Information Systems and Science for Energy

School of Computer Science Colloquium

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October 17, 2013
IPCC Report: 27 Sep 2013

- Warming of the climate system is unequivocal
Gasoline combustion

1 liter of gasoline = 2.27 kg of CO$_2$
Electricity generation > Transportation!

IPCC 2007
Today’s Electrical Grid
3 components

- Generation
- Transmission
- Distribution
Grid characteristics
1. Overprovisioned by design
2. Inefficient

5% better efficiency of US grid

= zero emission from 53 million cars

http://www.oe.energy.gov/
3. Aging

Post-war infrastructure is reaching EOL
4. Uneven

<table>
<thead>
<tr>
<th></th>
<th>TWh generated</th>
<th>Daily W/capita (2012 est.)</th>
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</thead>
<tbody>
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<td>China</td>
<td>4,938</td>
<td>395</td>
</tr>
<tr>
<td>US</td>
<td>4,256</td>
<td>1402</td>
</tr>
</tbody>
</table>

Wikipedia
5. Poorly measured
6. Poorly controlled

- Electrons are not addressible
7. Ridiculously cheap
Technology is changing the grid
1. Wind

2. Solar

The future is here now!

Wind and solar produced 60% of Germany’s electricity on October 3
3. Storage: the holy grail

- Global investment in energy storage technologies to reach $122 Billion by 2021: Pike Research

- Many new technologies
  - Batteries
  - Flywheels
  - Supercapacitors
  - Compressed air storage

...
4. Electric vehicles

- Spur research on lower-cost storage
- Huge consumers of electricity
5. Pervasive sensing
6. Pervasive computation

Freescale KL02 microcontroller 1.9 mm x 2.0 mm
7. Pervasive communication
8. Pervasive control

Control 4’s EMS-100 in-home display
Current grid    "Smart" grid

Centralized ▪ Decentralized
Little to no storage ▪ Storage rich
High carbon ▪ Renewables/low carbon
Poorly measured ▪ Sensing rich
Poorly controlled ▪ Control rich
Ossified ▪ Flexible
Inefficient ▪ Energy frugal
OK, we're done, right?
Maybe not...
1. Matching demand and supply

2. Storage is expensive

- Buying 1 KWh = 10c
- Storing 1 KWh = ~$450!
3. Controlling distributed generators

**Number of residential net metered customers**

- **x-axis:** Year (2003 to 2012)
- **y-axis:** Number of customers (0 to 300,000)

Graph showing an exponential increase in the number of residential net metered customers from 2003 to 2012.
4. Control over many time scales
5. Communication is complex
6. Consumers have no incentive to save

- Energy savings of 10%
- $10/month
7. Utilities have no incentive to save!
Mission

To use information systems and science to

- increase the efficiency
- reduce the carbon footprint

of energy systems
3 Approaches

1. Exploiting equivalency of grid and Internet*
2. Problem-oriented research
3. Data-driven research*

* novel
1. Grid = Internet

Grid  Internet

Electrons  =  Bits
Load  =  Source
Communication link  =  Transmission line
Battery/energy store  =  Buffer
  Demand response  =  Congestion control
Transmission network  =  Tier 1 ISP
Distribution network  =  Tier 2/3 ISP
Stochastic generator  =  Variable bit rate source
Equivalence theorem

Every trajectory on the LHS has an equivalent on the RHS

- can use teletraffic theory to study transformer sizing

A. Guidelines for transformer sizing

HydroOne’s guidelines

Prediction from teletraffic theory

Can also quantify impact of storage

B. TCP for EV charging

- 1 EV = 5 homes
- Creates hotspots
- Real-time AIMD control of EV charging rate
- Solution is both fair and efficient

C. Matching supply and demand
“Rainbarrel” model

- uncontrolled stochastic input
- uncontrolled stochastic output

What barrel size to avoid overflow and underflow “with high probability”?
Envelopes are computed from a dataset of trajectories.

lower envelope \leq \sum \text{input} \leq \text{upper envelope}

lower envelope \leq \sum \text{output} \leq \text{upper envelope}
Stochastic envelopes

\[ P((\Sigma \text{ input} - \text{lower envelope}) > x) = ae^{-x} \]

\[ P((\text{upper envelope} - \Sigma \text{ input}) > x) = be^{-x} \]
Analytic results

- Minimizing storage size to smooth solar/wind sources
- Optimal participation of a solar or wind farm in day-ahead energy markets*
- Modeling of imperfect storage devices*
- Optimal operation of diesel generators to deal with power cuts in developing countries*

Joint work with Y. Ghiassi-Farrokhtal, S. Singla, and C. Rosenberg
2. Problem-oriented research

- Problem formulation
- Modeling
- Analysis
- Design
- Implementation
- Evaluation

Increase efficiency, reduce carbon footprint

- Optimization
- Queueing theory
- Network calculus
- Control theory
- Network flow
- Algorithms

