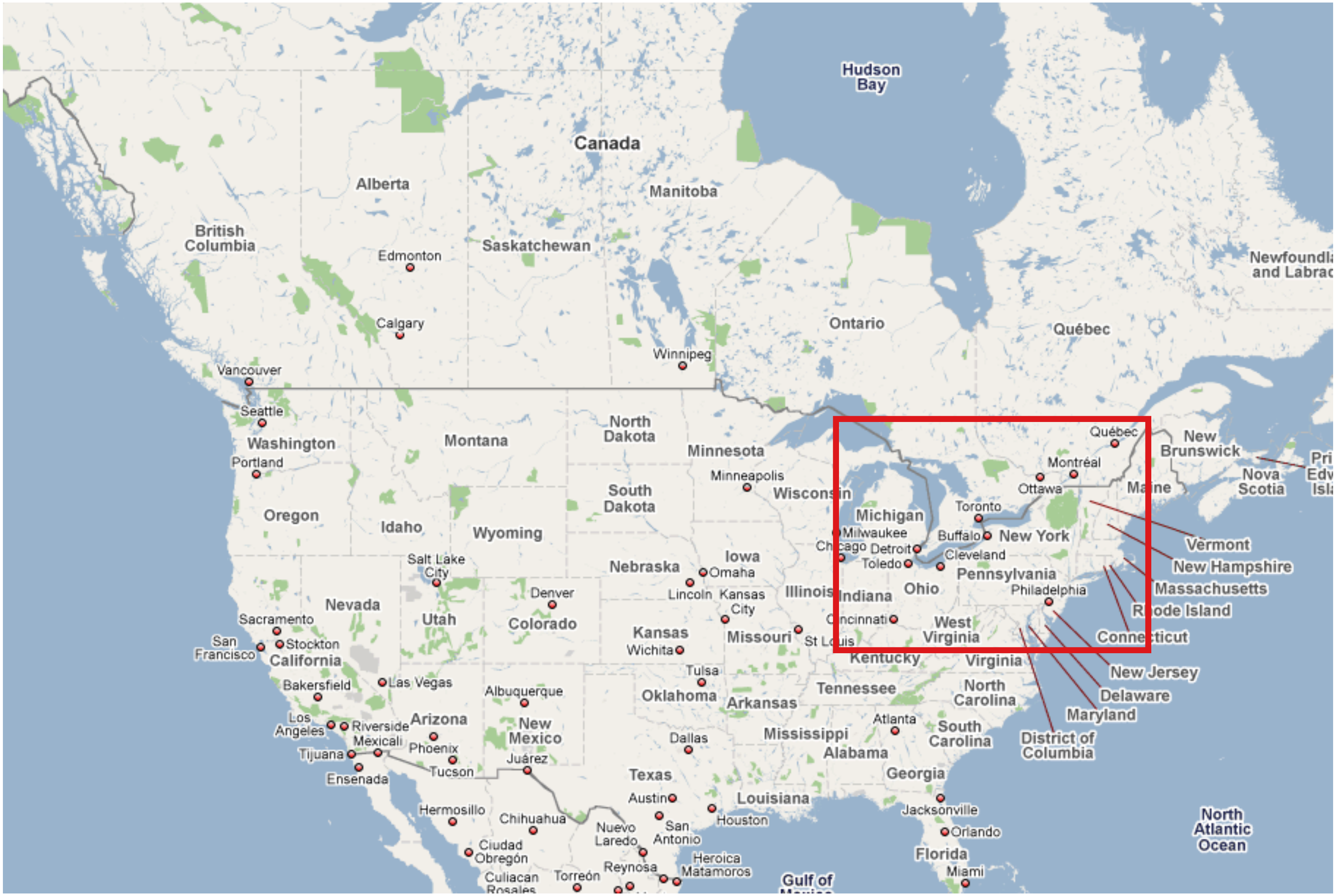
A Networking Approach to the Smart Grid

S. Keshav

Joint work with Prof. Catherine Rosenberg, ECE, UW

Waterloo?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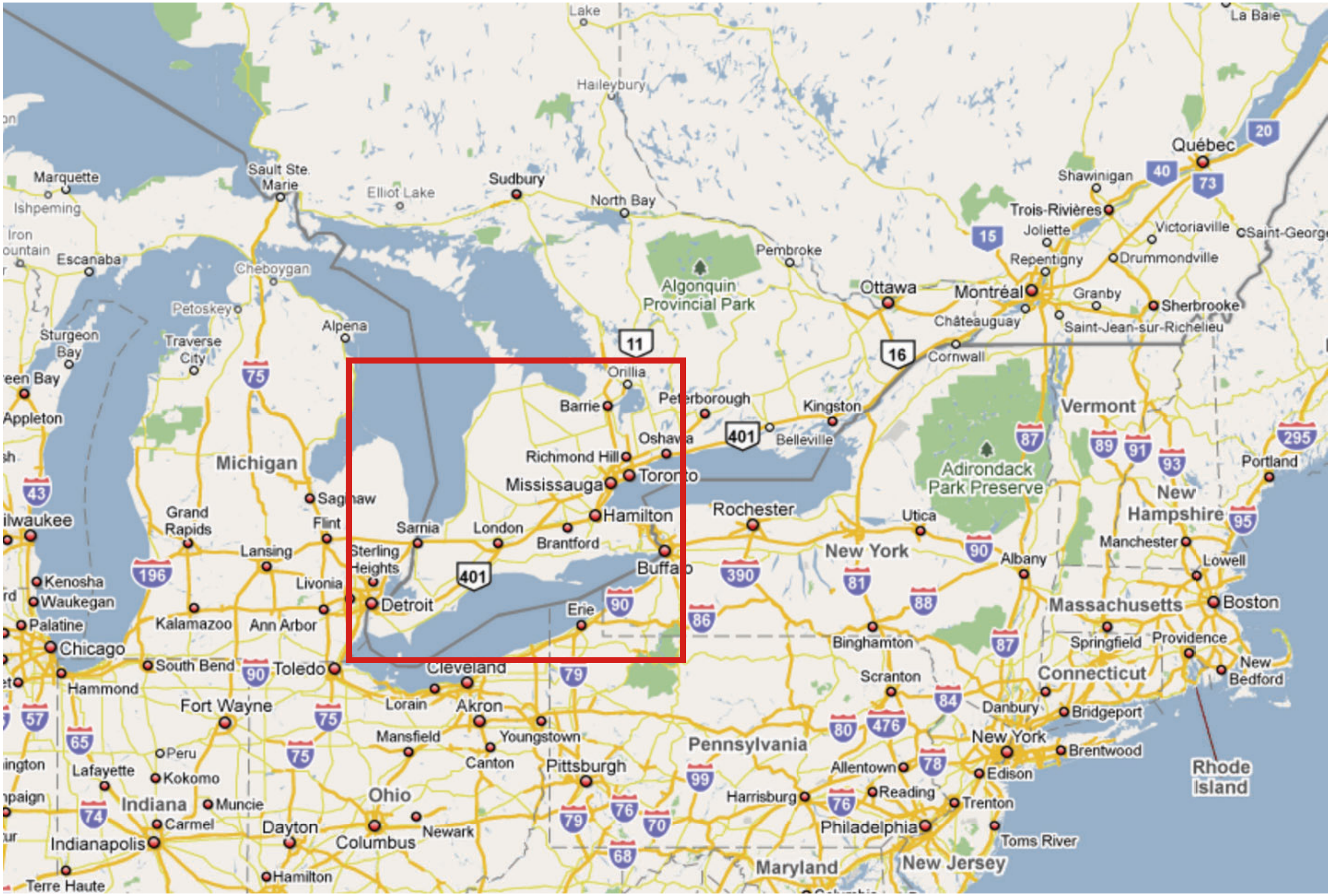
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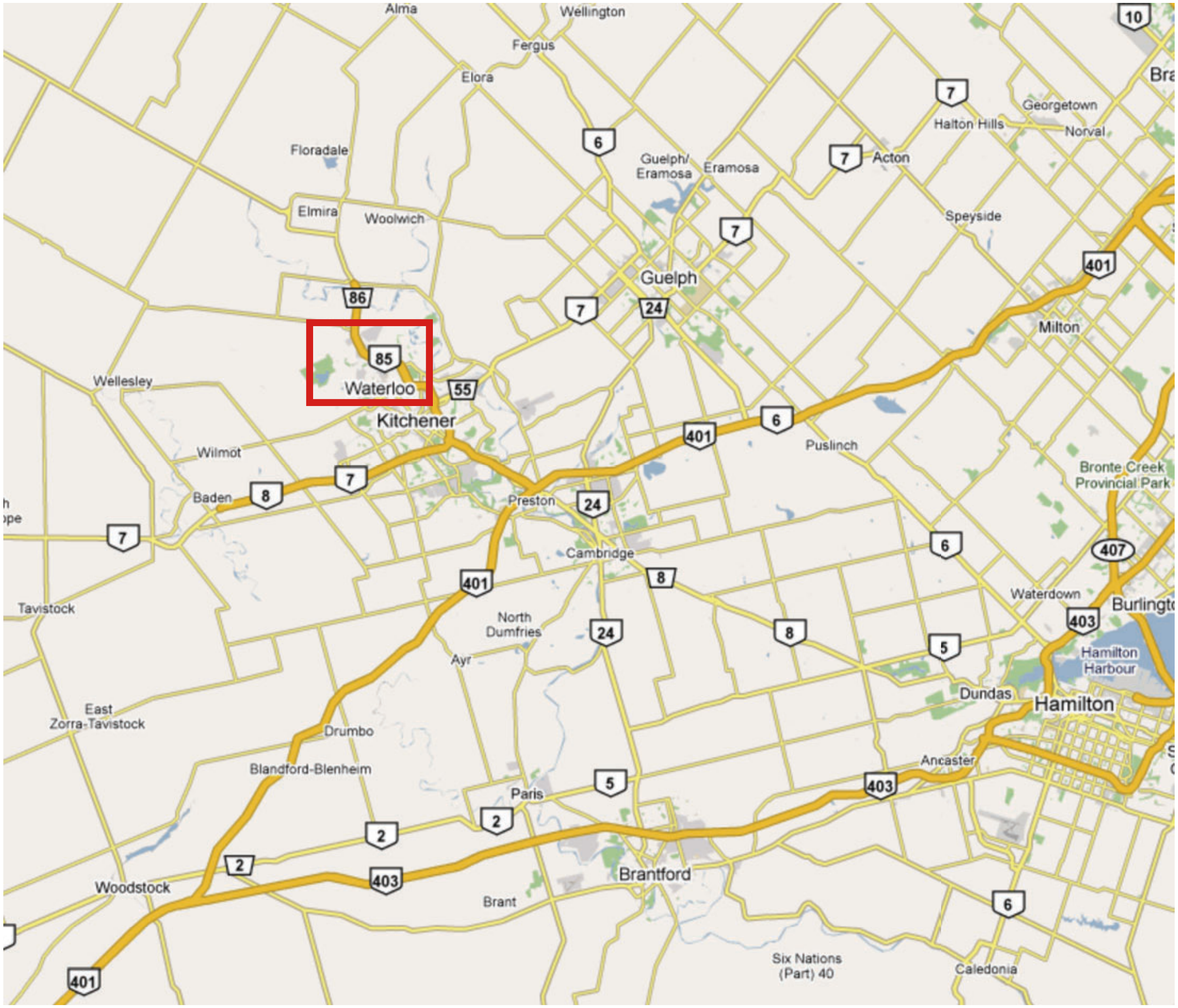

