Using Residential Electric Loads in Energy and Ancillary Services Markets

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Background

- As more wind and solar are added to the grid there will be more need for power system services, like load following and regulation [Makarov et al., "Operational Impacts of Wind Generation on California Power Systems," 2009].

- These services could be provided by new generators, energy storage, and/or demand response.

- We usually think of using LARGE loads for Demand Response (DR).

- In our work, we simulate small residential loads to determine how well populations of loads could provide load following.

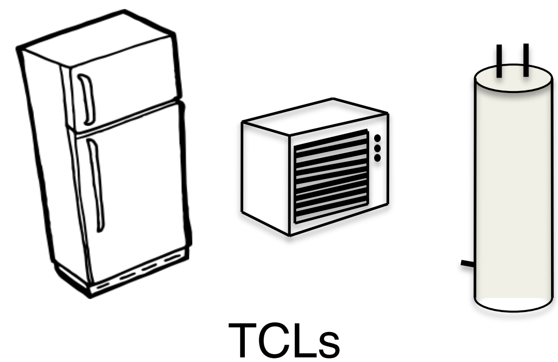
Why Small??

more reliable – spatially distributed – simple local controls

continuous, not discrete, control response

Thermostatically Controlled Loads (TCLs)

- Refrigerators, water heaters, air conditioners, electric space heaters, etc.

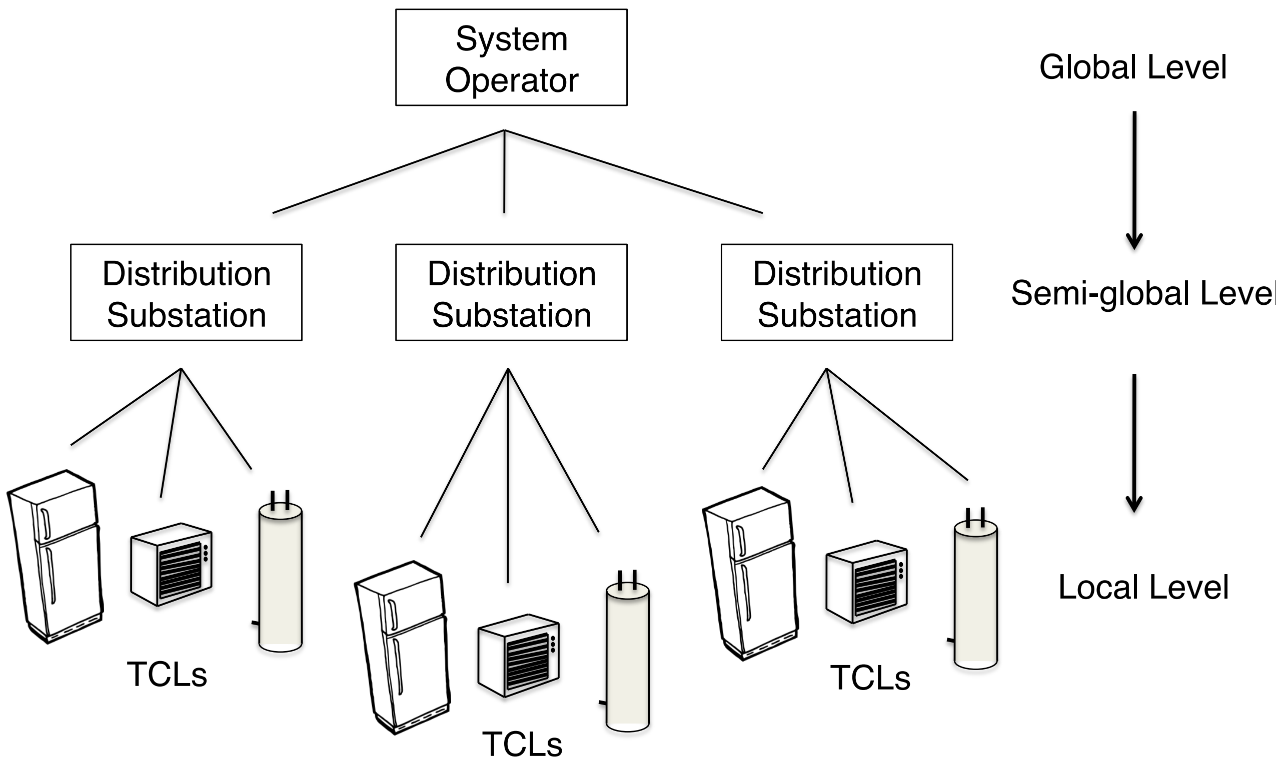


- Hysteretic ON/OFF control

- Store thermal energy in temperature dead-bands like batteries store chemical energy

How would we control TCLs?

Our Goal: high resolution control with minimal sensing/communications infrastructure



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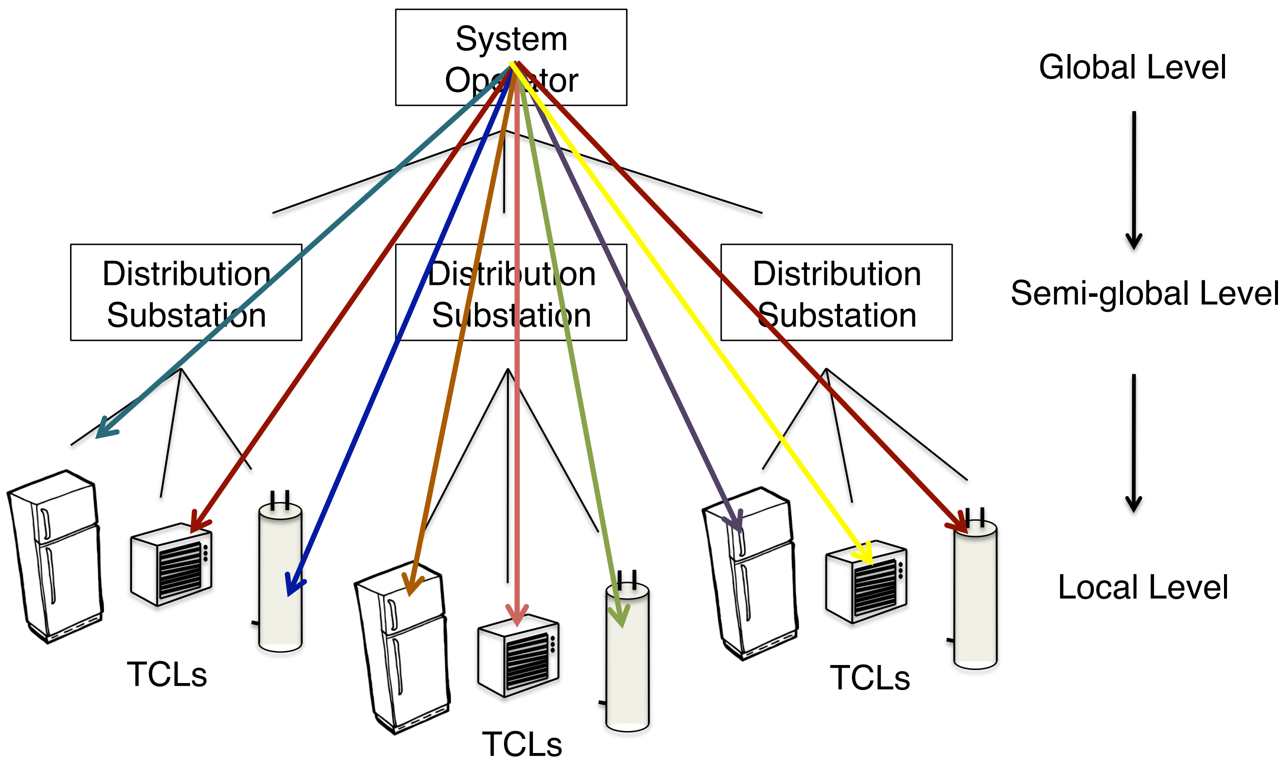

