Control of building demand for energy efficiency and grid support services

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Joint work with Sean Meyn, Ana Busic, and
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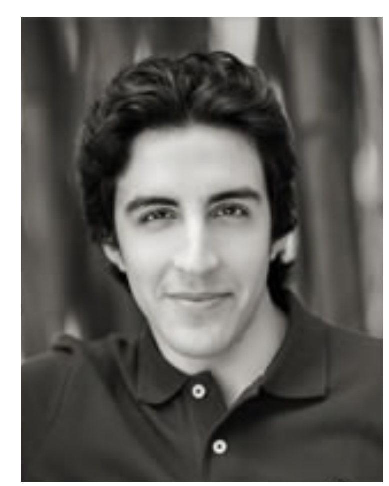
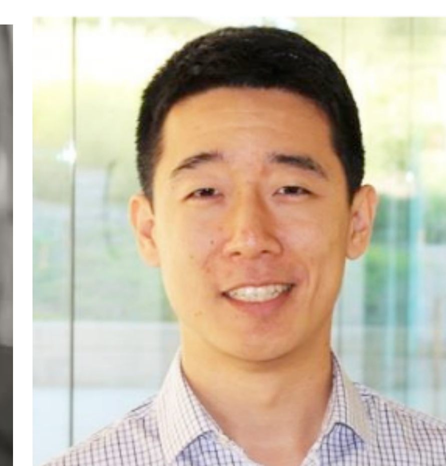
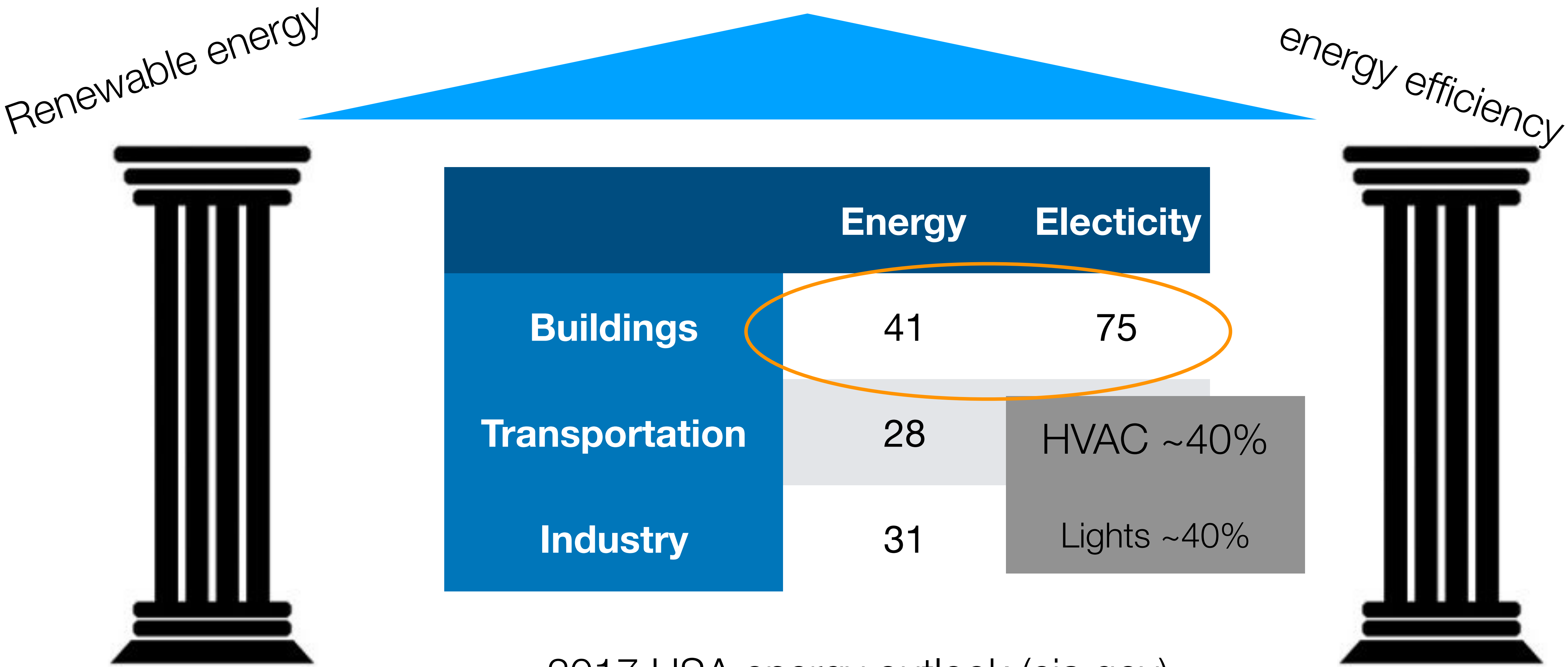



Grid Science Winter School and Conference, Santa Fe, Jan 9, 2019

Sustainable energy infrastructure



	Energy	Electicity
Buildings	41	75
Transportation	28	
Industry	31	

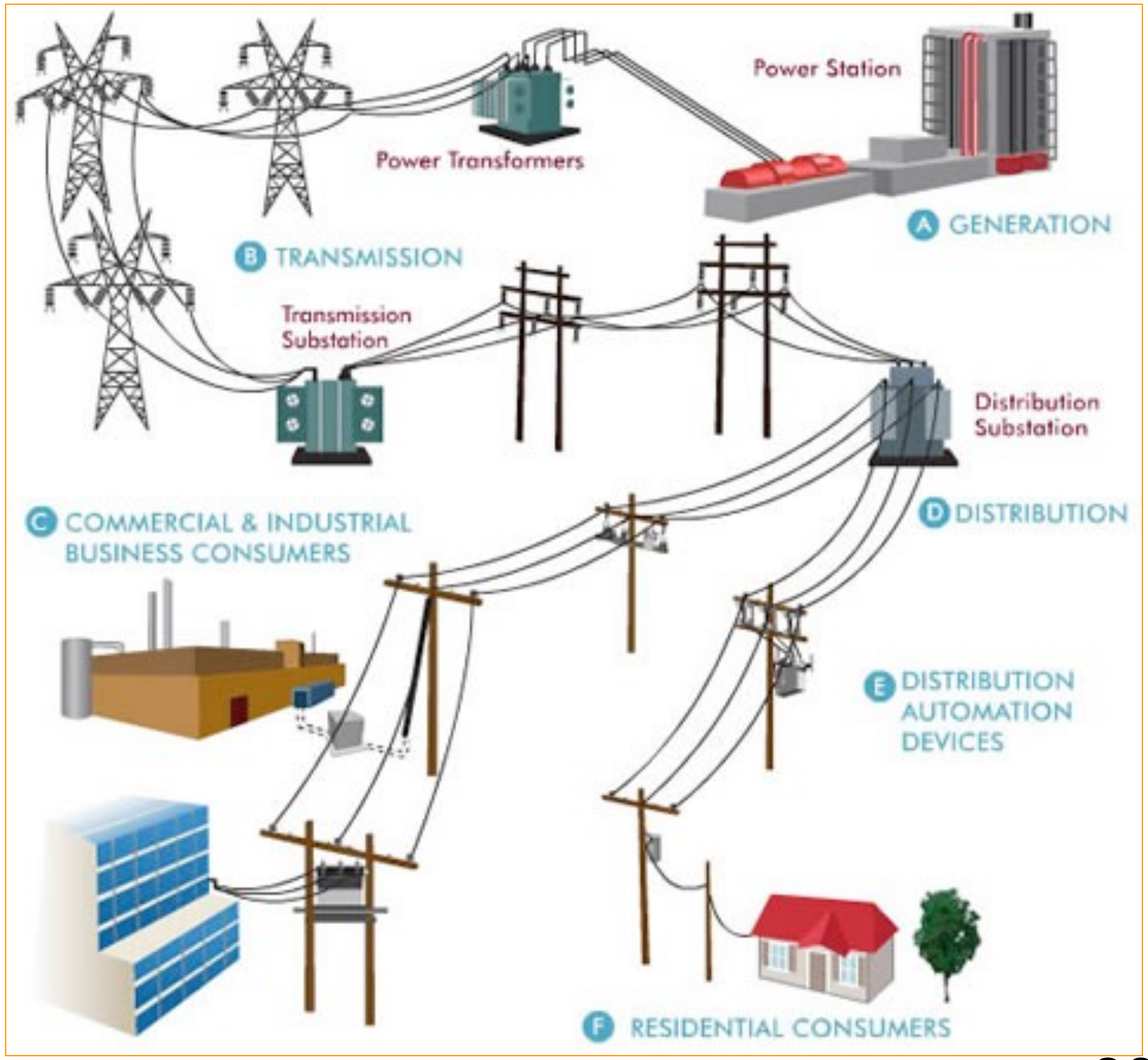
HVAC ~40%

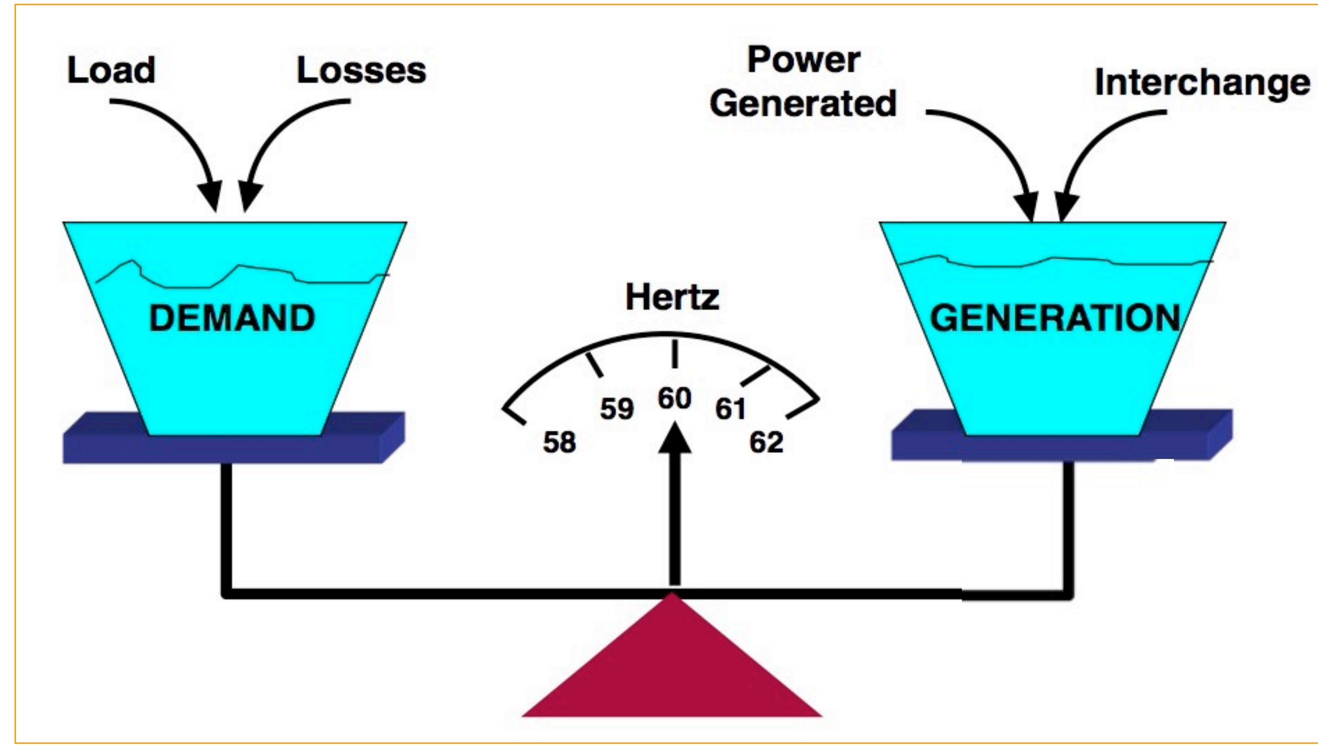
Lights ~40%

2017 USA energy outlook (eia.gov)

Renewable energy: solar and wind

Power grid: demand and supply must always be balanced





2003 US blackout

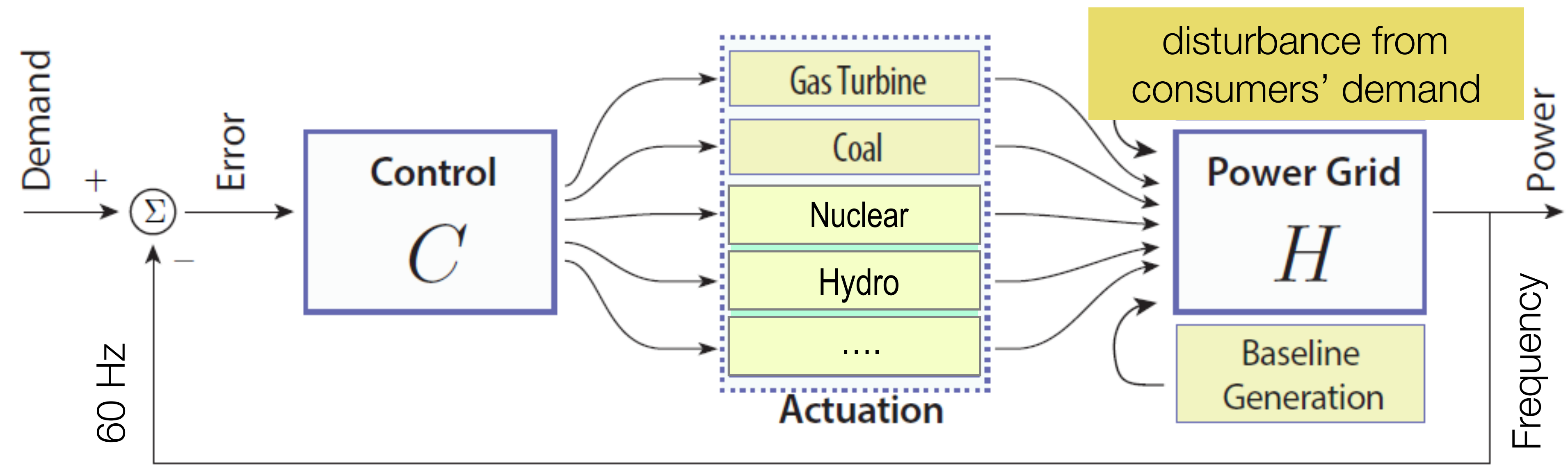
2012 India blackout

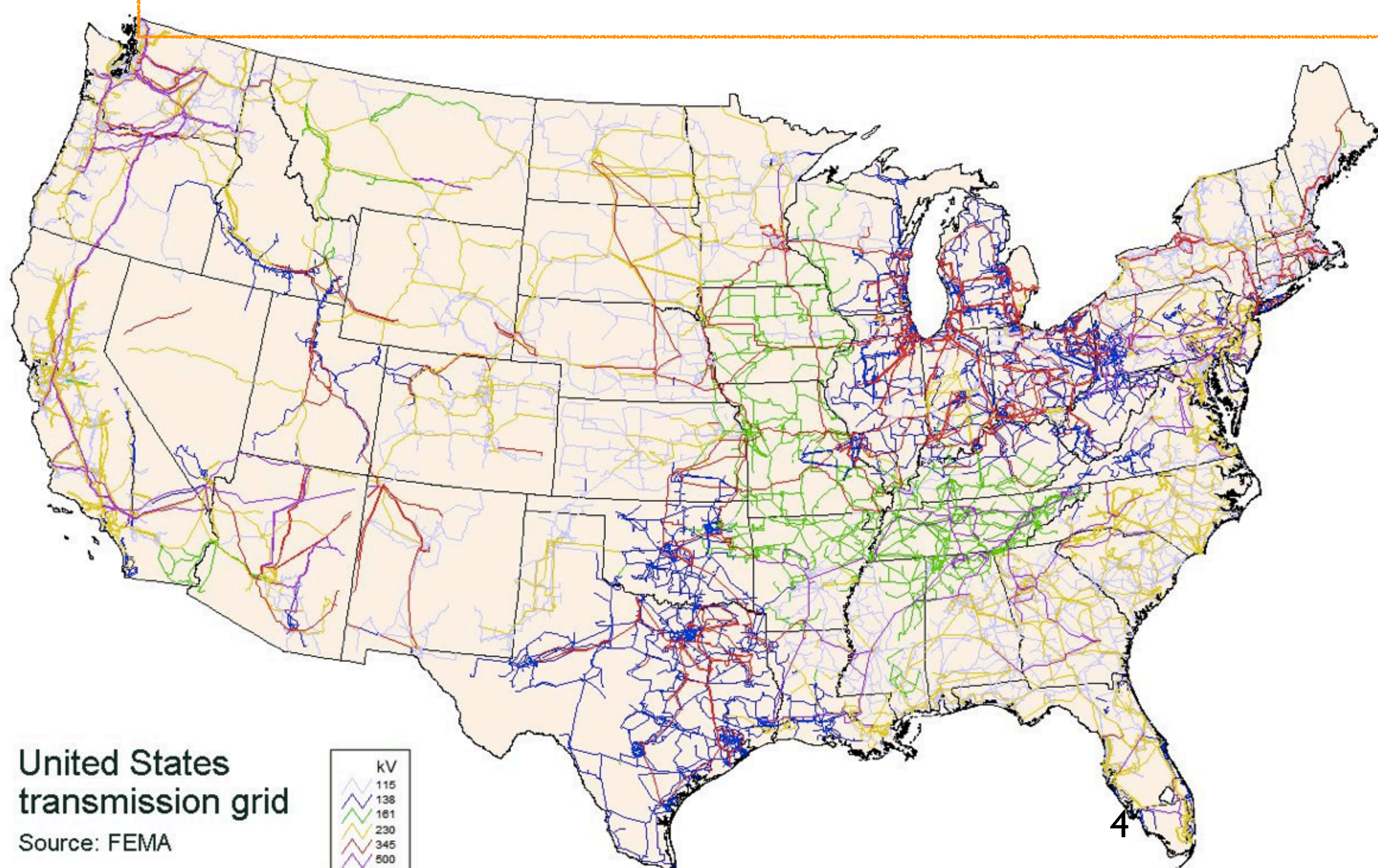
2011 California blackout

images courtesy: altenergymag.com, Time, indianexpress.com

Demand-supply balanced by controllable generators

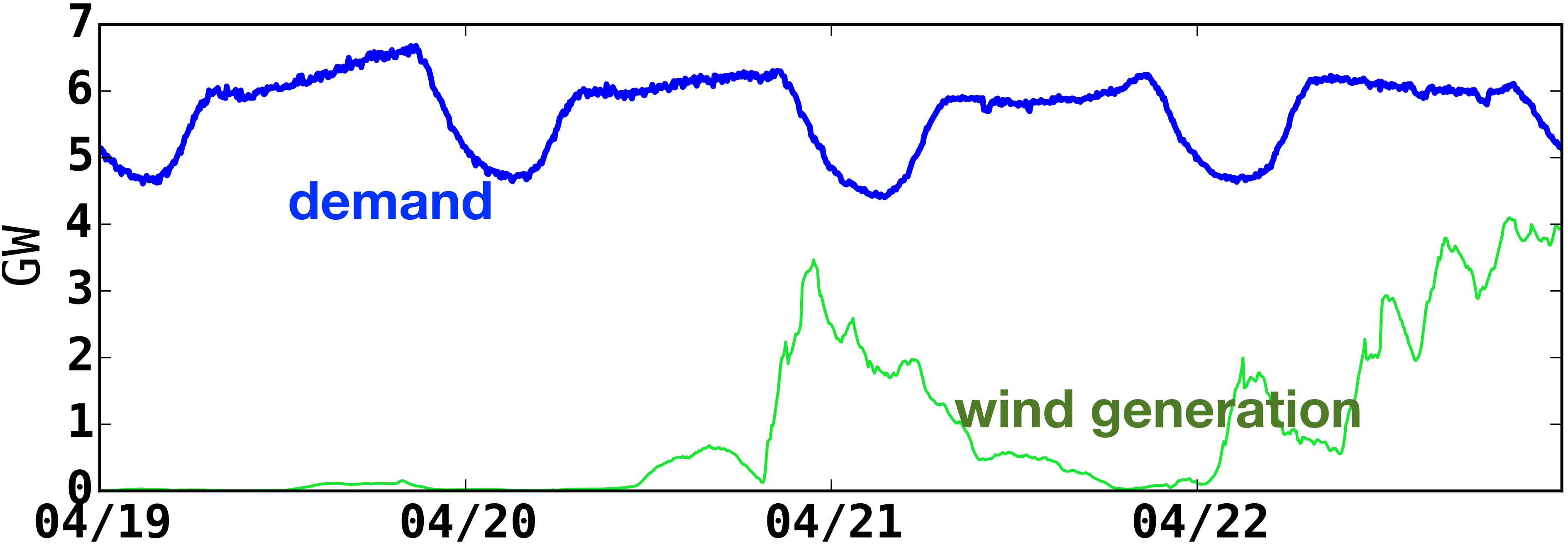
Grid control architecture (at present)

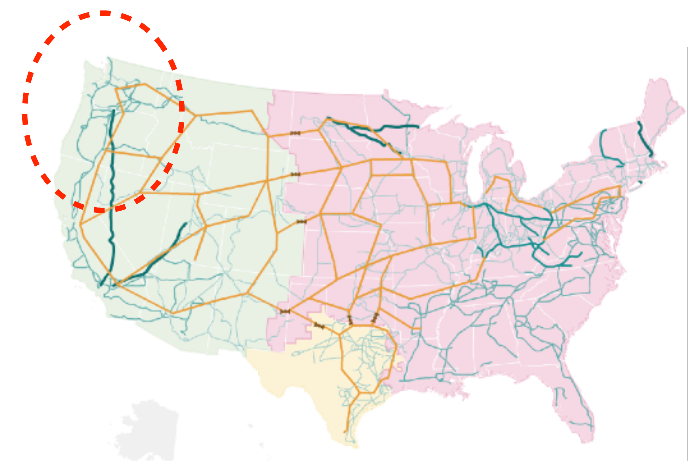


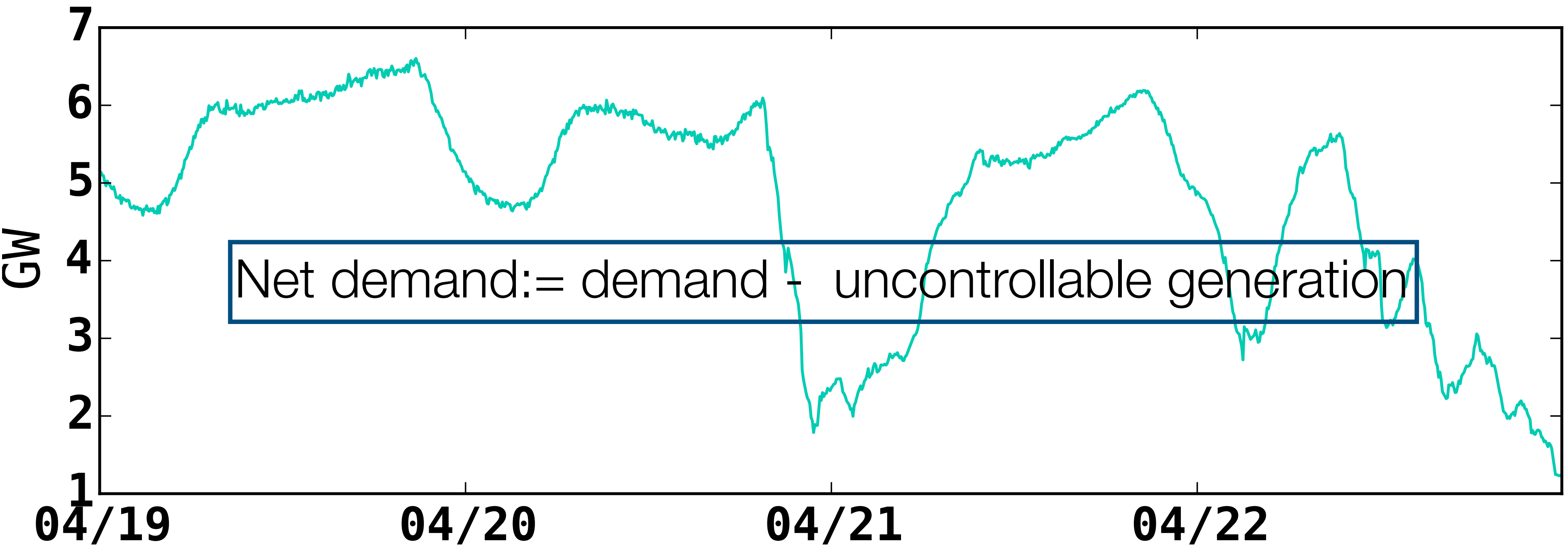


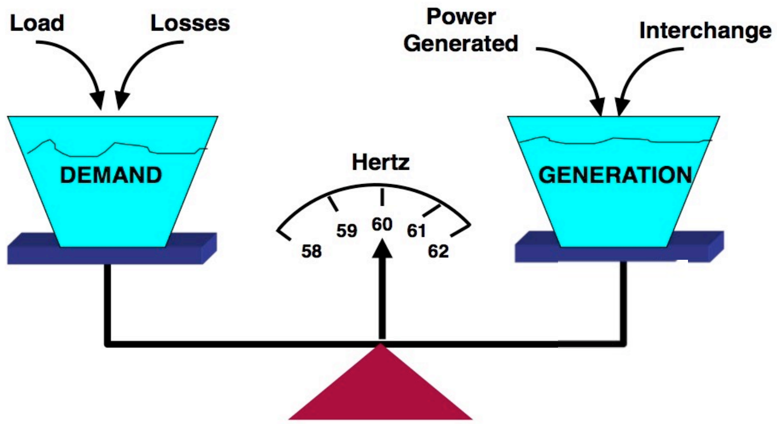
Grid operator: man & machine

A energy future with solar and wind?









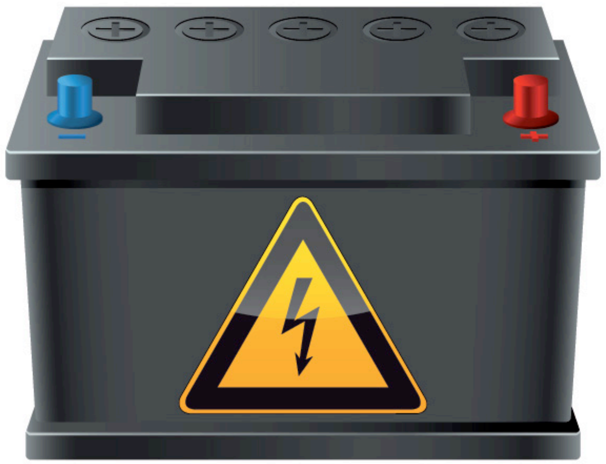
Need energy storage!

