Sustainable Energy Networks
- a Sensys grand opportunity

David E. Culler
University of California, Berkeley

Sensys 2012 Keynote
11-7-2012
Sustainability?

“Sustainable development should meet the needs of the present without compromising the ability of future generations to meet their own needs”

My Goal today

- Suggest ways SenSys community is and can be more engaged in achieving sustainable energy networks
Quantifying Sustainability…

**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: 37 => 55 million
  - Economic growth
CA2050: GHG 90% below 1990

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
CA2050 4 Part GHG Reduction Plan

- Efficiency
CA2050 4 Part GHG Reduction Plan

- Efficiency
- Electrify
CA2050 4 Part GHG Reduction Plan

- Efficiency
- Electrify
- Decarbonize the electricity
- Decarbonize the fuel
CA2050 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%
Scenarios

New Nuclear plant every 14 months for 40 years

New CCS facility every 9 mo. Exceeds saline aquifer

Resources exist
- 1.4% of CA land
- 43% agriculture
- 3.4% urban
The Problem: Supply-Demand Match

Baseline + Dispatchable Tiers  
Oblivious Loads

Generation  ->  Transmission  ->  Distribution  ->  Demand

Baseline + Dispatchable Tiers

Oblivious Loads

Transmission

Distribution

Demand

11/7/2012
An Engineering Marvel

- NA: 3 synch’d regions
- Lots of wires
  - 170k miles of >200 kv transmission
  - 6m miles of distribution
  - 3k miles of 500 kv DC
- 3,200 retail distributors
- 147 M customers
  - 125M res, 17.6 M com, 0.78 M ind.
- 10 ISO/RTO cover 2/3
- Little communication

http://www.nerc.com/docs/oc/rs/BA_BubbleDiagram_2011-10-03.jpg
Towards an ‘Aware’ Energy Network

Baseline + Dispatchable Tiers

Oblivious Loads

Non-Dispatchable Sources

Aware Interactive Loads

Communication

Transmission

Distribution

Generation

Demand
Classical view of the Energy Challenge

Markets

Imports

Supply

Transport

Load

Peaker
Single cycle nat. gas

Intermittent
Combined cycle nat. gas

Baseline
Geothermal
Hydro
Nuclear
Coal

Generators

Lines

Transmitters

Transformers

Meters

Distribution

Imports

Electronics
Appliance
Lighting
HVAC
Motors

Power Supplies
VFD
Control
Circuits

Efficiency
Modern Energy Network Challenges

**Information Plane**

- **Storage**
  - Pumped
  - Fluctuating
  - Renewable
  - Photovoltaic
- **Peaker**
  - Single cycle
  - nat. gas / bio
- **Intermittent**
  - Combined cycle
  - nat. gas / bio
- **Baseline**
  - Geothermal
  - Hydro
  - Nuclear
  - Nat.

**Physical Plane**

- **Supply**
  - Transformers
  - Lines
  - Meters
- **Transport**
  - VFD
  - Efficiency
  - Control
- **Load**
  - Power Supplies
  - Electronics
  - Appliance
  - Lighting
  - HVAC
  - Motors
  - Circuits
  - Usage
  - Schedule
- **Consumption**
  - Personal
  - Facilities
  - Industrial
  - Transportation

**Dates**

- 11/7/2012
- 16
Sensys? Creating the info plane
Smart Meters – the WSN Killer App?

Markets

Imports

Supply

Transport

Load

Peaker

Intermittent

Baseline

- Single cycle nat. gas
- Combined cycle nat. gas
- Geothermal
- Hydro
- Nuclear, Coal

Generators

Transmission

Distribuion

- Motors
- HVAC
- Lighting
- Appliance
- Power Supplies
- VFD
- Control
- Circuits
- Efficiency

- Electronics

Power Supplies

11/7/2012
Smart meter rollouts

Figure 2. Expected Smart Meter Deployments by State by 2015

- Open IPv6, ...
- Proprietary / Zigbee

Source: Institute for Electric Efficiency, Federal Energy Regulatory Commission

http://www.edisonfoundation.net/iee/Documents/IEE_SmartMeterRollouts_0512.pdf
Much more than meters and billing

http://www.openthegrid.com/docs/ipv6_in_smart_grid_field_area.pdf
Key WSN Research Developments