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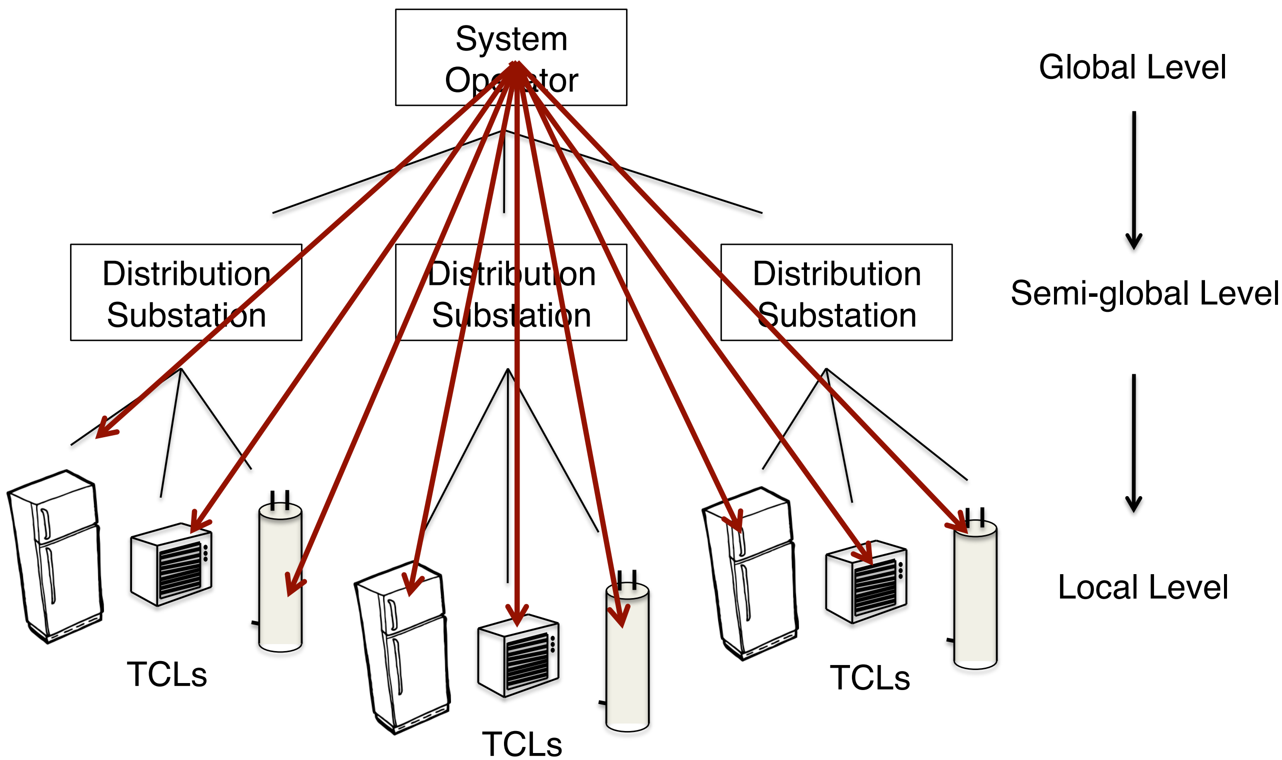

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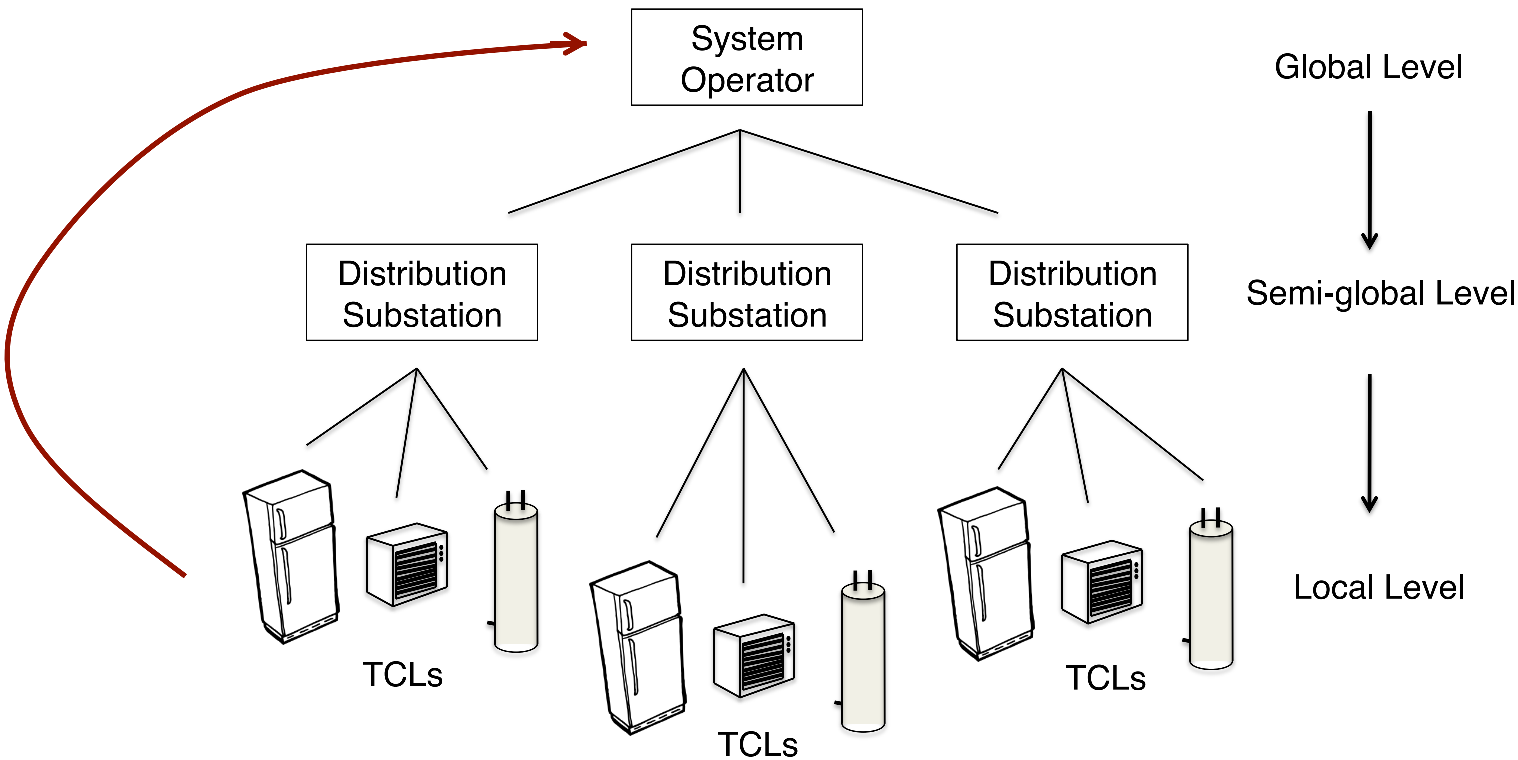

