From the Sunshine State to the Solar State

FESC Workshop: Integration of Renewable Energy into the Grid

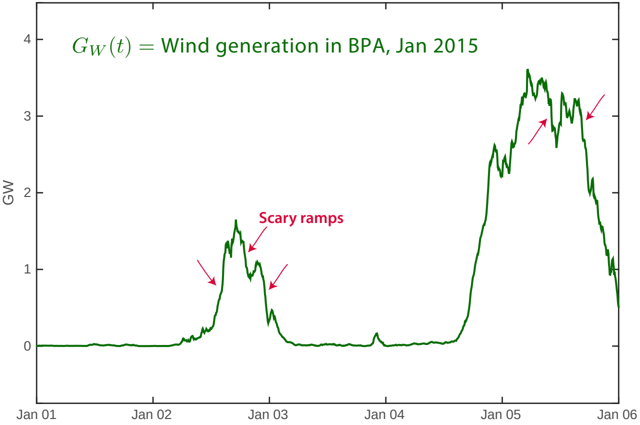
Orlando — Feb. 2-3, 2015

Sean P. Meyn
Florida Institute for Sustainable Energy

COGNITION & CONTROL IN COMPLEX SYSTEMS

Department of Electrical and Computer Engineering
Electrical and Computer Engineering
University of Florida

Thanks to my colleagues, Prabir Barooah and Ana Bušić
and to our sponsors NSF, AFOSR, DOE / TCIPG



$G_W(t)$ = Wind generation in BPA, Jan 2015
Scary ramps
GW
4
3
2
1
0
Jan 01
Jan 02
Jan 03
Jan 04
Jan 05
Jan 06

Challenges

Some of the Challenges

1. Large sunk cost (decreasing!)

Some of the Challenges

1. Large sunk cost (decreasing!)
2. Engineering uncertainty

Some of the Challenges

1. Large sunk cost (decreasing!)
2. Engineering uncertainty
3. Policy uncertainty

Some of the Challenges

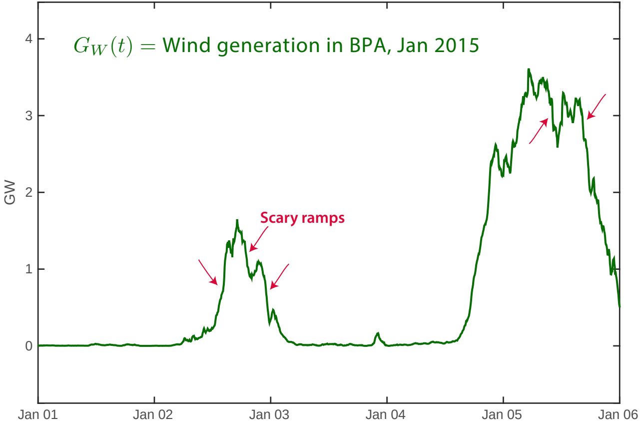
1. Large sunk cost (decreasing!)
2. Engineering uncertainty
3. Policy uncertainty
4. Volatility

Start at the bottom...

Some of the Challenges

What's so scary about volatility?

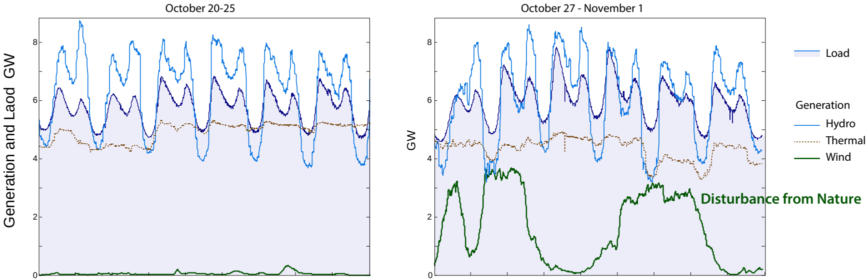
4. Volatility



Some of the Challenges

What's so scary about volatility?

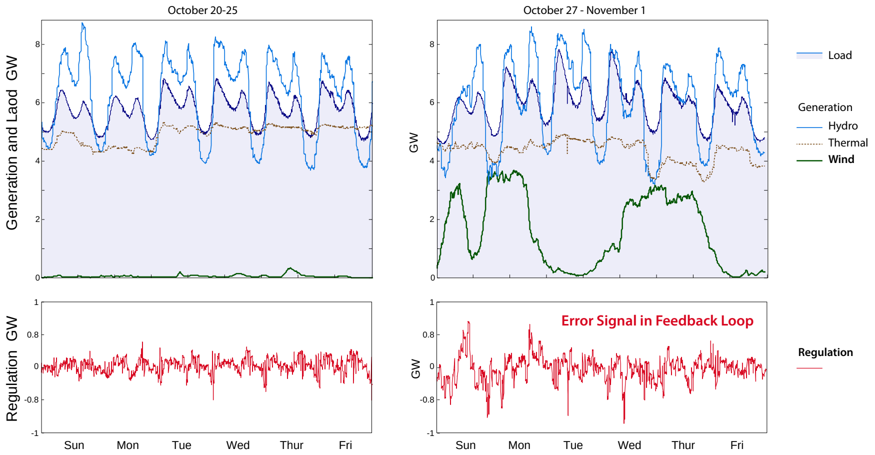
4. Volatility $\Longrightarrow$ greater regulation needs



Some of the Challenges

What's so scary about volatility?

4. Volatility $\Longrightarrow$ greater regulation needs



Comparison: Flight control

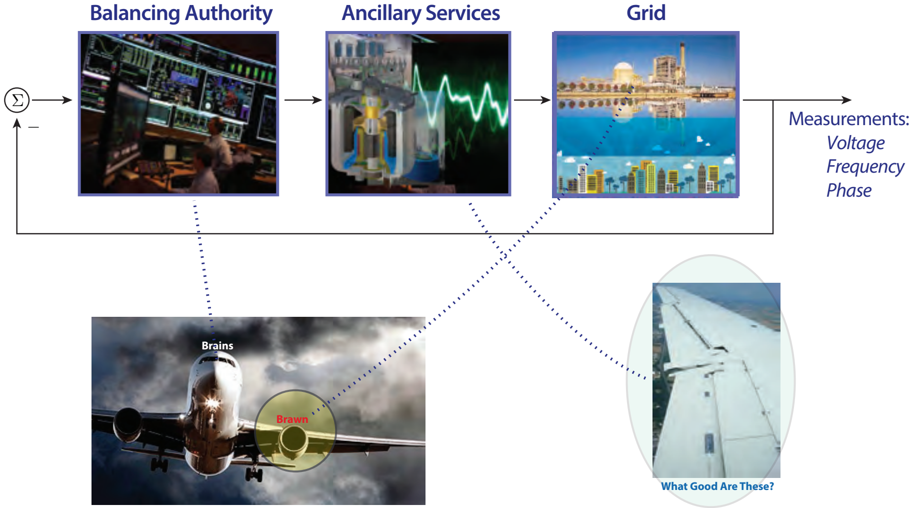
How do we fly a plane through a storm?

Comparison: Flight control

How do we fly a plane through a storm?