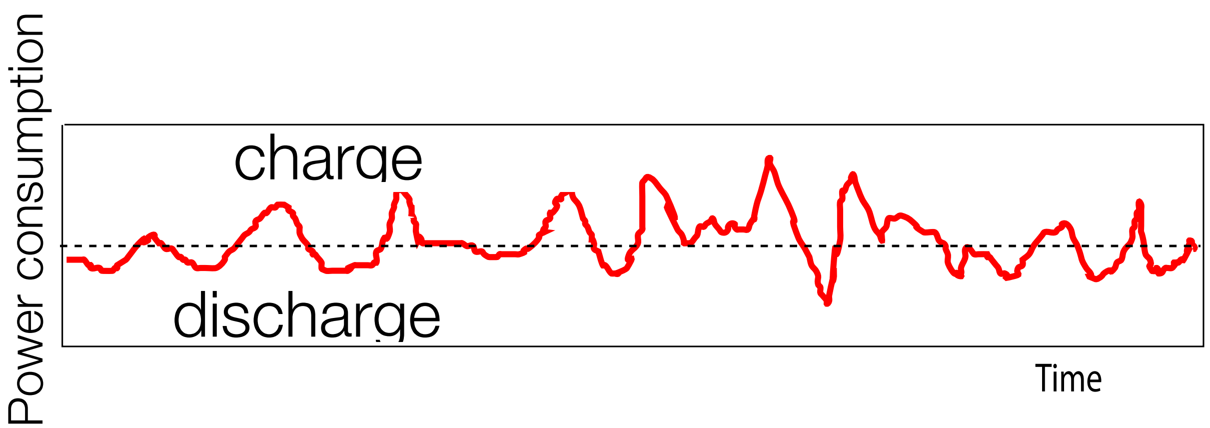
Batteries: Cost of electricity will increase by > 6 c/kWh*

“Virtual energy storage from flexible loads: distributed control with QoS constraints”, P. Barooah, in “Smart Grid Control: Opportunities and Challenges”, Springer 2018

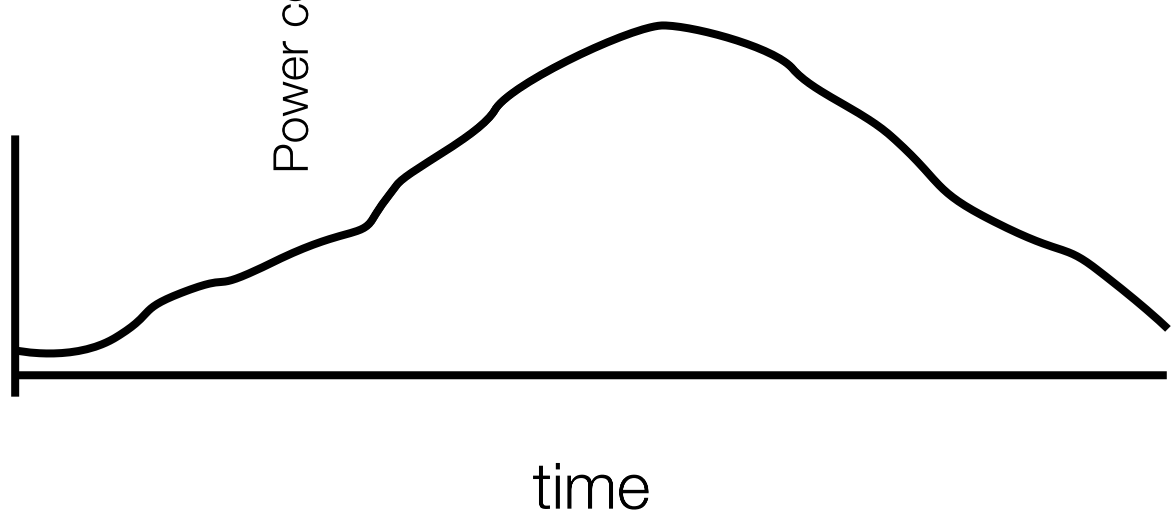
Virtual Energy Storage (VES)

“real” storage



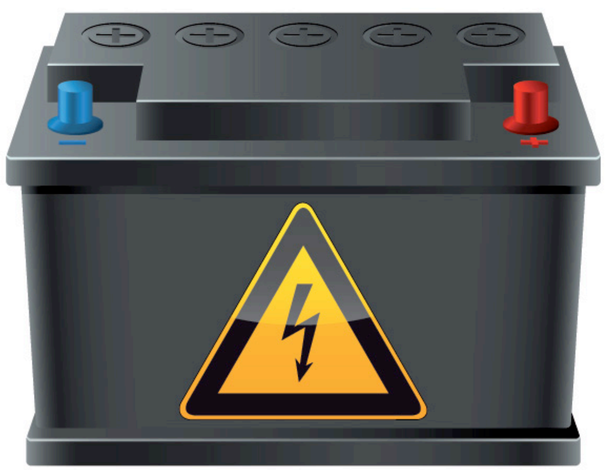


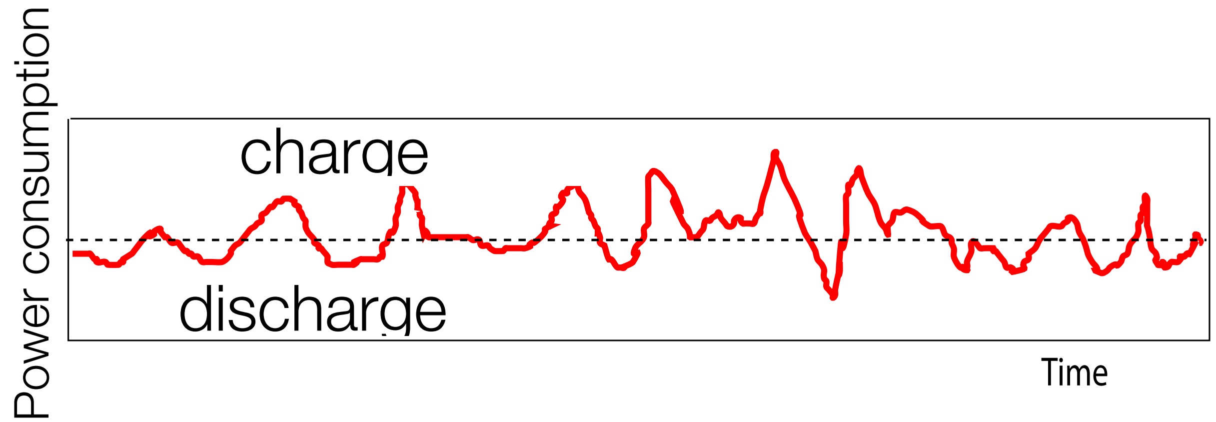
“virtual” storage



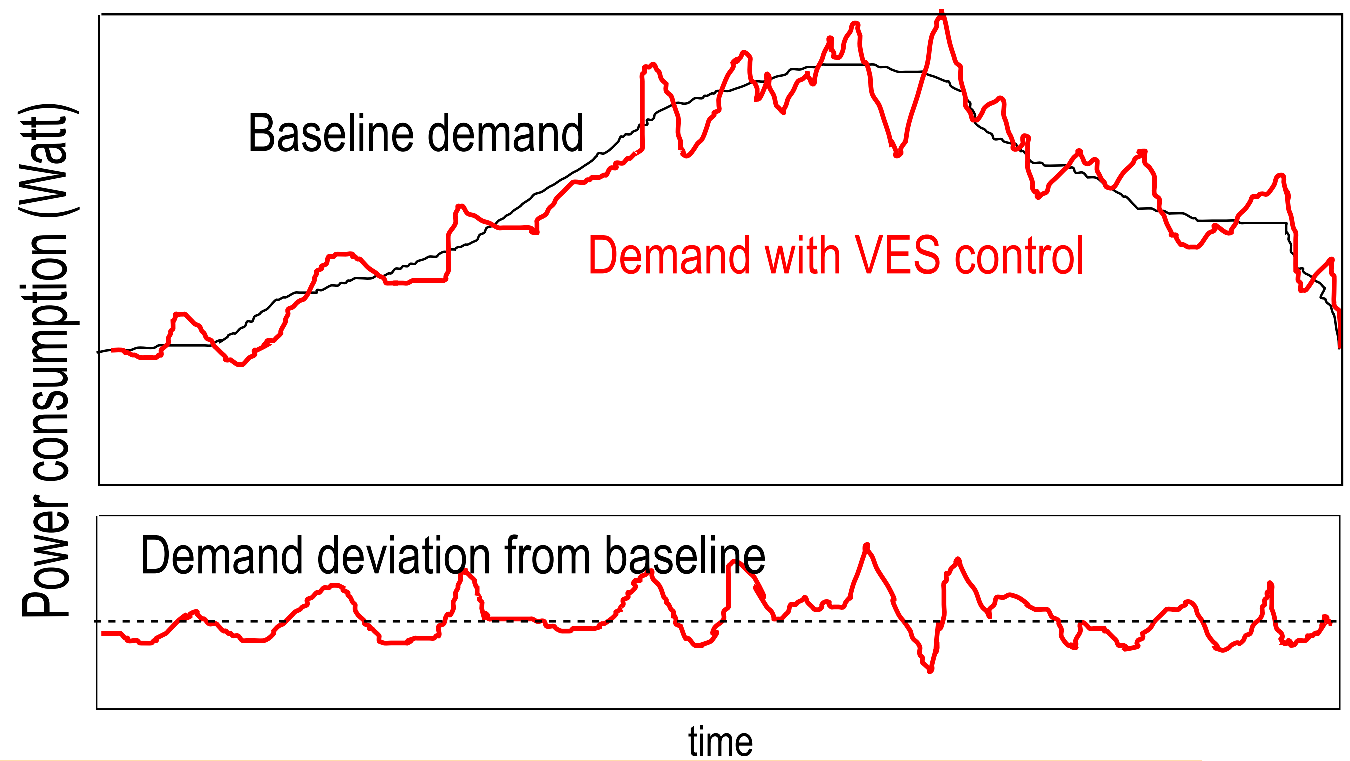
VES: zero mean variation of power demand (kW) over baseline

“real” storage





“virtual” storage
(one load or many)



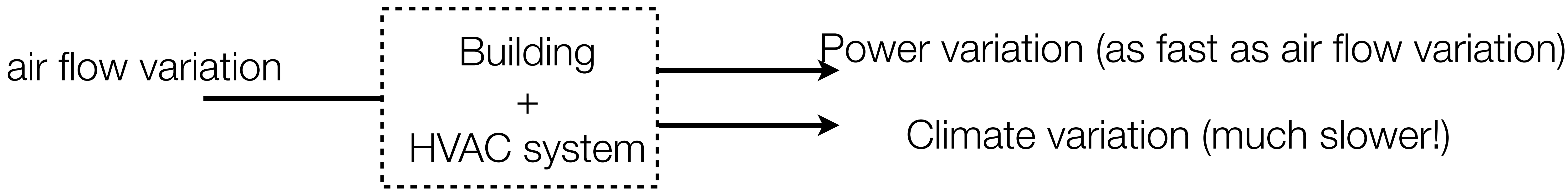
Q1. How can loads supply that while maintaining guaranteed bounds on consumers’ quality of service (QoS)?

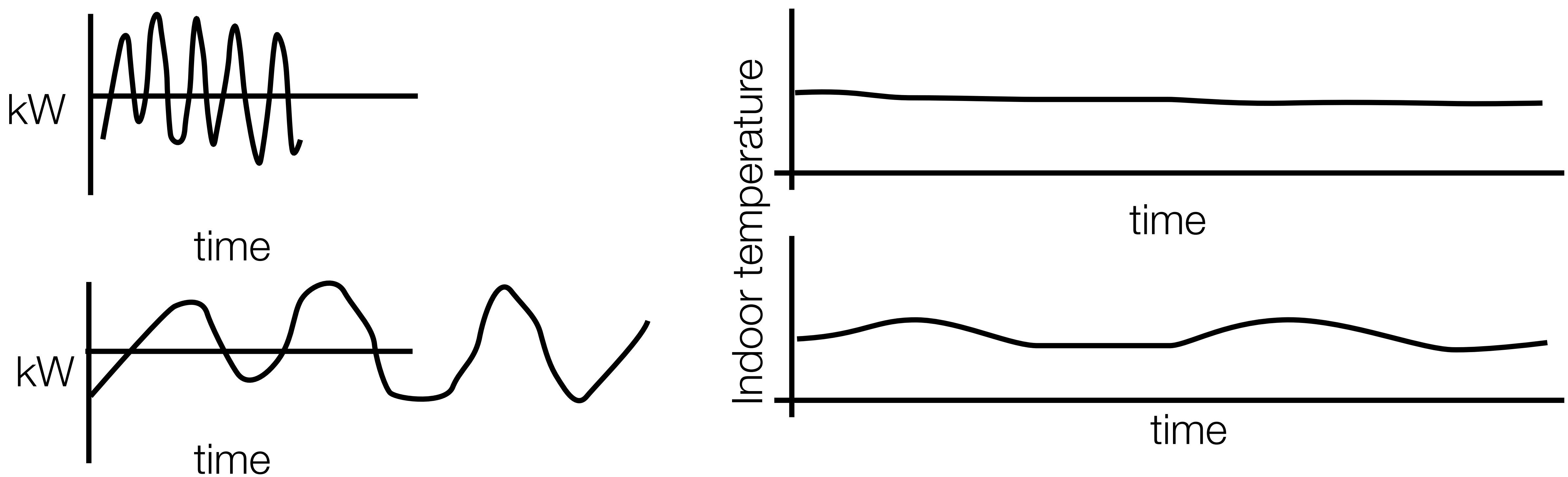
Q2. If QoS is maintained, how does it meet the storage needs of the grid?

Q1: How to ensure QoS constraints?

Ans: Constrain "bandwidth" of power variation

Example: Commercial building air conditioning (HVAC)

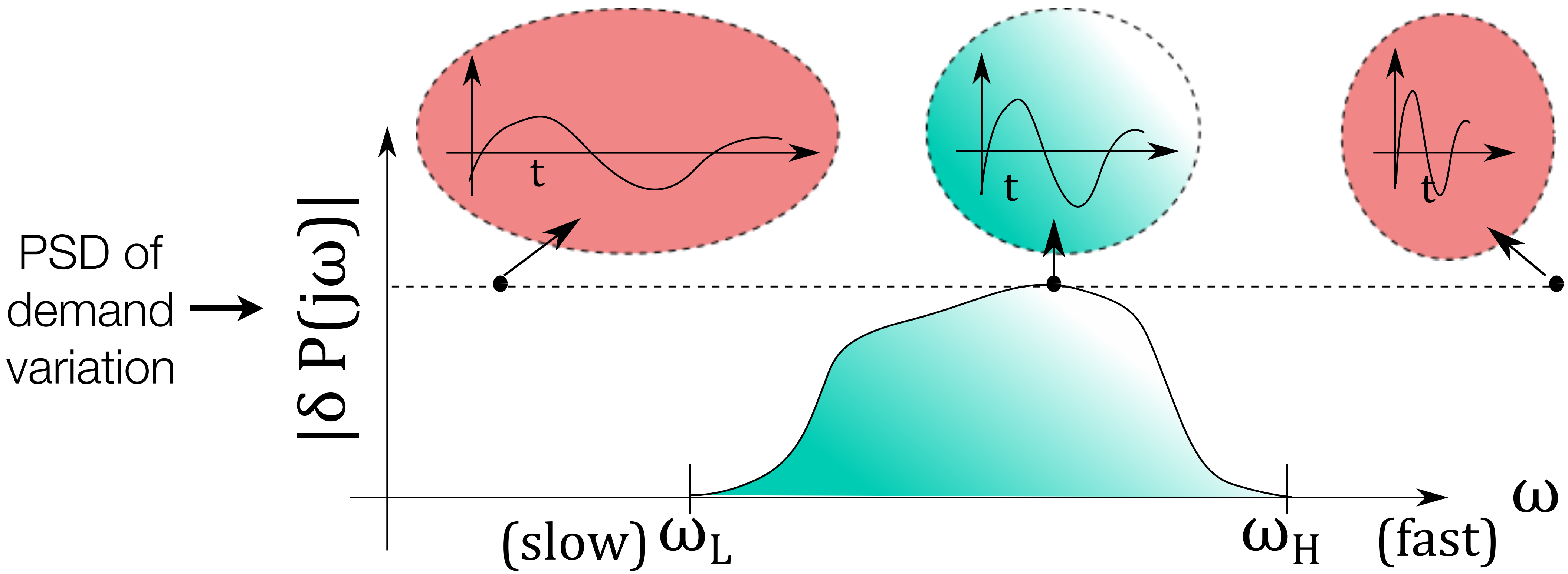




A virtual battery with charge/discharge cycle of ~ (1 min - 1 hour)

Q1: How to ensure QoS constraints?

Ans: constraint on QoS = constraint on Fourier transform



HVAC*

>4 hours		Seconds
Unacceptable temperature fluctuation	Just right!	Equipment degradation

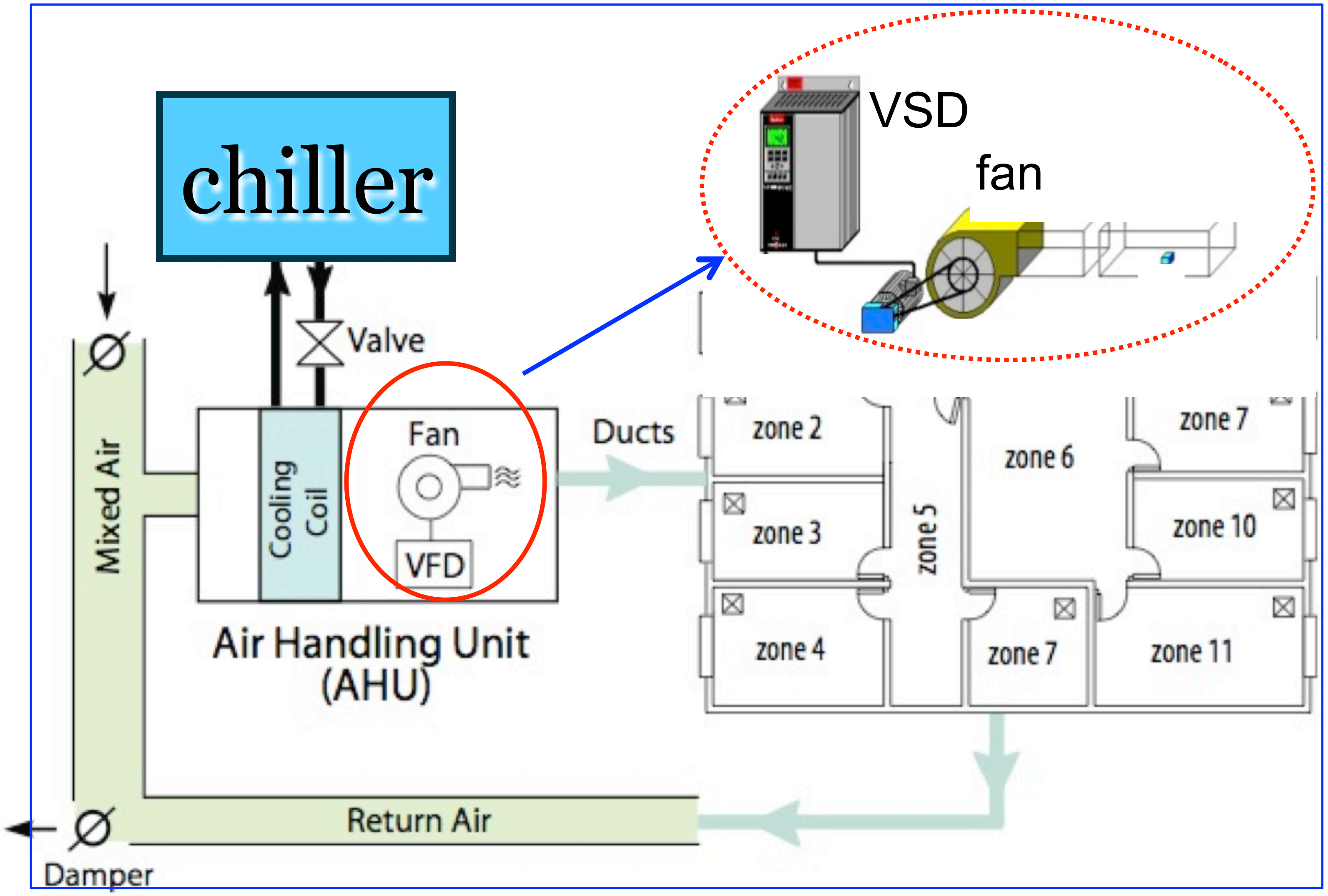
Pool pumps**

>12 hours		Minutes
Unacceptable Service	Just right!	Equipment degradation

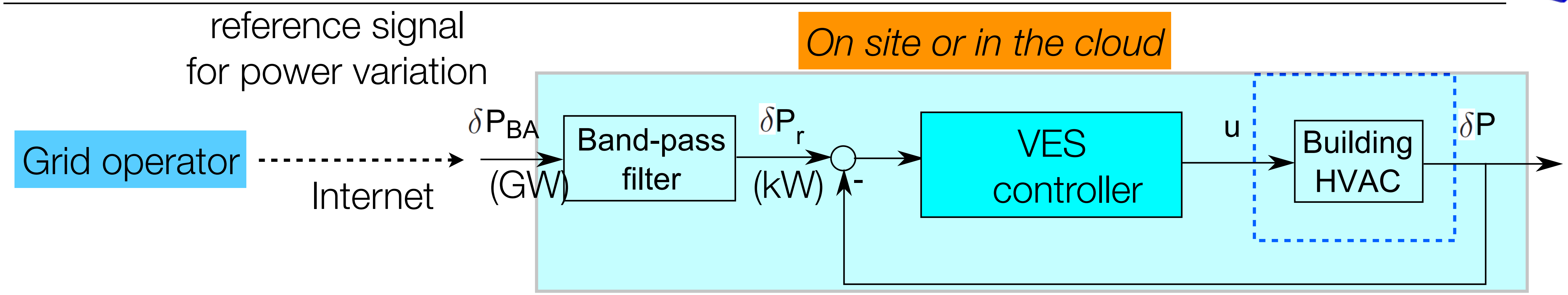
* Ancillary services through demand scheduling and control of commercial buildings, Y Lin, P Barooah, JL Mathieu, IEEE Transactions on Power Systems, Jan 2017

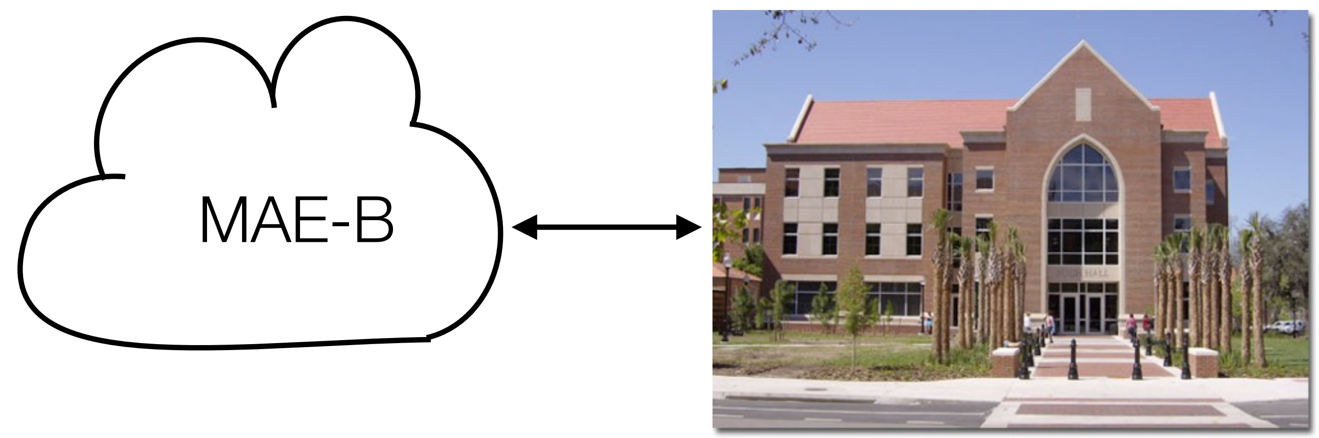
** Ancillary service to the grid using intelligent deferrable loads S Meyn, P Barooah, A Busic, Y Chen, J Ehren, *IEEE Transactions on Automatic Control*, Nov. 2015

VES from commercial building HVAC systems

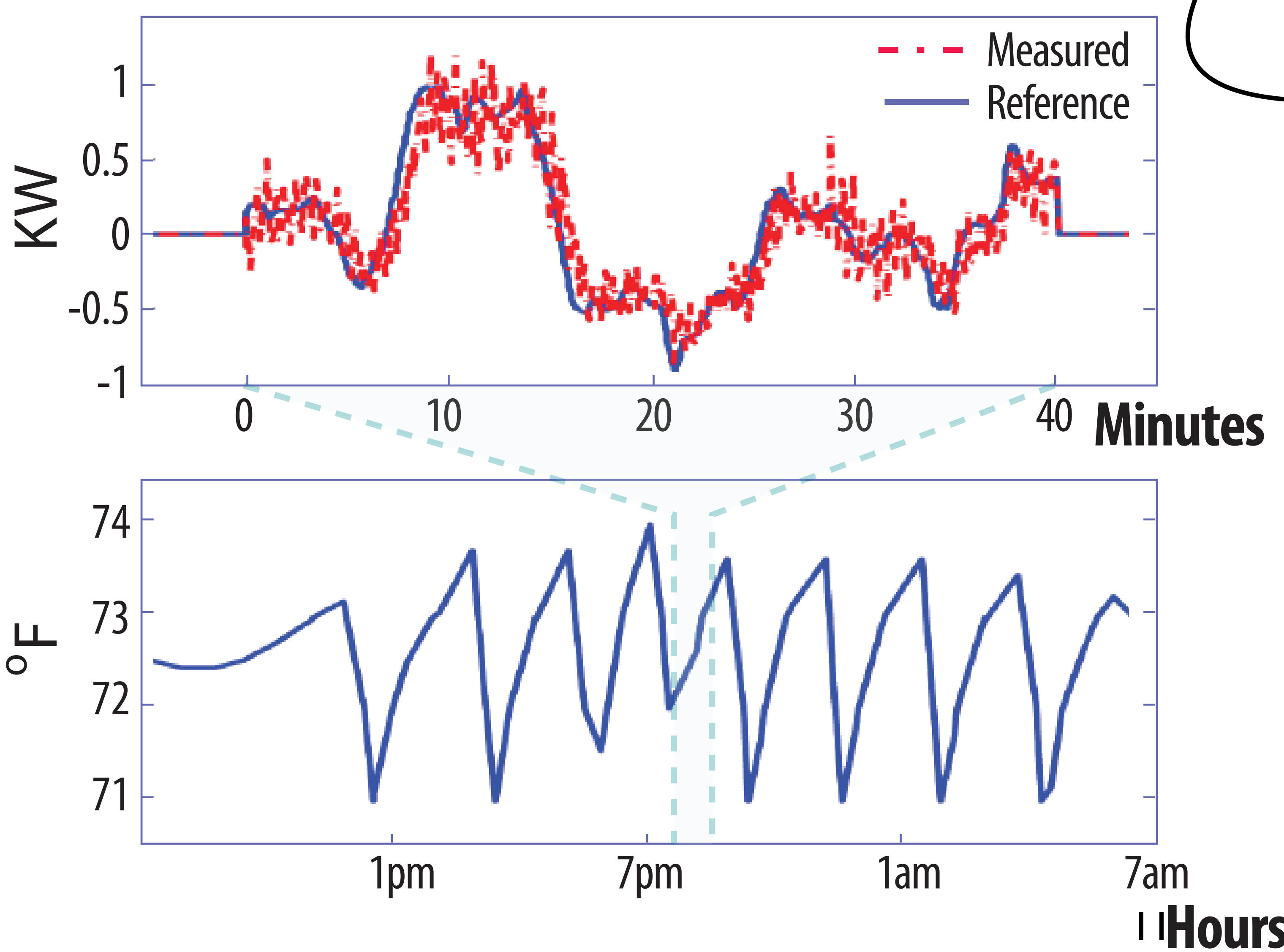


Demonstration at Pugh Hall, UF





u=Air flow rate in AHU2 in Pugh Hall



First experimental demonstration of a building providing “regulation” service*

* "Experimental evaluation of frequency regulation from commercial building HVAC systems", Y Lin, P Barooah, S Meyn, T Middelkoop, IEEE Transactions on Smart Grid 6 (2), 2015

Answers to Q1 (on QoS)

Q1. How to maintain QoS?

— The demand variation has to be band-limited (depending on type of load)

Q1. (part 2) How much VES capacity is out there?

