Working together to put CPS Technology on the Sustainability Table

David E. Culler
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August 2, 2011

What can we put on the table?

CPS contributions … ???

- Pervasive Embedded Monitoring Networks
- Power Proportional Design Techniques
- Application Independent Physical Information Representation
- Modeling and Analysis
- Multi-objective Intelligent Control
- Human-Centric Optimization
- Robust, Scalable Infrastructure Architecture

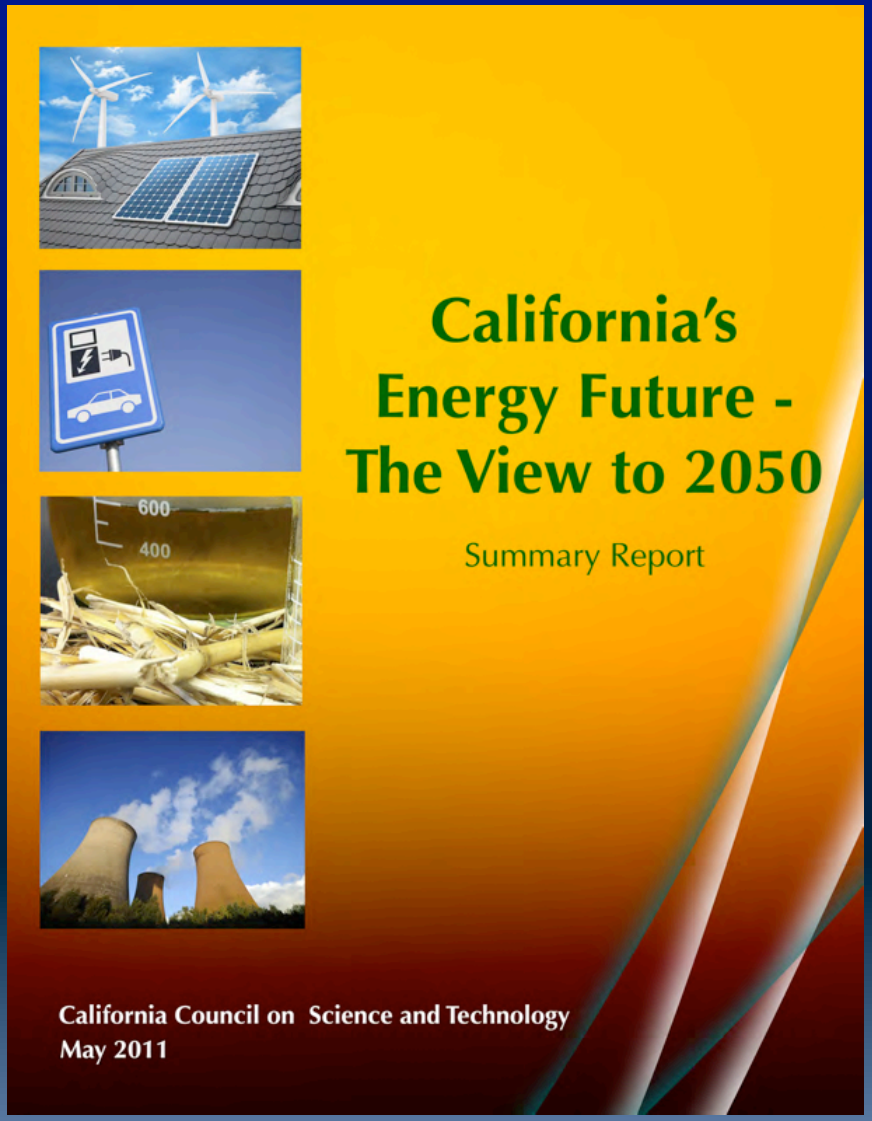
4/12/11 CPS 2011 95

Sustainability?

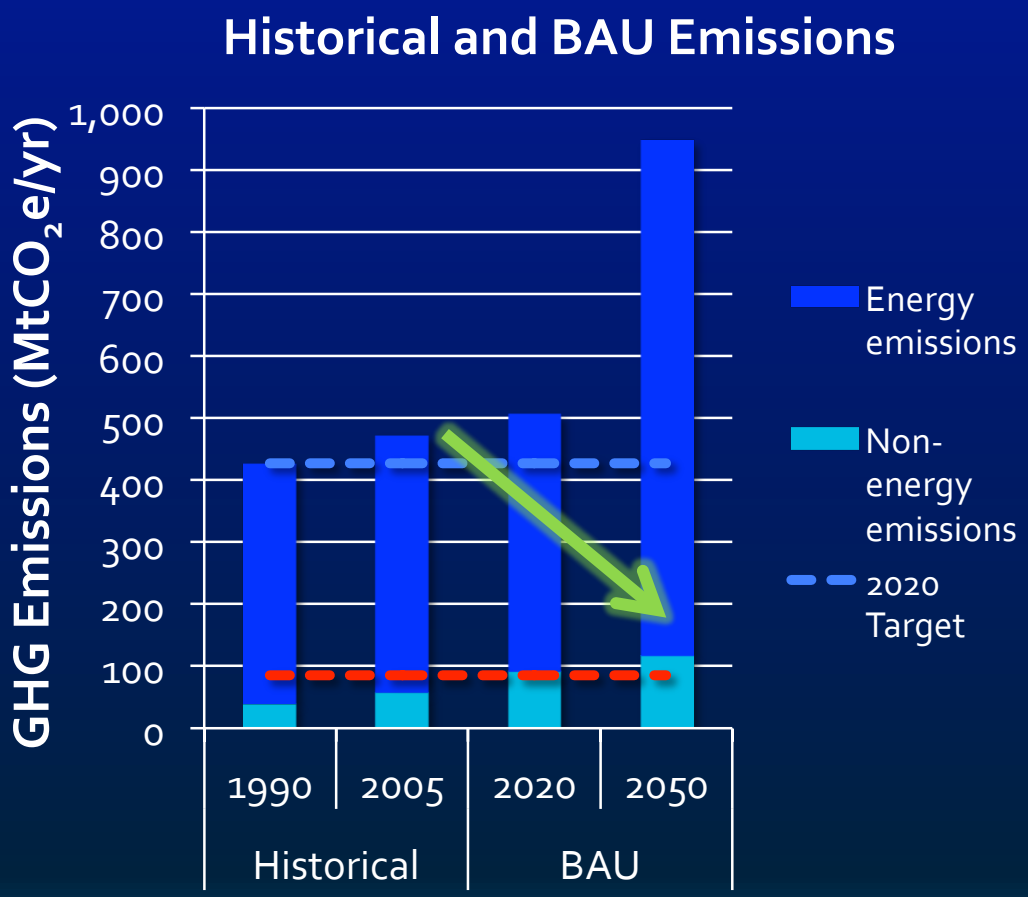
- "Sustainable development should meet the needs of the present without compromising the ability of future generations to meet their own needs"
  - Our Common Future, World Commission on Environment and Development, United Nations, 1987

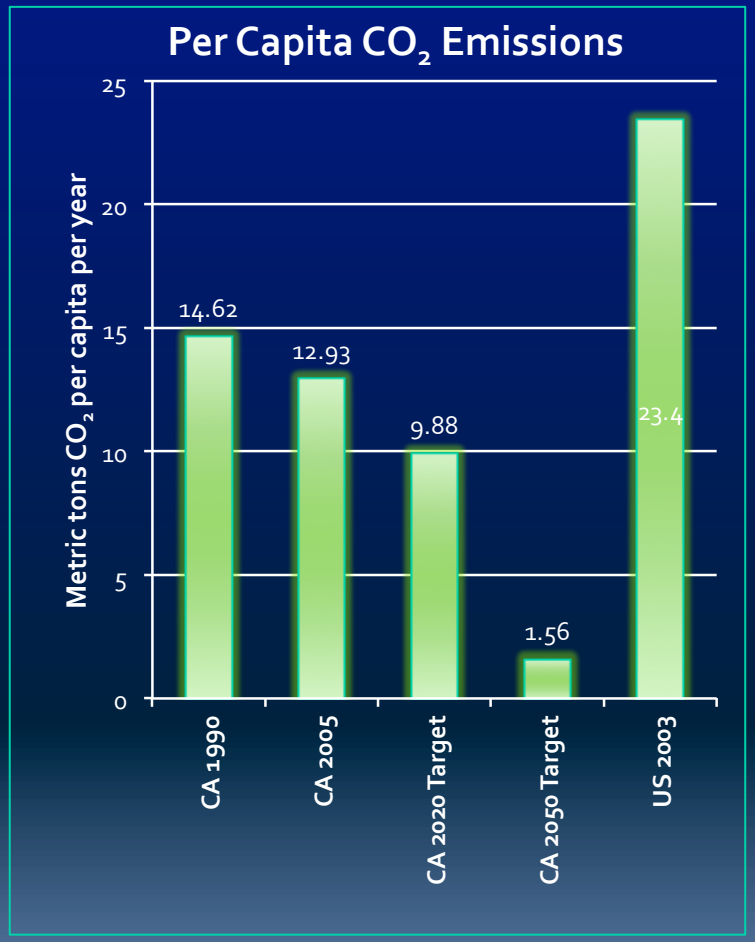
Quantifying it - California Law

- AB 32
  - Reduce GHG emissions to 1990 levels by 2020
- Governor's executive order S-3-05 (2005)
  - 80% reduction below 1990 levels by 2050
- Renewable Portfolio Standard
  - 33% renewables by 2020, 20% biopower procurement
- 480 => 80 mmT CO2e in 40 years
  - Population expected to grow from 37 => 55 million
  - Economic growth


California's
Energy Future -
The View to 2050
Summary Report
600
400
California Council on Science and Technology
May 2011

What it amounts to …





Can we do this?

CHAIR'S LECTURE: CALIFORNIA ENERGY FUTURES STUDY RESULTS
July 15, 2011

Jane C. S. Long

The short answer: **Yes, we can**

- We can achieve 80% cuts in emissions and still meet our energy needs.
- We can get ~60% of the cuts with technology we largely know about.
  - We basically know how to do this
  - A lot of this technology is in demonstration.
    - Deployment will depend on policy and innovation.
    - Note: We excluded extremely expensive technology
- We can get the rest of the cuts to 80% below 1990, but this will require new technology innovation and development.

But

Two major technology limitations will cause us to exceed the target:

- We don't have sufficient technology for load balancing without emissions
  - This is an especially big deal if we don't have baseload power
- We don't have enough technology choices "in the pipeline" for de-carbonizing fuel.
  - Need advanced biofuels, but it likely won't be enough
  - CCS may play a larger role in fuels than in electricity

My Take …

- We can't build our way to sustainability
- The discussion is focused on the *Physical*
  - New Windows, Materials, Motors, Biofuels, …
- Need to make the best of what we have, or will have, and how we use it…
- This takes observation, intelligence and control

⇒Demonstrable CPS technology on the table

⇒Efficiency & Supply-Following Loads

⇒10 years to innovate, 30 years to scale

What's on the Table? – buildings

Industry technology maturity –> complex

Bin	Technologies
1	Ultra high efficiency furnaces, controls and monitoring systems, waste heat recovery systems
2	Membrane technology for separations, super boilers, advanced/hybrid distillation, solar boiler systems
3	Integrated & predictive operations/sensors, advanced materials and processing, electrified process heating (e.g. microwave), process intensification
4	New membrane materials, advanced materials/ coatings

