Results from the Cory Hall Building-to-Grid (B2G) Testbed

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University of California, Berkeley
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“Energy permits things to exist; information, to behave purposefully.”
W. Ware, 1997
The Industrial Age Grid

Baseline + Dispatchable Tiers

Generation → Transmission → Distribution → Demand

Nearly Oblivious Loads
Imagine an Energy “Aware” Infrastructure

Baseline + Dispatchable Tiers

Transmission

Distribution

Demand

Oblivious Loads

Non-Dispatchable Sources

Communication

Aware Interactive Loads

Transmission

Generation

Demand

Distribution

Communication
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
Our Buildings

- <20% Power Prop.
- Wasteful
- Predictable
- Sculptable?
Our Buildings

Use

Servers, PDUs, CRACs

HVAC

IT and Plug Load

Lighting

Design

Annual Consumption

Environmental

Operational

kWh/sq ft

0
2,000,000
4,000,000
6,000,000
8,000,000
10,000,000
12,000,000

KL

Soda

McCones

Kos

LSA

Cory

National average

Non

01/05

Custom period: 2008-01-05

Soda Hall Power Consumption: 494 KW

Chart by amCharts.com

22:00 - 22:00
Cory B2G Testbed

- Pervasive monitoring of a large complex load
- To understand energy spend, reduce it, forecast
- and optimize in concert with an intelligent grid

Conventional Electric Grid

- Generation
- Transmission
- Distribution
- Load

Conventional Internet
Building-Scale Monitoring Architecture
The 3 Views

Environments & Activity

Climate Plant

- Cooling Tower
- Condenser Pump
- Chiller
- Chilled Water Pump
- Air Handling Unit
- Reheater
- Air Conditioner
- Return Air Vent
- Supply Air Fan

Exhaust Air Fan

Load Tree

- CT: mains power monitoring
- panel level power monitoring
- ACme: plug load energy monitor and controller

Building Environmental Manufacturing Infrastructure

Load Tree Diagram

- Load Tree: Machine Room, 1st Floor, 2nd Floor, 3rd Floor, Electrical Panel, Machine Shop, 4th Floor Lighting, 4th Floor Family, Light Zones, Power Strip, Power Strip, Power Strip

- Load Tree Diagram with Environment & Activity

- Temperature
- Humidity
- Vibration
- Pressure
Audit Methodology

- **Measure** the envelope
- **Map** the underlying load tree
- **Identify** major load points
- **Model, Instrument, Disaggregate**
  - specific instrument and analysis selection
- Apply recursively
The Total Bldg Envelope
State of the Art …
Layered Architecture

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

Analysis
- Presentation
- Logical
- Physical
Physical Tier

• 12 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
Power Flows
Electric Tree Monitoring

ION6200: mains power monitoring

DENT PowerScout18: branch level

VERIS E30: panel level

AC Meter: plug level monitoring and control
Main Switch Block

12.5kV 3 Phase

ION 6200

PSL PQUBE (2)

480V 3 Phase

Dent PowerScout (10)

RS-485

sMAP

eth0:pn-CEC

Ethernet VLAN

sMAP
• Connectivity: RS-485 – multi-drop serial protocol
  – need register map to interpret
• Data model: Modbus ("everything is a 16-bit register")
  – six circuits supported
• Three-phase power measurements
  – about 50 “channels” per three-phase circuit
• Registers updated at 2Hz
Ready for the Shutdown
Go
<table>
<thead>
<tr>
<th>Protocol</th>
<th>Year</th>
<th>Network</th>
<th>Target Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modbus</td>
<td>1979</td>
<td>RS-485, TCP/IP</td>
<td>Industrial Control</td>
</tr>
<tr>
<td>Fieldbus/HART</td>
<td>1988</td>
<td>various</td>
<td>Industrial Control</td>
</tr>
<tr>
<td>WirelessHART</td>
<td>2007</td>
<td>802.15.4e</td>
<td>Industrial control, wire replacement</td>
</tr>
<tr>
<td>SEP 2.0</td>
<td>2010</td>
<td>802.15.4</td>
<td>Home automation</td>
</tr>
</tbody>
</table>

- HUGE installed/legacy base
- Multiple generations of hardware and software in the same building
- Typical integration: proprietary vertical BMS
  - Data in at the bottom
  - Data products out at the top
<table>
<thead>
<tr>
<th>Type</th>
<th>Name</th>
<th>Connectivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric</td>
<td>ION6200</td>
<td>XML/proprietary</td>
</tr>
<tr>
<td>Electric branch meter</td>
<td>Dent Powerscout 3/18</td>
<td>Modbus/RS-485</td>
</tr>
<tr>
<td>Electric branch meter</td>
<td>PSL PQube</td>
<td>HTML table</td>
</tr>
<tr>
<td>Electric panel meter</td>
<td>Veris E30</td>
<td>Modbus/RS-485</td>
</tr>
<tr>
<td>Electric home meter</td>
<td>GE</td>
<td>ANSI C12.19/IR</td>
</tr>
<tr>
<td>Chilled water</td>
<td></td>
<td>4-20mA current loop</td>
</tr>
<tr>
<td>Steam condensate</td>
<td></td>
<td>Modbus/TCP</td>
</tr>
<tr>
<td>Environmental</td>
<td>Sun Blackbox</td>
<td>XML/proprietary</td>
</tr>
<tr>
<td>PCT (programmable thermostat)</td>
<td>Basys QW Series</td>
<td>Zigbee</td>
</tr>
<tr>
<td>Climate</td>
<td>Hydrowatch node</td>
<td>6lowpan/IPv6</td>
</tr>
</tbody>
</table>
Key Enabler: Hardware Abstraction

