Clean Energy Systems Integration Lab

Washington State University

DG-BEAT

- Software Features
- Included Databases
- National Results

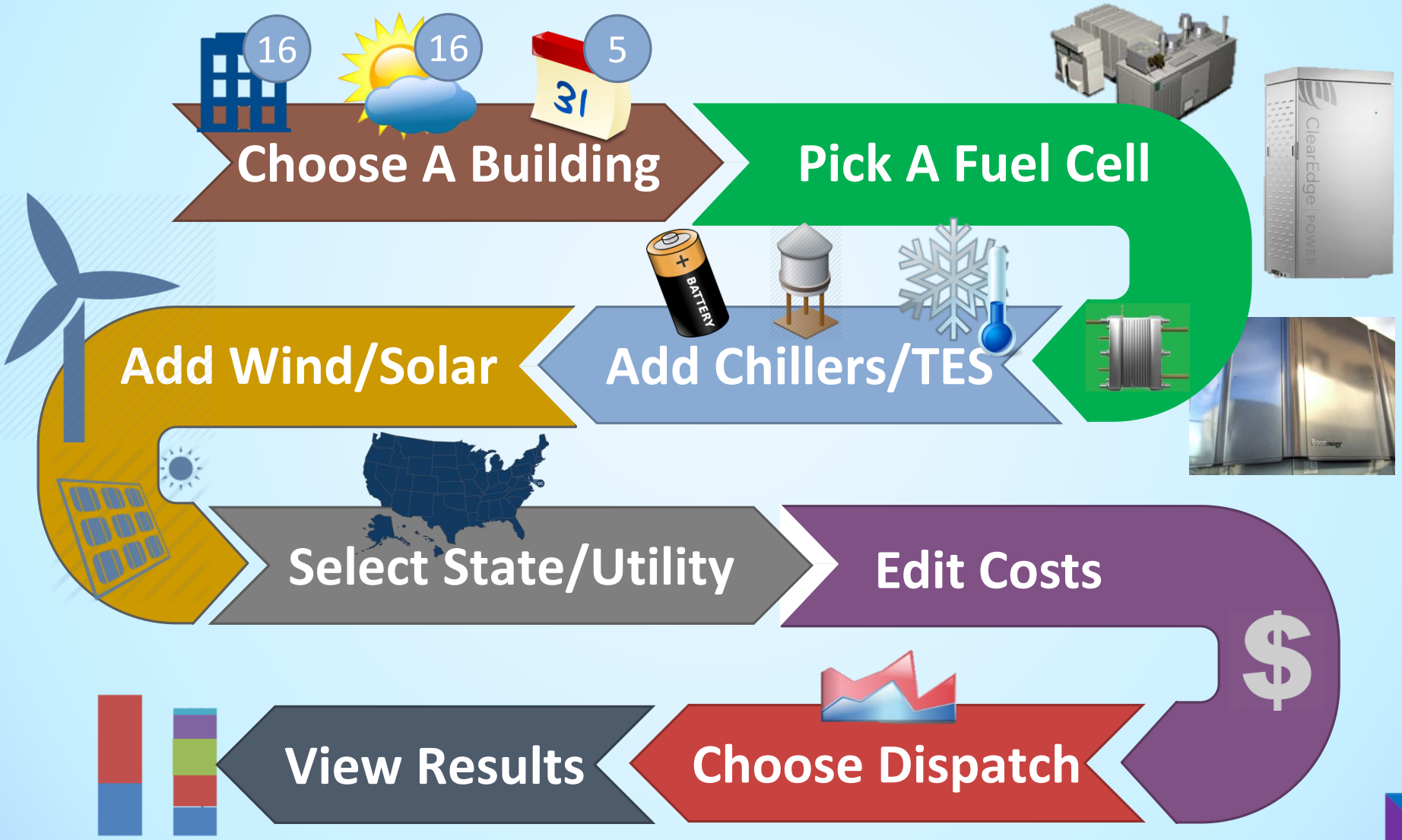
Introduction

- **DG-BEAT** is designed to allow the operator to assess the economics of installing stationary fuel cell systems in a variety of building types in the United States.
- Questions Addressed:
  - What is the commercial market for stationary fuel cell power?
  - What is the potential for greenhouse gas reduction from stationary fuel cells?
  - What are the appropriate system sizes which can serve the broadest market in the most economical fashion?
  - Are certain markets (climate region or utility provider region) or applications (building types) better suited to stationary fuel cell deployment?
  - Can stationary fuel cells support on-site or near-site renewable power?
  - Does CCHP play a role in the deployment of stationary fuel cell technology? If so what is the ideal configuration of absorption chillers, electric chillers, thermal storage, and electric storage?
  - Do campuses of building with or without district heating/cooling support the installation of stationary fuel cells?
  - How does market adoption rate and economies of scale in manufacturing affect the viable market price?

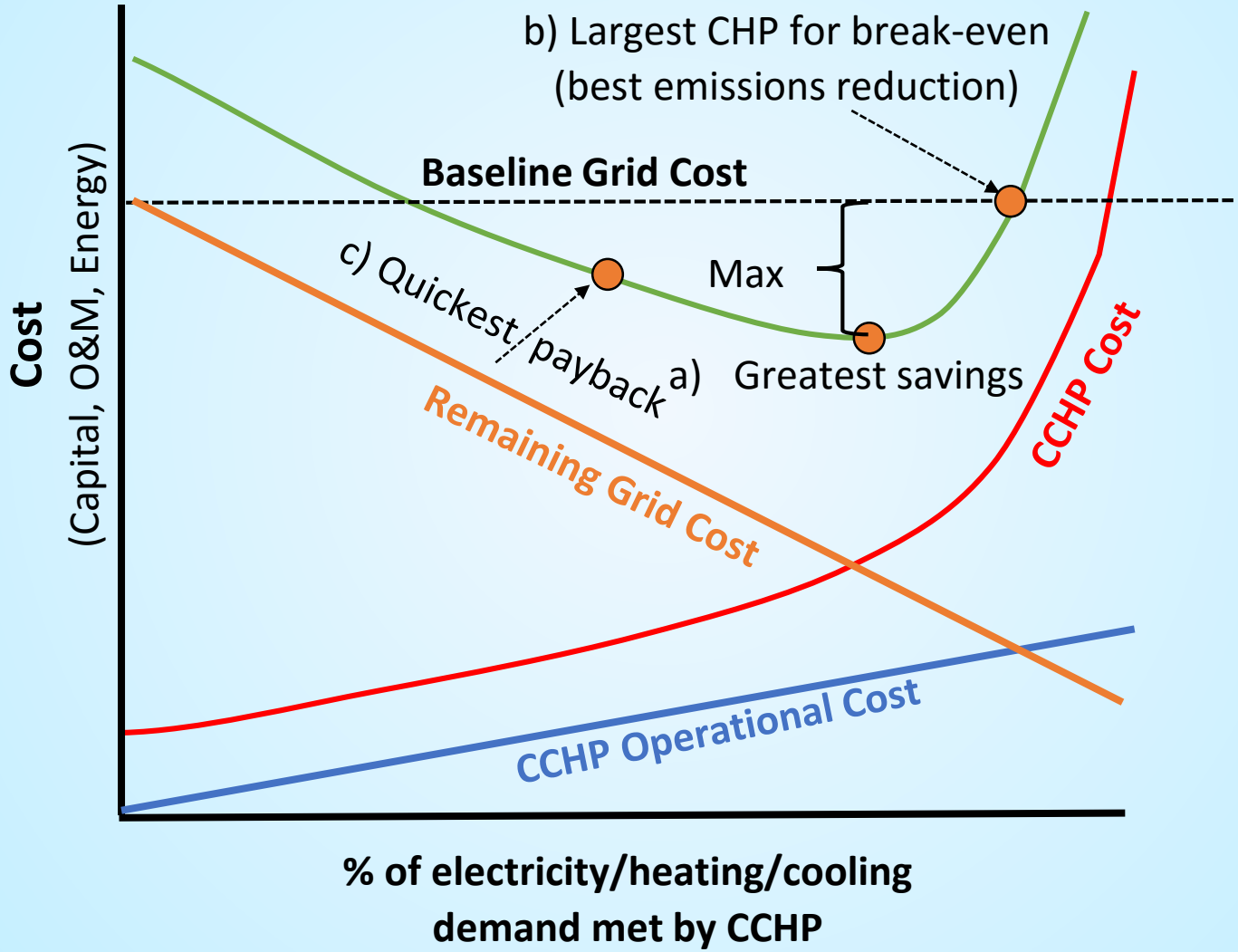
Users

- Building Energy Manager
  - Evaluate lifetime ownership costs of different DG installations for a specific building, category of building, or fleet of buildings
  - Evaluate local GHG and criteria pollutant reductions
- Fuel Cell Manufacturer
  - Identify markets by building type, climate, and utility provider
  - Determine size of market for specific FC installation
  - Evaluate co-benefits of deployment with heat recovery, absorption chiller or energy storage technology
  - Size battery/capacitor for best peak demand reduction
- Industry Supporters / Decision Makers
  - Estimate GHG and criteria pollutant reductions
  - Evaluate potential impact of targeted incentive programs
  - Determine impactful areas for future research

Distributed Generation Build-out Economic Assessment Tool (DG-BEAT)

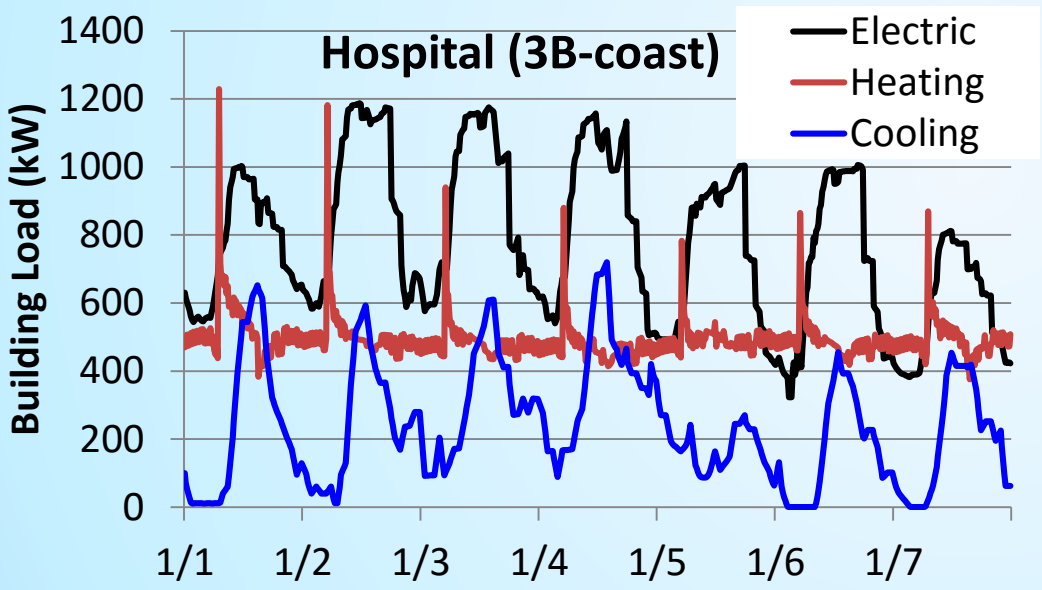


Cost Trends for Installed DG



Building Selection

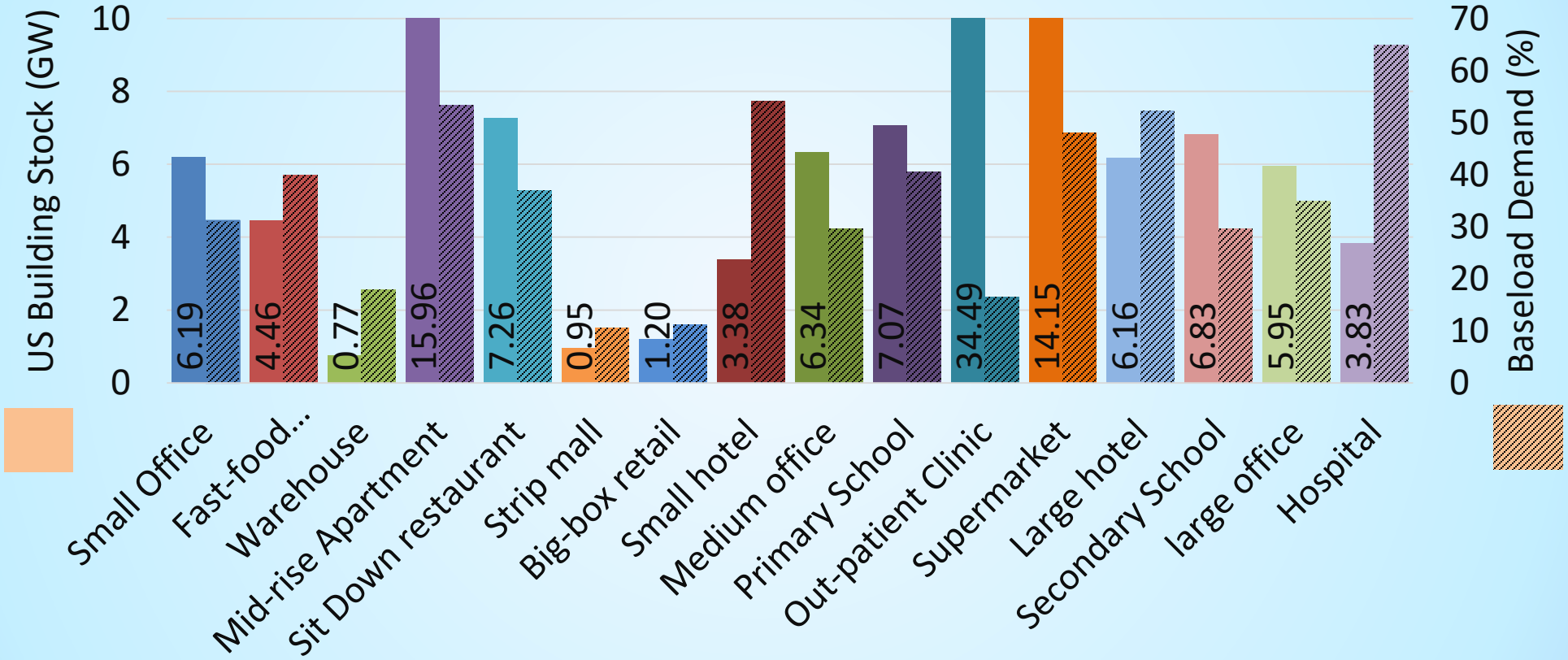
- What comprises a building profile?
  - 15 minute data for an entire year (35040 points)
  - Electricity, heating, cooling (as thermal kW & electric kW), electric refrigeration, and exterior lighting



