Addressing the Energy-Water Nexus in Sustainable Buildings & Communities

Mani Srivastava
mbs@ucla.edu
EE Dept. and CS Dept.
Networked & Embedded Systems Lab
UCLA
Energy and Water

Water for Energy
- Extraction & Refining
  - Fuel Production (Ethanol, hydrogen)
- Hydropower
- Thermo electric Cooling
- Extraction and Transmission
- Energy Associated with Uses of Water
- Drinking Water Treatment

Energy for Water

Source: Paul Reiter, International Water Association
It takes Water to make Energy

- Used in extraction of fuel, generation of electricity
  - Hydrofracking, plant cooling, coal washing, evaporative loss etc.
  - 40% of fresh water usage: equals that used in agriculture

<table>
<thead>
<tr>
<th>Electricity Generation Technology</th>
<th>Gallons of Water per MWh of Electricity</th>
<th>Gallons of Water for 60W light bulb for 1 year @ 12 hr/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas/Steam</td>
<td>7,400-20,000</td>
<td>1,945-5,256</td>
</tr>
<tr>
<td>Coal &amp; Oil</td>
<td>21,000-50,000</td>
<td>5,519-13,140</td>
</tr>
<tr>
<td>Nuclear</td>
<td>25,000-60,000</td>
<td>6,570-15,768</td>
</tr>
</tbody>
</table>

Source: Michael E. Webber, Scientific American, 2008.
And, it takes Energy to provide Water: “Water Embedded Energy” or “Watergy”

- World: 2-3% of world’s energy consumption for urban water usage
- US: 4% or 56 billion kWh/yr (enough for 5M homes) [EPA]
- CA (2001): 19% of electricity, 32% of natural gas [CEC]
- Punjab, India: 28% of total electricity consumption is attributed to tube-wells

And, it takes Energy to provide Water: “Water Embedded Energy” or “Waternergy”

- World: 2-3% of world's energy consumption for urban water usage
- US: 4% or 56 billion kWh/yr (enough for 5M homes) [EPA]
- CA (2001): 19% of electricity, 32% of natural gas [CEC]
- Punjab, India: 28% of total electricity consumption is attributed to tube-wells

Energy-Water Nexus in Buildings

- 73% of electricity
- 41% of total energy
- 34% of natural gas
Energy-Water Nexus in Buildings

- Buildings consume lots of energy

- 73% of electricity
- 41% of total energy
- 34% of natural gas
Energy-Water Nexus in Buildings

- Buildings consume lots of energy
  - thus, lots of water indirectly

![Bar chart showing energy consumption]

Source: Energy Analytics Office (EAO)
Energy-Water Nexus in Buildings

- Buildings consume lots of energy
  - thus, lots of water indirectly

- Buildings consume 12% water
  - but one that is very energy intense

**Figure 17**

*Residential Primary Energy End-Use Splits, 2006*

<table>
<thead>
<tr>
<th>End-Use</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space Heating</td>
<td>3.6%</td>
</tr>
<tr>
<td>Space Cooling</td>
<td>1.0%</td>
</tr>
<tr>
<td>Water Heating</td>
<td>4.7%</td>
</tr>
<tr>
<td>Lighting</td>
<td>6.2%</td>
</tr>
<tr>
<td>Electronics</td>
<td>7.2%</td>
</tr>
<tr>
<td>Refrigeration</td>
<td>8.1%</td>
</tr>
<tr>
<td>Wet Clean</td>
<td>11.6%</td>
</tr>
<tr>
<td>Cooking</td>
<td>12.4%</td>
</tr>
<tr>
<td>Computers</td>
<td>26.4%</td>
</tr>
<tr>
<td>Other</td>
<td>12.7%</td>
</tr>
<tr>
<td>* Energy Adjustment</td>
<td>5.7%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>7.2%</strong></td>
</tr>
</tbody>
</table>