— Nationwide capacity in the [1 - 10 min] time-scale is > 6 GW from fans alone*.
— With chillers, flexibility is in [30 mins - 2 hrs] time scale, capacity is 5 times**

Cost: Inexpensive (only change in software, no new hardware)

* H Hao, A Kowli, Y Lin, P Barooah, S Meyn, “Ancillary Service to the Grid through Control of Fans in Commercial Building HVAC Systems”, *IEEE transactions on smart grid*, 5(4), 2014

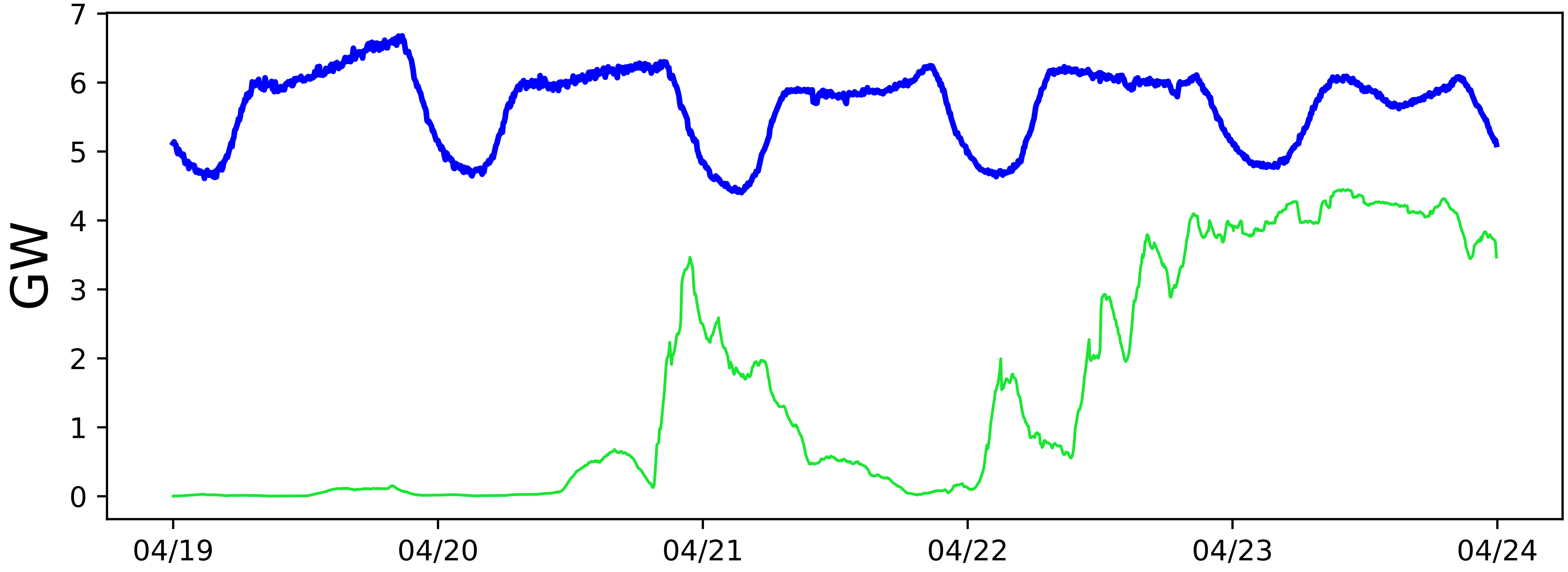
** Ancillary services through demand scheduling and control of commercial buildings, Y Lin, P Barooah, JL Mathieu, IEEE Transactions on Power Systems, Jan 2017

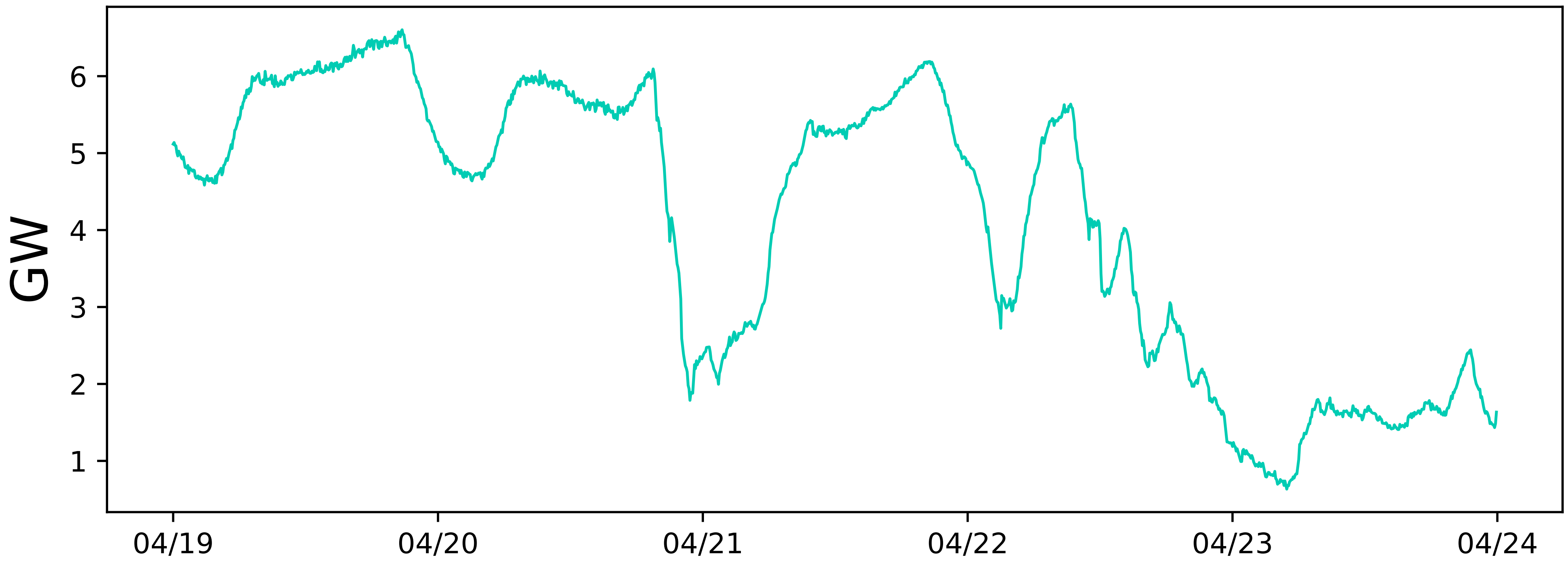
**Ancillary services through demand scheduling and control of commercial buildings, Y Lin, P Barooah, JL Mathieu, IEEE Transactions on Power Systems, Jan 2017

Q2: How to meet the grid's needs?

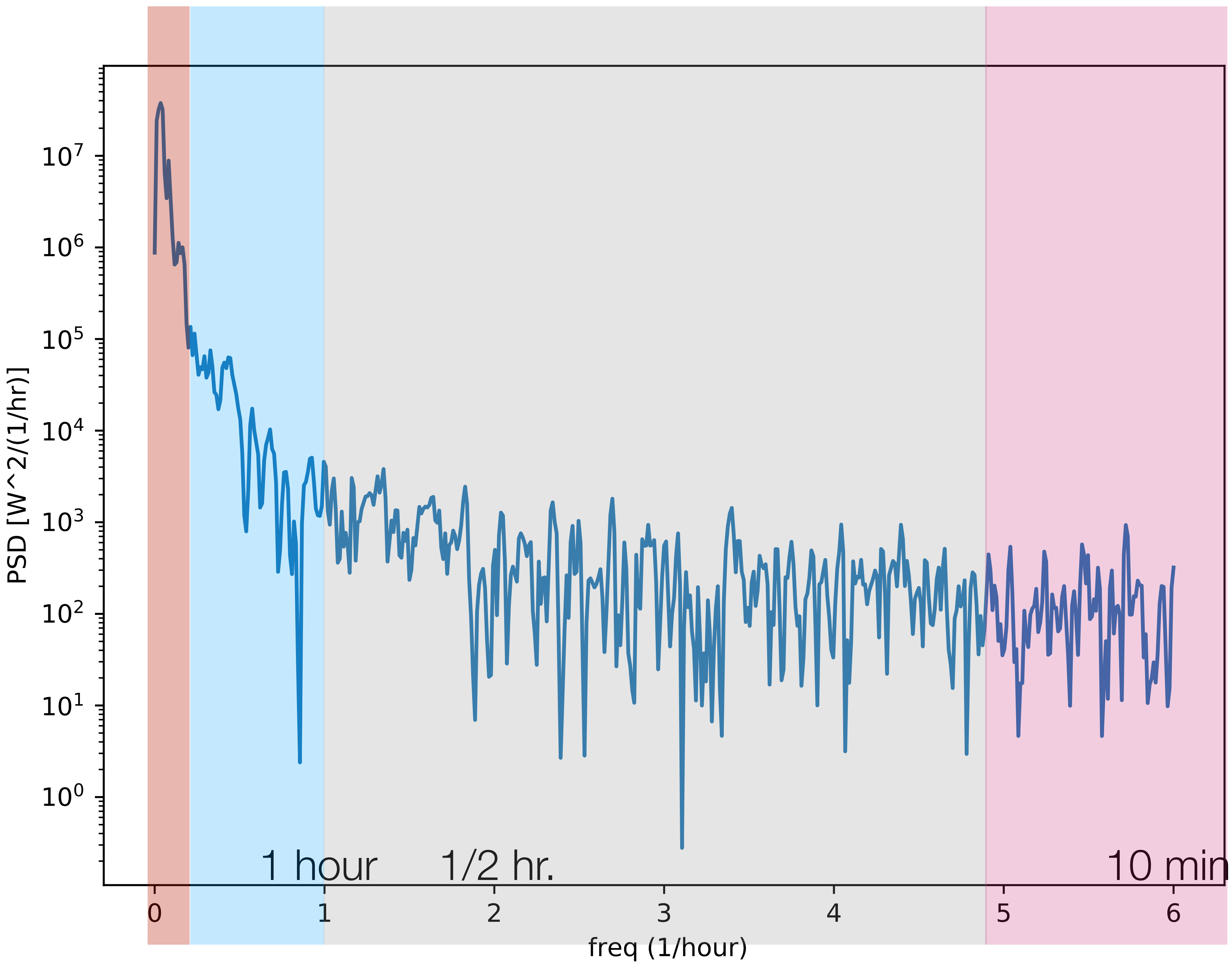
The net demand

Has to be supplied by controllable resources:
Controllable generators, batteries, …





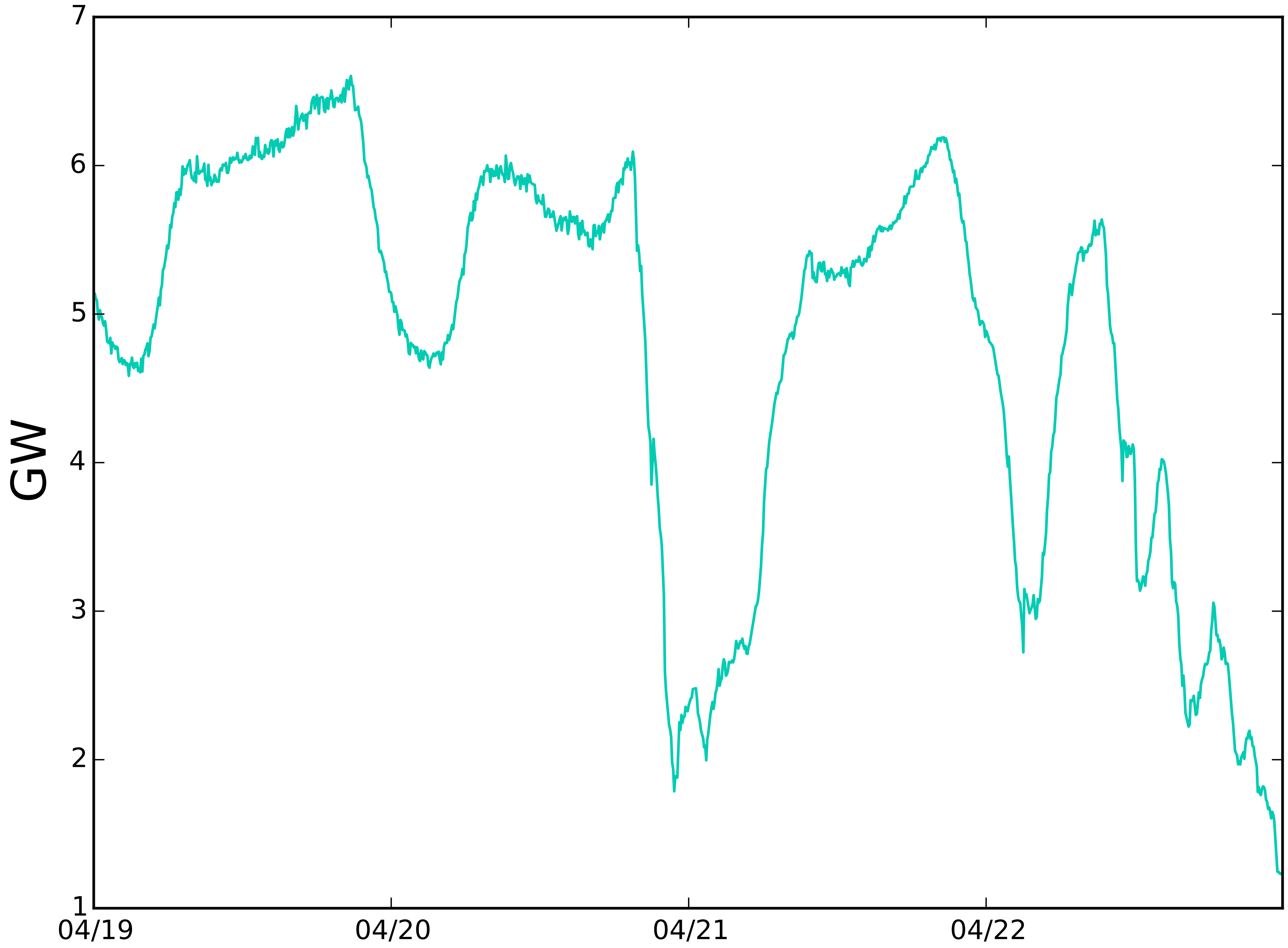
Net load as a function of frequency



Low freq **Medium freq (low)** **Medium freq (high)** **High freq.**

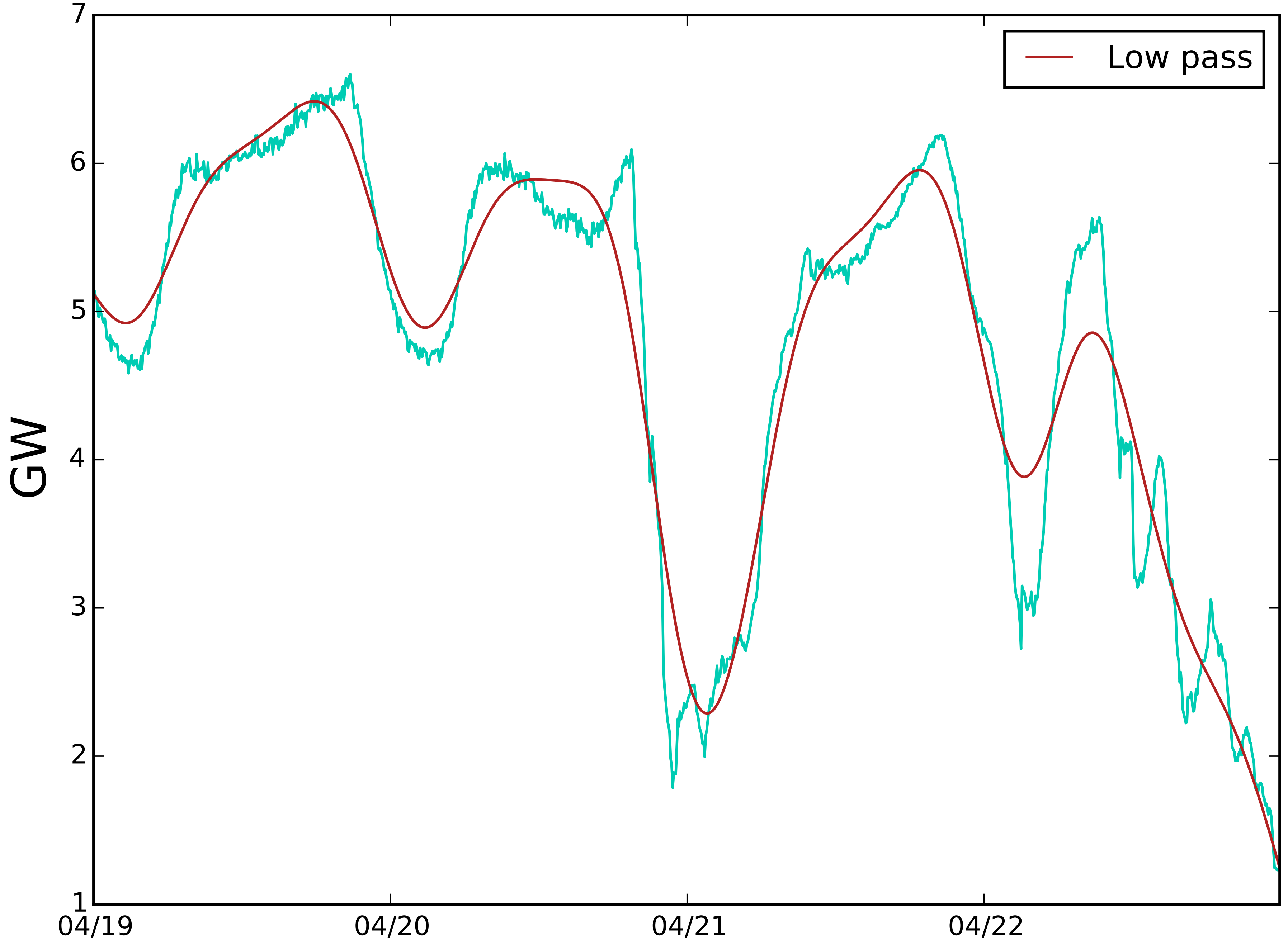
PSD estimate from BPA's data (Jan-June of 2018)

Ans. to Q2: Decompose net-load into distinct time-scales



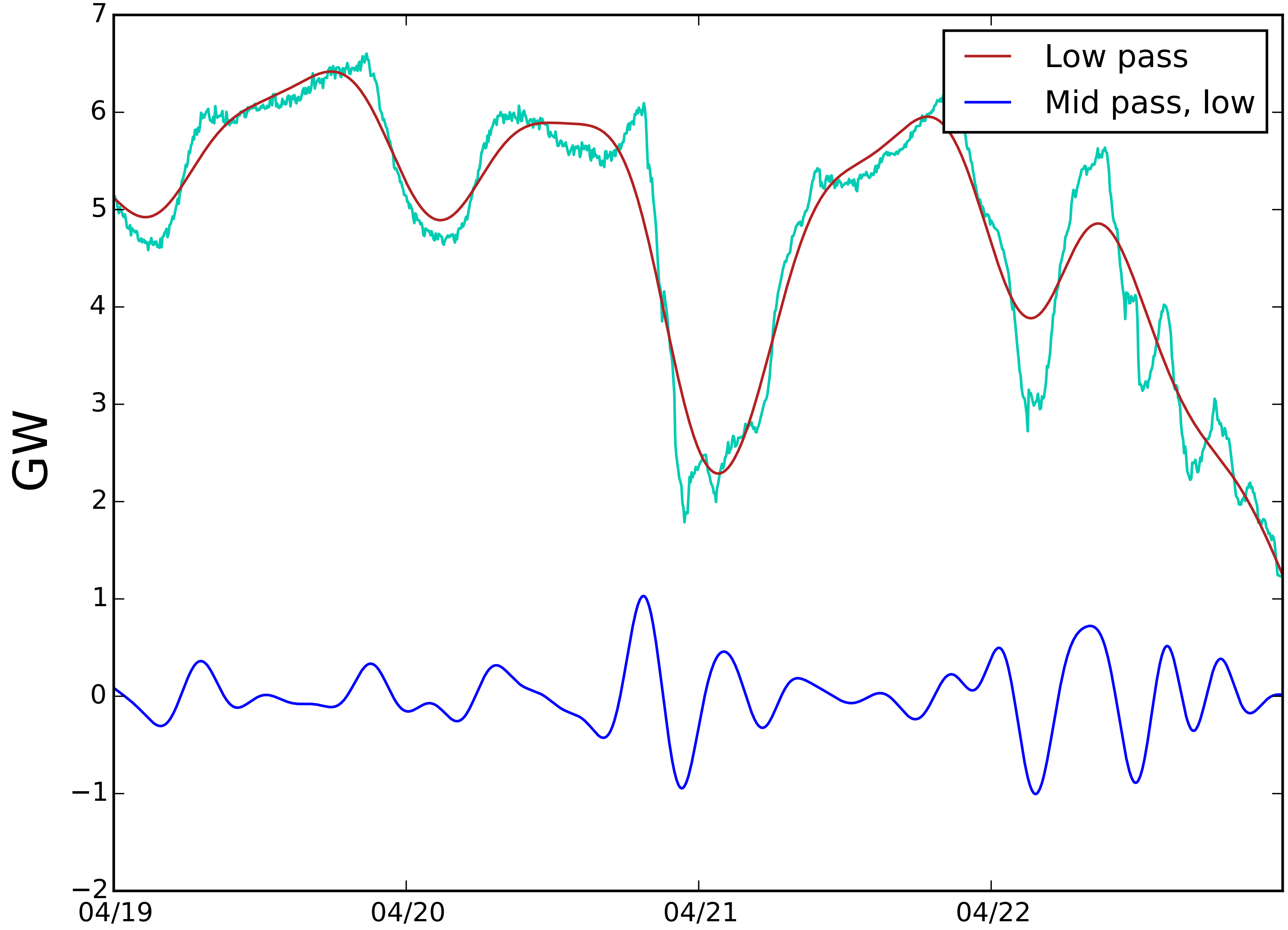
Low-pass component: Ideal for ...

Traditional generators



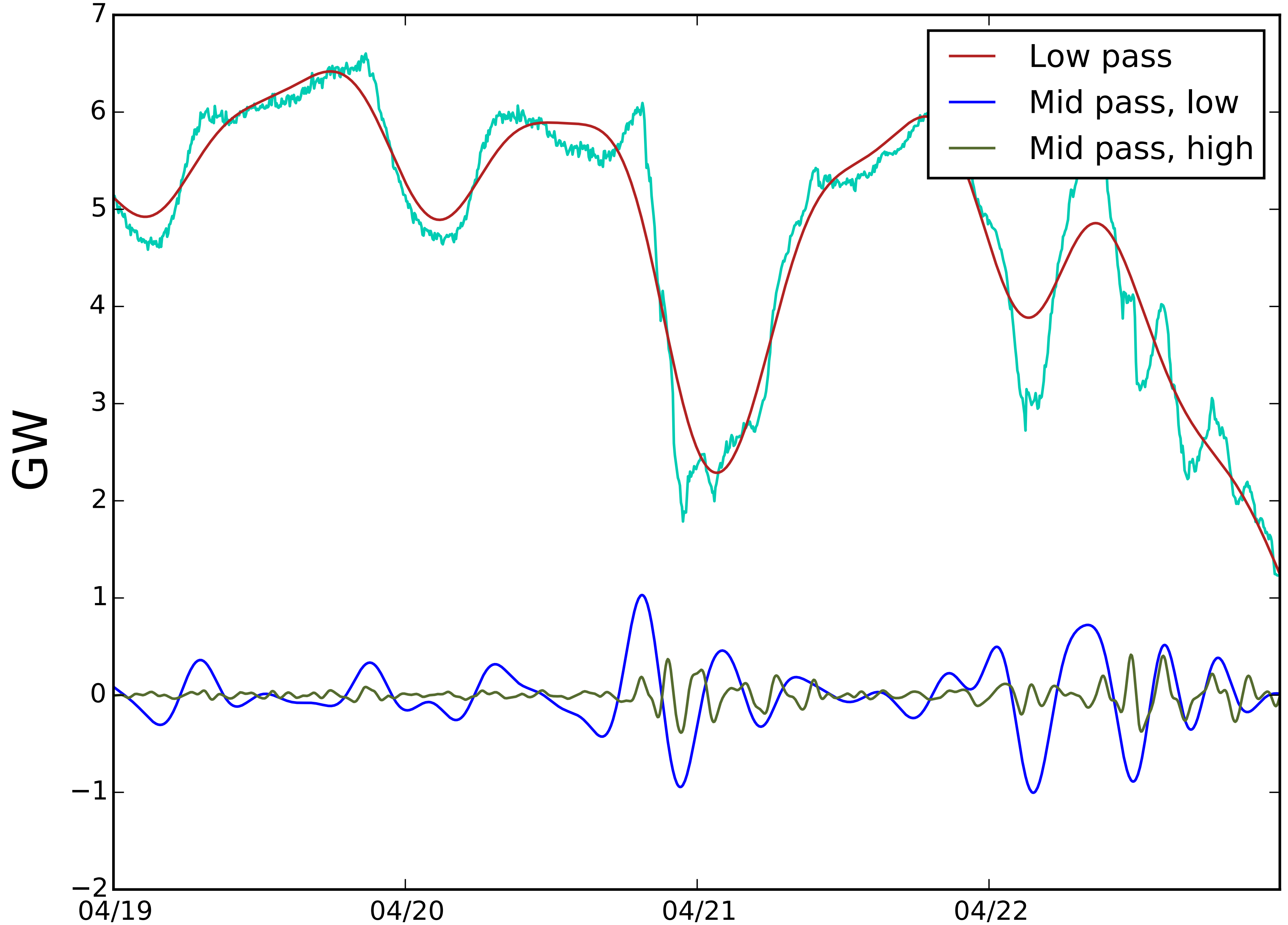
Mid-pass (low) component: Ideal for VES from...

Loads with flexibility of many hours (industrial production,…)



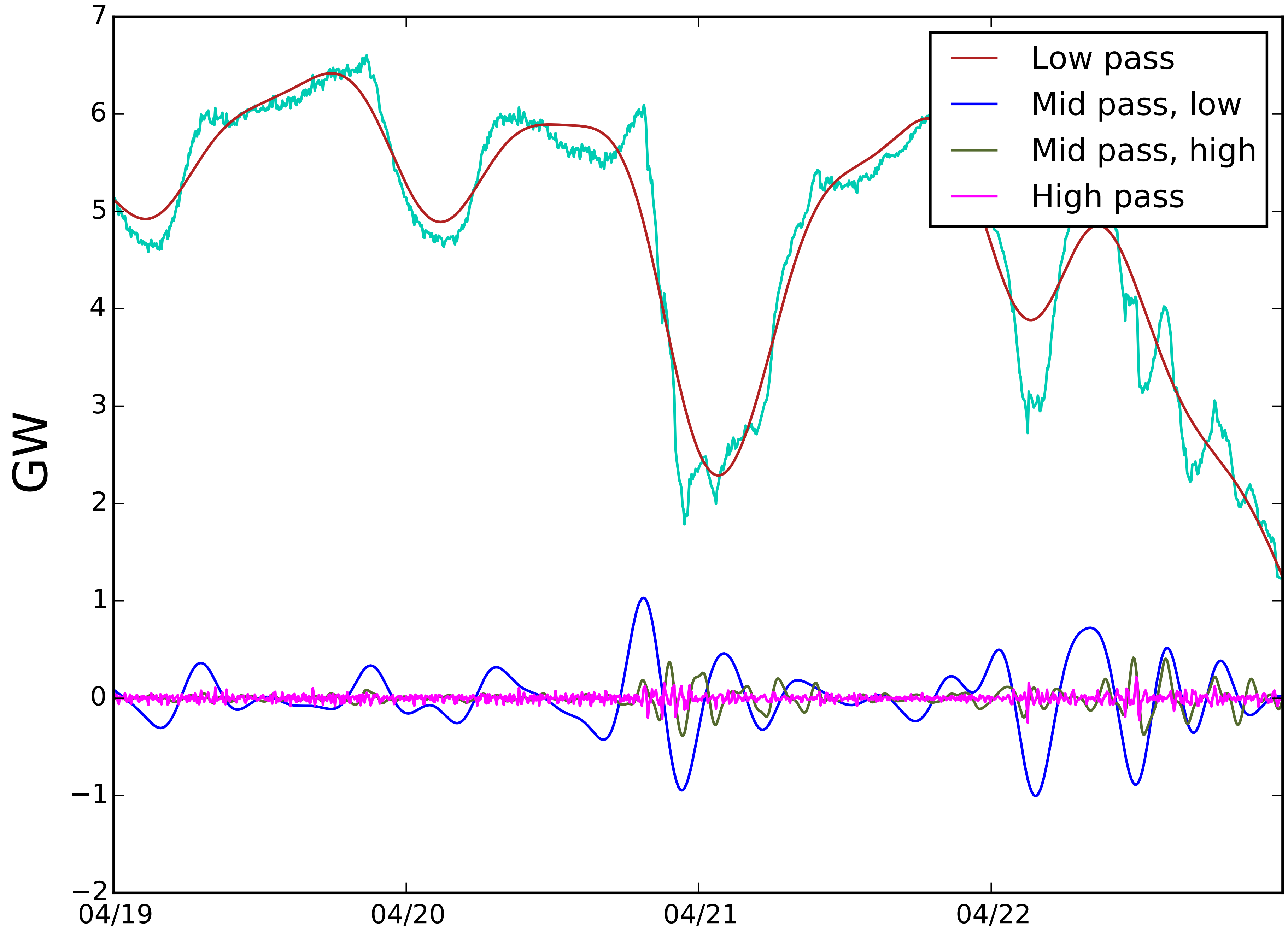
Mid-pass (high) component: Ideal for VES from...