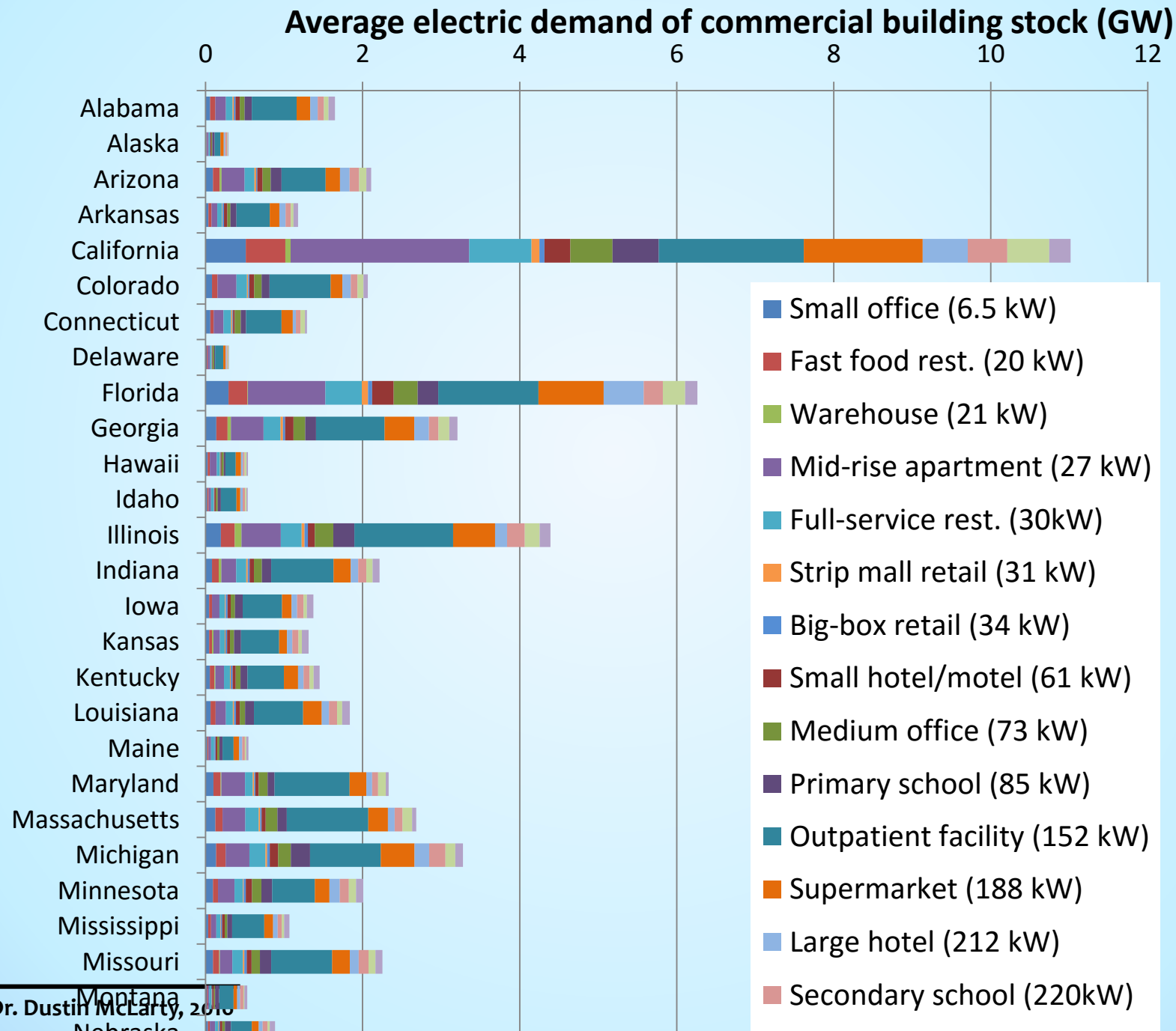
Building types	Locations
Restaurant: full-service (sit down)	Miami (ASHRAE 1A)
Restaurant: quick-service (fast food)	Houston (ASHRAE 2A)
School: primary school	Phoenix (ASHRAE 2B)
School: secondary school	Atlanta (ASHRAE 3A)
Office: large office	Los Angeles (ASHRAE 3B-Coast)
Office: medium office	Las Vegas (ASHRAE 3B-Inland)
Office: small office	San Francisco (ASHRAE 3C)
Hospitality: large hotel	Baltimore (ASHRAE 4A)
Hospitality: small hotel/motel	Albuquerque (ASHRAE 4B)
Health care: large hospital	Seattle (ASHRAE 4C)
Health care: outpatient facility	Chicago (ASHRAE 5A)
Retail: big-box, standalone retail store	Boulder (ASHRAE 5B)
Retail: retail strip mall	Minneapolis (ASHRAE 6A)
Retail: supermarket	Helena, MT (ASHRAE 6B)
Mid-rise apartment building	Duluth, MN (ASHRAE 7)
Unrefrigerated warehouse	Fairbanks, AK (ASHRAE 8)
Vintages	2010, 2007, 2004, Post-1980, Pre-1980

- Add any # of buildings to form a campus
- Scale a single building profile to match total load profile

Buildings Overview

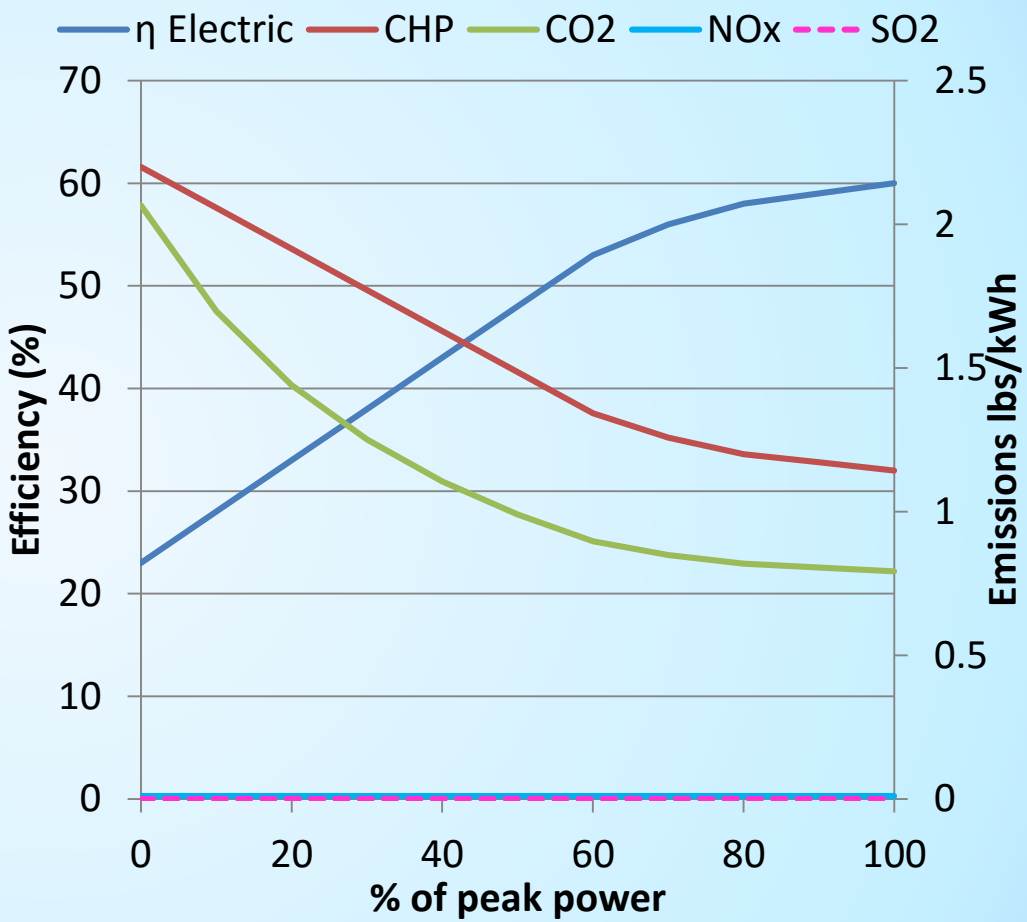


National Building Inventory



Fuel Cell Specification

- » Specify fixed parameters
  - > Size (kW or % zero-export size)
  - > Turndown ratio
  - > Response rate (%/s)
- » Specify performance curves
  - > Efficiency
  - > Heat recovery
  - > Emissions



Fuel Cell Sizing

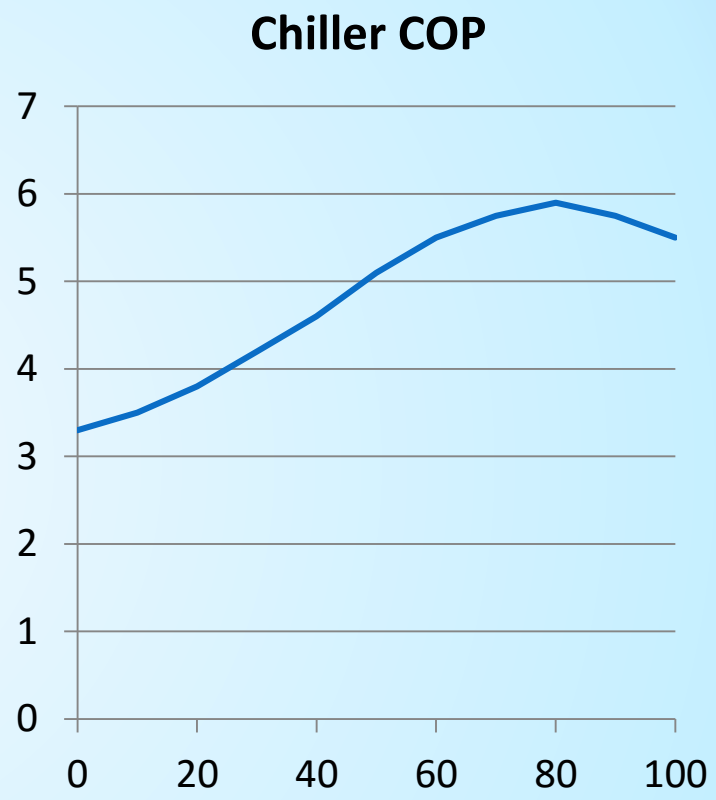
- Peak summer weekday demand:
  - Average profile for non-holiday weekdays during the summer months
- Fixed size:
  - Size set by specific FC system selected, i.e. DFC300
- 100% sizing:
  - Sized to meet ≈ peak summer demand, (ignores outliers 2% of points)
- Cost optimal sizing:
  - Iterates between the base load size & 100% size to find the best NPV
- Emissions optimal sizing:
  - Iterates between the base load size & 100% size to find the lowest net emissions

Sizing Equations

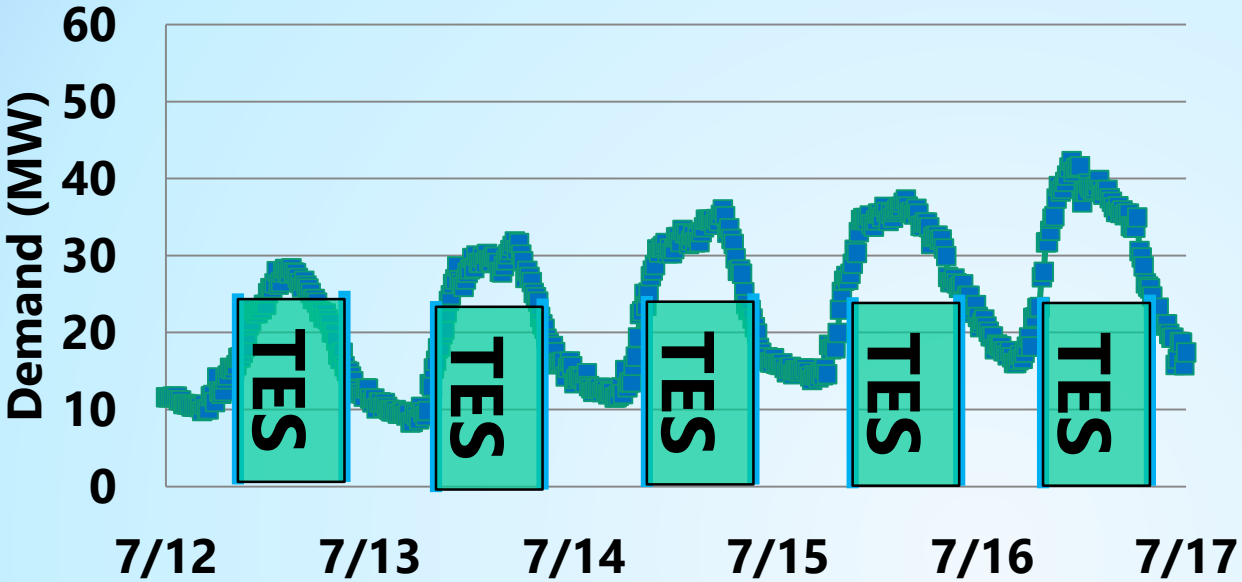
Sizing Method	Equations
Base Load	$DG_{size} = \min_{t}(demand_t) \quad \forall\, t \in year$
Weekend Dip *each day has 96 time segments	$Summer\ Week_{1-672} = \sum_{week \in summer} \frac{demand_{1-672,week}}{\#\ of\ summer\ weeks}$ $DG_{size} = \min_{9 \le t \le 664}(demand_t)$
Diurnal Dispatch, Load Following, & Emissions Control	$Summer\ Day_{1-96} = \sum_{\substack{day \in summer \\ day \in weekday}} \frac{demand_{1-96,day}}{\#\ of\ summer\ weekdays}$ $DG_{size} = \max_{1<t<96}(Summer\ Day_t)$
Optimal Cost Sizing	$DG_{size} \rightarrow \max\{NPC_{no\ DG} - NPC_{with\ DG}(DG_{size})\}$ $\min(demand_t) < DG_{size} < \max(demand_t)$
Optimal Emissions Sizing	$DG_{size} \rightarrow \max\{CO_2\ Emissions_{no\ DG} - CO_2\ Emissions_{with\ DG}(DG_{size})\}$ $\min(demand_t) < DG_{size} < \max(demand_t)\ \forall\, t \in year$
Additional Constraint Without Grid Sellback	$TD = \sum_{n=1}^{\#\ of\ DG\ sys} (DG_{size_n}) \Big/ \sum_{n=1}^{\#\ of\ DG\ sys} (DG_{size_n}/DG_{Turndown_n})$ $\sum_{n=1}^{\#\ of\ DG\ sys} (DG_{size_n}) \Big/ TD \le \min_{t}(demand_t) \quad \forall\, t \in year$

Chiller

- » Select type:
  - > Electric chiller
    - + Replaces integrated building HVAC
  - > Absorption chiller
    - + Powered from CHP exhaust only
- » Select parameters:
  - > Size (in kW or tons or % max demand)
  - > Nominal COP
  - > COP turndown curve