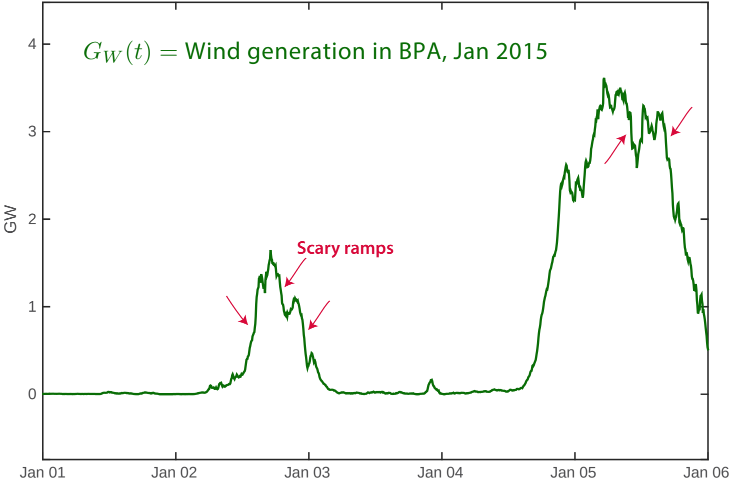
Comparison: Flight control

How do we operate the grid in a storm?



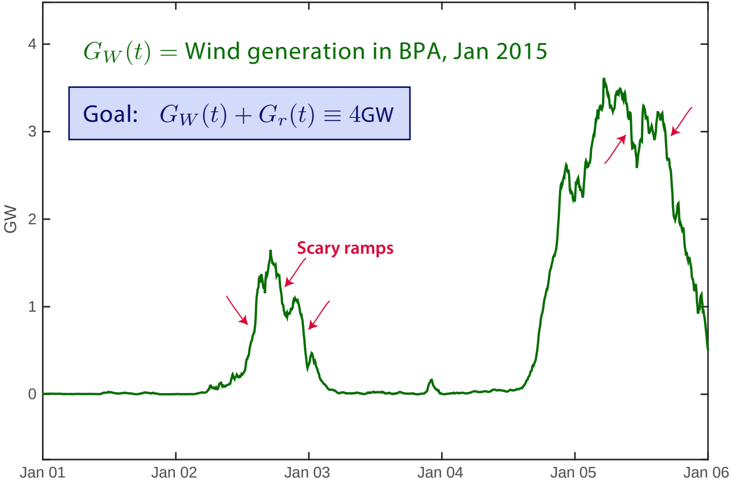
How do we operate the grid in a storm?

Disturbance decomposition



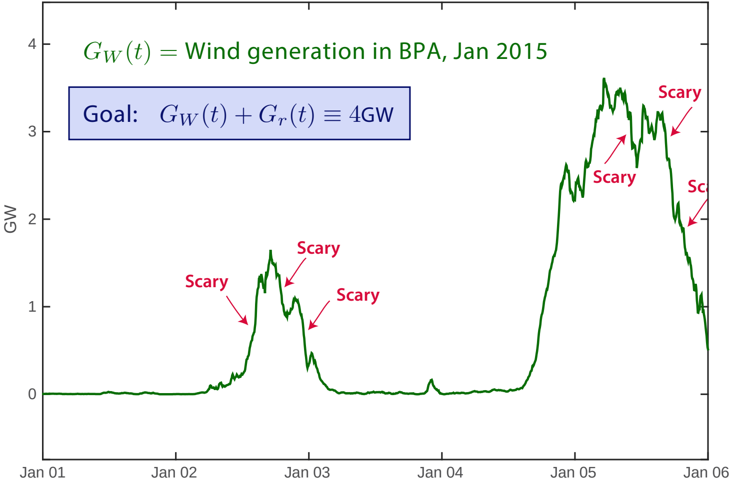
How do we operate the grid in a storm?

Disturbance decomposition



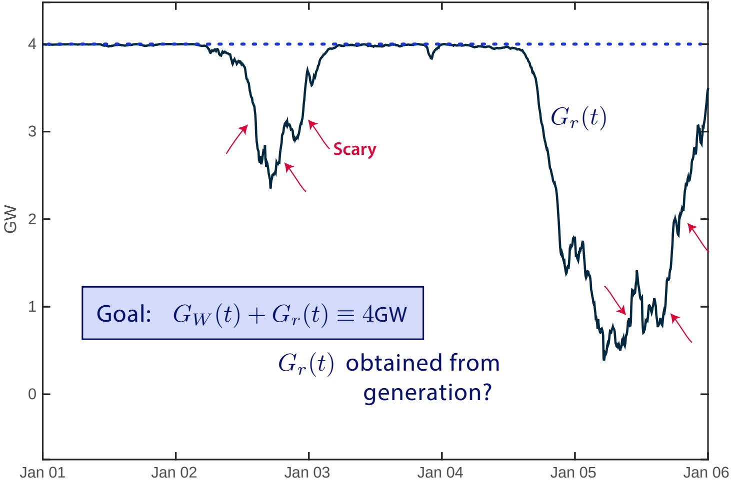
How do we operate the grid in a storm?

Disturbance decomposition



How do we operate the grid in a storm?

Disturbance decomposition

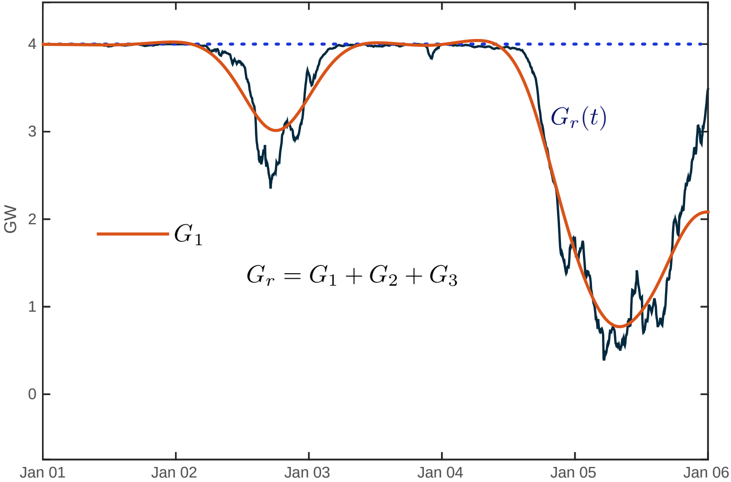


Goal: $G_W(t) + G_r(t) \equiv 4$GW

$G_r(t)$ obtained from generation?

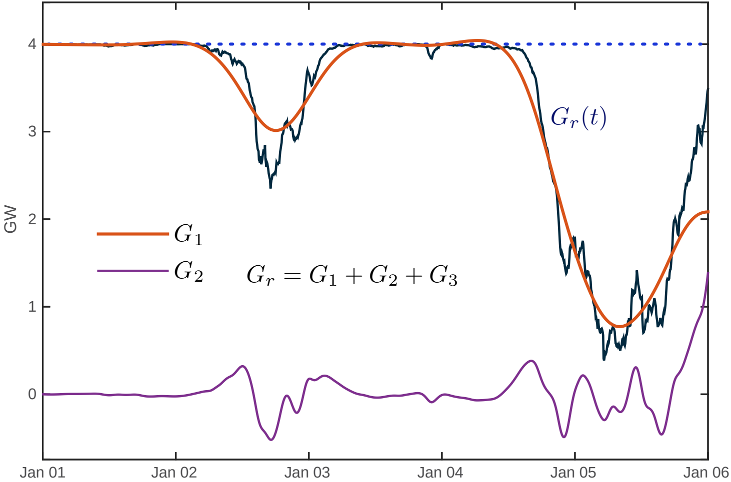
How do we operate the grid in a storm?