Deployed

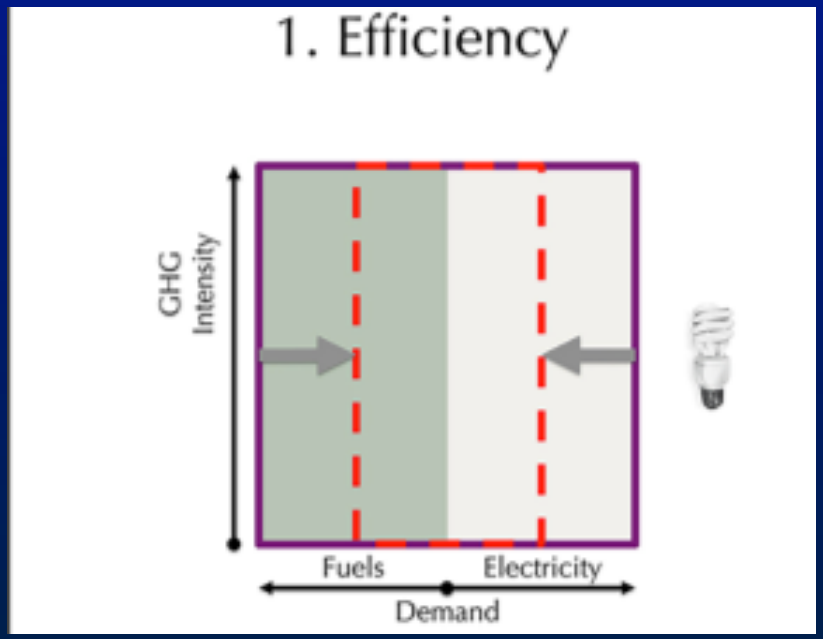
Demonstrated

Development

Research

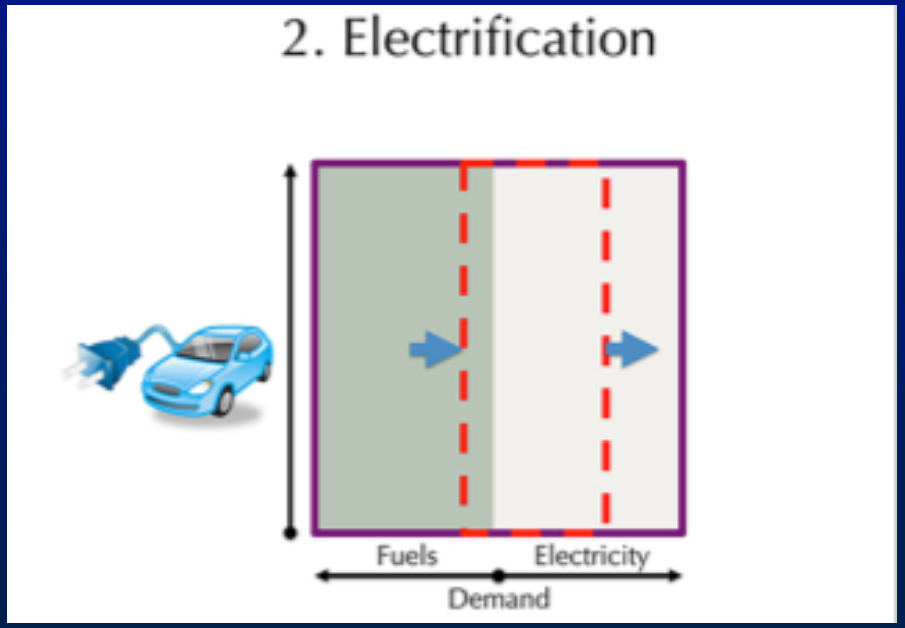
Concept

4 Part GHG Reduction Plan



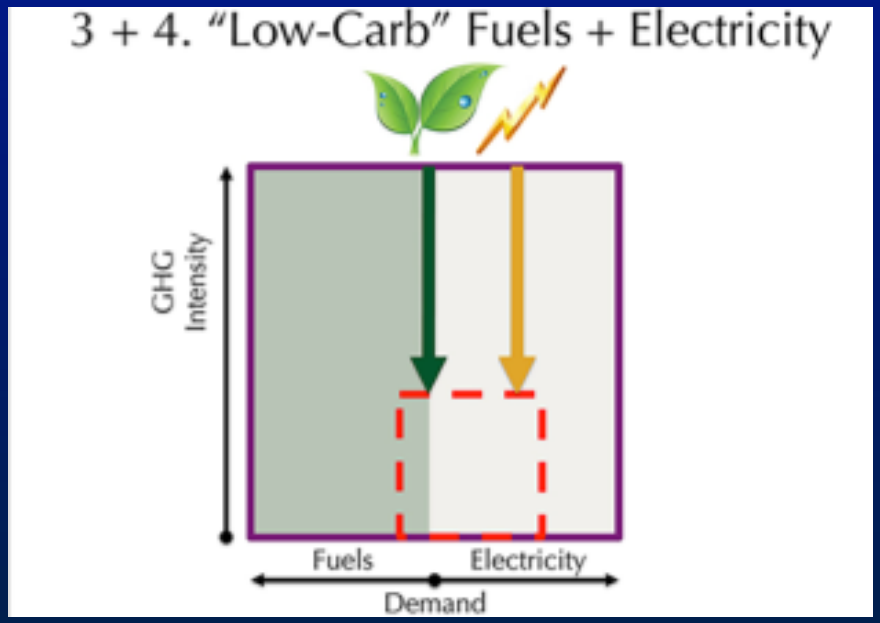
- Efficiency

4 Part GHG Reduction Plan



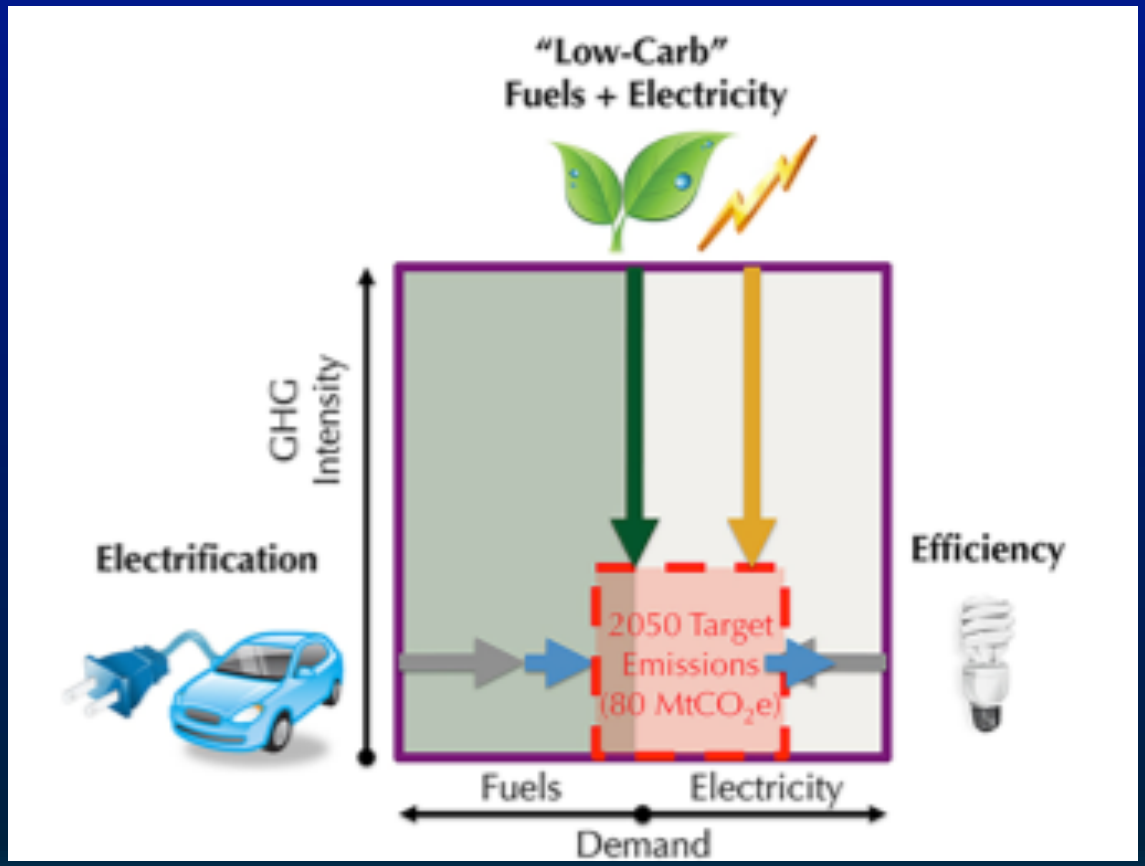
- Efficiency
- Electrify

4 Part GHG Reduction Plan



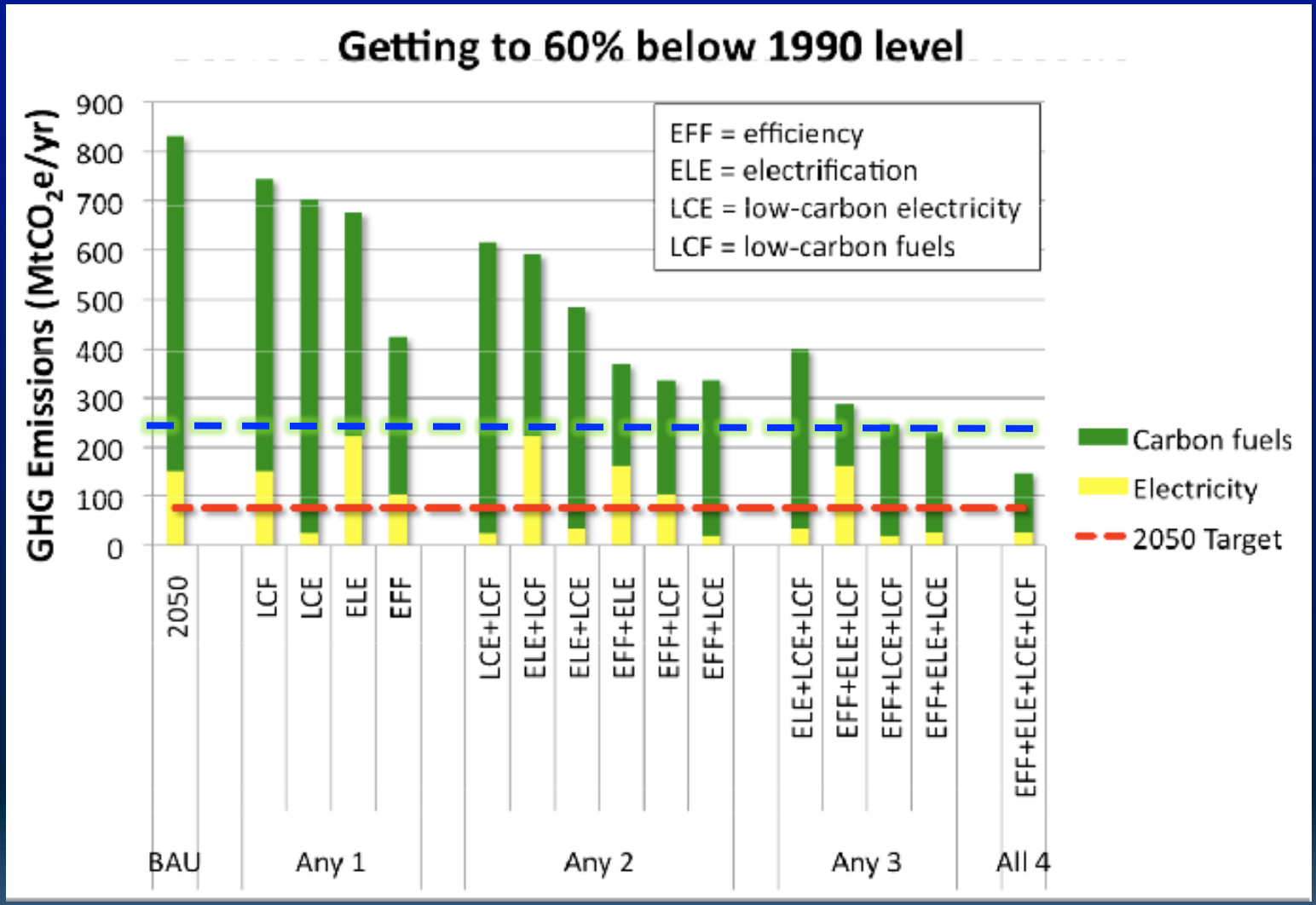
- Efficiency
- Electrify
- Decarbonize the electricity
- Decarbonize the fuel

4 Part GHG Reduction Plan



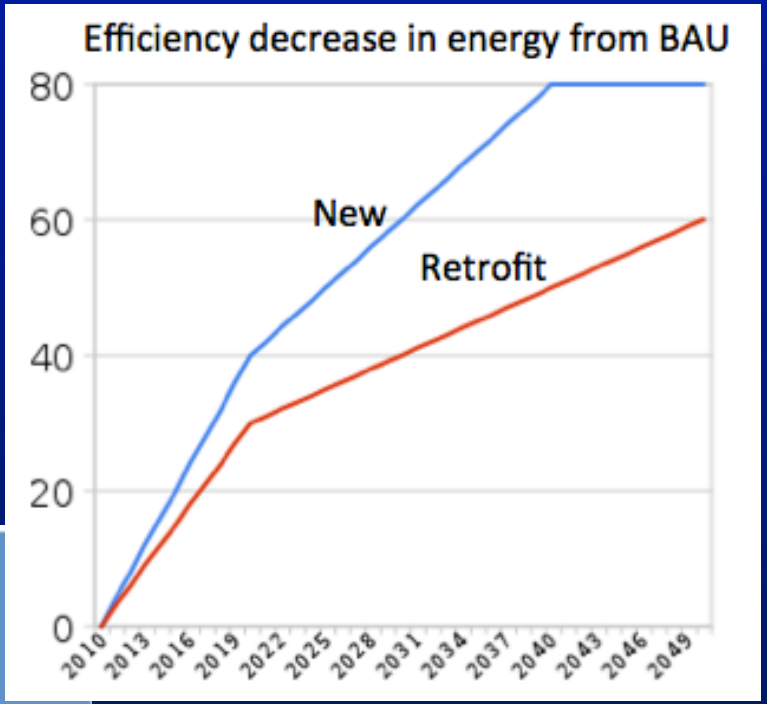
- Efficiency
- Electrify
- Decarbonize the electricity
- Decarbonize the fuel

All required for even 60% reduction



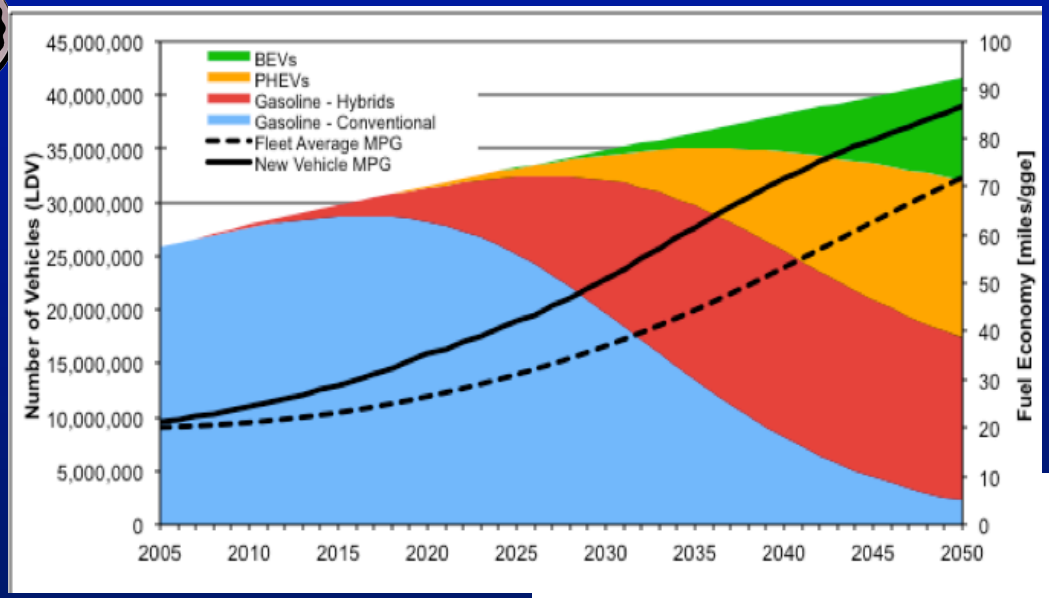
but still fall short of 80%

Efficiency



Percent energy decrease from BAU			
Buildings	40%	Cars	60%
Industry	0-15%*	Trucks	30%
* BAU 30-40% fr. 2005		Airplanes	50%
Electricity	**31%**	Bus, Rail	0%
Fuels	**52%**	Marine	40%

Electrification



Not just for cars!

Electrification saturation from BAU			
Buildings	70%	Cars	44%
Industry	12%	Trucks	18%
Change in demand		Airplanes	0%
Electricity	**+56%**	Bus, Rail	100%
Fuels	**-33%**	Marine	0%

Low Carbon Electricity Options

Nuclear	**Fossil/CCS**	**Renewables**
62% nuclear	62% fossil/CCS	90% renewables
44GW	49 GW	(70% intermittent)
33% renewables	33% renewables	160 GW
5% natl gas	5% natl gas load	10% natl gas
load balancing	balancing	load balancing

Build Rate

Strategy	Assumed Plant Size	Total Plant Capacity Needed in 2050	Build Rate 2011-2050 (Plants/Year)
Nuclear	1.5 GW	44 GW	0.73
Fossil/CCS	1.5 GW	54 GW*	0.90
Renewables Mix total		165 GW**	
- Wind	500 MW	59 GW	3.0
- Central Solar (CSP and PV)	500 MW	65 GW	3.3
- Distributed Solar PV	5 kW	22 GW	110,000
Biomass/CCS	500 MW	1.5 GW	0.77
CA Biofuels	50 Mgge/yr	5.5 bgge/yr	2.8
Hydrogen		8.0 bgge/yr	
- Natural Gas Reforming	0.5 Mgge/yr	0.8 bgge/yr	40
- Central Plant	440 Mgge/yr	7.2 bgge/yr	0.41

Table 5. Summary of supply build rates required.
*Gross capacity, assuming 10% parasitic loss from CCS (net capacity = 49 GW)
**Includes geothermal and hydropower not included in this table

The Renewables are there

Type	Share of Total Supply	Realistic Case Supply (GWh)	Capacity Factor	Generation Capacity Required in 2050 (GW)	CEC Resource Upper Limit (GW)	Fraction of Total Resource Consumed	Displaced land area (km^2)
Wind - onshore	30%	159,000	40%	45.4	150	30%	11,470 (230)*
Wind - offshore	10%	53,000	40%	15.1	293	5%	3,820 (80)*
Concentrated Solar Power (CSP)	20%	106,000	27%	44.8	1061	4%	1,620
Centralized Photovoltaic (PV)	10%	53,000	27%	22.4	17,000	0.1%	1,960
Distributed PV	10%	53,000	27%	22.4	78	29%	1,960 (0)*
Biomass	5%	26,500	85%	3.6	10.7	33%	35,600 (0)*
Hydroelectric	5%	26,500	30%	10.1	24	42%	1,430
Geothermal	10%	53,000	90%	6.7	25	27%	400
Total	100%	530,100		170.5			58,250 (5,710)*

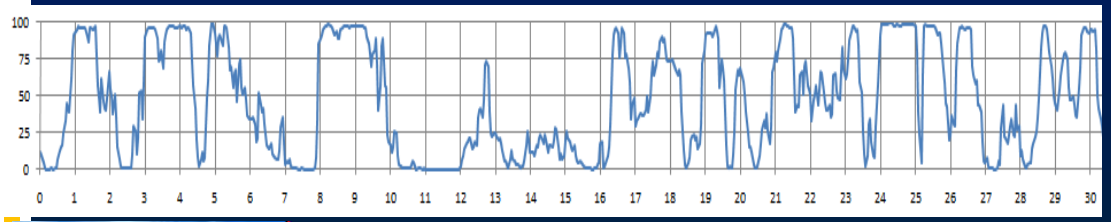
*About 1.4% of California land area

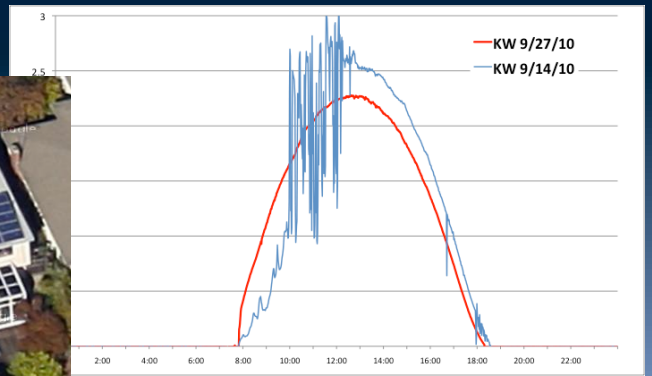
43% agriculture, 3.4% urbanized

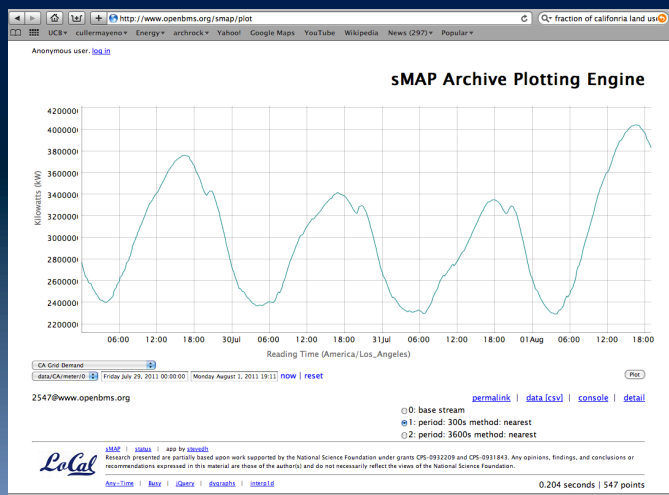
The Problem: Supply-Demand Match

Baseline + Dispatchable Tiers

Oblivious Loads

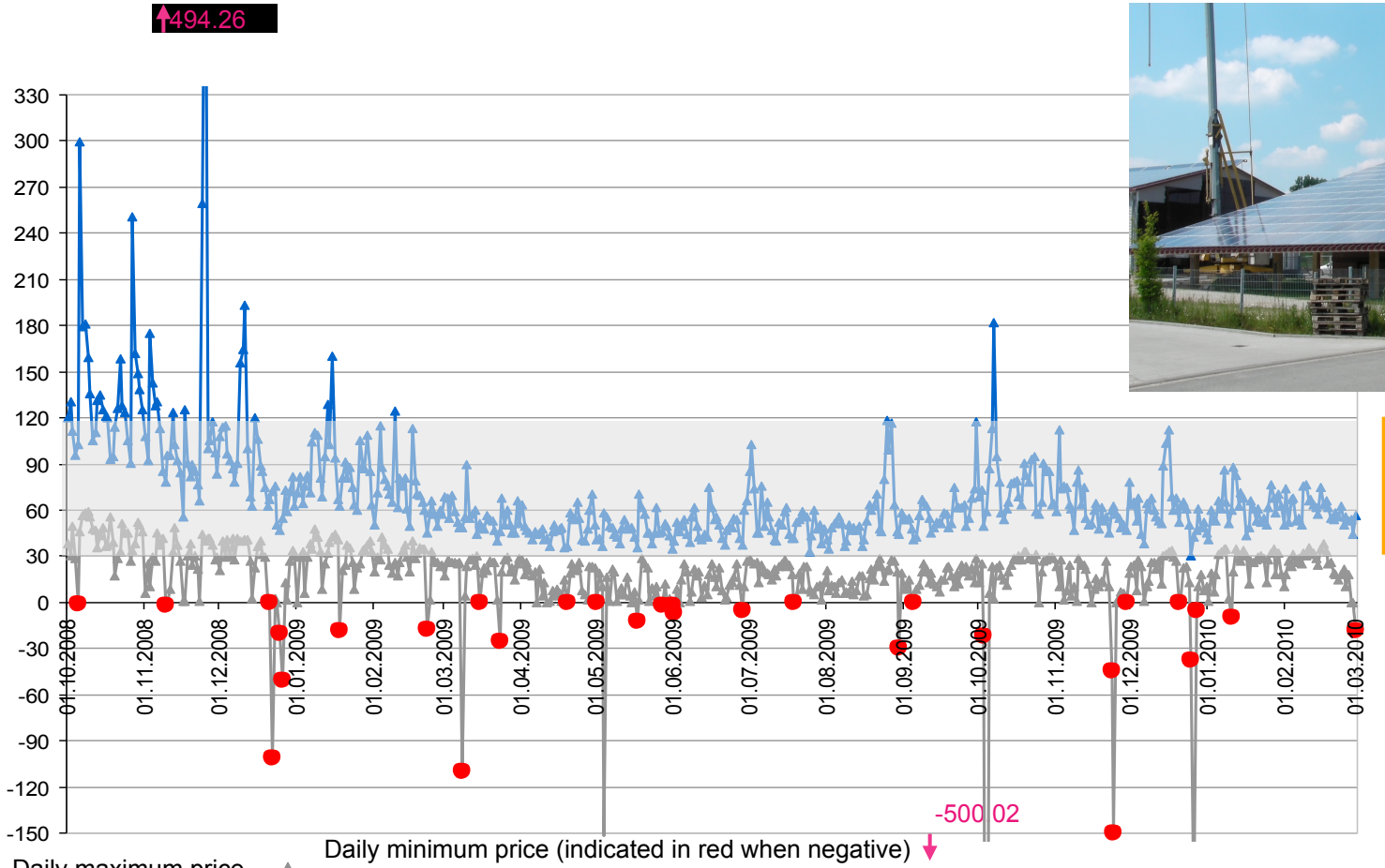






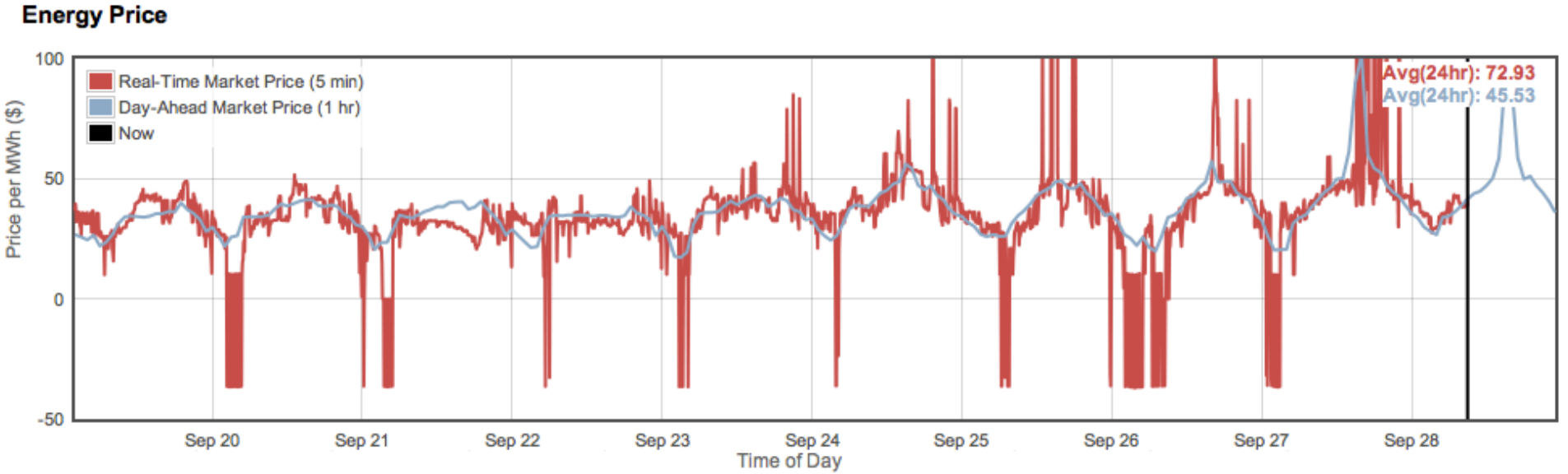
Load-following Supply (?)

