Enabling a Sustainable Energy Infrastructure – A CPS Grand Challenge

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CPS Week 4/13/2011

“Energy permits things to exist; information, to behave purposefully.”
W. Ware, 1997
Energy is THE Problem

- Energy and the environmental impact of extraction, use, and disposal
- THE problem of the Industrial Age
- We need to find Information Age solutions to THE Industrial Age Problem

- it starts with the Faustian bargain of oblivious consumption
The Grid: A Marvel of Industrial Age Design

- Deliver high quality low-cost power
- To millions of customers over thousands of miles
- Synchronized to <<16 ms cycle (60 Hz)
- With no orders, no forecasts, no plans
- No inventory anywhere in the supply chain
- To enable rapid economic & industrial growth through oblivious consumption
1. Energy becoming increasingly dear
   – increased cost of acquisition
   – inclusion of environmental costs

2. Improvements in energy efficiency cause high dynamic variability in the load
   – high peak-to-ave ratio, bursty

3. Limitations of existing grid present transmission and distribution bottlenecks

4. Incorporation of renewable resources reduces control over supply
   – most are non-dispatchable (solar, wind)
Towards an “Aware” Energy Infrastructure

Baseline + Dispatchable Tiers

Oblivious Loads

Generation -> Transmission -> Distribution

Non-Dispatchable Sources

Aware Interactive Loads

Communication

Communication
The Roadmaps We’re Used to

Moore’s Law

Bell’s Law

Computers Per Person

1:1

1:10

1:100

1:1000

1:10000

1:100000

Mainframe

Mini

Workstation

PC

Laptop

PDA

Cell

Mote!

years


1965 Actual Data

MOS Arrays

MOS Logic 1975 Actual Data

1975 Projection

Memory

Microprocessor

1K 4K 16K 64K 256K 1M 4M 16M 64M 128M 256M 512M 1G 2G 4G

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A Different Kind of RoadMap

Energy Consumption in the United States 1949 - 2005

- Avoided Supply = 70 Quads in 2005
- If E/GDP had dropped 0.4% per year
- Actual (E/GDP drops 2.1% per year)
- New Physical Supply = 25 Q

- $1.7 Trillion
- 70 Quads per year saved or avoided corresponds to 1 Billion cars off the road

Source: LBNL

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Load-following Supply (?)

California Daily Peak Loads – 2006

POWER CONTENT LABEL

<table>
<thead>
<tr>
<th>ENERGY RESOURCES</th>
<th>2007 CA POWER MIX†</th>
<th>2007 CA POWER MIX*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eligible Renewable</td>
<td>55% (projected)</td>
<td>10% (for comparison)</td>
</tr>
<tr>
<td>Biomass &amp; waste</td>
<td>10%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Geothermal</td>
<td>15%</td>
<td>2%</td>
</tr>
<tr>
<td>Small hydroelectric</td>
<td>13%</td>
<td>6%</td>
</tr>
<tr>
<td>Solar</td>
<td>10%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Wind</td>
<td>11%</td>
<td>2%</td>
</tr>
<tr>
<td>Coal</td>
<td>16%</td>
<td>32%</td>
</tr>
<tr>
<td>Large Hydroelectric</td>
<td>12%</td>
<td>24%</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>16%</td>
<td>31%</td>
</tr>
<tr>
<td>Nuclear</td>
<td>1%</td>
<td>3%</td>
</tr>
<tr>
<td>Other</td>
<td>&lt;1%</td>
<td>0%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

* 50% of this product is specifically purchased from individual suppliers.
† Percentages are estimate annually by the California Energy Commission based on electricity sold to California consumers during the previous year.

For specific information about this electricity product, contact Company Name. For general information about the Power Content Label, contact the California Energy Commission at 1-800-555-7594 or www.energy.ca.gov/label.
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 @ CA

Energy Price

Price per MWh ($) vs. Time of Day

Real-Time Market Price (5 min)
Day-Ahead Market Price (1 hr)
Now

Avg(24hr): 72.93
Avg(24hr): 45.53

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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
Co-operative Energy Mgmt - a Cyber-Physical Grid

- Availability
- Pricing
- Planning

- Forecasting
- Tracking
- Market

- Monitor, Model, Mitigate
  - Deep instrumentation
  - Waste elimination
  - Efficient Operation
  - Shifting, Scheduling, Adaptation

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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
• Universal “narrow waist” – IP
• Horizontal Layering, not Vertical Integration
• Intelligence at the end-points, simple core
• Measure everywhere, continuously adapt