Disturbance decomposition



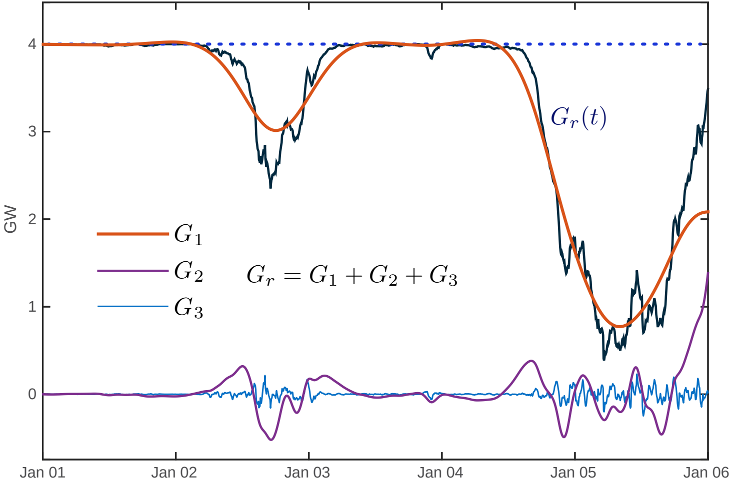
How do we operate the grid in a storm?

Disturbance decomposition



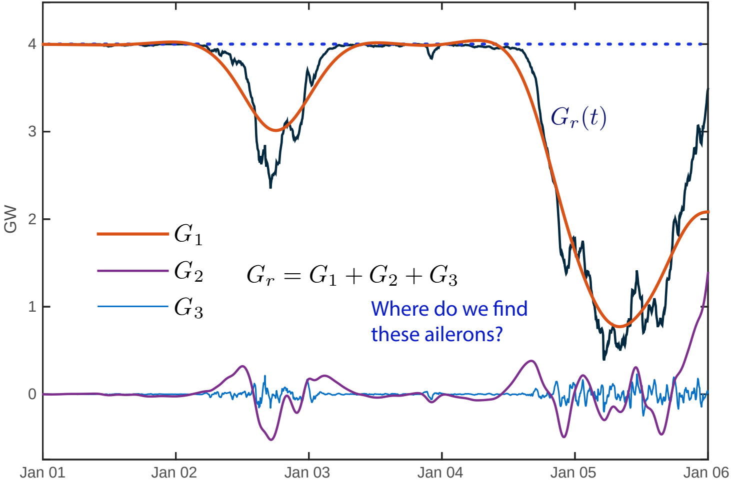
How do we operate the grid in a storm?

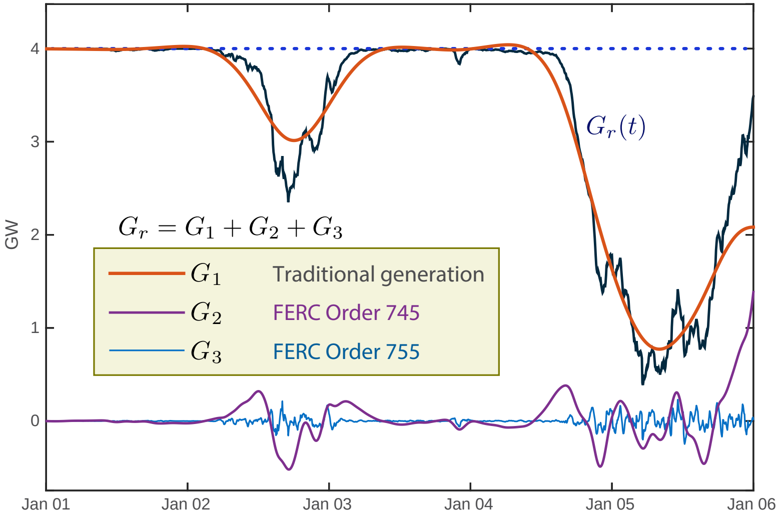
Disturbance decomposition



How do we operate the grid in a storm?

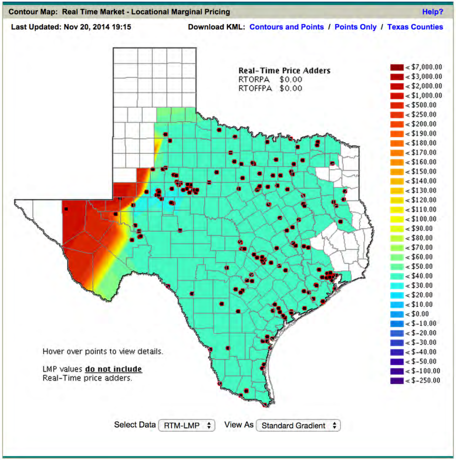
Disturbance decomposition

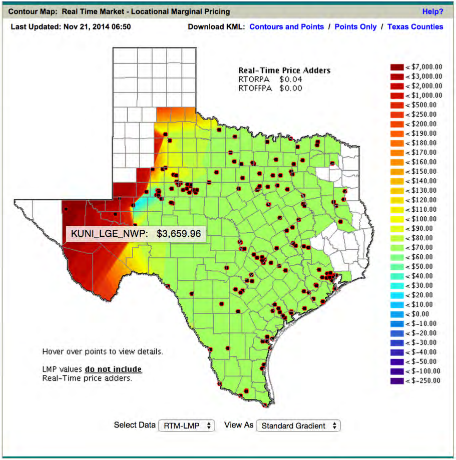




FERC Pilots the Grid

FERC 745: Demand & Generation smooth the Grid





Origin of FERC 745 – *Incentives for Demand Response*

EnerNOC's plea: (amongst others)

... demand response resources simply cannot be procured because they do not yet exist as resources. Such investment will not occur so long as compensation undervalues demand response resources.

Origin of FERC 745 – *Incentives for Demand Response*

EnerNOC's plea: (amongst others)
... demand response resources simply cannot be procured because they do not yet exist as resources. Such investment will not occur so long as compensation undervalues demand response resources.

FERC's Decision: The Commission concludes that paying LMP can address the identified barriers to potential demand response providers.

Origin of FERC 745 – *Incentives for Demand Response*

EnerNOC's plea: (amongst others)
... demand response resources simply cannot be procured because they do not yet exist as resources. Such investment will not occur so long as compensation undervalues demand response resources.

FERC's Decision: The Commission concludes that paying LMP can address the identified barriers to potential demand response providers.

FERC 745 is Born!

134 FERC ¶61,187
UNITED STATES OF AMERICA
FEDERAL ENERGY REGULATORY COMMISSION
18 CFR Part 35
[Docket No. RM10-17-000; Order No. 745]

Demand Response Compensation in Organized Wholesale Energy Markets
(Issued March 15, 2011)

Origin of FERC 745 – *Incentives for Demand Response*

EnerNOC's plea: (amongst others)
... demand response resources simply cannot be procured because they do not yet exist as resources. Such investment will not occur so long as compensation undervalues demand response resources.

FERC's Decision: The Commission concludes that paying LMP can address the identified barriers to potential demand response providers.