Growing proportion of renewables leads to higher price volatility. October 2008 to March 2010:
>**90 hours** with negative prices; highest price reached: +€500/MWh, lowest -€500/MWh



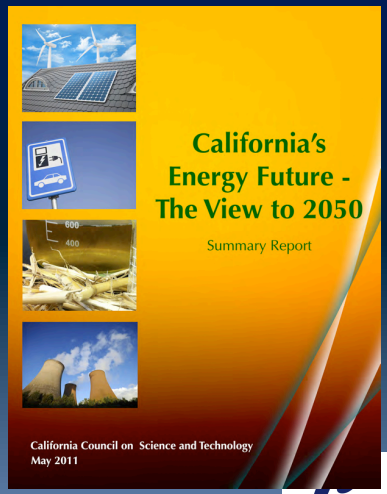
Source: EEX spot prices.

… and in CA

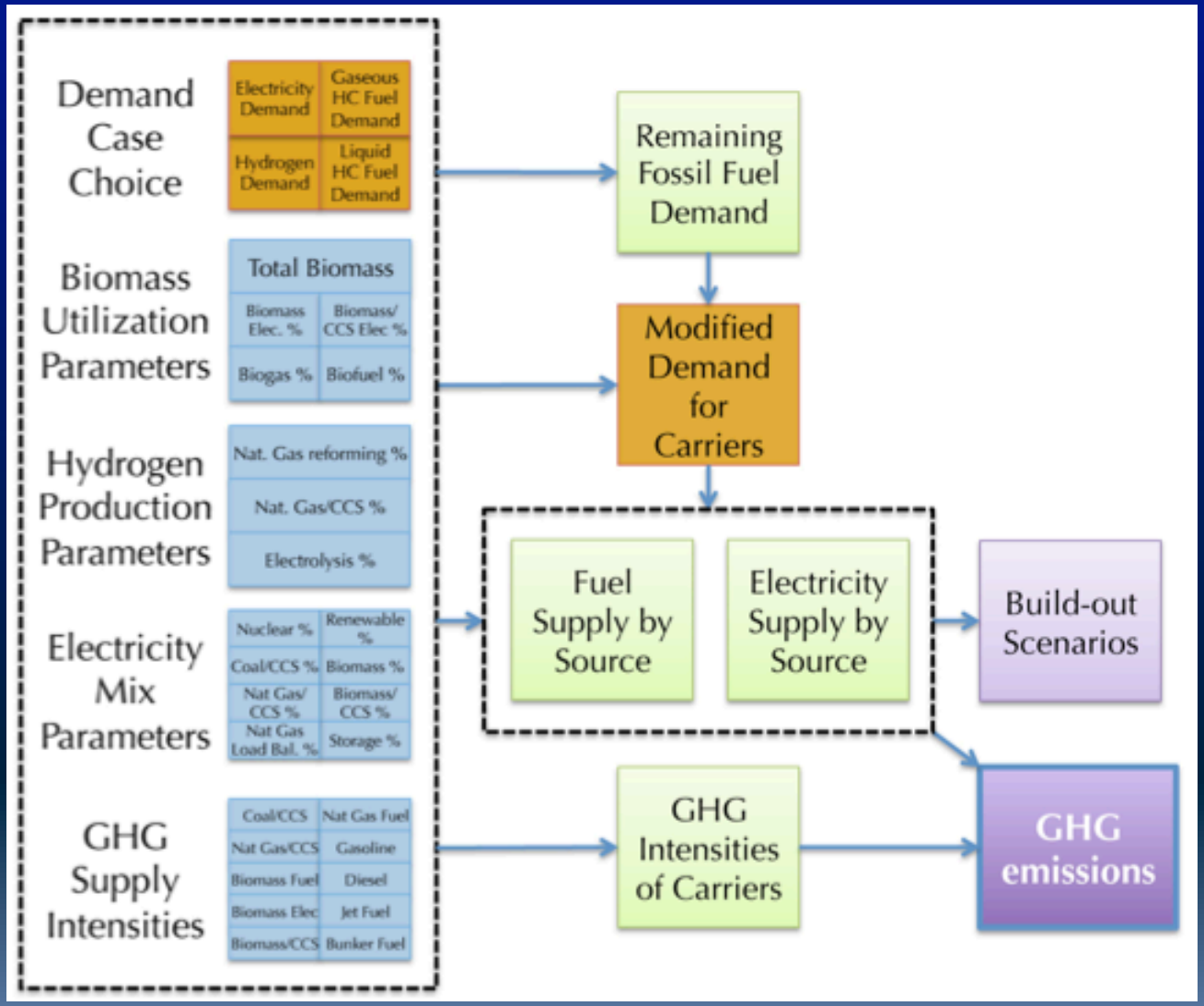

Energy Price
Real-Time Market Price (5 min)
Day-Ahead Market Price (1 hr)
Now
Avg(24hr): 72.93
Avg(24hr): 45.53
Price per MWh ($)
100
50
0
-50
Sep 20
Sep 21
Sep 22
Sep 23
Sep 24
Sep 25
Sep 26
Sep 27
Sep 28
Time of Day

Zero Emissions Load Balancing (ZELB)

- Just the emissions from the natural gas to *firm* the 33% renewables exceeds GHG target
- Even with 50% with natural gas & 50% with some yet-to-exist storage



We Understand Supply



Not demand

ZELB

- More challenging for the maximum renewables case
  - GW-days of storage needed
  - Smart grid solution is a challenge
    - Smart meter fiasco
    - Completely change business model to demand follows load vs load follows demand
    - Need whole different system of system control – but will this ever solve the GW-day problem?
- Would be easier to have significant baseload power
  - No more hydro likely
  - Renew interest in geothermal energy
  - Choose nuclear or CCS

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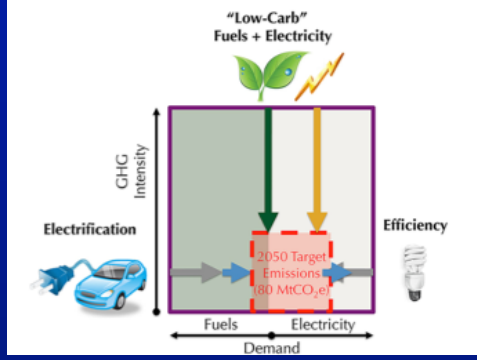
Limits to Renewable Penetration

- Variability, Intermittency of Supply

- Visibility into Availability of Supply
- Ability of Loads to Adapt
- Algorithms and Techniques for Reactive Load Adaptation

- Capability of the Infrastructure to maintain the match

CPS and the 4 Part GHG Reduction Plan



- Efficiency
- Electrify
- Decarbonize the electricity
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Monitoring, Analysis, Modeling, Waste Elimination, Power Proportionality, Optimal Control

Intelligence, Communication, adaptation in Everything

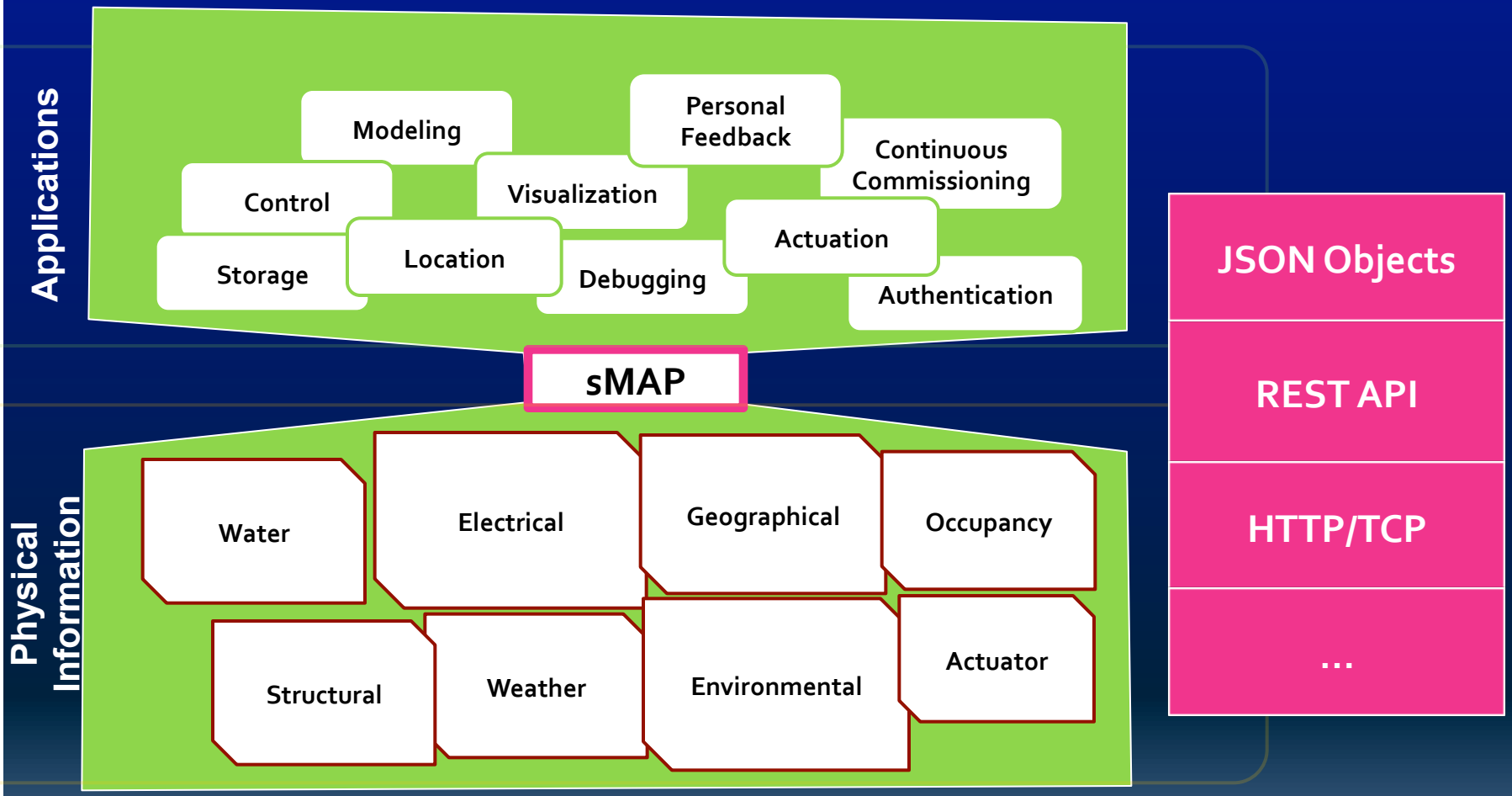
ZELB. Supply-Following Loads, Energy SLA, Cooperative Grid

CPS Technology …

- National-scale Physical Information Service
  - Data collection, streaming, archiving, querying
  - Modeling, Analysis, Control
  - Representation, metadata, life-cycle
  - Use others', contribute yours

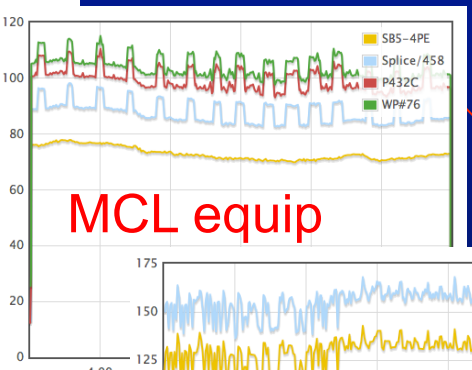
Some starts

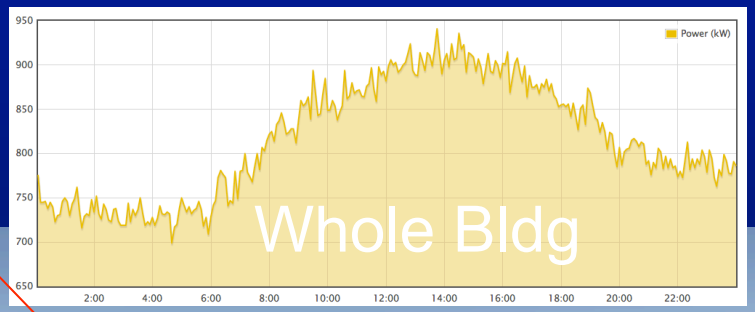
sMAP: Uniform Access to Diverse Physical Information