**Figure 18**

*US Commercial, 2006*

<table>
<thead>
<tr>
<th>End-Use</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lighting</td>
<td>3.8%</td>
</tr>
<tr>
<td>Space Cooling</td>
<td>4.1%</td>
</tr>
<tr>
<td>Space Heating</td>
<td>6.3%</td>
</tr>
<tr>
<td>Electronics</td>
<td>6.3%</td>
</tr>
<tr>
<td>Refrigeration</td>
<td>7.5%</td>
</tr>
<tr>
<td>Water Heating</td>
<td>12.1%</td>
</tr>
<tr>
<td>Computers</td>
<td>12.7%</td>
</tr>
<tr>
<td>Cooking</td>
<td>13.2%</td>
</tr>
<tr>
<td>Other</td>
<td>24.8%</td>
</tr>
<tr>
<td>* Energy Adjustment</td>
<td>5.7%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>11.6%</strong></td>
</tr>
</tbody>
</table>

Energy-Water Nexus in Buildings

- Buildings consume lots of energy
  - thus, lots of water indirectly

- Building consume 12% water
  - but one that is very energy intense

<table>
<thead>
<tr>
<th>Location</th>
<th>kWh/MG</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>3,263</td>
</tr>
<tr>
<td>Northern CA (indoor)</td>
<td>5,411</td>
</tr>
<tr>
<td>Northern CA (outdoor)</td>
<td>3,500</td>
</tr>
<tr>
<td>Southern CA (indoor)</td>
<td>13,021</td>
</tr>
<tr>
<td>Southern CA (outdoor)</td>
<td>11,110</td>
</tr>
</tbody>
</table>
Energy-Water Nexus in Buildings

- Buildings consume lots of energy
  - thus, lots of water indirectly

- Building consume 12% water
  - but one that is very energy intense

### TOTAL ENERGY IMPACT OF WATER USE IN BUILDINGS (CA)

<table>
<thead>
<tr>
<th></th>
<th>Electricity (GWh)</th>
<th>Natural Gas (Million Therms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Uses</td>
<td>250,494</td>
<td>13,571</td>
</tr>
<tr>
<td>Water Related</td>
<td>48,012</td>
<td>4,284</td>
</tr>
<tr>
<td>Urban Water</td>
<td>37,453</td>
<td>4,239</td>
</tr>
<tr>
<td>Residential + Commercial</td>
<td>29,371</td>
<td>2,330</td>
</tr>
<tr>
<td>Residential</td>
<td>18,168</td>
<td>2,077</td>
</tr>
<tr>
<td>Commercial</td>
<td>11,202</td>
<td>253</td>
</tr>
</tbody>
</table>

Towards a Smart Grid for Water

- **Smart water meters**
  - Leak alert
  - Pressure & quality management
  - Enforcement of water usage restrictions
  - Feedback to user

- **Better management of water networks**
  - Detect theft, faulty meters, and leaks
    - 40% leak loss, 47% UFW in Delhi
  - Reduce and diagnose mains breaks

- **Time-of-Use and Demand Pricing**
  - Water sensitive to variations in energy prices
  - Complexity of tariffs
    - delay between energy consumption and water use

- **Help with peak electric load shifting**
  - 30-40% of electricity in mid-size cities used by water wand waste-water utilities
  - Stored water and treated water as an energy assets
    - ~1500 MW of peak power shifting in CA

---

Revised Water Conservation Ordinance

as of: 8/25/10

Restricted to 3 Days a Week

Lawn-watering rules contributed to L.A. main breaks, experts find

Extreme changes in water pressure combined with aging infrastructure to create spectacular blowouts.

April 13, 2010 | By David Zahniser and Jessica Garrison
For truly sustainable buildings and communities, co-management of energy and water is essential.
How can IT help?

- **Replace**
  - Old Inefficient Appliances & Devices with New Efficient Ones

- **Detect & Repair**
  - Degradations and Failures in Building Infrastructure

- **Control Loads**
  - to Reduce Wastage and Manage Consumption

- **Modify Behavior**
  - of Building Users to Conserve Energy and Water
How can IT help?

