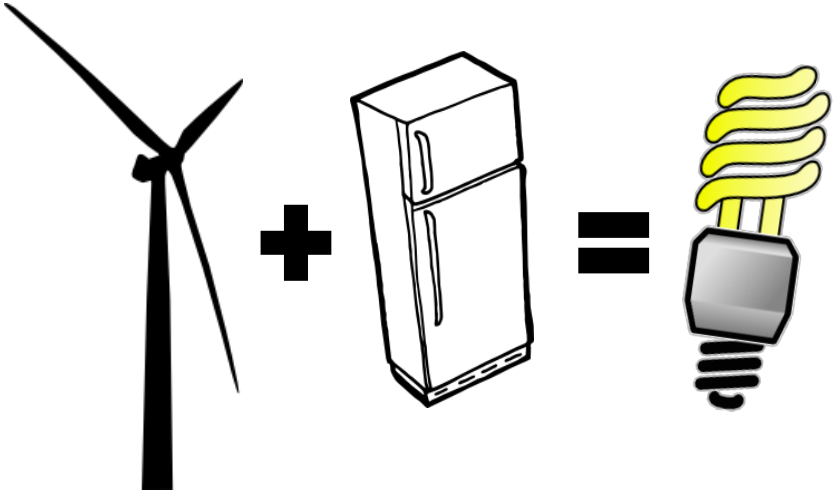
Stochastic Optimal Power Flow with Uncertain Reserves from Flexible Loads

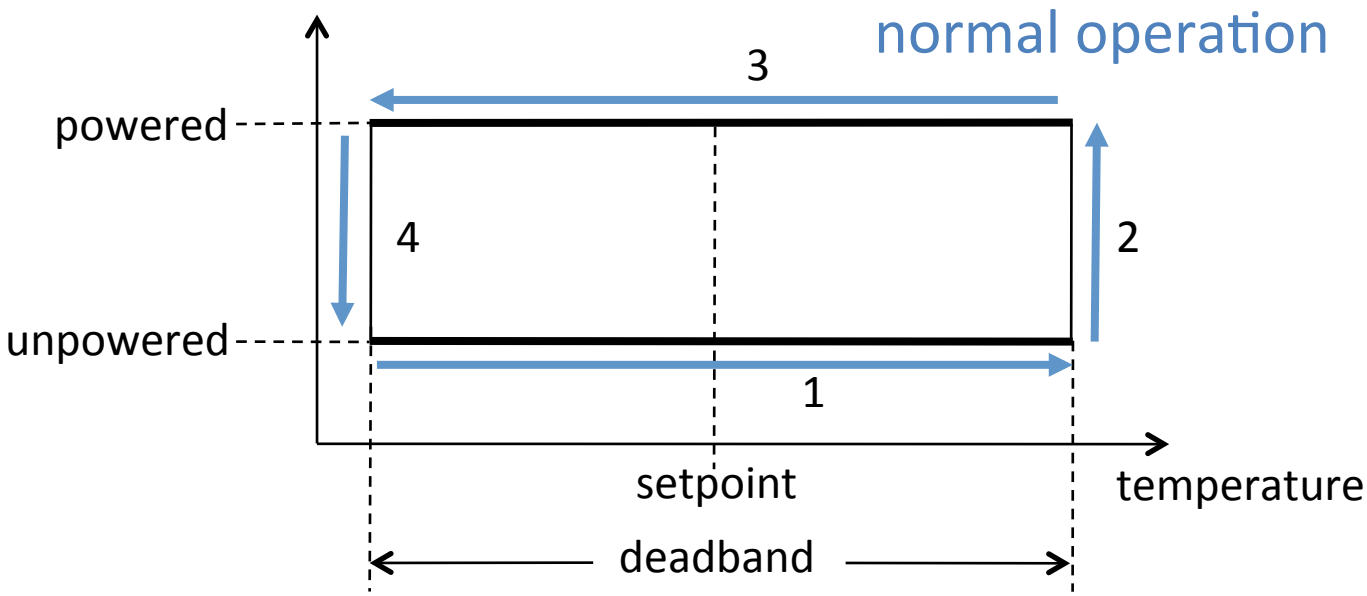
Johanna L. Mathieu
Assistant Professor
Electrical & Computer Engineering
University of Michigan, Ann Arbor

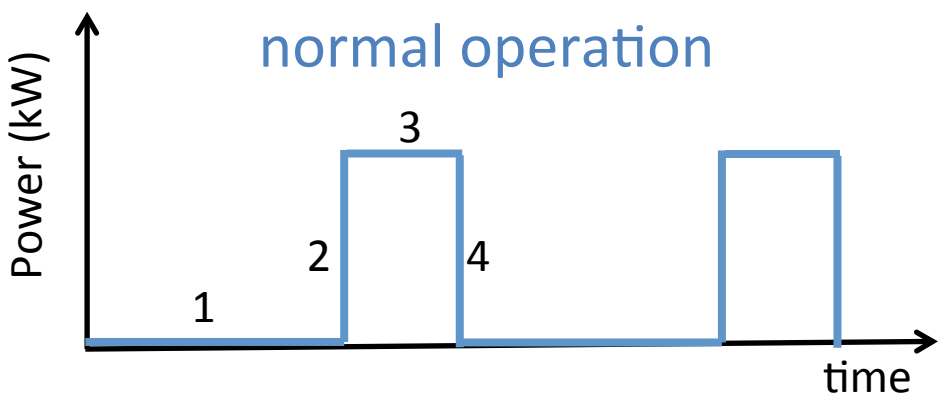


Joint work with Dr. Maria Vrakopoulou (Michigan, formerly ETH Zurich), Prof. Göran Andersson (ETH Zurich), and Prof. Siqian Shen (Michigan)

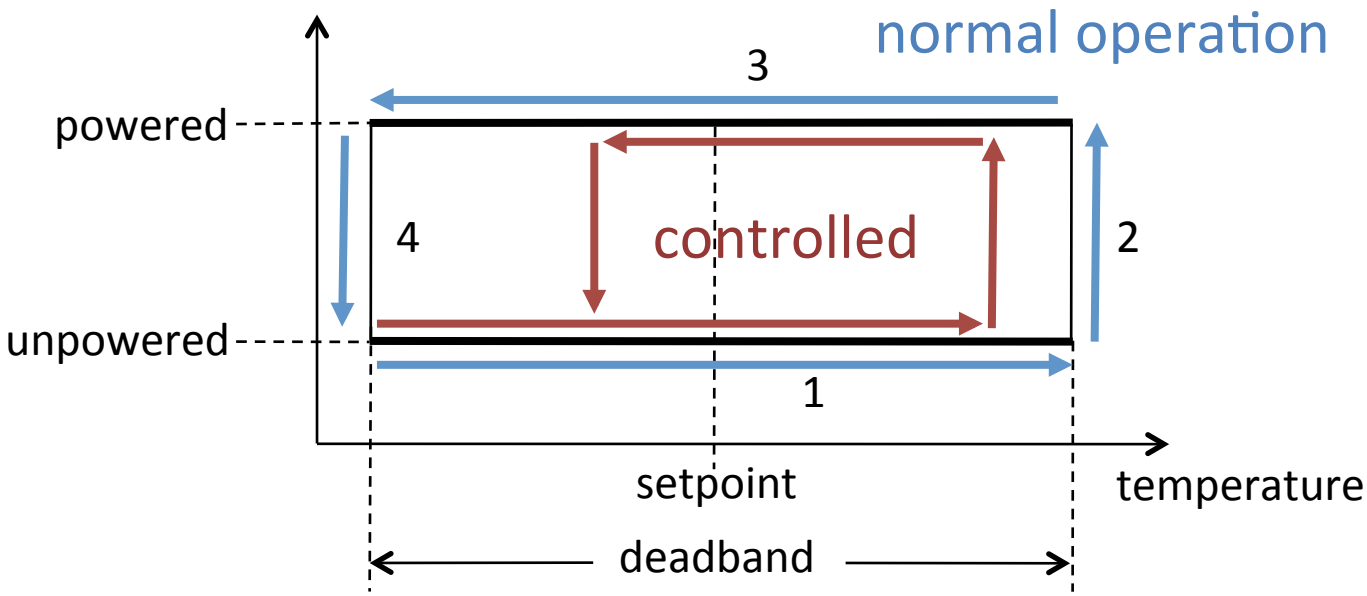
How can loads provide reserves?

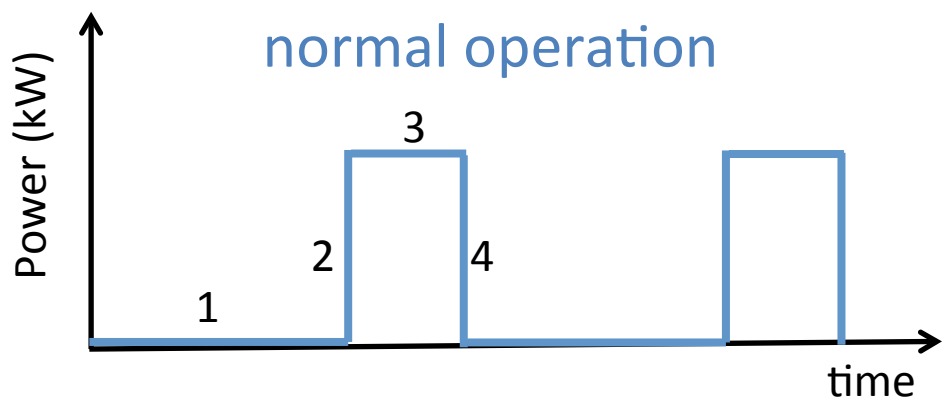
How can loads provide reserves?
→ your air conditioner is already flexible

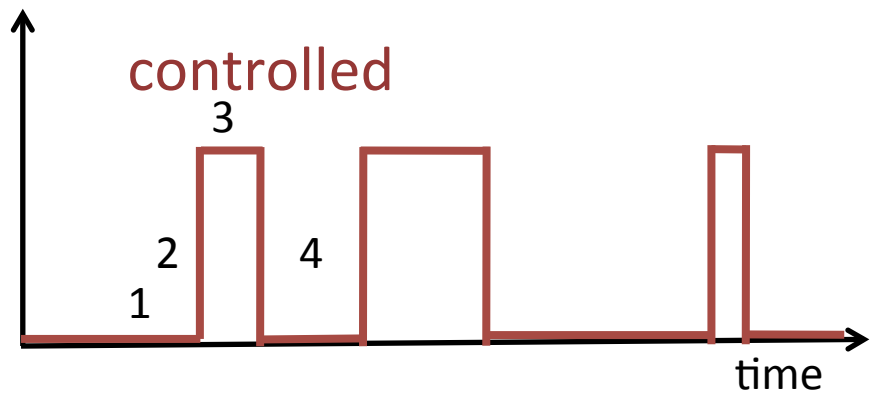




How can loads provide reserves?
→ your air conditioner is already flexible



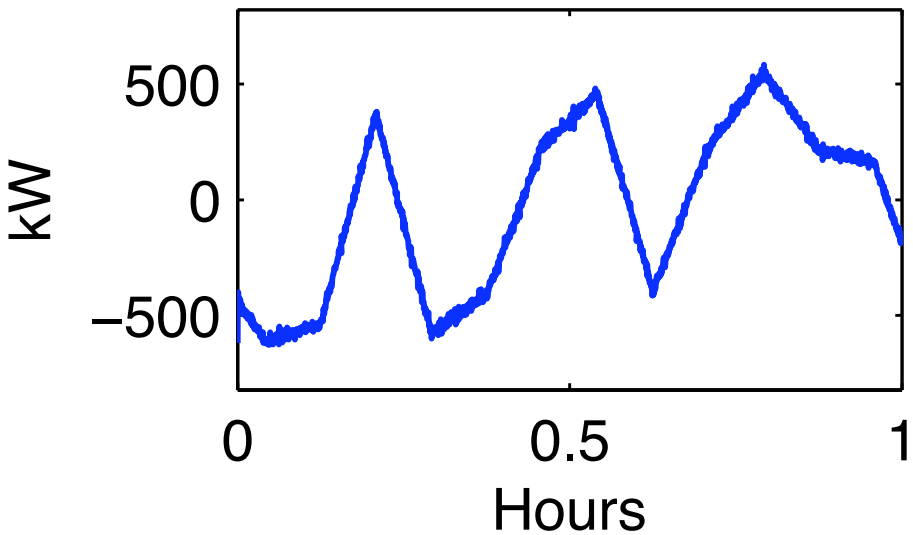




Thousands of coordinated thermal loads can track signals

→ Air conditioners, heat pumps, space heaters, electric water heaters, refrigerators