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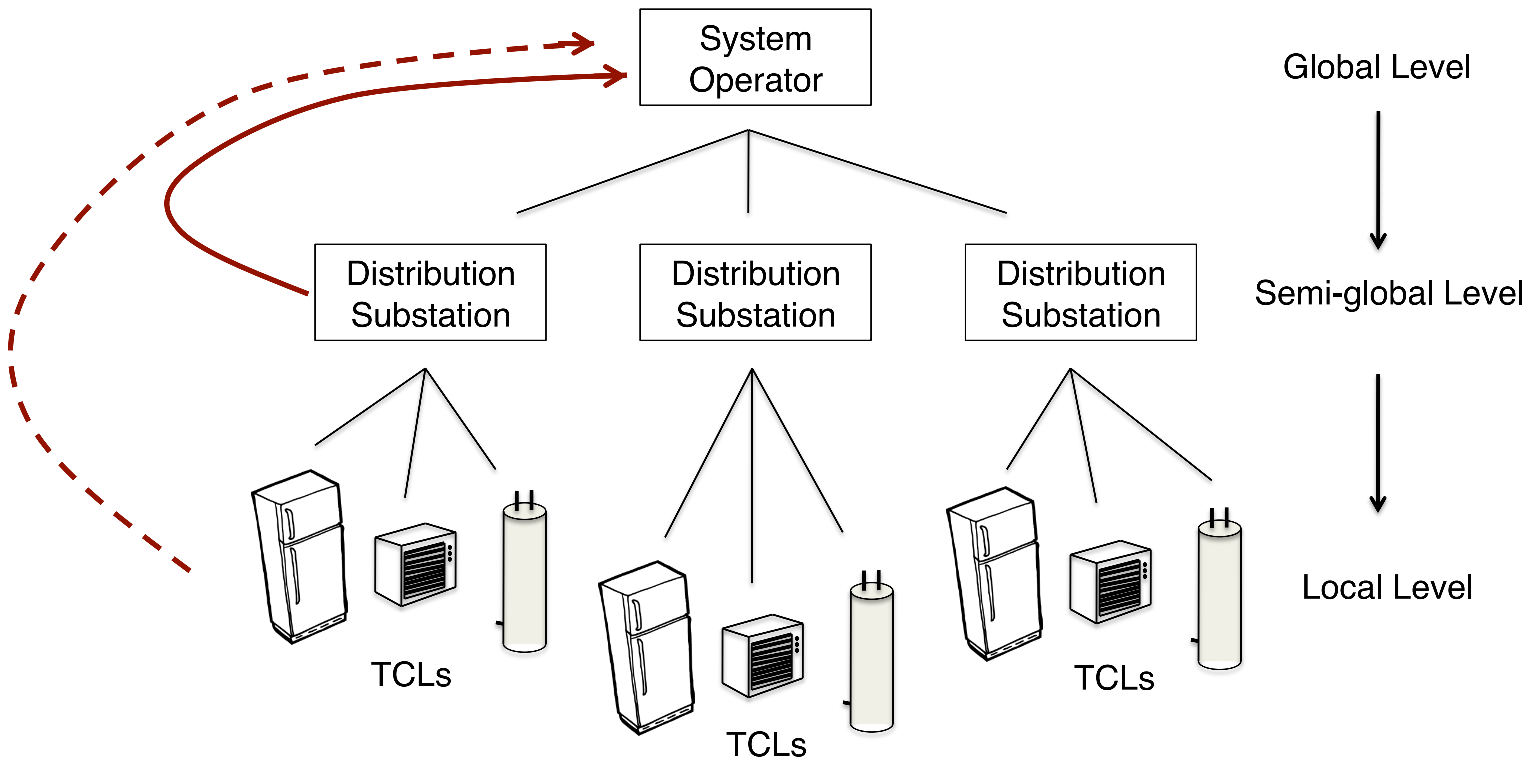

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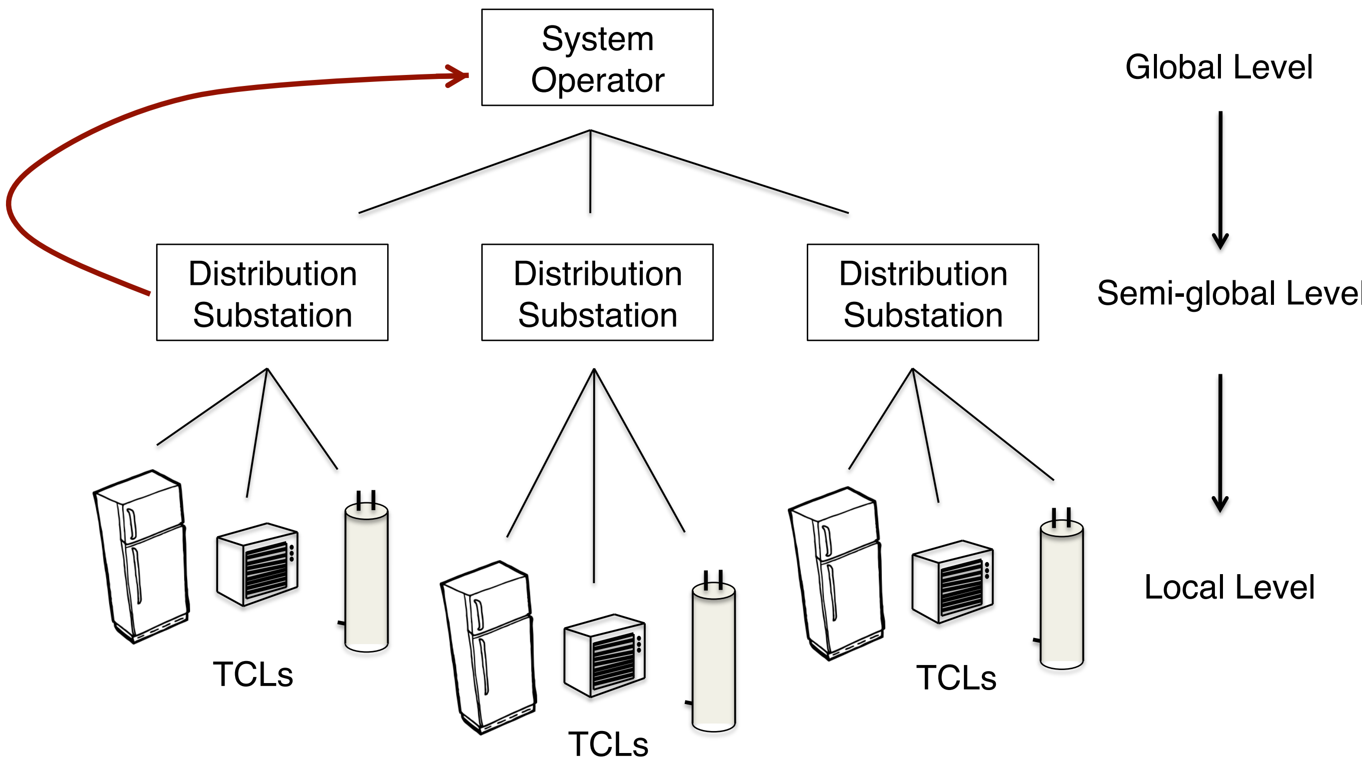
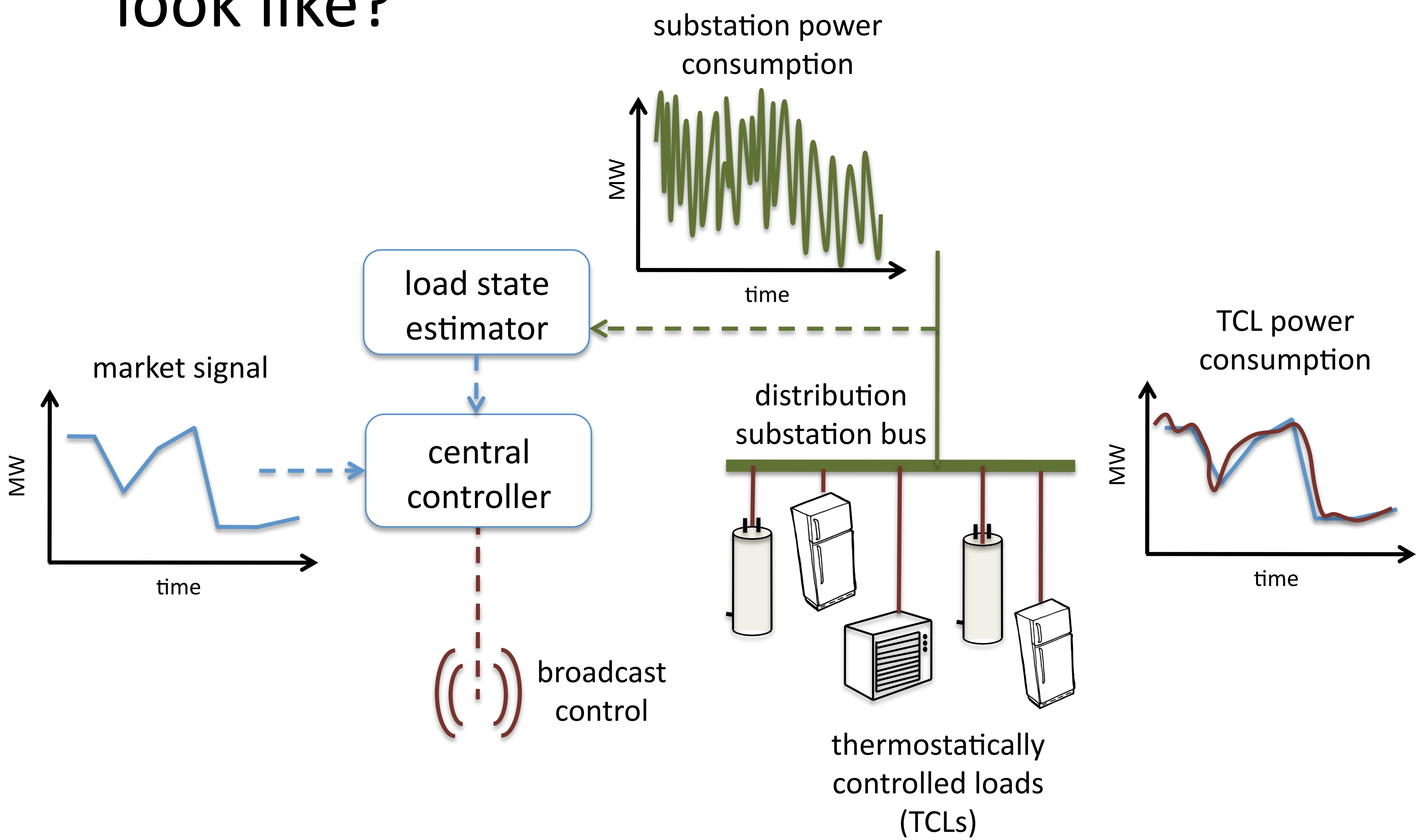


What might the low infrastructure case look like?