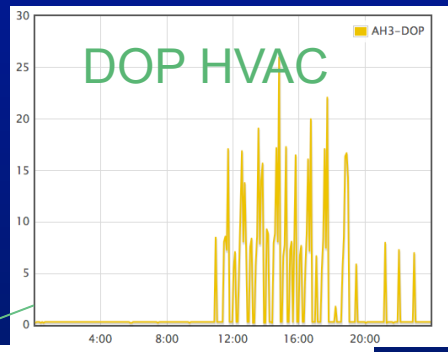


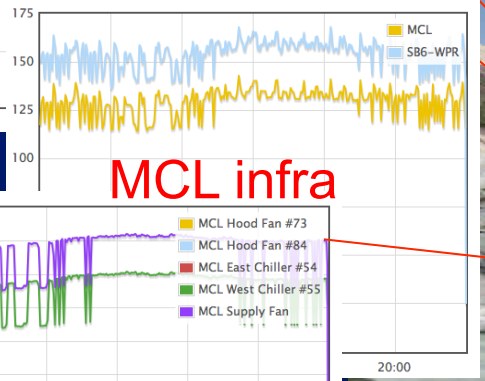
sMAP ecosystem

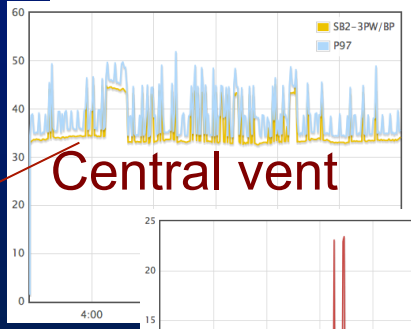
Cory CEC B2G Testbed

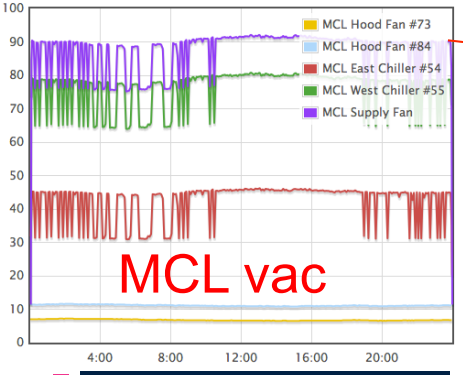


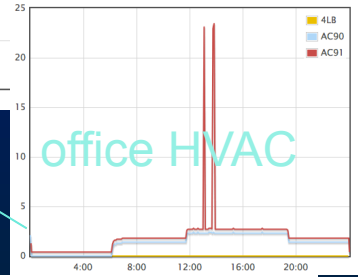


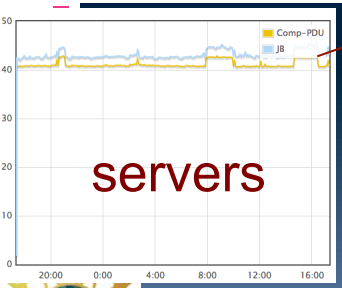


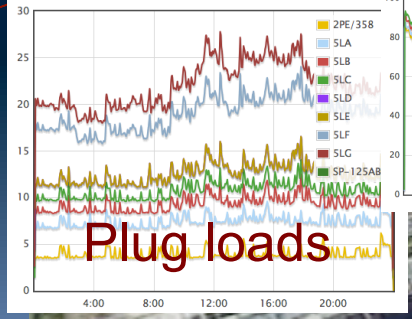


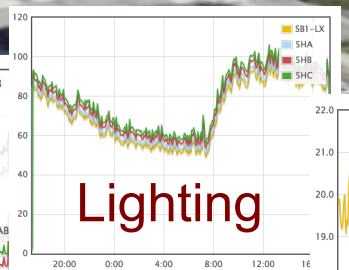


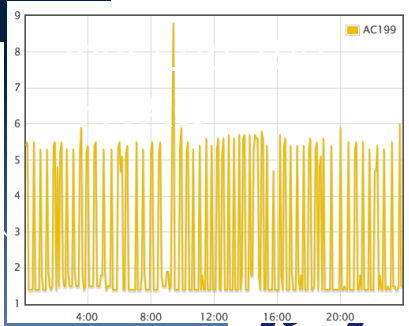




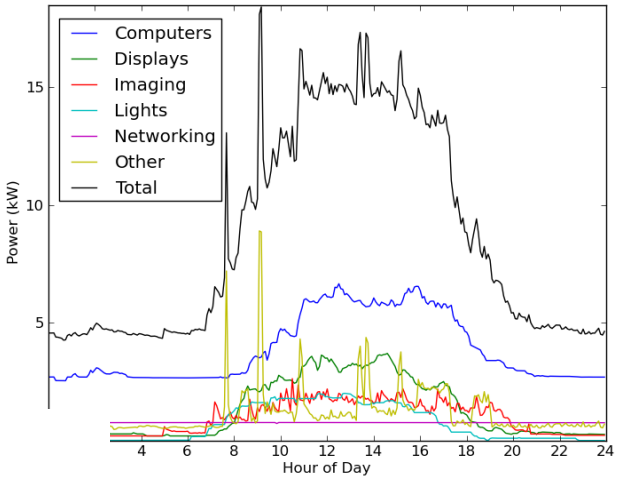


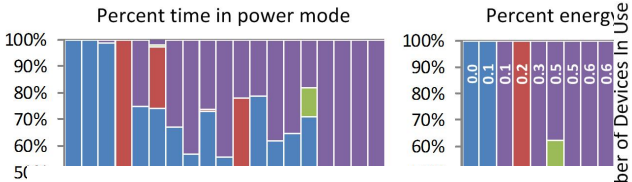


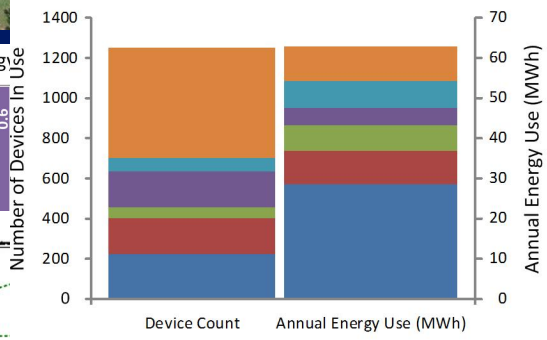


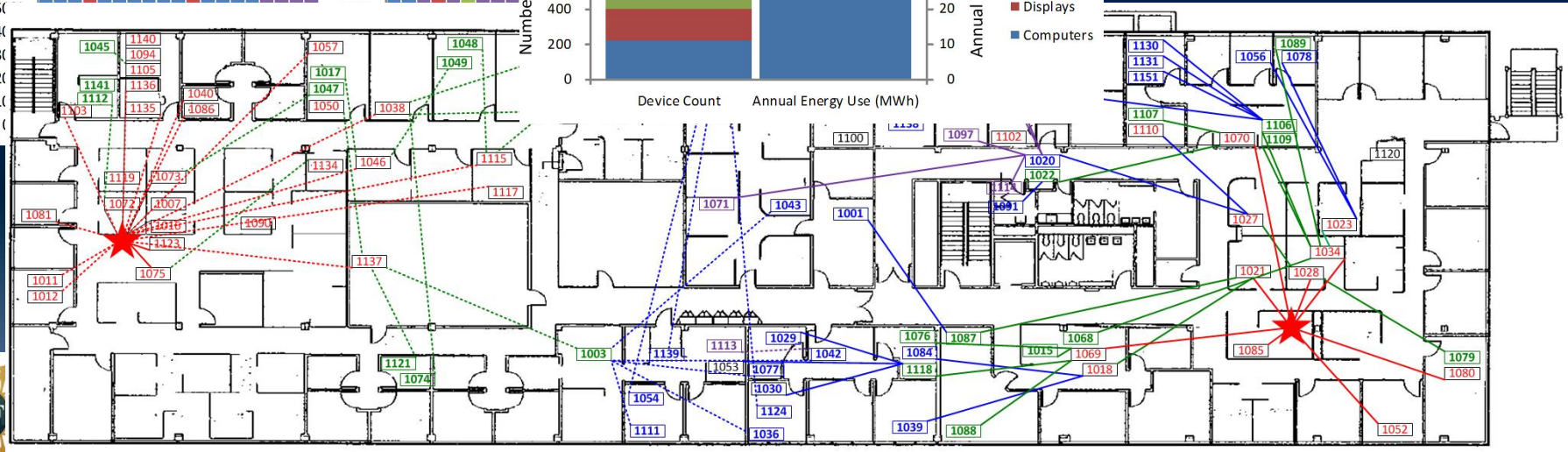


DOE MELS => Appliance Energy

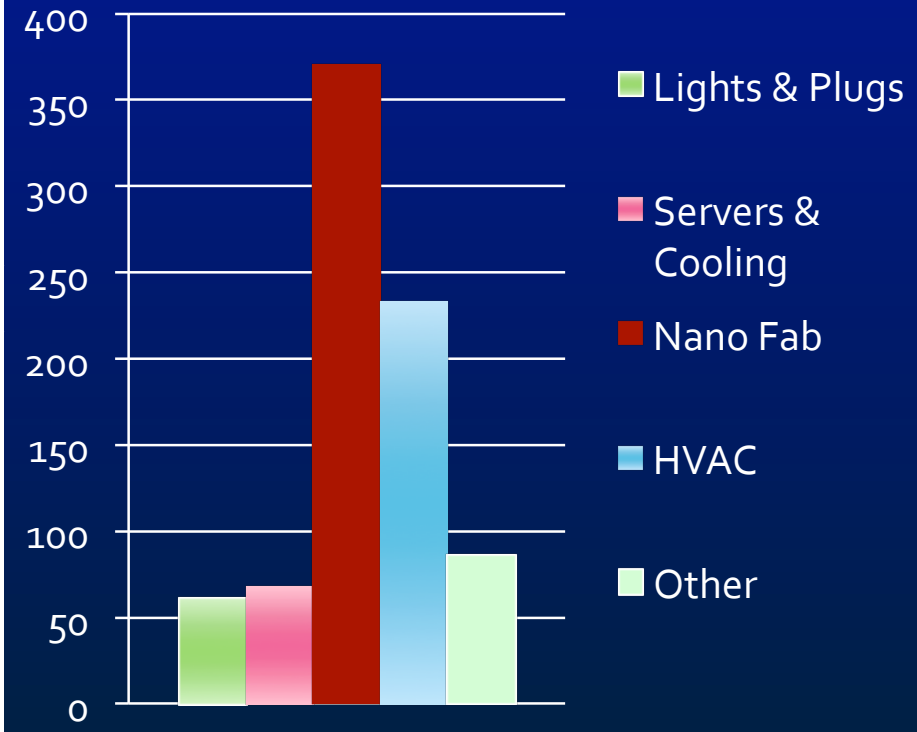




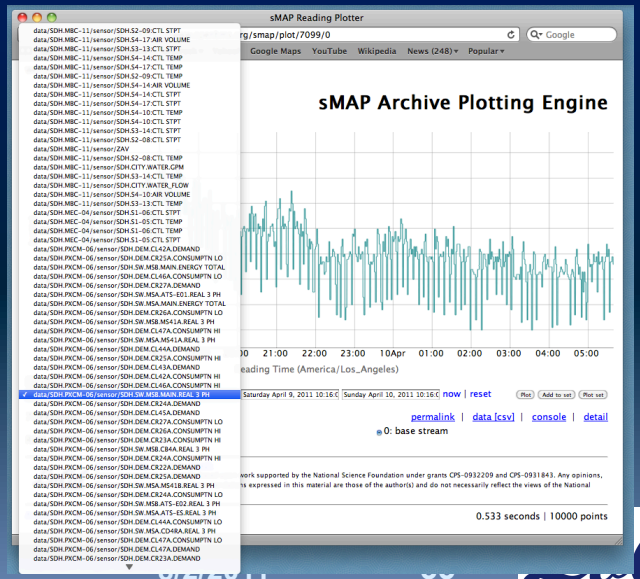




DOE/UCB/Siemens Auto Demand Response



Sutardja Dai Hall



www.openbms.org

BACNet => sMAP

Sensors, Actuators

Controllers

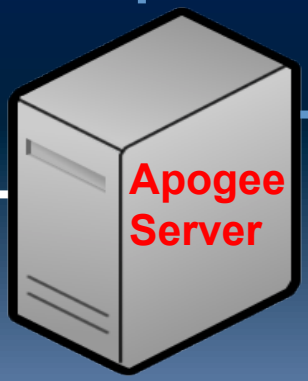
Siemens P2 over RS-485

Internet

Remote Login

sMAP

Modem



Apogee Server

BACnet/IP

Gateway

Data from 1 Modern Building

- 1358 control settings
  - Set points, Relays (lights, pumps, etc), Schedules
- 2291 meters/sensors
  - Power (building, floor, lights, chiller, pumps, etc)
    - Current, voltage, apparent, real, reactive, peak
  - Temp (rooms, chilled water, hot water)
  - Air volume
  - Alarms, Errors
- 2165 control outputs
  - Dampers, valves, min/max flow, fan speed, PID parameters
- 72 other

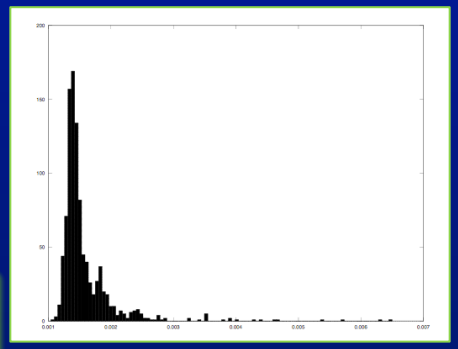
4+ million Commercial, 110+ million Residential

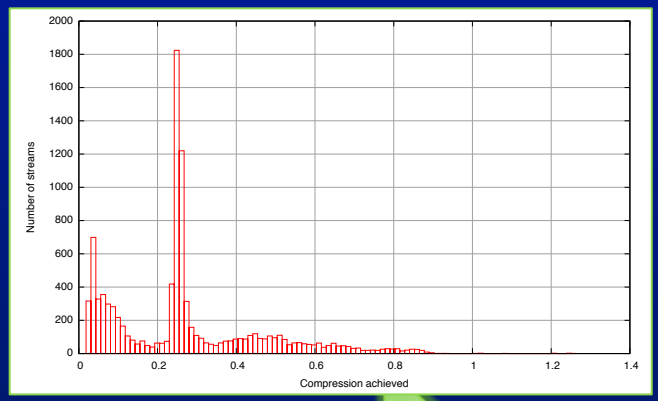
Current sMAP demography

Name	Sensor Type	Physical Layer	Sense Points	Channels
Cory Hall Submetering	Dent Three-Phase	Modbus + Ethernet	79	3318
Cory Hall Metering	ION and pQube Meters	HTTP/Ethernet	3	150
Cory Lab Temperature	TelosB	802.15.4 + Ethernet	4	8
Cory Lab Machines	ACme	804.15.4 + Ethernet	8	16
Cory Chilled Water	HeatX	Modbus + Ethernet	1	11
Cory Weather	Vaisala WXT520	SDI-12 + Ethernet	1	11
Soda Hall Sun Blackbox	Fan speed; environmental	Http/Ethernet	10	84
Soda Lab Machines	ACme	802.15.4 + Ethernet	40	80
Soda Lab Panel	Veris E30	Modbus + Ethernet	1	42
Soda SCADA Data	Barrington controls	RS-485/various	"1"	1670
LBNL Building 90	Acme	802.15.4 + Ethernet	550	1650
Campus Power Data	Obvius Aquisuite; various	XML/HTTP/Ethernet	4	100
Citris SDH BACnet	Siemens Apogee	BACnet/IP + RS-485	"1"	600+
Brower Buildinbg	Johnsons Control	BACnet	"1"	1500

A Stream Engine

insert





~300k pts/sec

resample
aggregate

query

streaming pipeline

Time-series Interface

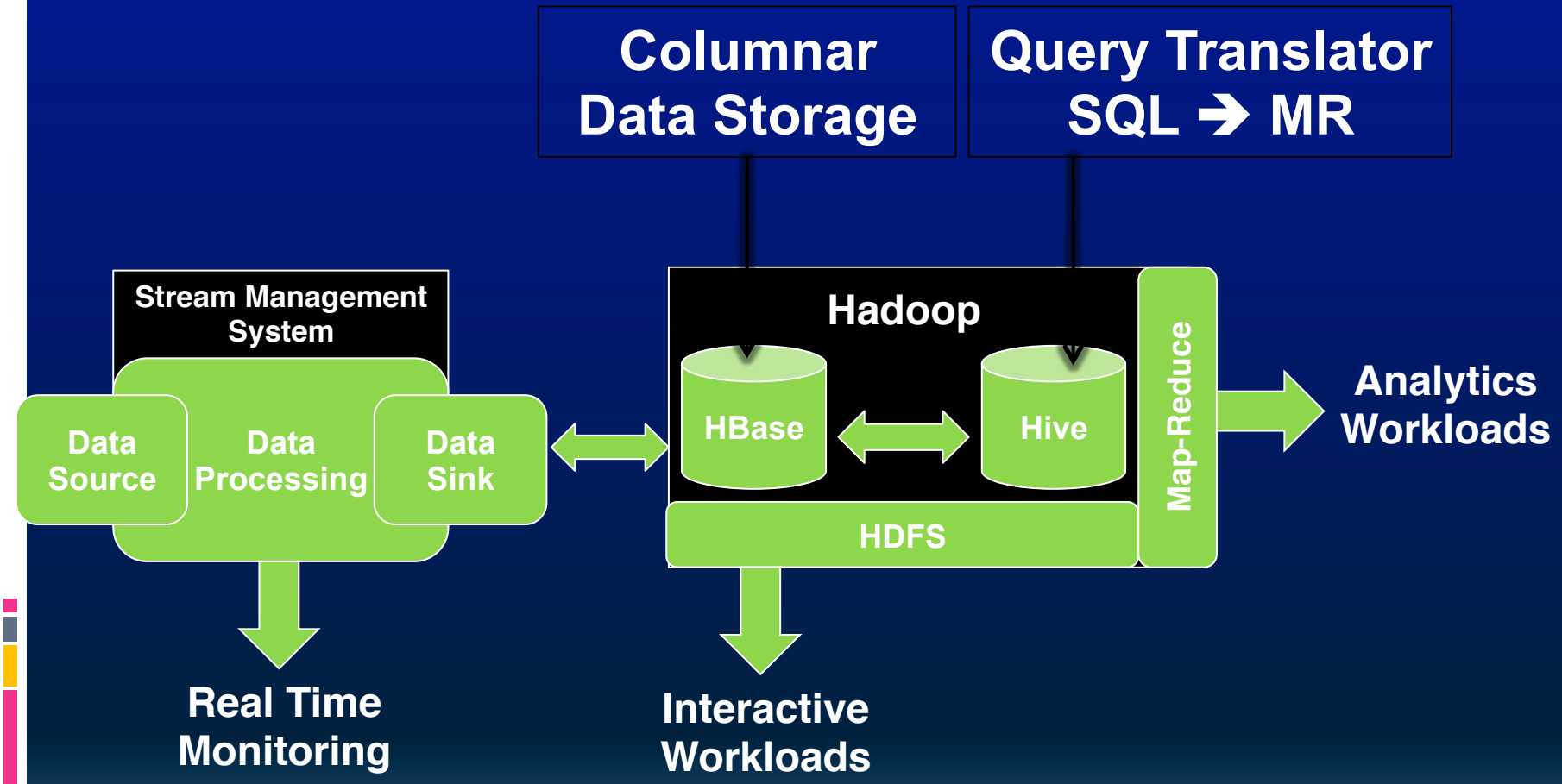
Bucketing | RPC | Compression | Storage mapper

Key-Value Store | SQL

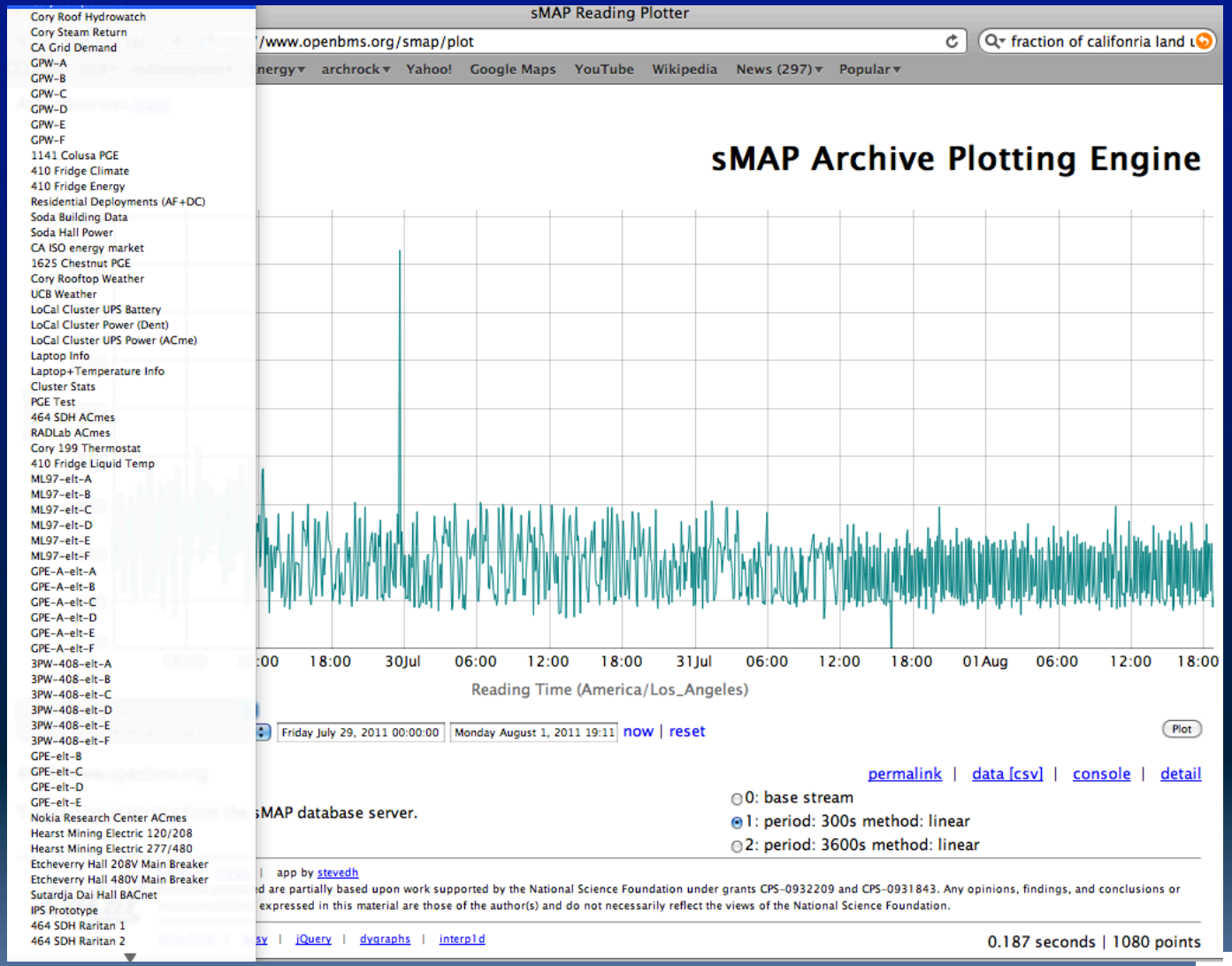
Page Cache | Lock Manager | Storage Alloc. | MySQL