⇒ Design for Change
⇒ Accommodate new technology
⇒ Enable new applications
⇒ Innovate in the Overlay
⇒ Web: simple, open, machine readable formats
No!
Grid Exists

Conventional Electric Grid

Generation
Transmission
Distribution
Load
Intelligent Energy Network as Overlay on Both Conventional Electric Grid Generation Transmission Distribution Load

Intelligent Power Switch

Source IPS

Buffer IPS

Load IPS

Conventional Electric Grid

Conventional Internet

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Innovate in a Virtual Private Grid
Questions…

• Where does the energy go?
  – how much is wasted?
  – how can the rest be optimized?

• How much *slack* is there?
  – Can it be exercised?
  – Energy storage? Electrical Storage?

• What limits renewable penetration?
  – vs storage, scheduling, cooperation

• What are the protocols involved?

• What is the System and network design?
Energy Slack

• The portion of energy usage that may be scheduled to meet an objective
  – Deferred (e.g., peak shaving)
  – Advanced (e.g., pre-cooling)
CPS contributions …

• Pervasive Embedded Monitoring Networks
Our Buildings

Annual Consumption

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Soda Hall

Soda Hall Power Consumption - 494 KW

Annual Consumption

kwh

kwh/sq ft

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Engineering 101

- Design, Plan, Size, and Test at **Full Load**
  - Performance measured at full Load
- Add headroom and safety margin
- Operate at **Partial Load**
Power Proportionality

![Graph showing Power Proportionality (idle = 0%)](image)

- **Consumption**
- **Productivity**
Power Proportionality

Power Proportionality (idle = 50%)

Consumption

Productivity

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Power-Proportional Buildings?

Cory Hall: Office + Semiconductor + IT

Min = 82% of Max

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Power-Proportional Buildings?

Stanley Hall: Office + BioScience
- 13 NMRs

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Min = 72% of Max
Power-Proportional Buildings?

Koshland Hall: Office +

Min = 69% of Max
Power-Proportional Buildings?

LeConte Hall: Office

Min = 31% of Max

Annual Consumption

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Is IT leading the way?

• Google
• Thousand of servers
• Millions of users
• Unlimited demand
• 25% utilized

Where does the Power go?

The Glue, not the processor

Core i7

Atom 333

Westmere

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Engineering 101 102

- Design, Plan, Size, and Test at Full Load
  - Performance measured at full Load
- Add headroom and safety margin
- Operate at Partial Load

- Repeat, designing for efficiency at Typical Load
CPS contributions …

- Pervasive Embedded Monitoring Networks
- Power Proportional Design Techniques
Building ↔ Grid Testbed

- large complex load
- >1,000 sense points
- Monitor, Model, Mitigate
- In concert with an intelligent grid

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The 3 Views

Operations and Environment

CT: mains power monitoring

Load Tree

ACme: plug load energy monitor and controller

Climate Plant

Temperature
Humidity
Vibration
Pressure

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State-of-Art monitoring
A Better State-of-Art
Physical Tier

- 10 Dent Powerscout 18-channel (6x3) electrical meters
  - RS485 – Ethernet/IP – sMAP
- 2 Power Standards Labs meters
  - Ethernet
- 2 (existing) ION 6200 meters
- 70 ACME Receptacle meters
  - 802.15.4/LoWPAN/IP
- 4 rooftop Solar/TSR/PAR/Temp/Hum
- Condensate meter, Obvius Steam
- Vaisala Meteorological Station
- *Existing SCADA integration*
- *Remote Programmable PCT => Action*
- *Interior usage, activity, environmental condition*
Layered Arch. for Physical Info

**Presentation**
- Portals
- User Feedback
- OADR
- Forecast

**Analysis**
- Simulation
- Recommissioning
- Diagnosis

**Logical**
- Meta-Data
- Model
- Physical Information
- Events
- Networks
- Repositories

**Physical**
- Building Systems
- Sensors
- Comms Links

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Along the way …
CPS contributions …

- Pervasive Embedded Monitoring Networks
- Power Proportional Design Techniques
- Application Independent Physical Information Representation
“Real World” Information
Dis-integrated – down the drain

- Security and Access Control
- Gas and Electric Usage
- Heating, AC, and Ventilation
- Water Usage, Temp., Quality
- Smoke, Fire, CO, Radon
- Smart Appliances
- Digital Health Devices
- Baby Monitor (Elder care)
- Entertainment System
- Video Game Consoles
- Exercise Units
- Clocks and Calendars
## Building Information “standards”