FERC 745 is Born!

134 FERC ¶61,187
UNITED STATES OF AMERICA
FEDERAL ENERGY REGULATORY COMMISSION
18 CFR Part 35
[Docket No. RM10-17-000; Order No. 745]

Demand Response Compensation in Organized Wholesale Energy Markets
(Issued March 15, 2011)

The outcome?

FERC 745 Is Dead!

FERC 745 Is Dead!

Conjecture: *It had to die.*

FERC 745 Is Dead!

Conjecture: *It had to die.*

FERC 745 Nirvana:

- Peaks shaved!

FERC 745 Is Dead!

Conjecture: *It had to die.*

FERC 745 Nirvana:

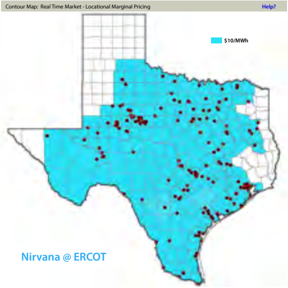
- Peaks shaved!
- Contingencies resolved in seconds!!
- Prices smoothed to Marginal Cost!

FERC 745 Is Dead!

Conjecture: *It had to die.*

FERC 745 Nirvana:

- Peaks shaved!
- Contingencies resolved in seconds!!
- Prices smoothed to Marginal Cost!

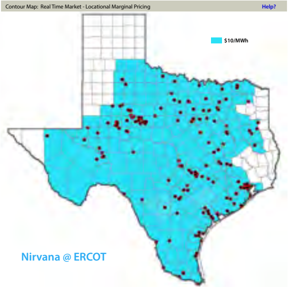


FERC 745 Is Dead!

Conjecture: *It had to die.*

FERC 745 Nirvana:

- Peaks shaved!
- Contingencies resolved in seconds!!
- Prices smoothed to Marginal Cost!



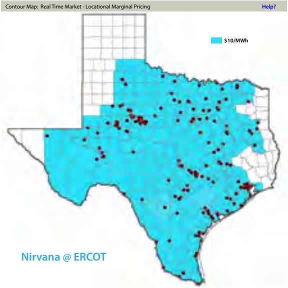
The problem: In this market, there is no **opportunity** without **crisis**

FERC 745 Is Dead!

Conjecture: *It had to die.*

FERC 745 Nirvana:

- Peaks shaved!
- Contingencies resolved in seconds!!
- Prices smoothed to Marginal Cost!



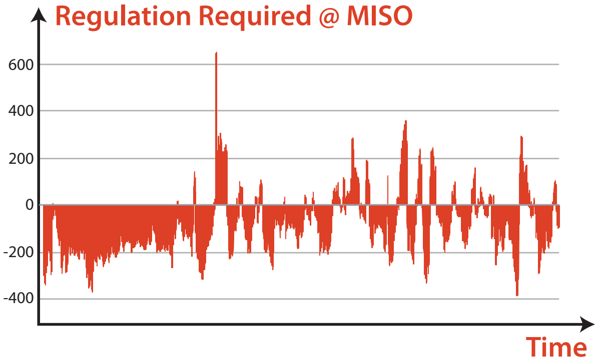
The problem: In this market, there is no **opportunity** without **crisis**

The paradox: In this nirvana,

there is no business case for demand response

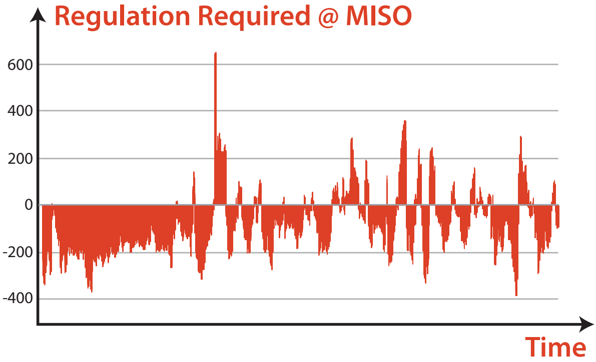
FERC Order 755

Pay-for-Performance



FERC Order 755

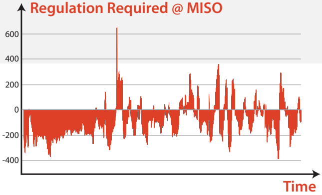
Pay-for-Performance



Requires ISO/RTOs to pay regulation resources
based on actual amount of regulation service provided
(speed and accuracy).

FERC Order 755

Pay-for-Performance

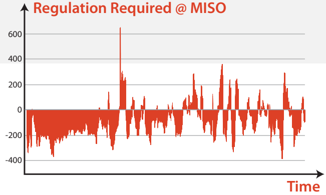


Two part settlement:

1. Uniform price for frequency regulation *capacity*
2. Performance payment for the provision of frequency regulation service, *reflecting a resource's accuracy of performance*

FERC Order 755

Pay-for-Performance



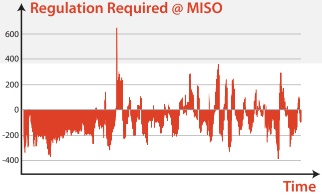
Two part settlement:

1. Uniform price for frequency regulation *capacity*
2. Performance payment for the provision of frequency regulation service, *reflecting a resource's accuracy of performance*

Performance?

FERC Order 755

Pay-for-Performance



Two part settlement:

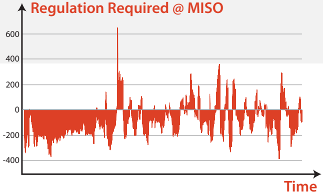
1. Uniform price for frequency regulation *capacity*
2. Performance payment for the provision of frequency regulation service, *reflecting a resource's accuracy of performance*

Performance? Now interpreted as *mileage*:

$$\text{Payment} \propto \int_0^T \left|\frac{d}{dt}G(t)\right| dt \qquad \text{(or discrete-time equivalent)}$$

FERC Order 755

Pay-for-Performance



Two part settlement:

1. Uniform price for frequency regulation *capacity*
2. Performance payment for the provision of frequency regulation service, *reflecting a resource's accuracy of performance*

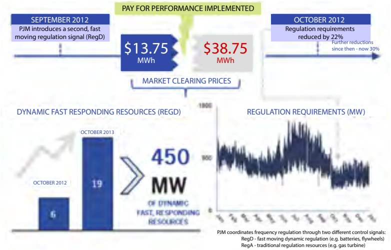
Performance? Now interpreted as *mileage*:

$$\text{Payment} \propto \int_0^T \left|\frac{d}{dt} G(t)\right| dt \qquad \text{(or discrete-time equivalent)}$$

Not perfect, but it is creating incentives

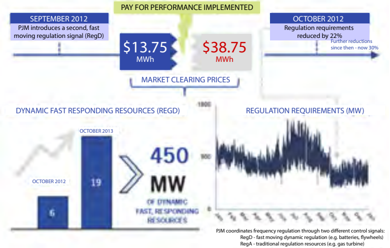
FERC Order 755

Not perfect



FERC Order 755

Not perfect



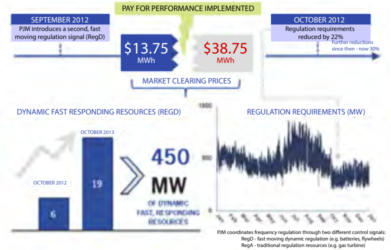
PJM's finding: Compensation on average is multiplied 3 times or more.