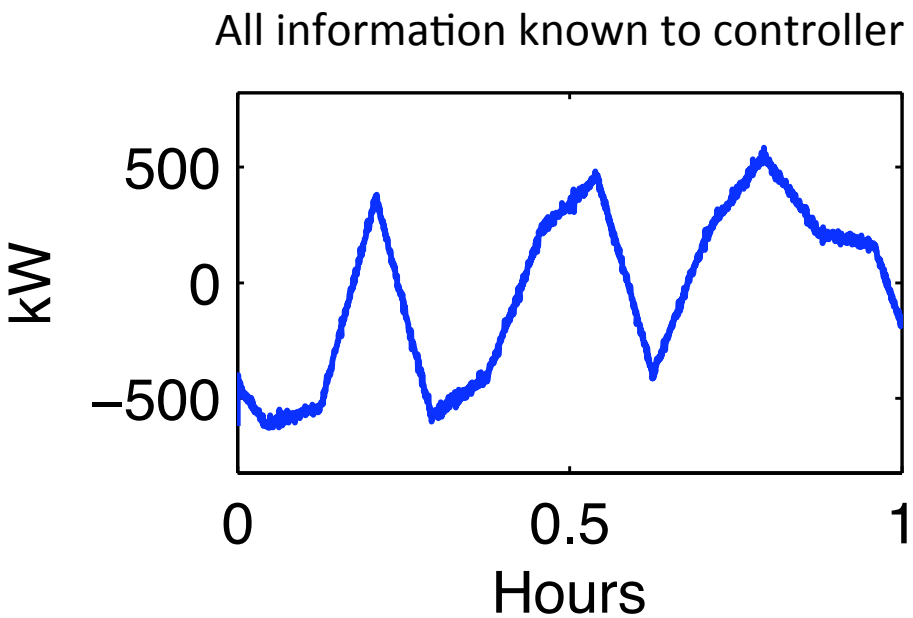
All information known to controller

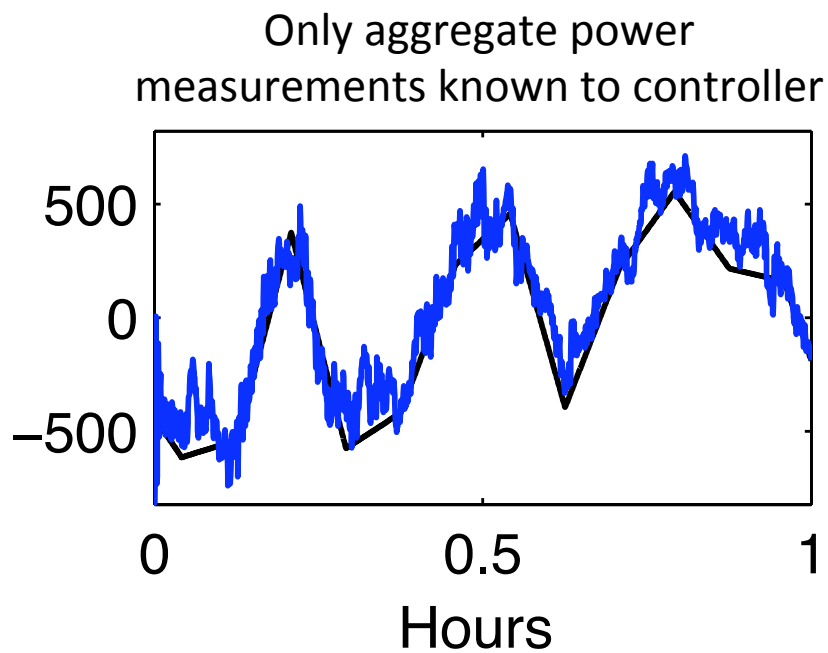


[Mathieu, Koch, and Callaway *IEEE Transactions on Power Systems* 2013]

Thousands of coordinated thermal loads can track signals

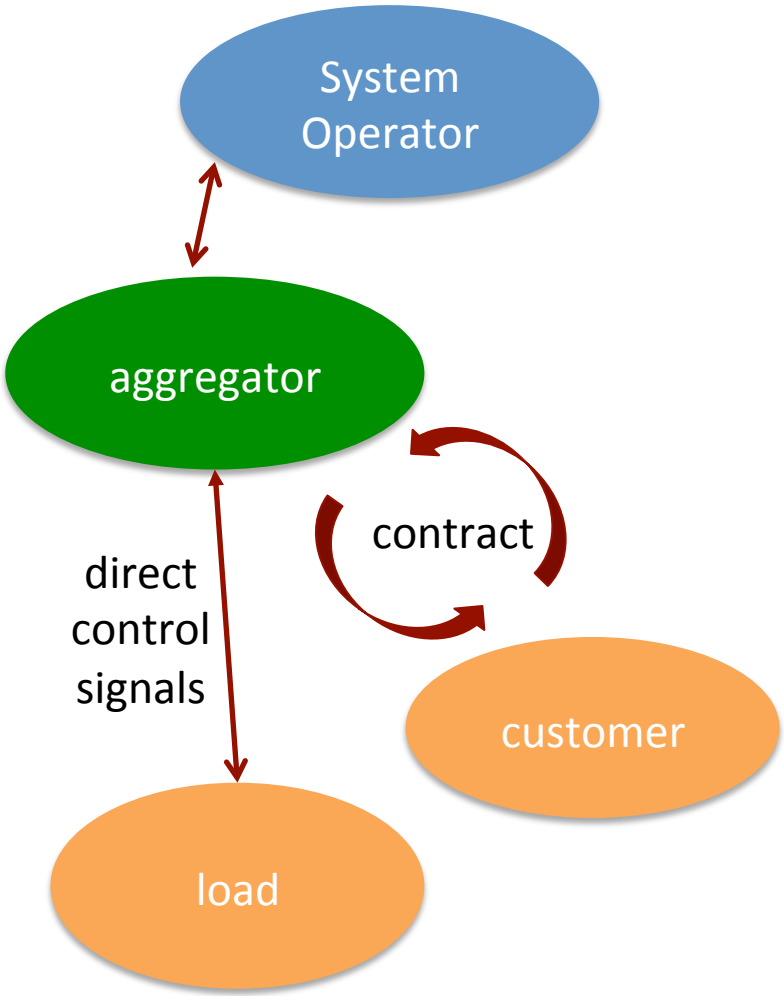
→ Air conditioners, heat pumps, space heaters, electric water heaters, refrigerators





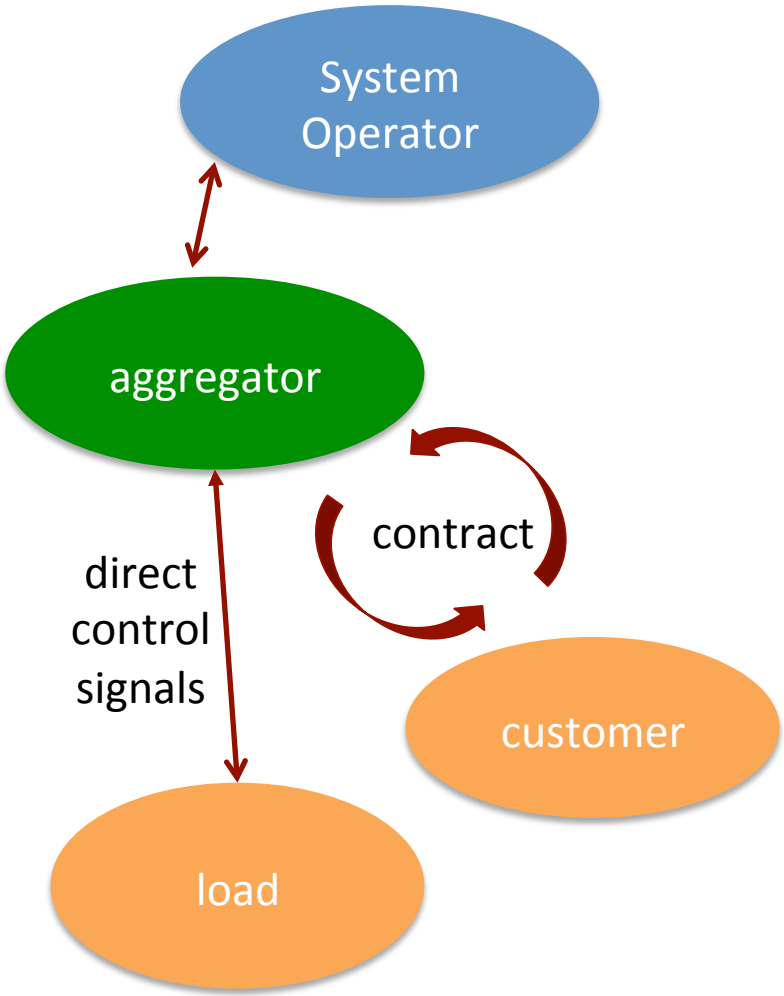
[Mathieu, Koch, and Callaway *IEEE Transactions on Power Systems* 2013]

Direct load control for fast, reliable power system service provision



Direct load control for fast, reliable power system service provision

→Distributed!
→Accurate?
→Cheap?
→Green?



“But load control will never be reliable enough to provide trustworthy reserves!”

“But load control will never be reliable enough to provide trustworthy reserves!”

- Why?
  - Too much uncertainty: People! Weather! etc.

“But load control will never be reliable enough to provide trustworthy reserves!”

- Why?
  - Too much uncertainty: People! Weather! etc.
- Two options:
  - Be conservative in how much reserve you schedule
  - Explicitly consider reserve uncertainty in the planning algorithm

Outline

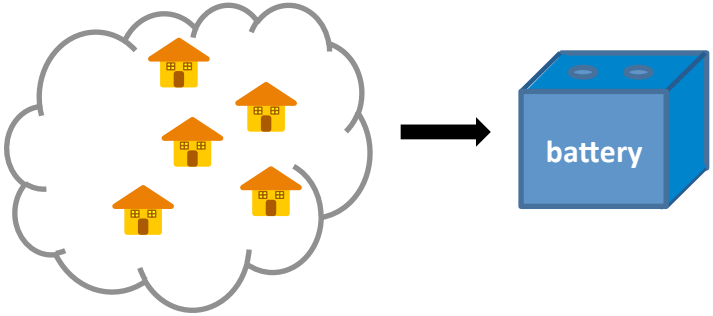
- Modeling reserves from loads
- Understanding uncertainty
- Stochastic optimal power flow
- Preliminary results
- New directions

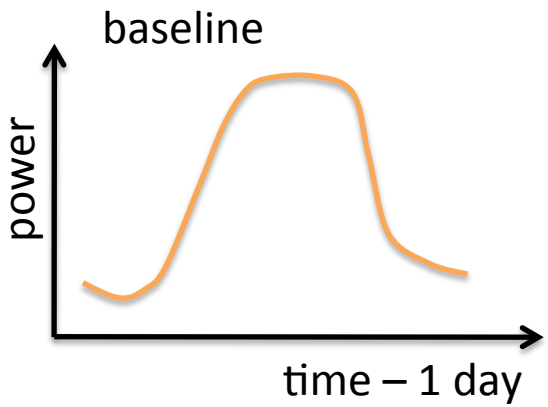
Outline

- Modeling reserves from loads
- Understanding uncertainty
- Stochastic optimal power flow
- Preliminary results
- New directions

Largely based on: Vrakopoulou, Mathieu, Andersson, "Stochastic Optimal Power Flow with Reserves From Demand Response." Proceedings of the Hawaii International Conference on Systems Science, 2014.