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

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

sMAP
IP Everywhere

sMAP Resources

sMAP
EBHTTP / IPv6 / 6LowPAN Wireless Mesh Network

sMAP
Vibration / Humidity

sMAP
Light switch

sMAP
Dent circuit meter

sMAP
Modbus

EBHTTP Translation
Proxy Server

sMAP Gateway

sMAP Gateway

RS-485

Applications

Internet

Google PowerMeter

Cell phone

Every Building

Database

IP Everywhere
sMAP restful web services

<table>
<thead>
<tr>
<th>URL</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>/</td>
<td>list resource under URI root [GET]</td>
</tr>
<tr>
<td>/data</td>
<td>list sense points under resource data [GET]</td>
</tr>
<tr>
<td>/[sense_point]</td>
<td>select a sense points [GET]</td>
</tr>
<tr>
<td>/meter</td>
<td>meters provide this service [GET]</td>
</tr>
<tr>
<td>/[channel]</td>
<td>a particular channel [GET]</td>
</tr>
<tr>
<td>/reading</td>
<td>meter reading [GET]</td>
</tr>
<tr>
<td>/format</td>
<td>calibration and units [GET/POST]</td>
</tr>
<tr>
<td>/parameter</td>
<td>sampling parameter [GET/POST]</td>
</tr>
<tr>
<td>/profile</td>
<td>history of readings [GET]</td>
</tr>
<tr>
<td>/reporting</td>
<td>create and query periodic reports [GET/POST]</td>
</tr>
</tbody>
</table>

POST requests supply JSON objects as arguments:

```json
POST: http://meter1.cs.berkeley.edu/reporting/create
{
  "ReportResource" : "/data/325/meter/*/reading",
  "Period" : 0, "Minimum" : 50, "Maximum" : 100 }
```
Typical Interaction

• Discover sMAP Instance
• Read/Poll
  – GET /data/ABC/sensor/real_power/formatting
  – GET /data/*//*/reading
• Subscribe
  – Create reporting instance with HTTP URL for “callback”
  – Specify fixed rate or each new report
  – Persists until deleted, times out, or fails
  – Incremental update (part of a resource) sometimes necessary
Design: Dent Powerscout 18

<table>
<thead>
<tr>
<th>Sense Point</th>
<th>Description</th>
<th>Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, B, C</td>
<td>Single-phase</td>
<td>real, apparent, reactive power + energy.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>power factor.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>current.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>phase-neutral voltage.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>phase-neutral voltage.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>voltage.</td>
</tr>
<tr>
<td>AB, BC, AC</td>
<td>Phase-to-phase</td>
<td>voltage.</td>
</tr>
<tr>
<td>ABC</td>
<td>Whole-circuit</td>
<td>real, apparent, reactive power + energy.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>power factor.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>current.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>phase-neutral voltage.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>line frequency.</td>
</tr>
</tbody>
</table>
Open Standards => Horizontal Integration

sMAP

Dent
Veris
PSL
Acme
ISO
SCADA
Obvius
Wunderground
sMAP – homogeneous access to heterogeneous information
Web Applications

sMAP

Amazon

Cloud

EveryBuilding

Push

{  
  "ReportResource" : "/data/ABC/sensor/true_power/reading",
}

{  
  "ReportResource" : "/data/*//*/*/reading",
  "ReportDeliveryLocation" : http://...amazonaws.com/append/basement-1-elt-A"
}

Dumping info for archive '5DPA1-elt-A'

DATA STORES
-------------------------------
/mnt/cory-vol/5DPA1-elt-A/2010-05-05T01:29:36.dat.gz| 4320-8639
/mnt/cory-vol/5DPA1-elt-A/2010-05-06T01:34:36.dat.gz| 8640-12959
/mnt/cory-vol/5DPA1-elt-A/2010-05-07T01:42:35.dat.gz| 12960-17279
/mnt/cory-vol/5DPA1-elt-A/2010-05-08T01:47:37.dat.gz| 17280-21599
/mnt/cory-vol/5DPA1-elt-A/2010-05-09T01:53:35.dat.gz| 21600-25919
/mnt/cory-vol/5DPA1-elt-A/2010-05-10T23:03:43.dat.gz| 30240-34559

INDICES
-------------------------------
ReadingTime

[Image: Diagram of sMAP and EveryBuilding with data stores and indices]
sMAP Ecosystem at Berkeley

- Gateways for legacy devices; native implementations for new ones
- Library of 8 different devices – currently represents XML/CSV feeds, Modbus, and embedded (mode-class)
Power Breakdown

sMAP Aggregate Plotting Engine

http://smap.cs.berkeley.edu/db/plot/?aggid=1&start=1278572880&end=1278659280

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Data tells stories...