- New technologies
  - Storage
  - EVs
  - Pervasive computation, sensing
  - Renewable generation

- Data
Smart Personal Thermal Comfort

Reduce building energy use with fine-grained thermal control of individual offices

Our insight
In a nutshell

- **Mathematical** comfort model
- When *occupied*, reduce comfort to the minimum acceptable level
- When *vacant*, turn heating off
- **Pre-heat**
- **Optimal** model-predictive control

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Graph showing temperature changes over time with occupancy spikes at specific times.
New technology: sensing

- Microsoft Kinect
- 5° infrared sensor
- Servos
- 90° infrared sensor
- Microcontroller
- Weatherduck sensor
Evaluation: clothing level estimation

- Root mean square error (RMSE) = 0.0918
- Linear correlation = 0.92
New technology: data mining for occupancy prediction

- Predict occupancy using historical data

Match previous similar history

Predict using matched records
Comparision of schemes

![Comparison of schemes graph](image-url)
3. Data-driven research

- Obtain dataset
  - Difficult!
  - Data mining
  - Machine learning
  - Big data analytics
  - What-if analysis
  - Simulation

- Problem formulation
  - Effect of new technologies
    - Storage
    - EVs
    - Pervasive computation
    - Renewable generation

- Analysis

- Insights
Problem

peak

average
What we’d like

peak

average
New technology

- ~5 million ‘smart meters’ installed in Ontario
Ontario Time-Of-Use (TOU) Scheme

Midnight       7 AM    11 AM    5 PM  7 PM    Midnight

off-peak     mid-peak     peak
Questions

- Is 2 the right number of seasons?
- Should they be 6 months long?
- Do they start at the right times?
- Do peak times correspond to load peaks?
- Does the scheme reduce peak loads?
Dataset

- Aggregate hourly energy use in Ontario for the last 10 years

Aggregate Ontario load for the first two weeks of May over 4 years
Answers

- Is 2 the right number of seasons? No
- Should they be 6 months long? No
- Do they start at the right times? No
- Do peak times correspond to load peaks? No
- Does the scheme reduce peak loads? No!
A better scheme

4 seasons

Other datasets

- Hourly electrical load from 26,000 homes in Ontario
- Hourly electrical load from 5,000 homes in Ireland
- Hourly water usage from 27,000 homes in Abbotsford
- Per-appliance energy use for ~500 appliances
- 50 commercial buildings’ energy use over 2-4 years (Pulse)
- 500 taxi driving records for 1 month (Cabspotting)
- 7 years of car rental records (Grand River Carshare)
- Hourly electricity prices and use for 10 years (IESO)
- Solar and wind production over 10 years (NREL)
- Weather records (Ontario)
Reflections on the research area
Energy research

**Pros**
- Rapidly growing research area
- Many open problems
- Industry interest and support
- Motivated students
- Potential for impact

**Cons**
- Requires learning new concepts and ideas
- Entrenched interests
- Difficult to obtain data
- Field trials nearly impossible
Many open research problems

- Renewable integration
- Multi-level control
- Non-cash incentive design for consumers
- Energy efficiency policies for utilities
- Storage size minimization in energy systems
- Incentives for EV adoption
- Data mining of energy data sets
- Peak load reduction
- HCI for energy applications
- Data center energy minimization
- Microgrid/nanogrid design
- Building energy use monitoring and reduction
Join us!

- ISS4E mailing list
- ISS4E seminar series starting October 2013
  - next speaker: Pascal van Hentenryck, 4pm on Oct. 24th
- Open weekly group meetings, 10:30-11:30 on Wednesdays in DC 1331
Conclusions

- Technology is changing the grid
- Computer Science has a role to play
- Opportunity for interesting, impactful research
Acknowledgements
ISS4E Faculty

Co-Director

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ISS4E students
WISE

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- Prof. Claudio Canizares (ECE)
- Prof. Kankar Bhattacharya (ECE)
Corporate sponsors

- Cisco
- hydroGencity
- Microsoft
- IBM
Our next project
Backup slides
What kills birds?

- According to Environment Canada
  - Wind turbines: 16,700
  - High-rise buildings: 64,000
  - Single family homes and low-rises: 22,000,000
  - Cats: 196,000,000

Impacts

- Physical
  - Extreme weather
  - Ocean acidification
  - Sea level rise
  - Ocean currents