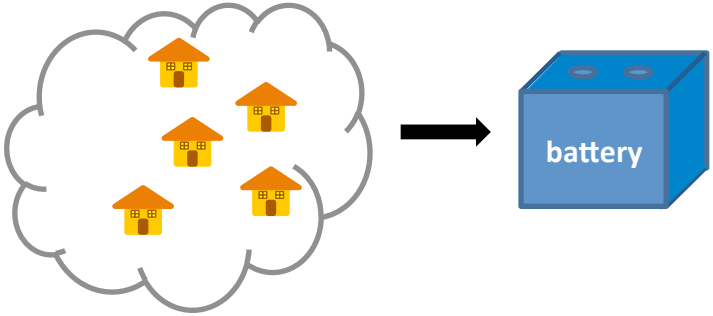
Time-varying "thermal battery" model

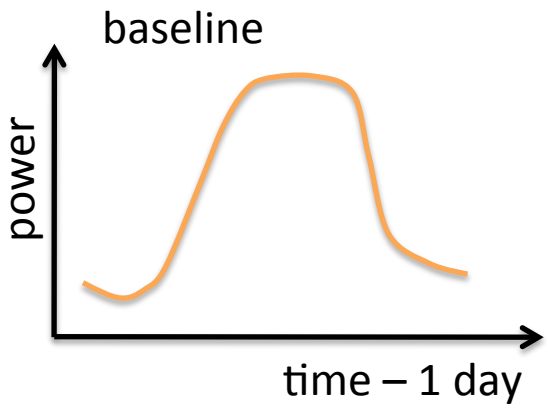


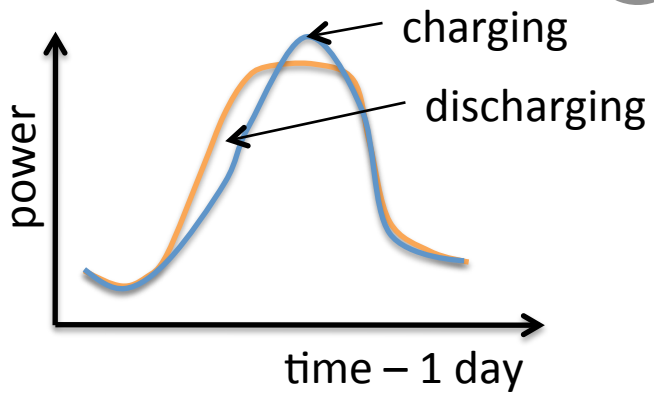


[Mathieu, Kamgarpour, Lygeros, & Callaway E*CC* 2013]

Time-varying "thermal battery" model

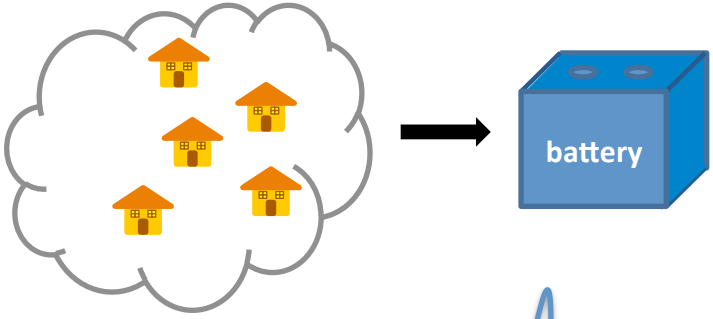


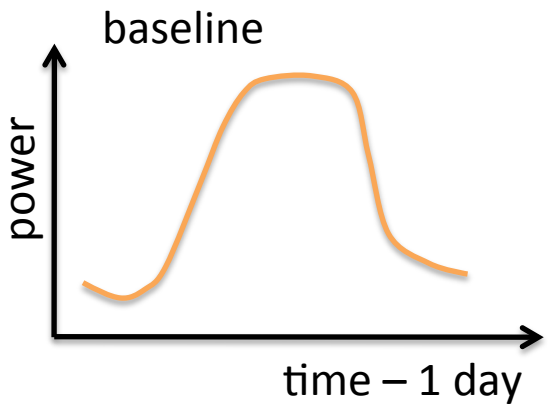


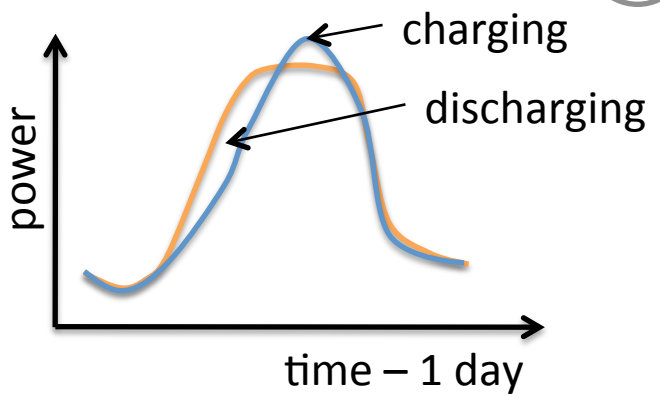


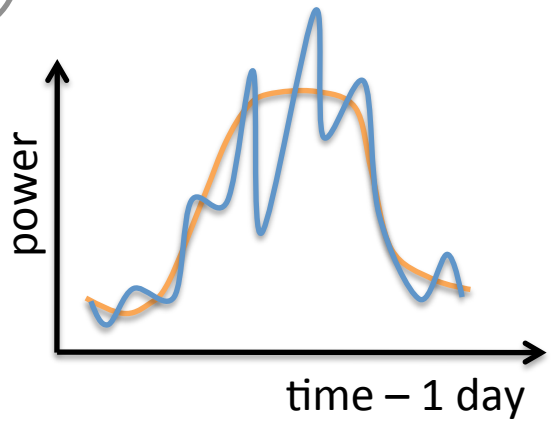
[Mathieu, Kamgarpour, Lygeros, & Callaway *ECC* 2013]

Time-varying "thermal battery" model



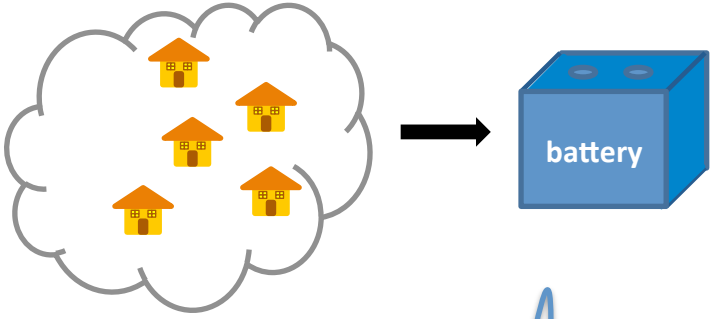


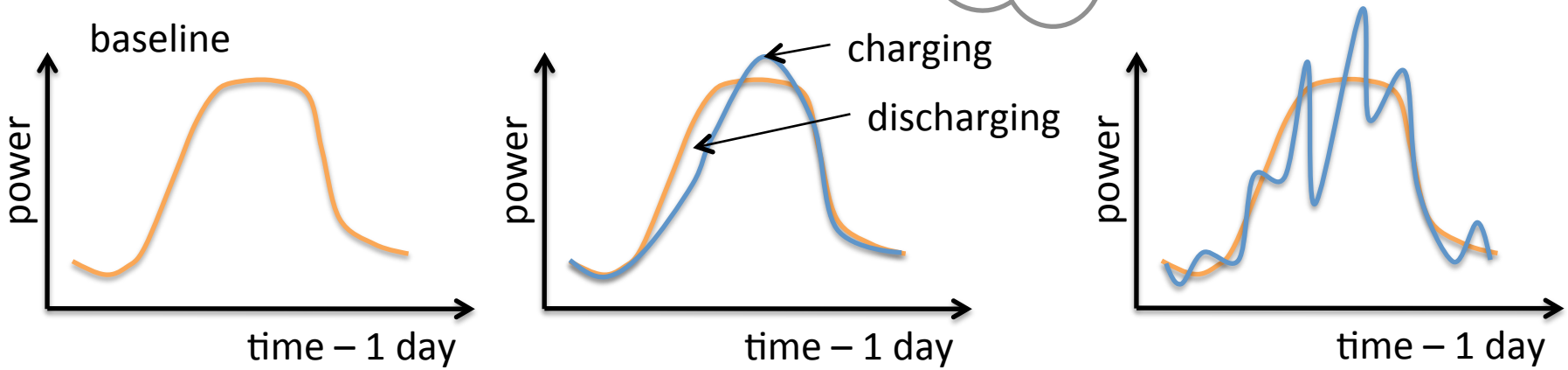




[Mathieu, Kamgarpour, Lygeros, & Callaway *ECC* 2013]

Time-varying "thermal battery" model

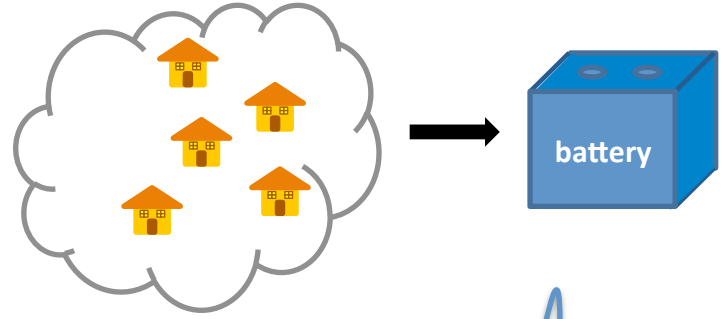


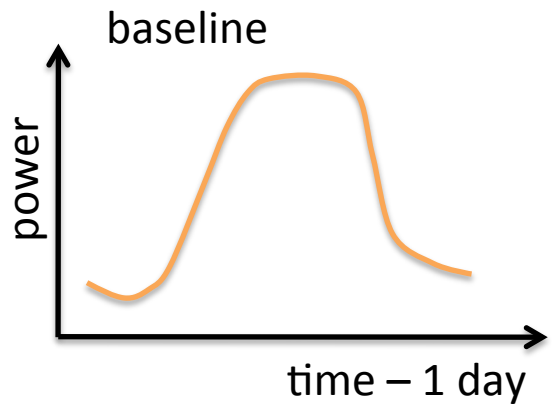


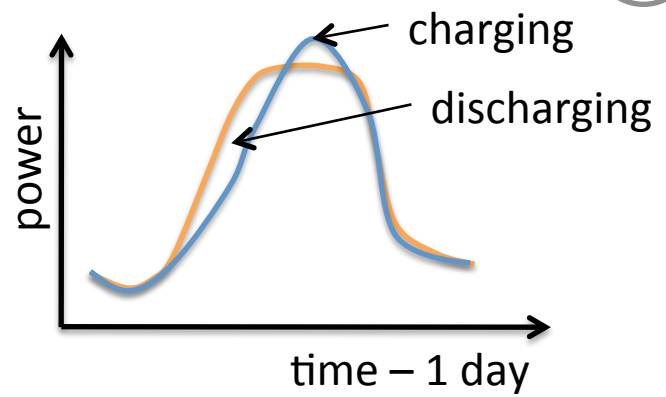
$$S(k+1) = S(k) + (P(k) - P_{\text{baseline}}(k))\Delta T$$

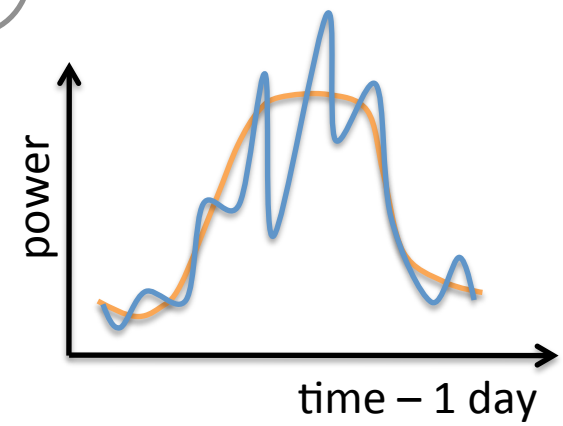
[Mathieu, Kamgarpour, Lygeros, & Callaway *ECC* 2013]

Time-varying "thermal battery" model





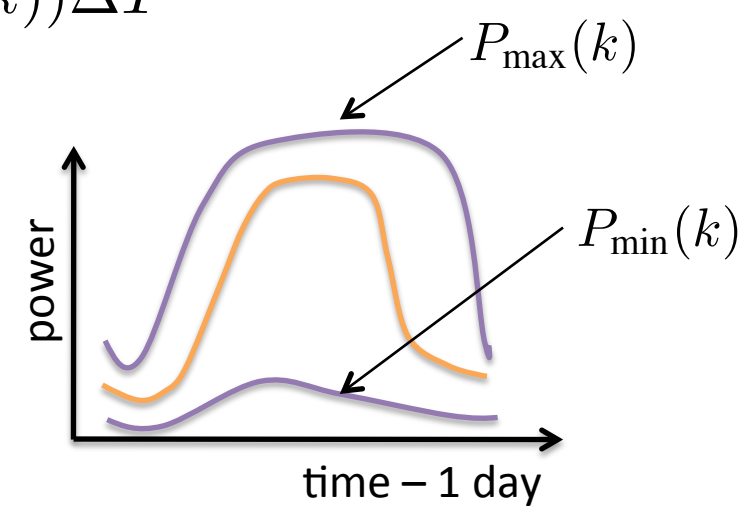




$$S(k+1) = S(k) + (P(k) - P_{\text{baseline}}(k))\Delta T$$

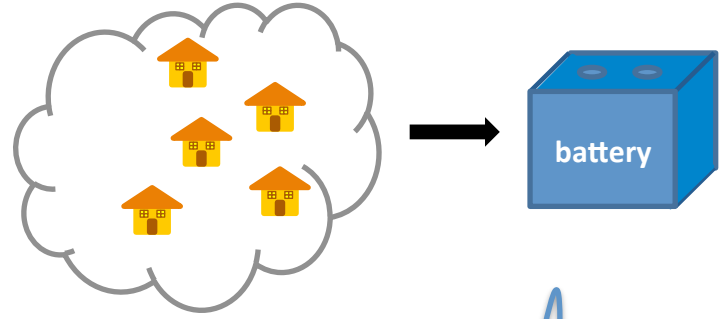
Mean power over an interval

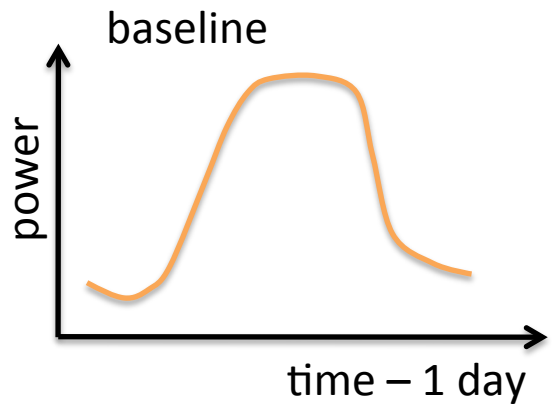
$$P_{\min}(k) \leqslant P(k) \leqslant P_{\max}(k)$$