readingdb

Scaling Out in the Cloud



15,000 pts and growing…



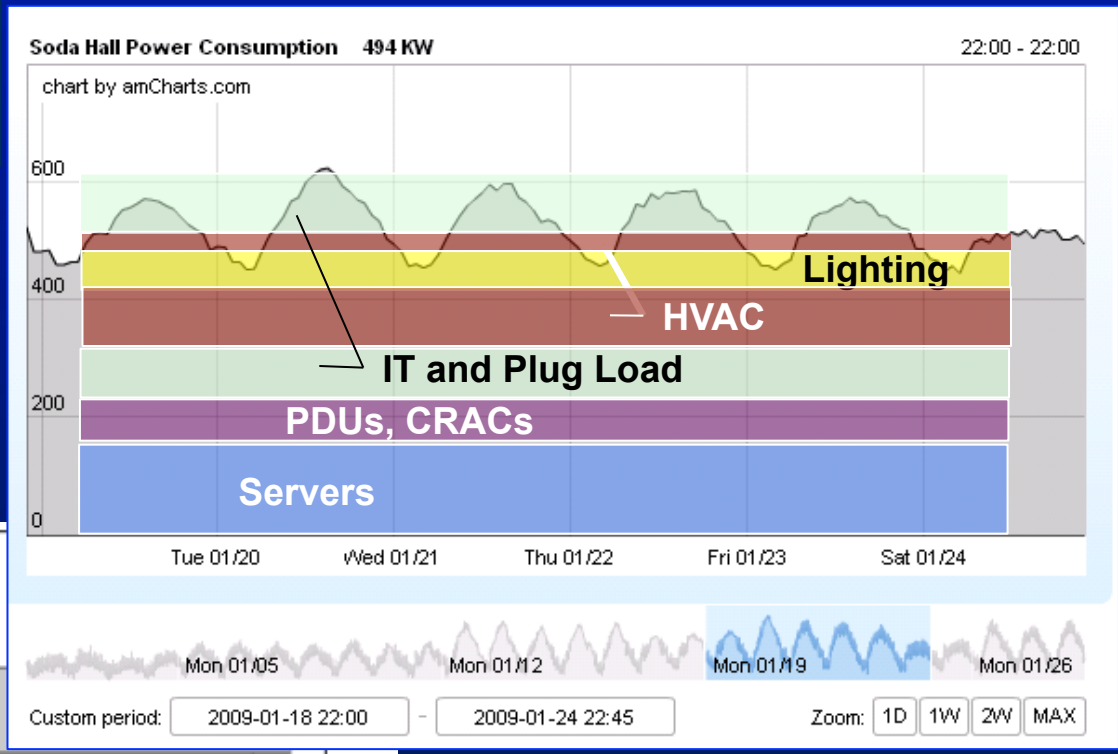
CPS Technology

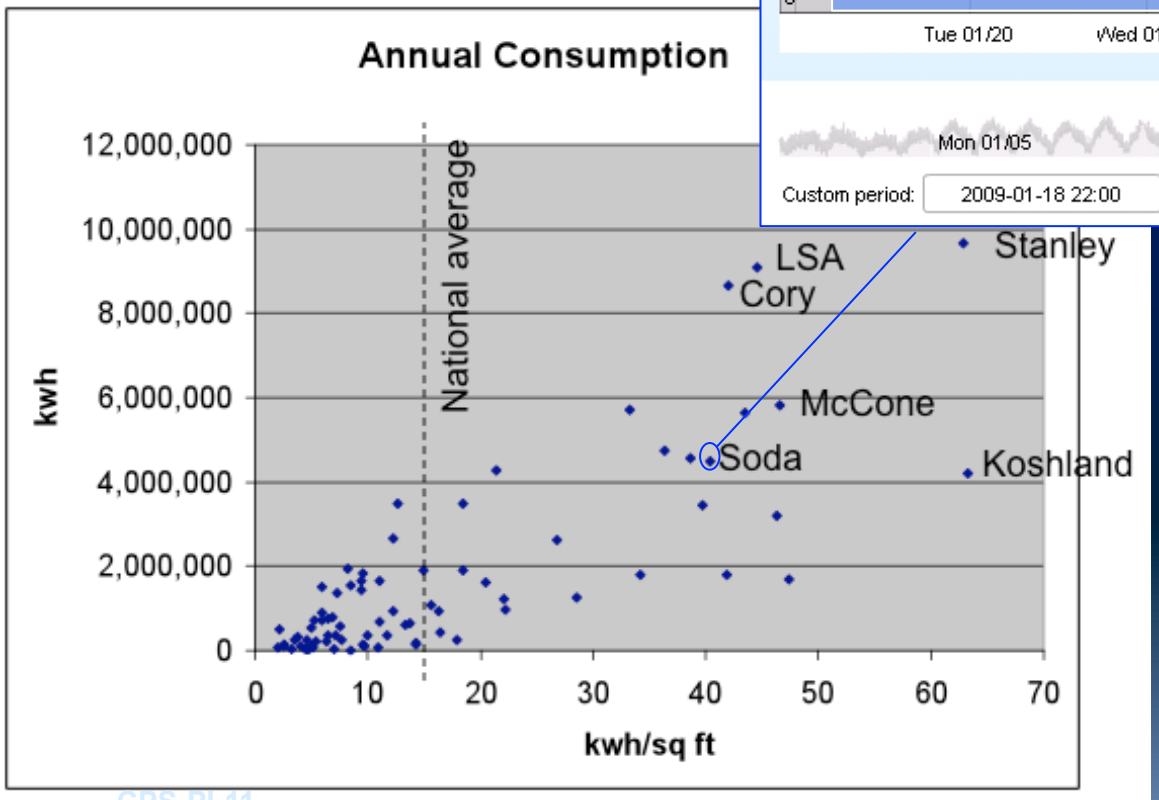
- National-Scale Physical Info Service
- Software foundations, platforms and solutions for Energy Efficiency and Agility

Stages of Energy Effectiveness

- Waste Not
  - Do Nothing Well !!!
- Power Proportionality
  - Peak Performance : Power => Safety
  - Optimize Partial Load - from nothing to peakl
- *Sculpting*
  - *Identify the energy slack and utilize it*
- *Negotiated Grid / Load / Human Interaction*
  - *Plan, Forecast, Negotiate, Manage*

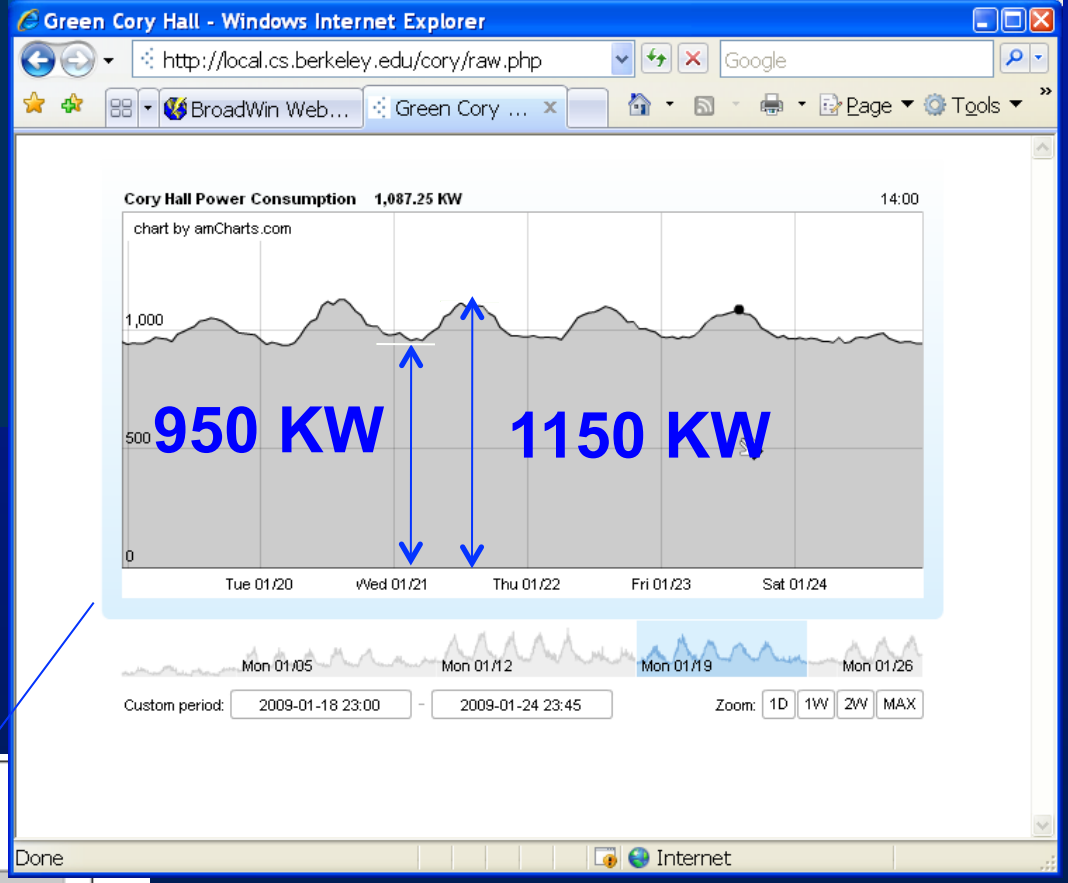
Our Buildings

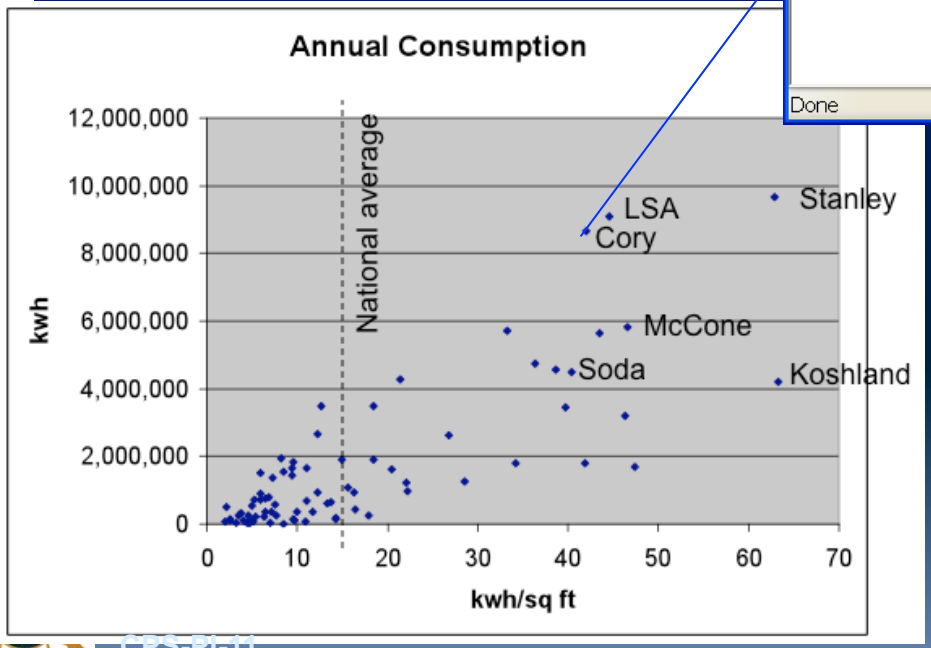




Power-Proportional Buildings ?

Cory Hall: Office + Semiconductor + IT

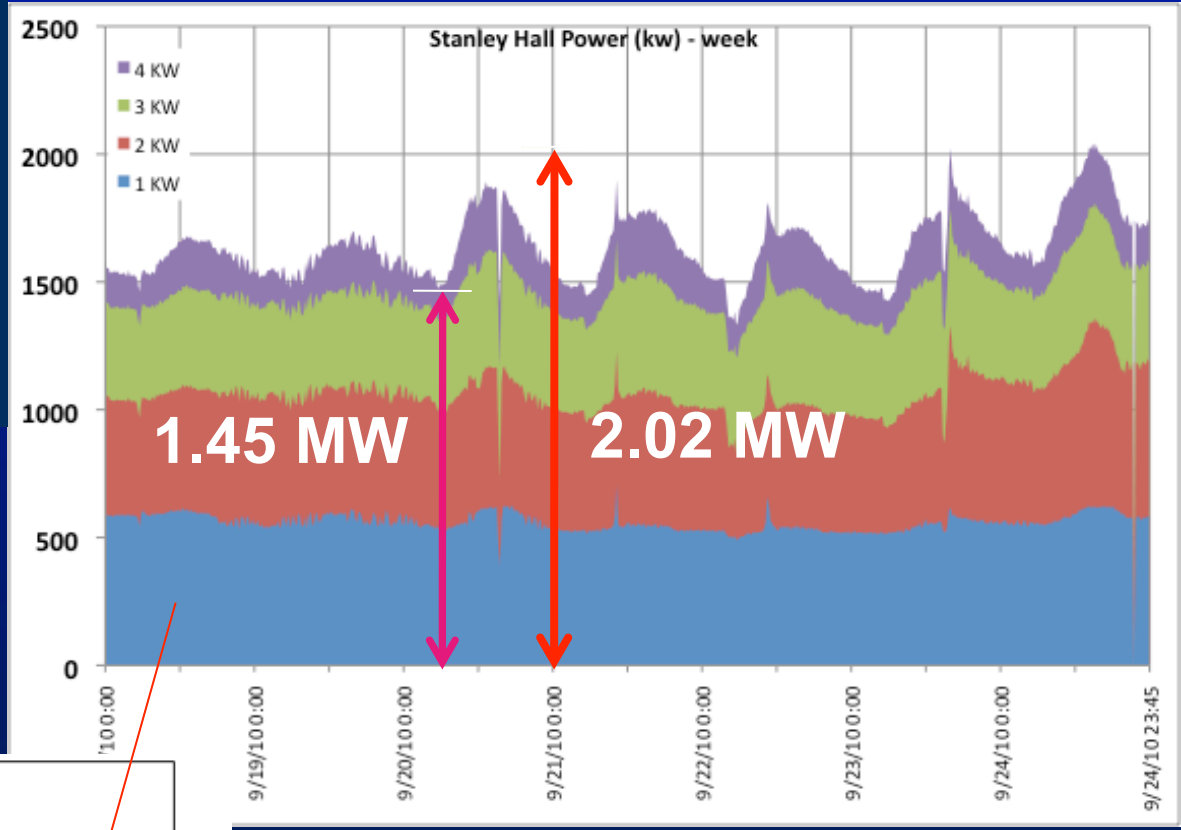


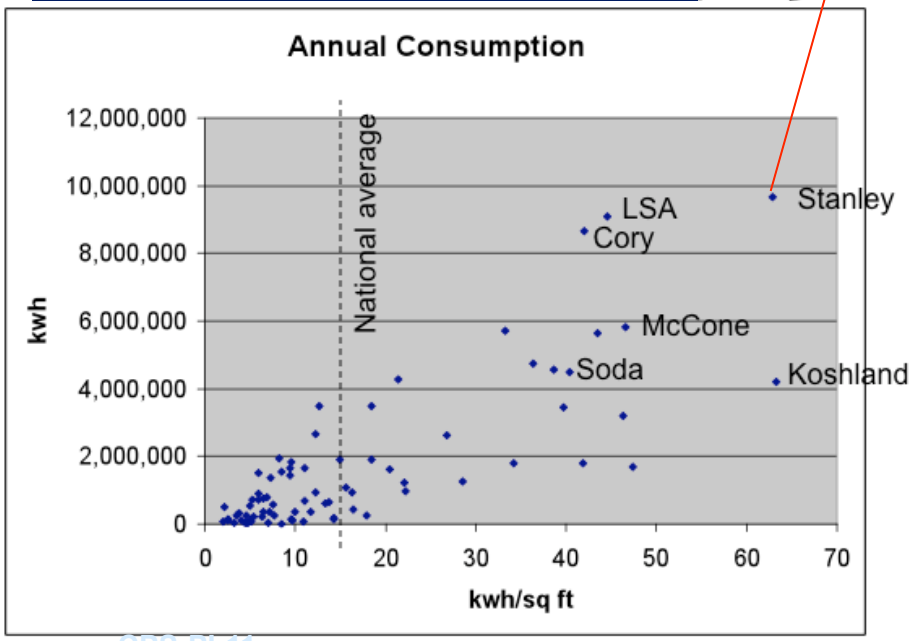


Min = 82% of Max

Power-Proportional Buildings ?

Stanley Hall:
Office + BioScience
- 13 NMRs

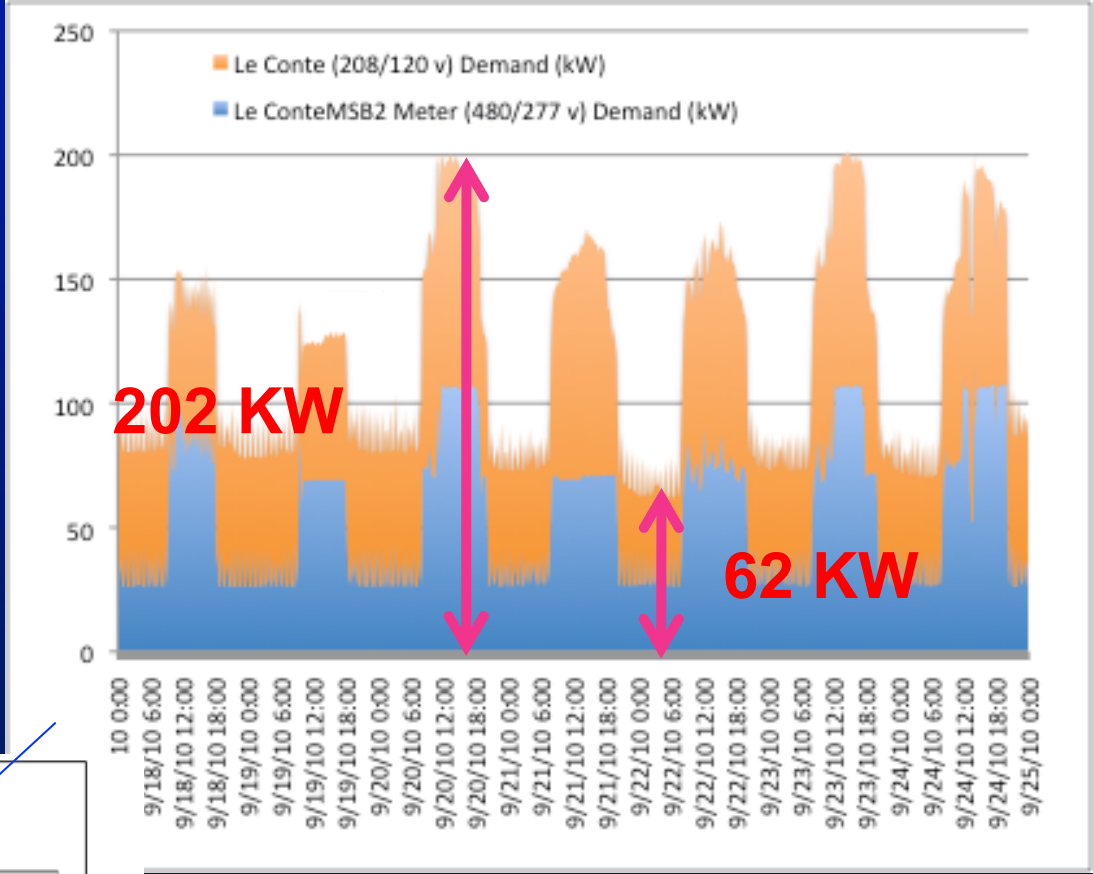


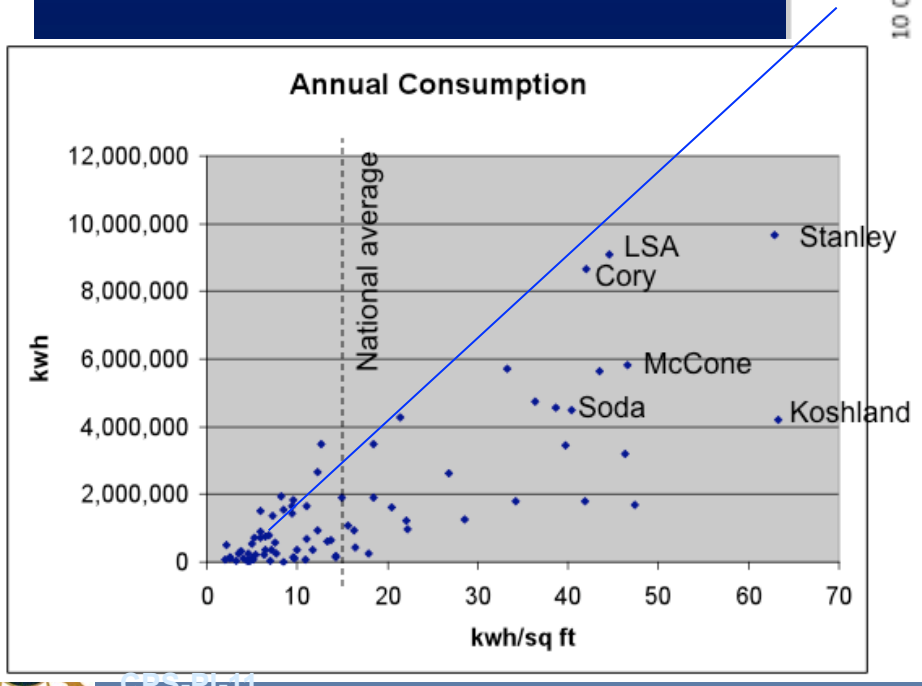


Min = 72% of Max

Power-Proportional Buildings ?