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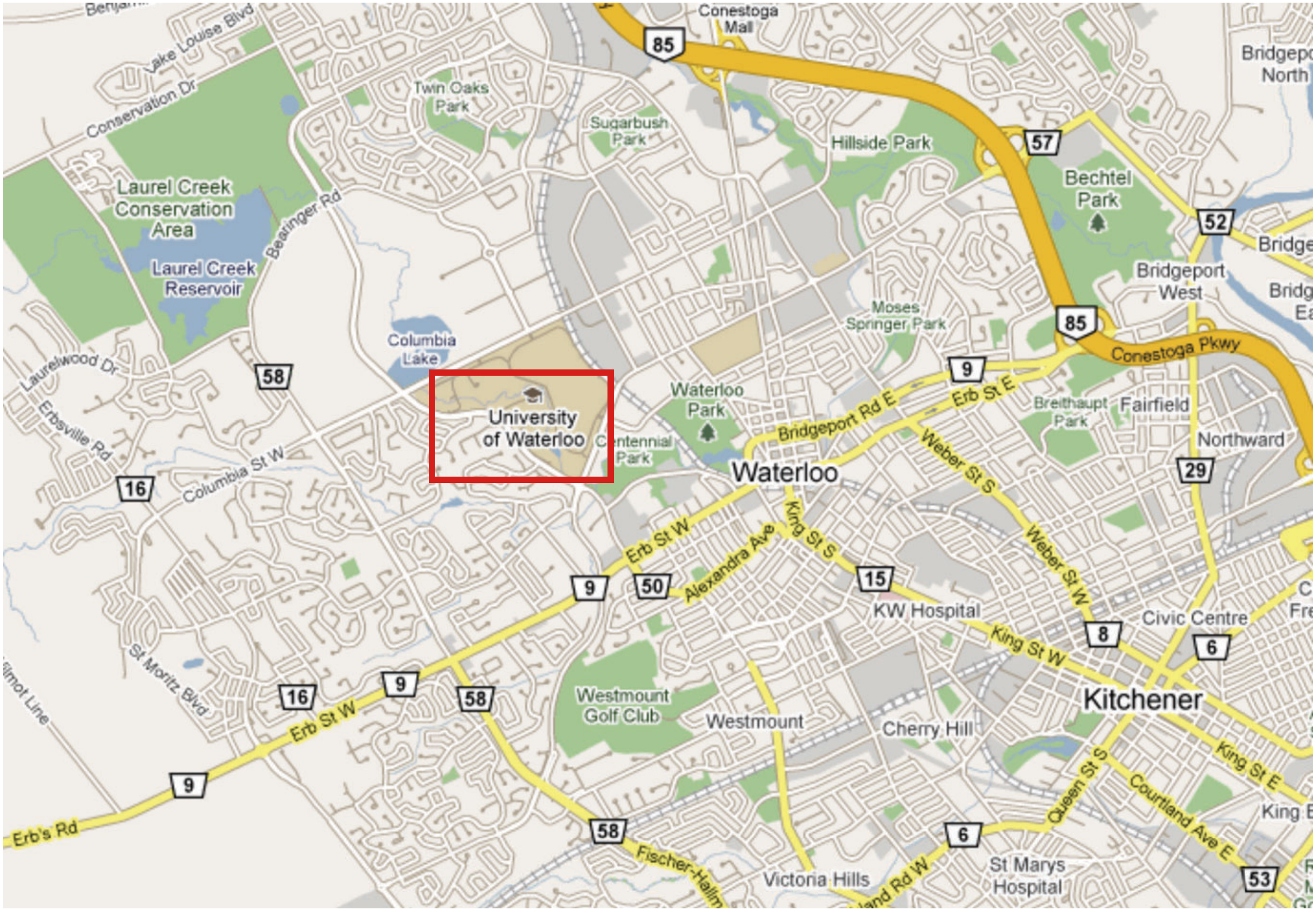

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Sugarbush Park
Hillside Park
Bechtel Park
Laurel Creek Conservation Area
Bearinger Rd
Laurel Creek Reservoir
Bridgeport West
Moses Springer Park
Columbia Lake
Conestoga Pkwy
Laurelwood Dr
University of Waterloo
Waterloo Park
Erb St E
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Breithaupt Park
Fairfield
Erbsville Rd
Centennial Park
Northward
Columbia St W
Waterloo
Weber St S
Erb St W
Alexandra Ave
King St S
KW Hospital
Civic Centre
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St Moritz Blvd
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Erb St W
Westmount Golf Club
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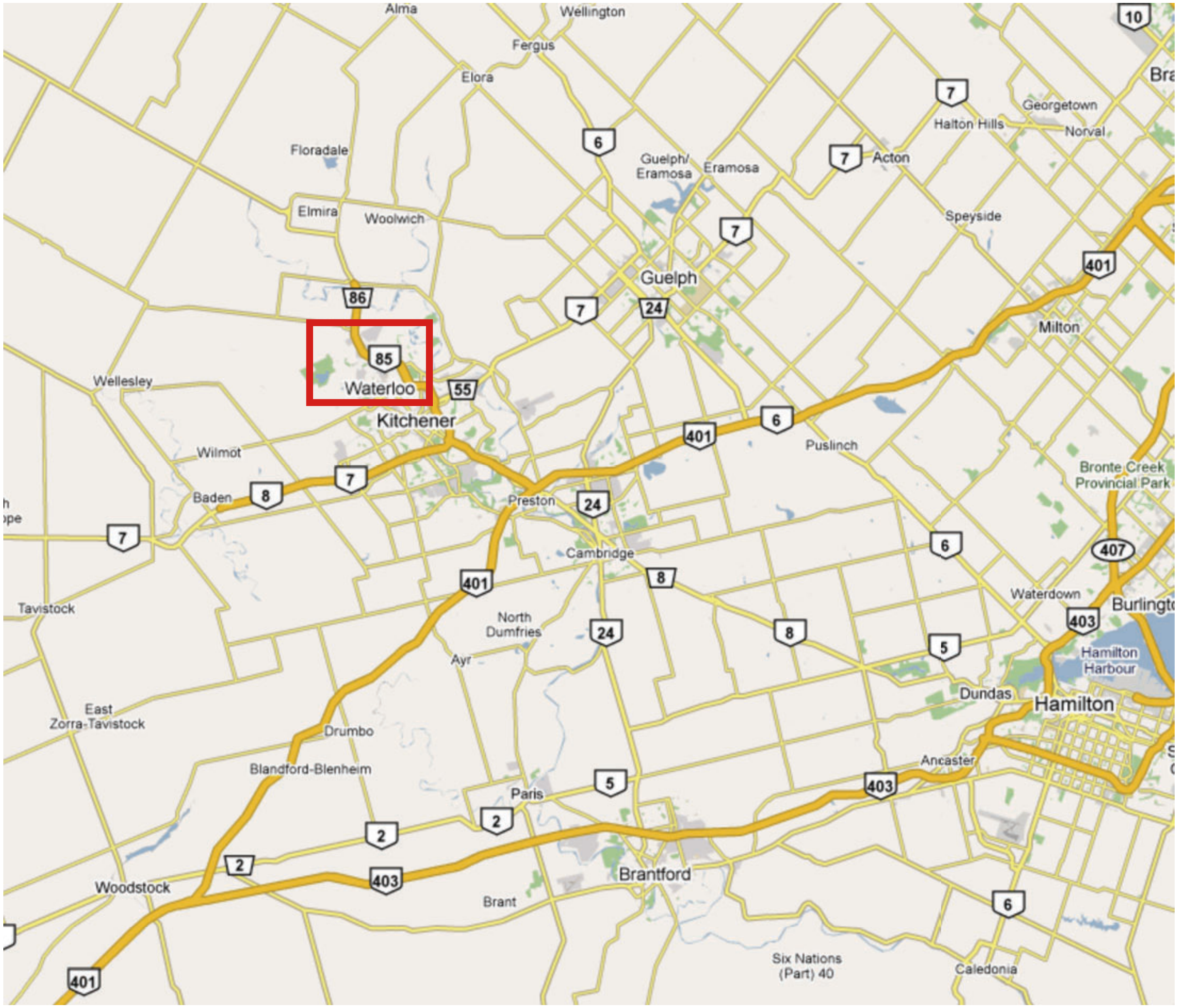