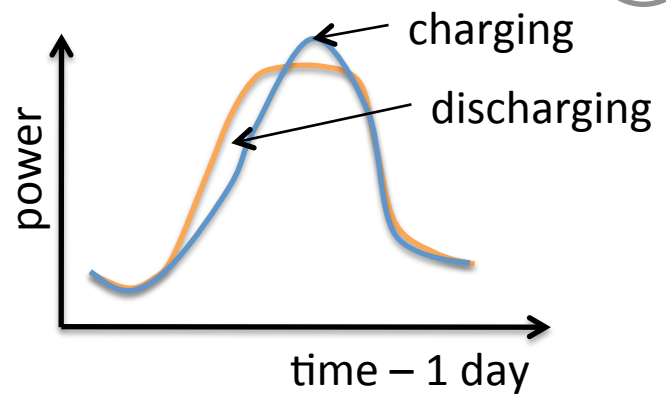


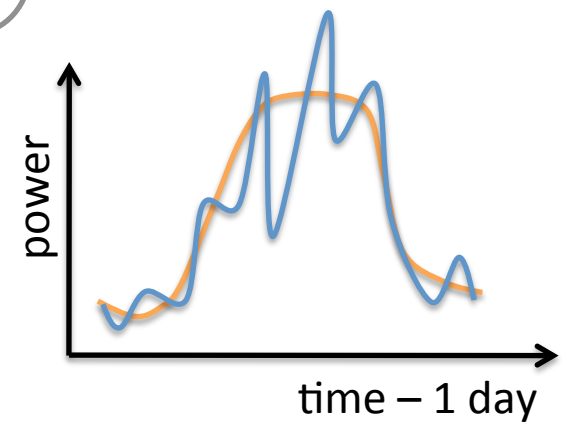
[Mathieu, Kamgarpour, Lygeros, & Callaway *ECC* 2013]

Time-varying "thermal battery" model









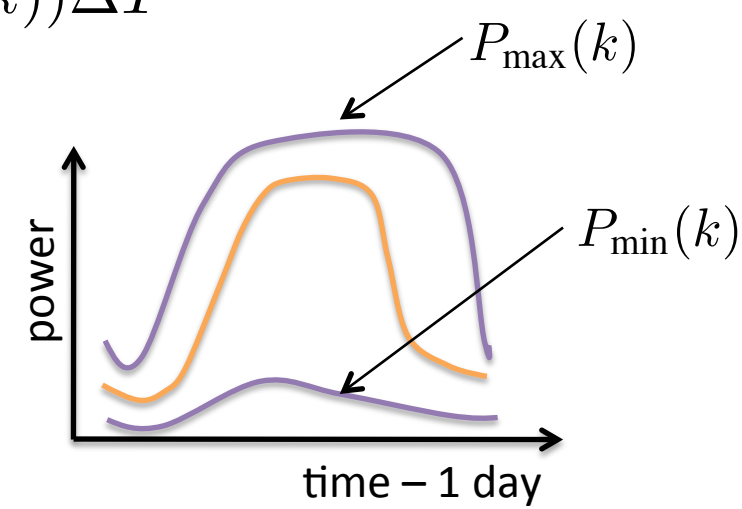
$$S(k+1) = S(k) + (P(k) - P_{\text{baseline}}(k))\Delta T$$

Mean power over an interval

$$P_{\min}(k) \leqslant P(k) \leqslant P_{\max}(k)$$

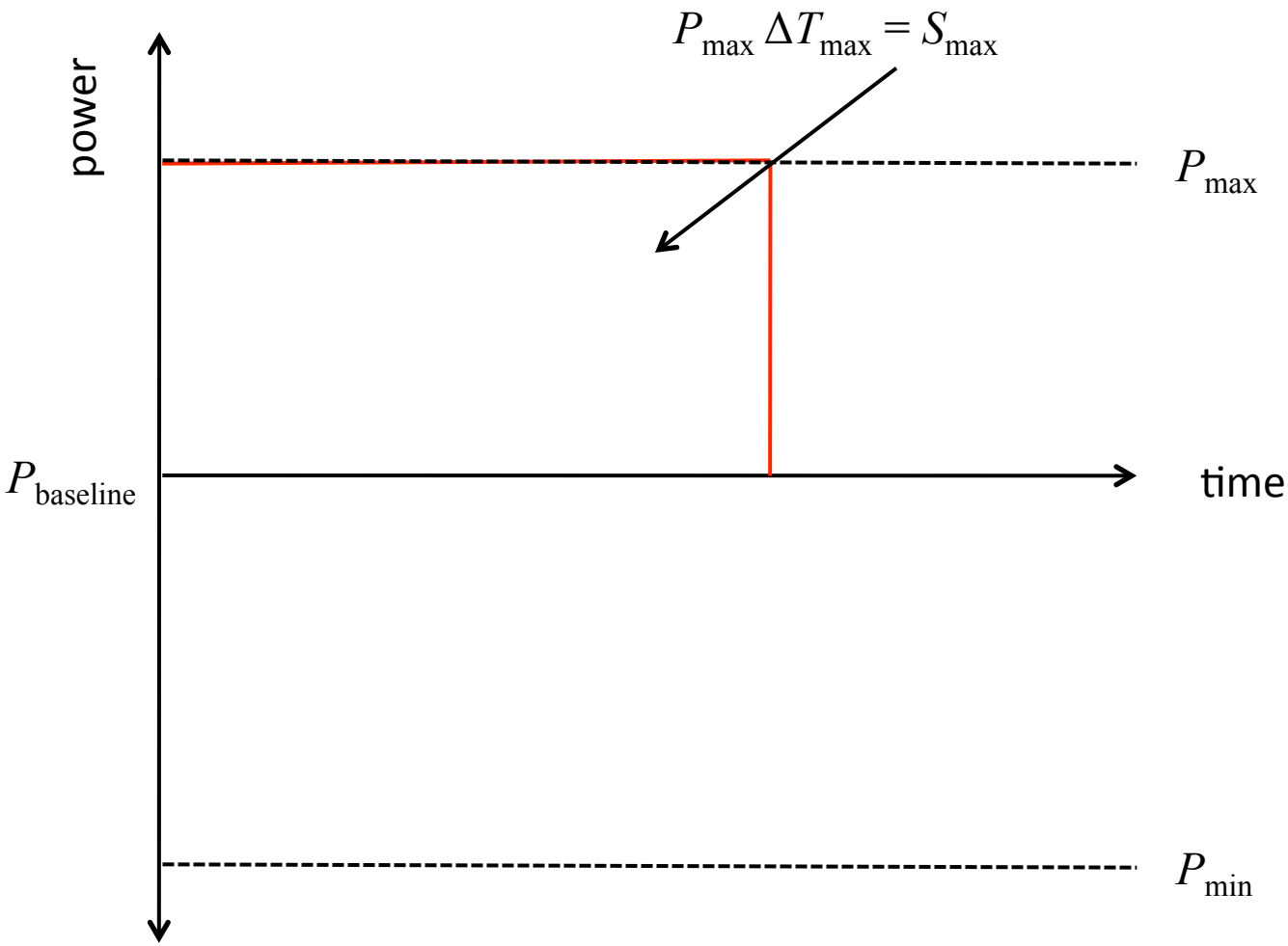
State of charge

$$S_{\min}(k) \leqslant S(k) \leqslant S_{\max}(k)$$

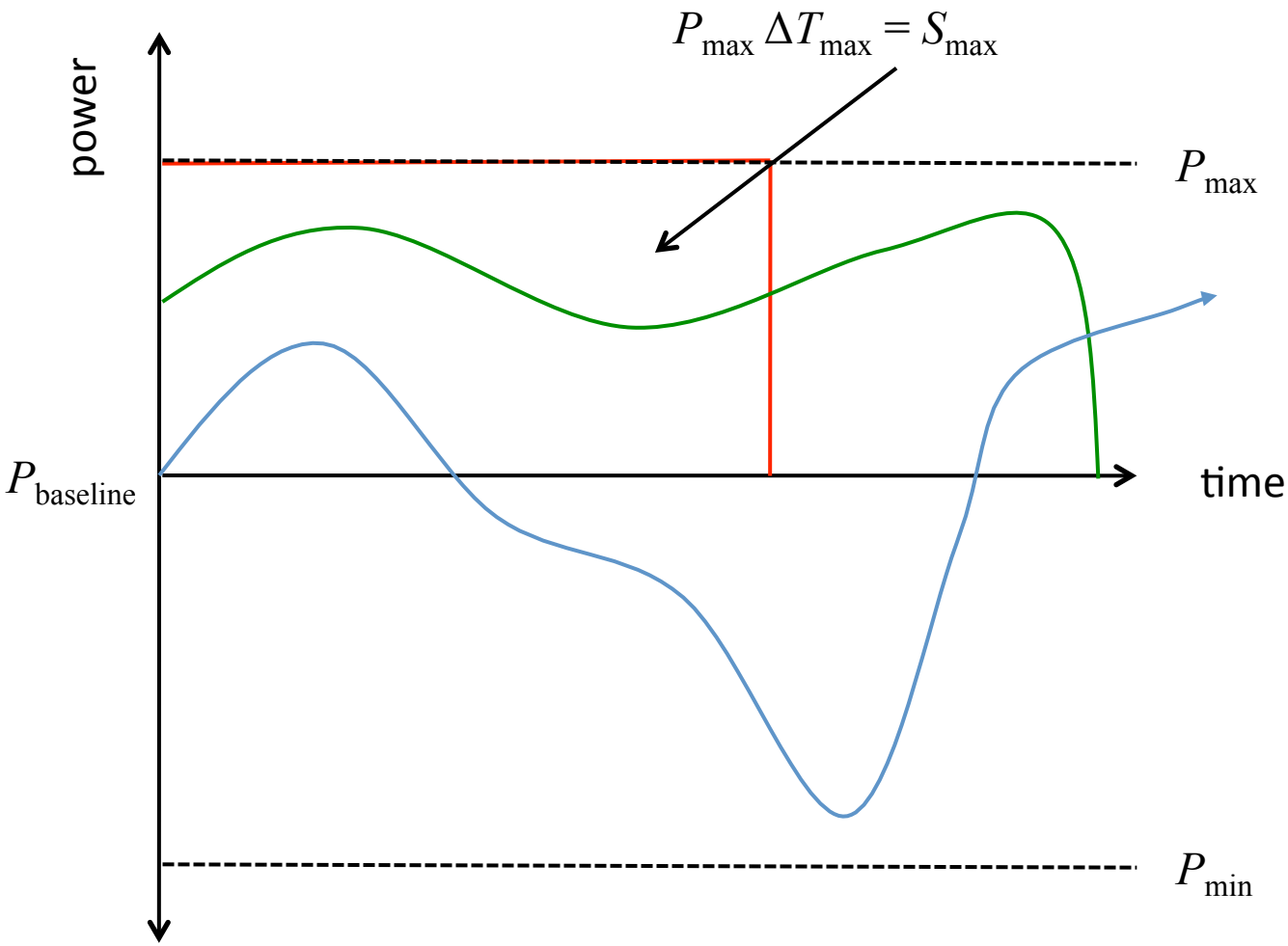


[Mathieu, Kamgarpour, Lygeros, & Callaway *ECC* 2013]

What are the power and energy capacity intuitively?