$\Longrightarrow$ Incentive to follow their fast moving RegD signal even if the unit is only capable of following at 50%.

Performance Based Regulation: Year One Analysis Regulation Performance Senior Task Force PJM Interconnection. Oct. 12, 2013

FERC Order 755

Not perfect



PJM's finding: Compensation on average is multiplied 3 times or more.

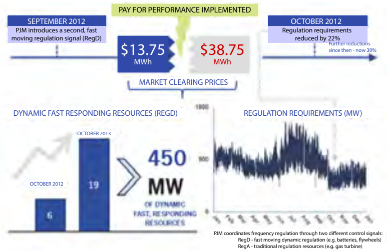
$\Longrightarrow$ Incentive to follow their fast moving RegD signal even if the unit is only capable of following at 50%.

Performance Based Regulation: Year One Analysis Regulation Performance Senior Task Force PJM Interconnection. Oct. 12, 2013

$\Longrightarrow$ *more FERC orders*

FERC Order 755

Not perfect



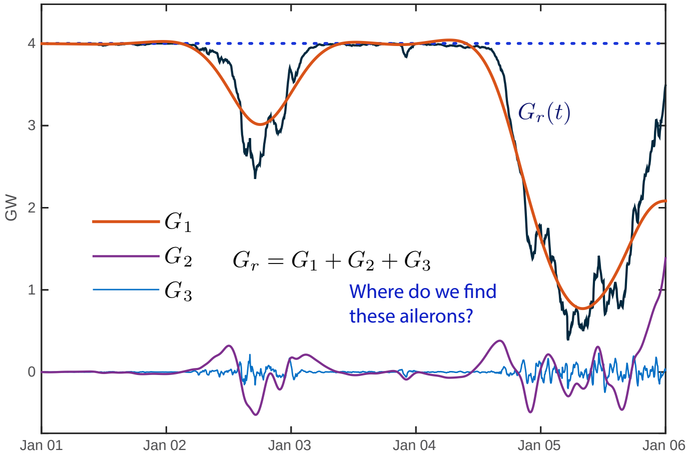
PJM's finding: Compensation on average is multiplied 3 times or more.

$\Longrightarrow$ Incentive to follow their fast moving RegD signal even if the unit is only capable of following at 50%.

Performance Based Regulation: Year One Analysis Regulation Performance Senior Task Force PJM Interconnection. Oct. 12, 2013

$\Longrightarrow$ *more FERC orders*

What is the value of regulation?



Demand Dispatch

We want: Responsive Regulation

Demand Dispatch the Answer?

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

We want: Responsive Regulation

Demand Dispatch the Answer?

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

- High quality AS? (Ancillary Service)
  Does the deviation in power consumption accurately track the desired deviation target?

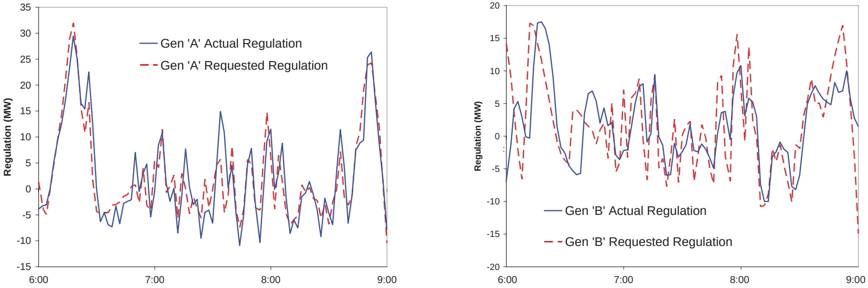
We want: Responsive Regulation

Demand Dispatch the Answer?

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

- High quality AS? (Ancillary Service)

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

We want: Responsive Regulation

Demand Dispatch the Answer?

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

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

We want: Responsive Regulation

Demand Dispatch the Answer?

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

- High quality AS?
- Reliable?
- Cost effective?
  This includes installation cost, communication cost, maintenance, and environmental.

We want: Responsive Regulation

Demand Dispatch the Answer?

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

- High quality AS?
- Reliable?
- Cost effective?
- Is the incentive to the consumer reliable?
  If a consumer receives a $50 payment for one month, and only $1 the next, will there be an explanation that is clear to the consumer?

We want: Responsive Regulation

Demand Dispatch the Answer?

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

- High quality AS?
- Reliable?
- Cost effective?
- Is the incentive to the consumer reliable?
- Customer QoS constraints satisfied?
  The pool must be clean, fresh fish stays cold, building climate is subject to strict bounds, farm irrigation is subject to strict constraints, data centers require sufficient power to perform their tasks.

We want: Responsive Regulation

Demand Dispatch the Answer?

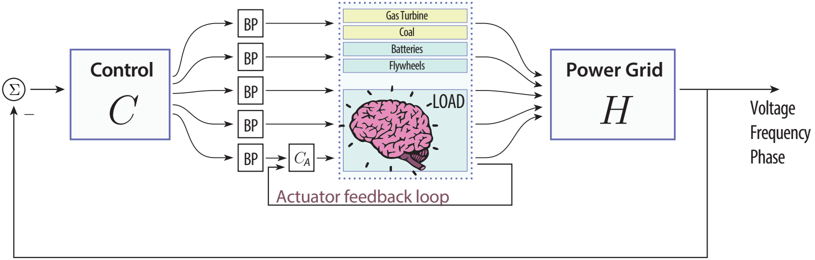
A partial list of the needs of the grid operator, and the consumer:

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

Demand Dispatch can do all of this! (by design)

Control Architecture

Frequency Decomposition for Demand Dispatch

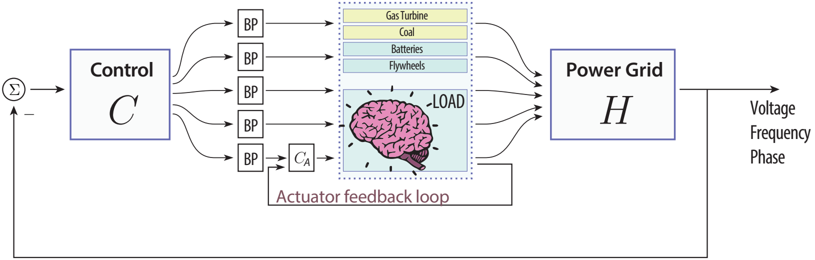


Today: PJM decomposes regulation signal based on bandwidth,

$$\mathrm{R} = \mathrm{RegA} + \cdots + \mathrm{RegD}$$

Control Architecture

Frequency Decomposition for Demand Dispatch



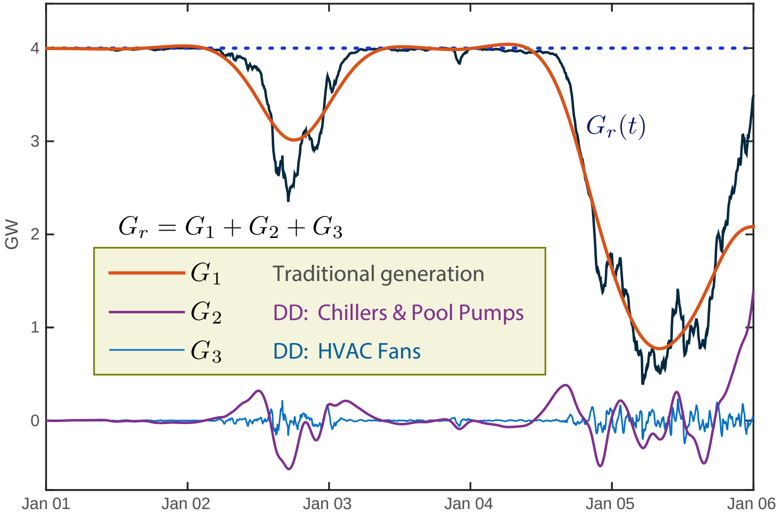
Today: PJM decomposes regulation signal based on bandwidth,

$$\text{R} = \text{RegA} + \cdots + \text{RegD}$$

Proposal: Each class of DR (and other) resources will have its own bandwidth of service, based on QoS constraints and costs.