- **Event-Driven Component-Base Operating System**
  - Framework for building System & Network abstractions
  - Low-Power Protocols
  - Hardware and Application Specific

- **Idle listening**
  - All the energy is consumed by listening for a packet to receive
  - => Turn radio on only when there is something to hear

- **Reliable routing on Low-Power & Lossy Links**
  - Power, Range, Obstructions => multi-hop
  - Always at edge of SNR => loss is common
  - => monitoring, retransmission, and local rerouting

- **Trickle – don’t flood** (tx rate < 1/density, and < info change)
  - Connectivity is determined by physical points of interest, not network designer.
  - never naively respond to a broadcast
  - re-broadcast very very very politely
The Mote/TinyOS revolution

Mote inside
- uP => Arm Cortex
- Radio => 802.15.4g narrow=band frequency hopper
- TinyOS too
- SOC from here

8 kB rom
½ kB ram

48 kB rom
10 kB ram
802.15.4
Idle Listening: 3 Basic Solutions

- **Scheduled Listening**
  - Arrange a schedule of communication Time Slots
  - Maintain coordinated clocks and schedule
  - Listen during specific “slots”
  - Many variants:
    - Aloha, Token-Ring, TDMA, Beacons, Bluetooth piconets, ...
    - S-MAC, T-MAC, PEDAMACS, TSMP, ...

- **Sampled Listening**
  - Listen for very short intervals to detect imminent transmissions
  - On detection, listen actively to receive
  - DARPA packet radio, LPL, BMAC, XMAC
  - Maintain “always on” illusion, Robust

- **Listen after send** (with powered infrastructure)
  - After transmit to a receptive device, listen for a short time
  - Many variants: 802.11 AMAT, Key fobs, remote modems,
  - Many hybrids possible
Or in industry speak ...

Open Standards Reference Model

App. Layer
- Web Services/EXI
- HTTPS/CoAP
- SNMP, IPfix, DNS, NTP, SSH, ...
- IEC 61968 CIM
- ANSI C12.19/C12.22
- DLMS COSEM
- IEC 61850
- IEC 60870
- DNP
- IEEE 1888
- MODBUS

TCP/UDP

Routing – RPL (RFC6550)
IPv6 / IPv4
Addressing, Multicast, QoS, Security

Comm. Network Layer

PHY / MAC Functionality
- IEEE 802.15.4 MAC
- 802.15.4e MAC enhancements
- IEEE 802.15.4 MAC (including FHSS)
- IEEE P1901.2 MAC
- 6LoWPAN (RFC 6282)
- IEEE 802.15.4g (FSK, DSSS, OFDM)
- IEEE P1901.2 PHY

- IETF RFC 2464
- IETF RFC 5072
- IETF RFC 5121
- IEEE 802.11 Wi-Fi
- IEEE 802.3 Ethernet
- 2G / 3G / LTE Cellular
- IEEE 802.16 WiMax
At incredible scale
ROLL & Sensys’ Role

- RPL retained fundamental routing diversity
  - Multiple DODAGs with selection
- Incorporated trickle density awareness

- Many questions for which the research was simply not there
  - Piece-wise source routing, routing stretch versus protocol complexity & state, routing metrics, ...
- Many issues for which the analysis is seriously incomplete
  - Local / global repair, loop formation, routing staleness, scaling, state management, trickle timers
- IETF, mobile, and industry rediscovering ...
- Where is the research community?
How do we start?
Grid Exists

Conventional Electric Grid

Generation
Transmission
Distribution
Load
Internet Exists

Conventional Electric Grid

Generation
Transmission
Distribution
Load

Conventional Internet
Intelligent Energy Network as Overlay on Both

Intelligent Energy Network

Source

Load IPS

Intelligent Power Switch

energy subnet

Conventional Electric Grid

Conventional Internet

Generation

Transmission

Distribution

Load
Where to Start?

Buildings

- 72% of electrical consumption (US),
- 40-50% of total consumption,
- 42% of GHG footprint
- US commercial building consumption doubled 1980-2000, 1.5x more by 2025 [NREL]

Where Coal is used

Prime target of opportunity for renewable supplies
Building Power Consumption

1MW 883 kW

11%
MVP (most valuable principle) of WSN

- Do nothing well
Power-Proportional Buildings?