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Year</th>
<th>Network</th>
<th>Example Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modbus</td>
<td>1979</td>
<td>RS-485, TCP/IP</td>
<td>Panel monitoring, alarms</td>
</tr>
<tr>
<td>Fieldbus/HART</td>
<td>1988</td>
<td>various</td>
<td>Industrial Control</td>
</tr>
<tr>
<td>BACnet</td>
<td>1995</td>
<td>ARCNET, Ethernet, IP, RS-232, etc.</td>
<td>HVAC, Lighting, Fire…</td>
</tr>
<tr>
<td>WirelessHART</td>
<td>2007</td>
<td>802.15.4e</td>
<td>Industrial control, wire replacement</td>
</tr>
<tr>
<td>Zigbee SEP 2.0</td>
<td>2011?</td>
<td>802.15.4</td>
<td>Plug-load monitoring</td>
</tr>
</tbody>
</table>

- **HUGE installed/legacy base**
- **Multiple generations of hardware and software in the same building**
- **Typical integration: proprietary vertical Building Management System (BMS)**
Narrow Waist?

Applications:
- Modeling
- Personal Feedback
- Continuous Commissioning
- Control
- Visualization
- Actuation
- Storage
- Debugging
- Authentication

Physical Information:
- Water
- Electrical
- Geographical
- Occupancy
- Structural
- Weather
- Environmental
- Actuator

sMAP

REST API
JSON Objects
HTTP/TCP

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sMAP Interaction

GET /data
[“weather”]

GET /data/weather
[“sensor”, “meter”]

GET /data/weather/sensor
[“temperature”, “wind”, “humidity”]

GET /data/weather/sensor/temperature/reading
{
  “Reading” : 23,
  “ReadingTime” : 1288385832,
  “ReadingSequence” : 123123
}

smap.cory.berkeley.edu

Discover

Access

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sMAP Design

• KISS: Sensing, Metering, Actuation
• Identify Sense Points and Channels
  – Sense point: physical point of instrumentation (e.g. weather station)
  – Channel: Stream of scalar readings (e.g. temperature)
• Map these to HTTP resources

```plaintext
/                      # list resource under URI root [GET]
data                # list sense points under resource data [GET]
[sense_point]    # select a sense points [GET]
meter           # meters provide this service [GET]
[channel]        # a particular channel [GET]
/reading         # meter reading [GET]
/format          # calibration and units [GET/POST]
/parameter       # sampling parameter [GET/POST]
/profile         # history of readings [GET]
```
Add “callbacks” to HTTP

POST requests supply JSON objects as arguments

Same semantics as a GET on ReportResource

Alternatives are “long get,” webevents/multipart HTTP style
Embedding sMAP

Emerging design pattern: define Internet-scale protocol, use adaptation layer where necessary

Preserve extensibility and self-describing properties of JSON
Keep it simple
IP Everywhere - A Real World Web

sMAP Resources

- sMAP
- AC plug meter
- Vibration / Humidity
- EBHTTP / IPv6 / 6LowPAN Wireless Mesh Network
- Edge Router
- Temperature/PAR/TSR
- Light switch
- Modbus
- Dent circuit meter
- vMap Gateway

Applications

- sMAP
- sMAP Gateway
- sMAP Gateway
- sMAP Gateway
- Proxy Server
- EBHTTP Transation

Internet

- Google PowerMeter
- Database
- Every Building
- Cell phone

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Energy Transparent Building

- Whole Bldg
- MCL equip
- MCL infra
- MCL vac
- servers
- Parking Lot
- Lighting
- Plug loads
- DOP HVAC
- Central vent
- office HVAC
- inst Lab 199 HVAC
- 4/12/11
- CPS 2011
Keeping an Eye on the Prize

• Monitor Based Commissioning
  – Eliminate simultaneous heat/cool
  – AC91 on schedule
Extracting Deeper
Missing Data for all devices (Apr 7th – 8th) – same for all other devices
Filtering and Detrending

Graph of the minutes average of ABC apparent power for Device 1A
daily and weekly patterns removed (27th March - 23rd September)

administrative holidays

Graph of the minutes average of ABC apparent power for Device 1A
daily and weekly patterns, semester/non-semester differentials removed (27th March - 23rd September)
CPS contributions …

• Pervasive Embedded Monitoring Networks
• Power Proportional Design Techniques
• Application Independent Physical Information Representation
• Modeling and Analysis
The Other Energy in Buildings

![Chart showing energy usage in different categories: HVAC, Lighting, Water Heating, Appliances, Other. The chart compares energy usage in 2010 and 2020 for residential and commercial sectors.]