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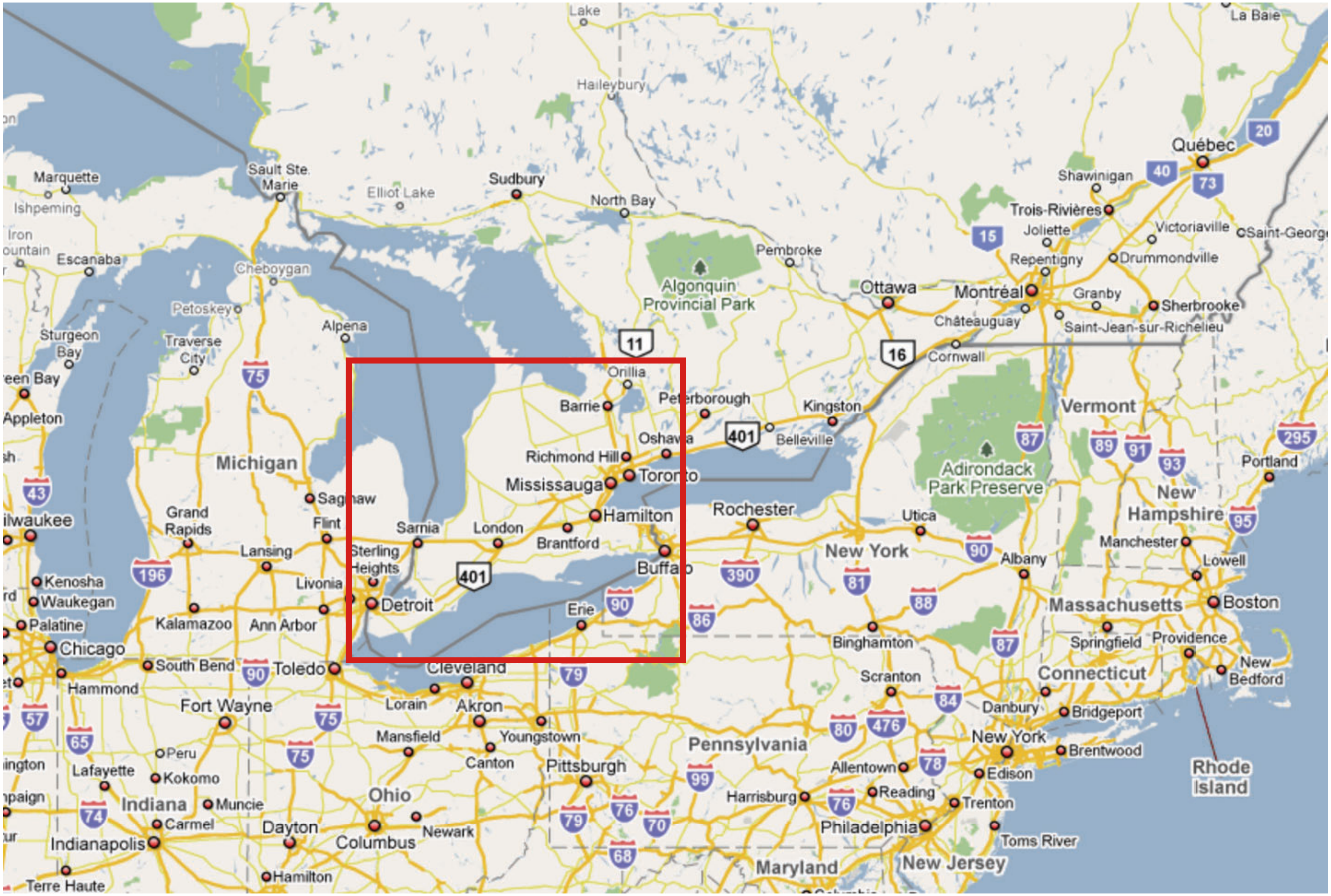

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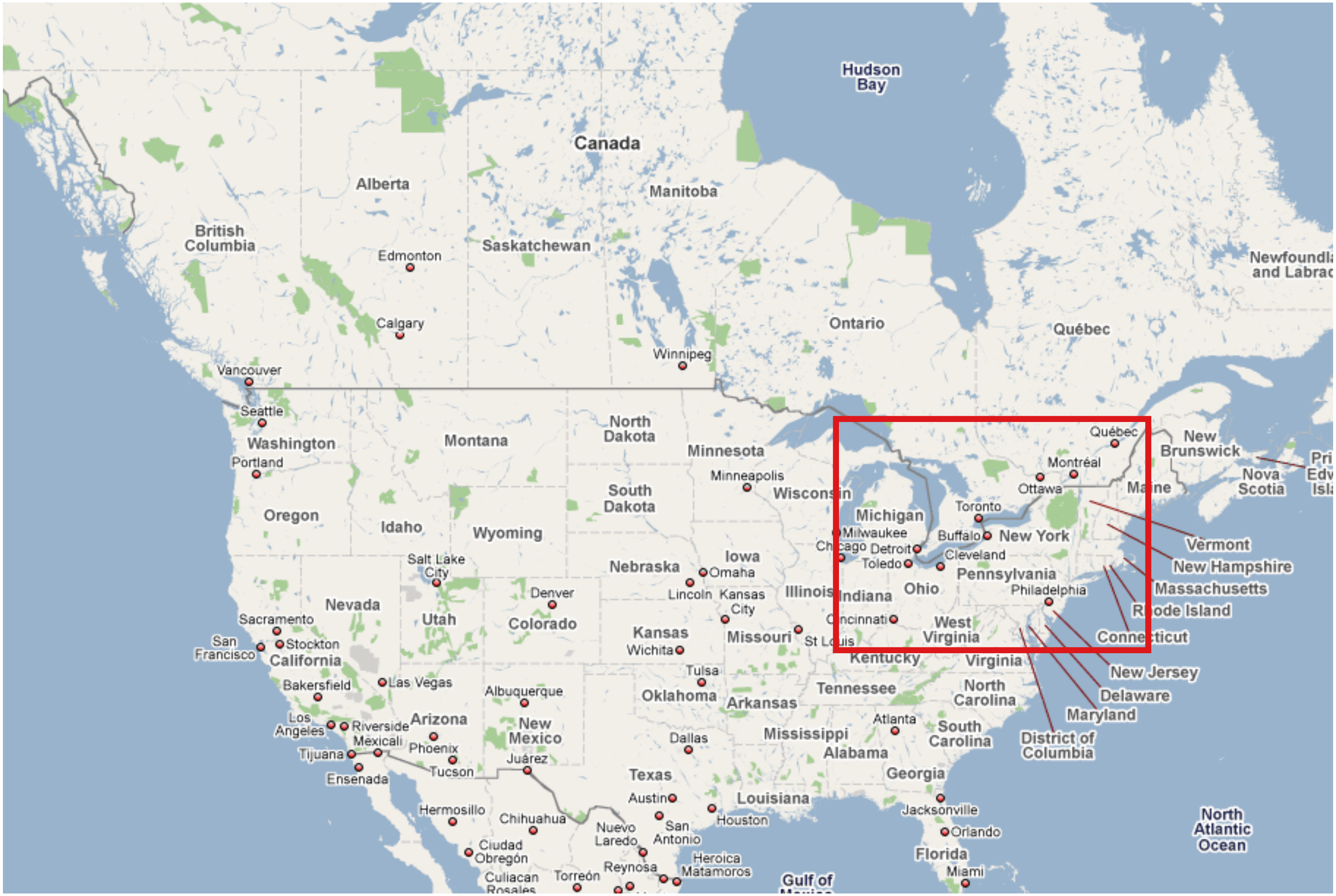
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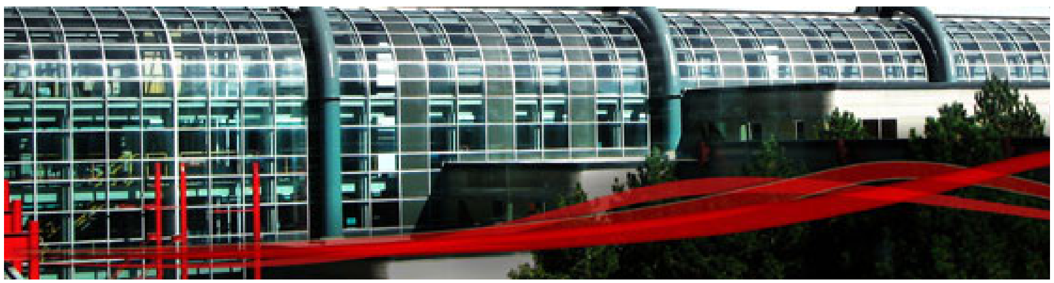
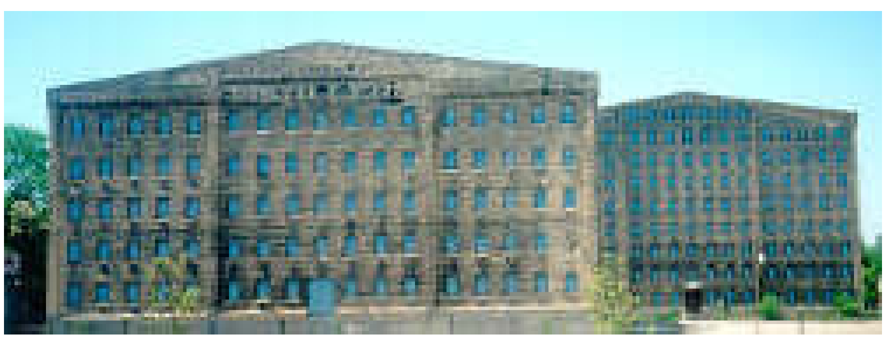
Reynosa
Heroica Matamoros
North Atlantic Ocean

Home of Maple, RIM/Blackberry



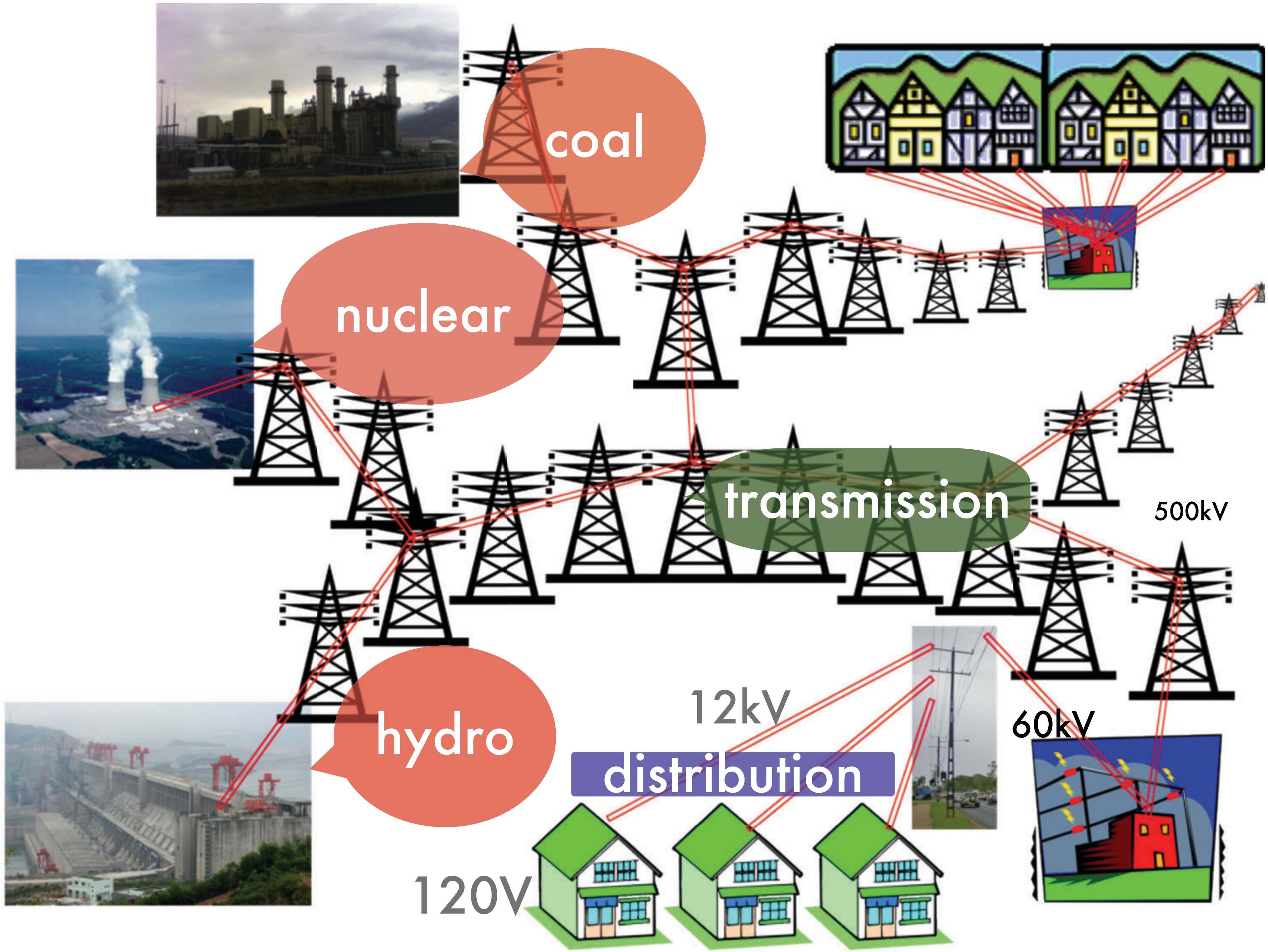
~25,000 students
~200 Math faculty
~70 CS faculty (part of Math)
~2000 CS undergraduates