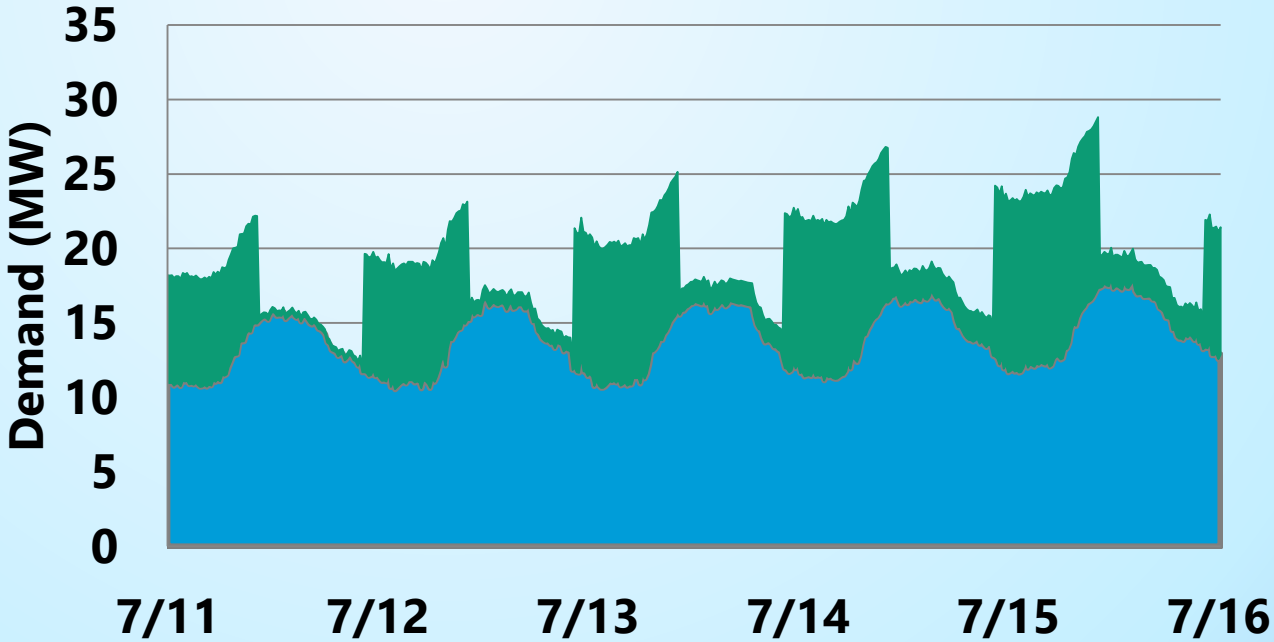
Thermal Energy Storage



» Objectives:

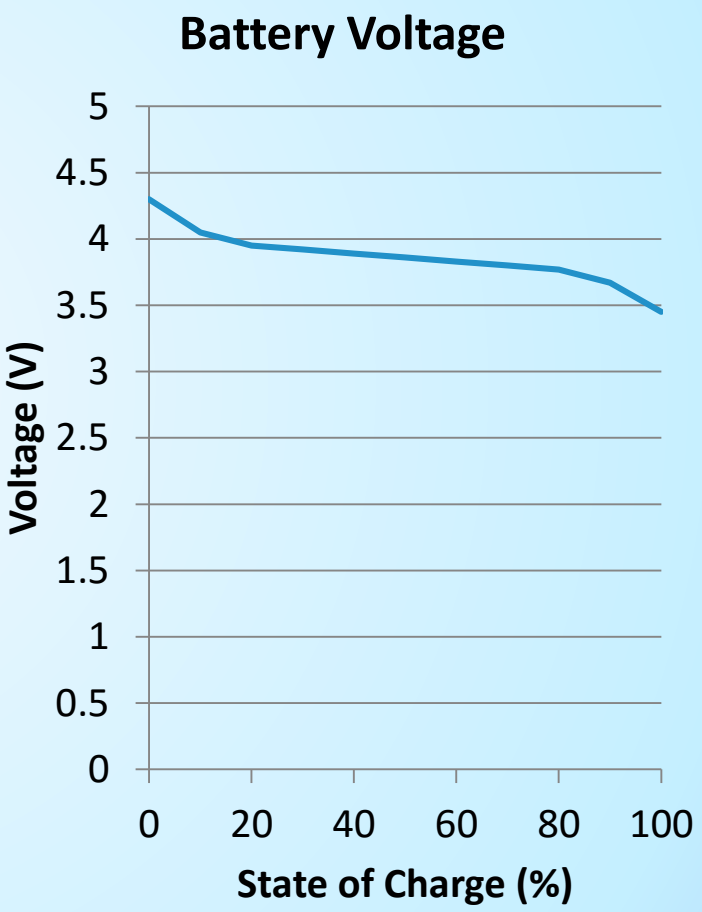
> Shift daytime cooling demand to previous night

> Flatten electric demand profile by operating chillers at steady-state



Battery

- » Select type:
  - > Lead-acid
  - > Nickel-cadmium
  - > Nickel-metal-hydride
  - > Lithium-Ion
- » Select parameters:
  - > Size (in kW or minutes of peak generation or % max peak shaving)
  - > Charge/Discharge characteristics
  - > Charging method
  - > Internal resistance
  - > Maximum depth of discharge
  - > Voltage vs. State-of-Charge curve



Chiller/TES/Battery Sizing

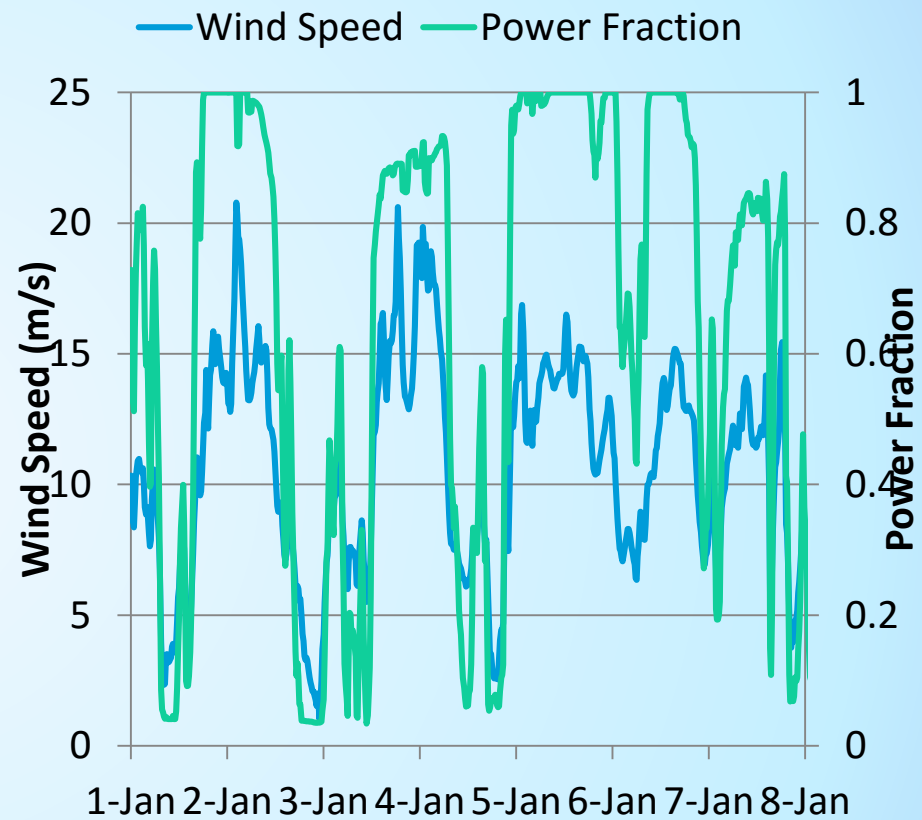
- Chiller:
  - Electric chiller required to meet 100% of peak summer demand
  - Can be smaller if absorption chiller or TES is included
- Thermal energy storage:
  - Sized to shift 100% of cooling from peak hours to off-peak
  - Sized for hottest day during summer on-peak months
- Battery:
  - Primary purpose is to reduce demand charges during FC ramping
  - Set by total kWh or hours of peak demand

Chiller/TES/Battery Sizing

Description	Equations
Thermal Energy Storage (ES) **(repeated daily)**	$\begin{cases} DG_t \\ ES_t \end{cases} \rightarrow \min\{\sum_{t=1}^{96}(demand_t - DG_t - ES_t)\cdot Price_{grid}\}$ Constrained by: $(DG_t + ES_t) \leq demand_t$ $ES_t \leq 0\ \forall\ t \in off-peak\ \ \&\ \ ES_t \geq 0\ \forall\ t \in on-peak$ $\sum_{off-peak}(ES_t) \leq ES_{capacity}$ DG_t is determined simultaneously according to the selected dispatch
Battery Electric Storage (BS) **(repeated daily)**	$\begin{cases} DG_t \\ BS_t \end{cases} \rightarrow \min\{\sum_{t=1}^{96}(demand_t - DG_t - BS_t)\cdot Price_{grid}\}$ Constrained by: $(DG_t + ES_t) \leq demand_t$ $-BS_{charge\ rate} \leq BS_t \leq BS_{discharge\ rate}\ \forall\ t \in off-peak$ $\sum_{t=1}^{n}(BS_t) \leq BS_{capacity}\ \ \forall\ n \leq 96$ $\sum_{t=1}^{96}(BS_{discharging}) = \eta_{round-trip}\sum_{t=1}^{96}(-BS_{charging})$

Wind Generation

- » 50 different state profiles
  - > 15 minute resolution
  - > Wind speed and % rated power
- » Parameter Specification:
  - > Rated Capacity (kw or % annual demand)
  - > Conversion Efficiency
  - > Rotor Diameter
  - > Tower Height
  - > Cut-in, rated, and shut-down wind speed
- » Calculation



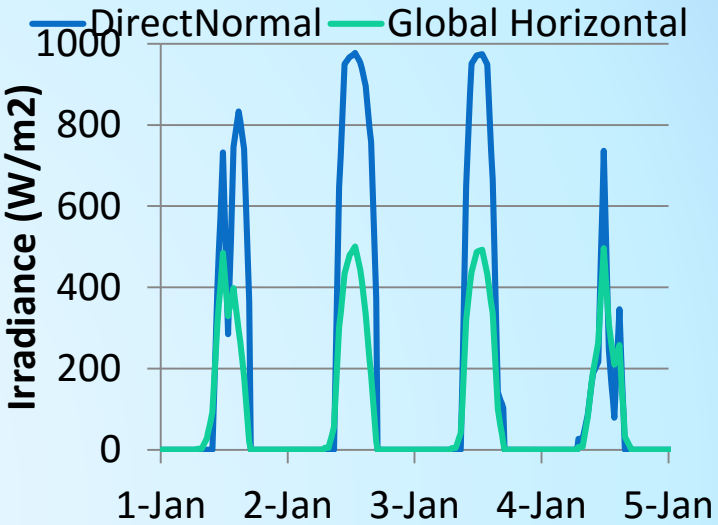
$$\rho = 1.1798 - 1.3793 \times 10^{-4} * H_{tower} + 5.667 \times 10^{-9} * {H_{tower}}^2$$

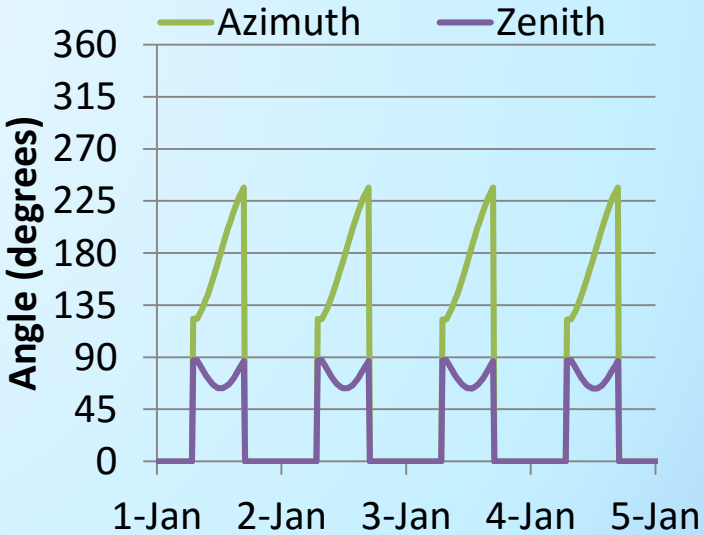
$$P_{wind} = \eta_{conversion} \cdot 0.5\rho \frac{\pi D_{turbine}}{4} \cdot WindSpeed^3$$

Solar Generation

- » 50 different state profiles
  - > 15 minute resolution
  - > Direct normal, global horizontal, azimuth & zenith
- » Type Selection
  - > Flat panel or concentrated
  - > Fixed, single-axis or dual-axis tracking
- » Parameter Specification:
  - > Rated Capacity (kw or m^2, or % annual demand)
  - > Solar to DC conversion efficiency (%)
  - > DC-AC conversion efficiency
  - > Azimuth angle & tilt angle
- » Calculation

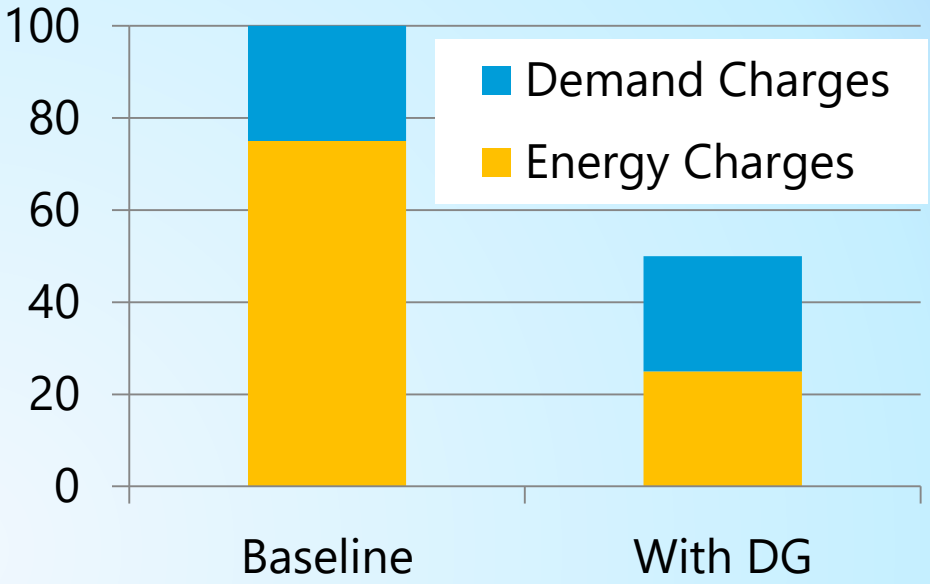
$$P_{solar} = P_{rated} \frac{Irrad_{direct\ normal}}{1000} \cdot \cos(Zenith - Tilt_{PV}) \cdot \cos(Azimuth_{sun} - Azimuth_{PV}) \cdot \eta_{conversion}$$