Cory Hall: Office + Semiconductor + IT

Min = 82% of Max

950 KW

1150 KW
Power-Proportional Buildings?

Stanley Hall: Office + BioScience - 13 NMRs

Min = 72% of Max

1.45 MW
2.02 MW
Power-Proportional Buildings?

Koshland Hall: Office + ???

Min = 69% of Max
Power-Proportional Buildings?

LeConte Hall: Office

Min = 31% of Max
Power Proportionality

![Graph showing Power Proportionality (idle = 0%) with axes labeled Load on the x-axis and Consumption on the y-axis, and Productivity indicated by a green arrow]

11/7/2012
Power Proportionality

![Graph showing Power Proportionality (idle = 50%)](image)
Doing Nothing Well ???
Power Proportional Buildings?

50 Ton Chiller

200 Ton Chiller

Etchevery Hall

Soda Hall

10 months

2 months

Scott McNally Bldg Manager

11/7/2012
The Building Challenge

Operations and Environment

Climate Plant

Electric Load Tree

- Vibration
- Humidity
- Temperature
- Pressure

Building Environmental Manufacturing Infrastructure

11/7/2012

ACme: plug load energy monitor and controller

CT: mains power monitoring

Panel level power monitoring
CEC B2G Testbed - An Energy Transparent Building

- Whole Bldg
- DOP HVAC
- Central vent
- office HVAC
- inst Lab 199 HVAC
- servers
- Plug loads
- Lighting
- Parking Lot
- MCL equip
- MCL infra
- MCL vac
The “Other” Energy Usage

Wireless plug meters on 611 of 1200 loads
sMAP – simple Monitoring and Action Protocol
Uniform Access to Diverse Physical Information
sMAP Virtual Energy-Lab Ecosystem

sMAP Resources
- California ISO
- EBHTTP/IPv6/6LowPAN Wireless Mesh Network
- Edge Router
- Proxy Server
- SCADA
- Modbus
- RS-485
- sMAP Gateway
- sMAP
- sMAP Gateway
- sMAP Gateway

Applications
- Google PowerMeter
- Amazon Web Services
- Every Building
- Cell phone
- Database

sMAP Resources
- Temperature/PAR/TSR
- Light switch
- AC plug meter
- Vibration/Humidity

sMAP

Internet

Virtual Energy-Lab Ecosystem
Factoring is critical

- Represent, transmit data and metadata
- Abstract underlying heterogeneity into simple data model

- Provide access to archived data
- Manage views, data cleaning

- Application-specific functionality built on exposed interfaces
sMAP is …

- Universal information representation for physical data
  - Self-describing, compact JSON schema, transportable over UDP/TCP...
  - Integrated metadata
- Software Architecture for physical data processing and actuation
  - Real-time and archival data, time-series DB
  - Adapters/Drivers for legacy and direct streams
  - Subscription, syndication, distillates
  - Query processing, visualization interface
- Resource-oriented web-service framework for embedded applications

http://code.google.com/p/smap-data
<table>
<thead>
<tr>
<th>Name</th>
<th>Sensor Type</th>
<th>Access Method</th>
<th>Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO Data</td>
<td>CAISO, NYISO, PJM, MISO, ERCOT, BPA</td>
<td>Web scrape</td>
<td>1211</td>
</tr>
<tr>
<td>ACme devices</td>
<td>Plug-load electric meter</td>
<td>Wireless 6lowpan mesh</td>
<td>344</td>
</tr>
<tr>
<td>EECS submetering project</td>
<td>Dent Instruments PowerScout 18 electric meters</td>
<td>Modbus</td>
<td>4644</td>
</tr>
<tr>
<td>EECS steam and condensate</td>
<td>Cadillac condensate; Central Station steam meter</td>
<td>Modbus/TCP</td>
<td>13</td>
</tr>
<tr>
<td>UC Berkeley submetering feeds</td>
<td>ION 6200, Obvius Aquisuite; PSL pQube, Veris Industries E30</td>
<td>Mosbus/Ethernet, HTTP</td>
<td>4269</td>
</tr>
<tr>
<td>Sutardja Dai, Brower Hall BMS</td>
<td>Siemens Apogee BMS, Legrand WattStopper, Johnson Control BMS</td>
<td>BACnet/IP</td>
<td>4064</td>
</tr>
<tr>
<td>UC Davis submetering feeds</td>
<td>Misc., Schneider Electric ION</td>
<td>OPC-DA</td>
<td>34 (+)</td>
</tr>
<tr>
<td>Weather feeds</td>
<td>Vaisala WXT520 rooftop weather station; Wunderground</td>
<td>SDI-12, LabJack/Modbus, web scrape</td>
<td>33</td>
</tr>
<tr>
<td>CBE PMP toolkit</td>
<td>Dust motes; New York Times BMS</td>
<td>CSV import; serial</td>
<td>874</td>
</tr>
<tr>
<td>NOA Weather Forecast</td>
<td>Meteorological (window, solar, cloud, etc)</td>
<td>Web</td>
<td>77740</td>
</tr>
<tr>
<td>SDH Air Quality</td>
<td>CO2, Temp, TSR, PAR, Hum</td>
<td>Wireless 6lowpan mesh</td>
<td>50</td>
</tr>
</tbody>
</table>