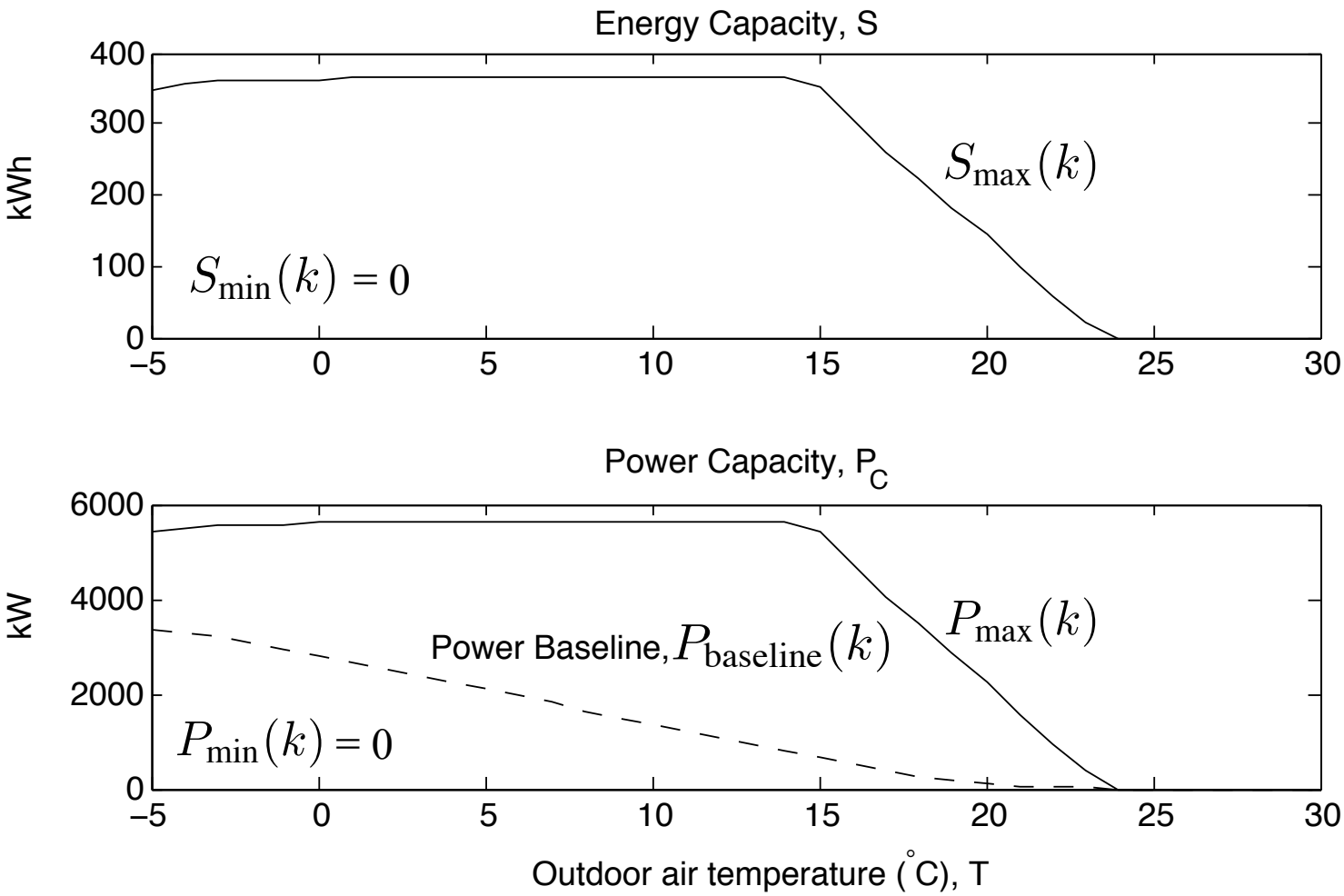


What are the power and energy capacity intuitively?