- **Replace**
  Old Inefficient Appliances & Devices with New Efficient Ones

- **Detect & Repair**
  Degradations and Failures in Building Infrastructure

- **Control Loads**
  to Reduce Wastage and Manage Consumption

- **Modify Behavior**
  of Building Users to Conserve Energy and Water

Which measures would work best from cost-benefit perspective for a building?
Information Technology can provide fine-grained **observability** *(how much? where? when? by whom? in what activity?)* and **controllability** of energy and water consumption.
Buildings as Human-Cyber-Physical Systems

Cyber
Infer-Model-Predict

Physical
(Building, Environment)

Human
Comfort, Productivity

SENSE STATE
CONTROL SUBSYSTEMS

SENSE STATE & PREFERENCES
MODIFY BEHAVIOR

AFFECT BEHAVIOR
RECONFIGURE
Human-aware Building Management

**Sense**
- Ambient & Physical Environment
- Disaggregated Energy & Water Consumption
- Occupant Behavior & Location

**Infer, Model, Predict**
- Fault & Inefficiency Detection
- Energy & Water Management
- Personalized Consumption Apportionment

**Control**
- Building Plant Actuation
- Occupant Feedback & Incentives

- Control the building
- Influence the occupants

End User
- Ambient Displays
- Dashboards
Research @ UCLA/CENS

**Sense**
- Ambient & Physical Environment
- Disaggregated Energy & Water Consumption
- Occupant Behavior & Location

**Infer, Model, Predict**
- Fault & Inefficiency Detection
- Energy & Water Management
- Personalized Consumption Apportionment

**Control**
- Building Plant Actuation
- Occupant Feedback & Incentives

**Viridiscope “Virtual Metering” System**
- Control the building
- End User
  - Ambient Displays
  - Dashboards
- Influence the occupants

Monday, June 27, 2011
Research @ UCLA/CENS

Sense

- Ambient & Physical Environment
- Disaggregated Energy & Water Consumption
- Occupant Behavior & Location

Infer, Model, Predict

- Personalized Consumption Apportionment
- Fault & Inefficiency Detection
- Building Plant Actuation

Year long study in UCLA dorm with 102 students in 65 rooms
Feedback about electricity use
Peer-pressure: rating of fellow residents via red/green dot
30% reduction in HVAC usage

Engage Study (Kaiser, Delmas)

Year long study in UCLA dorm with 102 students in 65 rooms
Feedback about electricity use
Peer-pressure: rating of fellow residents via red/green dot
30% reduction in HVAC usage

End User
- Ambient Displays
- Dashboards

Influence the occupants
Research @ UCLA/CENS

Sense

Ambient & Physical Environment
Disaggregated Energy & Water Consumption
Occupant Behavior & Location

Infer, Model, Predict

Fault & Inefficiency Detection
Energy & Water Management
Personalized Consumption Apportionment

Control

Building Plant Actuation
Occasional Feedback & Incentives
End User
Ambient Displays
Dashboards

Spotlight System

Control the building

End User

Influence the occupants

Monday, June 27, 2011
Research @ UCLA/CENS

Sense

- Ambient & Physical Environment
- Disaggregated Energy & Water Consumption
- Occupant Behavior & Location

Infer, Model, Predict

- Fault & Inefficiency Detection
- Energy & Water Management
- Personalized Consumption Apportionment

Control

- Building Plant Actuation
- Occupant Feedback & Incentives

Emerging Collaboration with IIITD & IBM IRL

Control the building

Influence the occupants

End User

Ambient Displays

Dashboards

Monday, June 27, 2011
Sensing Substrate

Sense

- Ambient & Physical Environment
- Disaggregated Energy & Water Consumption
- Occupant Behavior & Location

Infer, Model, Predict

- Inefficiency Detection
- Energy & Water Management
- Infer, Model, Predict

Control

- Building Plant Actuation
- Control

Challenge

Cost: $2-3/sqft-yr energy in US buildings

Scalability: large # of temporally overlapping and spatially distributed resource usage events