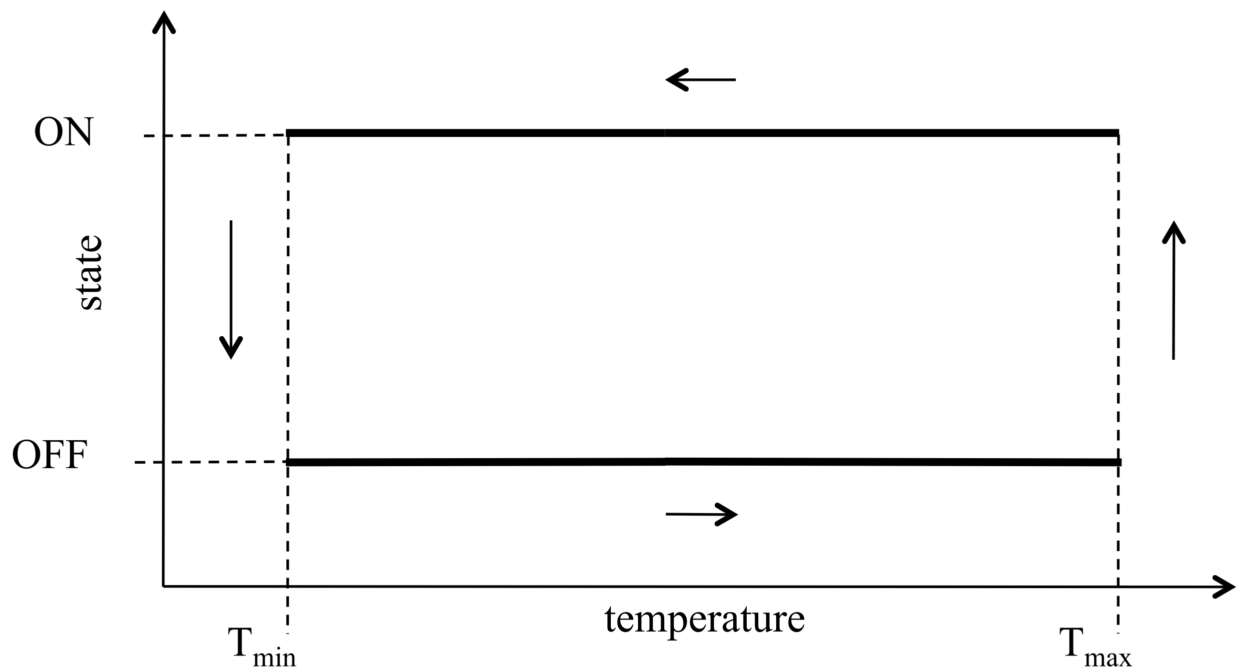


Presentation Outline

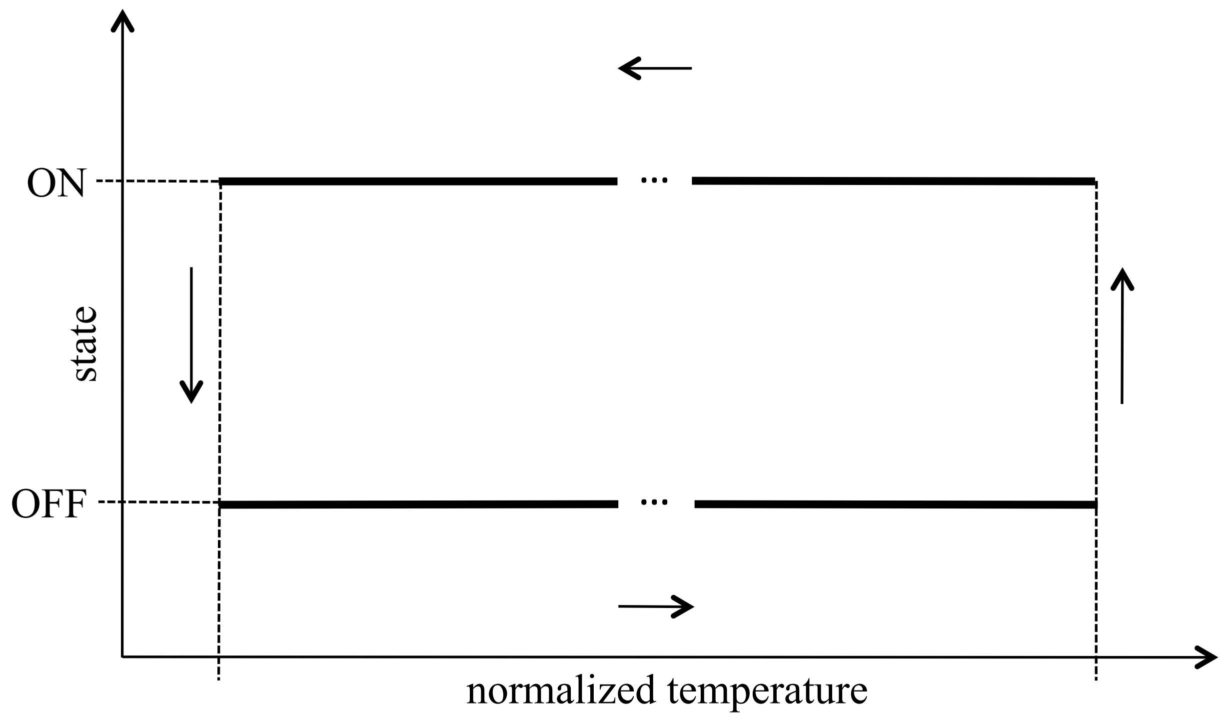
- Model of Heterogeneous TCL Populations
- Benefits of the Model
- The BIG Picture:
  - Resource Potential
  - Costs
  - Profits
- Policy Recommendations

TCL Deadbands

TCLs travel around a temperature dead-band, at a rate determined by their thermal capacitance, thermal resistance, power transfer rate, and the ambient temperature



Aggregated TCL Model: State bin transition model



Consider thousands of TCLs traveling around a normalized temperature dead-band.

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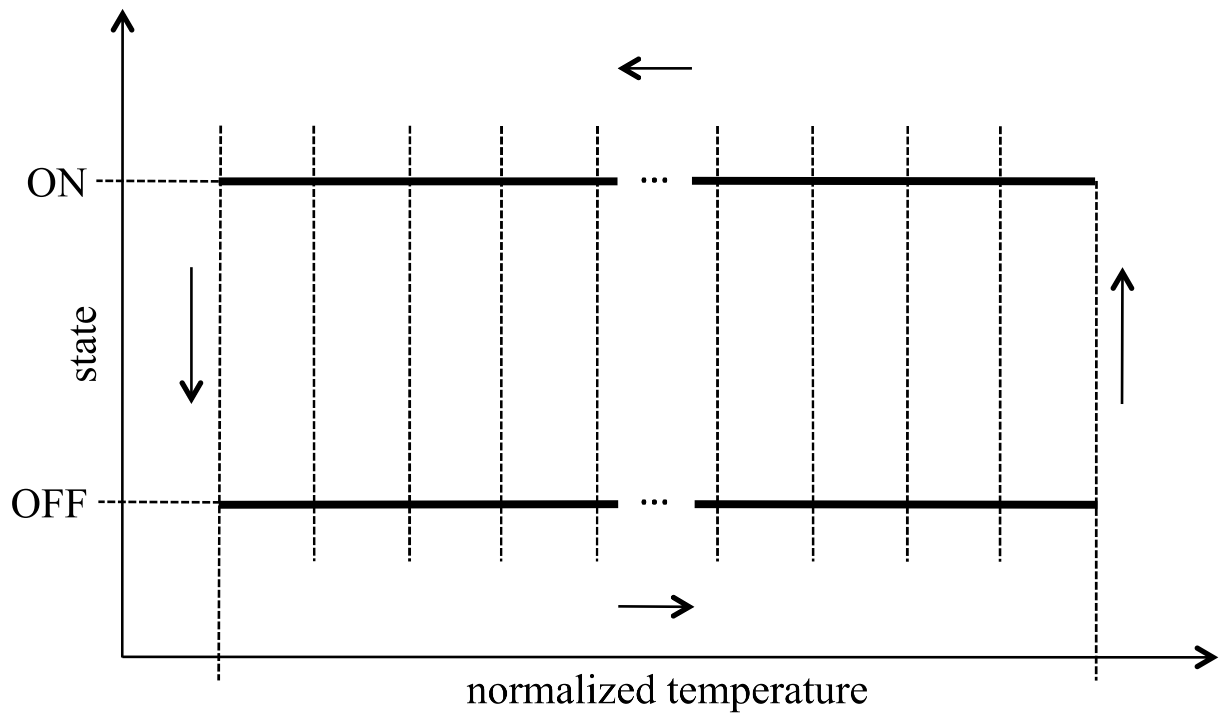

Divide it into $N_{\text{bin}}/2$ temperature intervals.