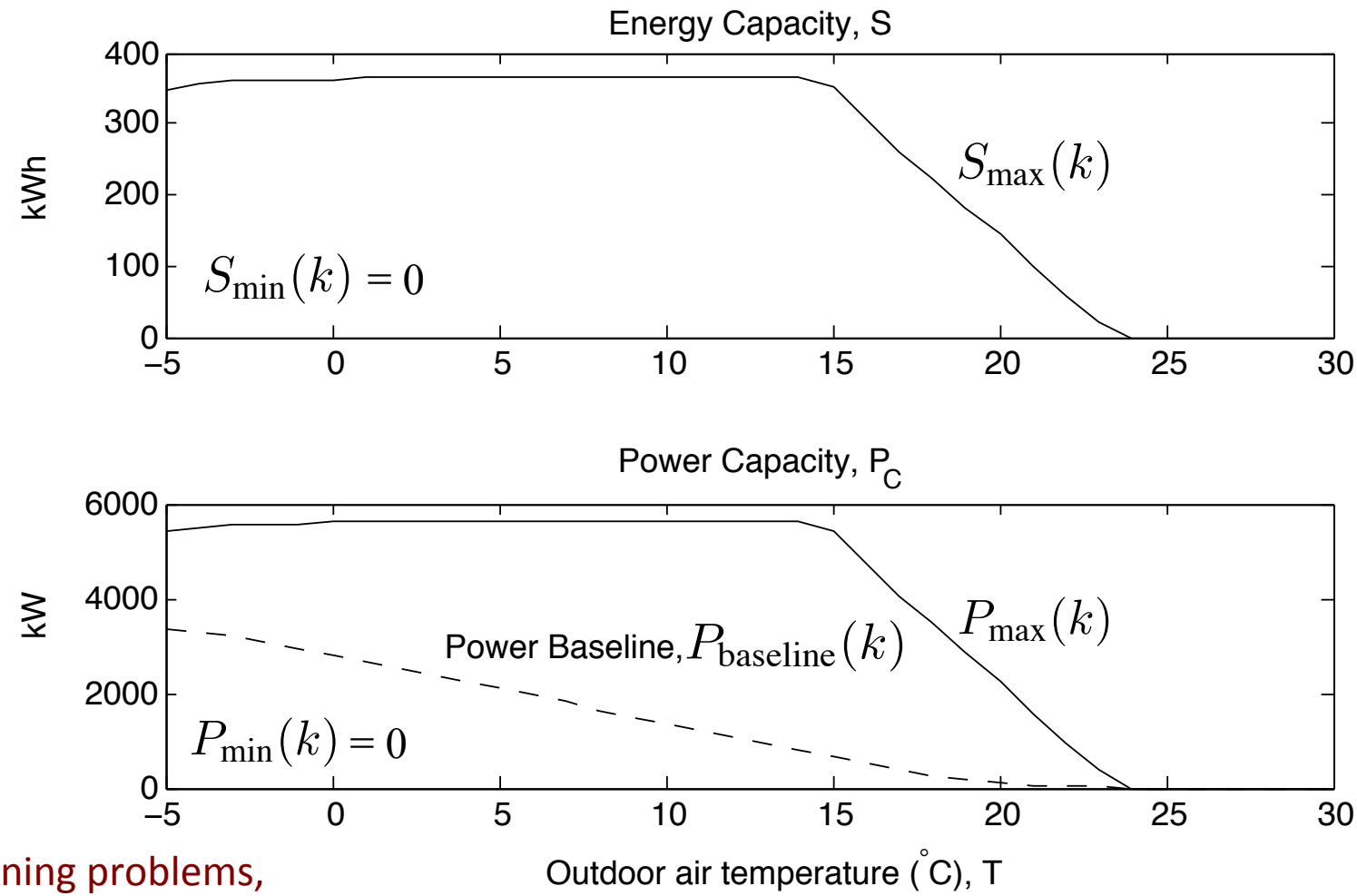
Time-varying power & energy capacities

1000 electric space heaters



Time-varying power & energy capacities

1000 electric space heaters

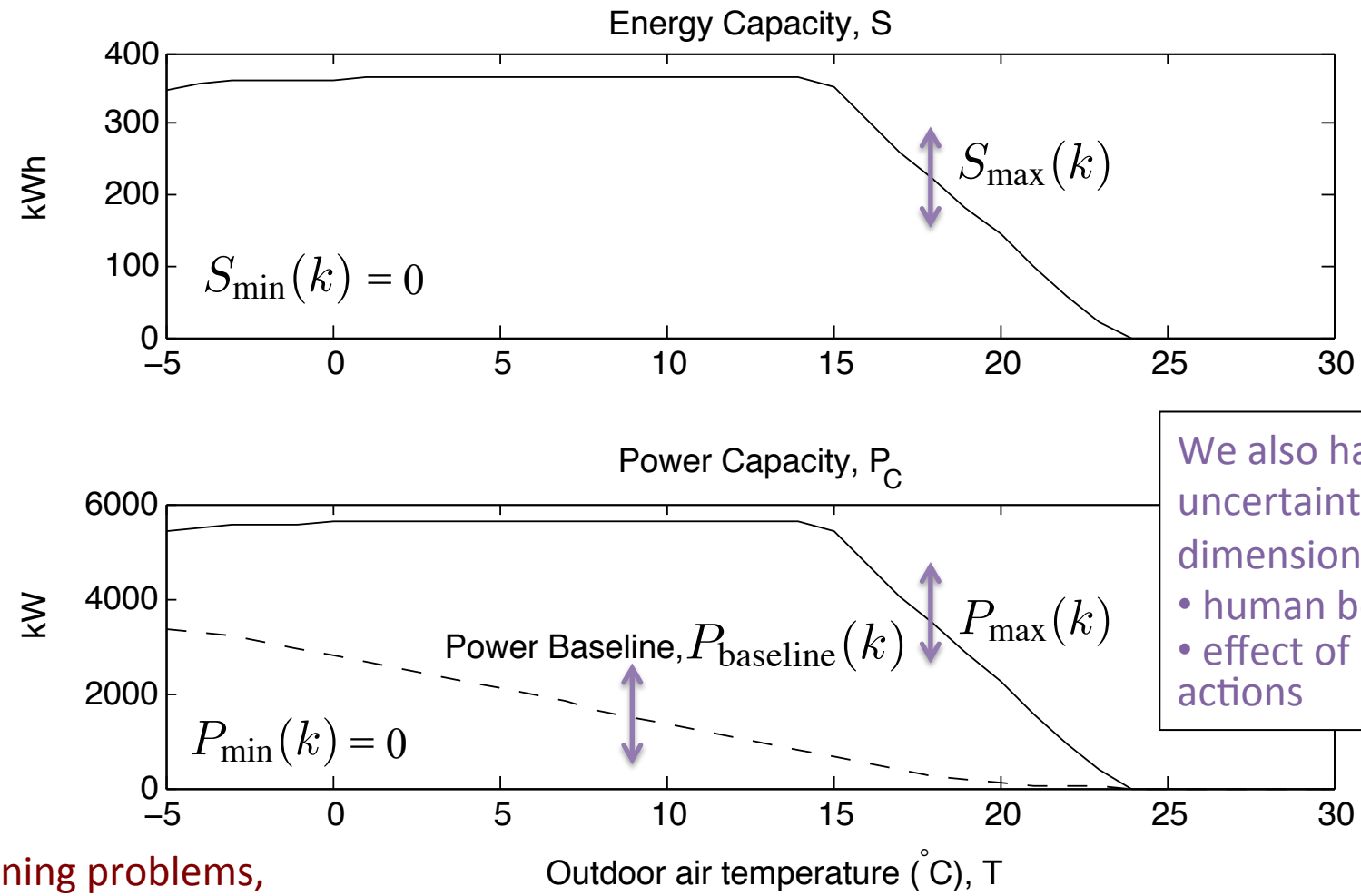


In planning problems, we have temperature forecast uncertainty

J. Mathieu, UMich

Time-varying power & energy capacities

1000 electric space heaters

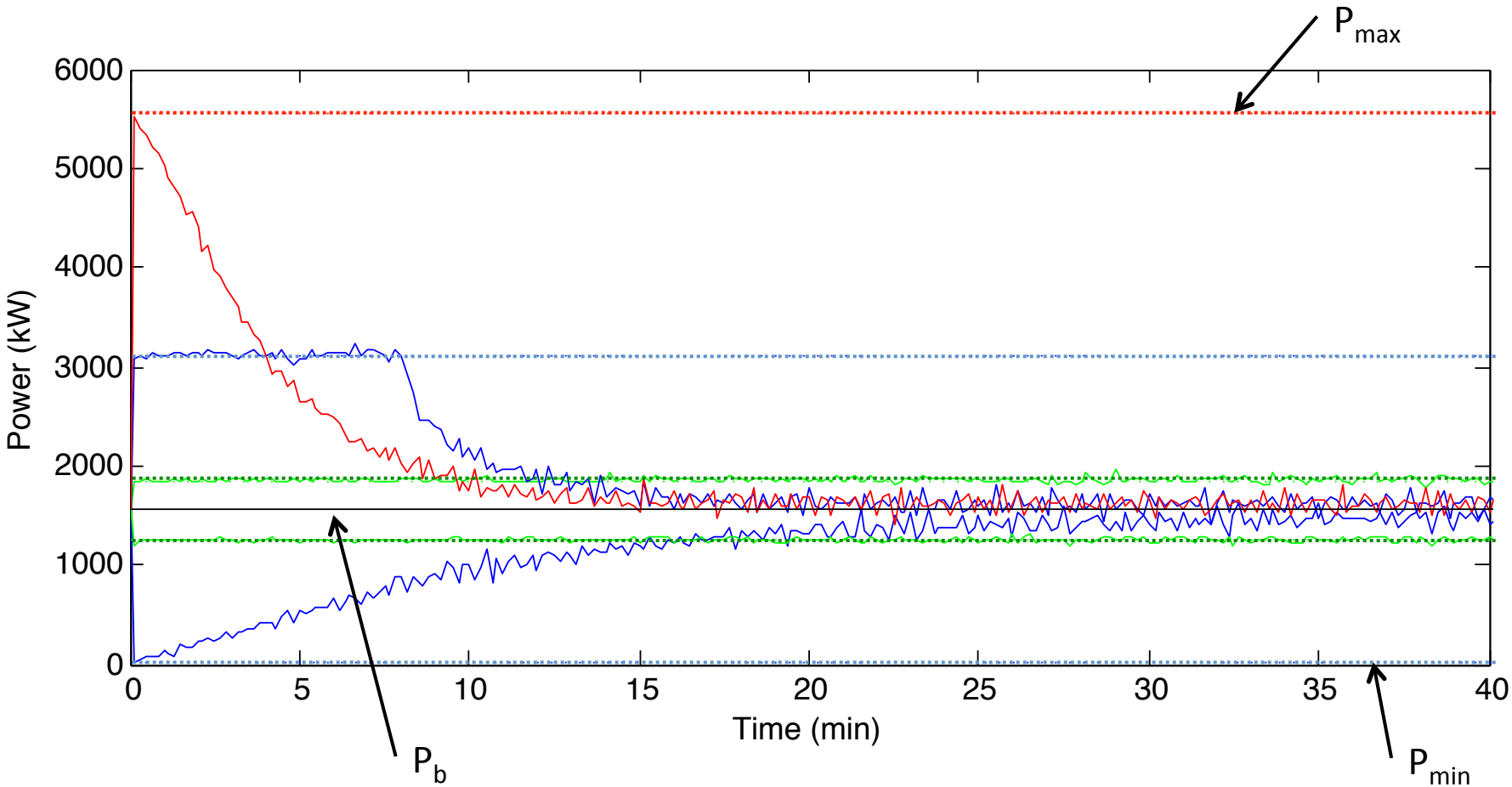


We also have uncertainty in this dimension!

- human behavior
- effect of past DR actions

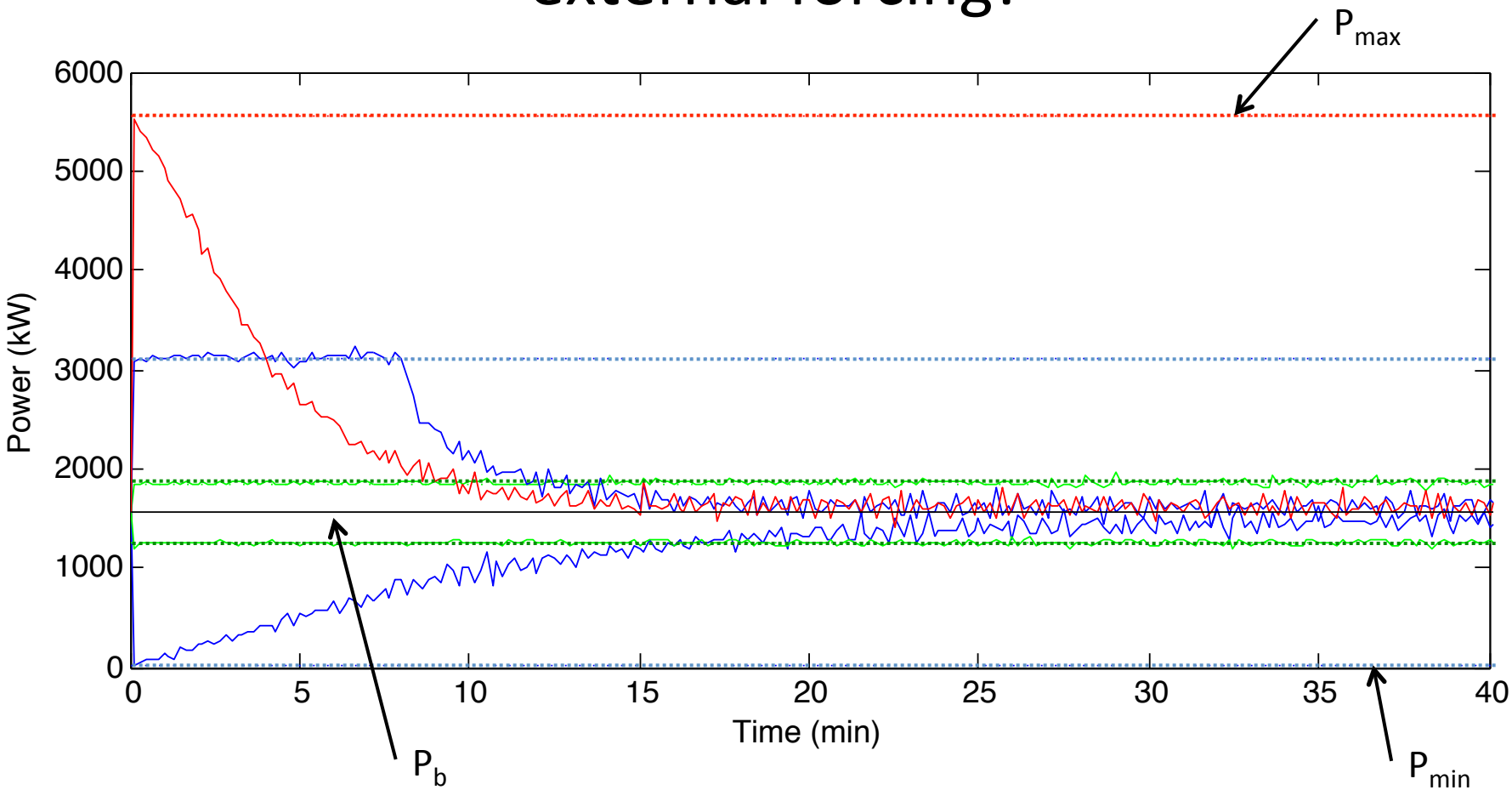
In planning problems, we have temperature forecast uncertainty

What if we try to hold a fixed trajectory?



What if we try to hold a fixed trajectory?

→ The power capacity is actually a function of external forcing!



Handling reserve uncertainty within a dc optimal power flow (DC-OPF) formulation

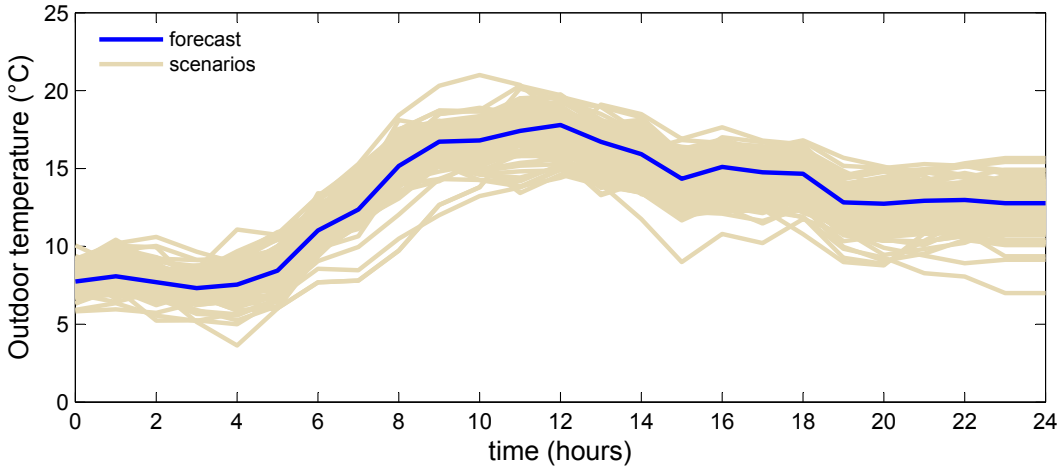
- Decision variables:
  - Generation set points & reserve levels
  - Load set points & reserve levels ← given that load flexibility is uncertain!

Handling reserve uncertainty within a dc optimal power flow (DC-OPF) formulation

- Decision variables:
  - Generation set points & reserve levels
  - Load set points & reserve levels ← given that load flexibility is uncertain!
- Objective: Minimize cost of energy generation and reserves subject to generator, load, and power system constraints

Handling reserve uncertainty within a dc optimal power flow (DC-OPF) formulation

- Decision variables:
  - Generation set points & reserve levels
  - Load set points & reserve levels ← given that load flexibility is uncertain!
- Objective: Minimize cost of energy generation and reserves subject to generator, load, and power system constraints
- Uncertainty:
  - Wind power
  - Outdoor temperature
    - →Load uncertainty
    - →DR uncertainty
    - →Reserve uncertainty



Reserve Modeling

- Secondary frequency control (AGC) provided by loads and generators
  - Assumes loads are cheaper!

Reserve Modeling

- Secondary frequency control (AGC) provided by loads and generators
  - Assumes loads are cheaper!

- Re-dispatch (15-minute market, Tertiary control) provided by generators
  - Covers power mismatch between expected and actual generation (as it does today)
  - Provides energy to return loads to their scheduled energy state (like CAISO's Regulation Energy Management)!

Solution Approach

- Chance-constrained OPF
- Solved with probabilistically robust design [Margellos, Goulart, and Lygeros 2012], inspired by a scenario-based technique [Calafiore and Campi 2006]
- Probabilistic guarantees

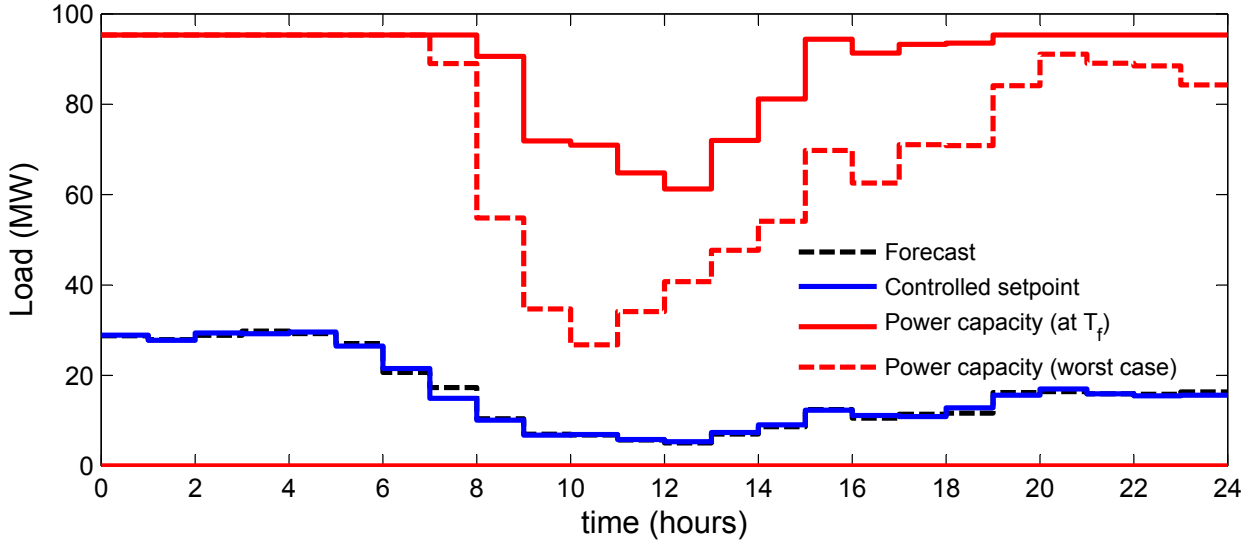
Solution Approach

- Chance-constrained OPF
- Solved with probabilistically robust design [Margellos, Goulart, and Lygeros 2012], inspired by a scenario-based technique [Calafiore and Campi 2006]
- Probabilistic guarantees

