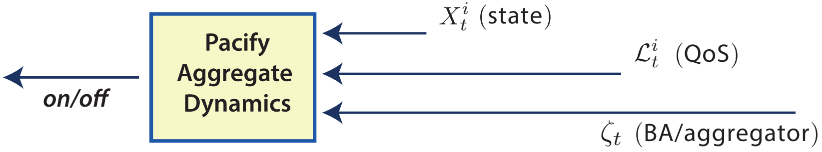
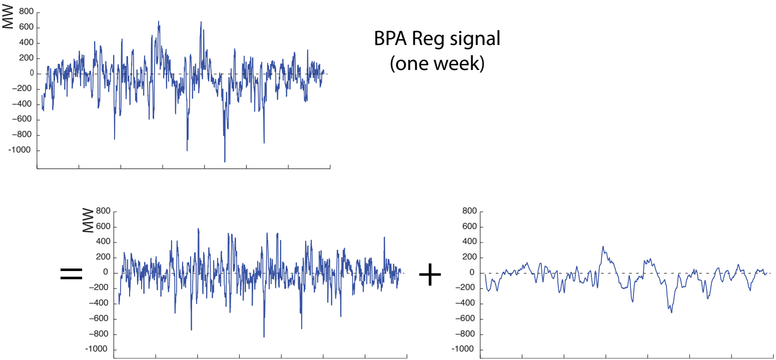
3. Newest innovation: additional filtering of ζ
   to invert mean-field dynamics
   in a specific frequency range



Control Architecture

Intelligence at the Load

Step 2: Condition Grid Reference Signal



Control Architecture

Intelligence at the Load

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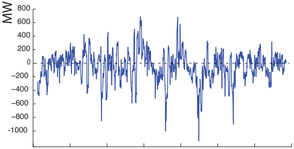
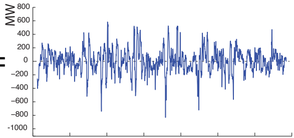
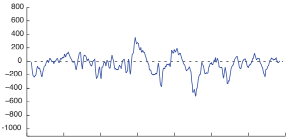


BPA Reg signal
(one week)

=



+



$= \text{HVAC} + \text{Pool Pumps}$

Control Architecture

Assume BA has measurements of aggregate power consumption

Step 3: Actuator Feedback Loop

Easily controllable by design

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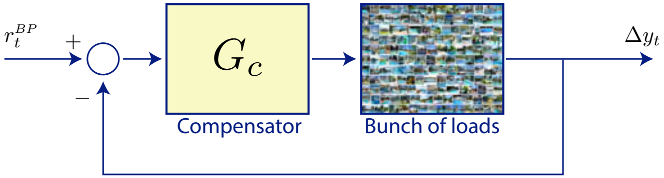

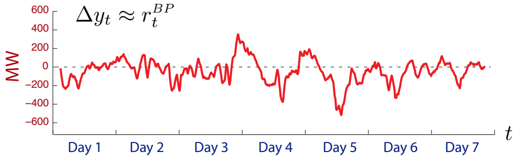

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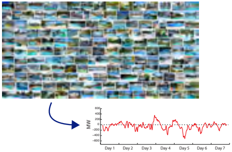
General Principles for Design



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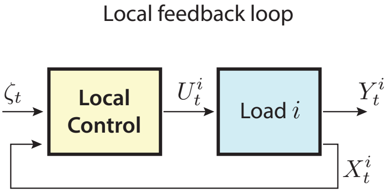
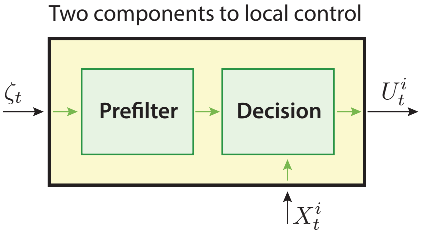
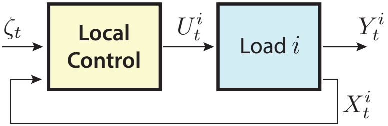




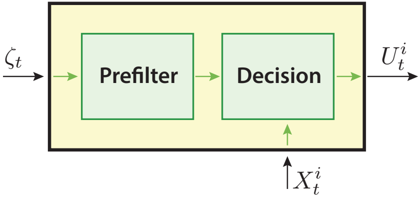
- Each load monitors its state and a regulation signal from the grid.

