Household Water and Energy Use - the Nexus that Connects Us

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Outline

• Perspectives on Water/Energy Analysis
• Purposes of Analysis
• Approaches to Analysis
• Alvar Escriva-Bou’s modeling results
• Hard parts/Opportunities/Conclusions
Water connects us all with each other and the world.

- Household Perspective
- Water and Energy Utility perspectives
- Society perspective – local, regional, national
- Global perspective

Each perspective has different purposes.
Purposes of Analysis - Households

- Happiness
- Minimize cost
- Reduce energy and water use
- Drought management

Households don’t pay for analysis.
Purposes of Analysis – Water & Energy Utilities

• Minimize cost
• Demand management – peak energy/water use
• Reduce energy and water use
• Drought management
• Other extreme events – outages, etc.
• Use data from smart meters, network sensors
• Utilities pay for analysis (but not enough).
Purposes of Analysis – Society

• Minimize cost
• Reduce energy and water use
• GHG emission reduction
• Drought management
• Utility and environmental regulation
• Societies pay little for analysis rarely.
Approaches to Analysis – Empirical

• Big and medium data – Econometrics, regression, machine learning – “top down”

• Advantages – Real data & experiences, immediate applicability, common methods

• Disadvantages – Conditions of calibration data, future changes, causality unclear

• Examples – Price elasticity of demand studies since Gottlieb 1963; gobs of local & meta-studies
Approaches to Analysis – Mechanistic

• Build demands from end-uses with behavioral assumptions, often optimization – “bottom up”

• Advantages – Mechanistic, detailed causal understanding of causes of demand and changes

• Disadvantages – Some end uses lack data; household motivations not completely clear; never completely mechanistic

• Examples – Rosenberg and Abdallah (2014); Escriva-Bou (2015); Lund (1995)
Alvar Escriva-Bou’s results +


Following...

1) Residential water and related energy, carbon footprint and costs in California*

– What energy and GHG emissions come from residential water end-uses?
– Does spatial variability and heterogeneity affect water and energy use?
– How do water and energy rate structures affect costs to households?

California Single-Family Home Study (over 700 households across 10 locations)

- Water end-use measurements
- Household characteristics survey
- Climates data (CIMIS stations)
- Residential Energy Consumption Survey and Energy efficiency standards for Water Heaters
- Water heater characteristics
- California Registry’s Power/Utility Workgroup
- Emission factors per energy utility

Water end-use model

- Probability distributions for parameters affecting water use
- Monte Carlo simulations
- Water Use per household as a composite of end uses
- Water rate structures

Water-related energy model

- Hot water distributions per end use
- Monte Carlo simulations
- Energy Use per household as a composite of water end uses
- Energy cost per water end use and household

Water and water-related energy costs

- Energy price

Carbon emissions

- GHG emissions per household and water end use
Water End-Use Model
Water End-Use Models

\[
Q_{\text{shower}} = \frac{(#\text{Std Shw}) \cdot (Q_{\text{Std}}) + (#\text{LowFlowShw}) \cdot (Q_{\text{LFSshw}})}{#\text{Showers}} \cdot (\text{Shower Length}) \cdot (\text{Shower Frequency}) \cdot (#\text{Residents})
\]

\[
Q_{\text{outdoor}} = \text{ET} \cdot (\text{AreaLawn} \cdot k_{\text{Lawn}} + \text{AreaGarden} \cdot k_{\text{Garden}} + \text{AreaPool} \cdot k_{\text{Pool}}) \cdot \text{ApplicationRatio}
\]

Monte Carlo analysis representing variability in 

- Household characteristics
- Users’ behaviors
- External conditions
CDF Toilet Model vs. Real Data in Davis

CDF Shower Model vs. Real Data in Davis
Water-Related Energy End-Use Model

• From End-Water Uses → Hot water, using hot water prob. distributions per end-use (EBMUD, 2002).