Source: DOE Building Energy Data Book 2009

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Misc. & Electronic Loads

LBNL Bldg 90
611 of 1200 loads

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BACNet => sMAP

• www.openbms.org

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• 15 different underlying sensors and stacks
• More then 125 instruments,
• >600 total ACme plug-load meters
• Strong integration tools for legacy:
  • BACnet/IP, Modbus RTU/TCP, various XML
• 6100 channels of high-resolution data
  • 125 sMAP “instances”
• It’s easy: simplest service is ~3 lines of Python
• OpenBMS.org: plotting, organization
  • 72GB data stored in high-performance BDB store
  • Metadata in MySQL
  • Together 350 inserts/sec
<table>
<thead>
<tr>
<th>Name</th>
<th>Sensor Type</th>
<th>Physical Layer</th>
<th>Sense Points</th>
<th>Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cory Hall Submetering</td>
<td>Dent Three-Phase</td>
<td>Modbus + Ethernet</td>
<td>79</td>
<td>3318</td>
</tr>
<tr>
<td>Cory Hall Metering</td>
<td>ION and pQube Meters</td>
<td>HTTP/Ethernet</td>
<td>3</td>
<td>150</td>
</tr>
<tr>
<td>Cory Lab Temperature</td>
<td>TelosB</td>
<td>802.15.4 + Ethernet</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Cory Lab Machines</td>
<td>ACme</td>
<td>804.15.4 + Ethernet</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>Cory Chilled Water</td>
<td>HeatX</td>
<td>Modbus + Ethernet</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>Cory Weather</td>
<td>Vaisala WXT520</td>
<td>SDI-12 + Ethernet</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>Soda Hall Sun Blackbox</td>
<td>Fan speed; environmental</td>
<td>Http/Ethernet</td>
<td>10</td>
<td>84</td>
</tr>
<tr>
<td>Soda Lab Machines</td>
<td>ACme</td>
<td>802.15.4 + Ethernet</td>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>Soda Lab Panel</td>
<td>Veris E30</td>
<td>Modbus + Ethernet</td>
<td>1</td>
<td>42</td>
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<tr>
<td>Soda SCADA Data</td>
<td>Barrington controls</td>
<td>RS-485/various</td>
<td>“1”</td>
<td>1670</td>
</tr>
<tr>
<td>LBNL Building 90</td>
<td>Acme</td>
<td>802.15.4 + Ethernet</td>
<td>550</td>
<td>1650</td>
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<tr>
<td>Campus Power Data</td>
<td>Obvius Aquisuite; various</td>
<td>XML/HTTP/Ethernet</td>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>Citrus SDH BACnet</td>
<td>Siemens Apogee</td>
<td>BACnet/IP + RS-485</td>
<td>“1”</td>
<td>134</td>
</tr>
</tbody>
</table>
CPS contributions ...

- Pervasive Embedded Monitoring Networks
- Power Proportional Design Techniques
- Application Independent Physical Information Representation
- Modeling and Analysis
PP Systems of nonPP pieces

Requests ↔ IPS

Load Distribution
Scheduling
Power Management

Computational “Spinning Reserve”

Request Rate
Predicted
Operating Capacity
Max Capacity

WikiPedia Request Rate

Efficiency (Requests/Joule)

Static Provisioning
Power Managed Provisioning

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Power Proportional Buildings?

Observations on a Campus in Beijing

- Electricity of Campus Buildings (A), kWh/m²/a

  - Average: 30
  - Average: 64
  - Average: 82

  Buildings with Fan Only
  Buildings with Split AC Units
  Buildings with Centralized AC System

Part-time, Part-space, Natural venting and light

Case study: AC in Residential buildings

Measured energy consumption in every units of a residential building in Beijing, 2006, split unit

Key reason:
- Part time
- Part space
- Open windows

Yi Jiang
Building Energy Research Centre
Tsinghua University P R China

Centre AC for residential buildings in Beijing: 19.8 kWh/m²,a

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Power Proportional Buildings?

50 Ton Chiller

200 Ton Chiller

Etchevery Hall

Soda Hall

10 months

2 months

Scott McNally Bldg Manager

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Stages of Energy Effectiveness

• Waste Not
  – Do Nothing Well !!!