**total: 93,242**

- [www.openbms.org](http://www.openbms.org)
Living Lab Approach: Innovate in a Virtual Private Grid

VPG

Generation
Transmission
Distribution
Load
sMAP Energy Markets, Ops, $, ...

http://www.isorto.org

Energy Price

- Real-Time Market Price (5 min)
- Day-Ahead Market Price (1 hr)
- Now
sMAP Solar, Wind, Meteorology

- 1450 Met feeds covering
- Cal Solar Initiative: 130,275 proj. 1370 MW
- Cal Utility Solar: 60 facilities 695 MW
- Cal Utility Wind: 134 facilities 4295 MW
sMAP generation

- CA generation plant locations, type, and rated power (> 0.1 MW) [CEC]
- Hourly output from each type of CA generation source for > 1 year [CAISO]

Modern Energy Network Challenges

**Information Plane**

- **Storage**
- **Fluctuating Renewable**
- **Photovoltaic**
- **Peaker**
- **Intermittent**
  - Combined cycle nat. gas / bio
  - Baseline
  - Geothermal
  - Hydro
  - Nuclear
- **Goal**

**Physical Plane**

- **Supply**
- **Transport**
- **Load**
- **Consumption**

- **Imports**
- **Storage**
- **Fluctuating Renewable**
- **Electronics**
- **Appliance**
- **Lighting**
- **HVAC**
- **Motors**
- **Power Supplies**
- **Control**
- **Circuits**
- **Usage**
- **Schedule**
- **Facilities**
- **Industrial**
- **Transportation**
- **Usage**
- **Pricing**

**Generators**

**Lines**

**Transformers**

**Meters**

**VFD**

**Efficiency**
What would the CA Grid be like @ 60% renewables?

G-20 Investment ($B)


Bloomberg New Energy Finance, Liebreich April 5, 2011
### CA grid today - Supplies

<table>
<thead>
<tr>
<th>Source</th>
<th>Rated (GW)</th>
<th>Capacity Factor</th>
<th>Total Energy (TWh)</th>
<th>% of Total Energy</th>
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<tbody>
<tr>
<td>Geothermal</td>
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<tr>
<td>Solar(^3)</td>
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<td><strong>Total</strong></td>
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<td><strong>100.0%</strong></td>
</tr>
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1 Mean delivered power divided by rated power (excl. import)
2 For imports, rating is the maximum observed power
3 Residential net factored into demand
CA grid today – Supply Challenge

CAISO Load Duration Curve

Sept '05 to Sept '06

- 50,085 MW Peak 7/24/06
- Greater than 45,000 MW 57 hours or 0.65%
- Greater than 40,000 MW 279 hours or 3.2%
- Greater than 35,000 MW 805 hours or 9.2%

Winter Peak 33,275 MW 12/14/05

CAISO Operational Needs from Demand Response Resources

Jim Detmers
Vice President, Operations
More views – time and blend
### CA grid today - Supplies

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<sup>1</sup> Mean delivered power divided by rated power (excl. import)

<sup>2</sup> For imports, rating is the maximum observed power

<sup>3</sup> Residential net factored into demand
A year in the today’s grid

Seasonal, Weekly, Daily variations
Many underlying factors

Peak: 47.1 GW
Min: 18.8 GW
Mean: 26.3 GW
A year … daily averages
A mid-summer’s week
A winter week’s tale
The Demand Duration Curve