Outline

- What is the grid?
- Why the smart grid?
- Challenges
- ISS4E
- Overview of projects

What is the grid?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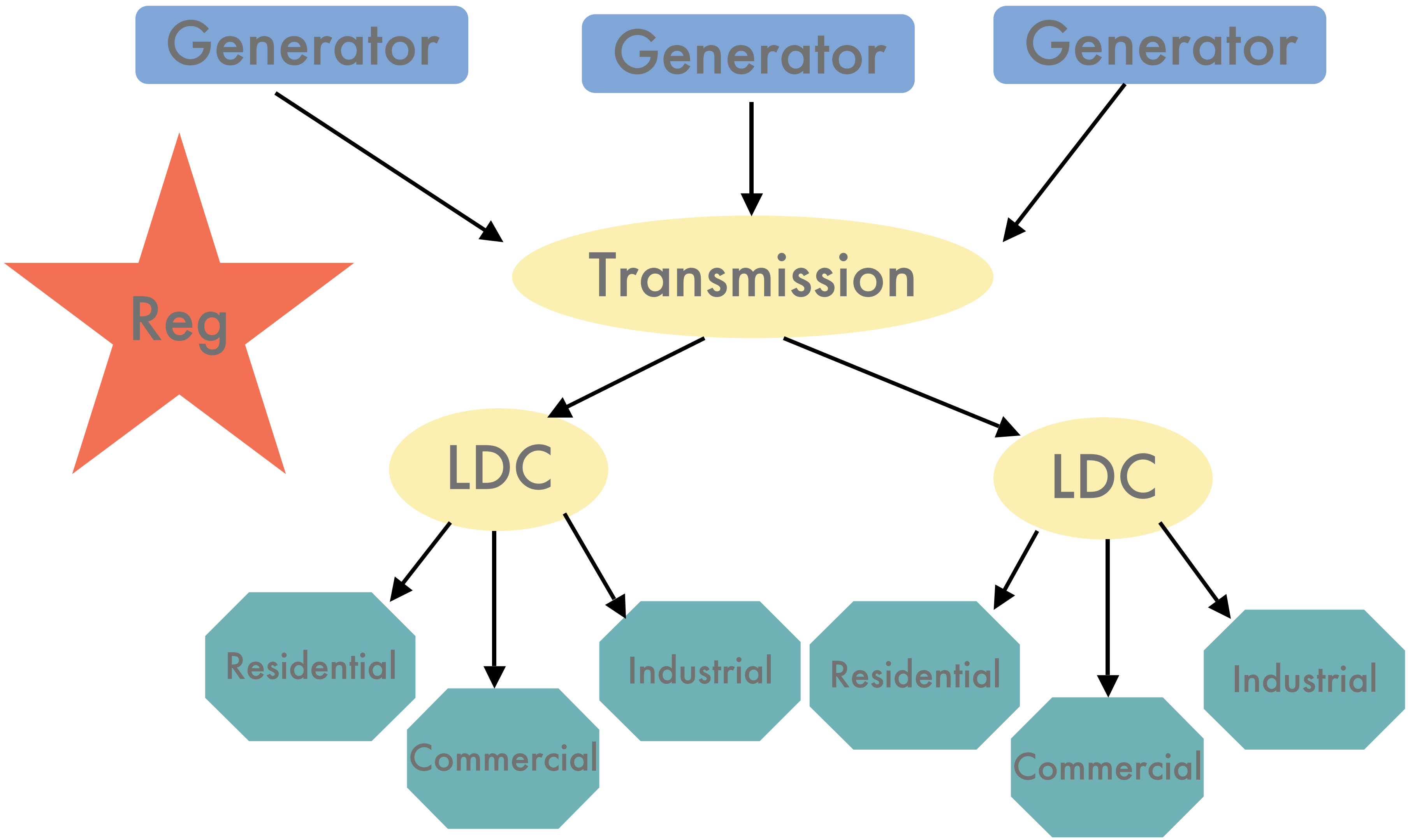
500kV
hydro
12kV
60kV
distribution
120V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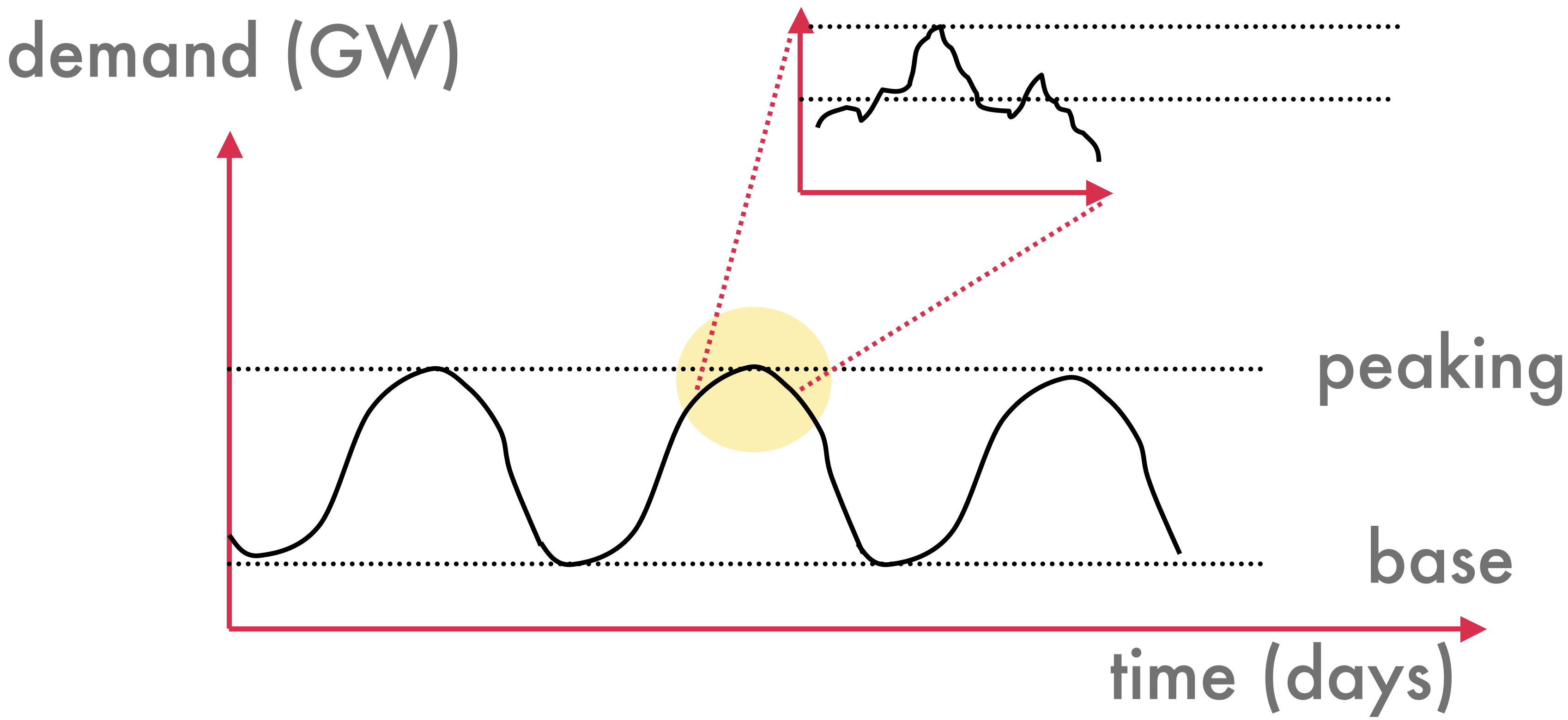
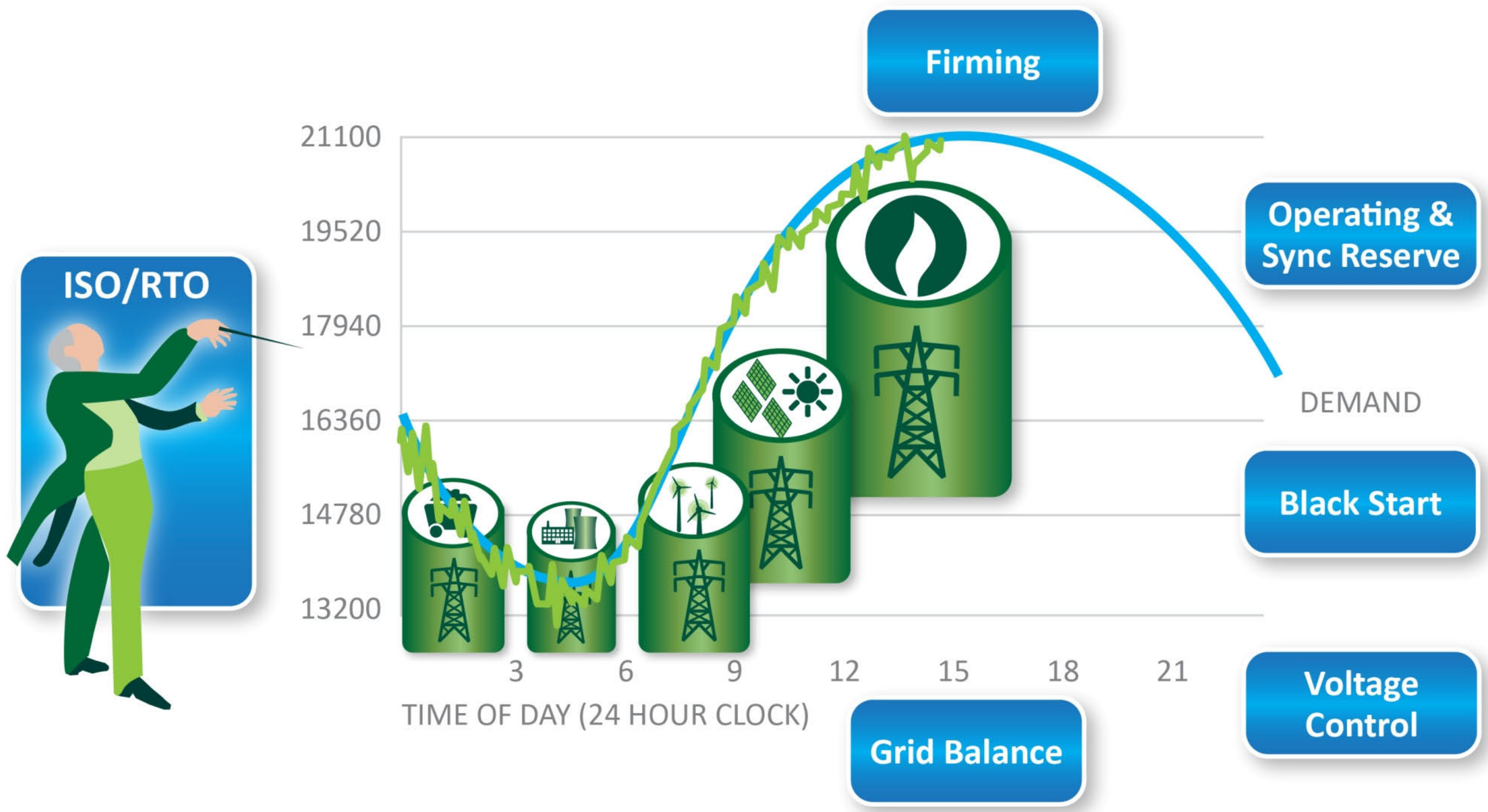
Daily variation