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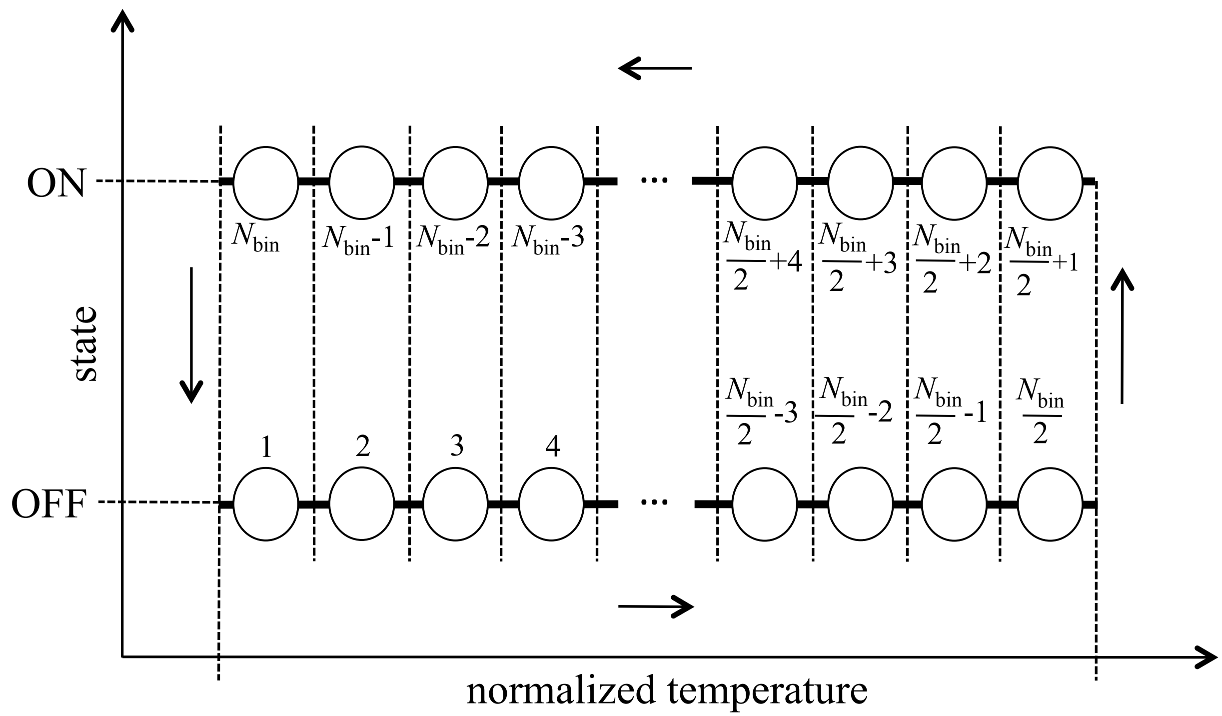

Divide each temperature interval into two state bins, for a total of N_{bin} state bins.

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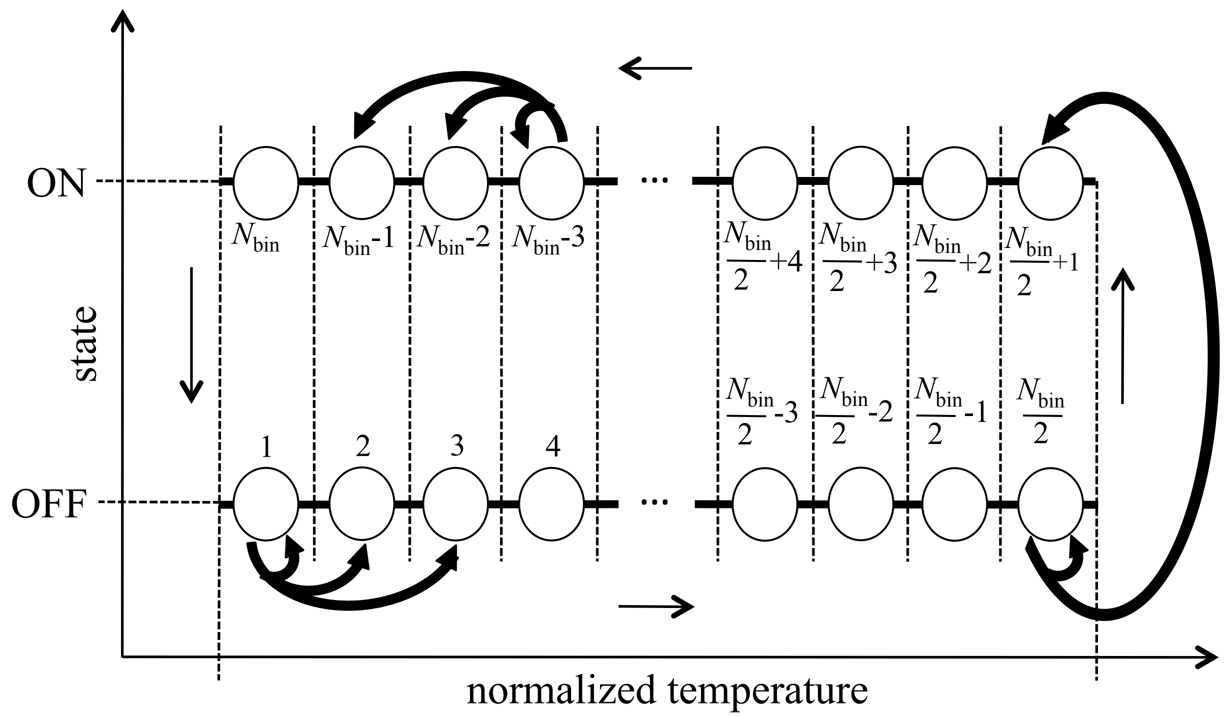

A Markov Transition Matrix describes the movement of TCLs around the dead-band.