Loads with flexibility of hours to minutes
(water pumps, water heaters, residential HVAC,..)

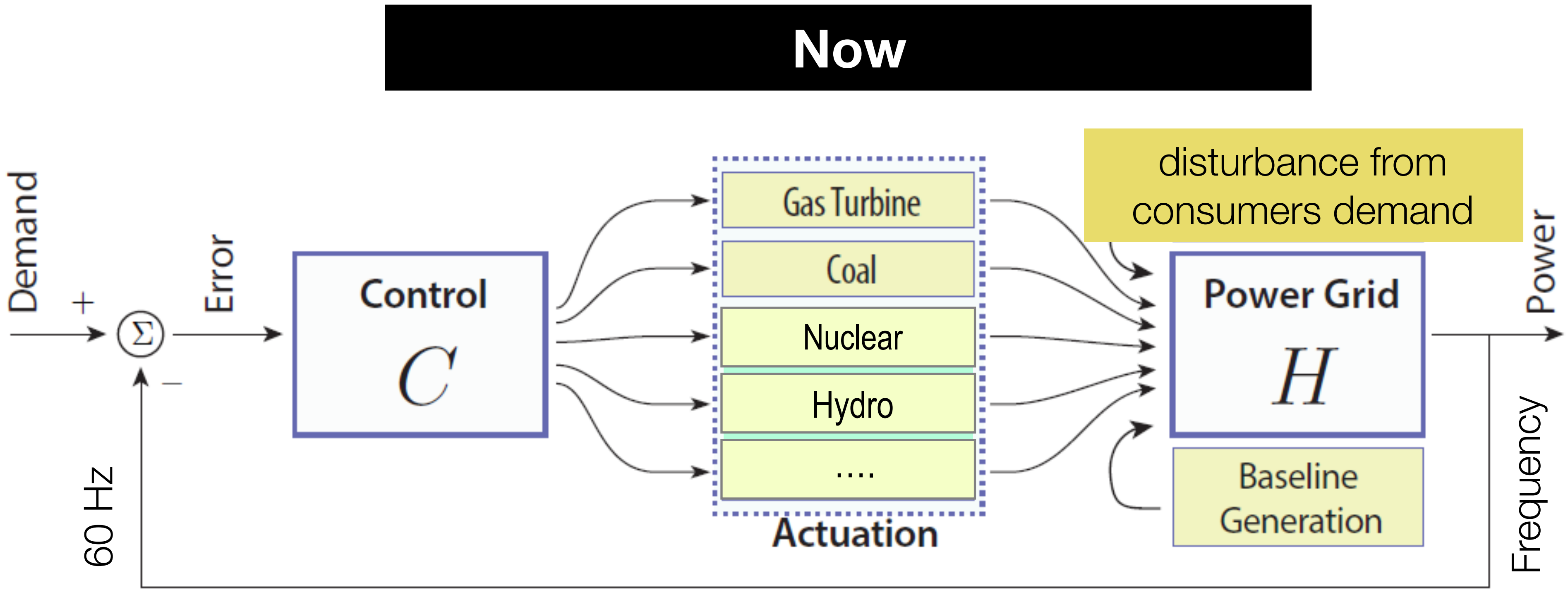


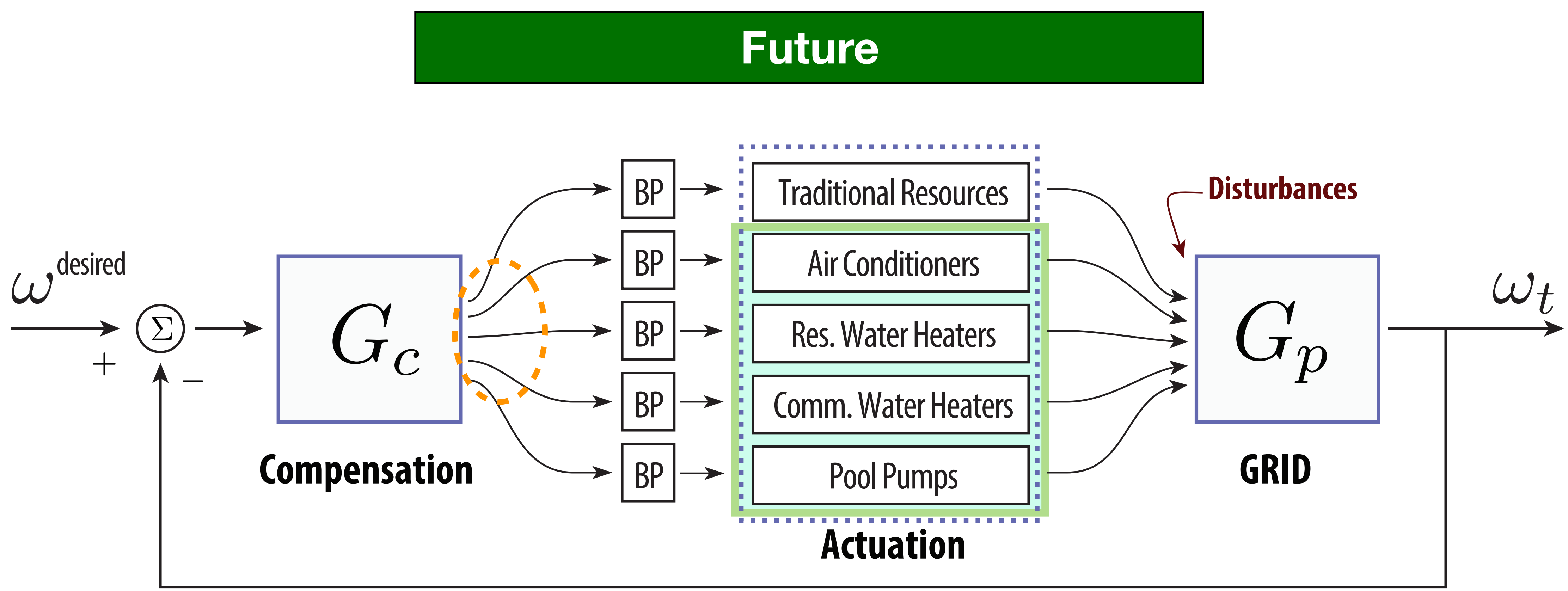
High-pass component: Ideal for VES from...

Loads with flexibility in minutes
(Commercial HVAC, batteries,...)

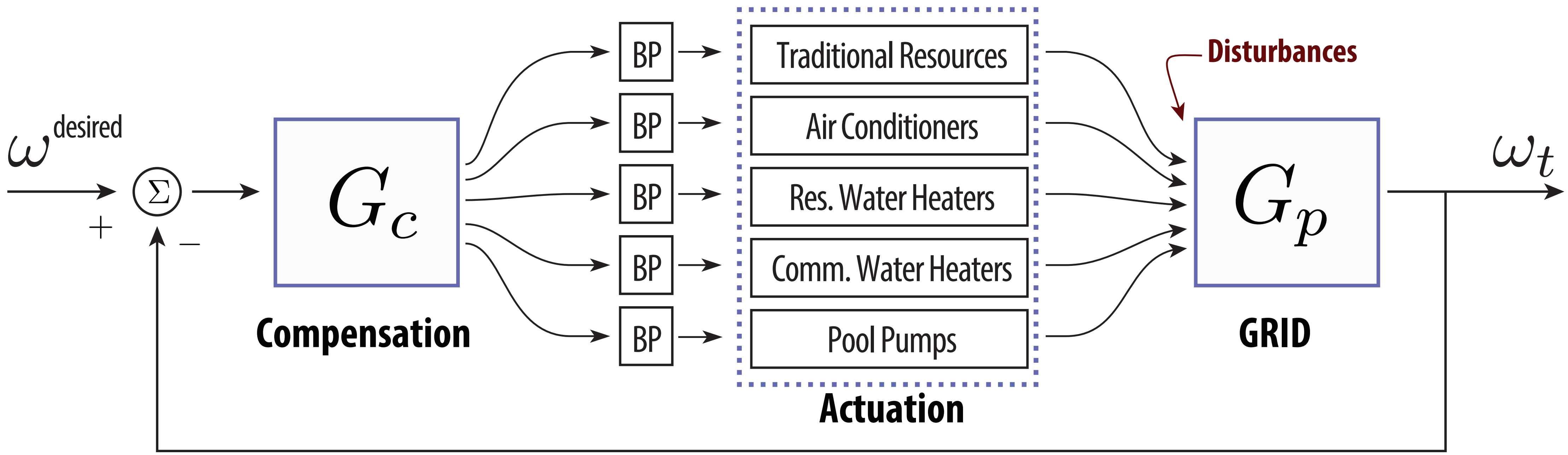


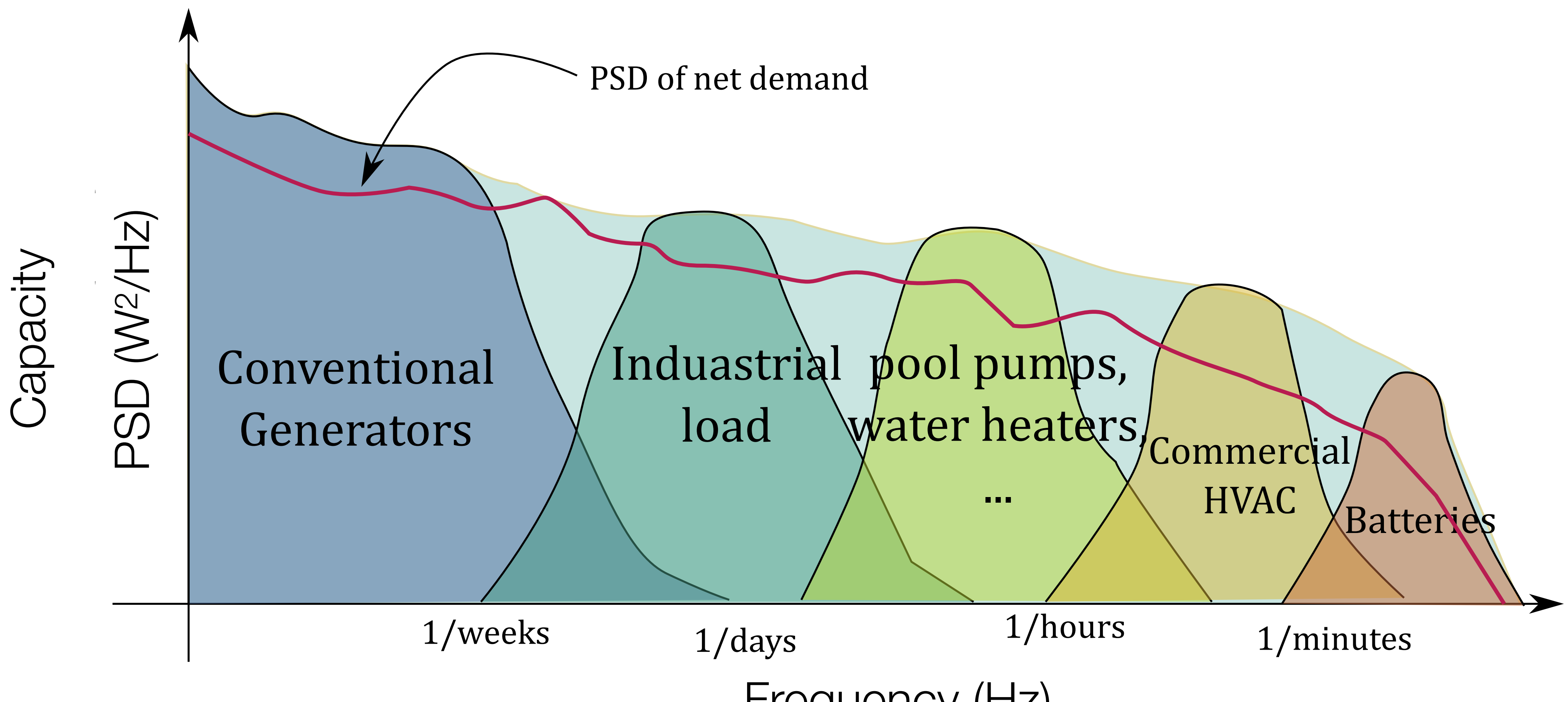
Green future with virtual batteries





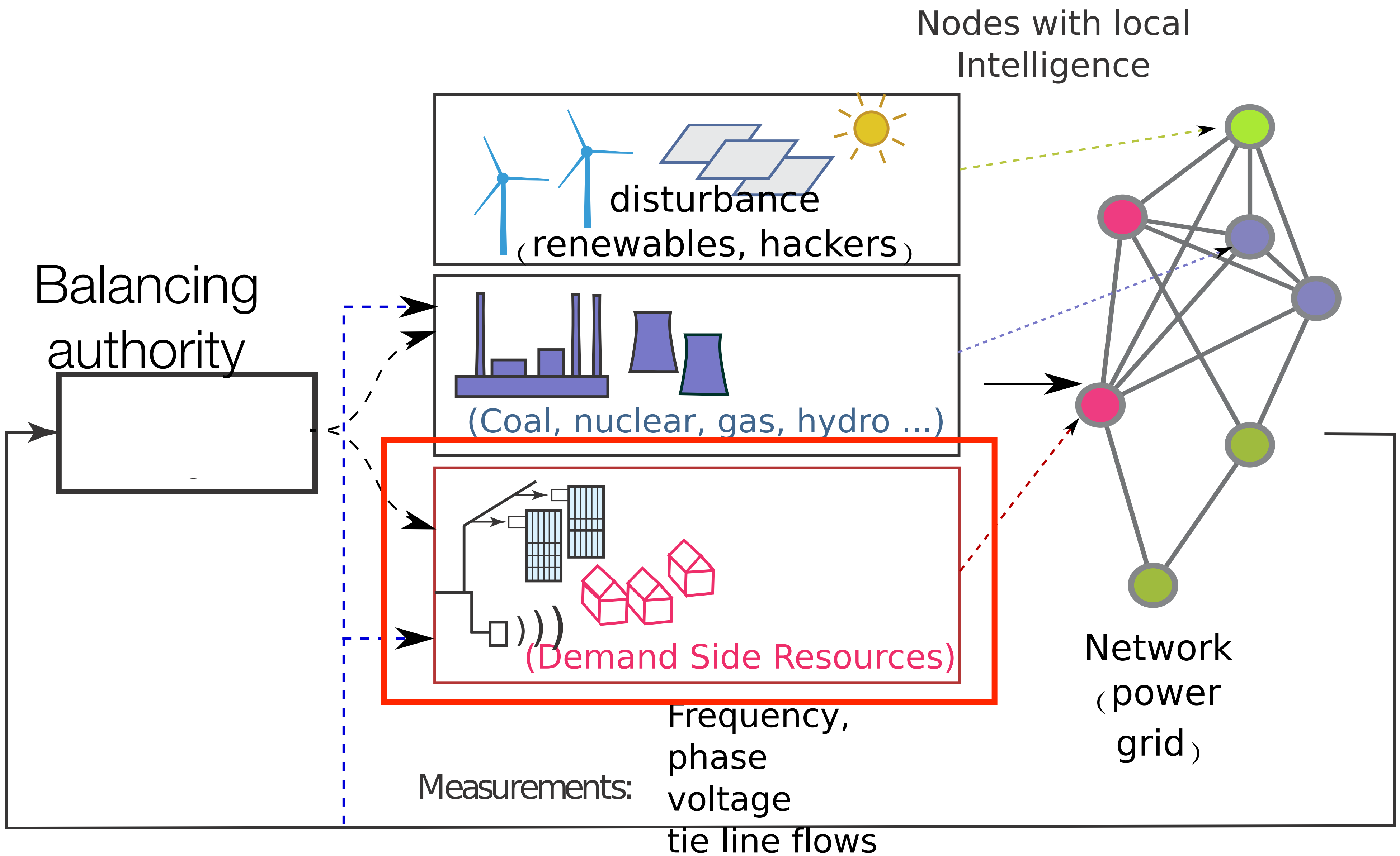
New resources for the future grid





The problem is coordination

Distributed control

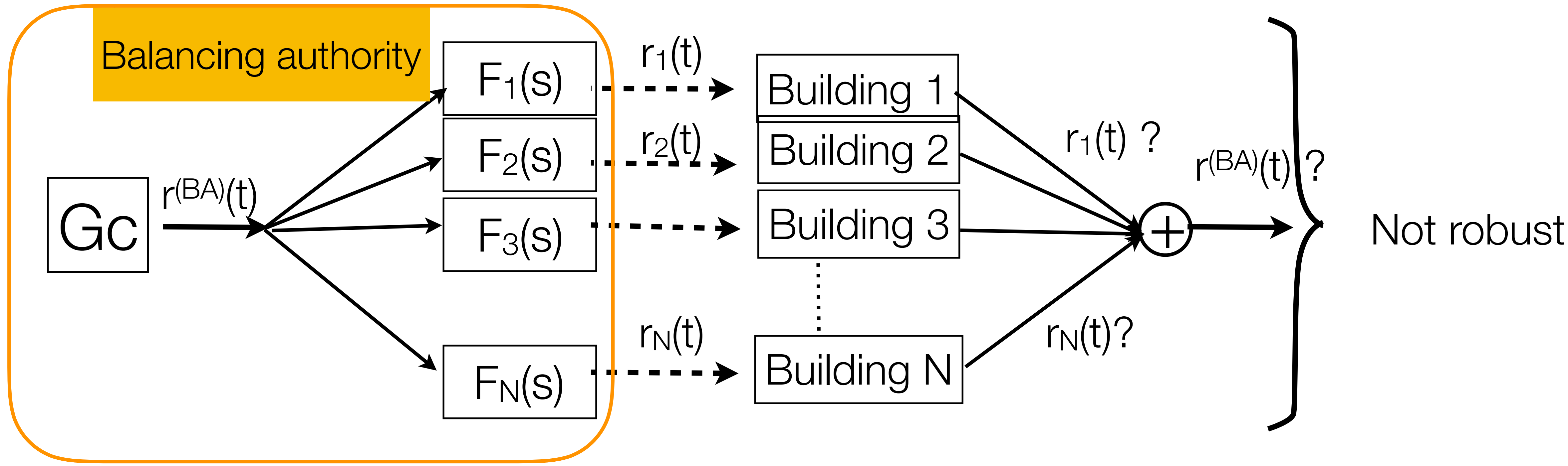


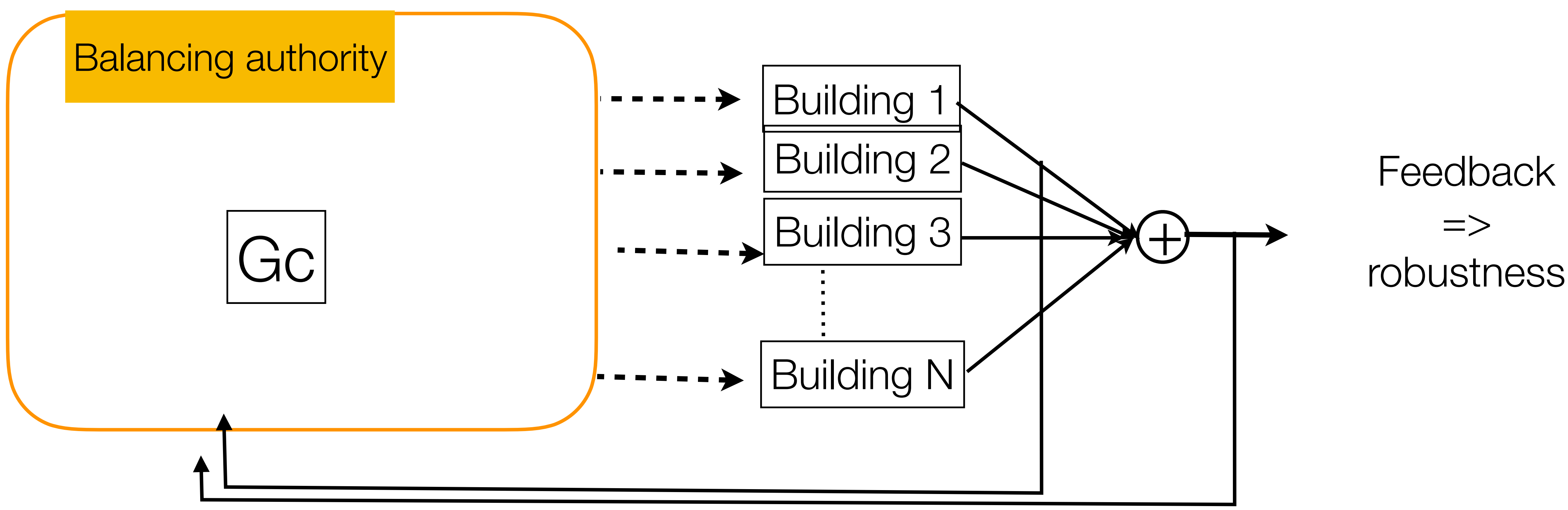
What properties must such a coordination satisfy:

1. Reliable and predictable to consumer
2. Reliable and predictable to grid operator

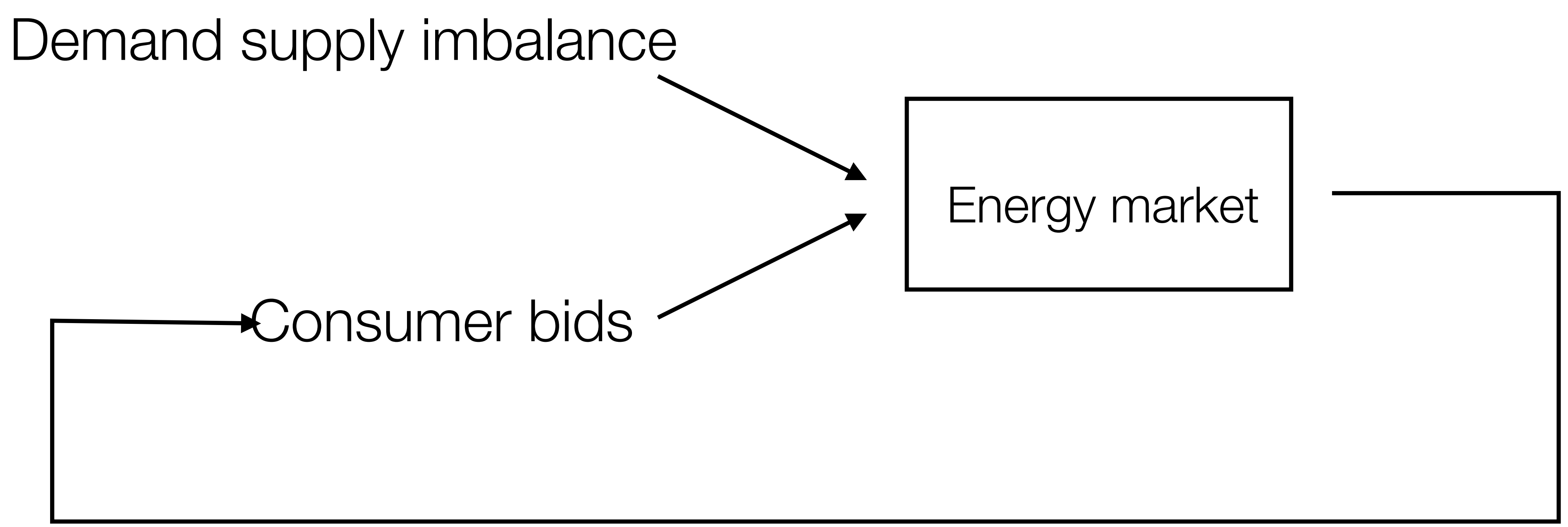
How to coordinate many loads?

Centralized decision-making is either not robust to uncertainty, or intractable in terms of communication/computation





1. Price based coordination



Demonstration: PNNL GridWise Project (*Hammerstrom et. al.*, 2007)

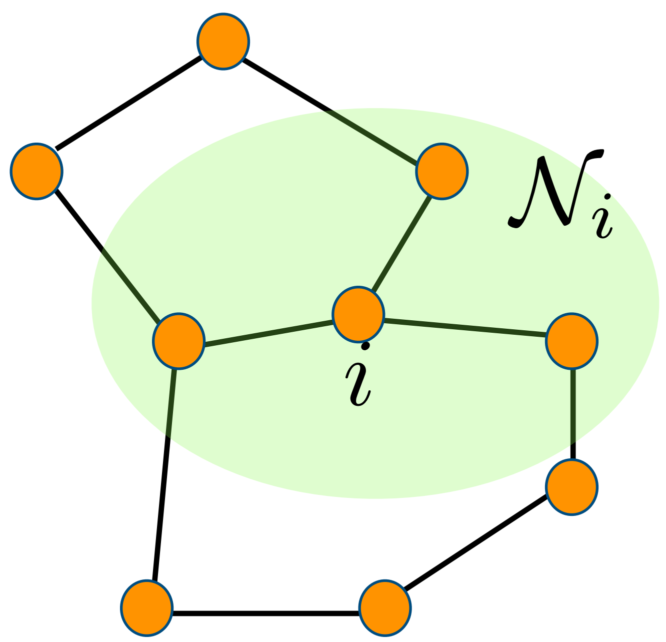
Risk: *large oscillations*
=> unreliable to both consumers and grid operators

2. Through inter-agent communication

Consensus

peer-to-peer averaging : information diffusion

$$x_{k+1}^{(i)} = \frac{1}{|\mathcal{N}_i|} \sum_{j \in \mathcal{N}_i} x_k^{(j)}$$



"All agent states converge to a common value"

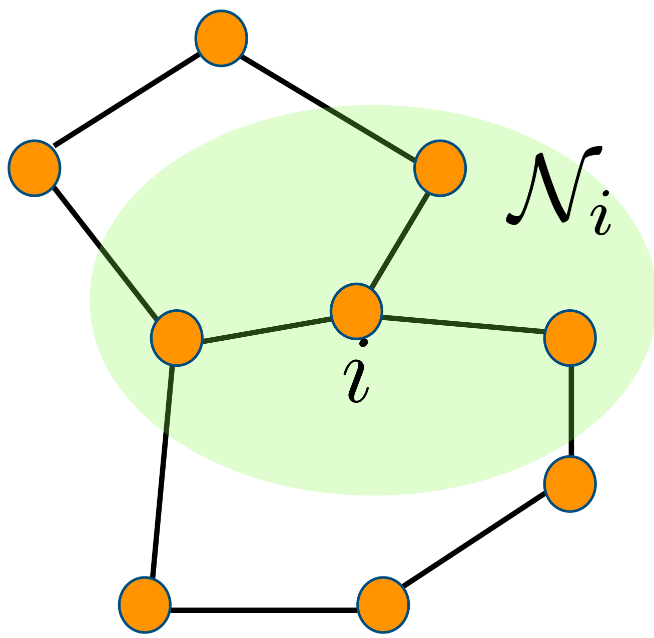
Distributed optimization can be performed through an information diffusion scheme (extensive literature)

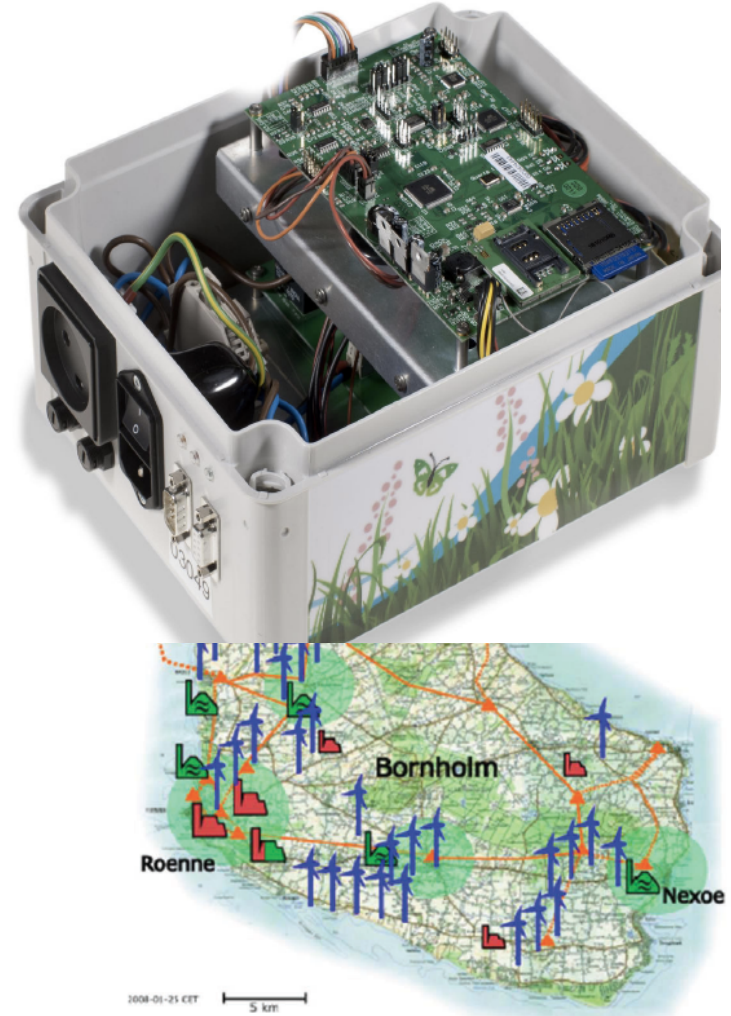
TITLE	CITED BY	YEAR
Coordination of groups of mobile autonomous agents using nearest neighbor rules A Jadbabaie, J Lin, AS Morse IEEE Transactions on automatic control 48 (6), 988-1001	7073	2003

Risk: ?