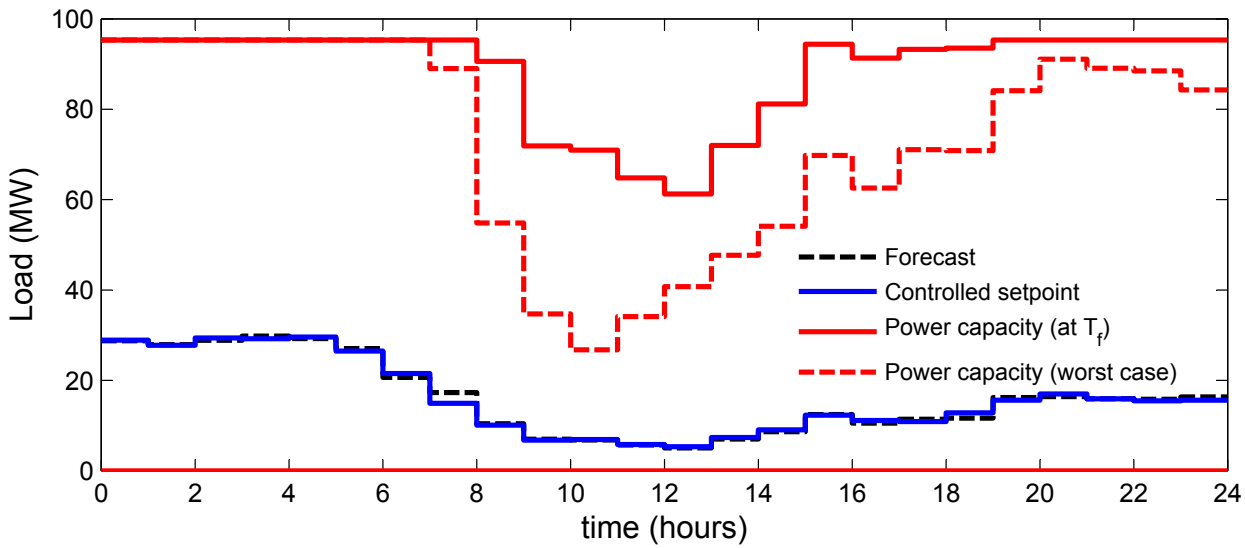
- More details this afternoon…

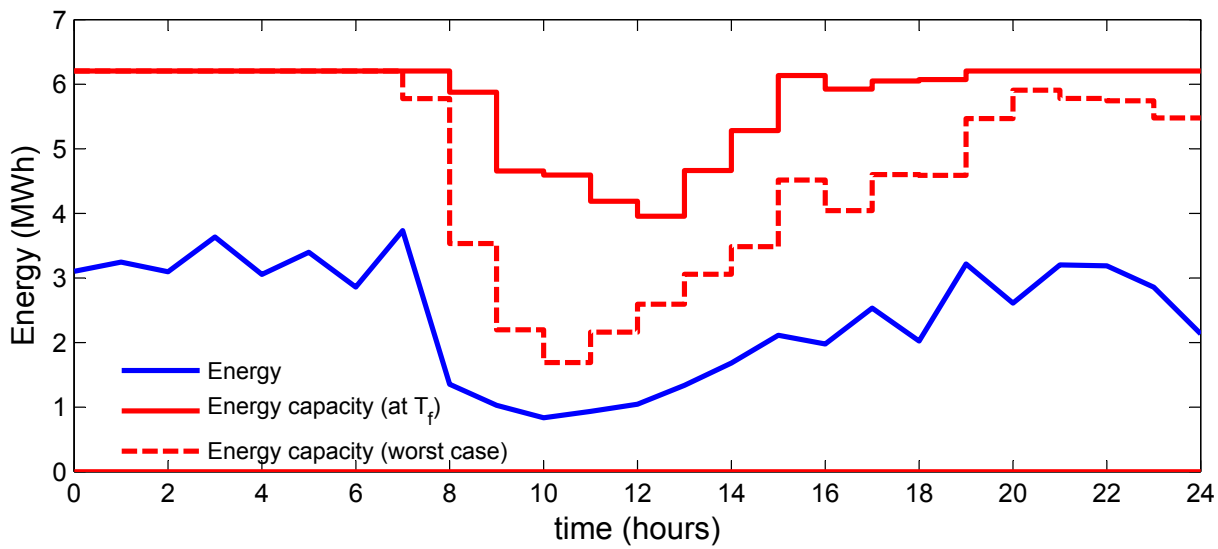
  "Quantifying the Trade-off Between Secure and Economic Operation of Power Systems Under Uncertainty" – Maria Vrakopoulou

How much does outdoor temperature uncertainty really matter?



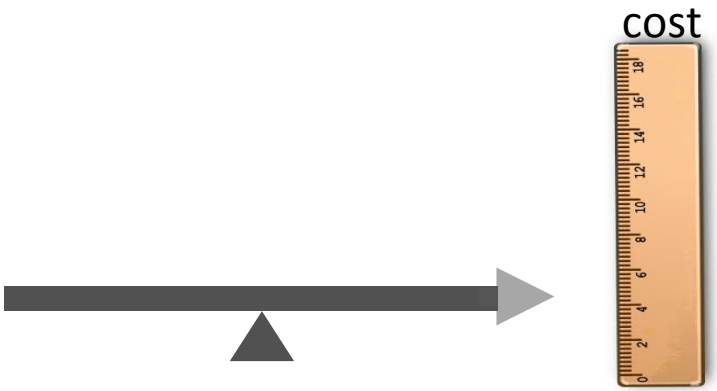
How much does outdoor temperature uncertainty really matter?