Control Architecture

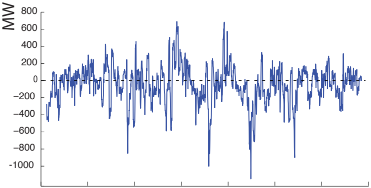
Frequency Decomposition for Demand Dispatch



Control Architecture

Frequency Decomposition for Demand Dispatch

Balancing Reserves from Bonneville Power Authority:

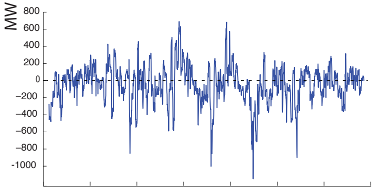


BPA Reg signal
(one week)

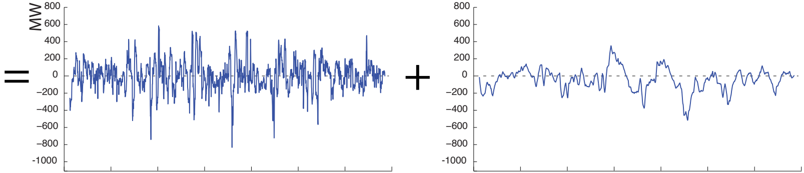
Control Architecture

Frequency Decomposition for Demand Dispatch

Balancing Reserves from Bonneville Power Authority:



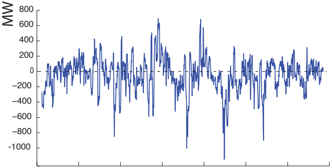
BPA Reg signal
(one week)



Control Architecture

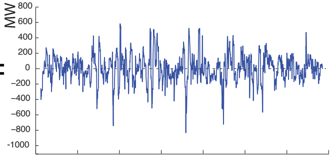
Frequency Decomposition for Demand Dispatch

Balancing Reserves from Bonneville Power Authority:

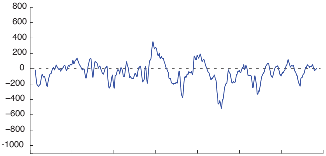


BPA Reg signal
(one week)

=

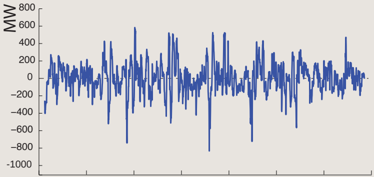


+



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

=



Buildings as Batteries

Buildings as Batteries

HVAC flexibility to provide additional ancillary service

- Buildings consume 70% of electricity in the US
  HVAC contributes to 40% of the consumption.

Buildings as Batteries

HVAC flexibility to provide additional ancillary service

- Buildings consume 70% of electricity in the US
  HVAC contributes to 40% of the consumption.
- Buildings have large thermal capacity

Buildings as Batteries

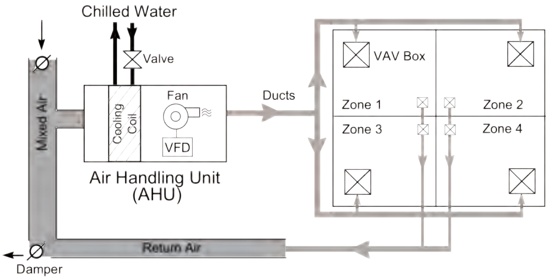
HVAC flexibility to provide additional ancillary service

- Buildings consume 70% of electricity in the US
  HVAC contributes to 40% of the consumption.
- Buildings have large thermal capacity
- Modern buildings have fast-responding equipment:
  VFDs (variable frequency drive)

Buildings as Batteries

HVAC flexibility to provide additional ancillary service

- Buildings consume 70% of electricity in the US
  HVAC contributes to 40% of the consumption.
- Buildings have large thermal capacity
- Modern buildings have fast-responding equipment:
  VFDs (variable frequency drive)



Buildings as Batteries

Tracking RegD at Pugh Hall — *ignore the measurement noise*

In one sentence:

Buildings as Batteries

Tracking RegD at Pugh Hall — *ignore the measurement noise*

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

Buildings as Batteries

Tracking RegD at Pugh Hall — *ignore the measurement noise*

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

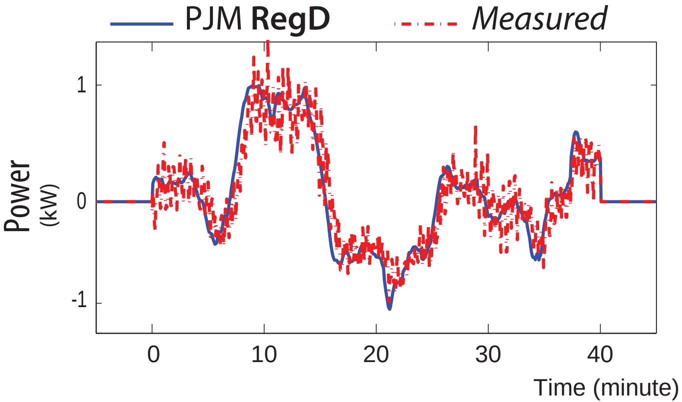
Result:

Buildings as Batteries

Tracking RegD at Pugh Hall — *ignore the measurement noise*

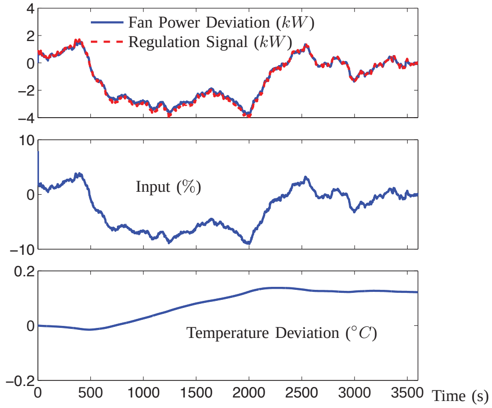
In one sentence: Ramp up and down power consumption, just 10%, to track regulation signal.

Result:



Pugh Hall @ UF

How much?