![Graph showing the demand duration curve with total power in GW on the y-axis and % of hours exceeded on the x-axis. The graph includes a table with %Hrs and GW values: Max 47.128, 99.9 45.398, 99.5 42.373, 99.0 39.786, 95.0 34.846, 90.0 32.086, 50.0 26.173, 0.0 18.792.]}
A Simple “what if”

- Take current demand, current activity, current technology, current deployment
- At a crude top-level scale (by category)
  - Represented by the time series
- Scale up the renewable portions
  - Preserve the seasonal, weekly, daily, hourly effects of mother nature *
- Scale back the fossil fuel based supplies
- With current demand as a reference
Example: Solar

![Solar Power Graph](image)

- Y-axis: Total Power (GW)
- X-axis: Months (Sep to Aug)
- Line: SOLAR - Present-Day

Legend: The graph illustrates the fluctuation of solar power generation throughout the year, with peaks in the summer months and troughs in the winter months.
Example: Solar Scaled
Example: Wind

![Graph showing total power (GW) for different months. The graph indicates fluctuations in power throughout the year, with peaks in certain months.]
Wind - Scaled
Joint Wind/Solar Scaling

<table>
<thead>
<tr>
<th>Source</th>
<th>Unscaled Rated (GW)</th>
<th>Scaled Rated (GW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>2.81</td>
<td>57.1</td>
</tr>
<tr>
<td>Solar</td>
<td>0.40</td>
<td>29.8</td>
</tr>
<tr>
<td>TOTAL</td>
<td>3.21</td>
<td>86.9</td>
</tr>
</tbody>
</table>
A Year in CA grid @ 60%

EXCESS: 2.6%
IMPORTS: 9.7%
THERMAL: 34.4%
WIND: 18.2%
SOLAR: 3.8%
BIOMASS/BIOGAS: 1.9%
GEOTHERMAL: 1.7%
HYDRO: 13.3%
SMALL HYDRO: 1.7%
NUCLEAR: 14.5%

Total CA Power (GW)

CA GRID DEMAND
A Summer Week @ 60%

- Total CA Power (GW)
  - EXCESS: 2.6%
  - IMPORTS: 0.0%
  - THERMAL: 0.0%
  - WIND: 41.6%
  - SOLAR: 21.0%
  - BIOMASS/BIOGAS: 1.8%
  - GEOTHERMAL: 3.2%
  - HYDRO: 15.9%
  - SMALL HYDRO: 1.9%
  - NUCLEAR: 15.4%
  - CA GRID DEMAND

- Graph showing total power generation from various sources over the summer week.
A Winter Week @ 60%

- Total CA Power (GW)
- EXCESS: 2.6%
- IMPORTS: 9.7%
- THERMAL: 18.2%
- WIND: 34.4%
- SOLAR: 6.8%
- BIOMASS/BIOGAS: 1.9%
- GEOTHERMAL: 4.0%
- HYDRO: 14.8%
- SMALL HYDRO: 1.4%
- NUCLEAR: 14.5%
- CA GRID DEMAND
## Current Grid vs. Scaled Scenario - 60% Renewables