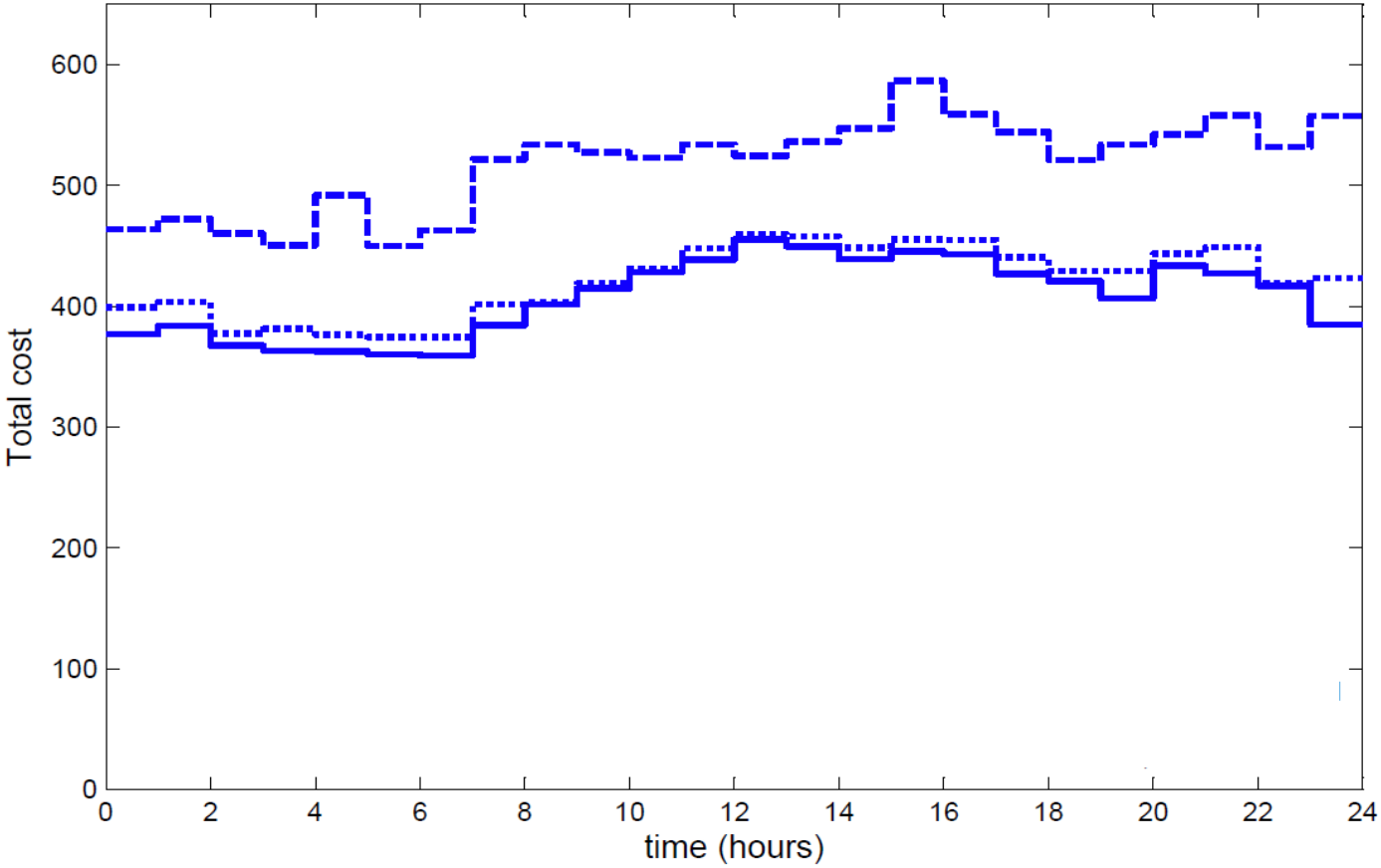




Operational costs

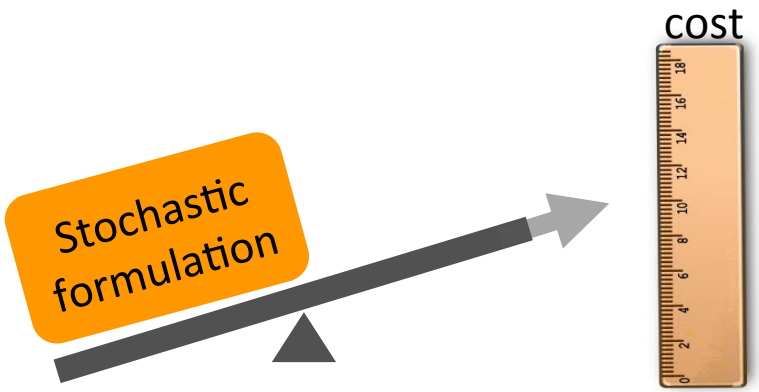
no load uncertainty, no control

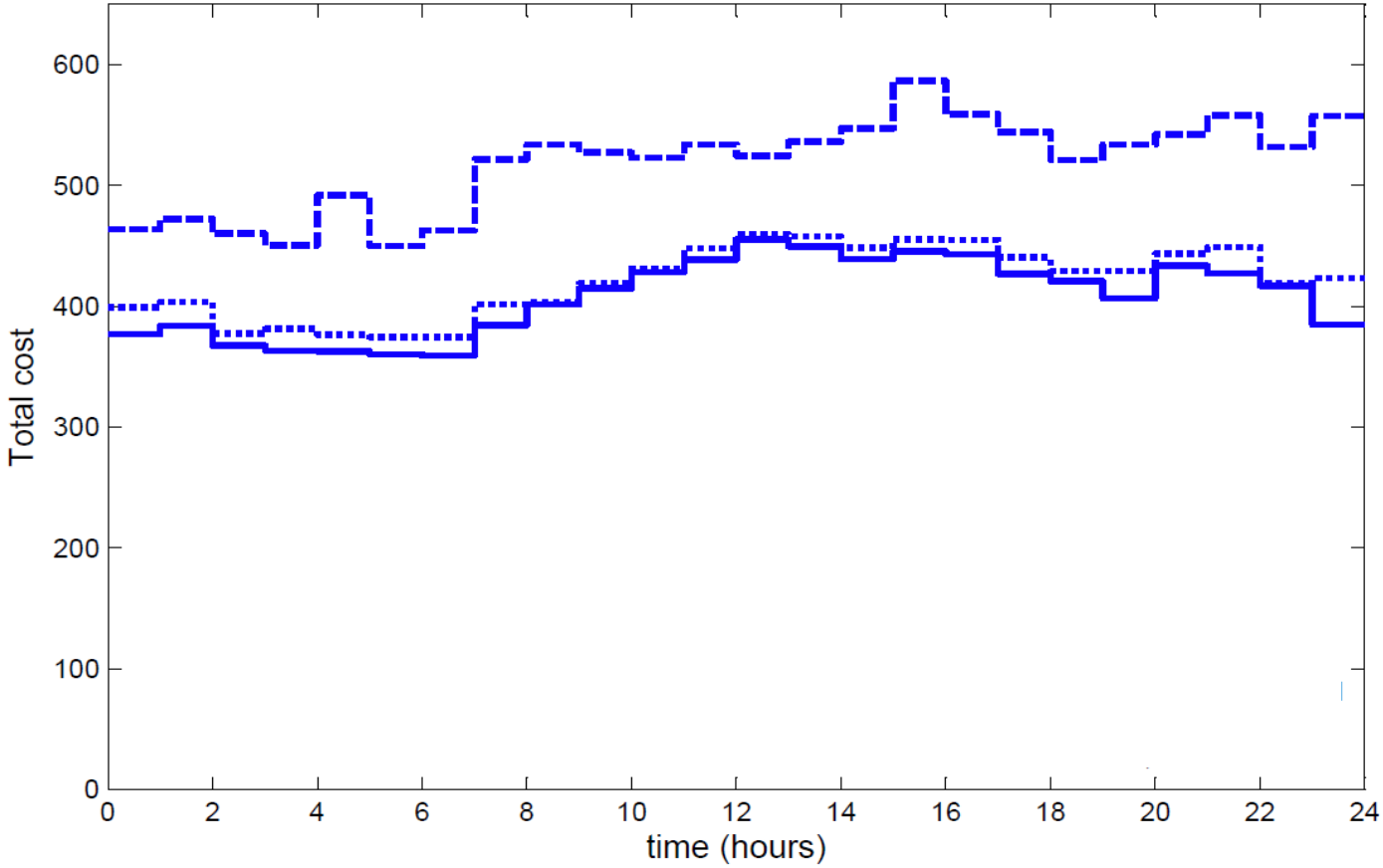




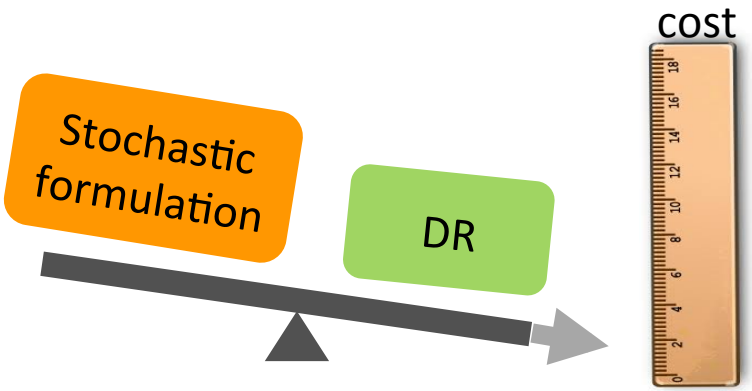
Operational costs

no load uncertainty, no control
uncertain load, no control

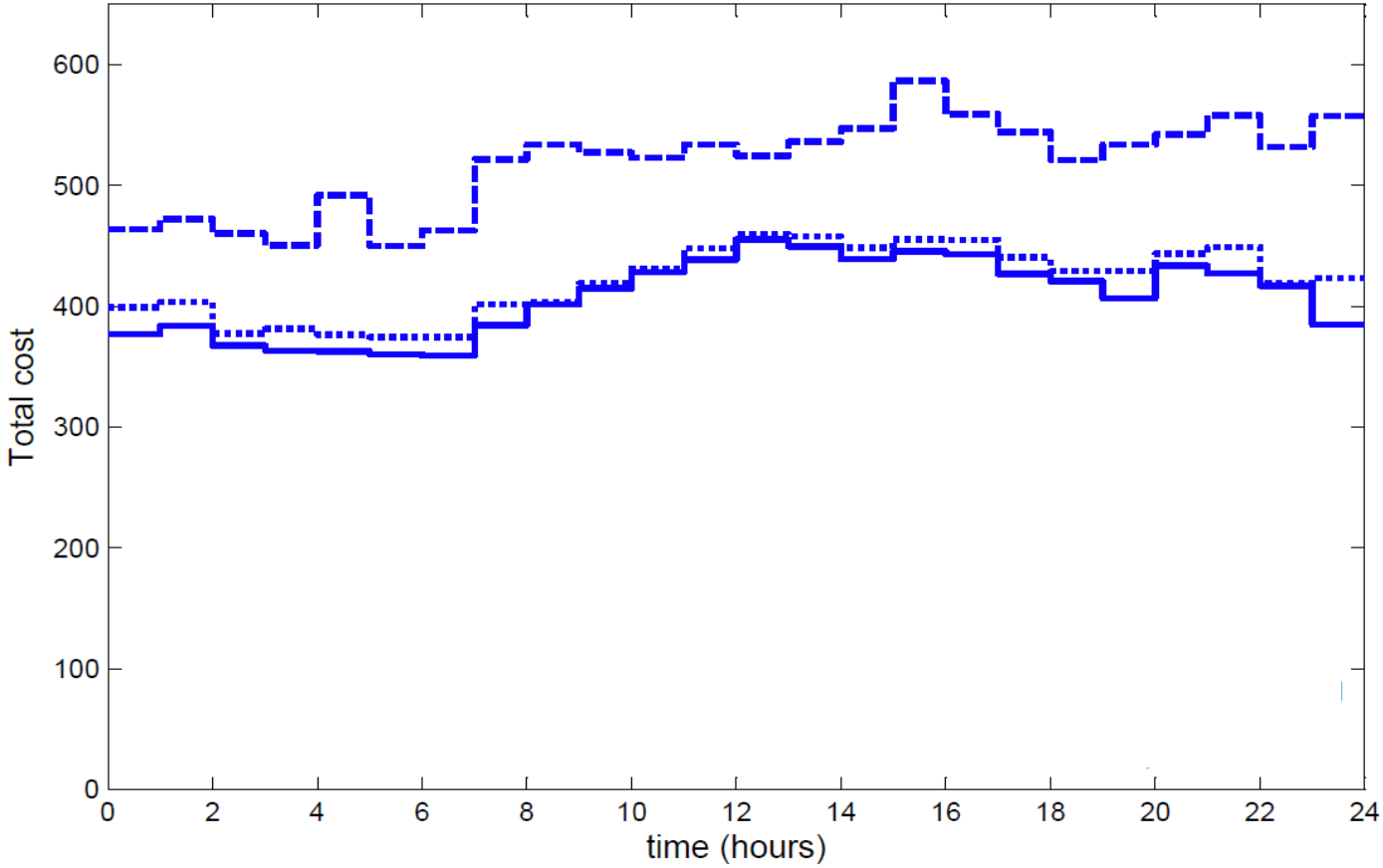




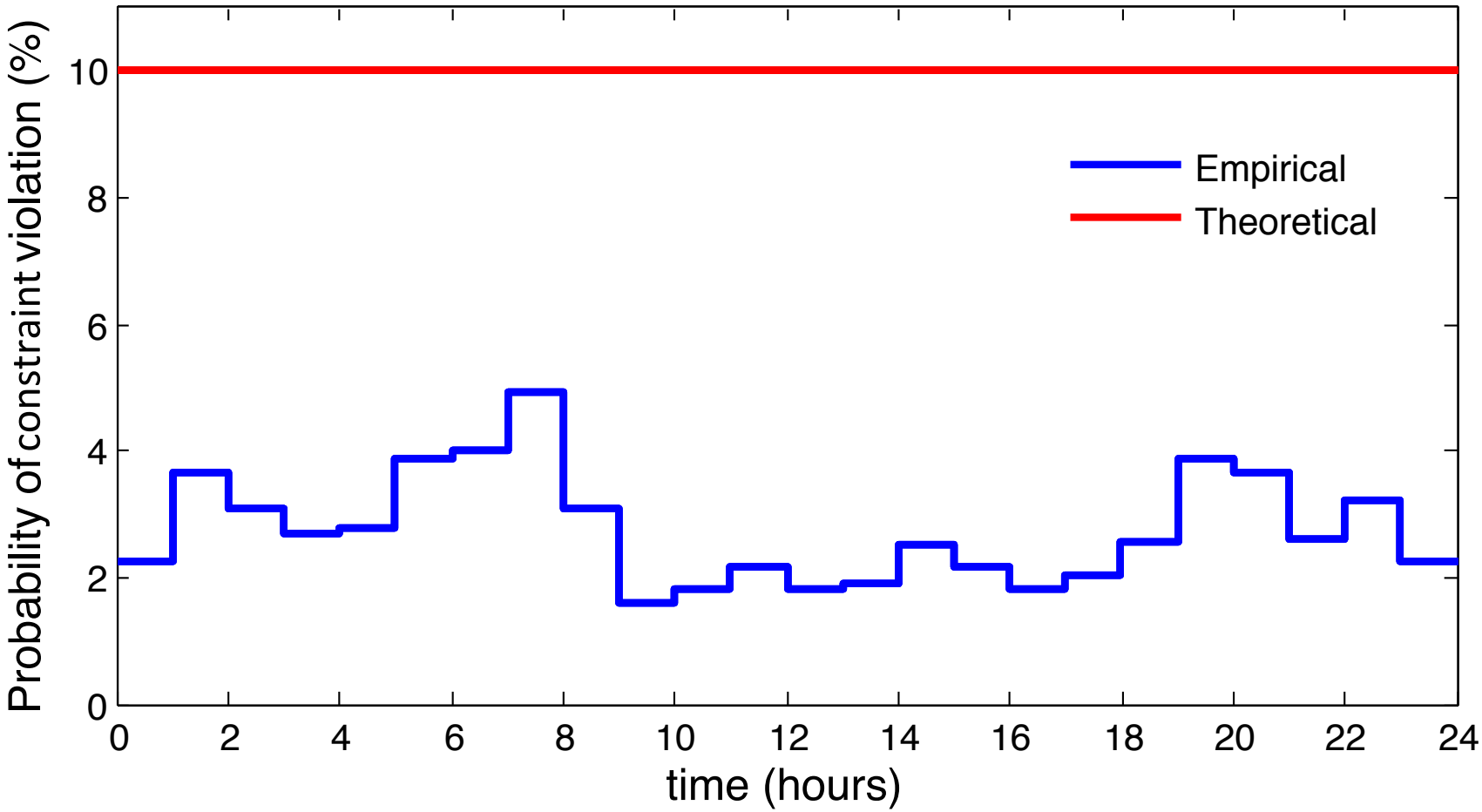
Operational costs



- no load uncertainty, no control
- uncertain load, no control
- uncertain load, control



How well do the probabilistic guarantees work?



Key Takeaway

Reserves from loads may not be of the same "quality" as those provided by generators, BUT we can *plan* for load uncertainty by explicitly considering it in our problem formulation

New directions…

- How do uncertainty and reserve costs interact?
- How can we handle the full complexity of load control uncertainty?
  - Multi-dimensional
  - Exogenous and endogenous
  - Non-stationary

New directions…

- How do uncertainty and reserve costs interact?
- How can we handle the full complexity of load control uncertainty?
  - Multi-dimensional
  - Exogenous and endogenous
  - Non-stationary
  - Insufficient data!

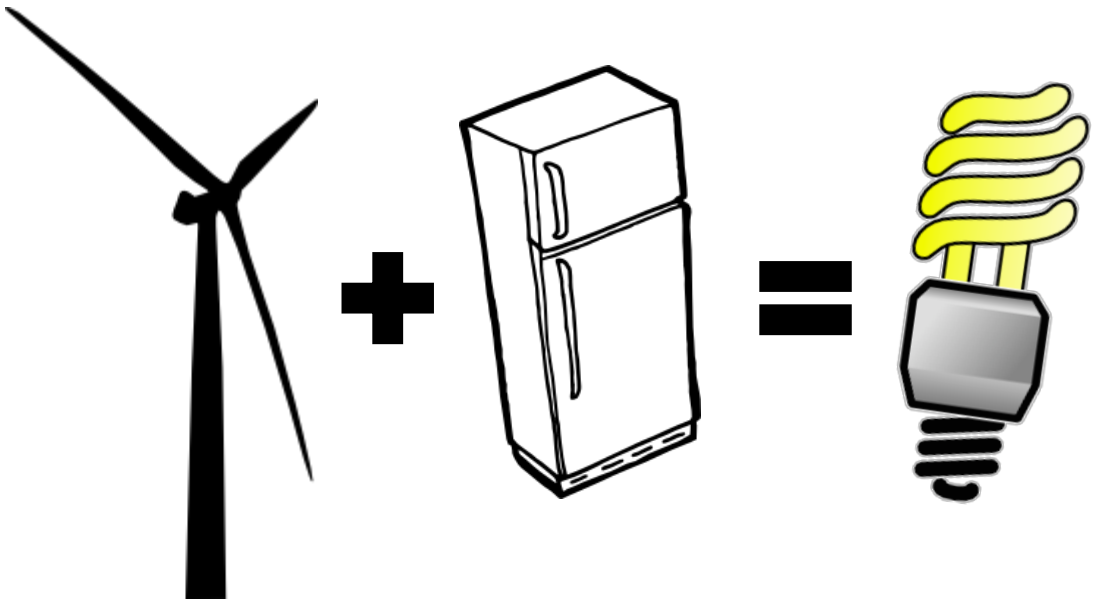
New directions…

- How do uncertainty and reserve costs interact?

- How can we handle the full complexity of load control uncertainty?
  - Multi-dimensional
  - Exogenous and endogenous
  - Non-stationary
  - Insufficient data!

Scenario-based approaches Vs. Robust formulations Vs. Analytical reformulation

THANK YOU! QUESTIONS?



Contact: Johanna Mathieu
jlmath@umich.edu