Utilities

- » Utility Costs
  - > Historical and forecasted rates
  - > Time-of-use electricity rates
    - ❖ 20+ pre-loaded rate structures
    - ❖ State average energy costs
  - > Net metering

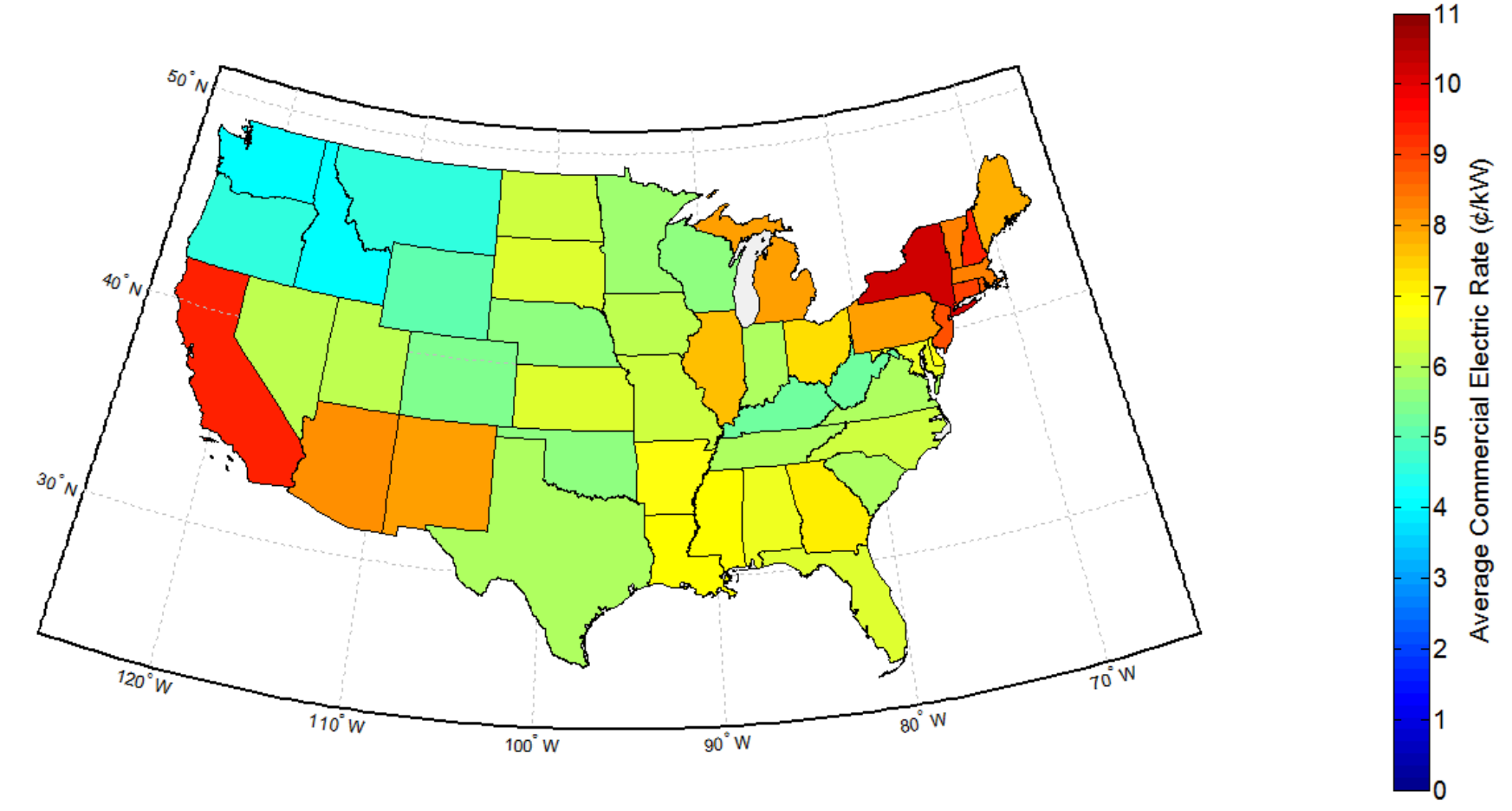


- » Equipment Costs
  - > Installation costs, scales with capacity (kW)
  - > Operation/maintenance costs, scales with capacity and operation (kW & kWh)
- » Energy costs vs. demand charges
- » 10 or 20-year NPV analysis
  - > Includes stack replacement
  - > Analyze financing methods, interest rates, offset electricity charges

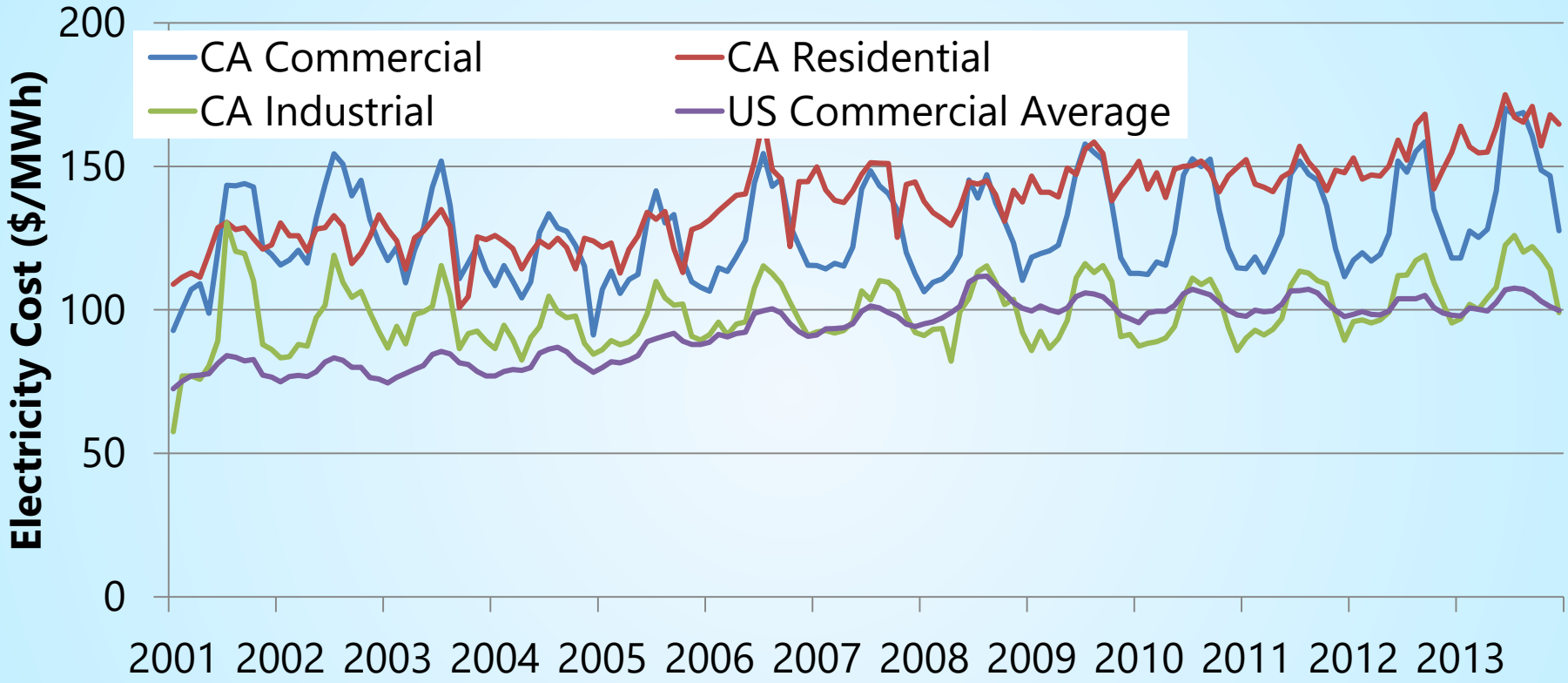
Utilities – Electric Rates

» EIA monthly rate data by state & sector

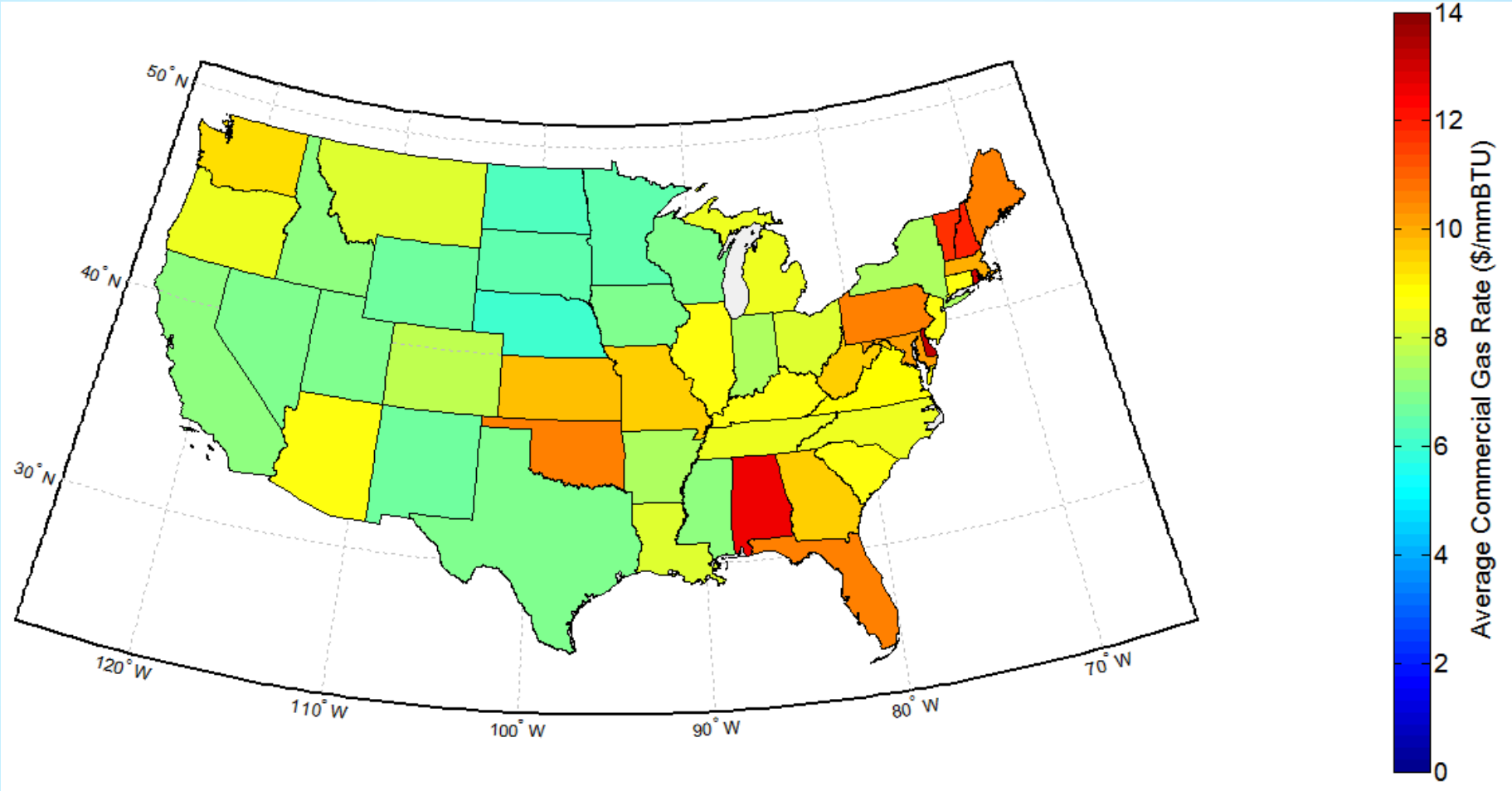
> Most of the financial results will appear largely similar to this map of average electric rates for commercial users since cost of electricity is dominant in NPV