- Social
  - Food supply
  - Water availability
  - Health

- Ecological
  - Species loss
  - Migration

Wikipedia
Carbon emitters
# Top emitters

## List of countries by 2008 emissions

<table>
<thead>
<tr>
<th>Country</th>
<th>Annual CO₂ emissions (in thousands of tonnes)</th>
<th>% of world emissions</th>
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</thead>
<tbody>
<tr>
<td>World</td>
<td>29,888,121</td>
<td>100%</td>
</tr>
<tr>
<td>China (ex. Macau, Hong Kong)</td>
<td>7,031,916</td>
<td>23.5%</td>
</tr>
<tr>
<td>United States</td>
<td>5,461,014</td>
<td>18.27%</td>
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<tr>
<td>European Union (27)</td>
<td>4,177,817</td>
<td>13.96%</td>
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<tr>
<td>India</td>
<td>1,742,698</td>
<td>5.83%</td>
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<tr>
<td>Russia</td>
<td>1,708,653</td>
<td>5.72%</td>
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<tr>
<td>Japan</td>
<td>1,208,163</td>
<td>4.04%</td>
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<tr>
<td>Germany</td>
<td>786,660</td>
<td>2.63%</td>
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<tr>
<td>Canada</td>
<td>544,091</td>
<td>1.82%</td>
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<td>Iran</td>
<td>538,404</td>
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<td>United Kingdom</td>
<td>522,856</td>
<td>1.75%</td>
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<td>South Korea</td>
<td>509,170</td>
<td>1.7%</td>
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Per capita carbon emissions

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<td>Trinidad and Tobago</td>
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<td>United Arab Emirates</td>
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<td>Bahrain</td>
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<td>New Caledonia</td>
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<td>Canada</td>
<td>16.4</td>
<td>15.2</td>
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Renewable energy

Fossil fuels are expressed with regard to their total reserves while renewable energies to their yearly potential.

Source: DLR, IEA WEO, EPIA's own calculations.
Pervasive communication

Trilliant Corp.
Estimated U.S. Energy-Related Carbon Dioxide Emissions in 2012: ~5,290 Million Metric Tons

Source: LLNL, 2013. Data is based on DOE/EIA-0035(2013–05), May, 2013. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Carbon emissions are attributed to their physical source, and are not allocated to end use for electricity consumption in the residential, commercial, industrial and transportation sectors. Petroleum consumption in the electric power sector includes the non-renewable portion of municipal solid waste. Combustion of biologically derived fuels is assumed to have zero net carbon emissions – the lifecycle emissions associated with producing biofuels are included in commercial and industrial emissions. Totals may not equal sum of components due to independent rounding errors. LLNL-M6-400527
Storage

Energy density

Power density

- Mechanical
  - Gravitation
  - Pumped hydro
- Thermo-electric
  - Heat
  - Molten salt
  - Thermoelectric
- Pressure heat
  - Compr. air (CAES)
  - A-CAES

Electrochemical

- Batteries
  - Lead acid
  - NiCd
  - NaS
  - NaNiCl
  - Lithium
  - Ni-MH
  - Metal air
- Flow cells
  - Vanadium
  - ZnBr
  - PSBr
- Hydrogen
  - Electrolyser & Fuel Cell

Electromagnetic

- Electric
  - Capacitors
  - Supercaps
- Magnetic
  - Superconducting (SMES)

“Bytes”

“Bits/s”

Graphs adapted from: A. Oudalov, C. Yuen and M. Holmberg, “Energy Storage is a Key Smart Grid Element”
- Model stochastic sources (solar, wind) and stochastic loads using Markov models or stochastic sample path envelopes
Pervasive communication

Chart 1.1: Global ICT developments, 2003-2013*

- Mobile-cellular telephone subscriptions
- Households with Internet access
- Individuals using the Internet
- Active mobile-broadband subscriptions
- Fixed-telephone subscriptions
- Fixed (wired) broadband subscriptions

Per 100 inhabitants/households

Note: * Estimate.
Source: ITU World Telecommunication/ICT Indicators database.
Carbon from gasoline combustion

- \(2C_8H_{18} + 25O_2 \rightarrow 16CO_2 + 18H_2O\)
- \(C_9H_{20} + 14O_2 \rightarrow 9CO_2 + 10H_2O\)
- \(2C_{10}H_{22} + 31O_2 \rightarrow 20CO_2 + 22H_2O\)
- \(C_{11}H_{24} + 17O_2 \rightarrow 11CO_2 + 12H_2O\)
- \(2C_9H_6 + 15O_2 \rightarrow 12CO_2 + 6H_2O\)
- \(C_7H_8 + 9O_2 \rightarrow 7CO_2 + 4H_2O\)
- \(4C_8H_7 + 39O_2 \rightarrow 32CO_2 + 7H_2O\)
- \(2C_8H_{10} + 21O_2 \rightarrow 16CO_2 + 10H_2O\)

- 1 liter of gasoline (~800g) produces 2.27kg of CO\(_2\)
Ontario Time-Of-Use (TOU) Scheme
<table>
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<tr>
<th>Publication venues</th>
<th>Conferences and workshops</th>
<th>Journals</th>
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<tr>
<td></td>
<td>eEnergy</td>
<td>IEEE Trans. Smart Grid</td>
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<td>IEEE PES magazine</td>
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