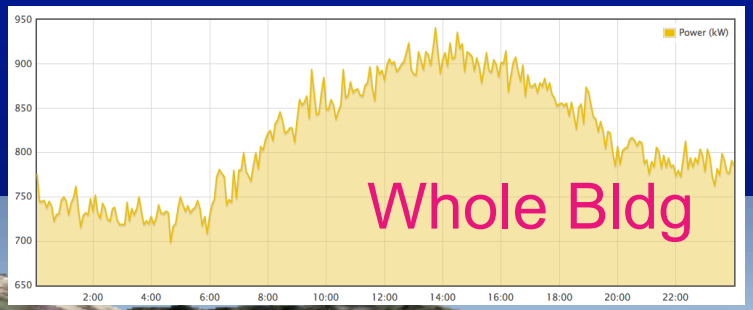
LeConte Hall: Office

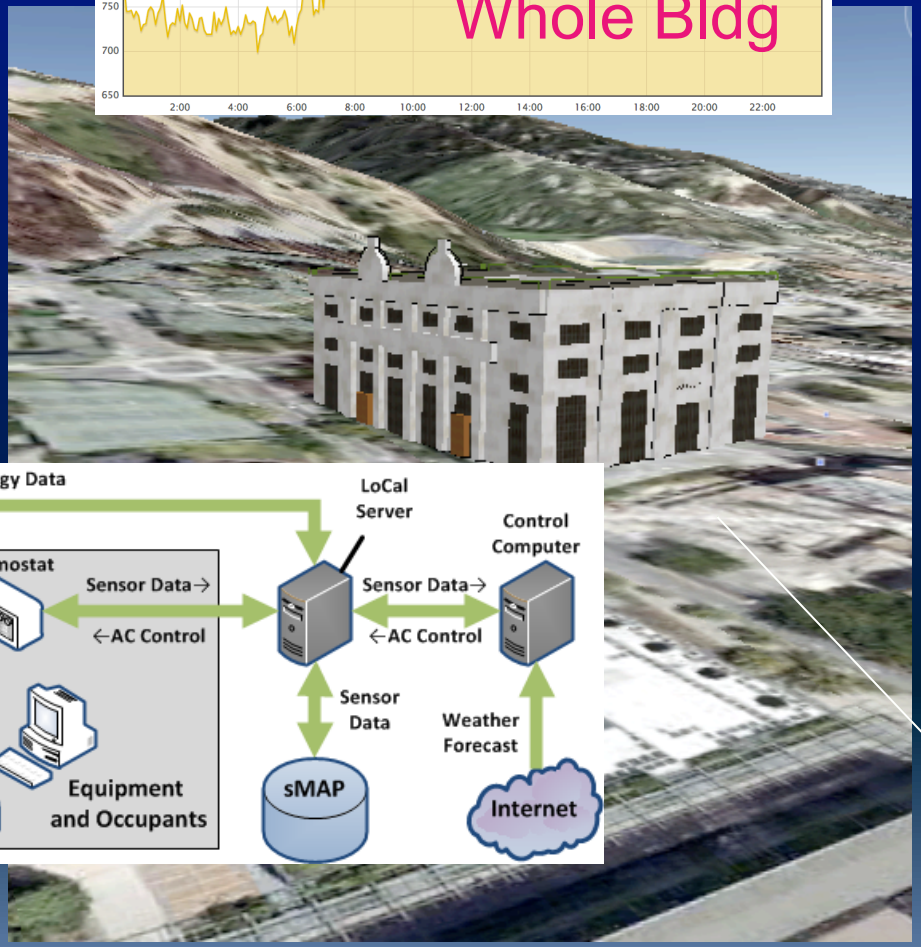




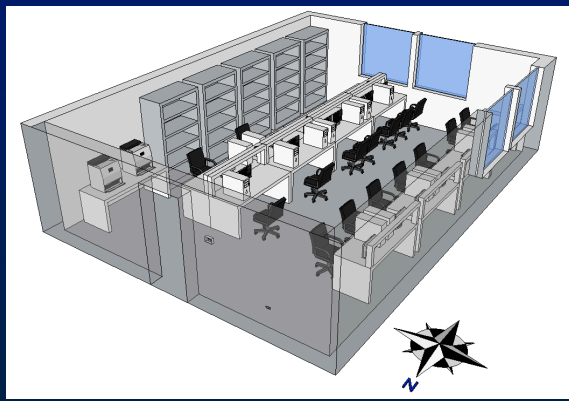
Min = 31% of Max

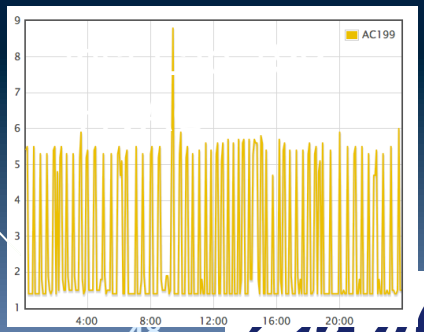
Re-Flash the HVAC …





LoCal + ActionWebs





Learning-based Model Predictive Control

- Mathematical model from Newton's law of cooling

time constant of room

weather

heating from occupants and equipment

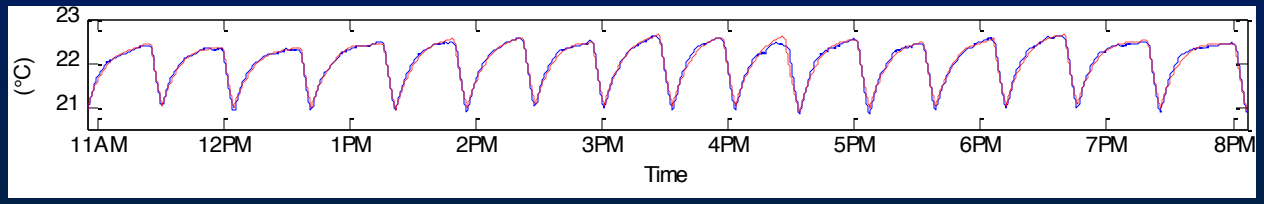
$$dT/dt = -k_r T - k_c u(t) + k_w w(t)) + q(t)$$

change in temperature over time

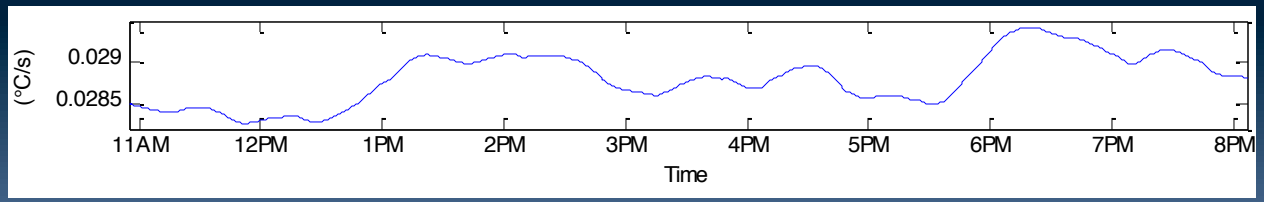
AC cooling

- Model identified using semi-parametric regression

Temperature:
Experimental (blue)
Simulated (red)



Heating from occupants and equipment



(Aswani, Master, Taneja, Culler, Tomlin, Proc. of IEEE, 2011)

Living Lab…

- LBMPC saved
  - 30% energy when hotter outside
  - 70% energy when cooler outside
- Standard MPC was inconsistent
- Two-position control was inefficient

	Method	Measured Energy	Estimated Energy	Tracking Error	Temperature Variation	Average External Load
Two-Position Control Experiment	LBMPC		23.6kWh	0.75°C	0.13°C	11.0°C
	Linear MPC		30.5kWh	0.62°C	0.30°C	11.0°C
	Two-Position	32.6kWh	35.1kWh	0.61°C	0.20°C	11.0 °C
LBMPC Experiment	LBMPC	11.8kWh	13.3kWh	0.86°C	0.17°C	7.2°C
	Linear MPC		8.6kWh	0.93°C	0.21°C	7.2°C
	Two-Position		34.5kWh	0.55°C	0.19°C	7.2°C

LBMPC to Minimize Energy…

- Estimates heating load using model

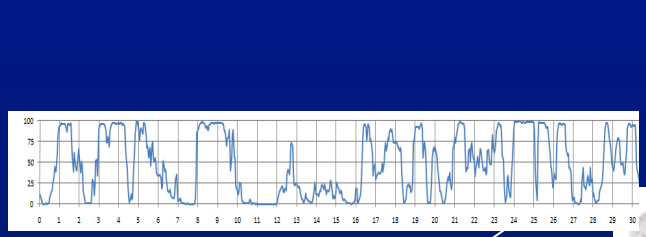
$$\hat{q}[m+i] = T[m] - \left(0.64 \cdot T[m-1] - 2.64 \cdot u[m-1] + 0.10 \cdot w[m-1]\right)$$

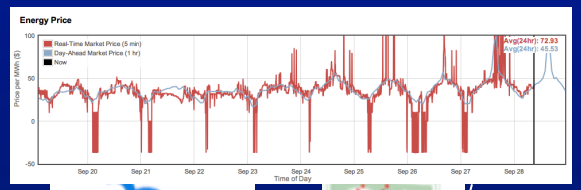
- Best control that considers estimated occupancy

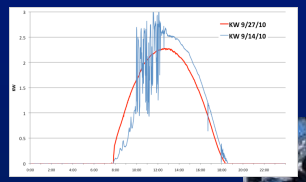
$$\begin{aligned}
\min_{u[\cdot]} \; & \textstyle\sum_{k=0}^{N} p \cdot (\tilde{T}[m+k] - T_d)^2 + \\
& + \textstyle\sum_{k=0}^{N=1} (r+\lambda) \cdot u[m+k] \qquad \textbf{Cost} \\
\text{s.t. } & \tilde{T}[m+i] = 0.64 \cdot \tilde{T}[m+i-1] - 2.64 \cdot u[m+i-1] \\
& \quad + 0.10 \cdot w[m+i-1] + \hat{q}[m+i-1] \\
& \overline{T}[m+i] = 0.64 \cdot \overline{T}[m+i-1] - 2.64 \cdot u[m+i-1] \\
& \quad + 0.10 \cdot w[m+i-1] + 6.98 \\
& \overline{T}[m+i] \in [20, 24] \qquad \textbf{Temperature Constraints} \\
& u[m+i-1] \in [0, 0.5] \qquad \textbf{AC Constraints}
\end{aligned}$$

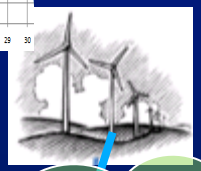
Temperature Dynamics

… or optimize to follow the supply







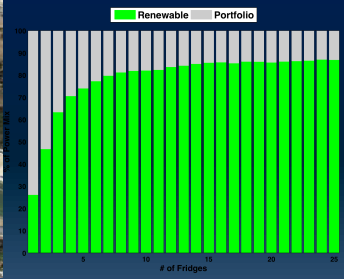


Generation

Transmission

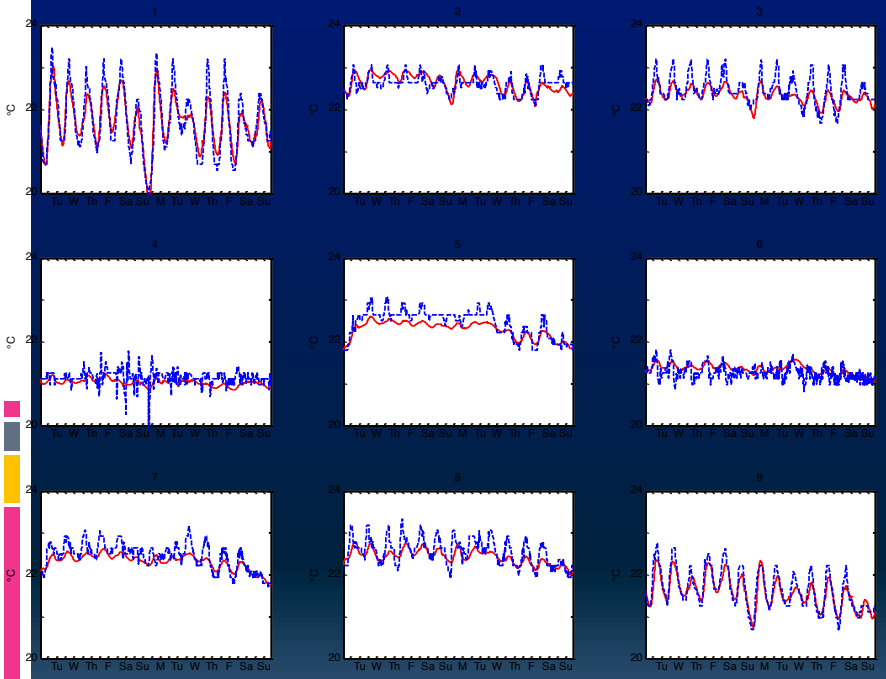
Distribution

Load

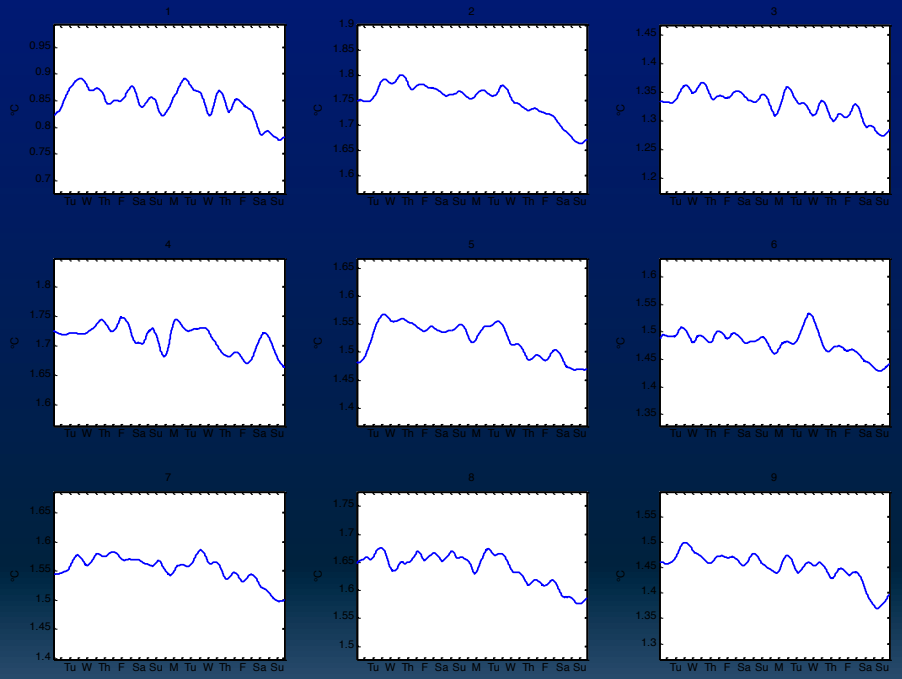


at Building-Scale, and beyond

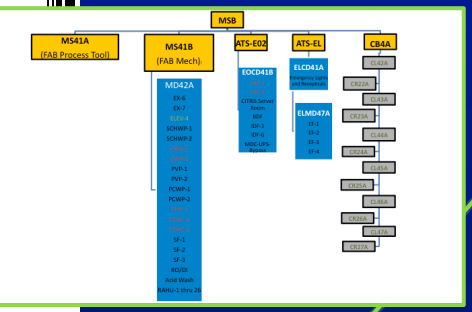
Temperature
Blue – Measured; Red - Simulated

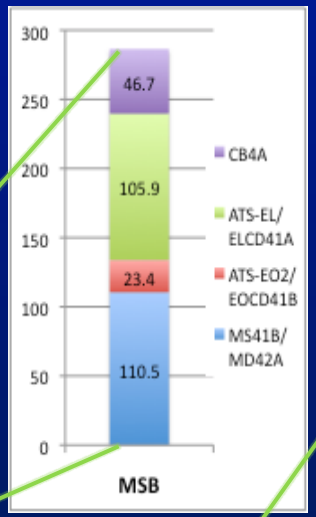


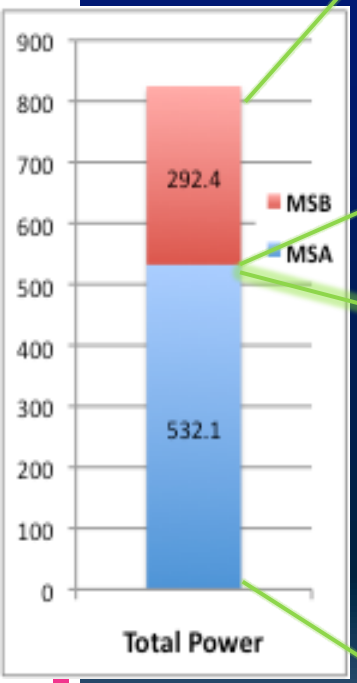
Heating from occupants, equipment, etc.