General Principles for Design

Local feedback loop



Two components to local control



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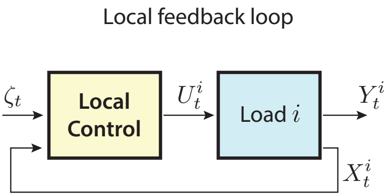
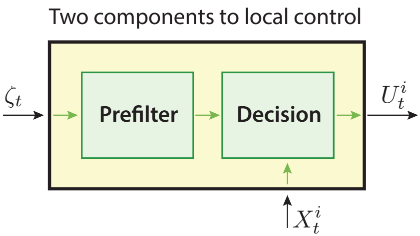




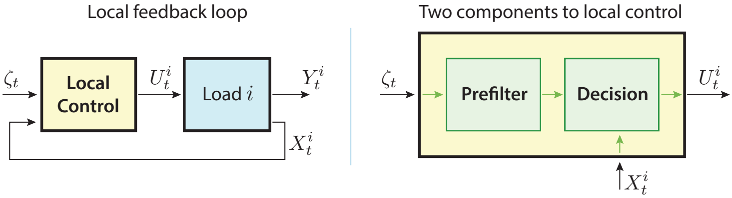
- Each load monitors its state and a regulation signal from the grid.
- Prefilter and decision rules designed to respect needs of load and grid
- Randomized policies required for finite-state loads

MDP model

MDP model

The state for a load is modeled as a controlled Markov chain.
Controlled transition matrix:

$$P_\zeta(x, x') = \mathsf{P}\{X_{t+1} = x' \mid X_t = x,\ \zeta_t = \zeta\}$$



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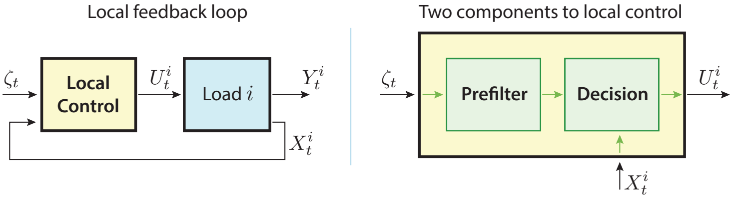

Questions:

- How to design P_ζ?
- How to analyze aggregate of similar loads?

How to analyze aggregate?

Mean field model, *R. Malhame et. al. 1984 –*

State process:

$$\mu_t(x) \approx \frac{1}{N} \sum_{i=1}^{N} \mathbb{I}\{X_t^i = x\}, \quad x \in \mathsf{X}$$

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Nonlinear state space model *Linearization useful for control design*

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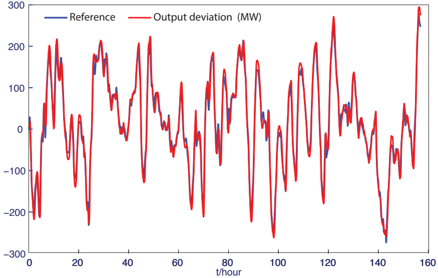

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Linearization useful for control design

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- Myopic Design: $P_\zeta(x,x') = \exp(\zeta\mathcal{U}(x') - \Lambda_\zeta(x))P_0(x,x')$.

  Encourages movement to x' if
  - $\zeta > 0$
  - Power consumption $\mathcal{U}(x') > 0$.