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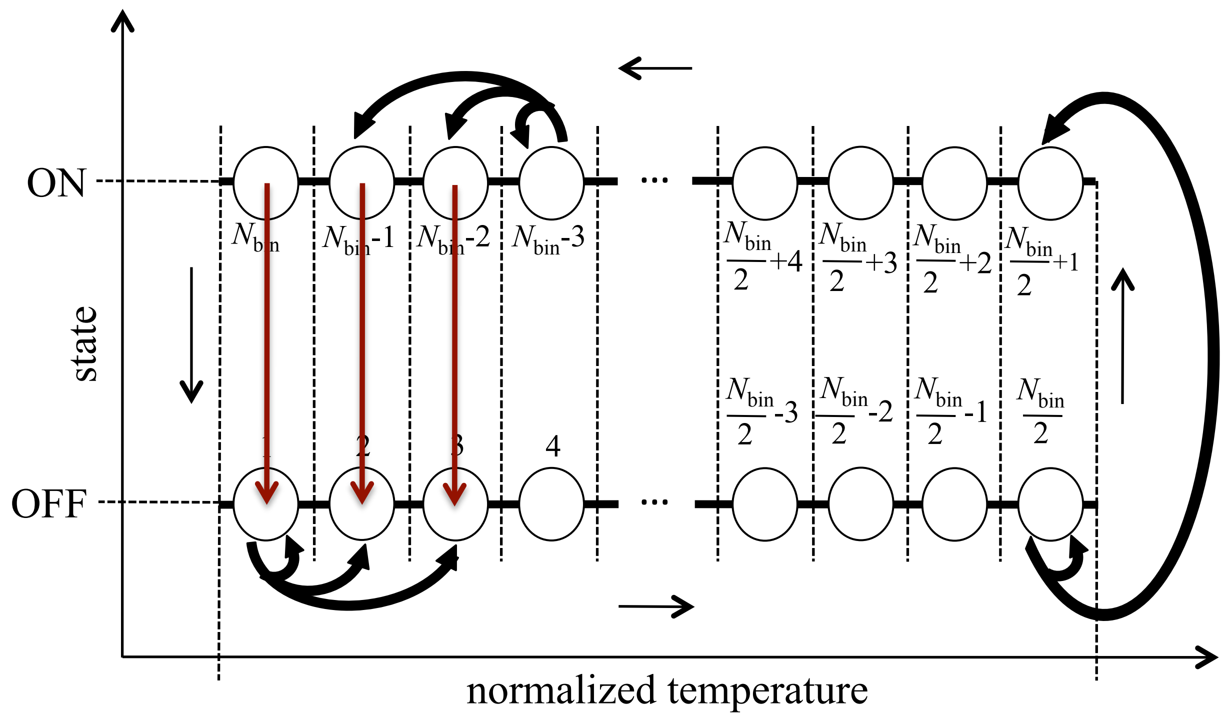

Forcing the system: decreasing aggregate power.

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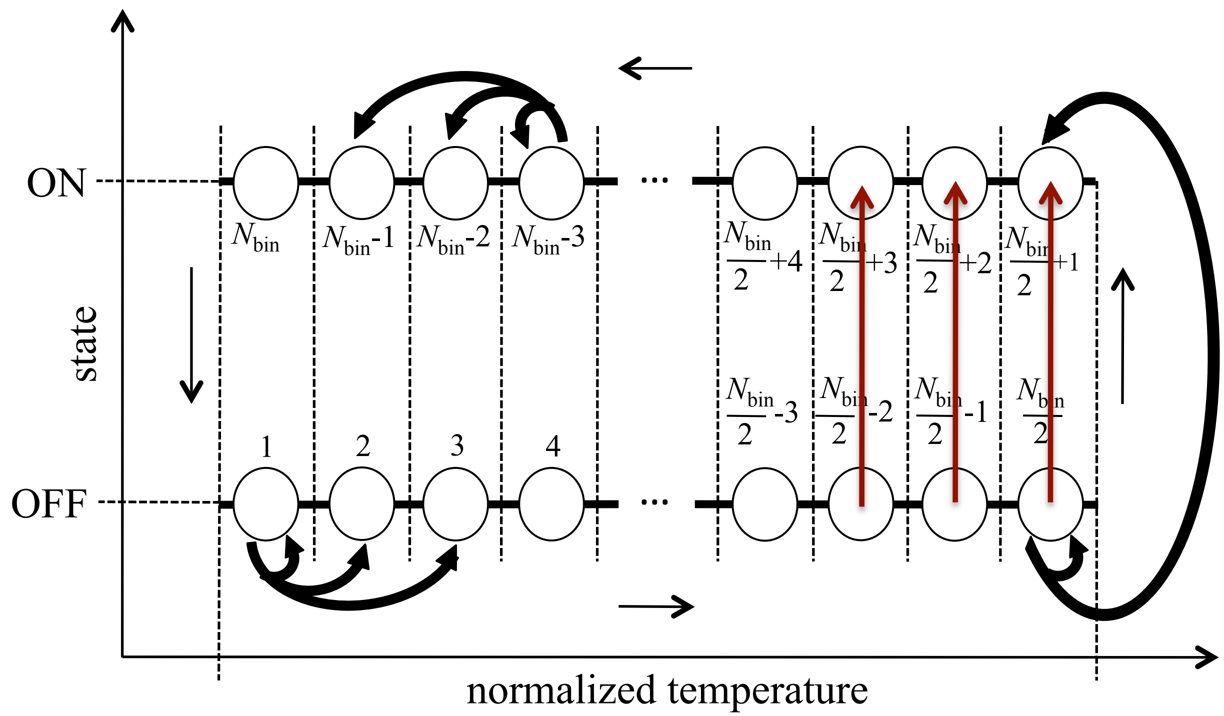
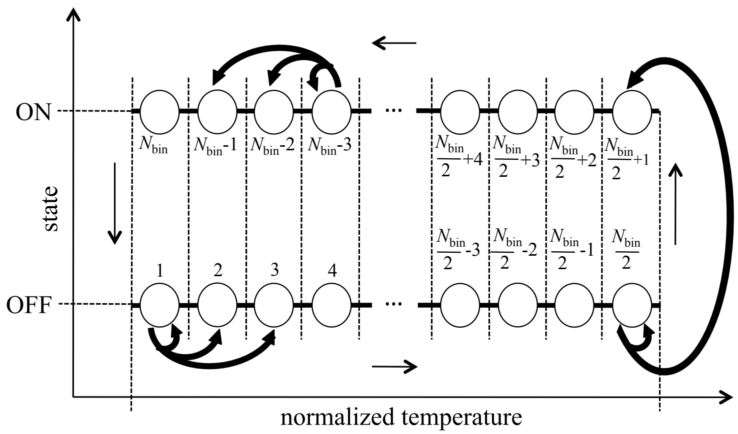


Forcing the system: increasing aggregate power.

State Bin Transition Model Equations



$$\boldsymbol{x}_{k+1} = \boldsymbol{A}\boldsymbol{x}_k + \boldsymbol{B}\boldsymbol{u}_k$$

$$\boldsymbol{y}_k = \boldsymbol{C}\boldsymbol{x}_k$$

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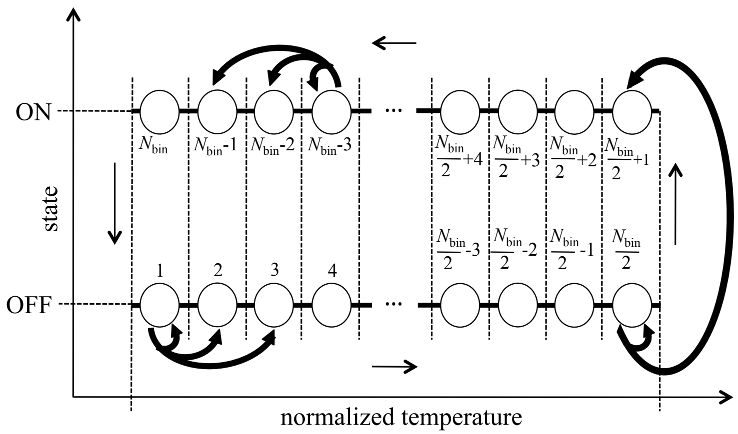

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$\boldsymbol{x}$ state vector that keeps track of the fraction of TCLs in each bin

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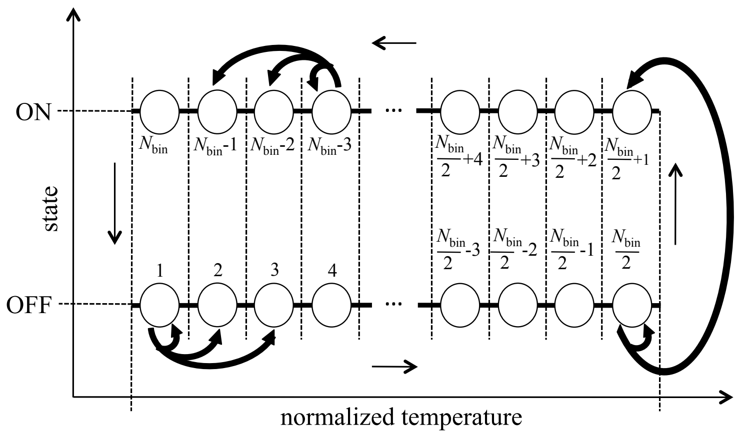