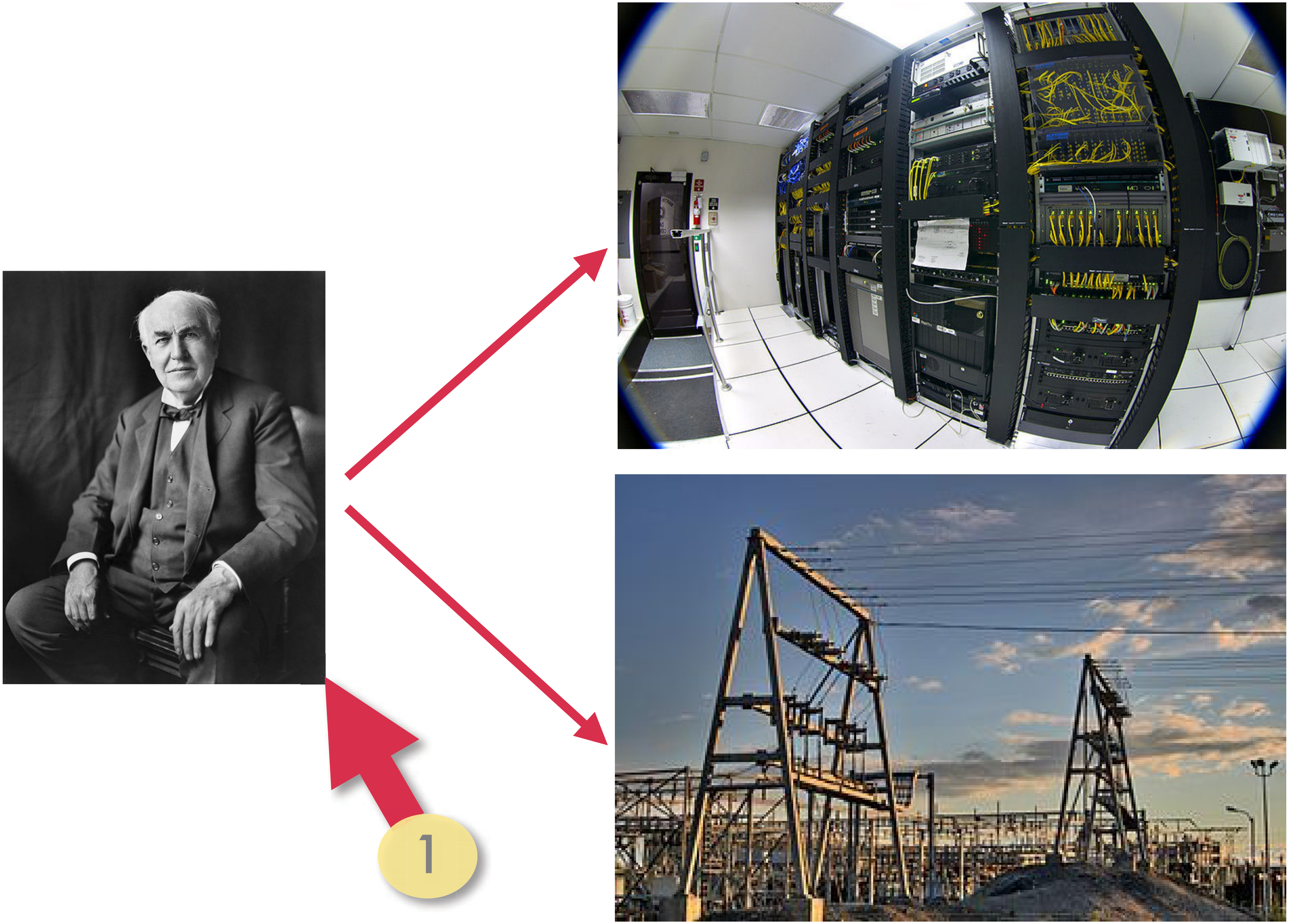


Slide courtesy of Malcolm Metcalfe, Enbala

Constraints

- Nearly uncontrolled demand
- Generation is complex, diverse, sometimes inflexible
- Reliability
- Almost no storage

Problems…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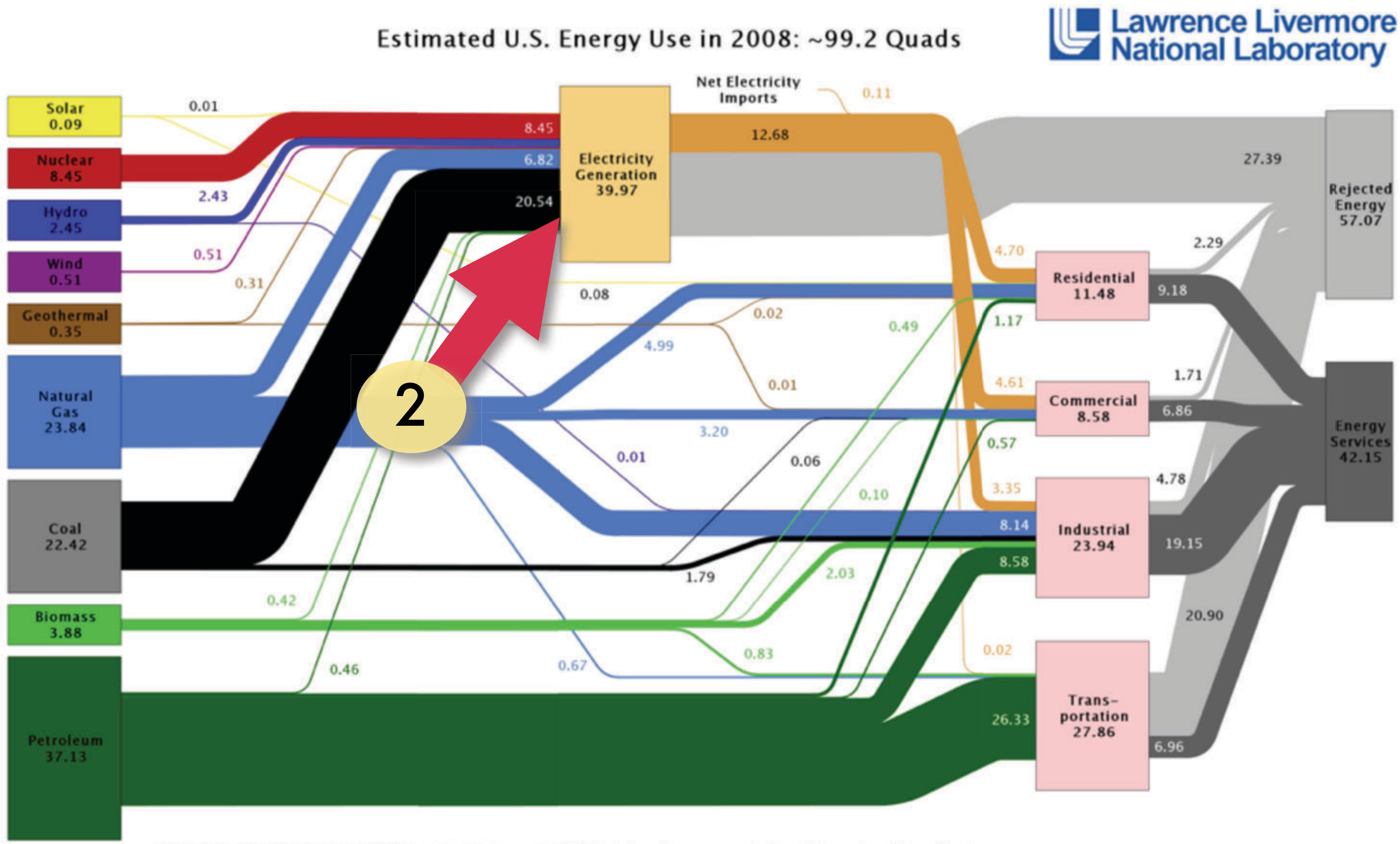
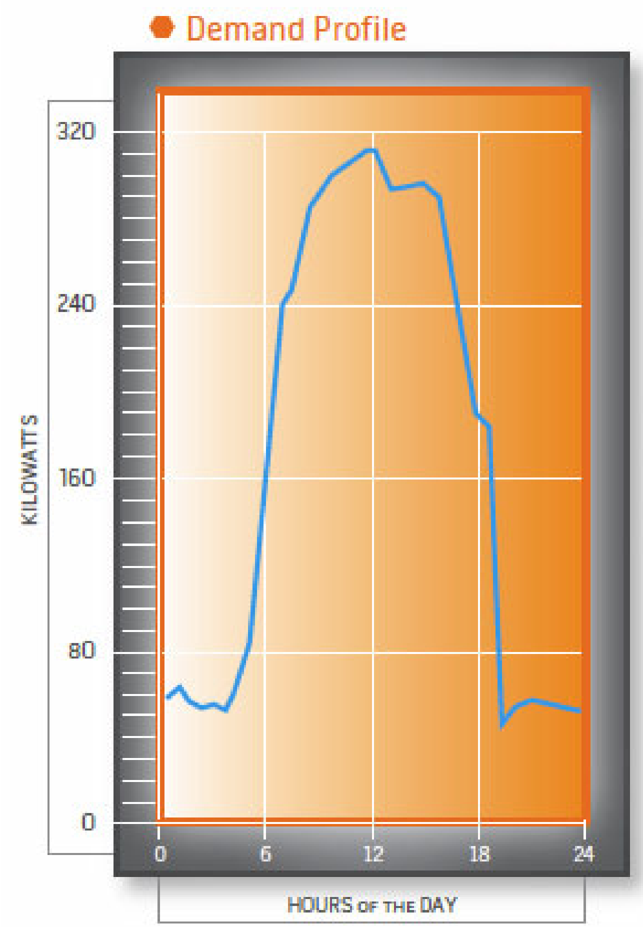