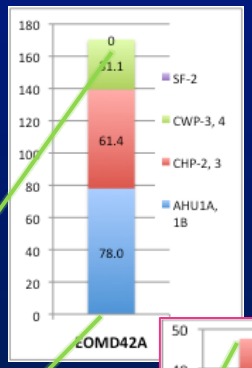


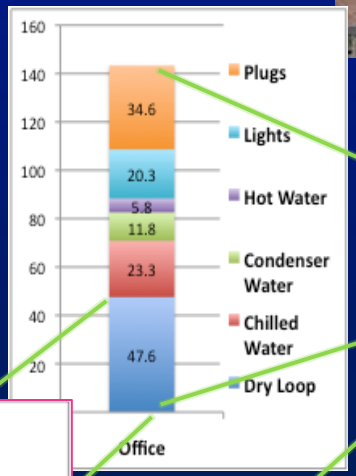
Making Sense out of Sensors

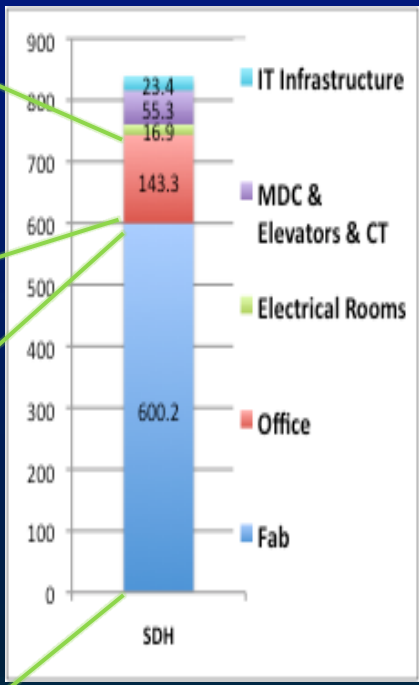


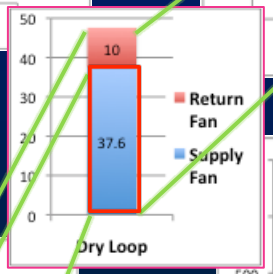


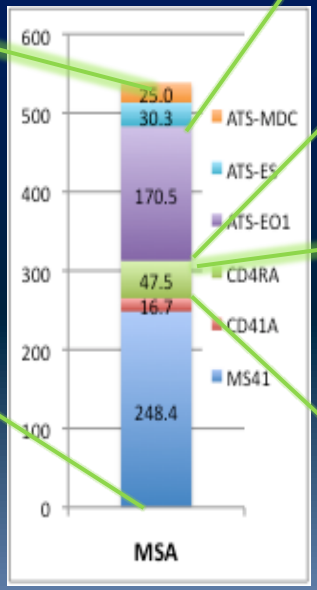


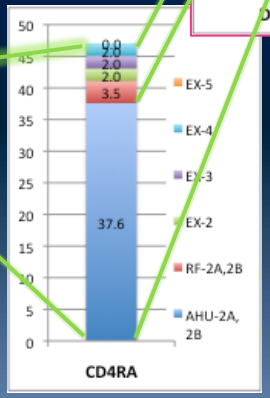


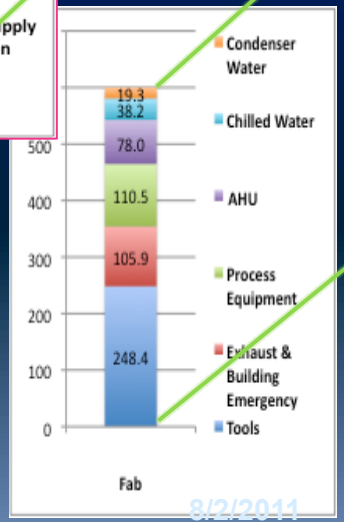




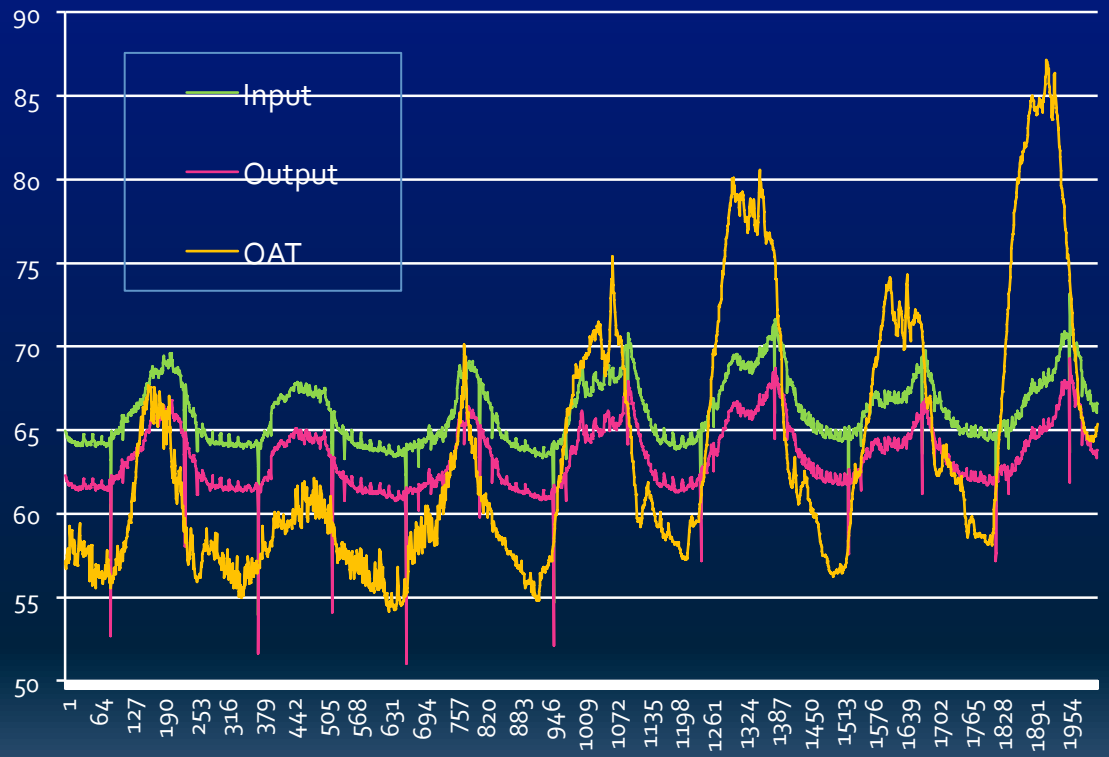




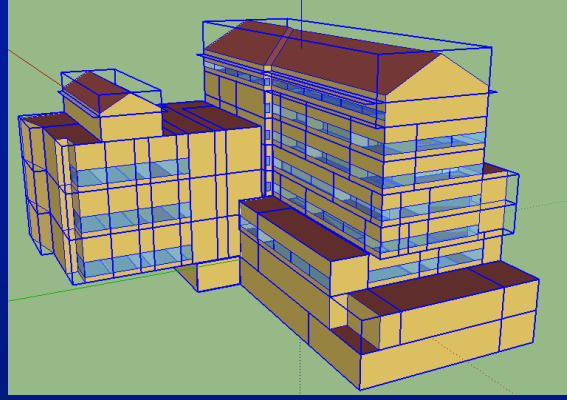




Supply Air Fan VFD



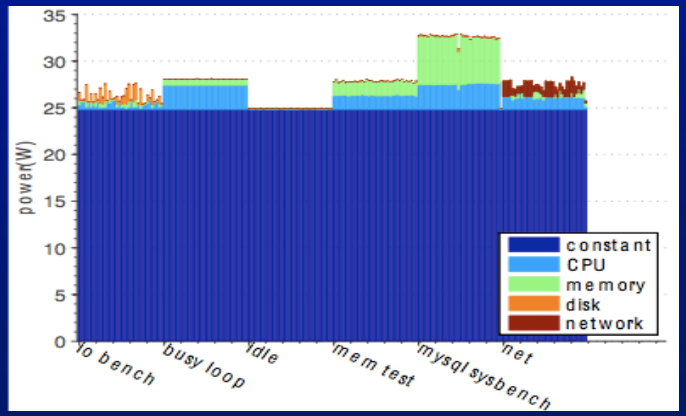
What's really going on?



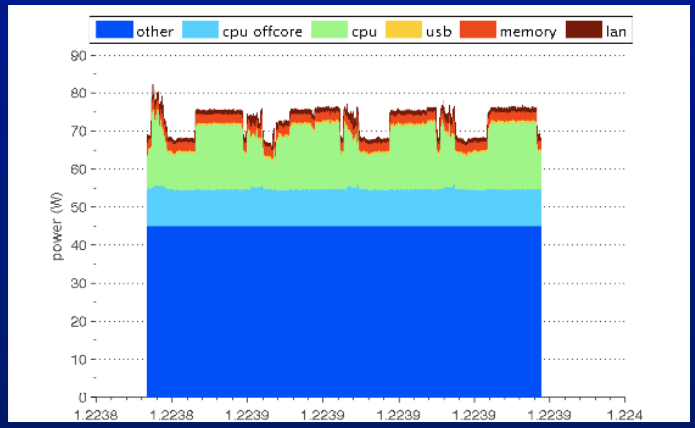
- Bring comfortable air from outside
- Cool it down till its really cold
- Push it out everywhere thru VAVs that are at minimum opening
- Reheat it to set point
- So the empty rooms will be comfortable

- This is going on everywhere!
- And we supply perfect, precious energy to do it!