Power grid: global state from local information

1. Grid-frequency can be measured at each node of the network
2. Frequency deviation provides an estimate of demand-supply imbalance in the whole grid (generator droop!)



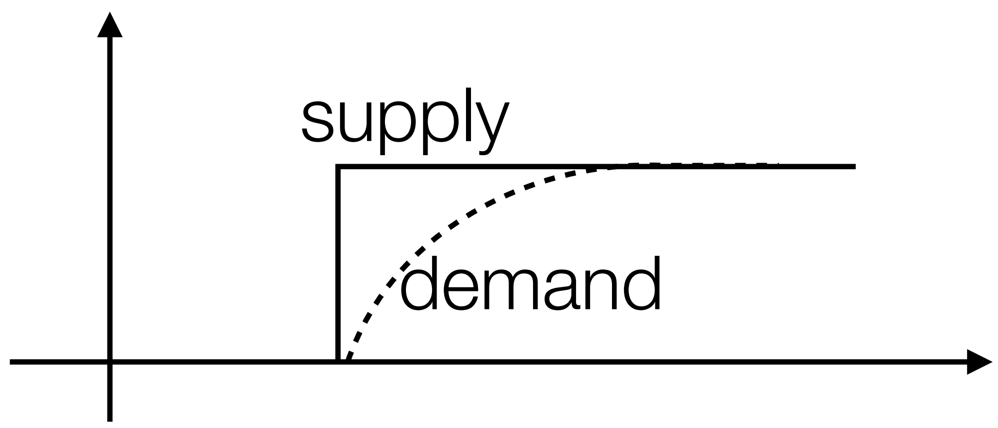


Demand as Frequency Controlled Reserve: Implementation and practical demonstration, Douglass et al., *ISGT Europe, 2011*

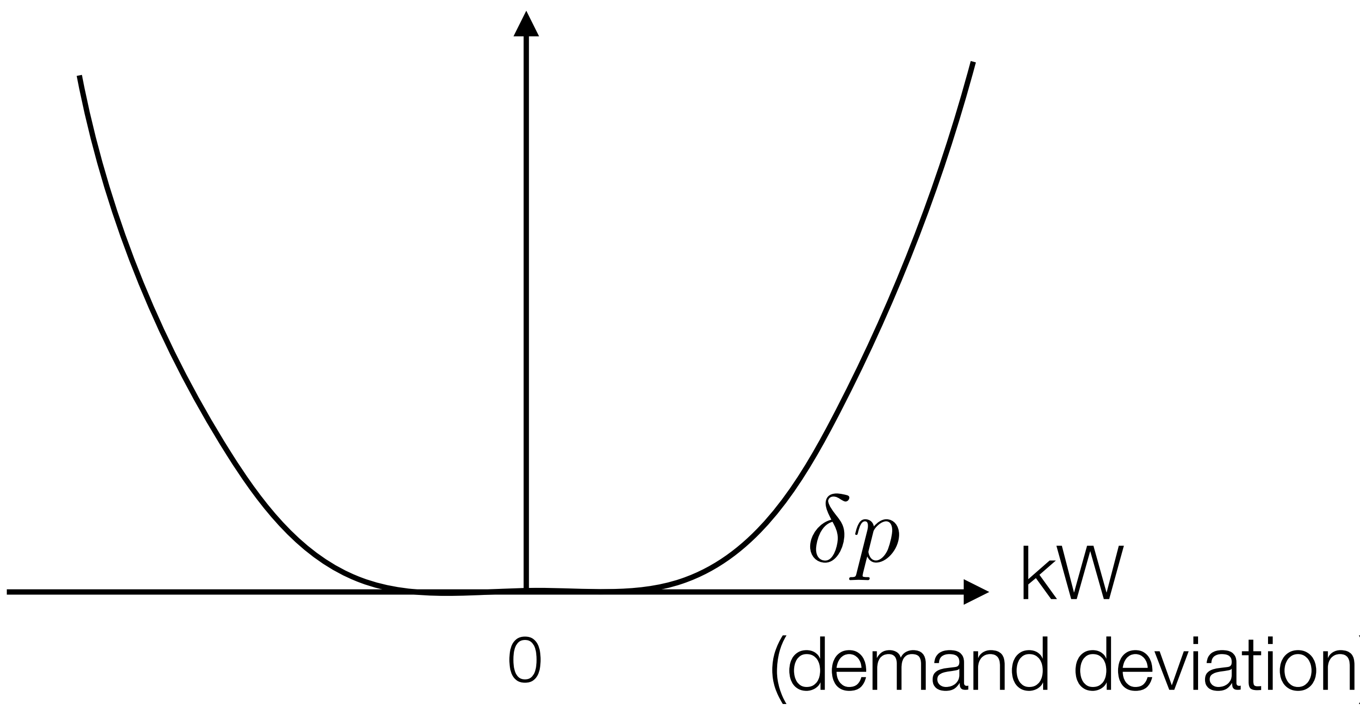
- Schweppe, 1980: (decentralized control of load with frequency measurement)

Recent: Distributed optimization without communication

Minimize total consumer disutility
Such that
Demand-supply imbalance = zero



Consumer disutility

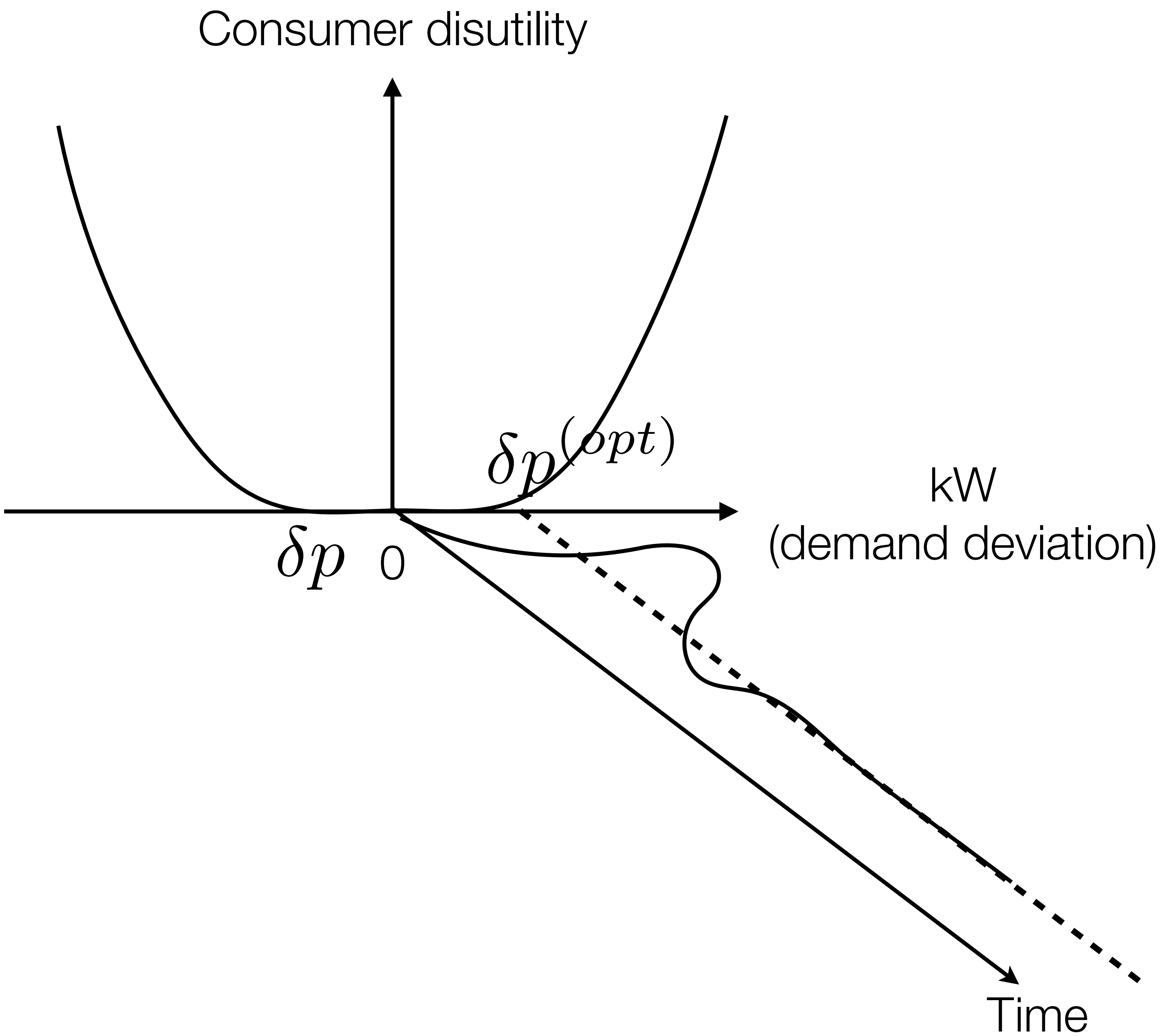


Communication free distributed algorithms to solve this problem:

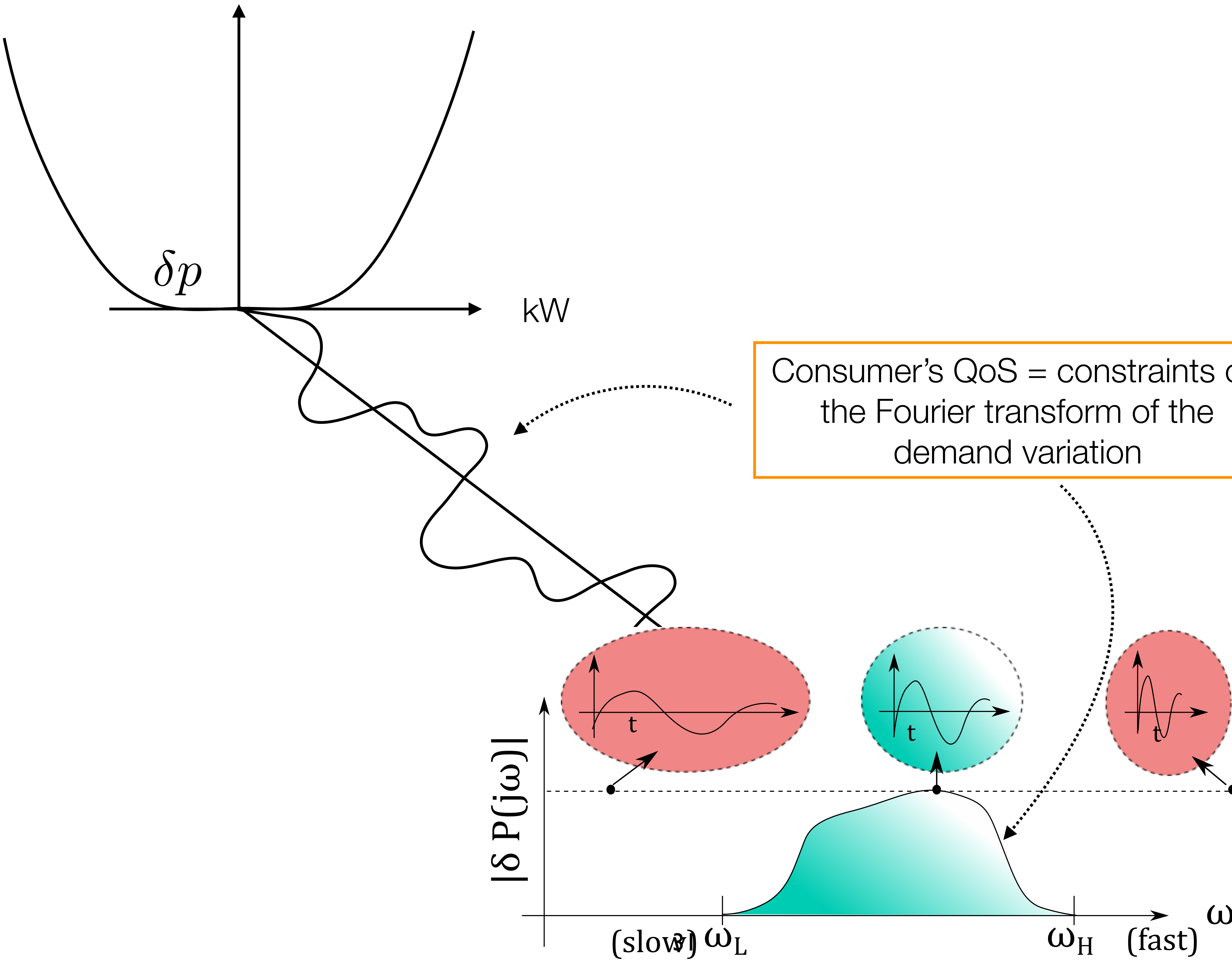
> S. Low and colleagues, (2013— …)
> Dorfler and colleagues,
> J. Cortes…,
> C. De Persis…

But…

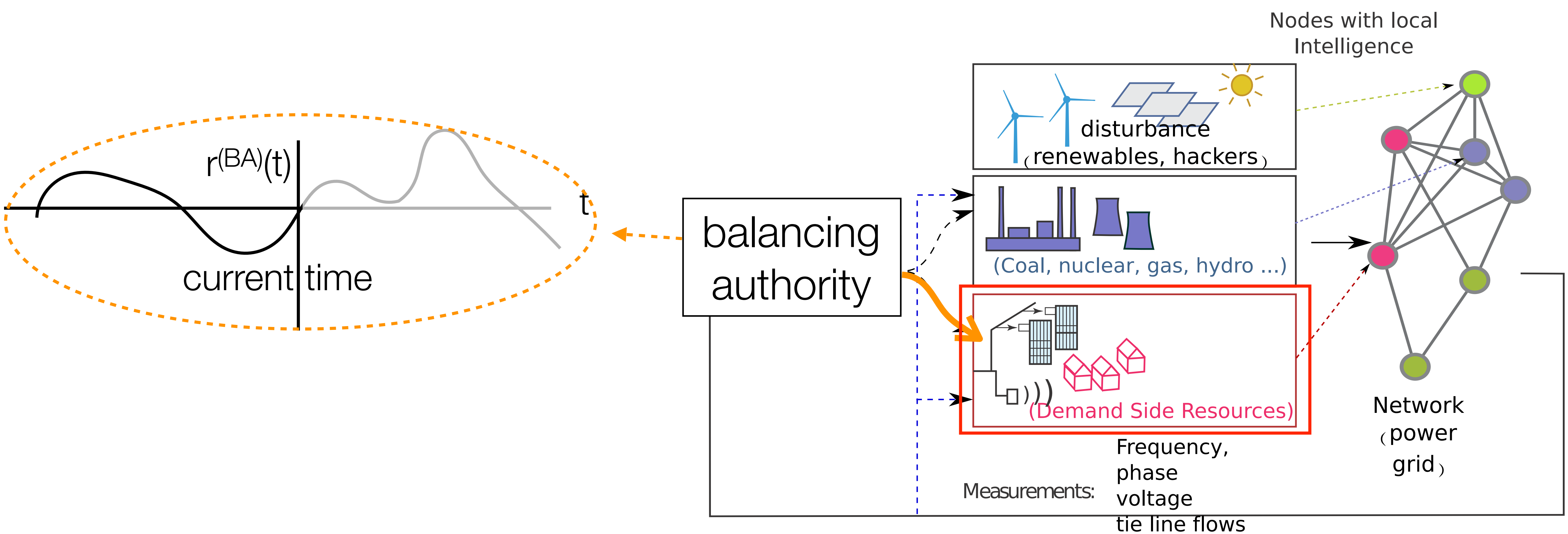
static optimization problem:
Consumer's QoS is only a function of kW, not kWh!



Need: Dynamic optimization (optimal control)



Our proposal: distributed optimal control w/o inter-agent com.



Hierarchical control architecture:

1. Broadcast from balancing authority to every flexible load:
   the *desired total demand deviation*
2. At each load:
   solve a finite, receding horizon optimal control problem (MPC)
   minimize grid-frequency deviation by varying my own demand,
   enforces constraints on demand variation to ensure QoS
3. Avoid high-gain instability by …

At a load, at every time instant t

$$\min_{u_t,\ldots,u_{t+N}} \sum_{k=t}^{t+N} \omega_k^2$$

local reference

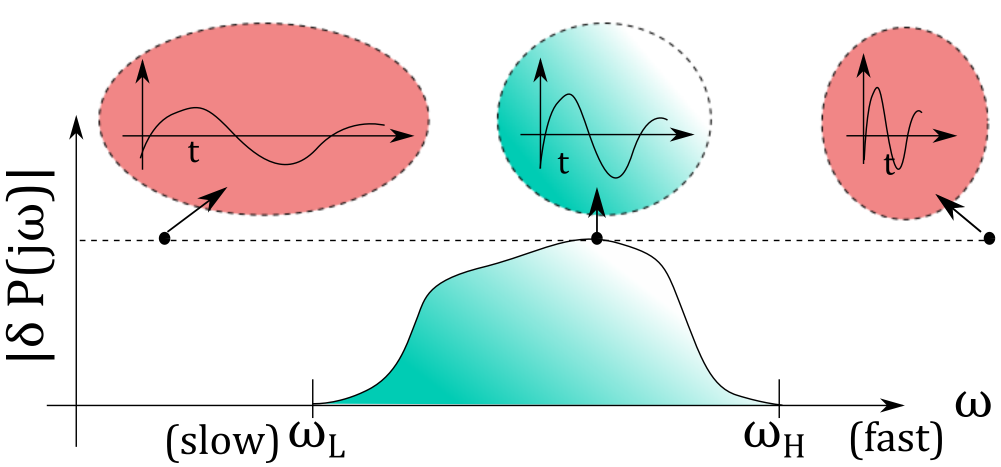
subject to

$$\omega_k = \mathrm{g}(\hat{r}_k - u_k)$$

$$\ldots \leq u_k \leq \ldots$$

$$|U_t| \leq \alpha_0, \ldots, |U_{t+N}| \leq \alpha_N$$

DFT of the control signal



Coordination to avoid instability:
online learning of local reference

$$\hat{r}_k = \rho_k r_k^{(BA)}$$

$$\rho_k = \left[\frac{r_k^{(BA)}}{u_k^{(all)}}\right] \rho_{k-1}$$

load i's estimate of total control effort of all loads

$$\omega_k = \mathrm{g}(r_k^{(BA)} - u_k^{(all)})$$

$$\Rightarrow u_k^{(all)} = r_k^{(BA)} - \frac{\omega_k}{\mathrm{g}}$$

Convergence and robustness

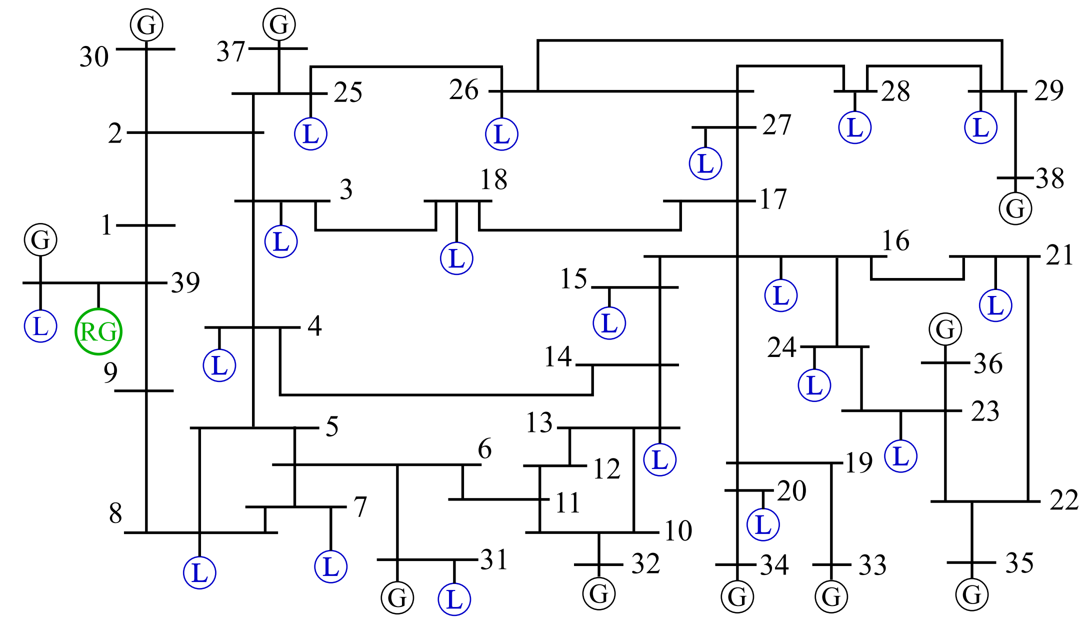
Theorem 1: Under highly idealized situations, the grid frequency converges to the nominal value*

Theorem 2: If measurement noise is very large, the local reference converges to 0.**

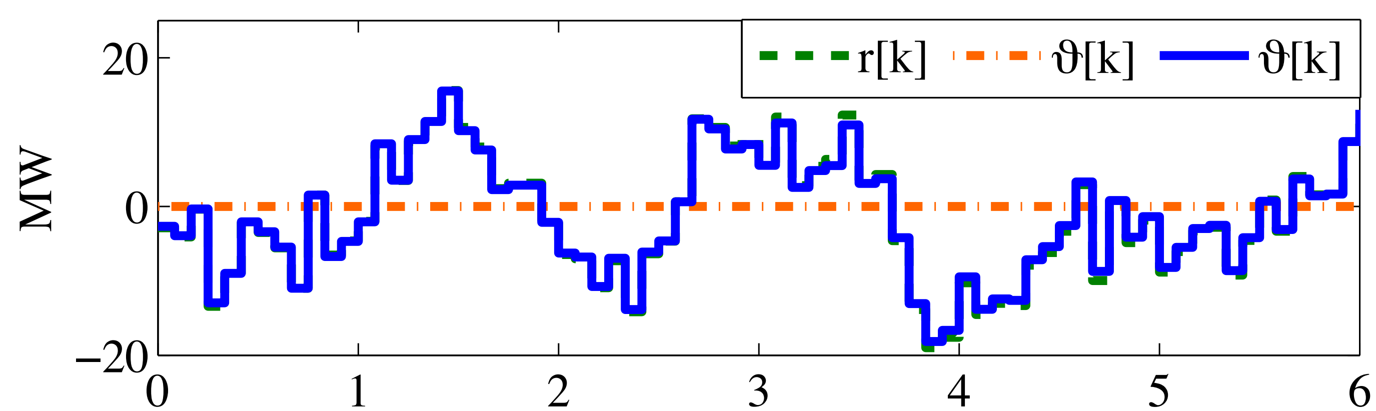
* "Virtual energy storage through decentralized load control with quality of service bounds", J Brooks, P Barooah, *American Control Conference*, 2017

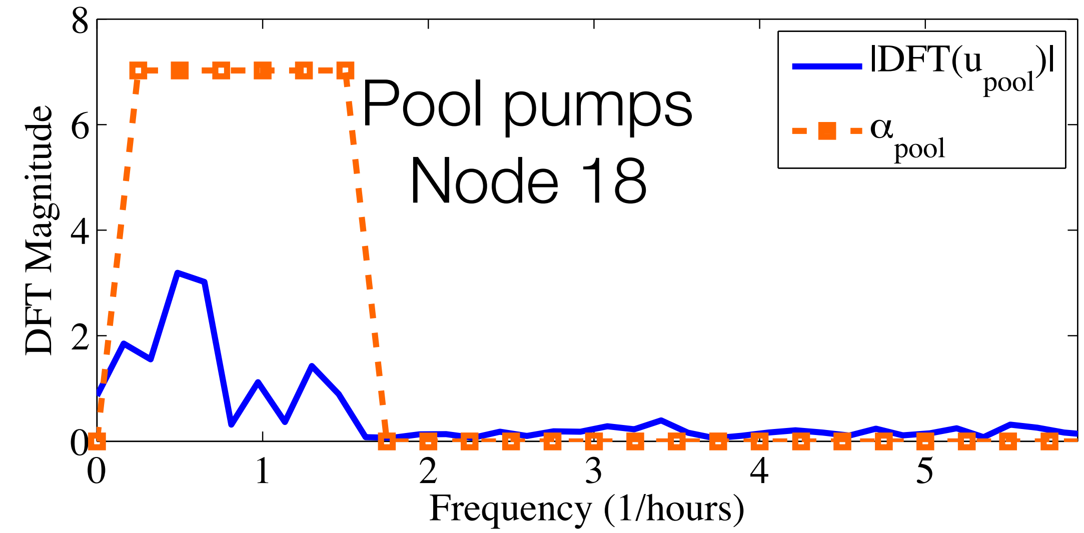
** Decentralized coordination of loads for ancillary services using MPC with Fourier domain constraints, J. Brooks, P. Barooah, *IEEE Trans. Smart Grid* (under review)