<table>
<thead>
<tr>
<th>Generation Type</th>
<th>Capacity / Peak (GW)</th>
<th>Total Energy (%)</th>
<th>Capacity Factor / Load Factor (%)</th>
<th>Capacity / Peak (GW)</th>
<th>Total Energy (%)</th>
<th>Capacity Factor / Load Factor (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Renewables</strong></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Geothermal</td>
<td>2.600 / 1.095</td>
<td>3.8%</td>
<td>38.7% / 92.0%</td>
<td>2.600 / 1.095</td>
<td>3.8%</td>
<td>38.7% / 92.0%</td>
</tr>
<tr>
<td>Biomass/Biogas</td>
<td>1.145 / 0.616</td>
<td>1.9%</td>
<td>43.5% / 80.9%</td>
<td>1.145 / 0.616</td>
<td>1.9%</td>
<td>43.5% / 80.9%</td>
</tr>
<tr>
<td>Small Hydro</td>
<td>1.380 / 0.646</td>
<td>1.7%</td>
<td>31.7% / 67.8%</td>
<td>1.380 / 0.646</td>
<td>1.7%</td>
<td>31.7% / 67.8%</td>
</tr>
<tr>
<td>Wind</td>
<td>2.812 / 2.470</td>
<td>3.1%</td>
<td>29.1% / 33.2%</td>
<td>57.116 / 22.995</td>
<td>34.4%</td>
<td>15.8% / 39.3%</td>
</tr>
<tr>
<td>Solar</td>
<td>0.403 / 0.457</td>
<td>0.4%</td>
<td>28.7% / 25.3%</td>
<td>29.792 / 30.636</td>
<td>18.2%</td>
<td>16.1% / 15.7%</td>
</tr>
<tr>
<td><strong>Non-Renewables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nuclear</td>
<td>4.456 / 4.581</td>
<td>14.6%</td>
<td>86.0% / 83.6%</td>
<td>4.456 / 4.581</td>
<td>14.5%</td>
<td>86.0% / 83.6%</td>
</tr>
<tr>
<td>Hydro</td>
<td>12.574 / 6.286</td>
<td>13.3%</td>
<td>27.7% / 55.5%</td>
<td>12.574 / 6.286</td>
<td>13.3%</td>
<td>27.7% / 55.5%</td>
</tr>
<tr>
<td>Imports</td>
<td>N/A / 11.055</td>
<td>28.0%</td>
<td>N/A / 66.6%</td>
<td>N/A / 9.291</td>
<td>2.6%</td>
<td>N/A / 7.2%</td>
</tr>
<tr>
<td>Thermal</td>
<td>44.339 / 27.014</td>
<td>33.3%</td>
<td>19.7% / 32.4%</td>
<td>44.339 / 19.528</td>
<td>9.7%</td>
<td>5.7% / 13.0%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>80.764 / 47.128</td>
<td>100.0%</td>
<td>32.6% / 55.8%</td>
<td>130.882 / 47.128</td>
<td>100.0%</td>
<td>20.1% / 55.8%</td>
</tr>
</tbody>
</table>
What Can we do to Make it Work?

- Design for deep penetration
  - Optimize for the whole, not peak production...
  - Use your off-grid intuition
- Efficiency for shaping
  - Poor power proportionality of buildings and other loads, especially at night
- Storage
  - Move energy in time
- Load scheduling (continuous DR)
  - Precooling, preheating, guardband adjustment
  - Deferral, acceleration
- Integrated Portfolio Management
  - Utilize resources in concert with non-dispatchables
- Curtailment
Load shifting to follow supply

Windrush? Sunrush? - energy agile industry?
A Day

Total CA Power (GW)

00:00 06:00 12:00 18:00

EXCESS
IMPORTS: 1.0%
THERMAL: 21.2%
WIND: 33.9%
SOLAR: 15.8%
BIOMASS/BIOGAS: 2.1%
GEOTHERMAL: 4.2%
HYDRO: 10.8%
SMALL HYDRO: 1.3%
NUCLEAR: 9.8%
CA GRID DEMAND
The Day with +/- 3 hours of shift

```
00:00 06:00 12:00 18:00
```

**Total CA Power (GW)**

- **EXCESS**
- **IMPORTS: 0.6%**
- **THERMAL: 16.4%**
- **WIND: 35.7%**
- **SOLAR: 19.1%**
- **BIOMASS/BIOGAS: 2.1%**
- **GEOTHERMAL: 4.2%**
- **HYDRO: 10.8%**
- **SMALL HYDRO: 1.3%**
- **NUCLEAR: 9.8%**

**CA GRID DEMAND:**

11/7/2012
How to match demand to supply?
Modern EE & CS Energy Challenges

Information Plane

Physical Plane

Storage
- Pumped
- Fluctuating Renewable
- Photovoltaic
- Peaker
- Single cycle nat. gas / bio
- Intermittent
- Combined cycle nat. gas / bio
- Baseline
- Geothermal
- Hydro
- Nuclear
- Coal

Supply

Transport

Load

Consumption

11/7/2012

VFD
- Efficiency
- Control
- Schedule
- Usage
- Pricing
- Transportation
- Industrial
- Personal
- Facilities
- Motors
- HVAC
- Lighting
- Appliance
- Electronics
- Supplies
- Circuits
- Power