Utilities – Electric Rates



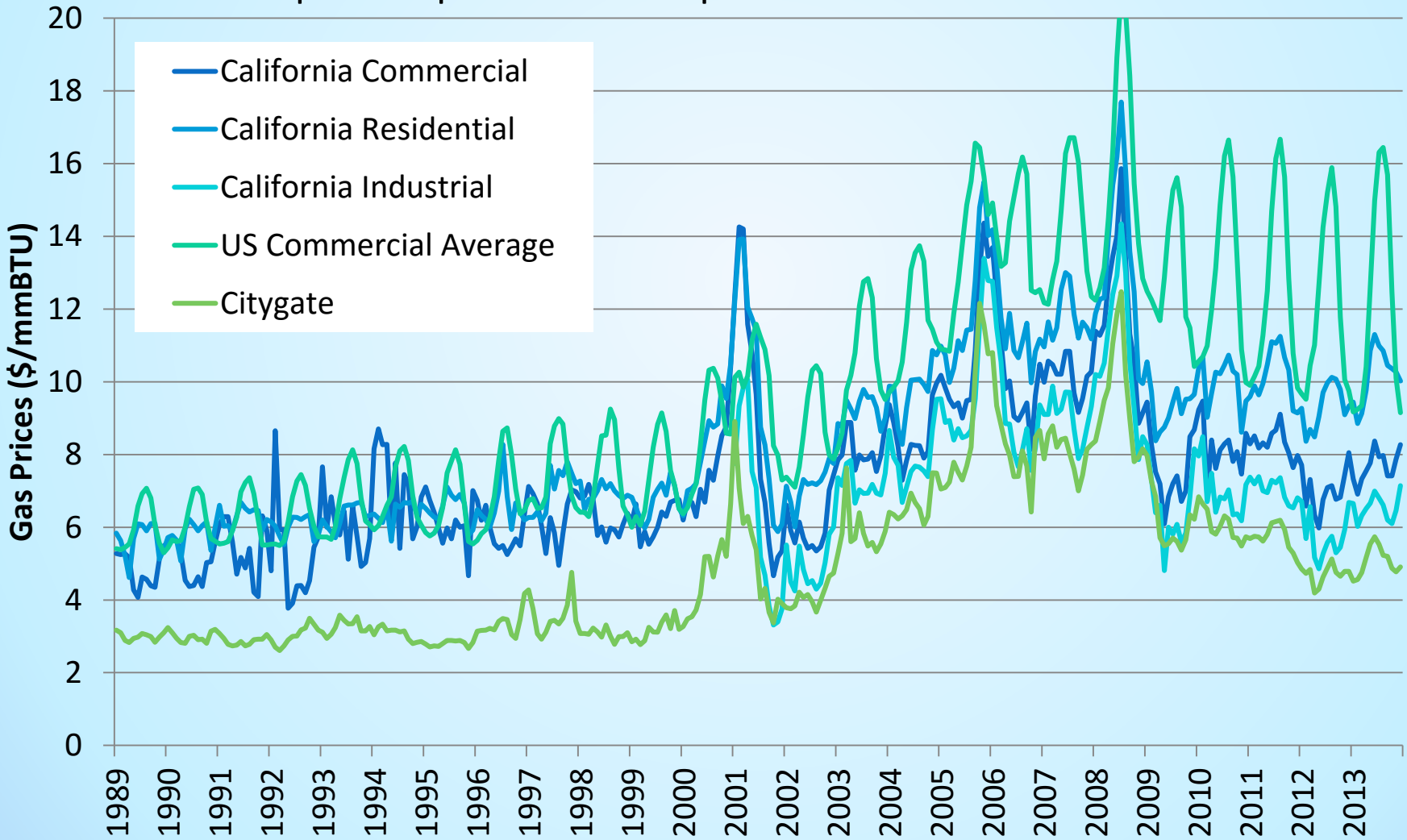
Utilities – Gas Rates



Utilities – Gas Rates

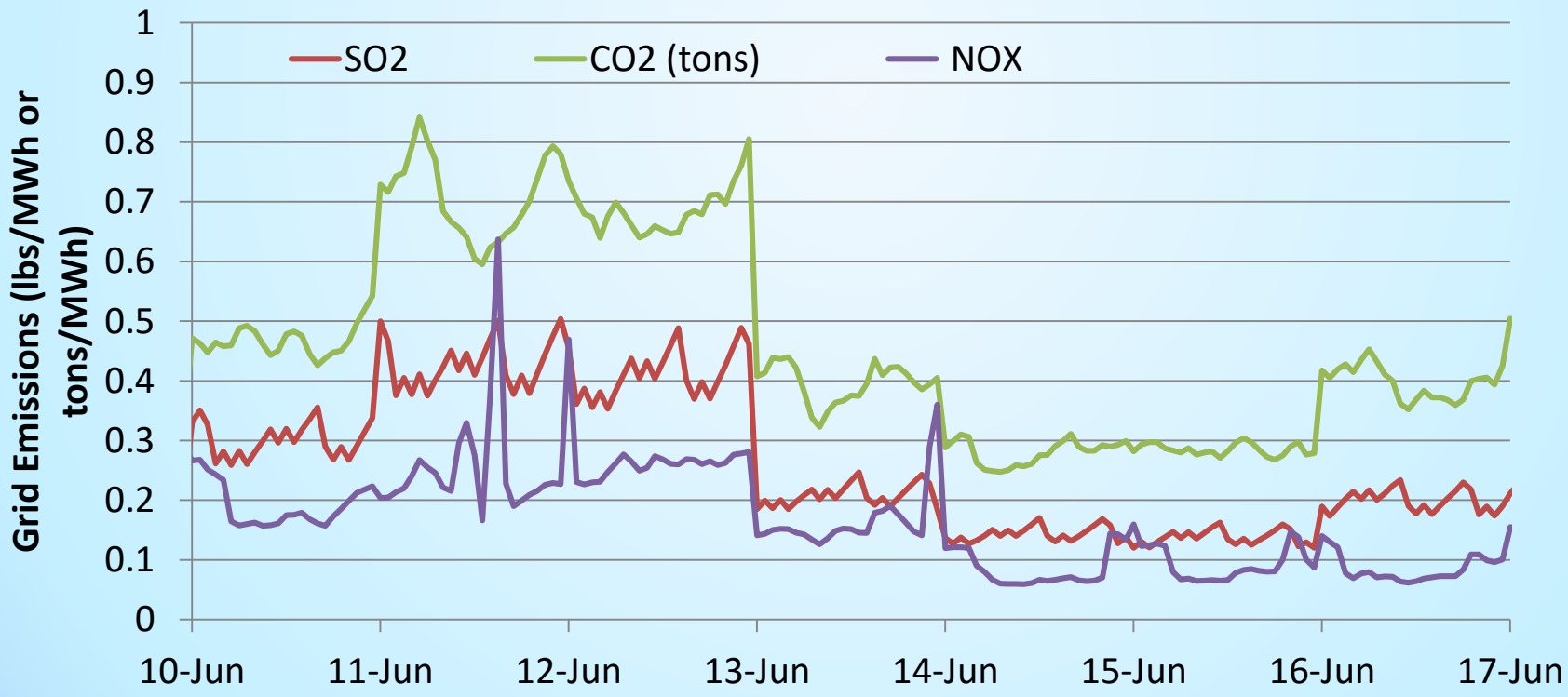
» EIA monthly rate data by state & sector

> Seasonal price dependence is important



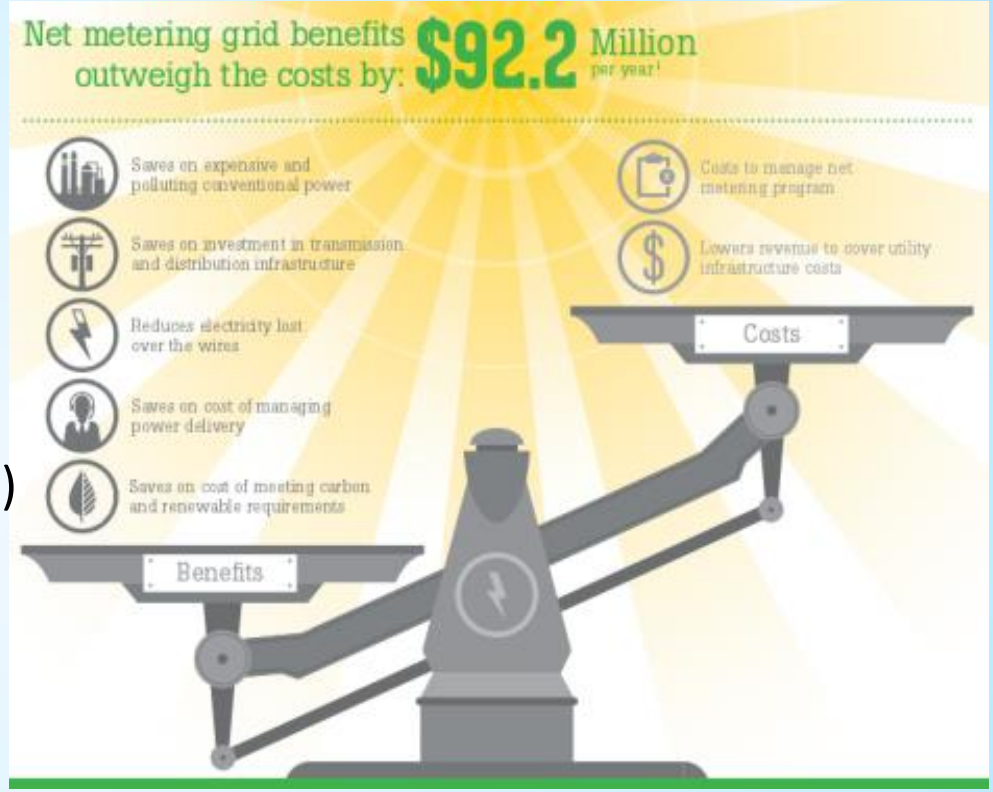
Utilities – Emissions

- Hourly emission data by state (CO_2, SO_2, NO_x)
  - EPA Acid rain program
  - NO_x profile from daily totals, assumed to have the same hourly profile as CO_2
  - Annual average emission factors within ±5% of eGRID values
  - Annual total generation within 10% of state totals from eGRID for 48 states
    - California and Texas datasets included 55% and 70% respectively
- Emissions vary greatly by region & season



CCHP Cost Benefits

- » Net Metering:
  - > Set on utilities page or results page
  - > Options include
    - + No net metering
    - + Fixed rate sellback
    - + TOU sellback (% of incoming charge)
- » Emission Credits
  - > Not included
- » CHP or FC incentives
  - > Not included



References: 1) Annual net benefits to non-solar ratepayers once 5% cap is reached, from Evaluating the Benefits and Costs of Net Energy Metering in California, Crossborder Energy, January 2013 2) San Onofre nuclear plant outage costs top $300 million, Los Angeles Times, November 2012 3)SEIA CA Fact Sheet, January 2013 4)CSI California Solar Statistics data

Dispatch & Control

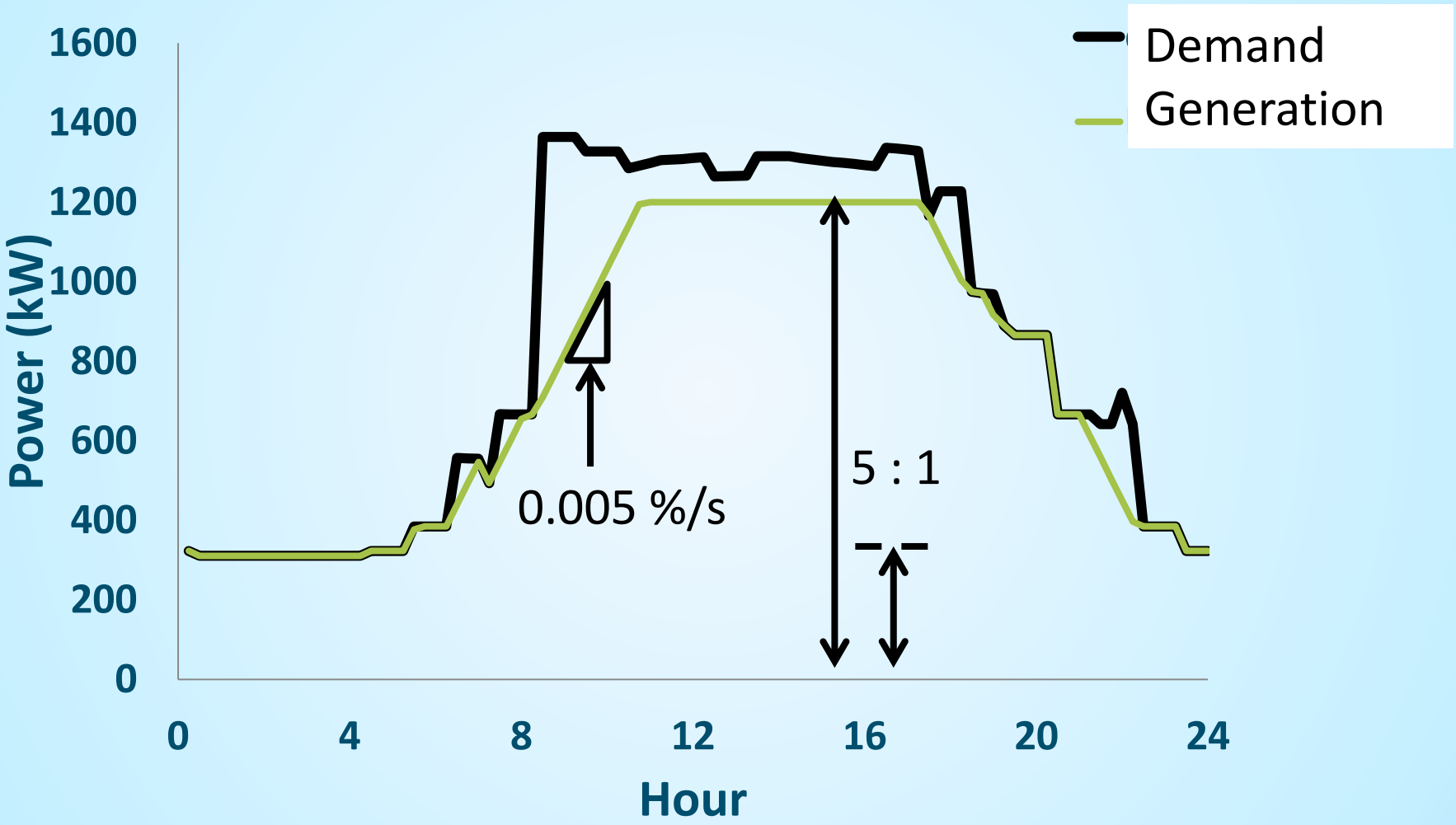
» Goal: Minimize costs given specific equipment performance and constraints

» Tools: 1) Reduce energy charges through self-generation
2) Reduce demand charges with smart dispatching

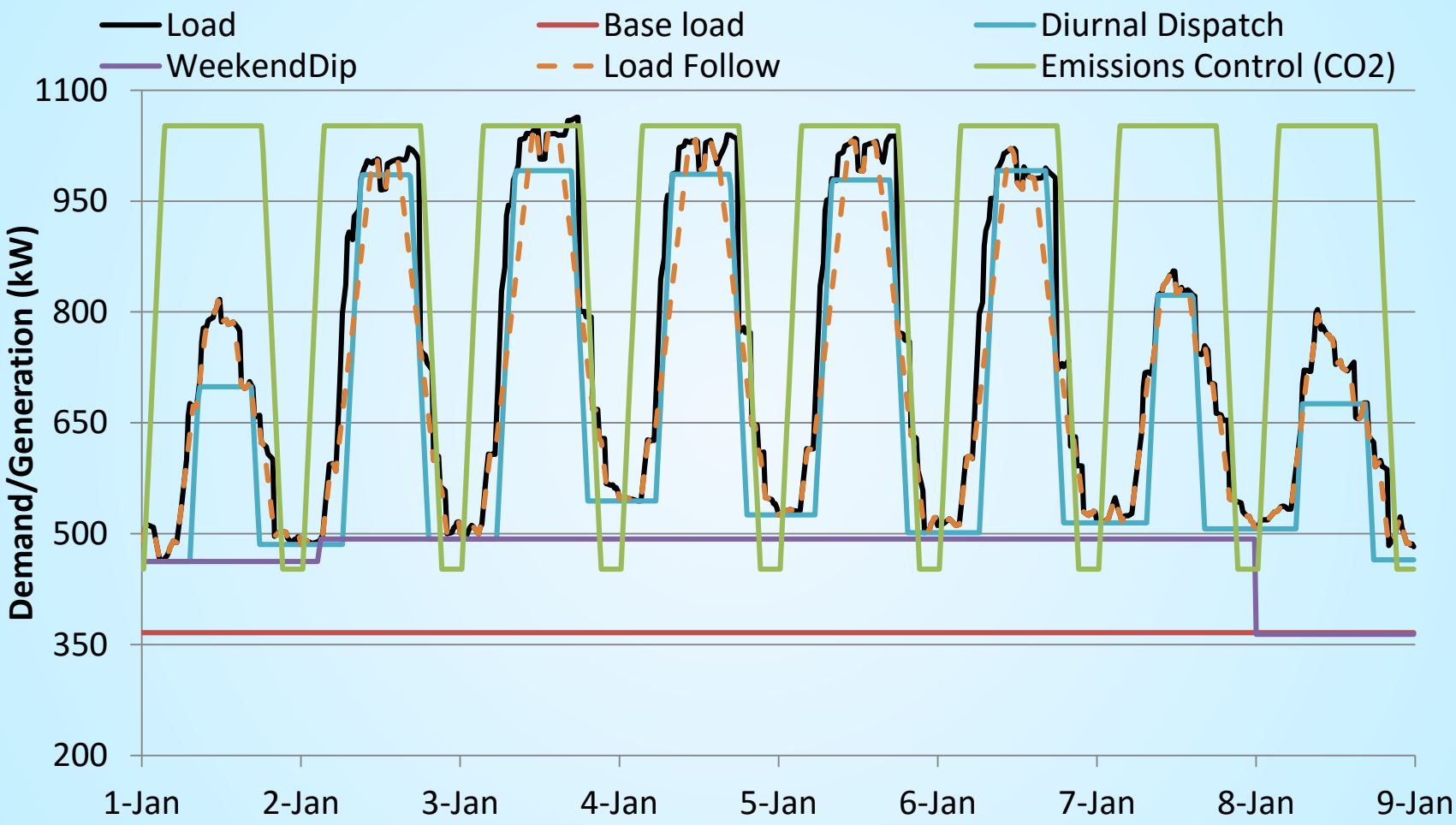
» Five strategies:
- > Base load
- > Diurnal peaking
- > Weekend dip
- > Load following
- > Emissions Optimization