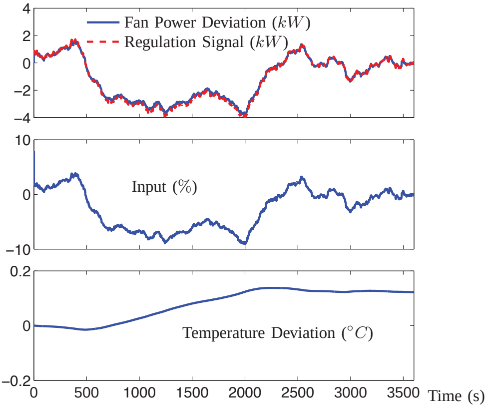


- ▷ One AHU fan with 25 kW motor: > 3 kW of regulation reserve
- ▷ Pugh Hall (40k sq ft, 3 AHUs): > 10 kW

Indoor air quality is not affected

Pugh Hall @ UF

How much?



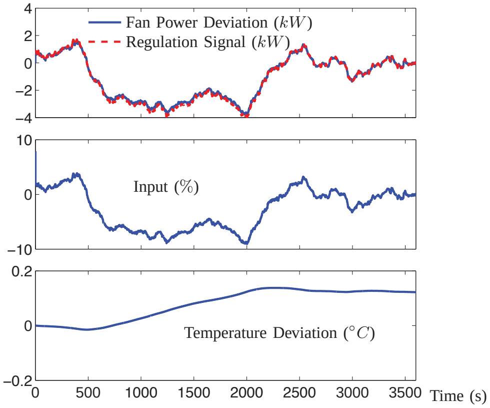
- One AHU fan with 25 kW motor:
  $>$ 3 kW of regulation reserve
- Pugh Hall (40k sq ft, 3 AHUs):
  $>$ 10 kW

Indoor air quality is not affected

- 100 buildings:
  $>$ 1 MW

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

- 100 buildings:
  $>$ 1 MW

That's just using the fans!

Buildings as Batteries

What do you think?

Questions:

- Capacity?

Buildings as Batteries

What do you think?

Questions:

- Capacity? *Tens of Gigawatts* from commercial buildings in the US

Buildings as Batteries

What do you think?

Questions:

- Capacity? *Tens of Gigawatts* from commercial buildings in the US
- Can we obtain a resource as effective as today's spinning reserves?

Buildings as Batteries

What do you think?

Questions:

- Capacity? *Tens of Gigawatts* from commercial buildings in the US
- Can we obtain a resource as effective as today's spinning reserves?

Yes!! Buildings are well-suited to balancing reserves,
and other high-frequency regulation resources

Buildings as Batteries

What do you think?

Questions:

- Capacity? *Tens of Gigawatts* from commercial buildings in the US
- Can we obtain a resource as effective as today's spinning reserves?

Yes!! Buildings are well-suited to balancing reserves,
and other high-frequency regulation resources

much better than any generator

Buildings as Batteries

What do you think?

Questions:

- Capacity? *Tens of Gigawatts* from commercial buildings in the US
- Can we obtain a resource as effective as today's spinning reserves?

Yes!! Buildings are well-suited to balancing reserves,
and other high-frequency regulation resources

much better than any generator

- How to compute *baselines*?

Buildings as Batteries

What do you think?

Questions:

- Capacity? *Tens of Gigawatts* from commercial buildings in the US
- Can we obtain a resource as effective as today's spinning reserves?

Yes!! Buildings are well-suited to balancing reserves,
and other high-frequency regulation resources

much better than any generator

- How to compute *baselines*?

Who cares? The utility or aggregator is responsible for the equipment – the consumer cannot 'play games' in a real time market!

Buildings as Batteries

What do you think?

Questions:

- Capacity? *Tens of Gigawatts* from commercial buildings in the US
- Can we obtain a resource as effective as today's spinning reserves?

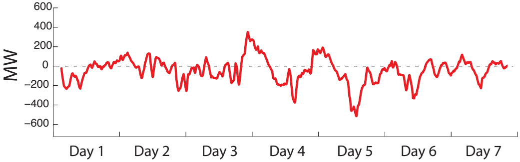
Yes!! Buildings are well-suited to balancing reserves, and other high-frequency regulation resources

much better than any generator

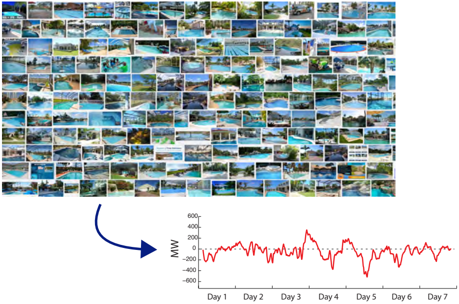
- How to compute *baselines*?

Who cares? The utility or aggregator is responsible for the equipment – the consumer cannot 'play games' in a real time market!

What open issues do you see?



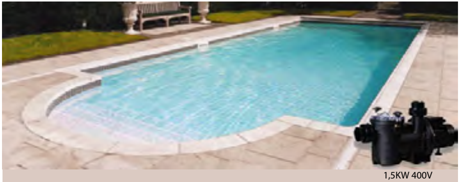
Intelligent Pools in Florida



Intelligent Pools in Florida

Example: One Million Pools in Florida

How Pools Can Help Regulate The Grid

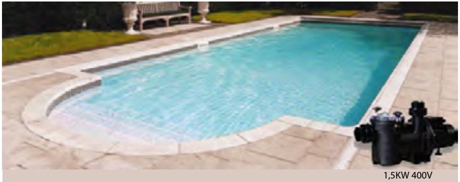


Needs of a single pool

- Filtration system circulates and cleans: Average pool pump uses 1.3kW and runs 6-12 hours per day, 7 days per week

Example: One Million Pools in Florida

How Pools Can Help Regulate The Grid

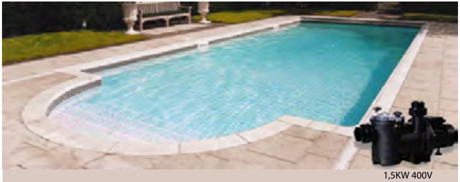


Needs of a single pool

- Filtration system circulates and cleans: Average pool pump uses 1.3kW and runs 6-12 hours per day, 7 days per week
- Pool owners are oblivious, until they see *frogs and algae*

Example: One Million Pools in Florida

How Pools Can Help Regulate The Grid

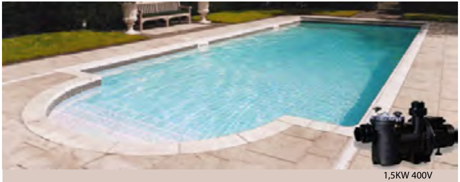


Needs of a single pool

- Filtration system circulates and cleans: Average pool pump uses 1.3kW and runs 6-12 hours per day, 7 days per week
- Pool owners are oblivious, until they see *frogs and algae*
- Pool owners do not trust anyone: *Privacy is a big concern*

Example: One Million Pools in Florida

How Pools Can Help Regulate The Grid



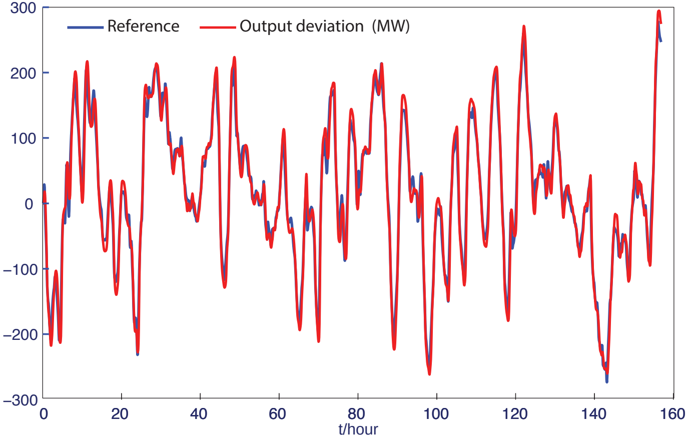
Needs of a single pool

- Filtration system circulates and cleans: Average pool pump uses 1.3kW and runs 6-12 hours per day, 7 days per week
- Pool owners are oblivious, until they see *frogs and algae*
- Pool owners do not trust anyone: *Privacy is a big concern*

Randomized control strategy is needed.