Ease: deployment, calibration, maintenance

Monday, June 27, 2011
Sensing for Energy & Water Use Disaggregation

Direct Metering

AC Plug
Current Transducers
Energy Meter
Current
Voltage
Appliance

Direct Metering

Water Pipe
Direct Sensor
In-line Water Flow Meter
Sensing for Energy & Water Use Disaggregation

<table>
<thead>
<tr>
<th>Direct Metering</th>
<th>Direct Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Plug</td>
<td>In-line Water Flow Meter</td>
</tr>
<tr>
<td>Current Transducers</td>
<td>Water Pipe</td>
</tr>
<tr>
<td>Energy Meter</td>
<td>Direct Sensor</td>
</tr>
<tr>
<td>Voltage</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th># of Sensors</th>
<th>Direct</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cost/Sensor</th>
<th>Direct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium - High</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sensor Installation</th>
<th>Direct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Difficult</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Calibration</th>
<th>Direct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factory</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Accuracy Scaling</th>
<th>Direct</th>
</tr>
</thead>
<tbody>
<tr>
<td>→</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cost Scaling</th>
<th>Direct</th>
</tr>
</thead>
<tbody>
<tr>
<td>↑</td>
<td></td>
</tr>
</tbody>
</table>
Sensing for Energy & Water Use Disaggregation

<table>
<thead>
<tr>
<th></th>
<th>Direct</th>
<th>Signature</th>
</tr>
</thead>
<tbody>
<tr>
<td># of Sensors</td>
<td>N</td>
<td>1</td>
</tr>
<tr>
<td>Cost/Sensor</td>
<td>Medium - High</td>
<td>High - Very High</td>
</tr>
<tr>
<td>Sensor Installation</td>
<td>Difficult</td>
<td>Easy</td>
</tr>
<tr>
<td>Calibration</td>
<td>Factory</td>
<td>Training</td>
</tr>
<tr>
<td>Accuracy Scaling</td>
<td>↑</td>
<td>↓</td>
</tr>
<tr>
<td>Cost Scaling</td>
<td>↑</td>
<td>→</td>
</tr>
</tbody>
</table>
Sensing for Energy & Water Use Disaggregation

Virtual Metering
- AC Plug
- Indirect Sensor (Magnetic, Light, Acoustic)
- Energy Inference Engine
- Appliance

Virtual Metering
- Water Pipe
- Indirect Sensor (Vibration Sensor)
- Flow Rate Inference Engine

Viridiscope System @ CENS/UCLA

<table>
<thead>
<tr>
<th></th>
<th>Direct</th>
<th>Signature</th>
<th>Virtual</th>
</tr>
</thead>
<tbody>
<tr>
<td># of Sensors</td>
<td>N</td>
<td>1</td>
<td>N</td>
</tr>
<tr>
<td>Cost/Sensor</td>
<td>Medium - High</td>
<td>High - Very High</td>
<td>Low - Medium</td>
</tr>
<tr>
<td>Sensor Installation</td>
<td>Difficult</td>
<td>Easy</td>
<td>Easy</td>
</tr>
<tr>
<td>Calibration</td>
<td>Factory</td>
<td>Training</td>
<td>Automatic</td>
</tr>
<tr>
<td>Accuracy Scaling</td>
<td>➝</td>
<td>↓</td>
<td>➝</td>
</tr>
<tr>
<td>Cost Scaling</td>
<td>↑</td>
<td>➝</td>
<td>↑</td>
</tr>
</tbody>
</table>
Sensing for Energy & Water Use Disaggregation

Wireless sensors still way too costly.
Signature analysis has limits & issues.
What will be the eventual solution?