Supply

Transport

Load

Consumption
Interesting Sensor Networks

- 151 Temperature Sensors
- 50 Electrical Sub-meters
- 12 Variable Speed Fans
- 138 Air Dampers
- 312 Light Relays
- 6 Variable Speed Pumps
- 121 Controllable Valves

> 6,000 Sense and Control Points

Sutardja Dai Hall
Built in 2009
140k sq. ft.
Controls are Widely Available

Bancroft Library:
- Built in 1949
- 100k sq. ft.
- 5,000 points

>70% of large buildings have digital controls

U.S. Energy Information Administration, 2009
Measure => Model => Mitigate

Mathematical model from Newton’s law of cooling

\[
\frac{dT}{dt} = -k_r T - k_c u(t) + k_w w(t) + q(t)
\]

- change in temperature over time
- time constant of room
- weather
- heating from occupants and equipment
- AC cooling

Model identified using semi-parametric regression

Temperature:
- Experimental (blue)
- Simulated (red)

Heating from occupants and equipment
Learning-Based Model Predictive Control

Experimental LBMPC: 12.6kWh Consumed

Temperature

Control Action

Simulated Hysteresis Control: 29.7kWh Consumed (estimated)

Temperature

Control Action

LBMPC adjusts for internal dynamics, avoids over-cooling, trades off duty cycle and switching frequency

(Aswani, Master, Taneja, Culler, Tomlin, 2011)
Supply-Following Computational Loads

Background Processing (shiftable)

QoS (fidelity & latency)

IPS

Requests

Availability

Forecasts

Power

Controllable Storage
Energy-Availability Driven Scheduling

Non-dispatchable, variable supply

Pacheco wind farm

Power proportional, grid-aware loads

Scientific computing cluster
Energy “Slack”

Thermostatically Controlled Load

Set Point
Guard band

IPS

Graphs showing temperature, humidity, light, and power over time.
Everyday Slack and Control

6 kg. NH₄Cl in 19.1% aqueous solution
From Auto Demand Response ...
To Personalized Automated Lighting

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

Python Control Process
MySQL
WWW
Python Django
sMAP
BACnet
Gateway
Real Energy Savings

SDH 4th Floor Lighting Energy Usage

Colab Savings.
Floor kW.
Collab kW.
Network of Control Loops

- **Cooling Tower Loop**
  - Condenser Water Pump (CWP)
  - Always on max

- **Cold Water Loop**
  - Chiller
  - 45°F setpoint
  - Chilled Water Pump (CHP)
  - Always on max

- **Cooling Coil & Valve**
  - 55°F setpoint

- **Supply Fan**
  - (Air Handler Unit – AHU)
  - 336 Pa setpoint

- **Air Handling Loop**
  - **Economizer Loop**
  - **Exhaust Air**
  - **Return Fan**

- **Hot Water Loop**
  - **Dampers (VAVs)**
  - Heating Coils & Valves
  - 70°F setpoint

- **Outside Air Intake**
  - **Supply Fan**
  - **Cooling Tower Loop**

- **VAV Loop**

- **Chiller**
  - 45°F setpoint

- **Chilled Water Pump (CHP)**
  - Always on max

11/7/2012
Script the building …
<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Status</th>
<th>Start Date</th>
<th>End Date</th>
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<tbody>
<tr>
<td>Matusko</td>
<td>ID experiment</td>
<td>Approved</td>
<td>April 14, 2012</td>
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<td>ID experiment</td>
<td>Pending</td>
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<td>Yin</td>
<td>Precooling Test</td>
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<td>April 28, 2012</td>
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<td>Yin</td>
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<td>Pending</td>
<td>June 16, 2012</td>
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<td>Precooling Test on 4th floor</td>
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<tr>
<td>Yin</td>
<td>Precool test at 464</td>
<td>Pending</td>
<td>June 29, 2012</td>
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<tr>
<td>Matusko</td>
<td>Identification experiment</td>
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<tr>
<td>Matusko</td>
<td>ID experiment - 4th floor</td>
<td>Approved</td>
<td>July 5, 2012</td>
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August 2012

<table>
<thead>
<tr>
<th>Mon</th>
<th>Tue</th>
<th>Wed</th>
<th>Thu</th>
<th>Fri</th>
<th>Sat</th>
<th>Sun</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>
There's a bldg app for that ...
Empirical models, including external factors, and monitoring, provide rapid, focused feedback.