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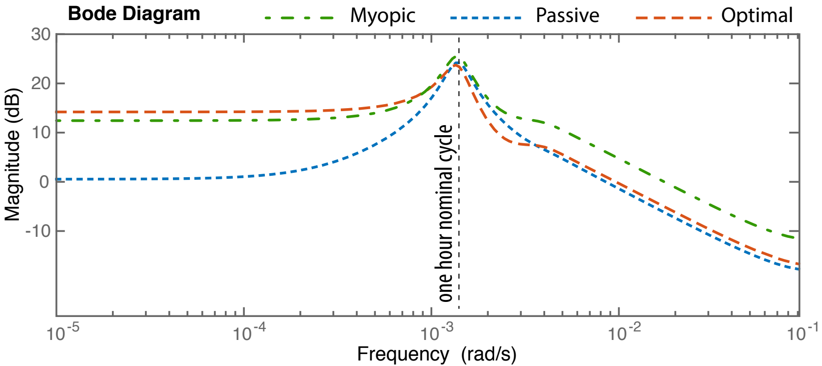
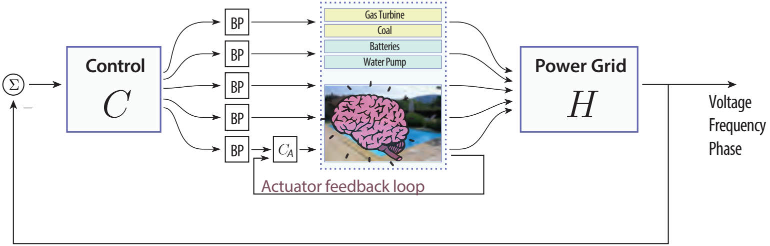
  We have shown that the linearized MFM is passive if P_0 is reversible.
- An alternative to the optimization approach: *Passivity by design*

Nonlinear state space model: $\mu_{t+1} = \mu_t P_{\zeta_t},\ y_t = \langle \mu_t, \mathcal{U} \rangle$

Linearization useful for control design



Three designs for a refrigerator: transfer function $\zeta_t \to y_t$



Questions and Conclusions

Question of Time Scales

Question: Can a smart fridge provide synthetic droop?

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- There is hope: *They did a good job in the past!*
- Other local services may also be feasible and valuable

Electrical load disconnect device with electronic control

US 8328110 B2

ABSTRACT

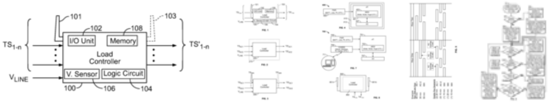
Electrical load spreading arrangements reduce peak power demand. An enclosure houses an electronic circuit board, which receives at a first input terminal a first thermostat control signal from a thermostat intended to control a first air conditioning unit and at a second input terminal a second thermostat control signal from a thermostat intended to control a second AC unit. A controller on the circuit board is programmed with instructions stored in a memory coupled to the controller causing the controller to monitor the first and second input terminals to determine the timing and duration of the thermostat control signals passed to the output terminals for activating or deactivating the AC units such that overlapping operation of the AC units is reduced particularly during peak demand periods. A similar arrangement may be applied to a broader class of HVAC equipment, including water heaters, for example.

Publication number	US8328110 B2
Publication type	Grant
Application number	US 12/499,347
Publication date	11 Dec 2012
Filing date	8 Jul 2009
Priority date	8 Jul 2009
Fee status	Paid
Also published as	US20110006123
Inventors	Jeffrey O. Sharp
Original Assignee	Schneider Electric USA, Inc.
Export Citation	BiBTeX, EndNote, RefMan

Patent Citations (5), Classifications (8), Legal Events (3)

External Links: USPTO, USPTO Assignment, Espacenet

IMAGES (5)



Question: What is the State of Charge

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- Estimating the *baseline* is a philosophical question

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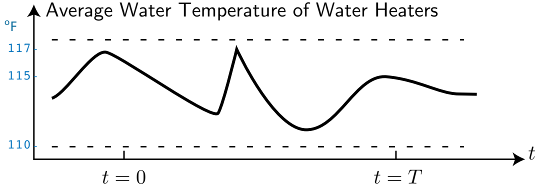

Function of average water temperature

Question: Impact on Consumers

The Mean Field Model is based on the Law of Large Numbers

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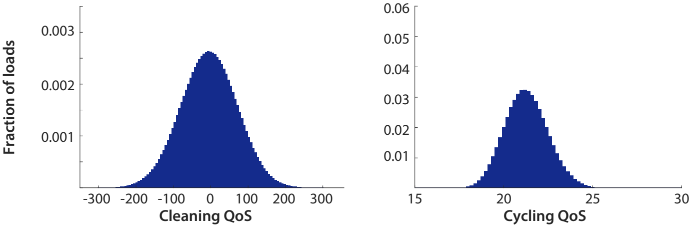
There is an associated Central Limit Theory