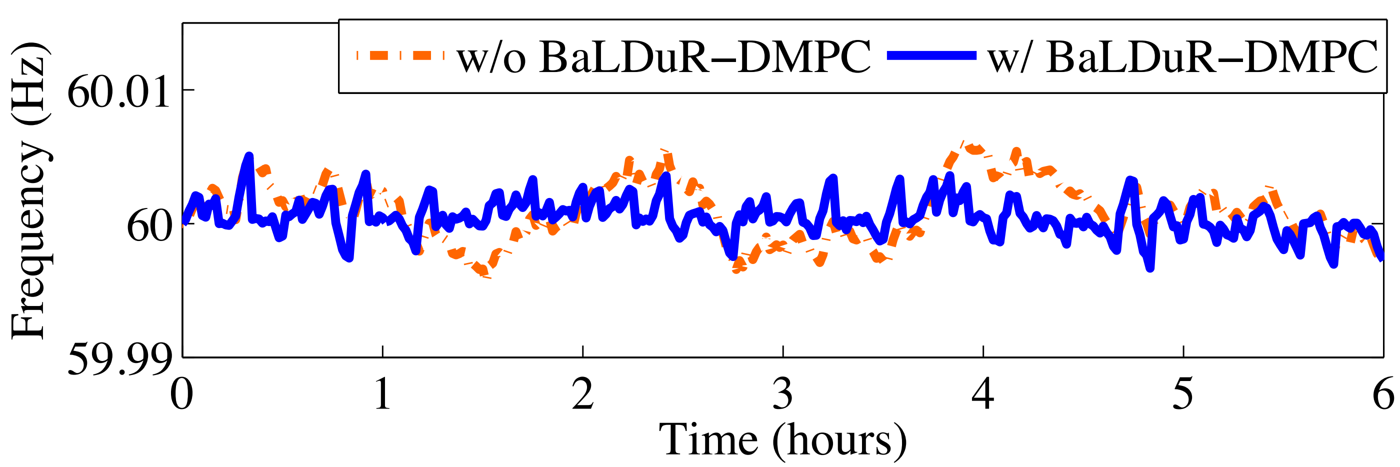
Simulations with IEEE 39 bus test network

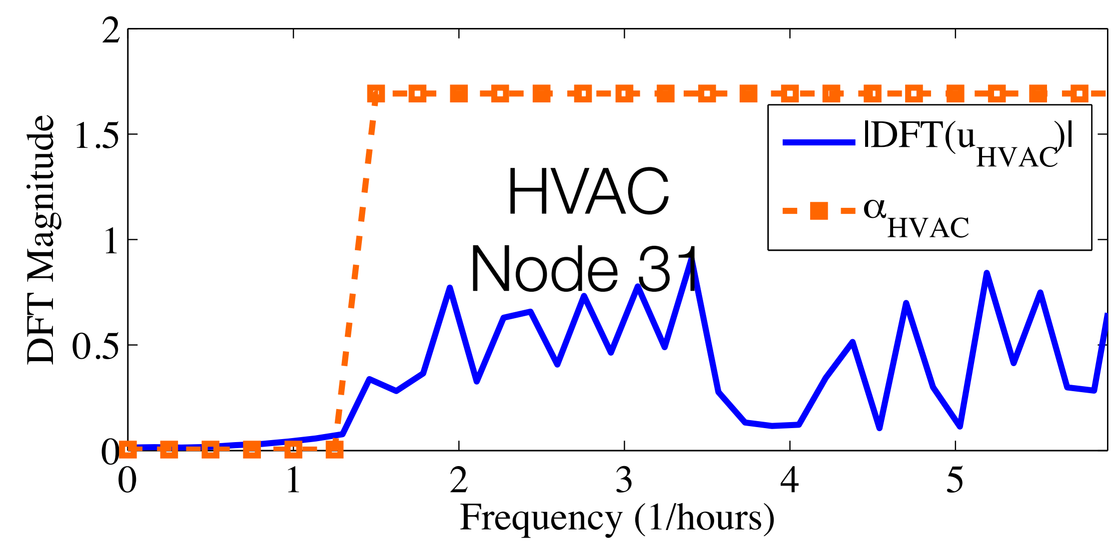


Load type	Frequency band
Refrigeration loads	[1/30 minutes, 1/5 minutes]
HVAC loads	[1/1 hour, 1/5 minutes]
Industrial smelting loads	[1/2 hours, 1/1 hour]
Pool pumps	[1/6 hours, 1/1 hour]



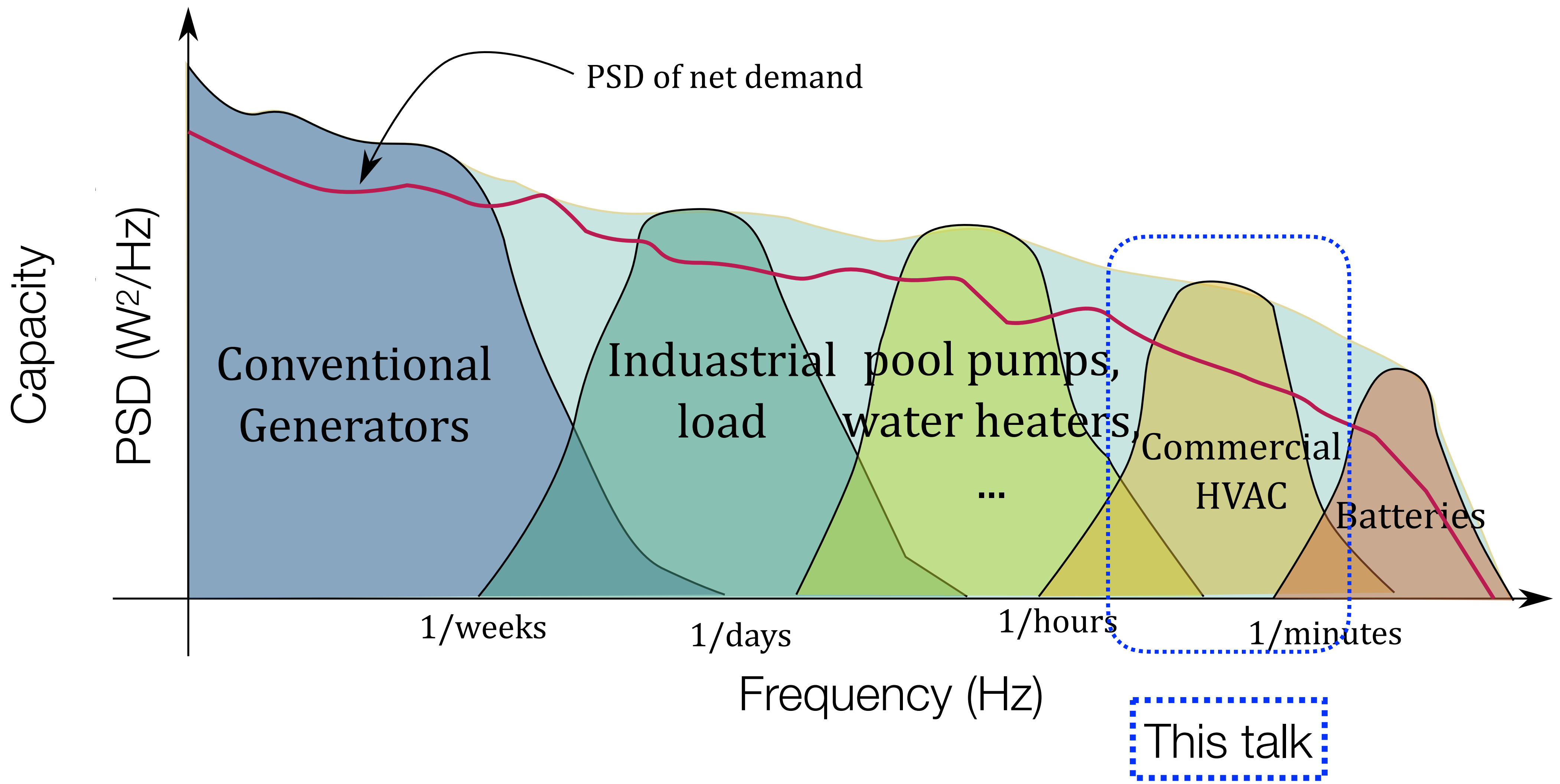




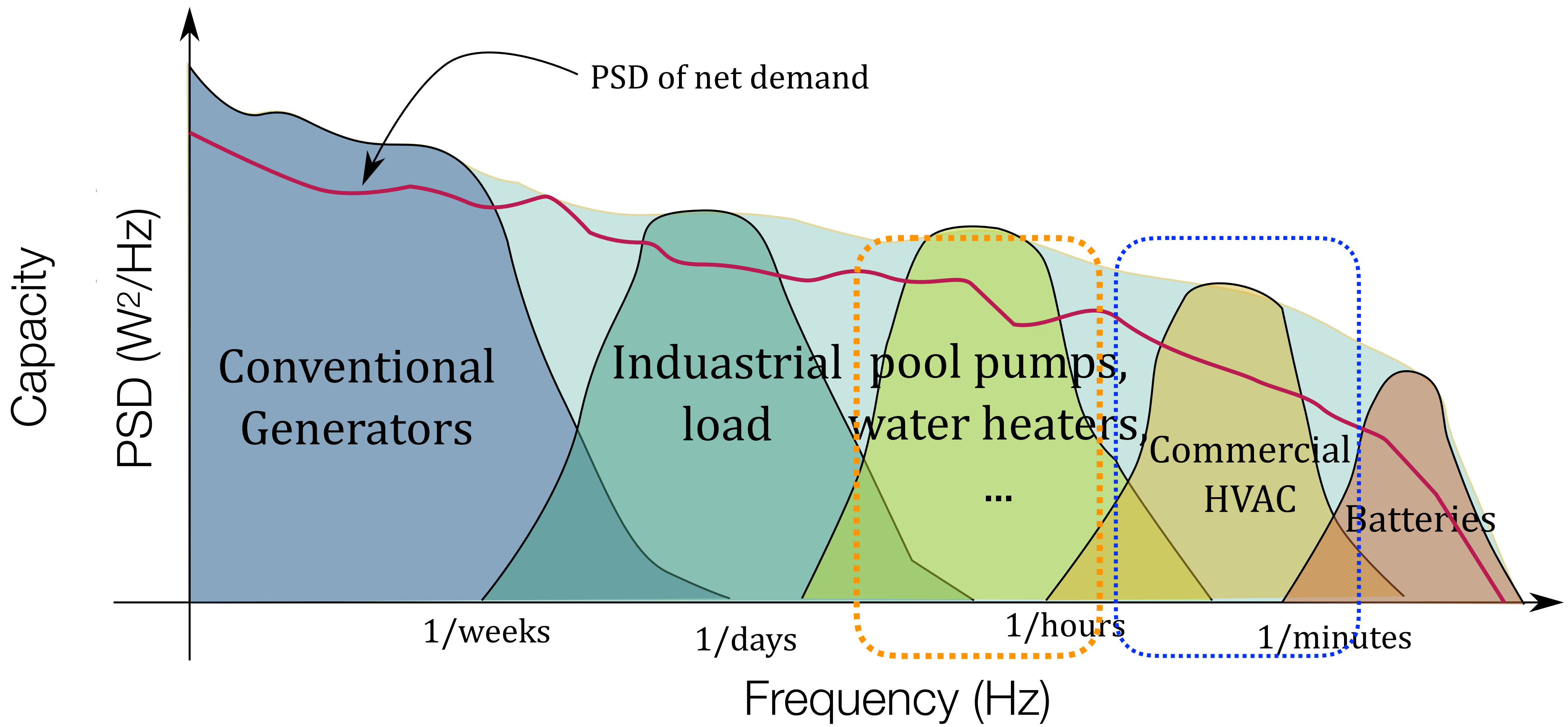


** Decentralized coordination of loads for ancillary services using MPC with Fourier domain constraints, J. Brooks, P. Barooah, *IEEE Trans. Smart Grid* (under review)

Distributed control #1: Continuously variable loads



Distributed control #2: on/off loads

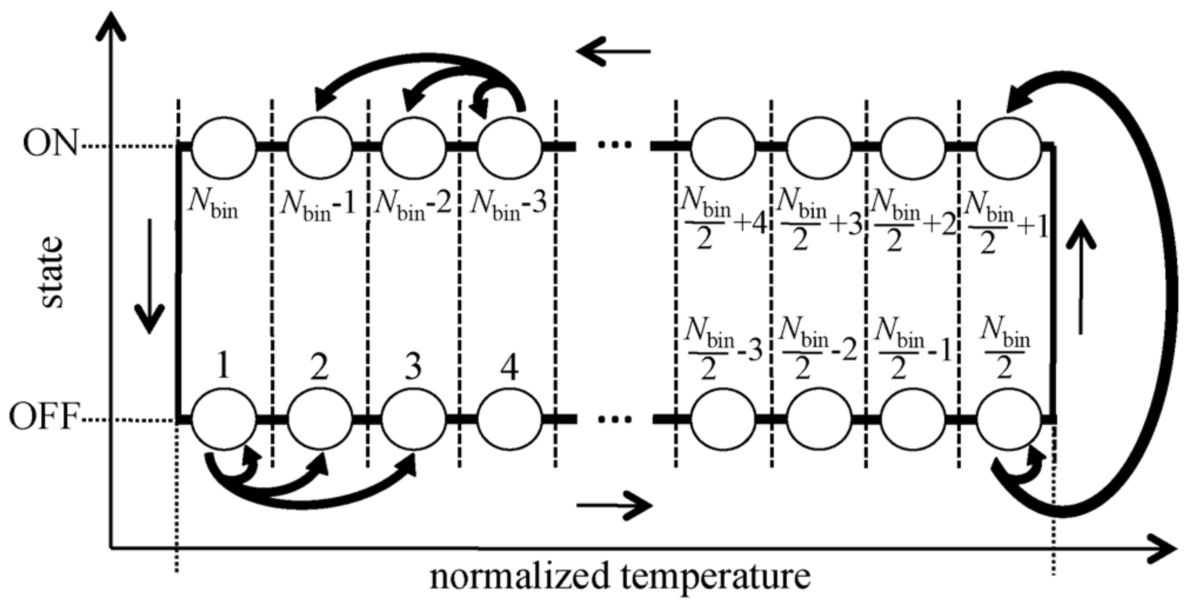


Challenge: combinatorial explosion

1. S Meyn, P Barooah, A Busic, J Ehren, “Ancillary service to the grid from deferrable loads: The case for intelligent pool pumps in Florida”, *IEEE Conf. on Decision and Control* (CDC), 2013
2. S Meyn, P Barooah, A Busic, Y Chen, J Ehren, Ancillary service to the grid using intelligent deferrable loads”, *IEEE Transactions on Automatic Control*, Nov. 2015.
3. A. Coffman, A. Busic, P. Barooah, “A Study of Virtual Energy Storage From Thermostatically Controlled Loads Under Time-Varying Weather Conditions”, *Intl. Conf. on high Performance Buildings*, Purdue Univ., July 2018.
4. A. Coffman, A. Busic, P. Barooah, "Virtual Energy Storage from TCLs using QoS persevering local randomized control", 5th ACM International Conference on Systems for Built Environments (BuildSys), Nov 2018

Coordination of on-off loads

Bin models:
1. Malhame and colleagues, 1992-
2. Mathieu et al., 2013
3. LANL group..

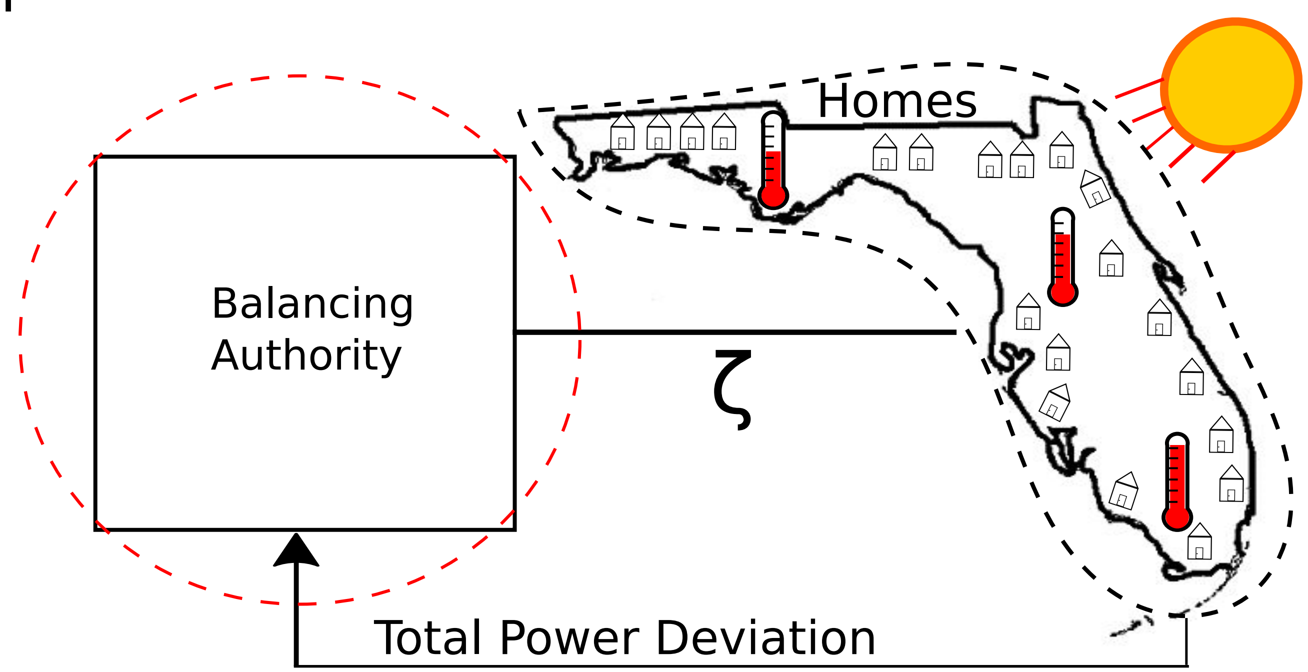


LTI (Markovian) model
Difficulty is in control

Randomized Control at UF/INRIA

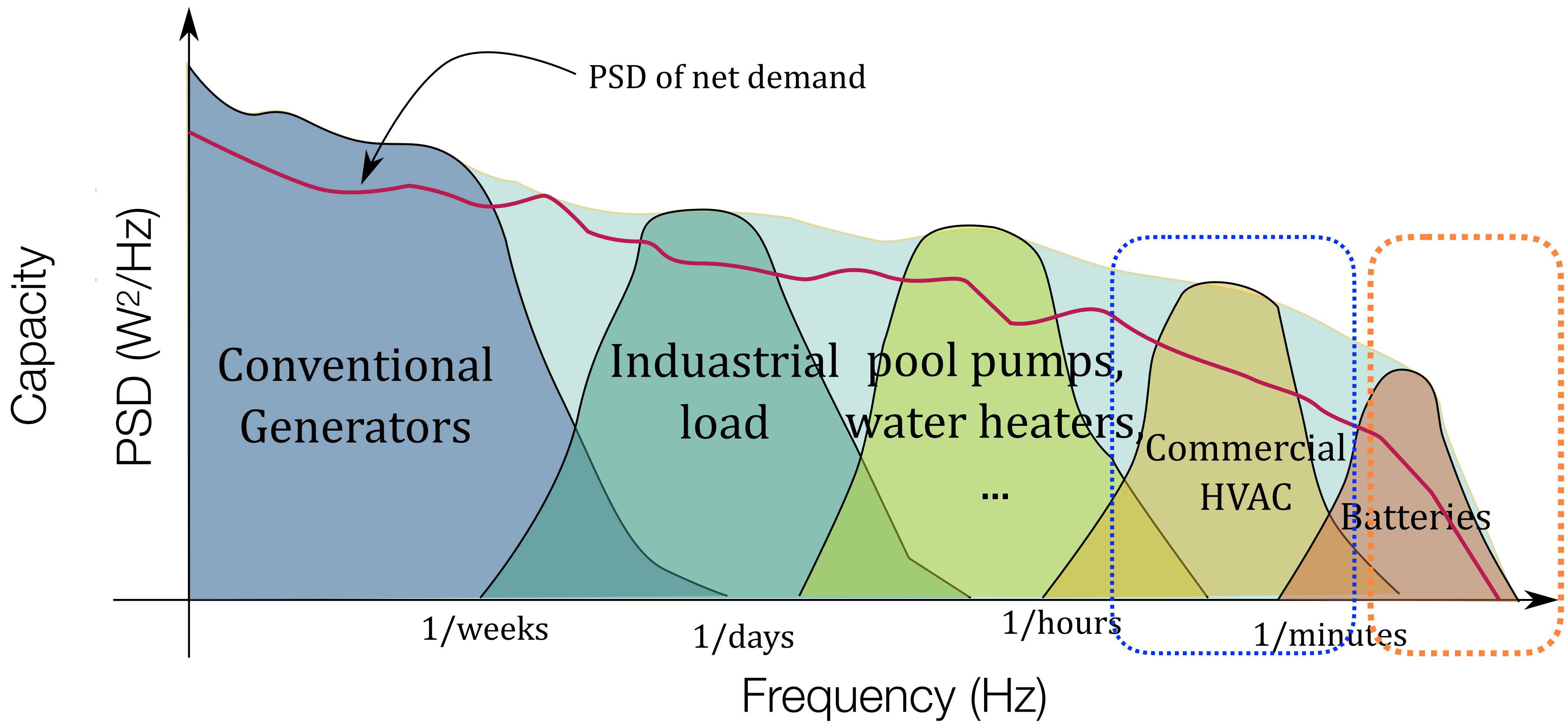
Meyn, Busic, Barooah (2013-…)

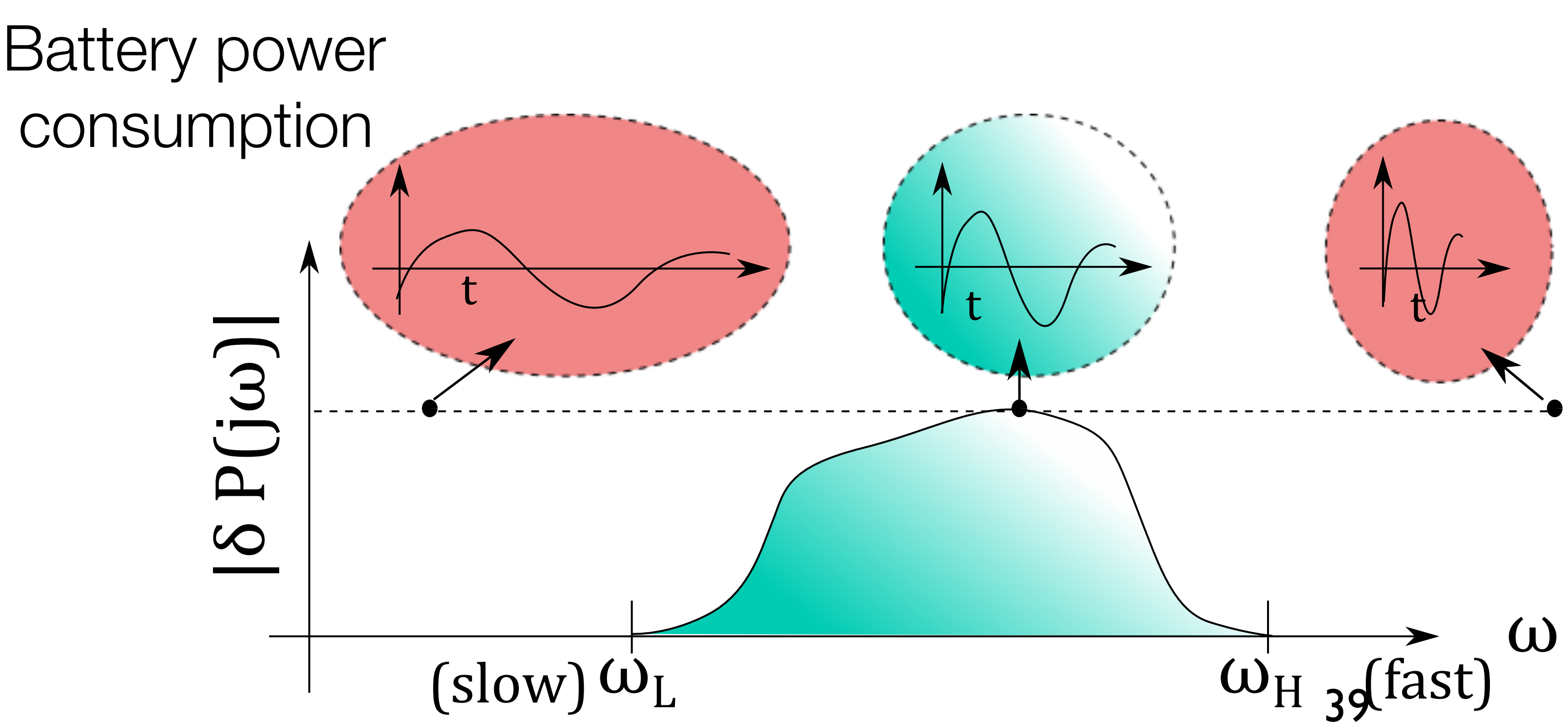
1. Replace the thermostat by a (baseline) randomized controller that mimics deterministic behavior (zeta=0)
2. Grid operator broadcasts zeta to all TCLs:
   LLN=> probability of one TCL on = fraction of TCLs on
3. zeta is computed by using classical control techniques



1. A. Coffman, A. Busic, P. Barooah, "Virtual Energy Storage from TCLs using QoS persevering local randomized control", 5th ACM International Conference on Systems for Built Environments (BuildSys), Nov 2018

Distributed control #3: (real) batteries





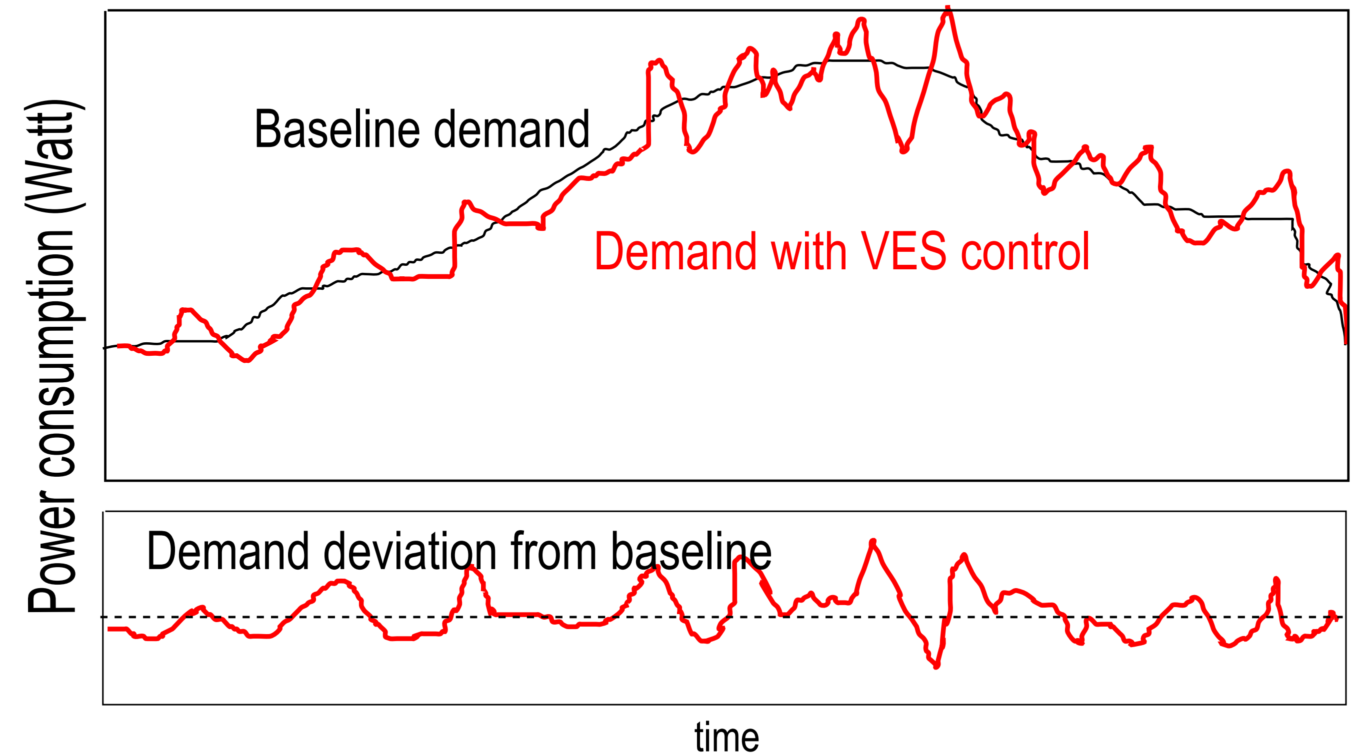
“A Customer Centric Approach to the Use of Residential Batteries for Distribution Network Support”, S. R. Deeba, P. Barooah, R. Sharma, J. Brooks and T. K. Saha, *IEEE Trans. Smart Grid* (in press)

Open problems

> Characterizing the virtual battery capacity

> Hao *et al.*, 2015 (Aggregate flexibility of ….)