» Constraints
- > System performance
- > Turndown ratio
- > Slew rate
- > Load predictibility

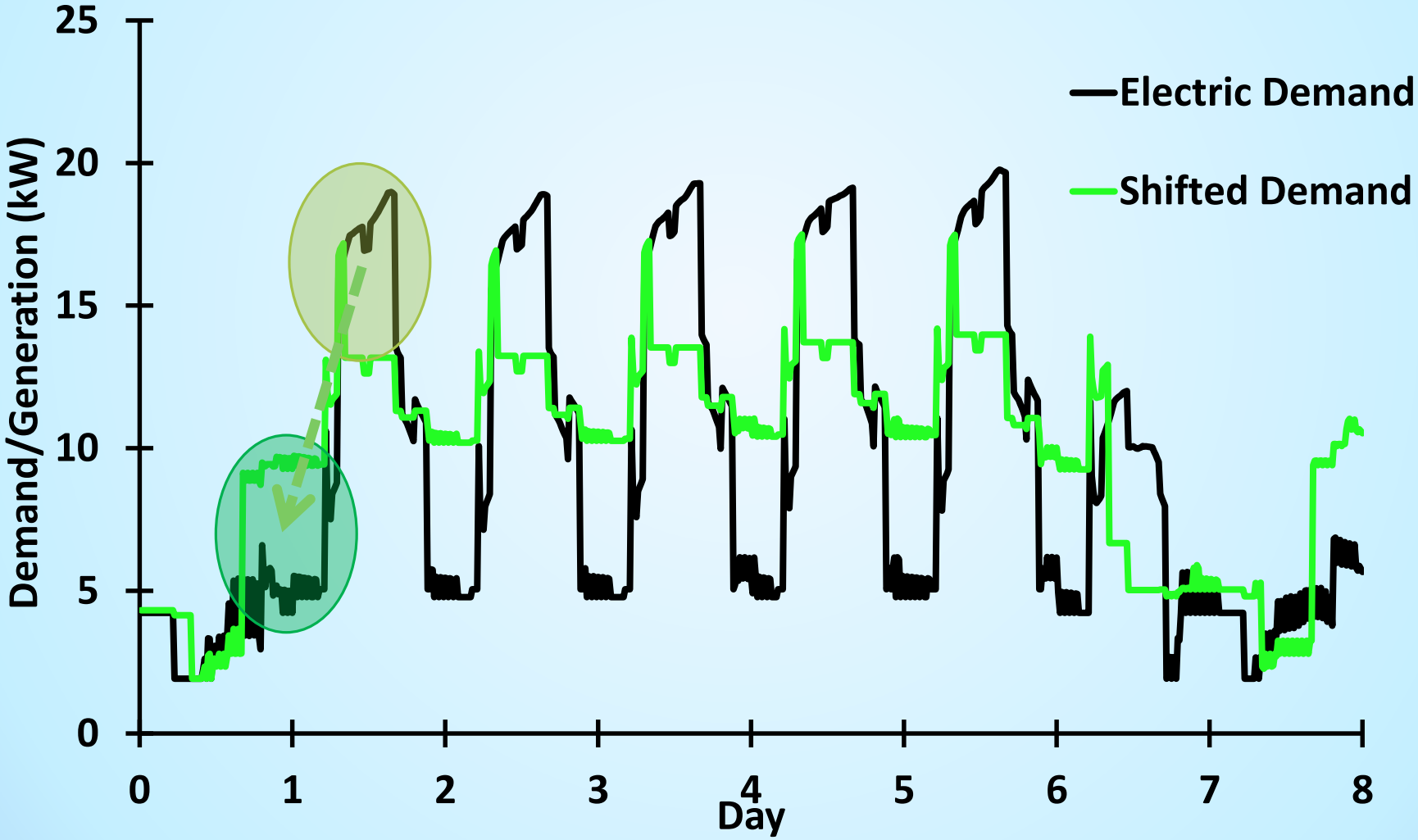
Constraints



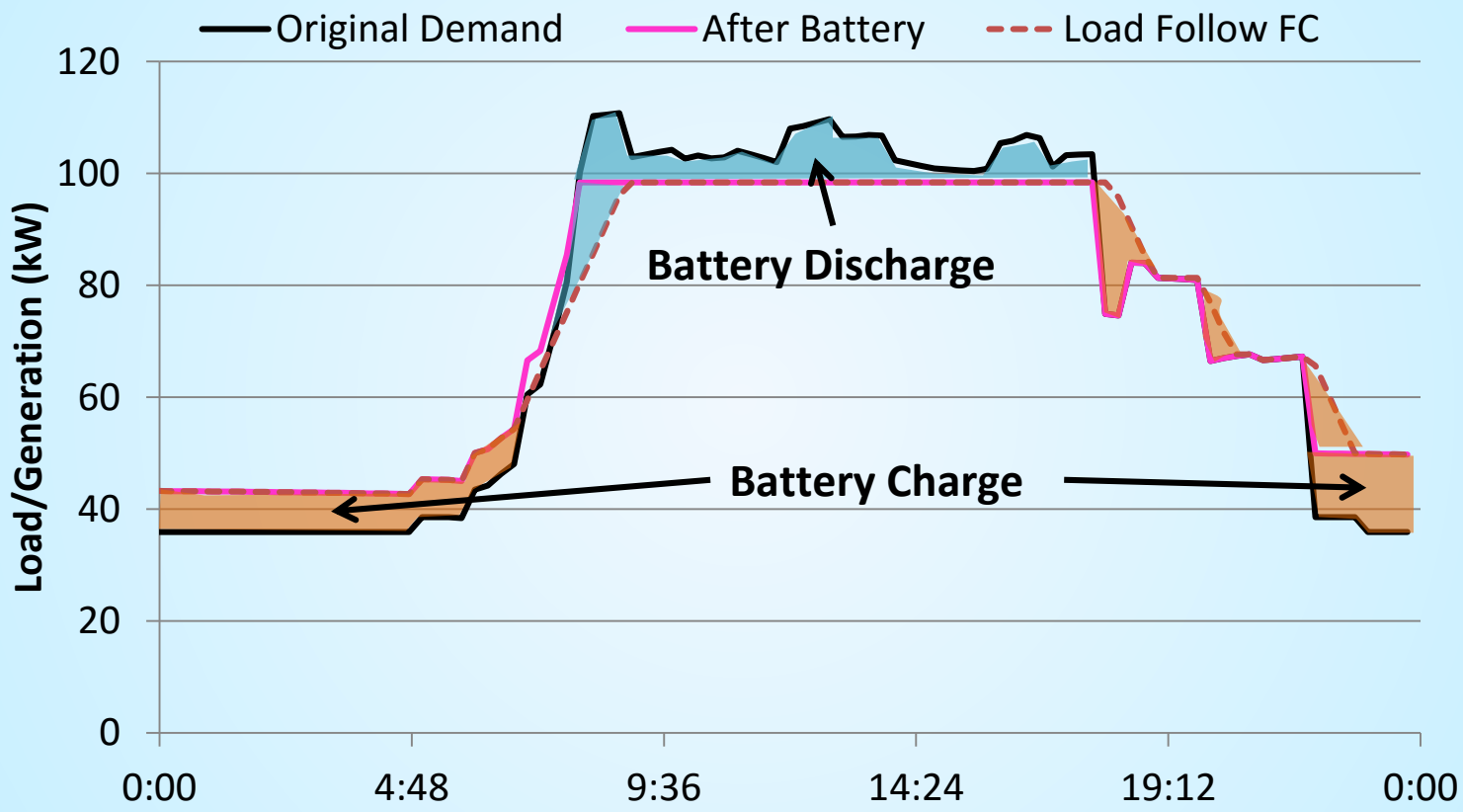
Dispatch Comparison



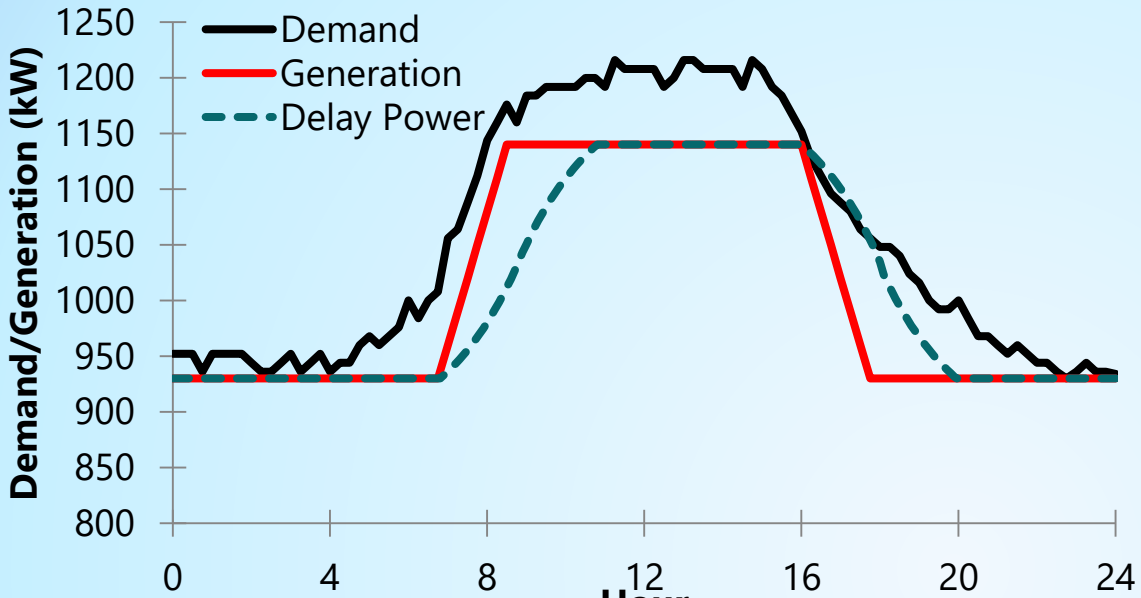
Energy Storage Shift



Battery Peak Shaving

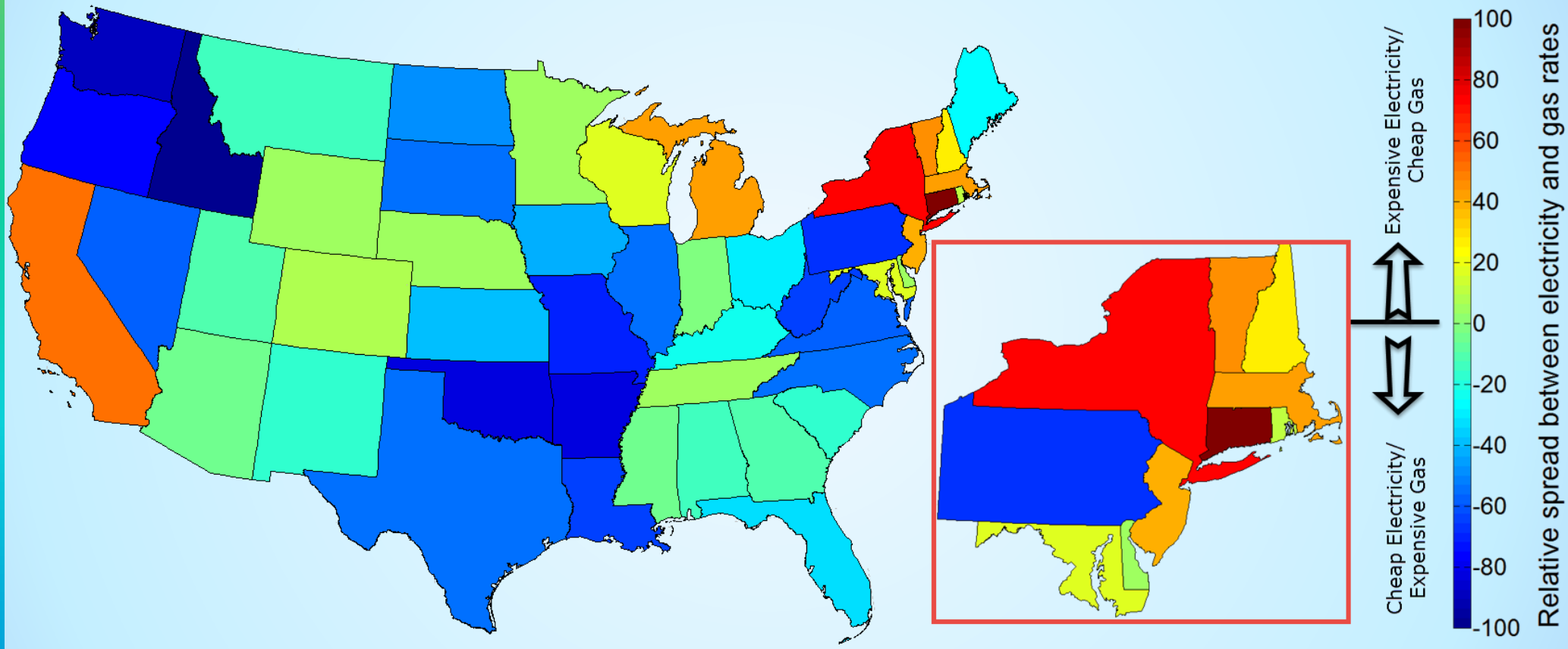


Predicting Load

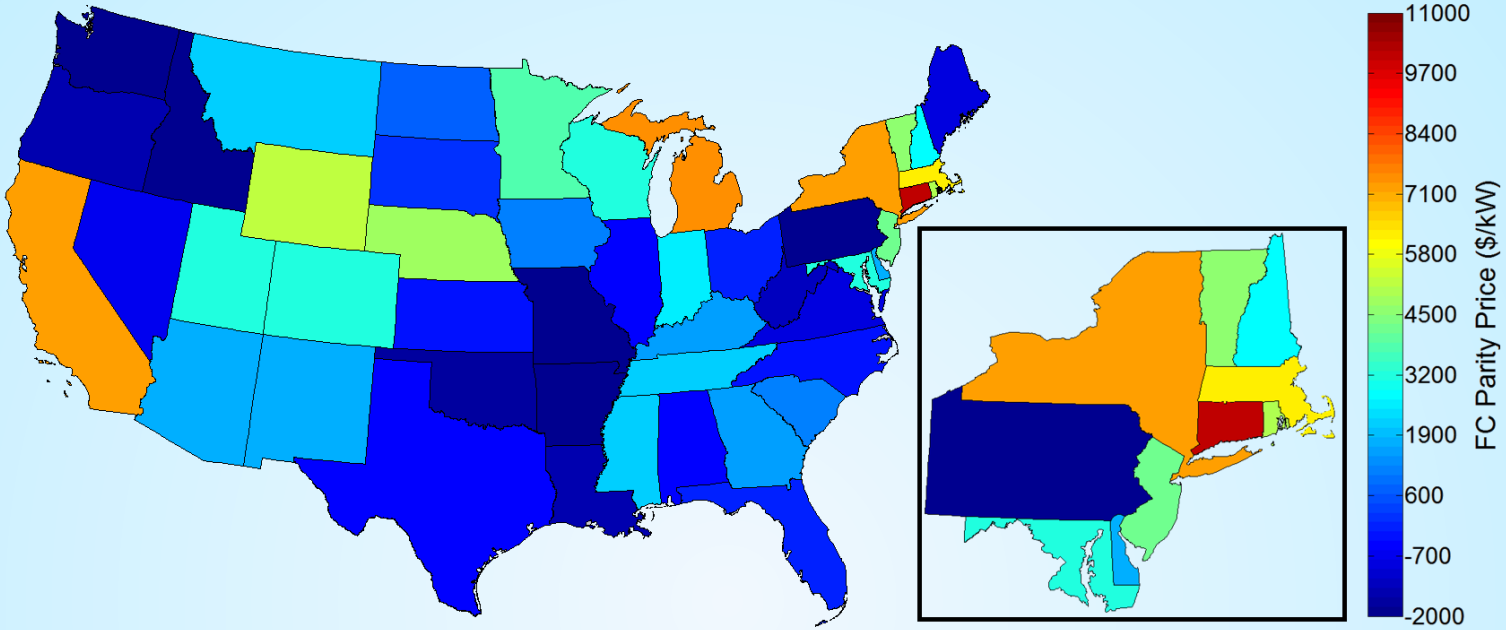


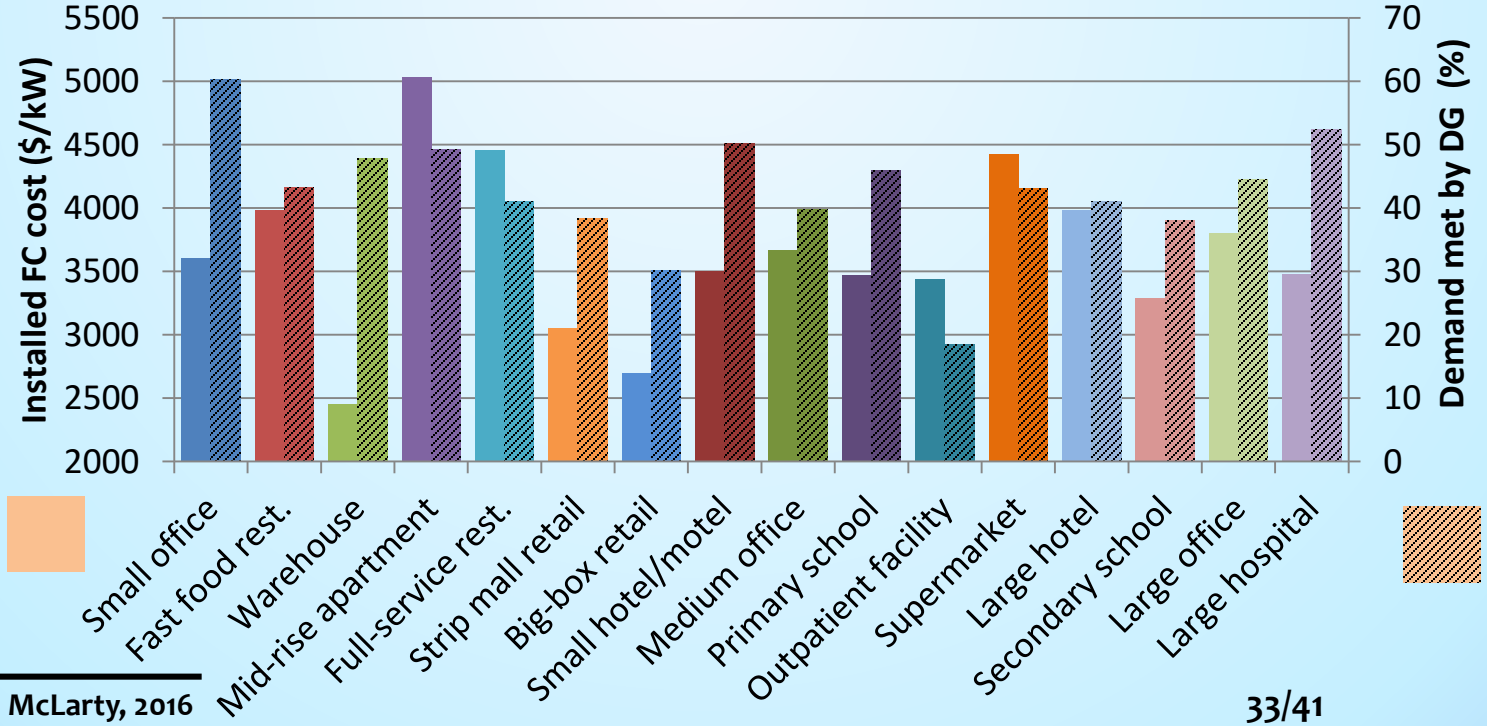
» Solutions: Batteries, ultra-capacitors, resistance heater, safety margin, predictive control