Dynamically set economizer, supply air temp, min airflow, reheat.

RMSE = 5.6%
Savings: 16.52%
25.4 kW
Where is this going: BOSS and Software Defined Buildings

1. Hardware presentation layer: sMAP
2. Hardware abstraction layer: device-specific logic
3. Time-series service: the archiver
4. Reliable control inputs: the transaction manager
5. Security: the authorization service

portable, robust applications for the physical environment
CyberPhysical Building Systems

Building Integrated Operating System

Empirical Models

Physical Models

BIM

Cyber

Physical Building

Occupant Satisfaction

Planning

Visualization

Multi-Objective Model-Driven Control

Security, Fault, Anomaly Detect & Management

Activity/Usage Streams

Pervasive Sensing

Legacy Instrumentation & Control Interfaces

Process Loads

Occupant Demand

Control and Schedule

Human-Building Interface

Transport

Light

Electrical

HVAC

BMS

drvers
drvers
drvers

Local Controllers
Modern EE & CS Energy Challenges

Information Plane

Physical Plane

Supply

Transport

Load

Consumption

Storage

Pumped

Fluctuating Renewable

Wind

Photovoltaic

Peaker

Single cycle

nat. gas / bio

Intermittent

Combined cycle

nat. gas / bio

Baseline

Geothermal

Hydro

Nuclear

Goal

Generators

Lines

Transformers

Meters

VFD

Efficiency

Control

Usage

Schedule

Pricing

Personal

Facilities

Industrial

Transportation

Power Supplies

Fluctuating

Renewable

Electronics

Appliance

Lighting

HVAC

Motors

Storage

Imports

Storage

Fluctuating Renewable

Storage

Electronics

Appliance

Lighting

HVAC

Motors

Personal

Facilities

Industrial

Transportation

Usage

Schedule

Pricing

Information Plane

Physical Plane

Supply

Transport

Load

Consumption

11/7/2012
Synchrophasors

- Synchronized Phasor Measurement Units (PMUs) distributed across the transmission system
  - 30 Hz sampling of voltage, current, frequency & phase
  - Synchronized (<< ms) via GPS
  - Aggregated at Phasor Data Concentrator (PDC)
  - “wide area situational awareness”
The power of observability

- Power Systems Applications
  - Enhanced state estimation, Operator visualization
  - Black Start visibility, Line impedance derivation
  - Oscillatory mode detection & damping
  - Post-disturbance analysis, Islanding
  - Power network model validation

It Can Fall Apart in Three Minutes

Aug 14, 2003

Phase Difference before the Blackout

Cleveland – Michigan Angle

Aug 14, 2003
Currently ~500 PMUs in US grid
The issues to solve?

- Sensor placement
  - Huge complex grid, few expensive PMUs
- Time synchronization
  - Higher fidelity requires tighter synchronization
  - Especially as we move to the distribution tier
- Latency
- Data rates (!), storage, query
- Continuous, unattended operation
  - Especially during crises
- Analytics, Prognostics, ...
DIY Synchrophasors

Implementation and Application of an Independent Texas Synchrophasor Network

Dr. W. Mack Grady, The University of Texas at Austin
David Costello, Schweitzer Engineering Laboratories, Inc.

Fig. 10. Voltage phase angle change during generator trip

Fig. 18. Wind generation in ERCOT on March 10, 2009

Fig. 19. Voltage phase angle changes during spike in wind generation
What happens when?

- Push observability throughout distribution tier?
- Into consumption tier?
- Electrify more and more of the transportation?
- The loads become efficient, power proportional, and grid responsive?
From a Grid to an Energy Network

- Availability
- Pricing
- Planning

- Forecasting
- Tracking
- Market

Monitor, Model, Mitigate
- Deep instrumentation
- Waste elimination
- Efficient Operation
- Shifting, Scheduling, Adaptation
IT and the 4 Part GHG Reduction Plan

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

Monitoring, Analysis, Modeling, Waste Elimination, Power Proportionality, Optimal Control

Intelligence, Communication, adaptation in Everything

ZELB. Supply-Following Loads, Energy SLA, Cooperative Grid
What made me think it was time for WSN research?
Why the next tier of internet is here?
Thanks