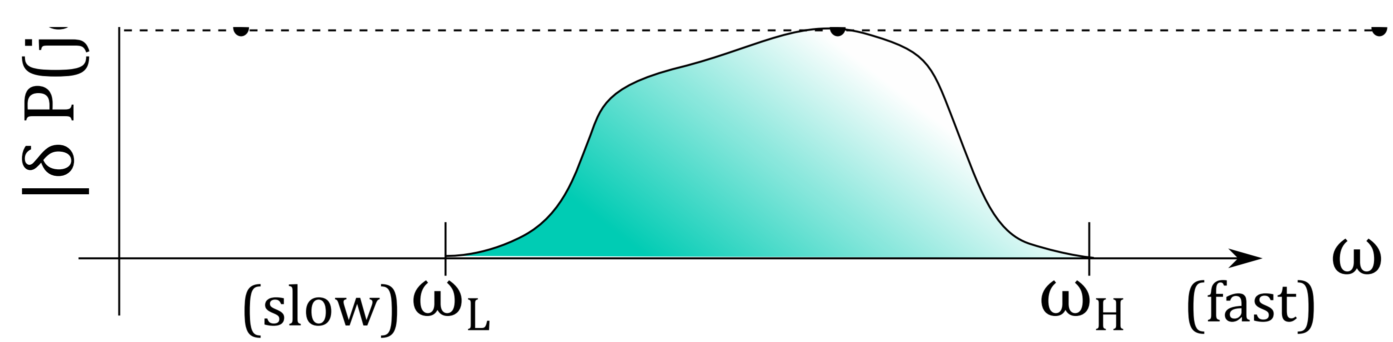
> ….



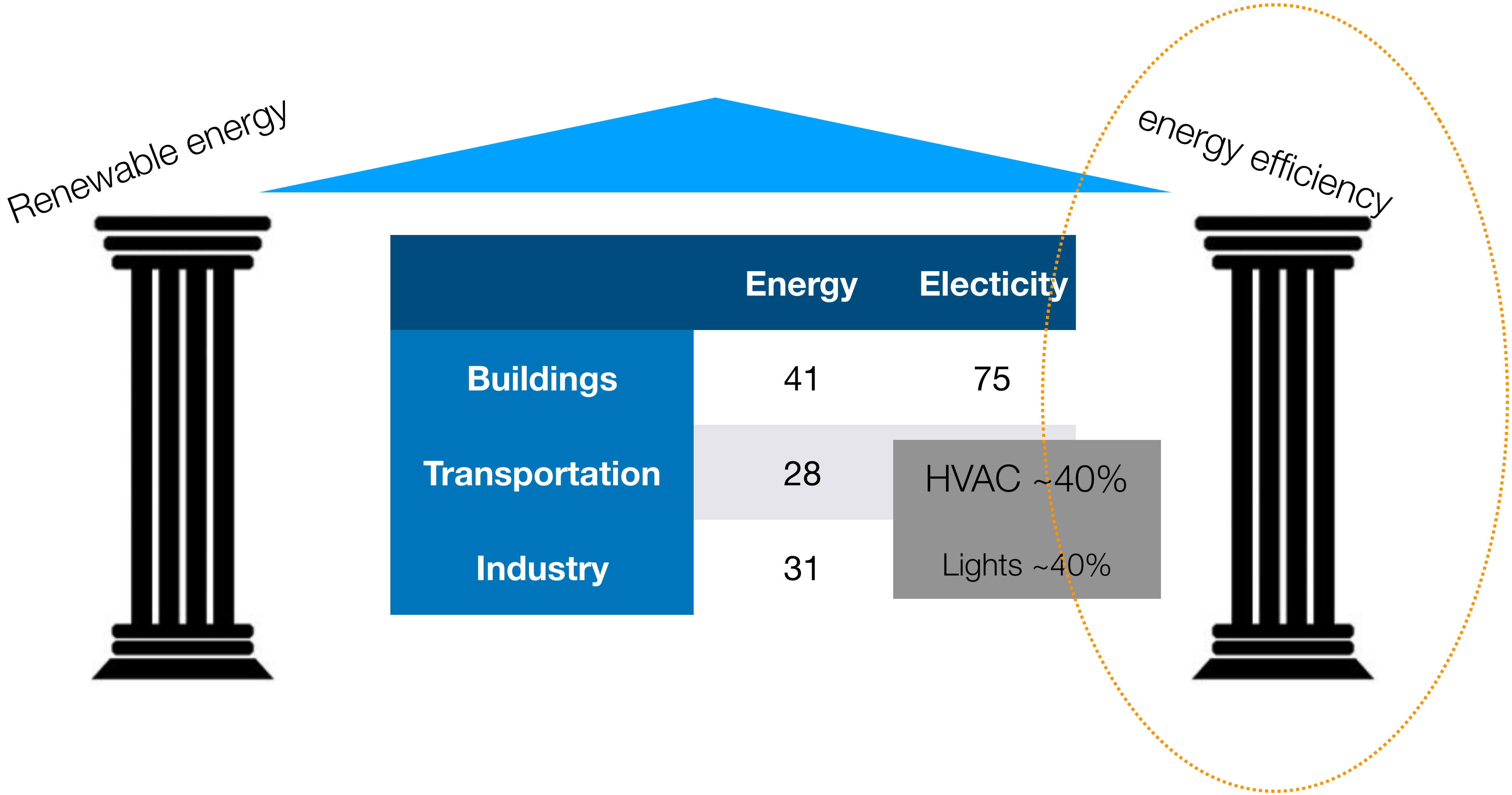
> Cost of VES

> Energy efficiency (the baseline!)

> ….



Energy Efficiency



	Energy	Electicity
Buildings	41	75
Transportation	28	
Industry	31	

HVAC ~40%

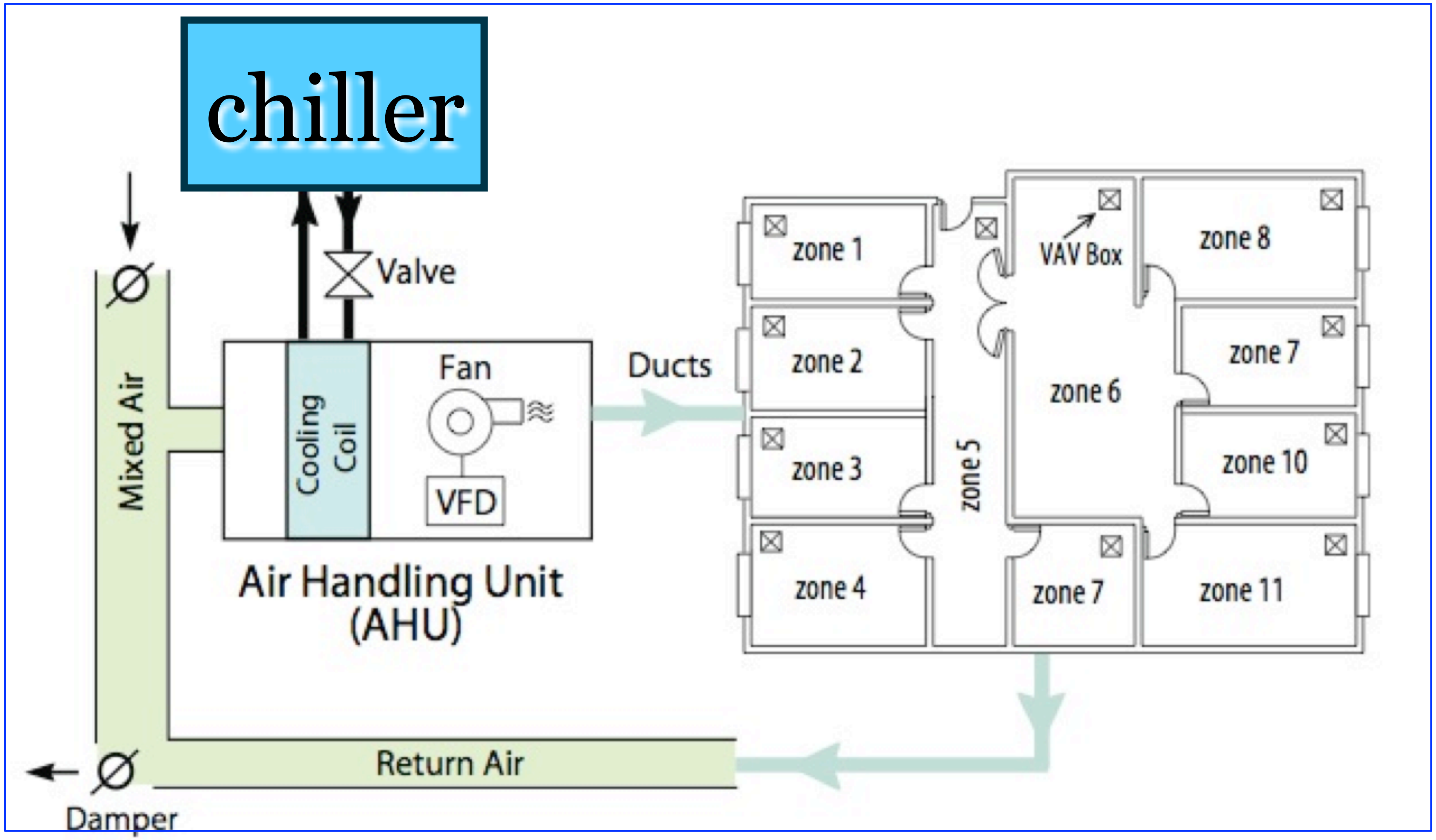
Lights ~40%

Control of building HVAC systems

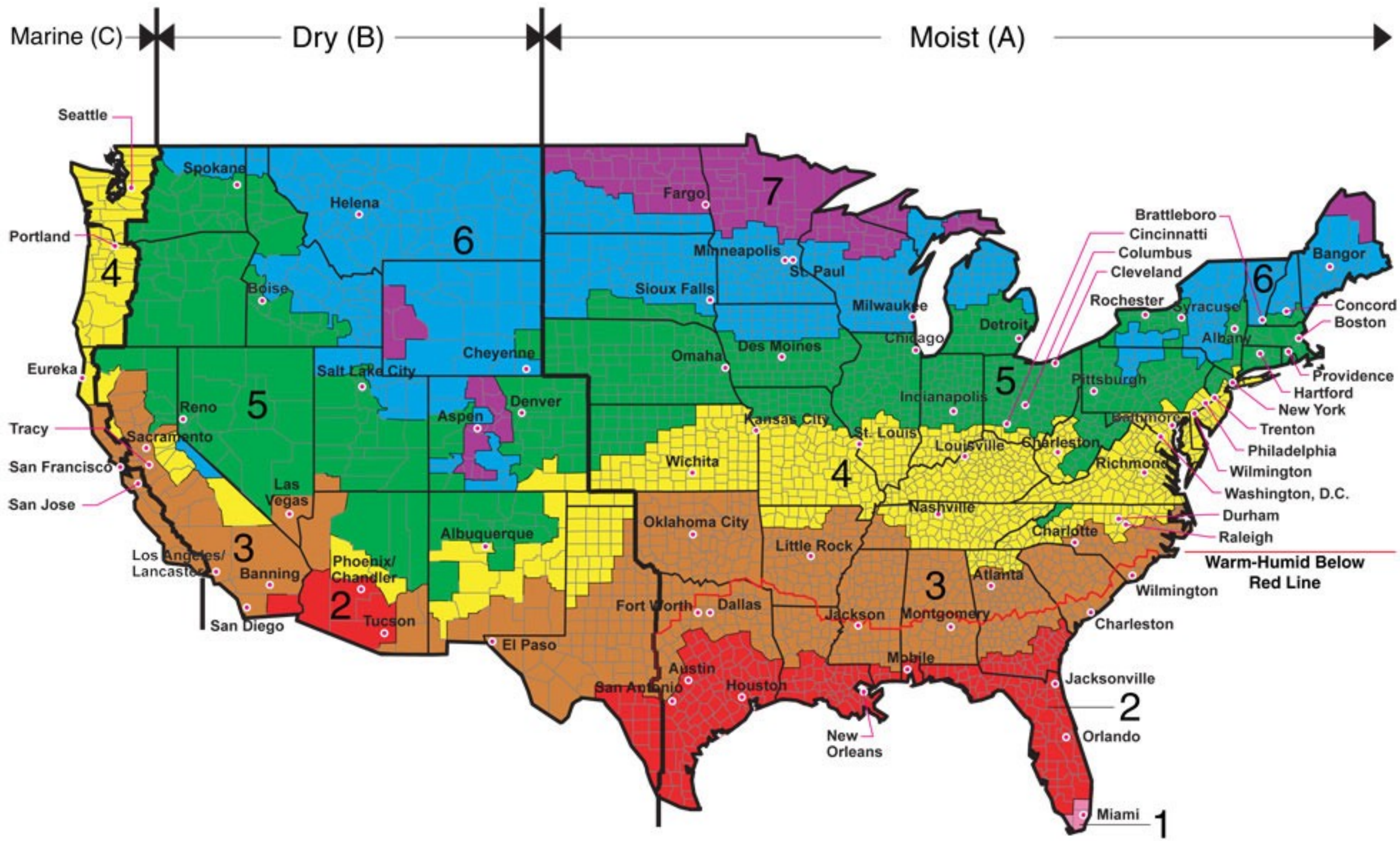
Key constraints:

1. **Thermal comfort**
   Temperature
   Humidity
2. **Indoor Air Quality** (ventilation/outdoor air)

Typical commercial HVAC system



ASHRAE climate zone map

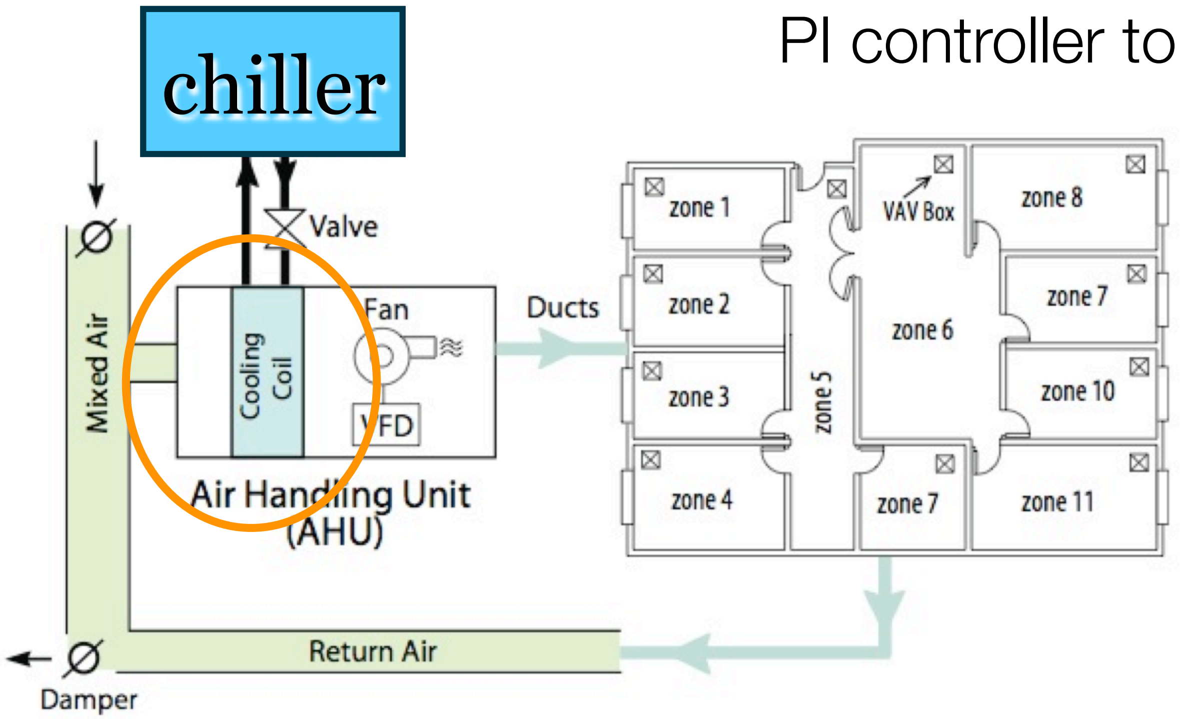


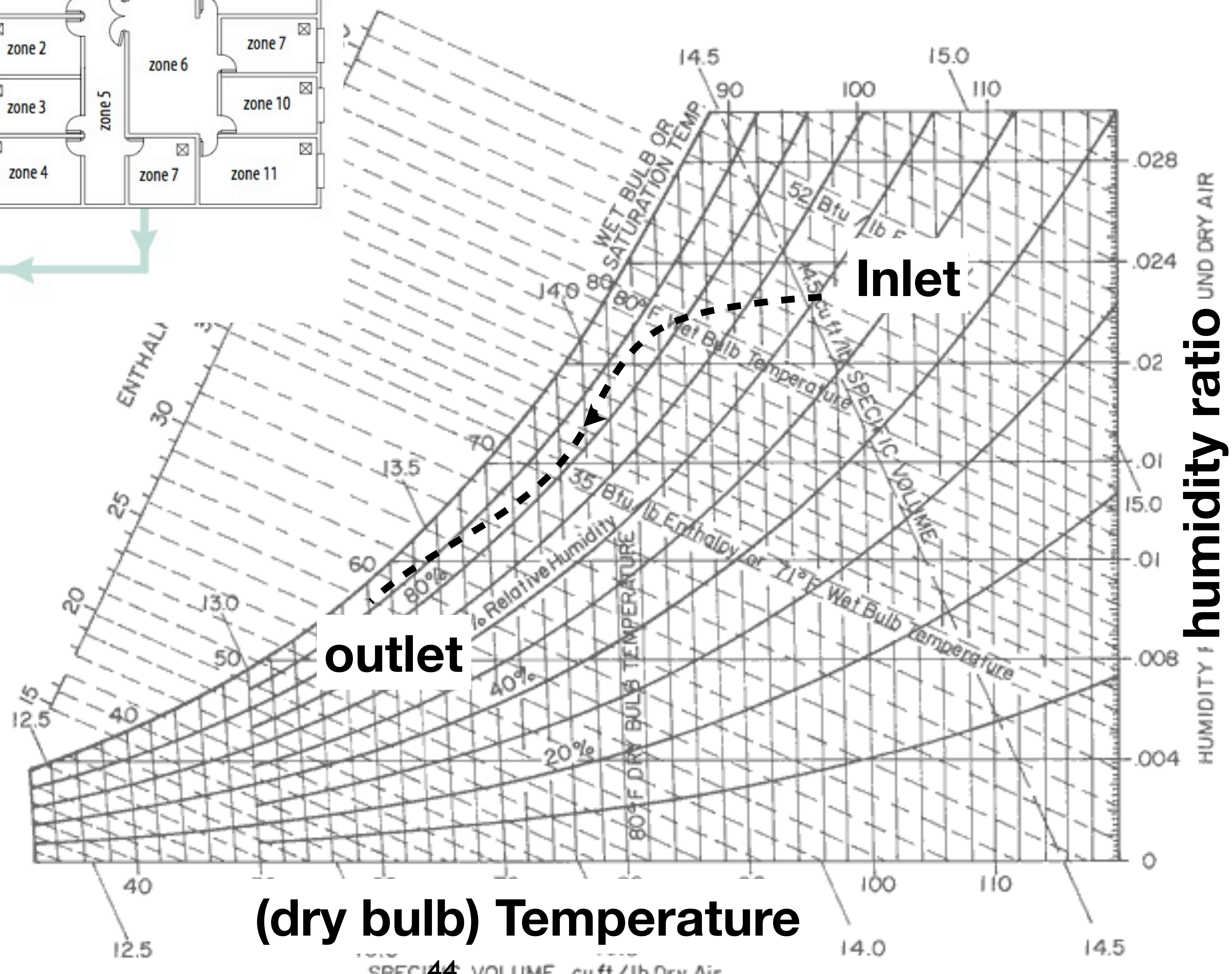
All of Alaska in Zone 7 except for the following Boroughs in Zone 8: Bethel, Dellingham, Fairbanks, N. Star, Nome North Slope, Northwest Arctic, Southeast Fairbanks, Wade Hampton, and Yukon-Koyukuk

Zone 1 includes: Hawaii, Guam, Puerto Rico, and the Virgin Islands

Dehumidification at the cooling coil

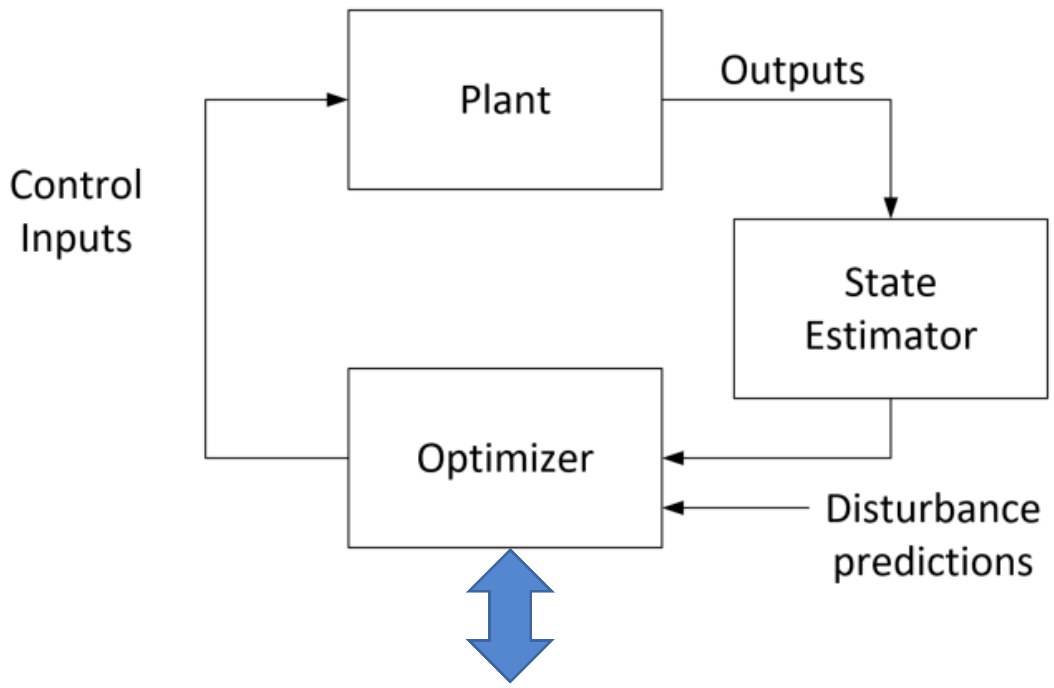
PI controller to maintain T_ca set point