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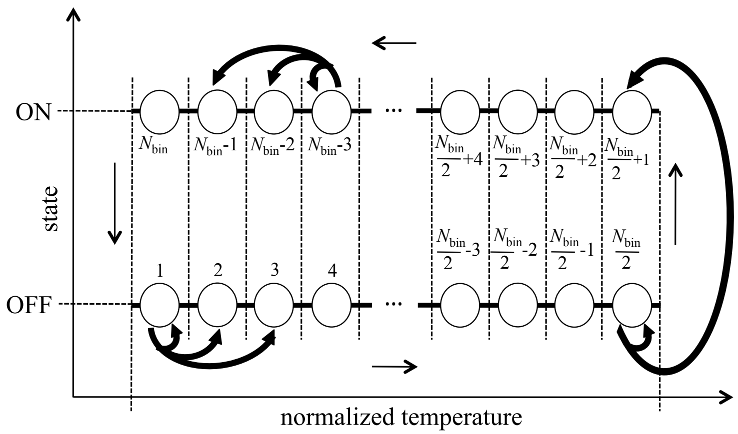

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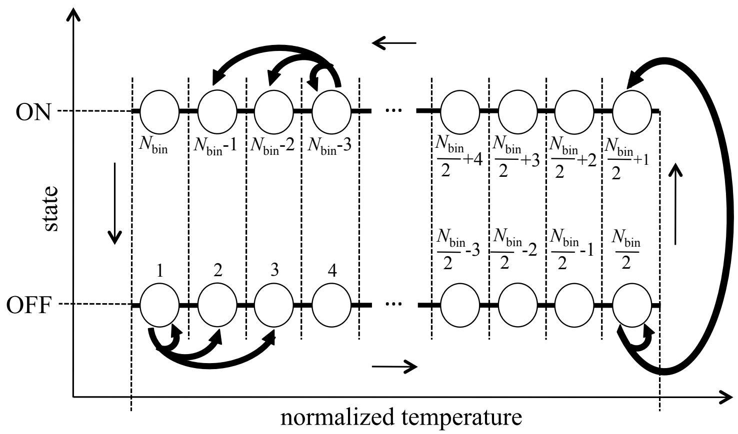

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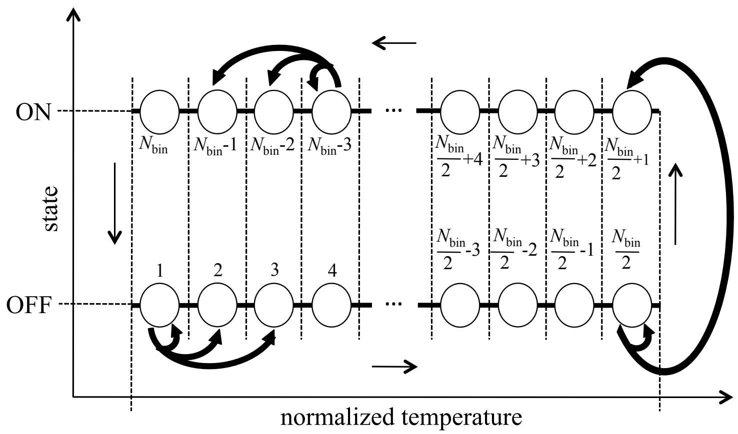

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(1) just the aggregate power consumption of the TCLs
(2) both the aggregate power consumption of the TCLs and all of the states

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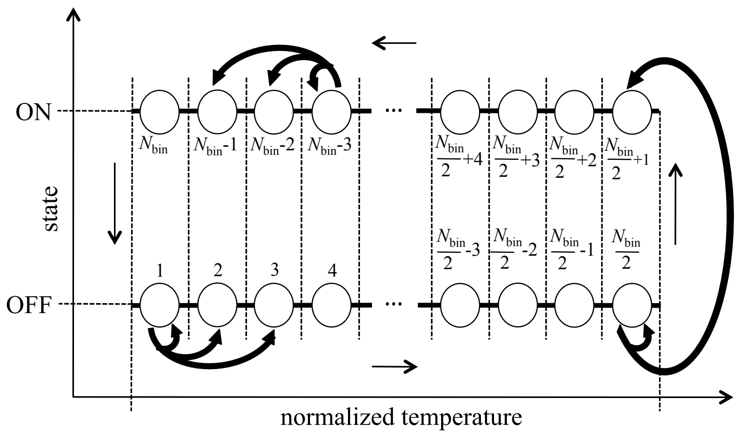

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$\boldsymbol{C}$ a vector or matrix that translates the current state to the system output

TCLs in Load Following Markets

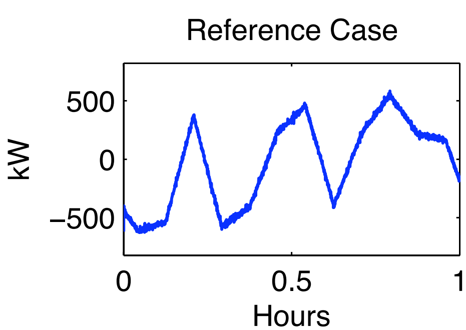
TCL performance in load following markets depending upon the information available both offline and in real time for:

- System identification (model building)
- State estimation (estimating the $\boldsymbol{x}$-vector)
- Aggregate power estimation
  - Based on power measurements sent from the loads
  - Based on other information sent from the loads
  - Based on information sent from distribution stations

Simulation Results

1,000 air conditioners controlled with a one step look ahead proportional controller

All information available in real time



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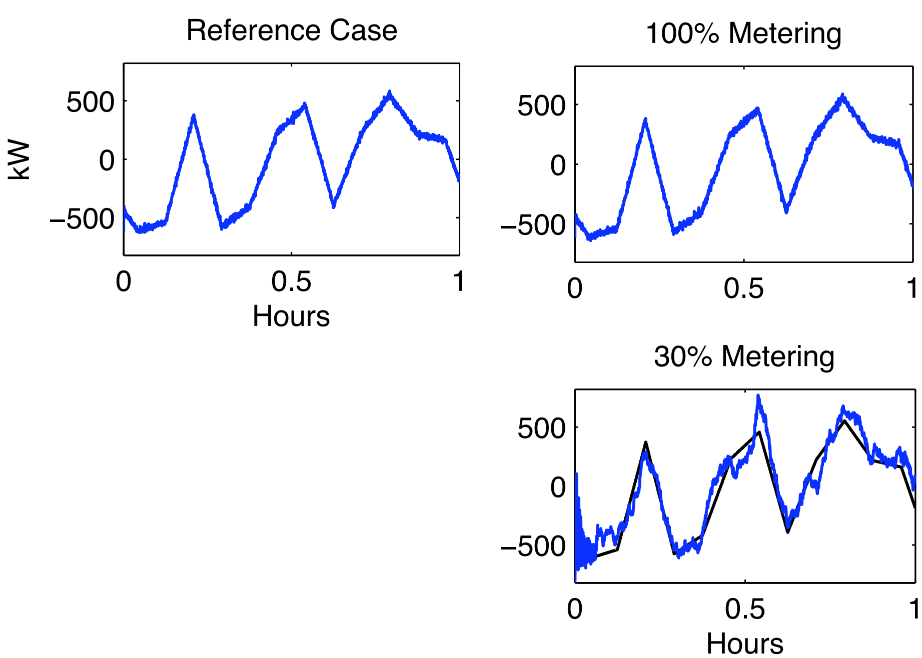