National Survey Results

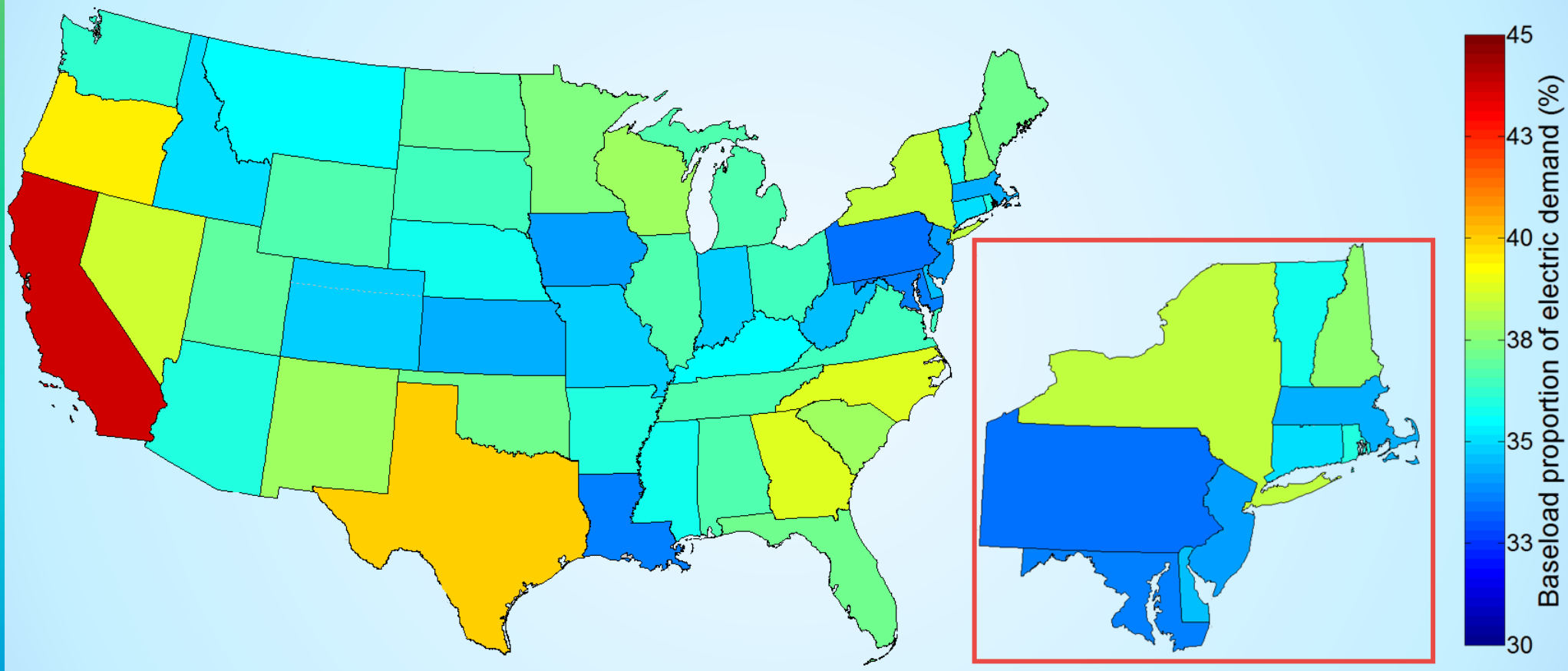


Results – Grid Parity Cost

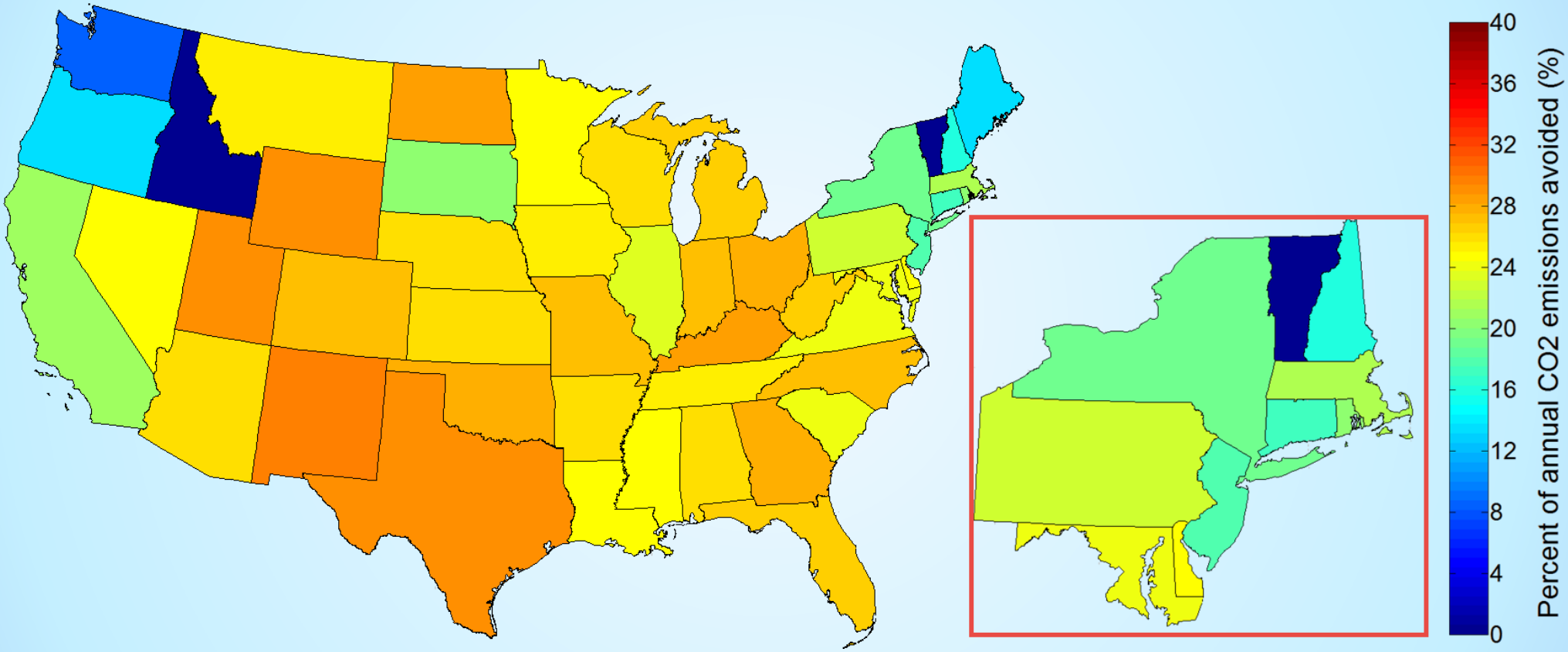




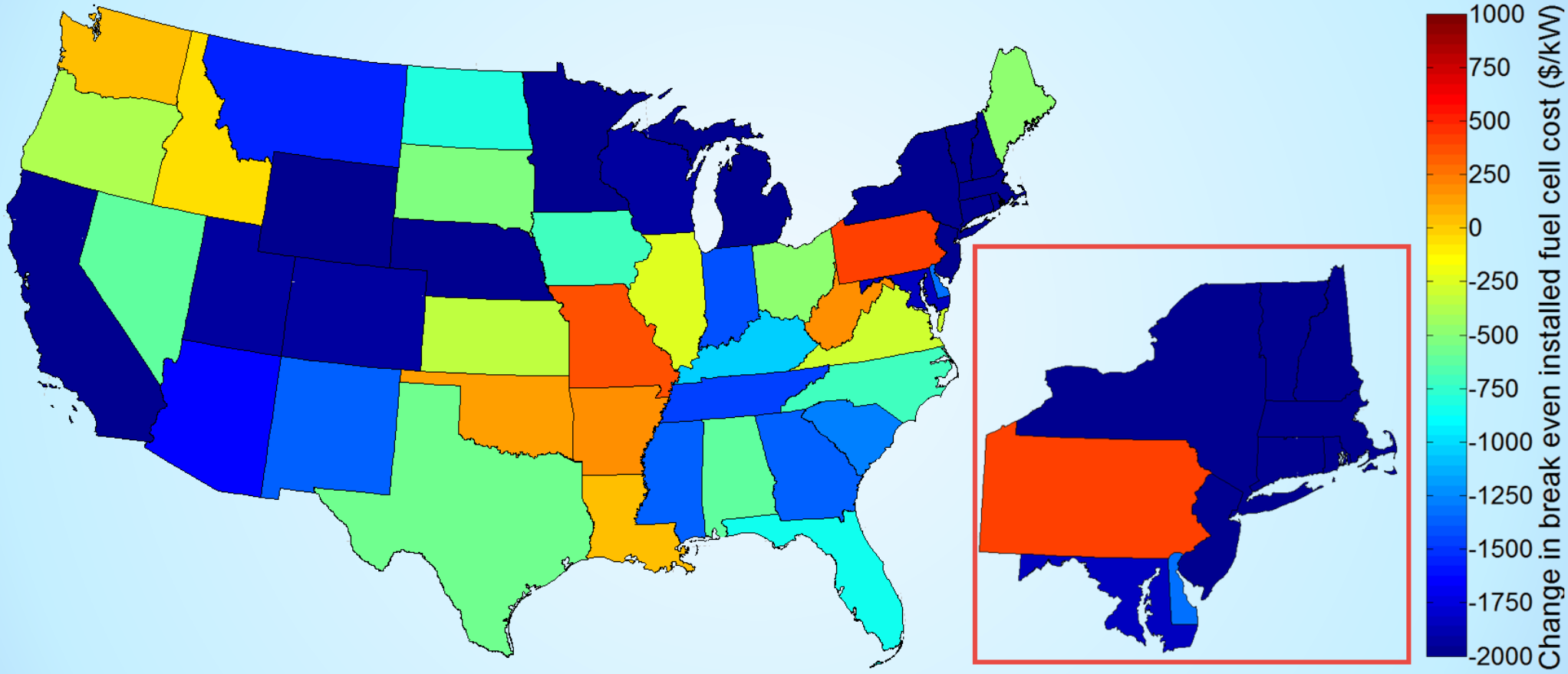
% Demand met by on-site FC



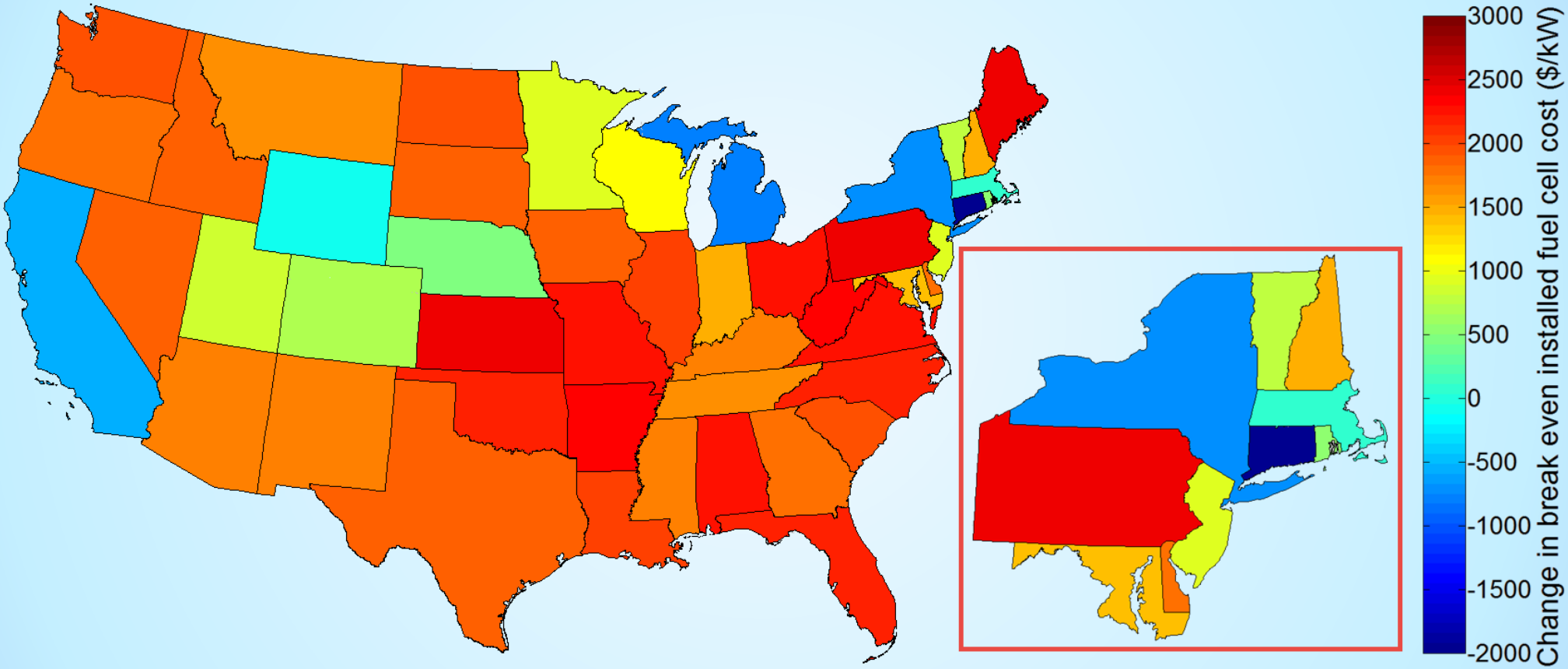
Annual CO2 reductions