QoS over one week for a population of swimming pools

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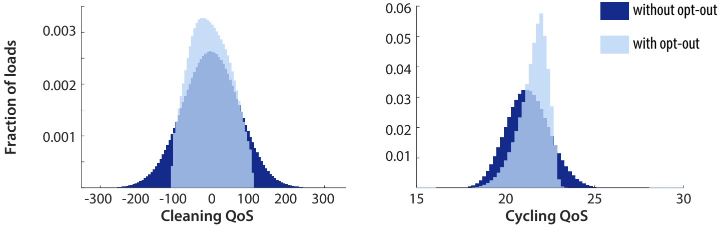

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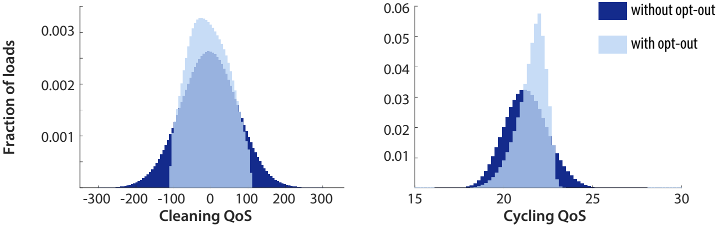


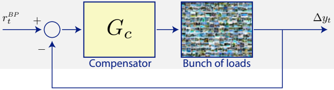
QoS over one week for a population of swimming pools

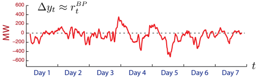
More generally:

- What is the cost to consumers? Any additional cycling or energy cost?
- A better science for enforcing QoS/cost constraints

Question: Value of Performance

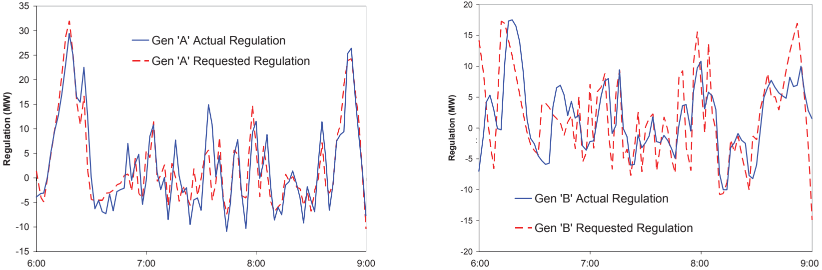
Do we need such accurate tracking?





If I had one million pools,
my problems would be solved! -TB, 2015

Fig. 10. Coal-fired generators do not follow regulation signals precisely....
Some do better than others



Regulation service from generators is not perfect

Frequency Regulation Basics and Trends — Brendan J. Kirby, December 2004

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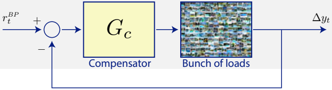

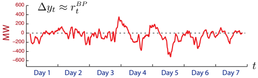

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The grid today is reliable*, despite the poor services offered by generators

Questions remain:

- What is the cost of poor tracking?
- How do we deal with dynamics/uncertainty in capacity of virtual storage from loads?

*despite hurricanes

Question: Control Architecture

Smart Fridge / Dumb Grid?

Local intelligence at each load $\Longrightarrow$ *ensemble looks like a giant battery.*

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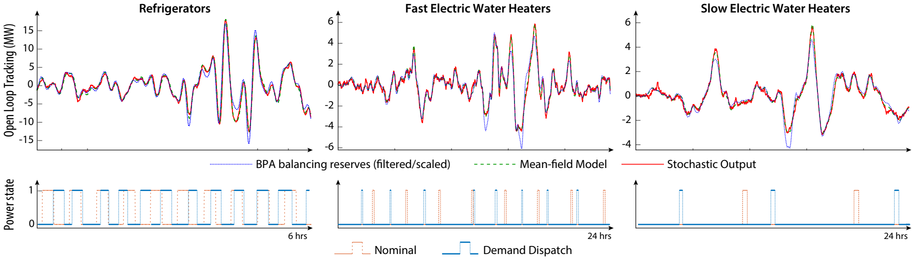
Open-loop tracking with 40,000 heterogeneous TCLs:



Demand dispatch with heterogeneous intelligent loads, HICSS 2017

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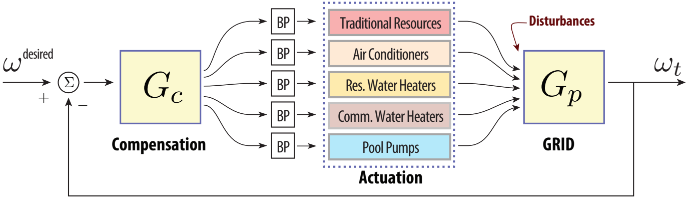
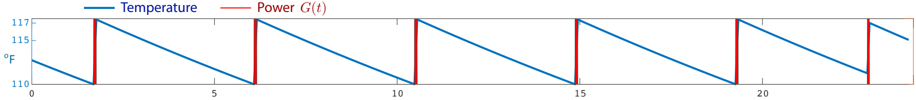
- Does one-way communication suffice?



Questions: Markets

Rationality $\Longrightarrow$ risk-aware

Since Schweppe, there has been a passion for competitive equilibrium analysis, with power treated as the commodity of interest.



Residential Water Heater: *Consumer Wants Hot Water* $\mathcal{U}(G(t))$ *??*

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A rational agent last week in San Francisco wants a **shower** ...

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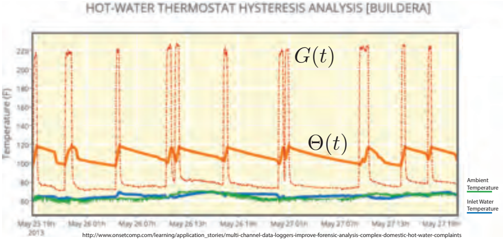

Typical water heater trajectories

$\Theta(t)$: Temperature

$G(t)$: Power consumption

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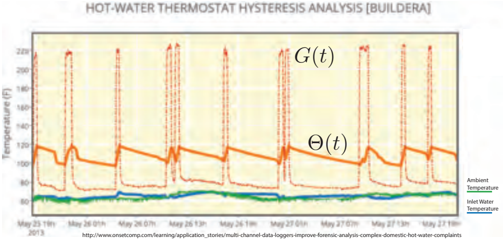

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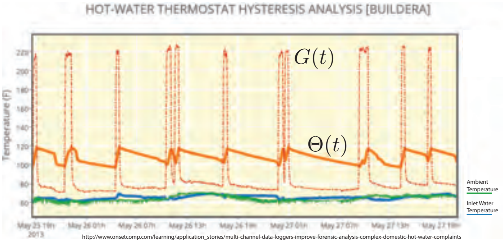

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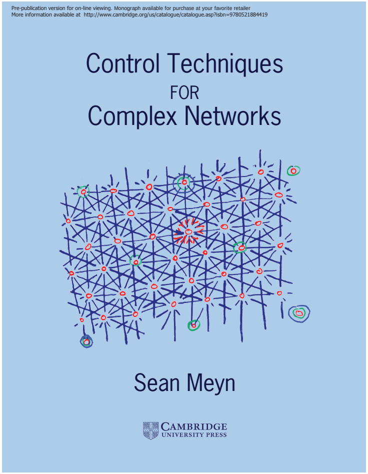
  - Requires cost/value calculations for virtual energy storage

Thank You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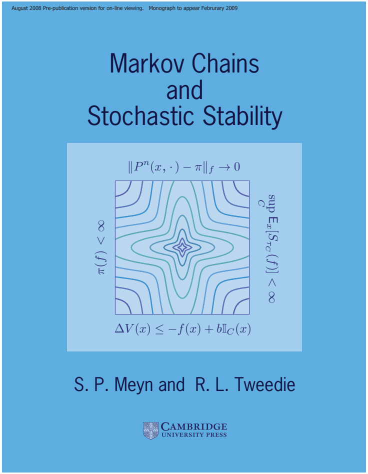
August 2008 Pre-publication version for on-line viewing. Monograph to appear Februrary 2009
Markov Chains
and
Stochastic Stability
$\|P^n(x,\cdot)-\pi\|_f \to 0$
$\pi(f) < \infty$
$\sup_C \mathsf{E}_x[S_{\tau_C}(f)] < \infty$
$\Delta V(x) \le -f(x) + b\mathbb{I}_C(x)$
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