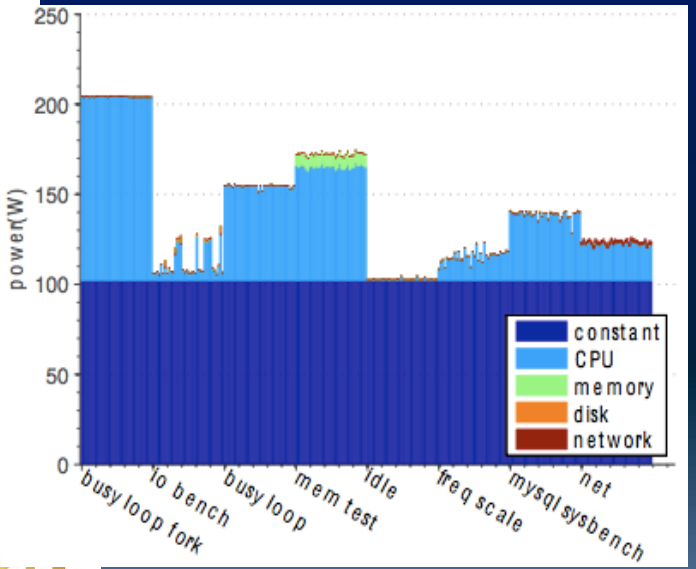
And IT is no better …



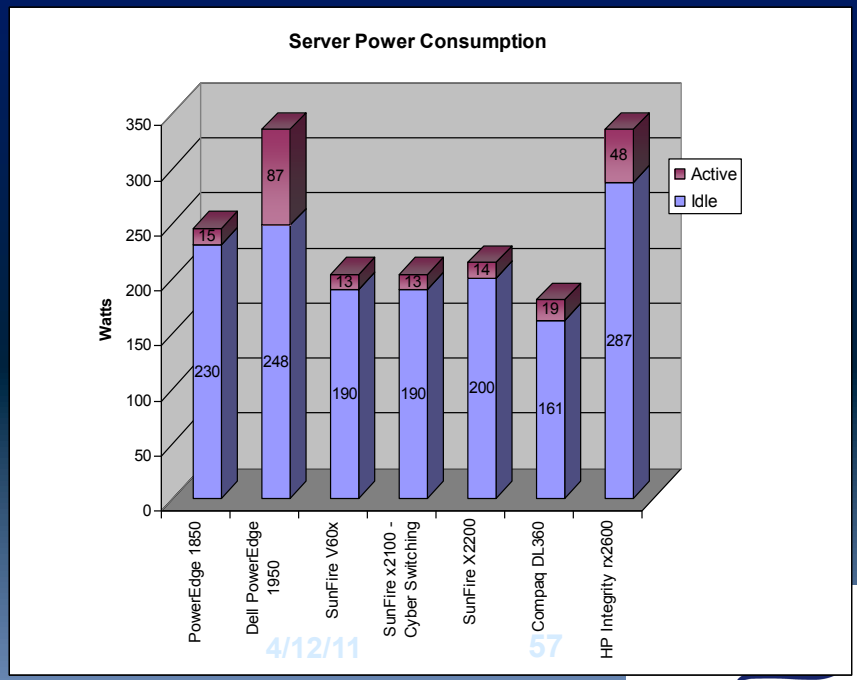
Atom 333



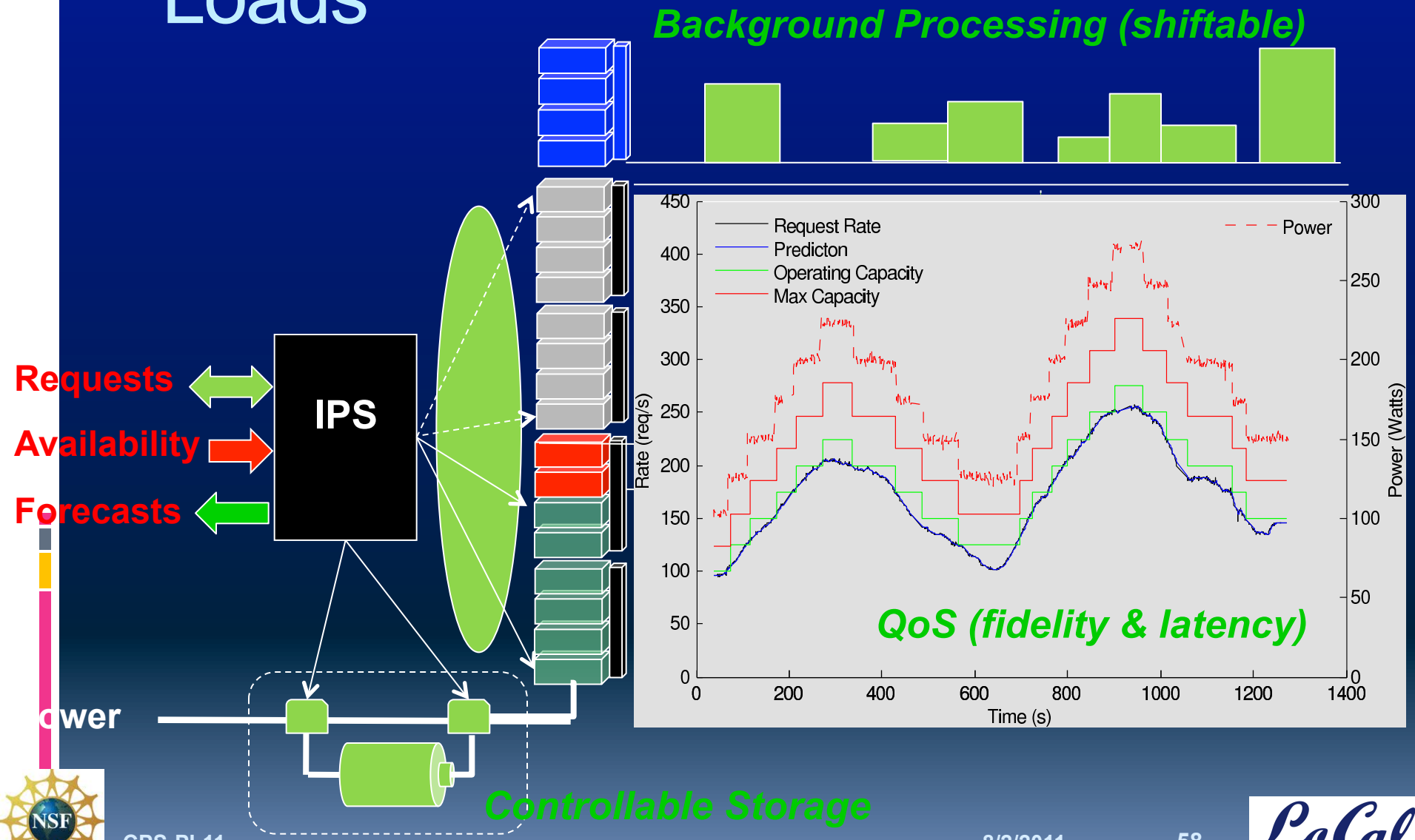
Westmere



Core i7

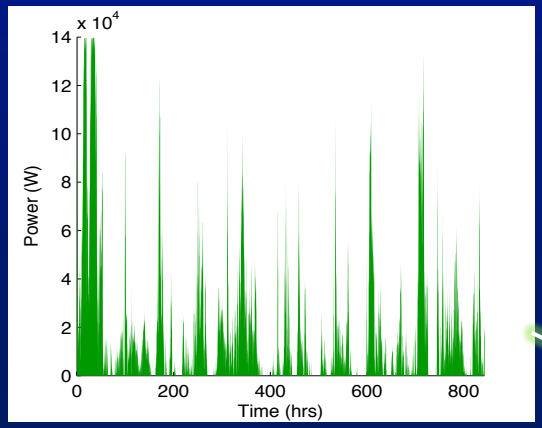


Supply-Following Computational Loads

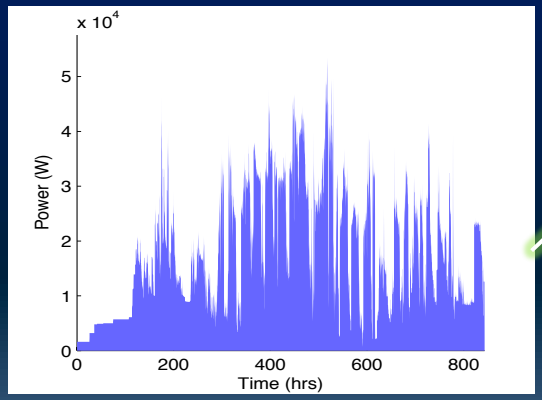


Energy-Availability Driven Scheduling

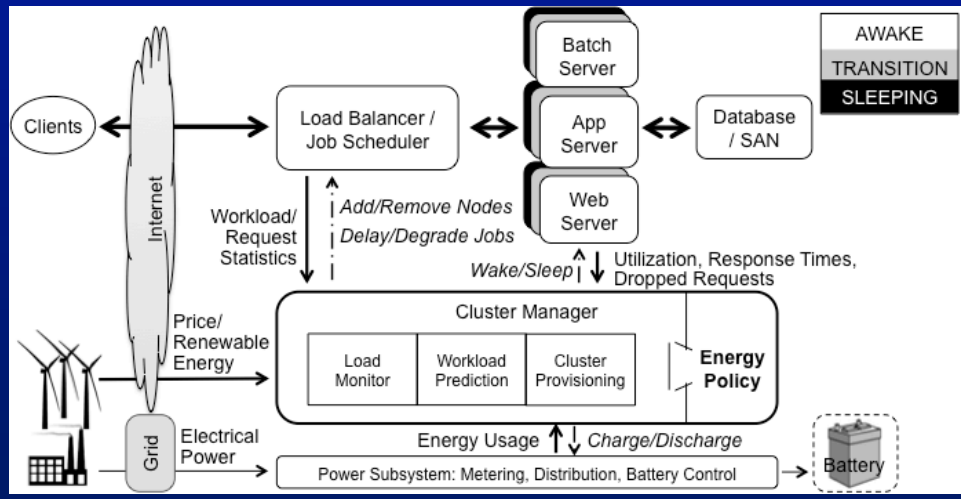
Non-dispatchable, variable supply



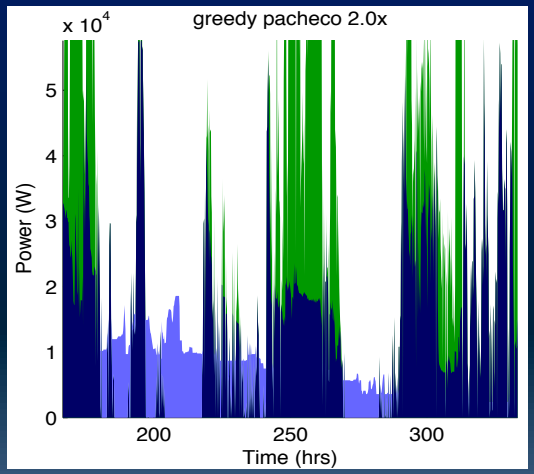
Pacheco wind farm



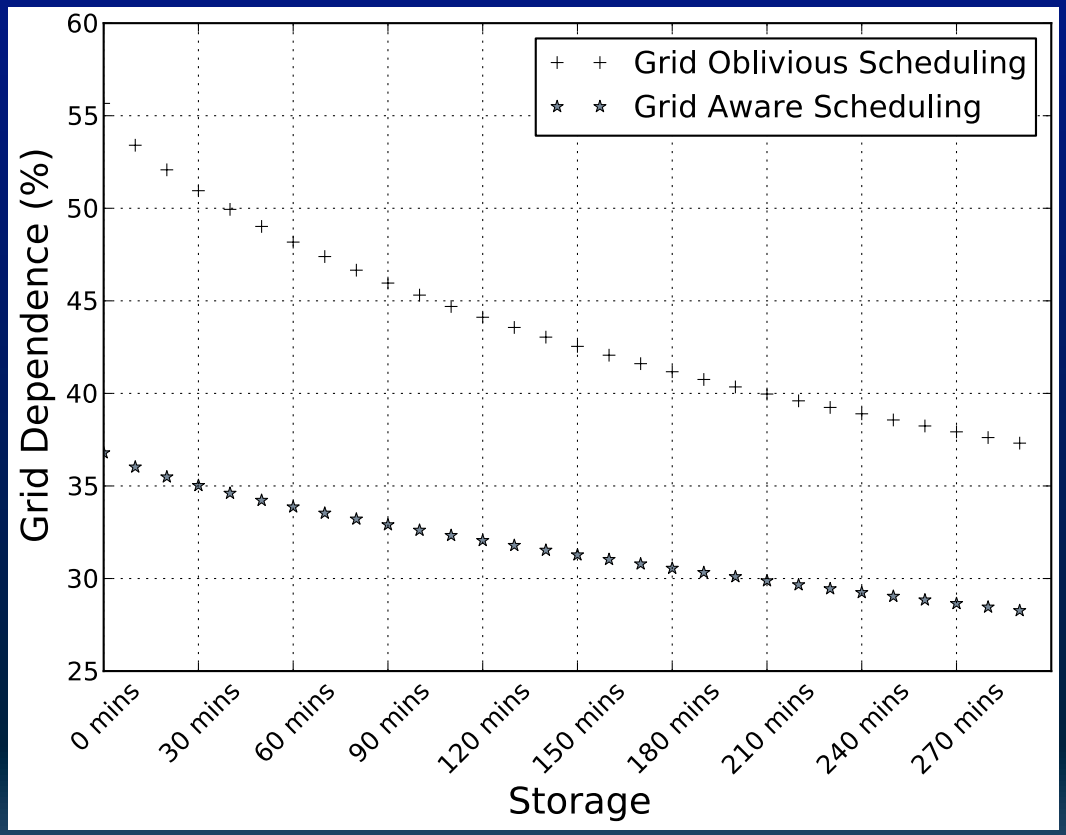
Scientific computing cluster



Power proportional, grid-aware loads



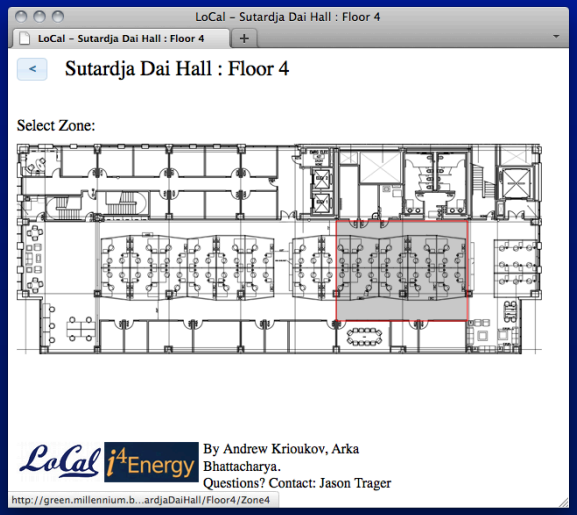
Scheduling & Energy Storage

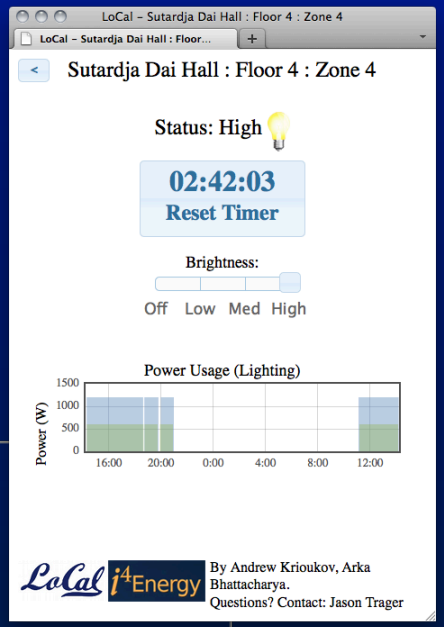


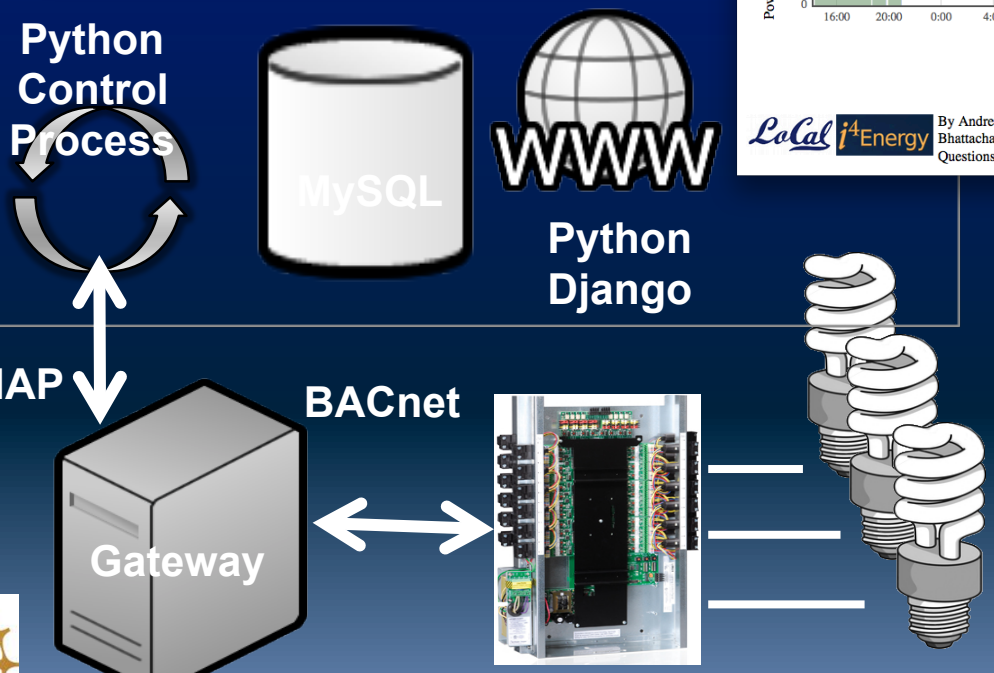
CPS Technology

- National Physical Info Service
- Software foundations for Energy Efficiency and Agility
- Infrastructure for Energy Innovation

Personalized Automated Lighting Control

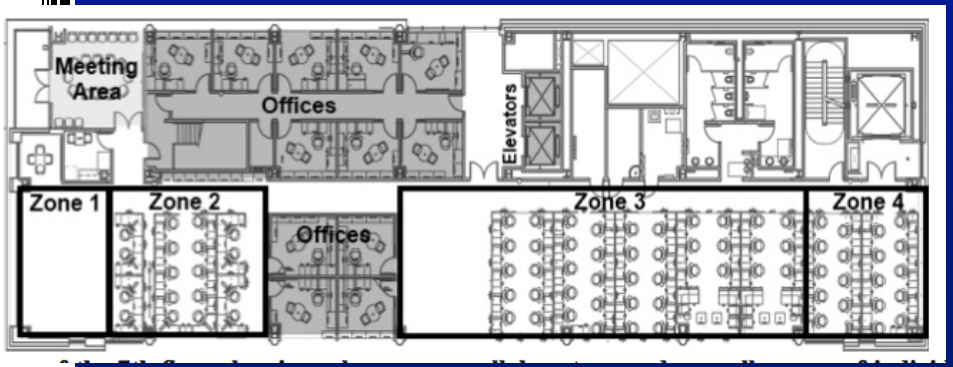


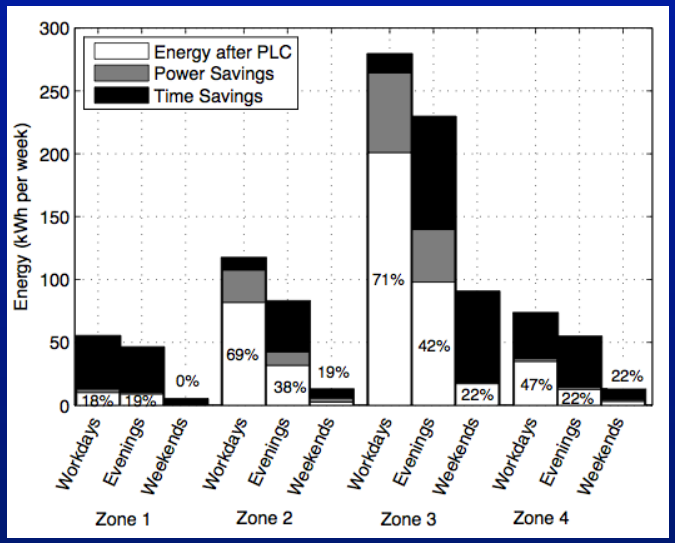


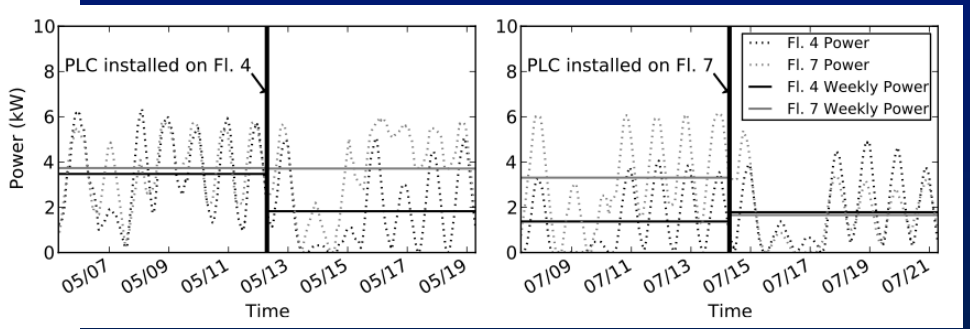


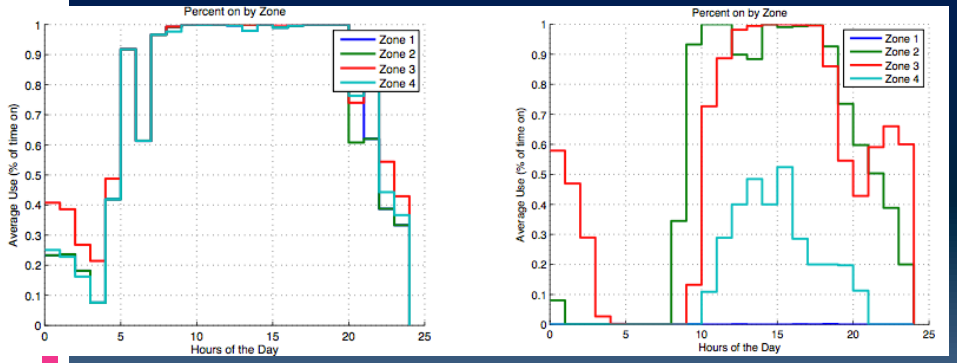
- Three controllable ballasts per fixture
- ~5 zones per floor

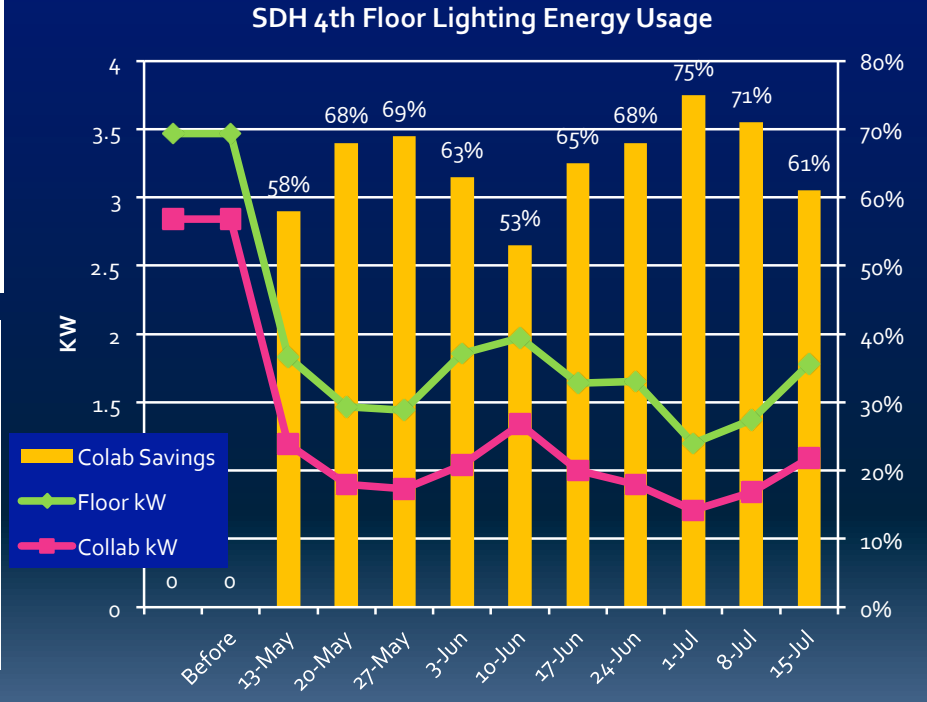
Real Energy Savings











From the agony of load-following …

Are we going to have base load power?

- If yes, then:
  - Do we want to deal with the issues of nuclear power

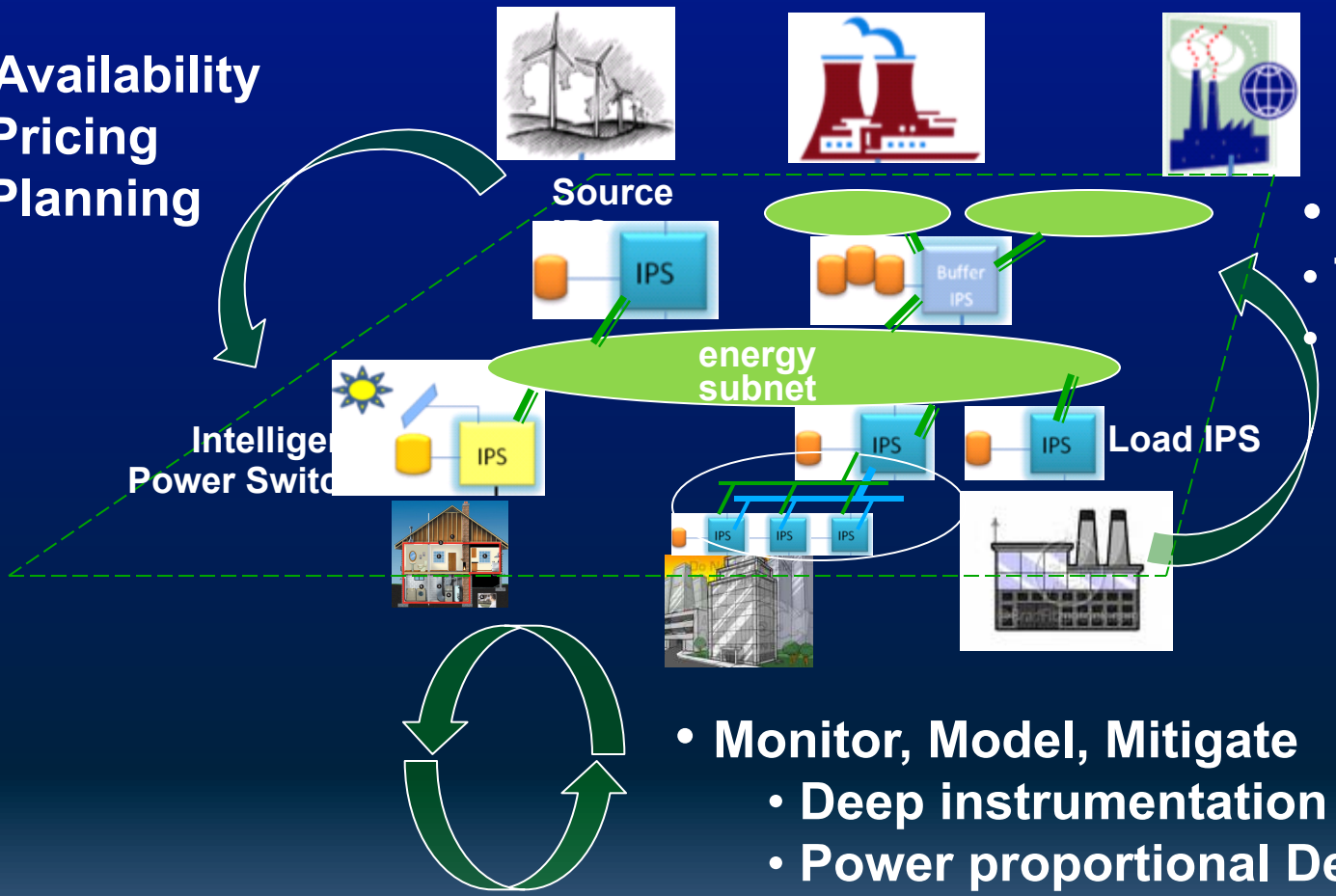
  or
  - Can we do CCS /fossil for baseload?
- If no, then
  - Accept the emissions associated with load balancing with natural gas?
  - Commit to completely restructure the electric utility?)
  - Will there be a major breakthrough in energy storage technology to handle GW-days of demand?
  - Should we decide to give up on electricity reliability?

CHAIR'S LECTURE: CALIFORNIA ENERGY FUTURES STUDY RESULTS
July 15, 2011

Jane C. S. Long

to Co-operative Energy Mgmt in a Cyber-Physical Grid

- Availability
- Pricing
- Planning



- Forecasting
- Tracking
- Market

- Monitor, Model, Mitigate
  - Deep instrumentation
  - Power proportional Design
  - Energy-Agile Control
- Shifting, Scheduling, Adaptation

Thanks