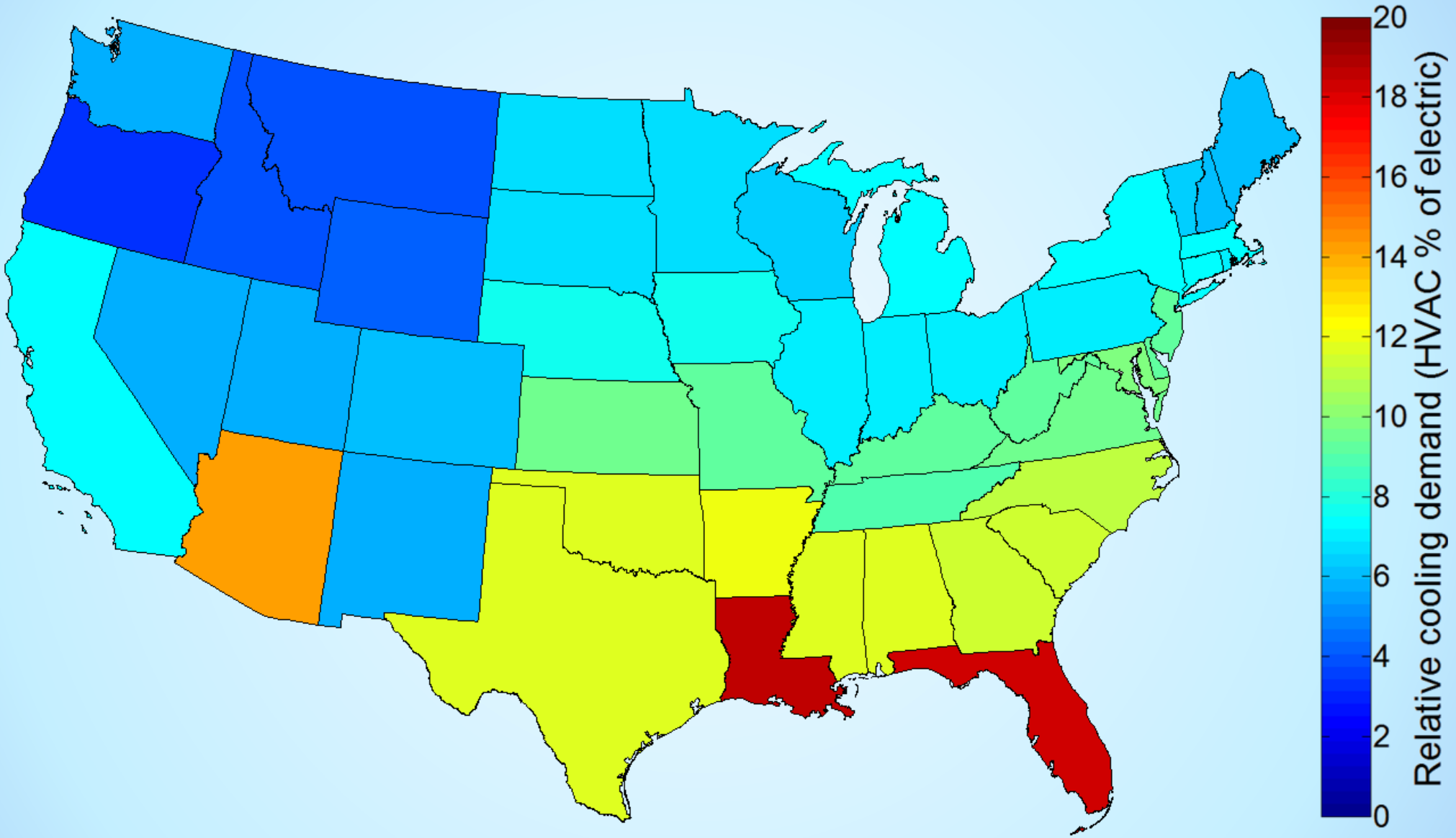
Diurnal Dispatch Control Strategy



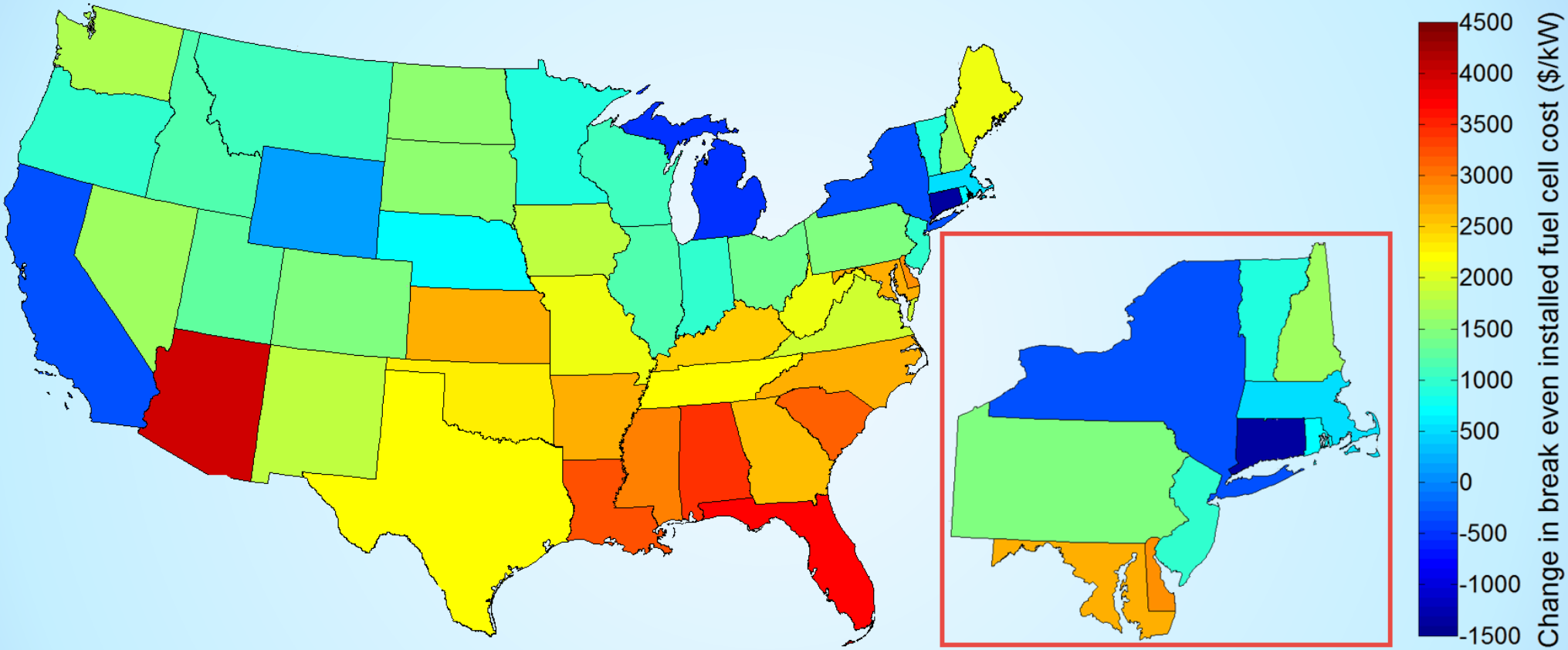
Grid Sell-back



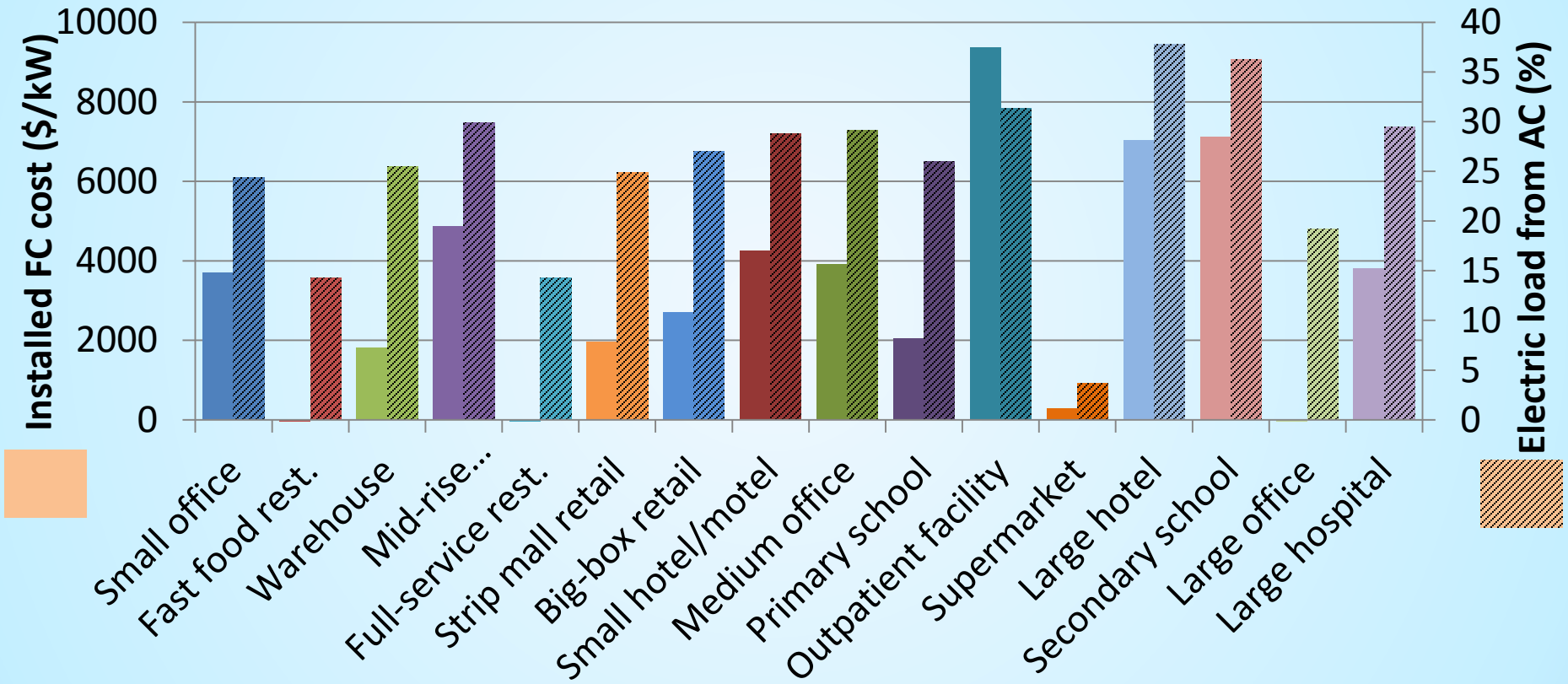
HVAC Load



Cold-Water Thermal Storage



Climate Dependence of FC Benefit



Absorption Chiller