Pools in Florida Supply G_2 – BPA regulation signal*

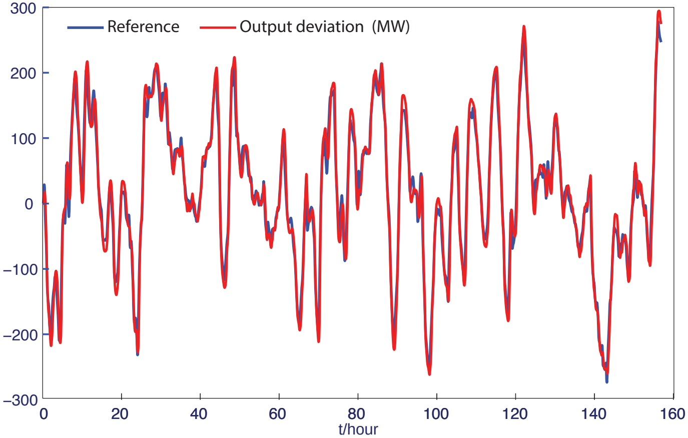
Stochastic simulation using $N = 10^5$ pools



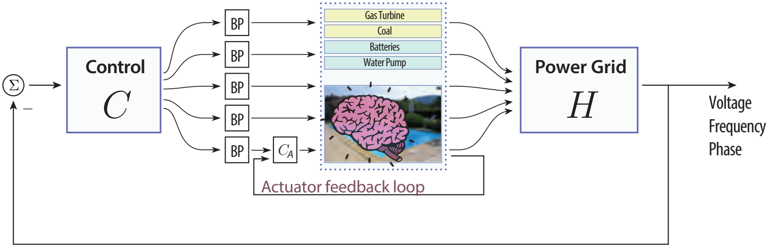
*transmission.bpa.gov/Business/Operations/Wind/reserves.aspx

Pools in Florida Supply G_2 – BPA regulation signal*

Stochastic simulation using $N = 10^5$ pools



Each pool pump turns on/off with probability depending on
1) its internal state, and 2) the BPA reg signal



Conclusions

Conclusions

Barriers to renewable energy

1. **Volatility**
   Not so bad! Demand Dispatch: an inexpensive and reliable resource

Conclusions

Barriers to renewable energy

1. **Volatility**
   Not so bad! Demand Dispatch: an inexpensive and reliable resource *by design*

Conclusions

Barriers to renewable energy

1. **Volatility**

   Not so bad! Demand Dispatch: an inexpensive and reliable resource *by design*

   Tremendous capacity in Florida

Conclusions

Barriers to renewable energy

1. **Volatility**

   Not so bad! Demand Dispatch: an inexpensive and reliable resource *by design*

   Tremendous capacity in Florida

2. Engineering uncertainty

   This is real We don't know why the grid is so reliable today.

   Need for better understanding of grid/distribution/social dynamics

Conclusions

Barriers to renewable energy

1. **Volatility**
   Not so bad! Demand Dispatch: an inexpensive and reliable resource *by design*
   Tremendous capacity in Florida
2. Engineering uncertainty
   This is real We don't know why the grid is so reliable today.
   Need for better understanding of grid/distribution/social dynamics
3. Policy uncertainty
   Scary!

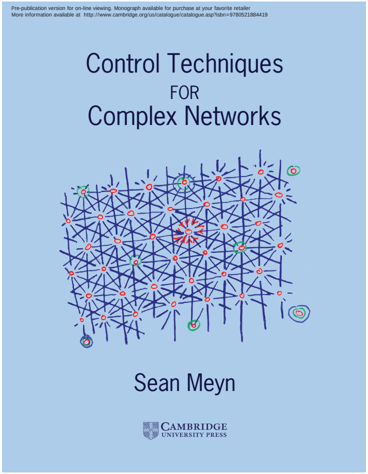
Conclusions

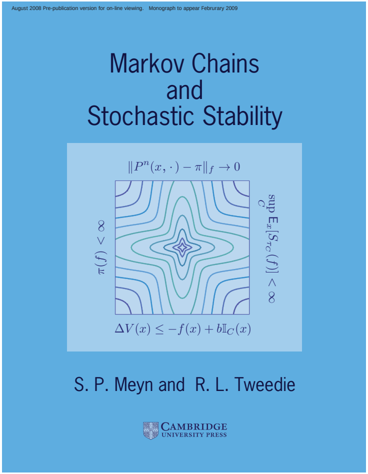
Barriers to renewable energy

1. **Volatility**
   Not so bad! Demand Dispatch: an inexpensive and reliable resource *by design*
   Tremendous capacity in Florida
2. Engineering uncertainty
   This is real We don't know why the grid is so reliable today.
   Need for better understanding of grid/distribution/social dynamics
3. Policy uncertainty
   Scary!

Need for Research in Engineering and Economics

Conclusions


Pre-publication version for on-line viewing. Monograph available for purchase at your favorite retailer
More information available at http://www.cambridge.org/us/catalogue/catalogue.asp?isbn=9780521884419
Control Techniques
FOR
Complex Networks
Sean Meyn
CAMBRIDGE UNIVERSITY PRESS


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

References

Selected References

More at www.meyn.ece.ufl.edu

- A. Brooks, E. Lu, D. Reicher, C. Spirakis, and B. Weihl. Demand dispatch. *IEEE Power and Energy Magazine*, 8(3):20–29, May 2010.
- H. Hao, T. Middelkoop, P. Barooah, and S. Meyn. How demand response from commercial buildings will provide the regulation needs of the grid. In *50th Allerton Conference on Communication, Control, and Computing*, pages 1908–1913, 2012.
- H. Hao, Y. Lin, A. Kowli, P. Barooah, and S. Meyn. Ancillary service to the grid through control of fans in commercial building HVAC systems. *IEEE Trans. on Smart Grid*, 5(4):2066–2074, July 2014.
- S. Meyn, P. Barooah, A. Bušić, Y. Chen, and J. Ehren. Ancillary service to the grid using intelligent deferrable loads. *ArXiv e-prints: arXiv:1402.4600 and to appear, IEEE Trans. on Auto. Control*, 2014.
- D. Callaway and I. Hiskens, Achieving controllability of electric loads. *Proceedings of the IEEE*, vol. 99, no. 1, pp. 184–199, 2011.
- P. Xu, P. Haves, M. Piette, and J. Braun, Peak demand reduction from pre-cooling with zone temperature reset in an office building, 2004.
- D. Watson, S. Kiliccote, N. Motegi, and M. Piette, Strategies for demand response in commercial buildings. In *Proceedings of the 2006 ACEEE Summer Study on Energy Efficiency in Buildings*, August 2006.