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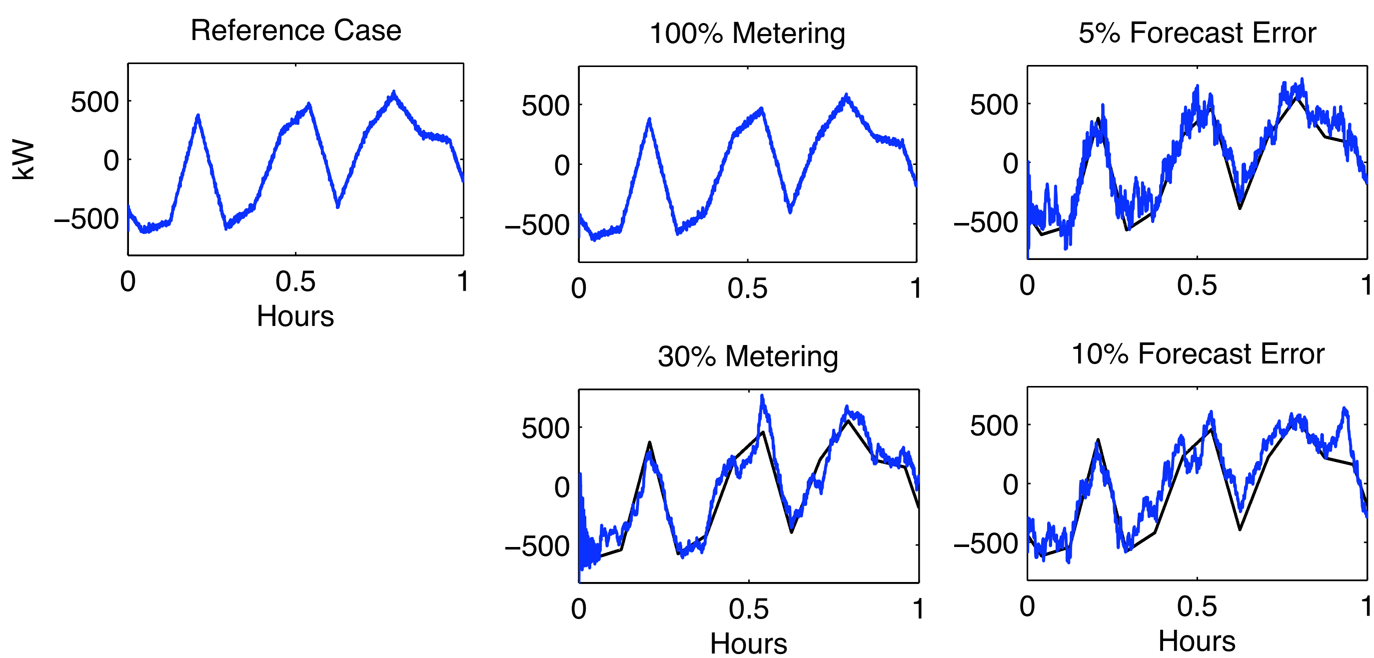

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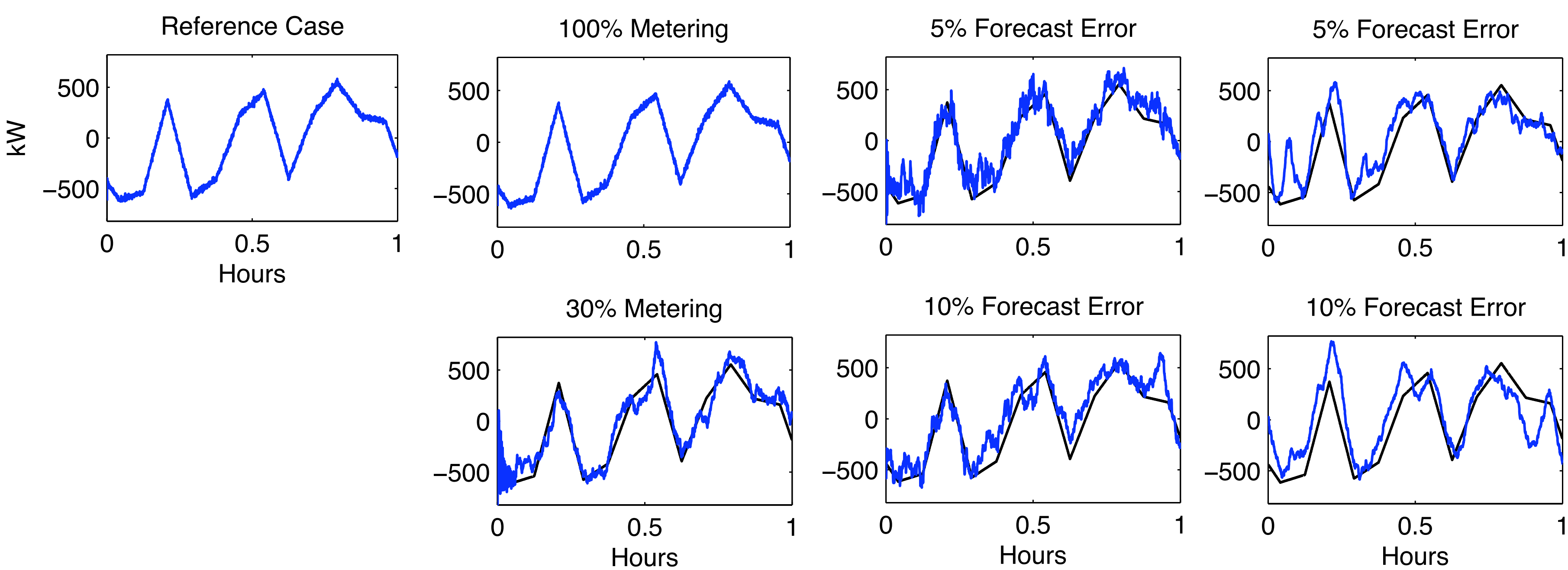

Benefits of the Model

- Model + State Estimator + Controller (MSEC) performs better than a simple Proportional Controller (PC) in most cases.

RMS Tracking Error of 1,000 Heterogeneous Air Conditioners in a Load Following Market
(as a percent of the population's steady state power consumption)

	100% metering	30% metering	5% forecast error	10% forecast error
MSEC	0.66%	4.5%*	4.9%	5.4%
PC	1.1%	4.3%	9.1%	10.5%

*This high error results from using a Kalman Filter on a system with non-Gaussian noise.

- The MSEC gives us additional insight into the behavior of the TCLs and the ability to control them in ways that minimize impact on the consumer.

Findings & Comments

- Using models, along with state and parameter estimation techniques, reduces the need for real-time information gathering and infrastructure.

  → expensive metering and telemetry may only be needed at the distribution substation level, not at each load

- Larger TCLs populations perform better.

- Aggregated TCLs have essentially no ramp constraints, but they have kWh capacity constraints.

- TCL aggregate power does not lag with respect to control signals.

Big Picture: Resource Potential

How big is the TCL 'battery'?

Estimates of kWh and kW Capacity for 1,000 Heterogeneous TCLs

	Energy (kWh)	Power increase (kW)*	Power decrease (kW)*
Air conditioners	2,500	6,300	1,600
Refrigerators	440	560	24
Heat pump heaters	1,700	6,000	1,900
Electric resistance water heaters	1,200	3,300	23

* From steady state, the actual available kW changes over time.

Estimates are sensitive to TCL parameters, e.g., deadband width
→ double the dead-band, approximately double the kWh capacity!

Big Picture: Costs

- What is needed?
  - Communications
  - TCL decision making
  - Possibly,
    - TCL temperature sensors
    - Distribution substation power meters
  - Installation → labor costs
  - Customer participation → financial compensation

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- To compete with a $400/kWh Li-ion battery, the cost of enabling infrastructure and labor for installation should be:
  - Less than $1,000 per air conditioner
  - Less than $176 per refrigerator
  - Less than $680 per heat pump heater
  - Less than $480 per electric resistance water heater

Big Picture: Profits

- TCLs participating in Regulation
  - $785-2,010/kW, 1 GW potential in USA (10 years)
    [Sandia, "Storage Benefit and Market Guide," 2010]

- TCLs participating in Load Following
  - $600-1,000/kW, 37 GW potential in USA (10 years)
    [Sandia, "Storage Benefit and Market Guide," 2010]
  - Energy cost savings through price arbitrage
    - 15 minute price arbitrage in Texas: 11% savings
      [RMI, "The Role of DR in an Increasingly Renewable Grid," 2011]
    - 5 minute price arbitrage in California: 8% savings
    - Analysis assumes:
      - DR operates at the margin
      - loads buying/selling power in the same market
      - perfect price forecasts

- Next step: more comprehensive and realistic physical system + market models

Policy Recommendations

- Design of new energy and ancillary services market products suited to loads, which do not have the same characteristics and constraints as generators.
  - Aggregations of small loads do not have ramp rates, but have strict kWh capacity constraints.
  - One idea: energy market product with a zero mean signal.

- Make it easier to engage residential loads in DR.
  - Resolve privacy issues through use of good communications standards.
  - Design appliance standards to enable fast-DR.

Contact Information

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More Information

J.L. Mathieu and D.S. Callaway, 2012. "State Estimation and Control of Heterogeneous Thermostatically Controlled Loads for Load Following," to appear in the Proceedings of the Hawaii International Conference on Systems Science (HICSS), Grand Wailea, Maui, HI, 4-7 Jan 2012.

S. Koch, J.L. Mathieu, and D.S. Callaway, 2011. "Modeling and Control of Aggregated Heterogeneous Thermostatically Controlled Loads for Ancillary Services," Proceedings of the 17th Power Systems Computation Conference (PSCC), Stockholm, Sweden, 22-26 Aug 2011.