<table>
<thead>
<tr>
<th></th>
<th>Direct</th>
<th>Signature</th>
<th>Virtual</th>
</tr>
</thead>
<tbody>
<tr>
<td># of Sensors</td>
<td>N</td>
<td>1</td>
<td>N</td>
</tr>
<tr>
<td>Cost/Sensor</td>
<td>Medium-High</td>
<td>High-Very High</td>
<td>Low-Medium</td>
</tr>
<tr>
<td>Sensor Installation</td>
<td>Difficult</td>
<td>Easy</td>
<td>Easy</td>
</tr>
<tr>
<td>Calibration</td>
<td>Factory</td>
<td>Training</td>
<td>Automatic</td>
</tr>
<tr>
<td>Accuracy Scaling</td>
<td>→</td>
<td>↓</td>
<td>↘</td>
</tr>
<tr>
<td>Cost Scaling</td>
<td>↑</td>
<td>→</td>
<td>↑</td>
</tr>
</tbody>
</table>
Viridiscope: An Auto-calibrating Fine-grained Water & Energy Metering Instrument

Cons

ption rate at main meter = \sum_{\forall i} \text{(Consumption rate at } i\text{-th end-point)}

or, \( M_R(t) = \sum_{\forall i} R_i(t) \)
Viridiscope: An Auto-calibrating Fine-grained Water & Energy Metering Instrument

Un-calibrated Indirect Sensors

Automatic Model Calibration

Real-time Main-meter Monitor

Consumption rate at main meter = \( \sum_{i} \text{(Consumption rate at } i\text{-th end-point)} \)

or, \( M_R(t) = \sum_{i} R_i(t) \)
Viridiscope: An Auto-calibrating Fine-grained Water & Energy Metering Instrument

Un-calibrated Indirect Sensors

Automatic Model Calibration

Real-time Main-meter Monitor

Model-based Appliance Power & Water Use Inferencing

Un-calibrated Indirect Sensors → Model-based Appliance Power & Water Use Inferencing → Normalized Estimation Error

Recalibration Trigger

Real-time Main-meter Monitor
Viridiscope: An Auto-calibrating Fine-grained Water & Energy Metering Instrument
Disaggregated Output: Energy

<table>
<thead>
<tr>
<th>Appliance</th>
<th>True Power[W]</th>
<th>Estimate<a href="Error">W</a></th>
</tr>
</thead>
<tbody>
<tr>
<td>Light 1</td>
<td>59.8</td>
<td>58.4(-2.32%)</td>
</tr>
<tr>
<td>Light 2</td>
<td>31.9</td>
<td>34.2(7.02%)</td>
</tr>
<tr>
<td>Massage Chair</td>
<td>46.2</td>
<td>45.8(-1%)</td>
</tr>
<tr>
<td>Table Lamp 1</td>
<td>68.1</td>
<td>69.3(1.73%)</td>
</tr>
<tr>
<td>Table Lamp 2</td>
<td>14.7</td>
<td>15(2.54%)</td>
</tr>
<tr>
<td>Water Heater</td>
<td>1623.6</td>
<td>1620.6(-0.18%)</td>
</tr>
<tr>
<td>TV</td>
<td>100.1</td>
<td>101(0.94%)</td>
</tr>
<tr>
<td>Laptop 1</td>
<td>38.9</td>
<td>38.3(-1.45%)</td>
</tr>
<tr>
<td>Laptop 2</td>
<td>31.4</td>
<td>29.2(-7%)</td>
</tr>
</tbody>
</table>
Disaggregated Output: Water

### Water Flow Rate Estimate of Pipe1 and Pipe2

<table>
<thead>
<tr>
<th>time (s)</th>
<th>Flow Rate (L/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Estimated Sum</td>
</tr>
<tr>
<td></td>
<td>Estimated Pipe1</td>
</tr>
<tr>
<td></td>
<td>Estimated Pipe2</td>
</tr>
</tbody>
</table>

### True Water Flow Rate Estimate in the main pipe

<table>
<thead>
<tr>
<th>time (s)</th>
<th>Flow Rate (L/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>True Sum</td>
</tr>
<tr>
<td></td>
<td>True Pipe2</td>
</tr>
</tbody>
</table>