Source: LLNL 2009. Data is based on DOE/EIA-0384(2008), June 2009. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports flows for non-thermal resources (i.e., hydro, wind and solar) in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 80% for the residential, commercial and industrial sectors, and as 25% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

3

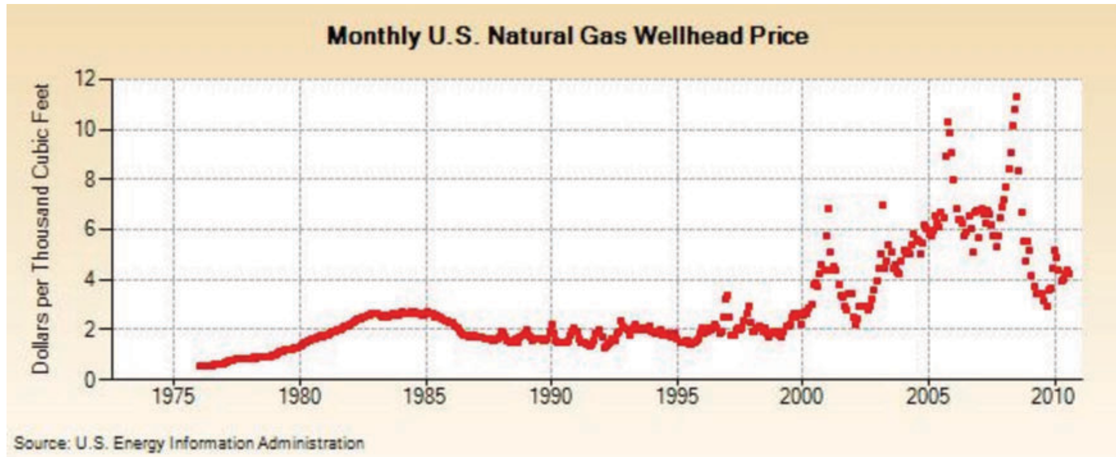
"15% of the generating capacity in Massachusetts is needed fewer than 88 hours per year"



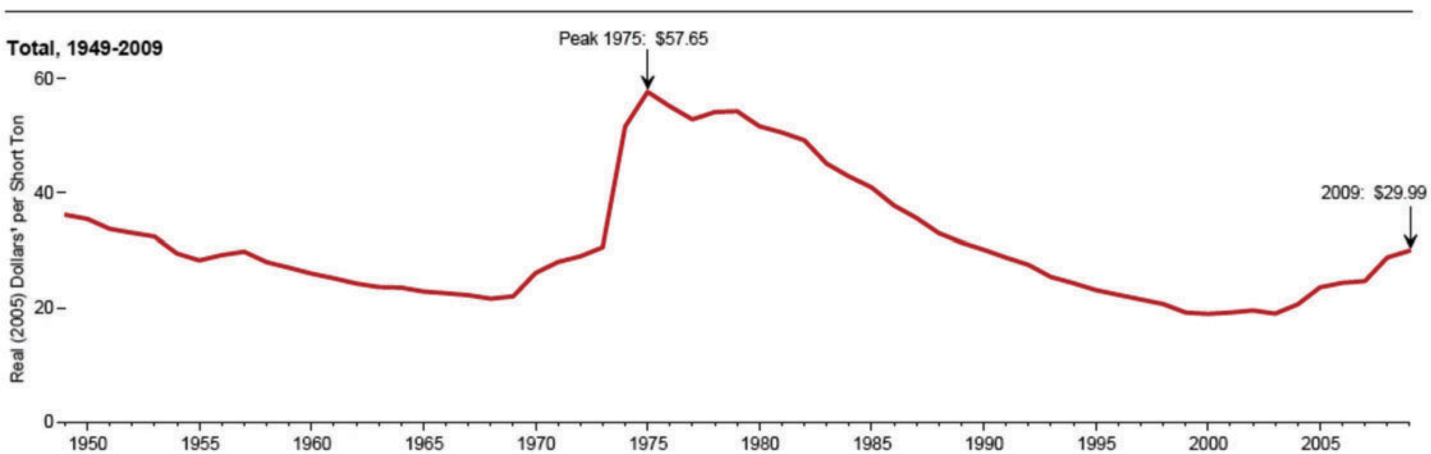
Philip Giudice, Commissioner, Massachusetts Department of Energy, Nov. 30, 2009

4 Energy price

U.S. Natural Gas Price
(Dollars per Thousand Cu. Ft.)
[1976-2010]

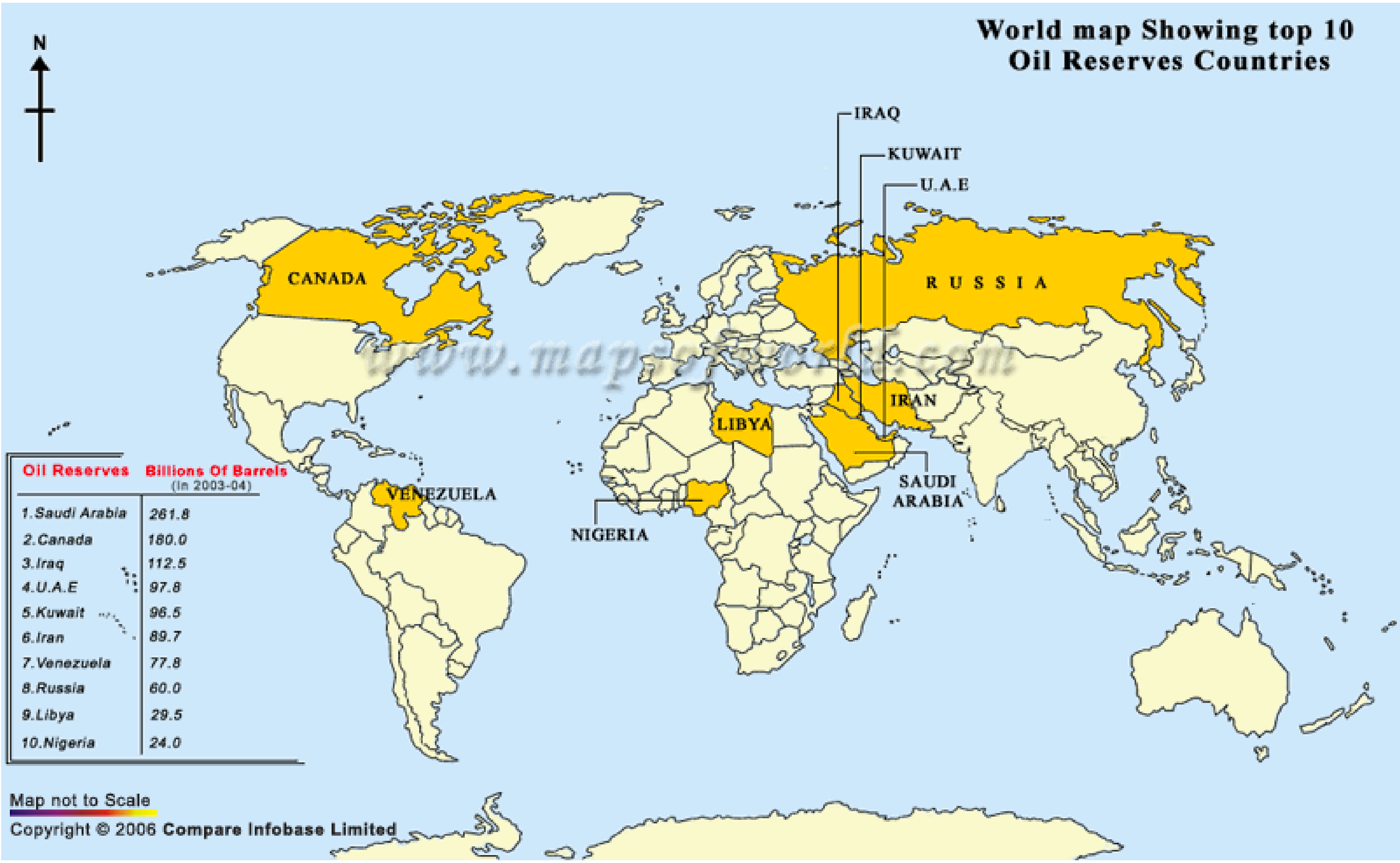


U.S. Coal Prices
in 2005 dollars
[1949- 2009]