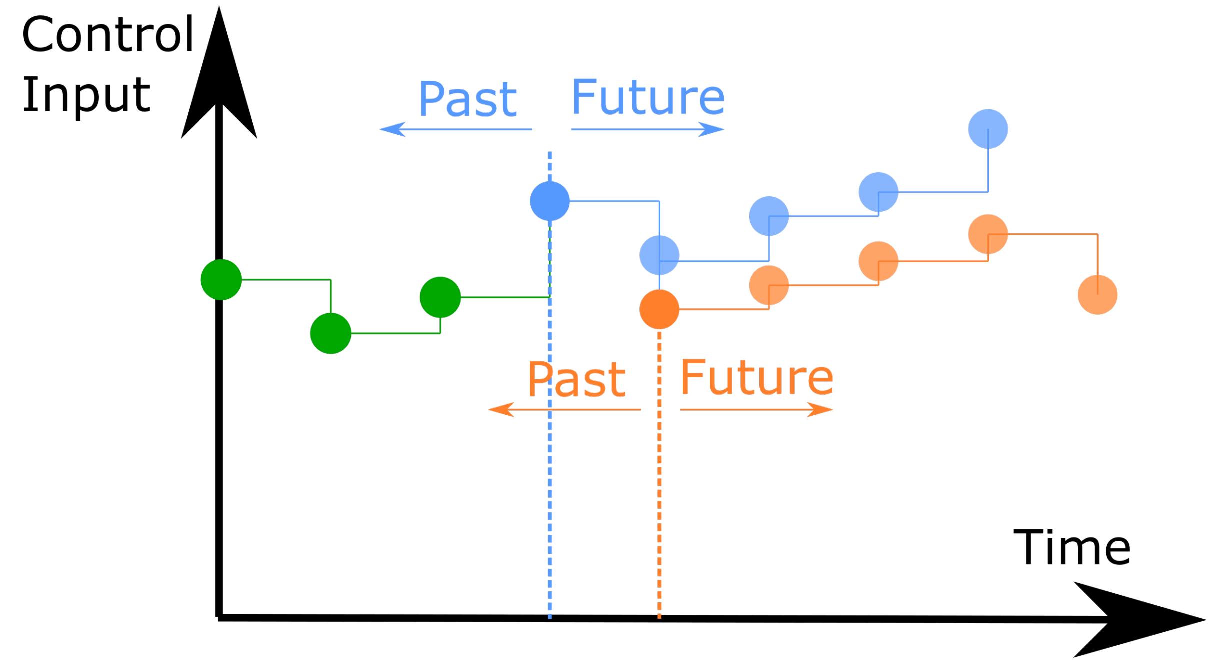




Existing work on energy efficient control of HVAC

Model Predictive Control





$$\min_{u(j,j+N-1),x(j,j+N)} \quad J(x,u)$$ Cost function

$$\boxed{x(j) = x_0 \ (\text{from measurements})}$$

$$x(k+1) = f(x(k), u(k), w(k)), \ k = j, j+N-1$$ Dynamic constraint

$$y(k) = h(x(k), u(k))$$

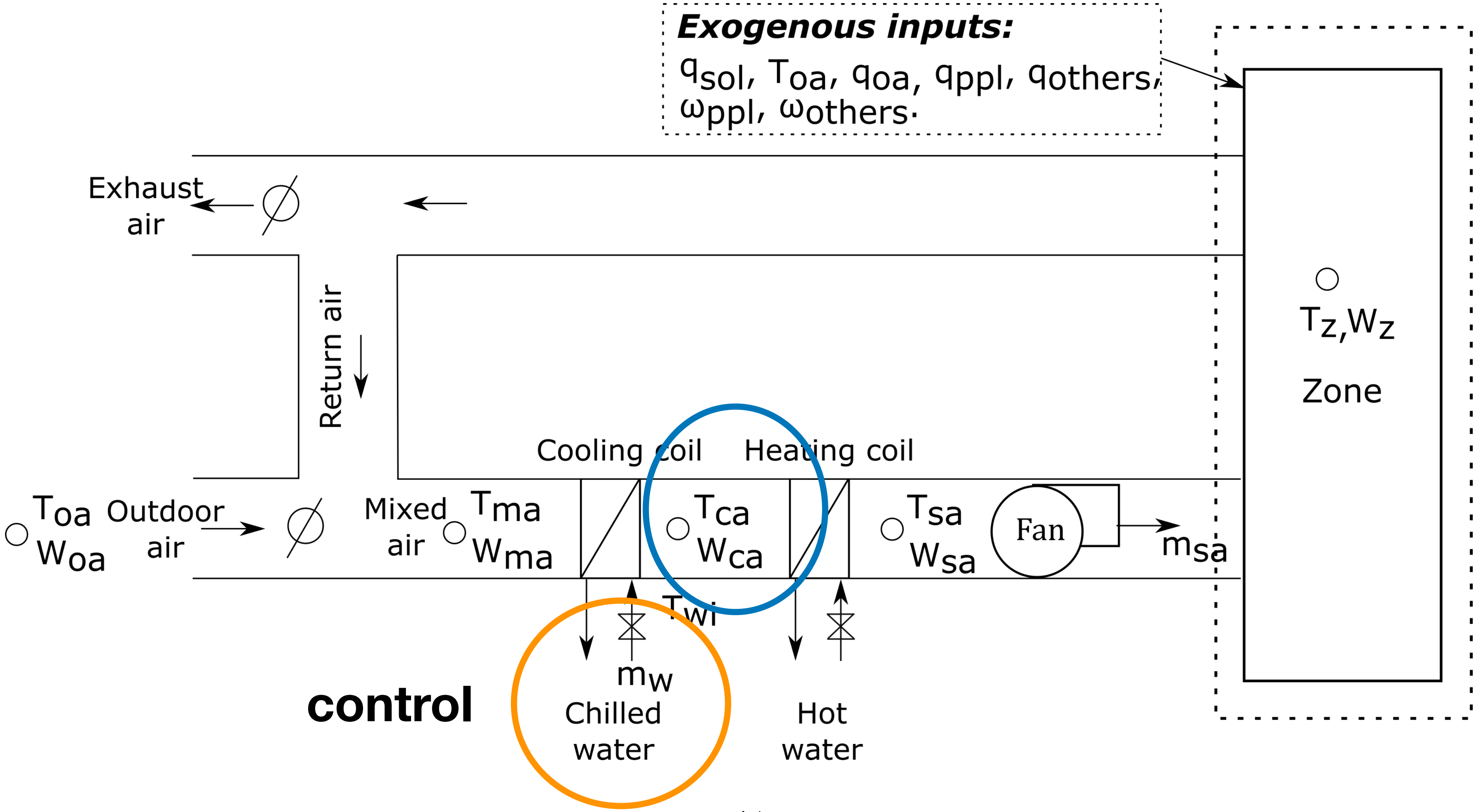
state and actuator constraints

Weakness of existing MPC solutions

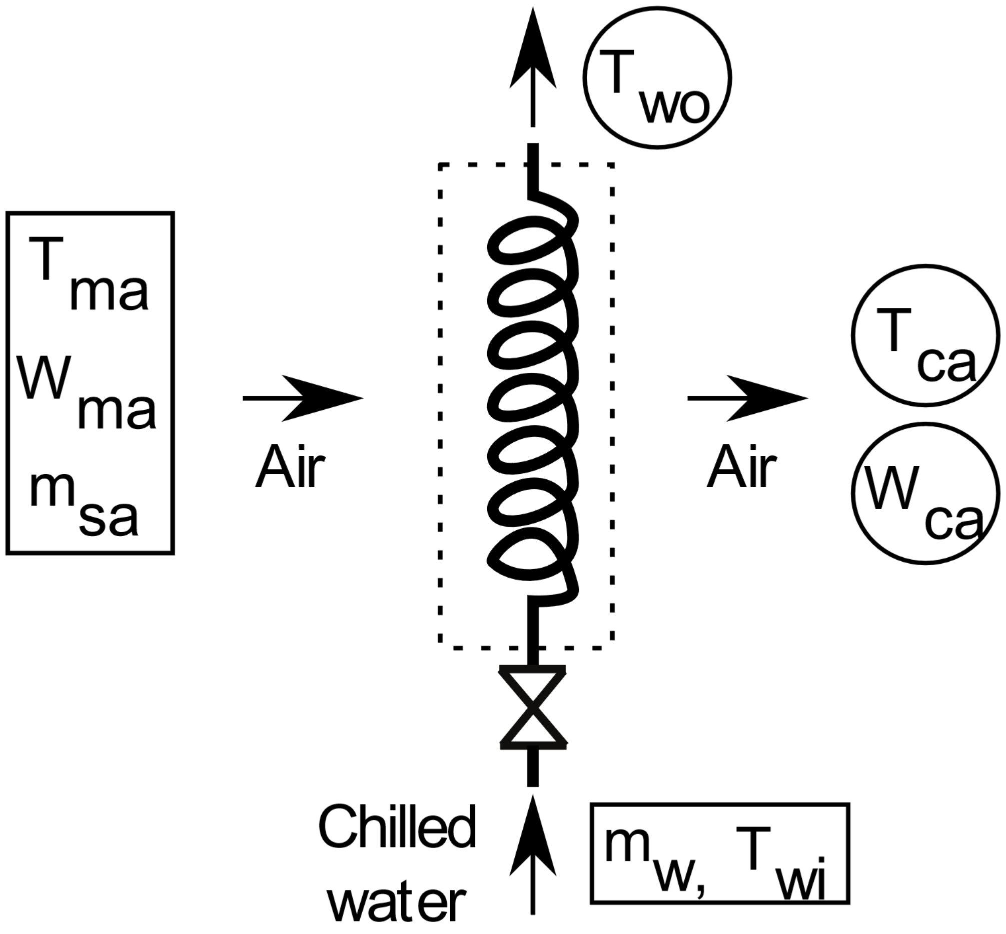
All prior work on MPC for buildings have ignored humidity.
Only considered temperature

$$C\dot{T} = -\frac{1}{R}(T - T_a) + q_{solar} + q_{occp} + q_{hvac}$$ **u**

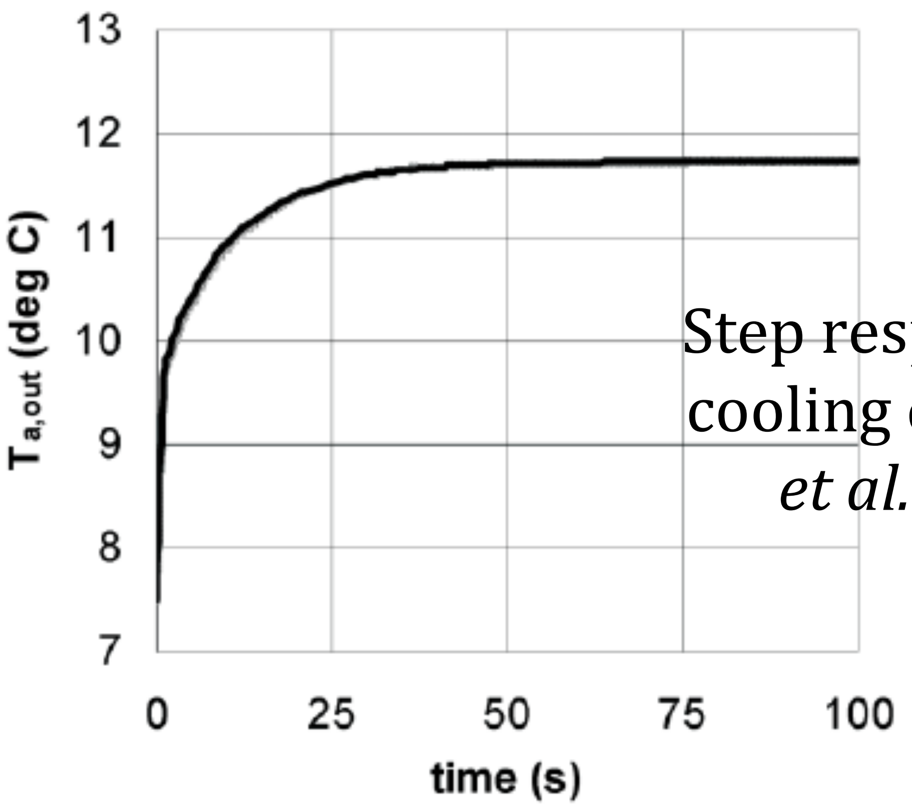
$$q_{hvac}(t) = m_a C_p (T_{ca} - T)$$



Cooling coil



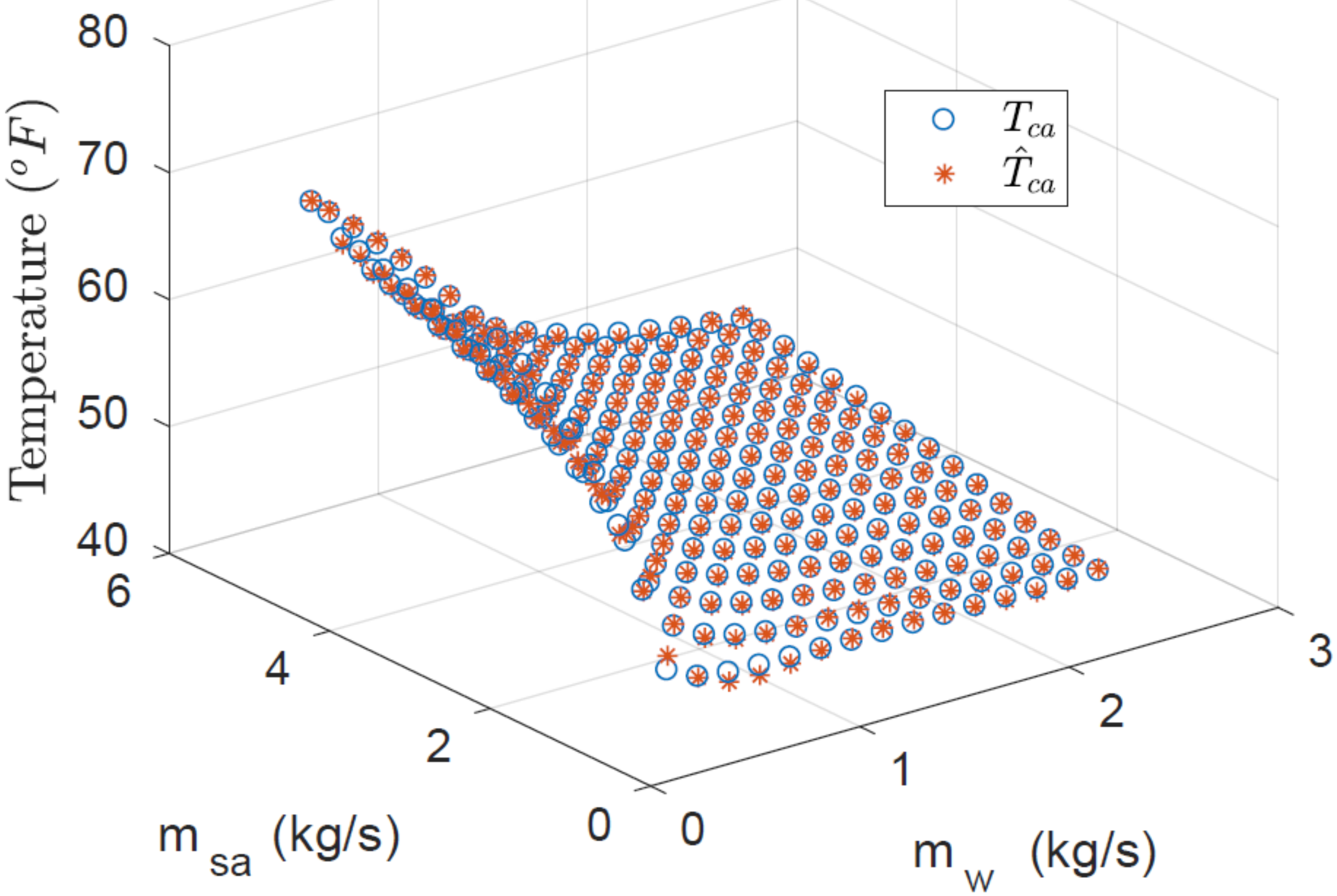
Model of cooling and dehumidification across a cooling coil:
Non-linear PDEs with many unknown parameters (Braun and colleagues…)

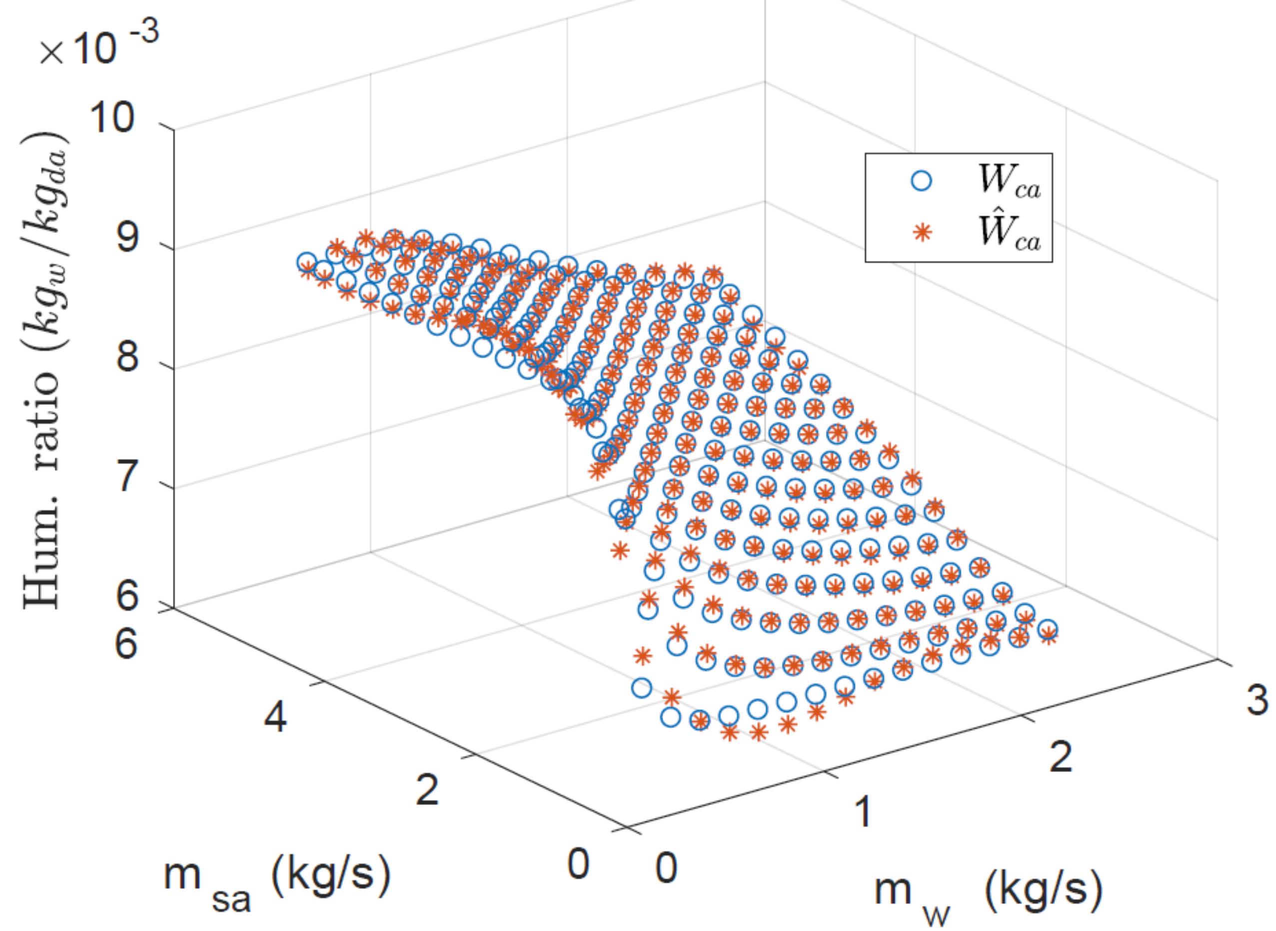


Step response of a cooling coil (Zhou *et al.* 2007)

A data-driven cooling coil model*

$$T_{ca} = f(m_{sa}, m_w) \qquad W_{ca} = g(m_{sa}, m_w)$$

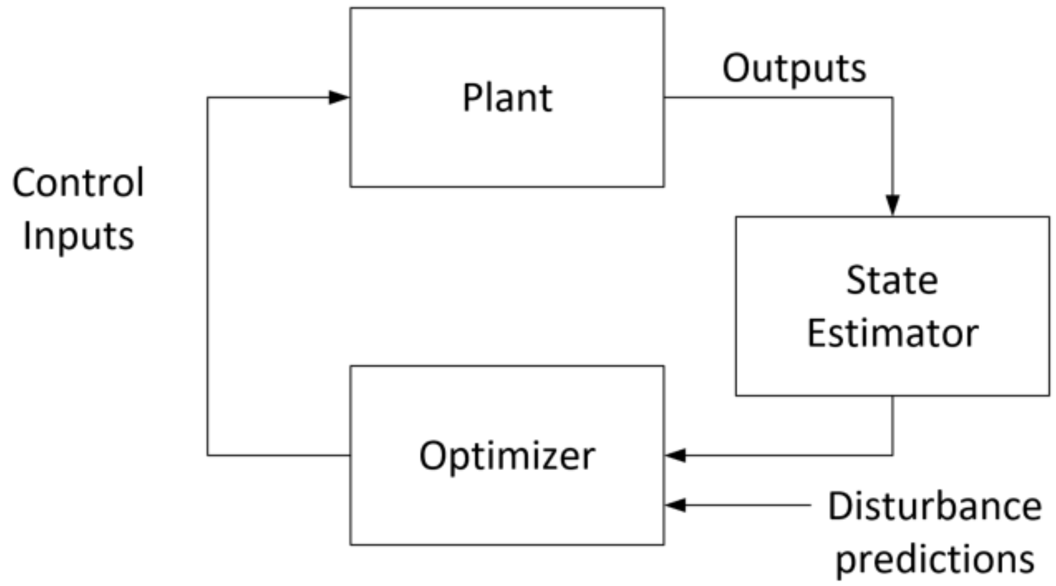




"MPC-Based Building Climate Controller Incorporating Humidity", N. S. Raman, K. Devaprasad, P. Barooah, *American Control Conference, 2019* (under review)

Proposed MPC formulation

Minimize total energy use (24 hours) subject to thermal comfort and air quality constraints



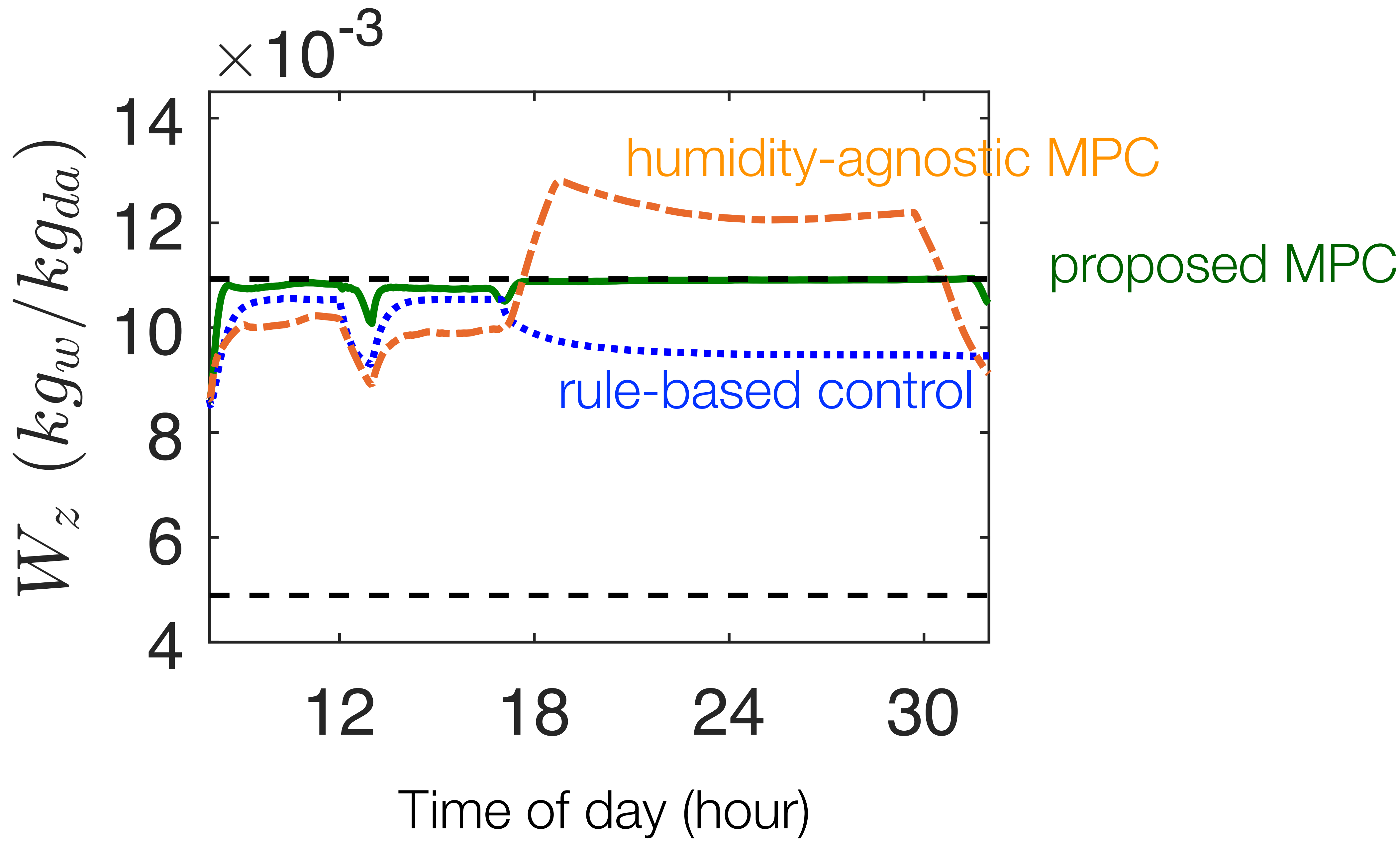
Lessons from simulation

With "humidity agnostic" MPC:
Low energy use with poor humidity (esp. during summer nights)

MPC with cooling coil model:
Able to maintain space humidity with almost the same energy use

Humidity constraint violation

August 6, 2016 (Gainesville, FL)



"MPC-Based Building Climate Controller Incorporating Humidity", N. S. Raman, K. Devaprasad, P. Barooah, *American Control Conference, 2019* (under review)

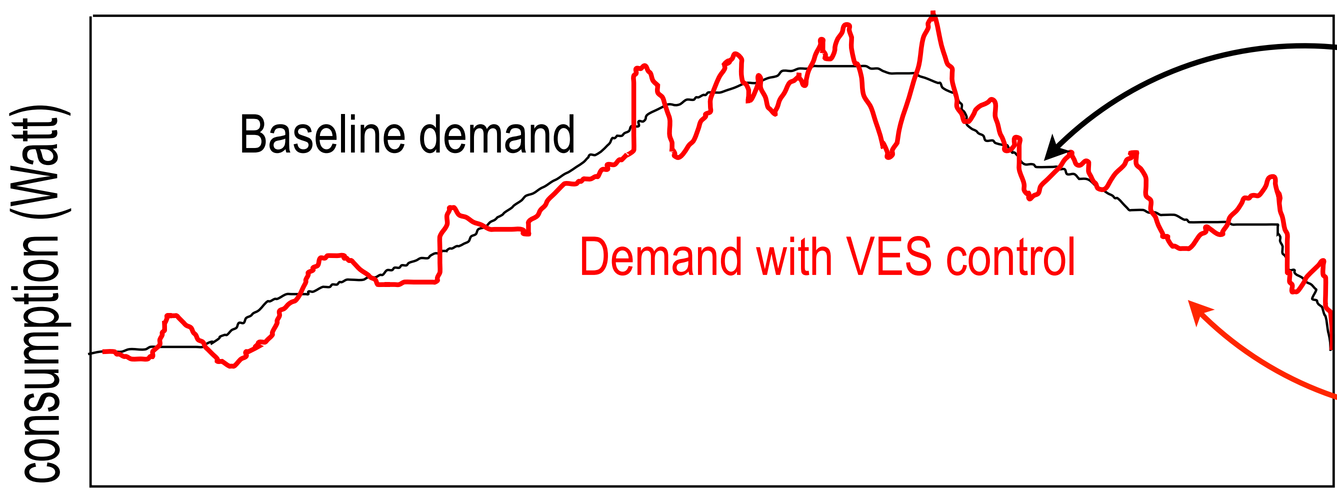
Open problems

1. Feasibility guarantee
2. Convex relaxation
3. Predictions requirements:
   - Weather (OK)
   - Occupancy for ventilation constraints (?)

Demonstration site at UF

Summary: smart building(efficient and flexible)

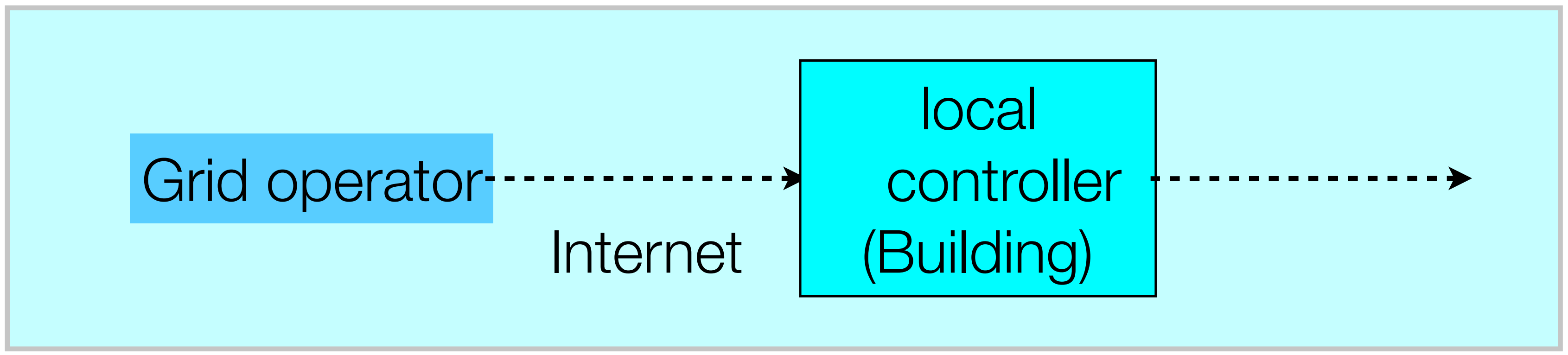
Energy efficiency vs. demand flexibility: Need for an unified formulation?



Baseline (energy efficiency!

demand flexibility (VES)

Consumer participation in demand flexibility: long term contracts
Value addition through energy efficiency, enhanced comfort, etc.



Local + Global

Thank you

1. P. Barooah, "Virtual energy storage from flexible loads: distributed control with QoS constraints", in "Smart Grid Control: Opportunities and Challenges", Springer 2018.
2. Y Lin, P Barooah, S Meyn, T Middelkoop, "Experimental evaluation of frequency regulation from commercial building HVAC systems", IEEE Transactions on Smart Grid 6 (2), 2015
3. Y Lin, P Barooah, JL Mathieu, "Ancillary services through demand scheduling and control of commercial buildings", IEEE Transactions on Power Systems, Jan 2017
4. J. Brooks, P Barooah, "Virtual energy storage through decentralized load control with quality of service bounds", *American Control Conference*, 2017.
5. J. Brooks, P. Barooah, "Decentralized coordination of loads for ancillary services using MPC with Fourier domain constraints", *IEEE Trans. Smart Grid* (under review)
6. S. Meyn, P Barooah, A Busic, Y Chen, J Ehren, Ancillary service to the grid using intelligent deferrable loads", *IEEE Transactions on Automatic Control*, Nov. 2015.
7. A. Coffman, A. Busic, P. Barooah, "Virtual Energy Storage from TCLs using QoS persevering local randomized control", 5th ACM International Conference on Systems for Built Environments (BuildSys), Nov 2018
8. S. R. Deeba, P. Barooah, R. Sharma, J. Brooks and T. K. Saha, "A Customer Centric Approach to the Use of Residential Batteries for Distribution Network Support", *IEEE Trans. Smart Grid* (in press)
9. Naren. S. Raman, K. Devaprasad, P. Barooah, MPC-Based Building Climate Controller Incorporating Humidity", *American Control Conference, 2019* (under review)
10. T. Zeng, P. Barooah, "Identification of Network Dynamics and Disturbance for a Multi-zone Building", *IFAC conference on Human Cyber Physical Systems*, Dec. 2018 (under review)
11. T. Zeng, J. Brooks, P. Barooah, "Simultaneous identification of building dynamic model and disturbance using sparsity-promoting optimization", *Automatica* (under review)

Financial support from the following organizations gratefully acknowledged