### Water Use by End-point

<table>
<thead>
<tr>
<th>Pipe Type</th>
<th>Error(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper 3/4&quot;</td>
<td>2.7</td>
</tr>
<tr>
<td>PVC 3/4&quot;</td>
<td>3.07</td>
</tr>
<tr>
<td>PVC 1&quot;</td>
<td>4.02</td>
</tr>
<tr>
<td>Copper 1/8&quot;</td>
<td>3.5</td>
</tr>
<tr>
<td>Threaded Stainless 1/4&quot;</td>
<td>2.7</td>
</tr>
<tr>
<td>Stainless 3/4&quot;</td>
<td>1.34</td>
</tr>
<tr>
<td>Stainless 1 3/4&quot;</td>
<td>0.41</td>
</tr>
<tr>
<td>Plastic Hose</td>
<td>2.56</td>
</tr>
<tr>
<td>Fine Threaded Stainless 1/4&quot;</td>
<td>0.02</td>
</tr>
<tr>
<td>Fine Threaded Stainless 1/4&quot;</td>
<td>1.57</td>
</tr>
</tbody>
</table>

---

**Monday, June 27, 2011**
Sensing Occupant Activity

- **Direct sensors**: RFID, PIR, Biometric, Camera etc.
  - Cost, intrusiveness, false positive/negative, insufficiently informative

- **Indirect “soft” sensors**: use available information opportunistically
  - Footprints of occupant activities on computer, phone, electrical and water networks, calendaring and room reservation systems

---

Control HVAC, Lighting etc.

Apportion Use for Feedback & Incentives
Energy Consumption in a Shared Space

OCCUPANTS

APPLIANCES

Monday, June 27, 2011
Energy Consumption in a Shared Space

Complex & Dynamic Usage Patterns

OCCUPANTS

APPLIANCES
Energy Consumption in a Shared Space

Challenging to apportion energy use to specific users
Statistical Causality Inference

Branch Circuit Monitor

Network Gateway

Granger Causality Analysis

Y G-causes X if $X[0..t] \cup Y[0..t]$ predicts $X[t+1]$ better than $X[0..t]$

$X_t = \sum_{j=1}^{m} a_j X_{t-j} + \sum_{j=1}^{m} b_j Y_{t-j} + \epsilon_t$

# of non-zeros

Monday, June 27, 2011
Statistical Causality Inference

Set of Occupants

- User1
- User2
- User3
- User4
- User5
- User6
- User7
- User8

Electric Circuits

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9

Association

Branch Circuit Monitor
Network Gateway
Granger Causality Analysis

Monday, June 27, 2011
Closing the Loop: Engaging the Occupants

- Guide occupant behavior towards a desired equilibrium

- Mechanisms
  - Information feedback
    - information that would affect occupant actions once they see it
  - Incentives
    - exploit social norms via games, competition etc. with points or other awards

- Learning and modeling challenge
  - Interaction of an occupant with building subsystems
    - driven by ambient conditions, time of day, personal state etc.
    - capture as probabilistic priced timed automata
  - Collective interaction of a group of occupants with building subsystems
    - mediated through devices and appliances
    - dominating vs. dominated

Collaboration with Dolecek and Tabuada
Privacy Implications of Fine-grained Metering

- Very revealing of one’s personal habits and life patterns!
  - signature analysis of whole-house smart electric & water traces

![Synchronous Water/Power Usage(Bathroom Use)](image1)

![Number of Flashes in a house](image2)
• Water-Energy Nexus is a challenge, but also opportunity that can be beneficially exploited in sustainable buildings

• Informed resource usage and better management enabled by fine-grained deep inspection of consumption

• Challenges and opportunities for IT
  ‣ Cost
    - hardware, installation, calibration, and maintenance
  ‣ Human element
  ‣ Scalability
    - across building type, climatic regions, and socio-economic-regulatory environment
  ‣ Ease of use and unobtrusiveness
  ‣ Privacy
Thank you!

http://nesl.ee.ucla.edu/research/spotlight