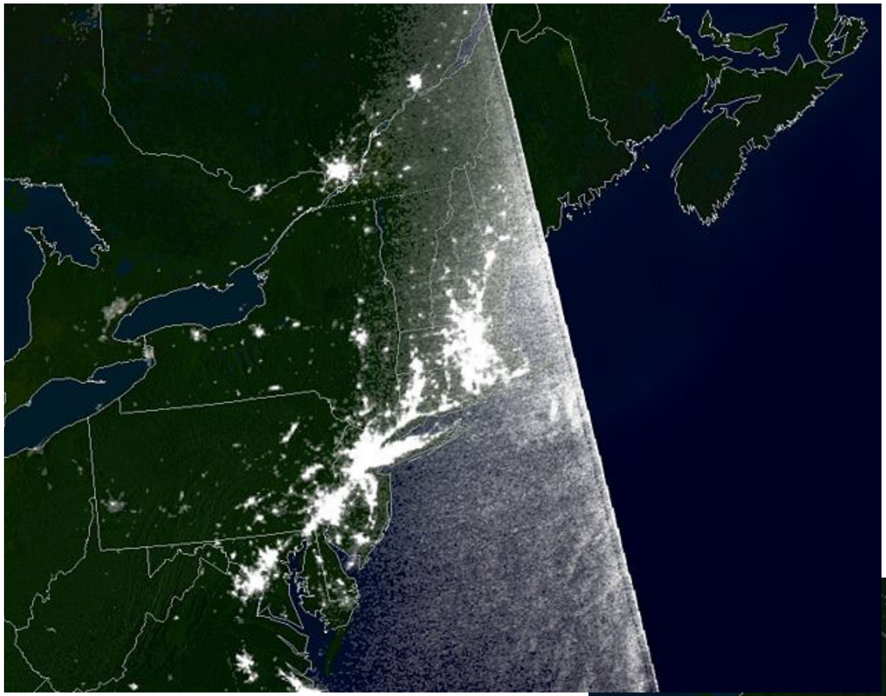
From US EIA http://eia.doe.gov

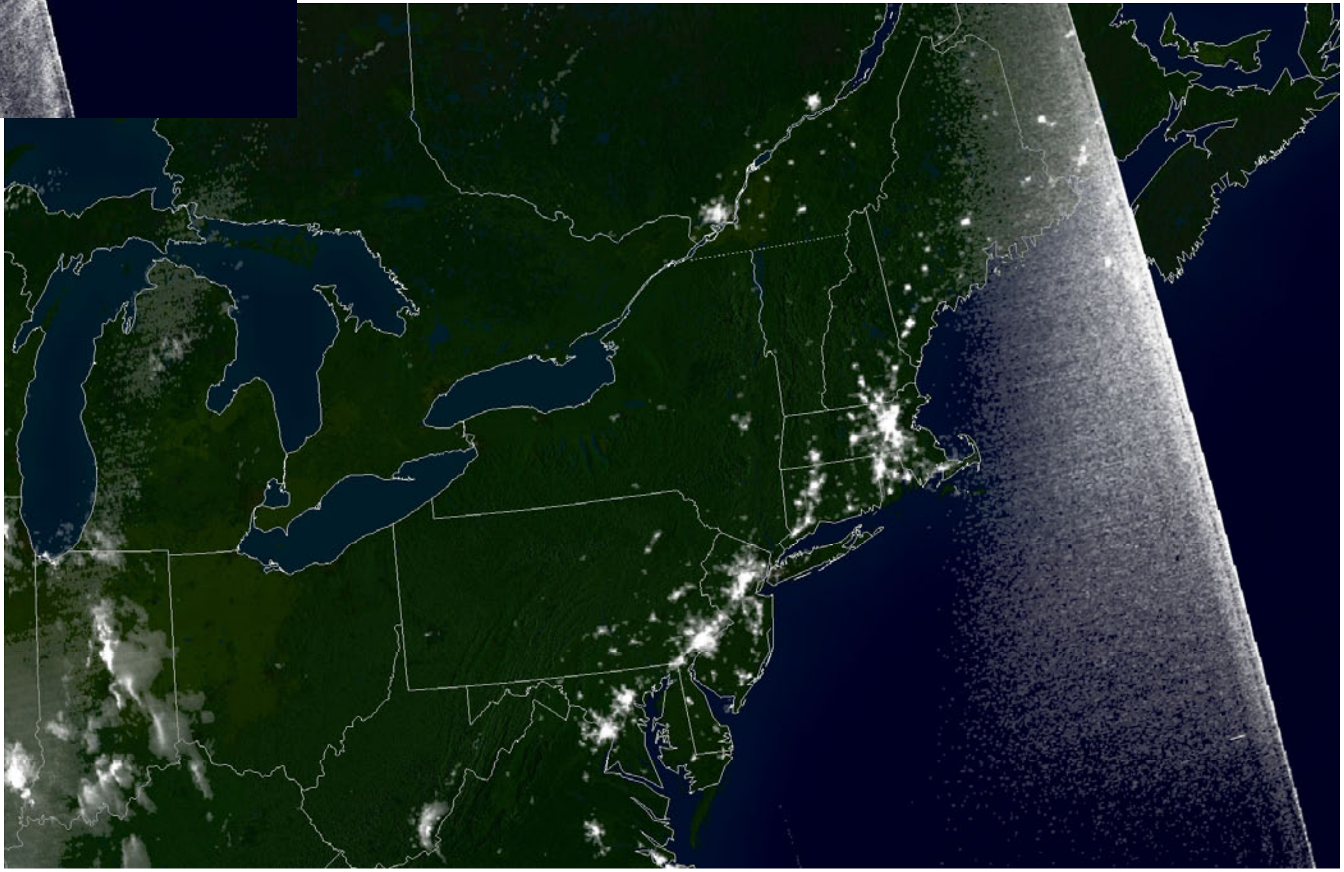
5 Energy security



From mapsofworld.com

6 Cascading failures





7 Metering

?

8 EVs

9 Lead times

Facts…

- If the grid were just 5% more efficient
  - equivalent to permanently eliminating the fuel and greenhouse gas emissions from **53 million** cars.
- If every American household replaced just one incandescent bulb with CFL
  - would conserve enough energy to light 3 million homes

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

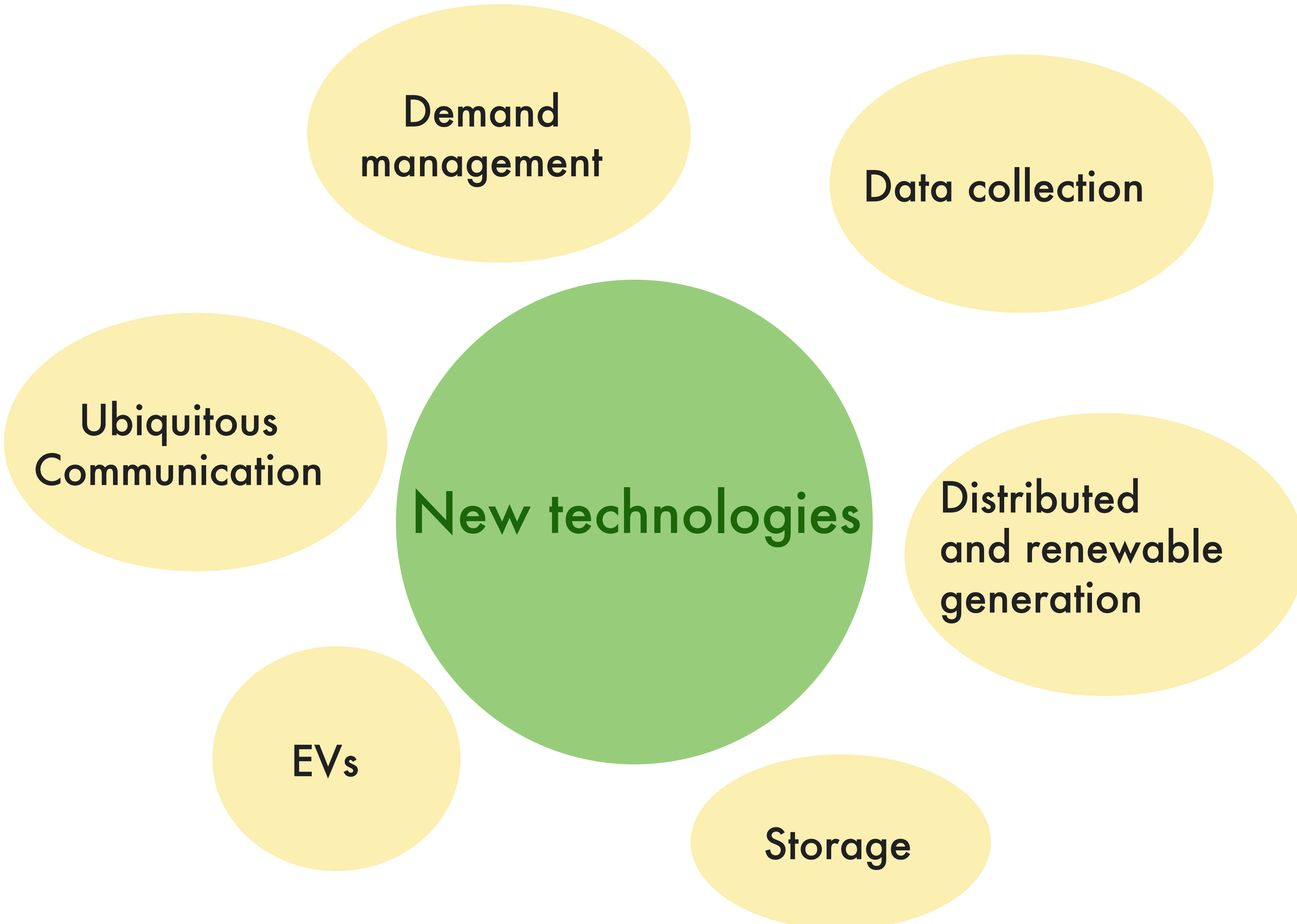
Facts

- **TWh generated (2008 est.)**
- US 4,369
- China 3,457
- India 830
- Canada 651

- **Daily kWh/capita (2008 est.)**
- 39.25
- 7.04
- 2.02
- 51.50

Great opportunities!

The smart grid


Demand management
Data collection
Ubiquitous Communication
New technologies
Distributed and renewable generation
EVs
Storage