- Monitor Based Commissioning
  - Eliminate simultaneous heat/cool
  - AC91 on schedule
* Will continue decline on circuit 4PE as tools move.
Figure 3-7
Condensate flowing to drain

FINAL REPORT
MBCX PROJECT:
CORY HALL
UNIVERSITY OF CALIFORNIA
BERKELEY

Table 3-1
Condensate pump and steam trap repair savings

<table>
<thead>
<tr>
<th>Energy</th>
<th>Savings at Building</th>
<th>Savings at Campus Meter</th>
<th>Cost Savings ($/therm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam</td>
<td>9,099 Thers</td>
<td>11,734 Thers</td>
<td>$11,374</td>
</tr>
</tbody>
</table>

2010-03-23T16:14:21-07:00 INFO: loaded 'http://local.cs.berkeley.edu:8007/data/steam/sensor/0/profile'
2010-03-23T16:14:21-07:00 INFO: loaded 'http://local.cs.berkeley.edu:8007/data/steam/sensor/0/formatting'
Extracting Deeper

MCL-eth-A – 26-April

5PA-eth-A – 26-April

35B-eth-A – 26-April

Reactive power delta (kVAR)

Real power delta (kW)

Date

Real power (kW)

Date

Real power (kW)
Energy “Slack” Example

Thermostatically Controlled Load

IPS

![Temperature Graph]

![Humidity Graph]

![Power Graph]
Supply-Following Loads

- Portfolio Energy
- Renewable Energy
- Saved Energy

Oblivious
Supercool
Wide Guardband

Energy Used (kWh)

Supply Power (kW)

Time

Energy-aware - Wide Guardband
MELs with LBNL

Figure 3.6. Percent time and energy in power modes for 19 computers metered over a work week. Each column represents an individual computer sorted from left to right by increasing energy use. Energy use is dominated by time in the on (active) mode even when time in that mode is small.
Demos

• Schedule and Tree
  – http://jackalope.cs.berkeley.edu:3000/tree

• Time series
  – http://smap.cs.berkeley.edu/db/plot/?
    stream=249&start=1270702260&end=1278651060&sub=5

• Time-series-difference scatter plot
  – http://smap.cs.berkeley.edu/db/plot/vs.html

• Aggregates
  – http://smap.cs.berkeley.edu/db/plot/agg.html
Phone App

http://local.cs.berkeley.edu:8011/data/325/

http://local.cs.berkeley.edu:8011/data/325/sensor/real_power/profile
Basis for Grid-Responsive Bldgs

Portable Applications
- Modeling
- Debugging
- Continuous Commissioning
- Personal Feedback
- Actuation and Control
- Visualization

Core Services
- IS4 (storage)
- Location
- Authentication

sMAP Interface
IPv6 / 6LowPAN Wireless Mesh Network
Proxy
SCADA
Modbus

Authentication
Location
Core Services
...
Stages of Energy Effectiveness

• Waste elimination
  – Do Nothing Well !!!

• Power Proportionality
  – Power : Performance (utilization)
  – Partial Load - from nothing to peak

• Sculpting
  – Identify the energy slack and utilize it

• Negotiated Grid / Load / Human Interaction
  – Plan, Forecast, Negotiate, Manage
Building Scale Monitoring Architecture

Diagram showing various components and connections such as JSON Schema, Verisschema, IPv6 / 6LowPAN Wireless Mesh Network, PAR/TSR, ACme, Temperature, Humidity, Edge Router, Internet, Database, Weather, Season, Occupancy, AutoShutDownManager, Server Load, etc.

Key components include:
- Generation
- Transmission
- Distribution
- Load
- Electric Grid

Connections and data flow through external info bus, physical information bus, and user info bus.
Intelligent Energy Network

- Availability
- Pricing
- Planning

Intelligent Power Switch

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

- Forecasting
- Tracking
- Market

Source IPS

Buffer IPS

Load IPS

energy subnet
A New View

[Diagram showing various loads and systems including Occupant Loads, Process Loads, Transport, Light, Electrical, HVAC, and BMS.]
Cyber / Physical Buildings

Cyber

- Activity Models
- Physical Models
- BIM
- Building Integrated Operating System
- Multi-Objective Model-Driven Control
- Fault, Attack, Anomaly Detect & Management

Physical Building

- Process Loads
- Transport
- Light
- Electrical
- HVAC
- Human-Building Interface

- Occupant Demand

- Control Plan and Schedule
- Activity/Usage Streams
- Pervasive Sensing
- Legacy Instrumentation & Control Interfaces

- External
- BITs

Building Integrated Operating System

- External
- Activity Models
- Physical Models