• Energy Calculation - WHAM (Lutz et al., 1999):

\[
Q_{in} = \frac{vol \cdot den \cdot Cp \cdot (T_{tank} - T_{in})}{\eta_re} \cdot \left(1 - \frac{UA \cdot (T_{tank} - T_{amb})}{P_{on}}\right) + 24 \cdot UA \cdot (T_{tank} - T_{amb})
\]

Household characteristics
Users’ behaviors
External conditions
California overall results per household

80% of total water-related energy
2% total per capita GHG emissions
Household water and energy per city

- Southern California:
  - Los Angeles: 170.4 kWh/day, 17.7 GPD
  - IRWD: 138 kWh/day, 20.7 GPD
  - SD City: 177 kWh/day, 25 GPD

- Northern California:
  - EBMUD: 157.2 kWh/day, 15.7 GPD
  - SCWA: 11.7 kWh/day, 11.6 GPD
  - Davis: 9.7 kWh/day, 9.7 GPD

Energy use [kWh/day]
Indoor water use [GPD]
Household water and energy costs per city
Heterogeneity in consumption

Water and Energy Use per Household

Target:
- Water savings x 2.0
- Energy & GHG emissions savings x 2.4
- Economic savings x 2.3
Results show potential for joint management
Policy implications from mechanistic modeling

• Faucet + shower ≈ 80% water-related energy
• Air and inlet temperatures affect energy use
• “Willingness to adopt” conservation depends on:
  – Current consumption
  – Household stock
  – Water and energy prices
• Targeting
  – More than doubles cost-effectiveness of rebates
2) Least-cost water conservation mix for California households considering energy

– What is the least-cost water conservation mix for households, given water and energy prices?
– Does including energy affect willingness to adopt conservation actions?
– How significant are own- and cross-price elasticities?

The economics behind the model: Complementarity of demand

Complementarity

Water heating

Energy

Indoor hot water

Indoor cold water

Outdoor water

Air conditioned

Appliances

Space heating

U_o

q_{Eb}

q_{Ea}

q_{wb}

q_{wa}
Household optimization process

• Each household has conservation options
  – Long-term: Retrofits
  – Short-term: Behavioral

• Each action has
  – Cost
    » Annualized costs for retrofits
    » “Hassle costs” for behavioral changes
  – Effectiveness
    » Water
    » Energy
    » Greenhouse gas emissions
Conservation Actions: Savings and Technological Shifts

Flow (GPM)

Retrofitted Appliance
Normal Appliance
Optimization Model

Minimize TOTAL COST = \sum_{wlt} C_{wlt} \cdot X_{wlt} + \sum_{elt} C_{elt} \cdot X_{elt} + 

\left[ B \cdot \left( \sum_{we} p_{we} \cdot \left( \sum_{ee} p_{ee} \cdot D \cdot \left( \sum_{wst} C_{wst} \cdot X_{wst,we,ee} + \sum_{est} C_{est} \cdot X_{est,we,ee} \right) + B_{W,we} + B_{E,ee} \right) \right) \right]

Subject to:

- Decision variables are binary
- Savings are less than initial use (upper bound) and resource availability
- Mutually exclusive actions
- Interdependence among actions
Water savings for long-term actions
Energy savings for water-related actions
Increased conservation when energy is included

• Adoption rate:
  • Retrofit shower: +7.9%
  • Retrofit clothes washer: +1.7%
  • Reduce shower length: +3.2%
  • …

• Increased savings:
  • Indoor water savings: +24%
  • Energy savings: +30%
  • GHG savings: +53%
Demand functions and elasticities

Water own-price elasticity $\varepsilon_{ww} = -0.05$

Energy own-price elasticity $\varepsilon_{ee} = -0.03$

Energy water-price elasticity $\varepsilon_{ew} = -0.02$

Water energy-price elasticity $\varepsilon_{we} = -0.004$
Policy implications from Mechanistic Modeling