• Power Proportionality
  – Peak Performance : Power => Safety
  – Optimize Partial Load - from nothing to peak!

• Sculpting
  – Identify the energy slack and utilize it

• Negotiated Grid / Load / Human Interaction
  – Plan, Forecast, Negotiate, Manage
Energy “Slack”

Thermostatically Controlled Load

- IPS
- Set Point
- Guard band

Graphs showing temperature and slack over time.
Supply-Following Loads

Expanded Guard band

Oblivious
Supercool
Wide Guardband

Portfolio Energy Renewable Energy Saved Energy

% of Power Mix

Power (W)

Start Energy (J/MJ)

Supply Power (W)

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Energy-aware - Supercool
Supply-Following Computational Loads

Background Processing (shiftable)

QoS (fidelity & latency)

Controllable Storage

IPS

Requests
Availability
Forecasts

Power

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QoS 2011
Wind-Aware Computational Science Clusters

![Diagram of Work and Slack with Start Time, Duration, and Deadline](image1)

![Graph of Coefficient of variation in wind energy availability](image2)

![Graphs of Cluster Wind Energy, Cluster Grid Energy, and Wind Power](image3)

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... and in buildings

Figure 3. Annual energy use for the prototype in San Francisco with VAV minimum fractions at 10%, 20%, and 30%.
Model Predictive Control

Whole Bldg

LoCal

AC
Cool Air

Thermostat
AC Signal

Sensor Data →
AC Control

Room

Equipment and Occupants

sMAP
Sensor Data
Weather Forecast

Internet

LoCal Server

Control Computer

inst Lab 199
HVAC

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Measure => Model => Mitigate

- Mathematical model from Newton’s law of cooling

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

- Model identified using semi-parametric regression

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

Heating from occupants and equipment

(Aswani, Taneja, Master, Culler, Tomlin, 2011, submitted)
Experimental Hysteresis Control: 31.7 kWh Consumed

Temperature

Control Action

Simulated LBMPC: 19.0 kWh 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, submitted)
Cyber / Physical Buildings

Cyber

Physical Building

Activity Models

Physical Models

BIM

Building Integrated Operating System

Multi-Objective Model-Driven Control

Fault, Attack, Anomaly Detect & Management

Control Plan and Schedule

Activity/Usage Streams

Pervasive Sensing

Legacy Instrumentation & Control Interfaces

Occupant Demand

Process Loads

Transport

Light

Electrical

HVAC

BMS

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CPS contributions …

• Pervasive Embedded Monitoring Networks
• Power Proportional Design Techniques
• Application Independent Physical Information Representation
• Modeling and Analysis
• Multi-objective Intelligent Control
Personal View into the Energy World

MetaData
Data
Repository & Services

Object Information

Rad Lab Refrigerator

ENERGY STAR qualified for lower utility bills, the GE MFD2562VE model can handle 26 cu. ft. of groceries and features the SmoothClose glide-out freezer drawer that’s easy to open and close, even when full. Plus, for fresh-tasting water on the double, the door opens to the PureChiller internal water dispenser with PUR retractable filter.

Available Services:
- “Energy” - Public Access
- “Actuation” - Private Access
- “User History” - Root Access

Services

- “Energy” Service
- Graph Energy Usage
  Visualize average power of appliance.
- “Actuation” Service
- "User History" Service

Avg. Energy Usage - Last Five Hours

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A MultiScale Study

[Diagram showing various components such as Internet, Grid, Energy Network, Data center, and Power proportional service manager.]

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The Grid – What’s Broken

Generation
Transmission
Distribution
Load
System Design for Scale

• Decoupling, Modularity
• Divide & Conquer
• Building Block + Rule of Composition
• Interface, API, Protocol

• System properties defined at the interfaces
each side must meet its responsibility
  – Generous on receive, Strict on Transmit
  – Level-restoring Logic, Routers, Objects, …
The Grid – The Fix

Generation
Transmission
Distribution
Load

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Intelligent Power Switch

- PowerComm Interface: Network + Power connector
- Scale Down, Scale Out

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A Minimal IPS

AC In → 14 V DC Power Supply → Battery Charge Controller → Load Controller → Inverter → AC Out

<table>
<thead>
<tr>
<th>Utility AC</th>
<th>ON</th>
<th>OFF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output OFF</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>CHG Battery</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>Run from Battery</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>Run from Utility</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>Charge and Run</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

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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
Thanks