- Including water-related energy should increase water conservation (and energy and GHG savings).
- Outdoor and toilet save most water; shower, faucet and clothes washer better save energy.
- Behavioral actions: Much to do!
3) Coupling hourly end-use and utility-scale water-energy models

- How much energy and GHG emissions are embedded in urban water cycle?
- What are effects of water conservation on water and energy utilities?
- Are there synergies for water and energy utilities working together?
Water and energy at the utility scale

- Wholesale Electricity Market
  - Price is highly variable
- Energy Utility
  - Sells energy
- Customers
  - Pay fixed rates!!!

Institutions
- Property Rights
- Water Markets

Water Utility
- Sells water
  - Cost has some variability

Power Unit
- Sells water
- Sells energy
- Water Source
EBMUD Example

Pardee and Camanche Reservoirs

Total Supply: 17604 MG/year (out of 64868 MG/year)

Leland
Pop. ≈ 130,000
6,391 MG/year
Elevation: 150 feet – 45 m

Danville
Pop. ≈ 75,000
3661 MG/year
Elevation: 350 feet – 107 m

San Ramon
Pop. ≈ 150,000
7553 MG/year
Elevation: 550 feet – 168 m

Total Supply: 17604 MG/year
(out of 64868 MG/year)
Water-related energy consumption in the urban water cycle - EBMUD > $12 million/year

Urban water cycle
Total emissions per capita: 406 kg CO₂/year
4.5% total emissions per capita in CA
Shifting Water Use Peaks to Off-Peak Energy Hours Has Economic Benefits
Results

• Optimal water conservation
  – Water use: 6% reduction
  – Energy use: 5% reduction
  – GHG emissions: 5% reduction
  – Energy cost for water utility: 4.5% reduction
Results

- Demand-response (peak shaving): Outdoor, clothes washer and dishwasher use are moved to off-peak hours.
  - Water use: Equal
  - Energy use: Equal
  - GHG emissions: Needs more discussion
  - Energy cost for water utility: 3% reduction
  - Energy cost for energy utility: 4% reduction
Policy implications

• Saving water reduces some GHG emissions.
• Synergies exist for water and energy utilities working together.
• Temporal water demand management can be very effective to reduce energy peaks.
Hard Parts Left to Do

- Outdoor water use and WTP estimation
- Monte Carlo modeling for outdoor use
- Energy - Hot water heater efficiency
- Getting data organized – starting to happen
- Testing models systematically and reconciling with empirical modeling
Effects of Climate and Land Use

- Larger lawns & warmer, drier climate increase landscape water use
- Landscape type will also affect!

Figure 8. Effects of Climate and Land Use on Outdoor Water Needs of Turf Grass

Hanak and Davis, 2009
Opportunities

• Smart meter data will drown us in data
• Commercialize mechanistic modeling
• Integrate with other supply and demand management activities at social, utility, and household scales
• Include more risk and financial analysis
Conclusions

• Nexus modeling is harder, but more interesting and useful than just yacking about X-Y-Z nexus

• Mechanistic modeling, better organizes problem with more flexibility and insights than empirical modeling alone

• Empirical and Mechanistic modeling should work better together

• Future looks bright for research and applications
Water and People in California

Average annual runoff (land area)
- 66% (20%)
- 24% (20%)
- 9% (20%)
- 1% (10%)
- 0.1% (30%)

Population Distribution
- 80% Population (2.5% of Area)
- 10% Population (2.5% of Area)
- 5% Population (5% of Area)
- 5% Population (90% of Area)
- Main Highways
California depends on an engineered statewide network.
## Effects of Climate and Land Use

- **Average Water Requirements of Turf Grass for Small Single-Family Lots**

<table>
<thead>
<tr>
<th>Region</th>
<th>Yard Size (sf)</th>
<th>Weighted Average ET0 (inches/year)</th>
<th>Annual Water Requirements (af)</th>
<th>Increase over Region with Lowest Need</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Francisco Bay Area</td>
<td>6,308</td>
<td>45.9</td>
<td>0.19</td>
<td>—</td>
</tr>
<tr>
<td>South Coast</td>
<td>7,623</td>
<td>49.8</td>
<td>0.25</td>
<td>31%</td>
</tr>
<tr>
<td>San Joaquin Basin</td>
<td>7,060</td>
<td>54.4</td>
<td>0.26</td>
<td>33%</td>
</tr>
<tr>
<td>Tulare Basin</td>
<td>7,711</td>
<td>56.2</td>
<td>0.29</td>
<td>50%</td>
</tr>
<tr>
<td>Sac. Metro region</td>
<td>8,129</td>
<td>56.8</td>
<td>0.31</td>
<td>59%</td>
</tr>
<tr>
<td>Inland Empire</td>
<td>8,858</td>
<td>56.2</td>
<td>0.33</td>
<td>72%</td>
</tr>
</tbody>
</table>

Hanak and Davis, 2006
AU and CA urban water use

- Urban CA could reduce use by 30-50+% with AU use rates.

<table>
<thead>
<tr>
<th>Location</th>
<th>Residential Use, gpcd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland, OR</td>
<td>58</td>
</tr>
<tr>
<td>Albuquerque, NM</td>
<td>74</td>
</tr>
<tr>
<td>Tucson, AZ</td>
<td>97</td>
</tr>
<tr>
<td>Denver, CO</td>
<td>104</td>
</tr>
</tbody>
</table>

| California                | 104                   |
| San Francisco             | 46                    |
| Oakland/East Bay          | 73-83                 |
| San Diego                 | 73-92                 |
| San Jose                  | 81-85                 |
| Los Angeles               | 91-99                 |
| **Sacramento**            | **113-120**           |

| Australia                 | 54                    |
| Melbourne                 | 40                    |
| Brisbane                  | 45                    |
| Canberra                  | 50                    |
| Sydney                    | 55                    |
| Perth                     | 75                    |

Cahill and Lund, 2009
Biggest difference in AU and CA use is usually outdoors

<table>
<thead>
<tr>
<th>End Use</th>
<th>California East Bay Area</th>
<th>California</th>
<th>Perth</th>
<th>Melbourne</th>
<th>Gold Coast</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Use, gpcd</td>
<td>% of total</td>
<td>Use, gpcd</td>
<td>% of total</td>
<td>Use, gpcd</td>
</tr>
<tr>
<td>Toilet</td>
<td>20</td>
<td>21%</td>
<td>13</td>
<td>10%</td>
<td>9</td>
</tr>
<tr>
<td>Shower/Bath</td>
<td>15</td>
<td>16%</td>
<td>13</td>
<td>10%</td>
<td>14</td>
</tr>
<tr>
<td>Washing Machine</td>
<td>14</td>
<td>15%</td>
<td>10</td>
<td>8%</td>
<td>11</td>
</tr>
<tr>
<td>Faucets</td>
<td>10</td>
<td>11%</td>
<td>11</td>
<td>9%</td>
<td>7</td>
</tr>
<tr>
<td>Leaks</td>
<td>5</td>
<td>5%</td>
<td>10</td>
<td>8%</td>
<td>2</td>
</tr>
<tr>
<td>Other</td>
<td>1</td>
<td>1%</td>
<td>2</td>
<td>1%</td>
<td>1</td>
</tr>
<tr>
<td>Outdoor</td>
<td>30</td>
<td>32%</td>
<td>67</td>
<td>53%</td>
<td>55</td>
</tr>
<tr>
<td>Total</td>
<td>95</td>
<td>100%</td>
<td>126</td>
<td>100%</td>
<td>99</td>
</tr>
</tbody>
</table>

Melbourne 25””
Queensland 48””
Perth 29””

Cahill and Lund, 2006