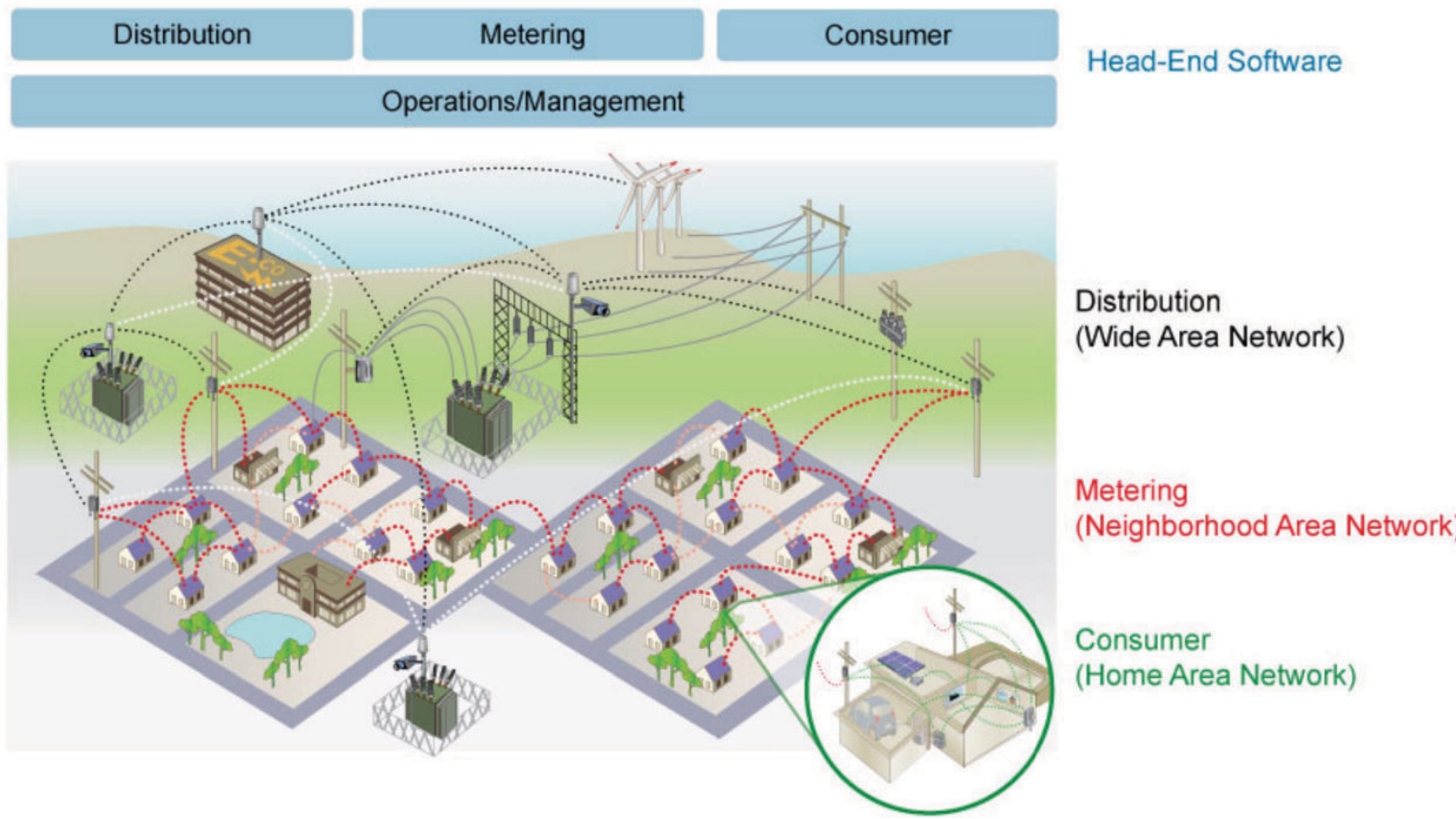


Image courtesy Trilliant Corp.

Challenges

Bi-directional energy flows

Renewables
- millions
- non-dispatchable
- intermittent

Consumer incentivization

Smart Grid

Reliable communication
- sensors

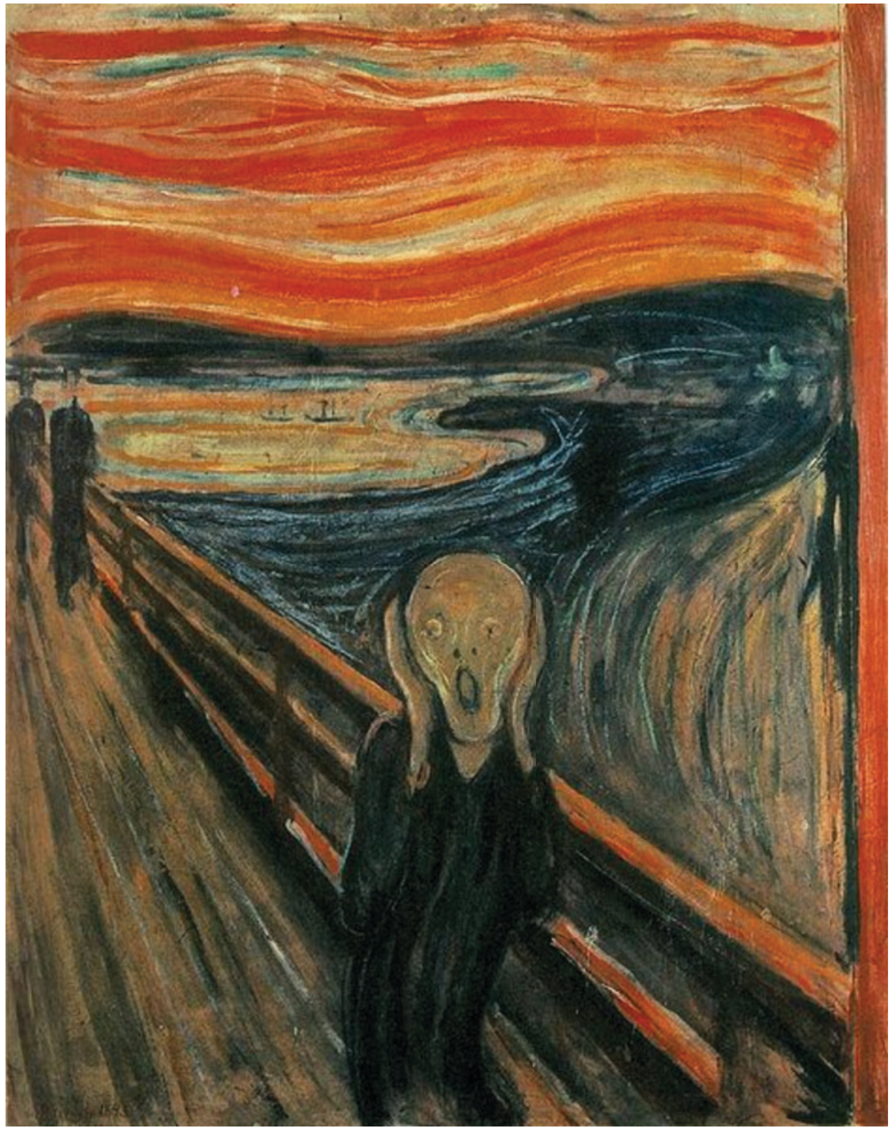
Exploiting elastic loads

Storage

A relatively static, predictable, stable system with inelastic loads and a few points of control

A highly dynamic system with elastic loads and millions of points of control

A paradigm shift

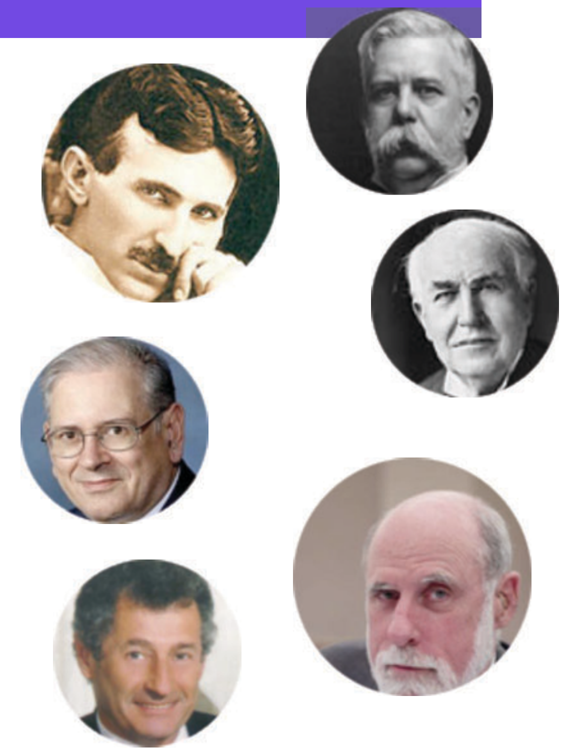


Beyond green networking

- Internet **concepts** can be used to smarten and green the grid

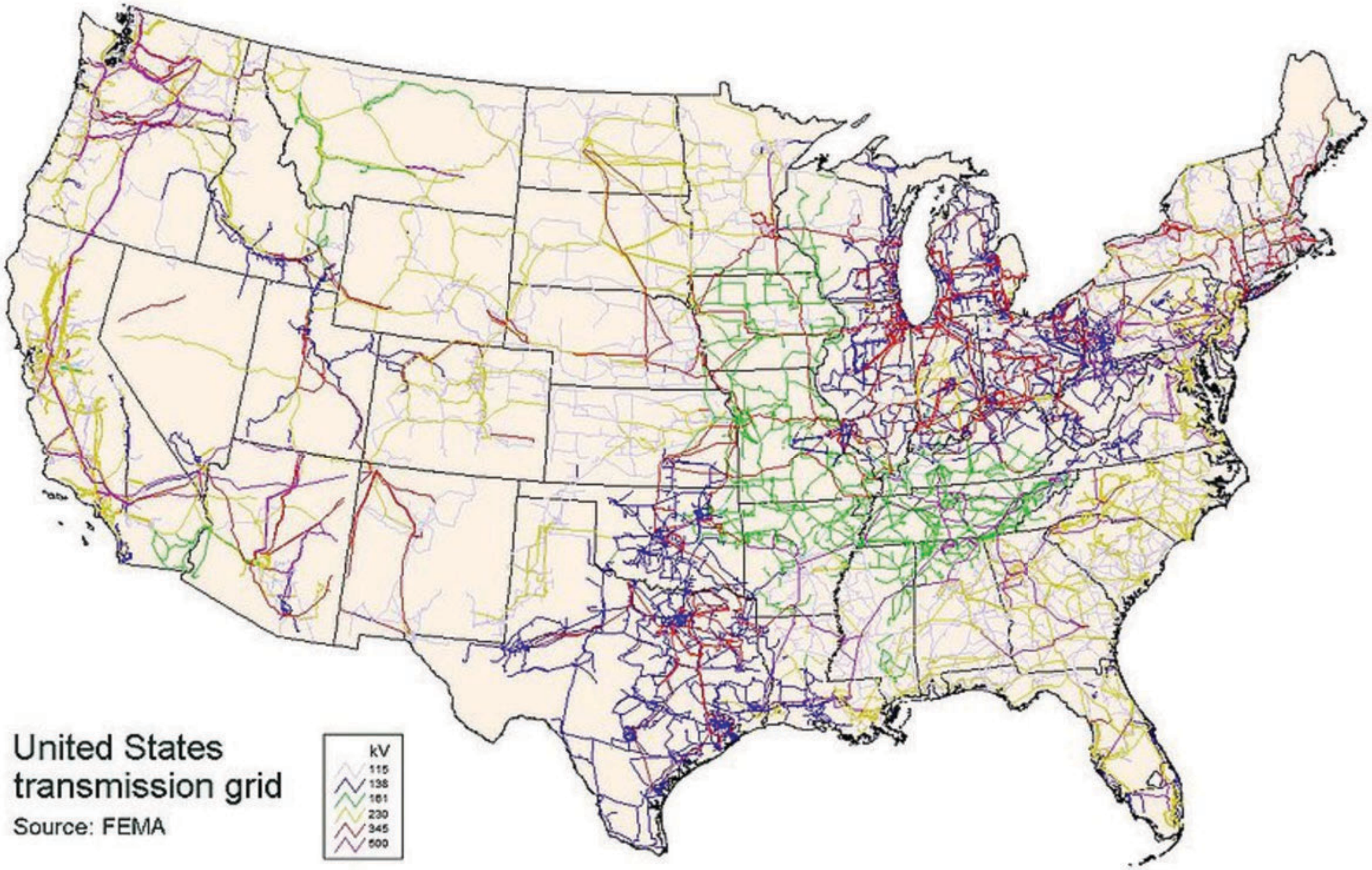
Similarities

- Vast
- Historically similar
  - bottom up + top down



Similarities

- Both match geographically distributed demands with distributed generation


United States
transmission grid
Source: FEMA
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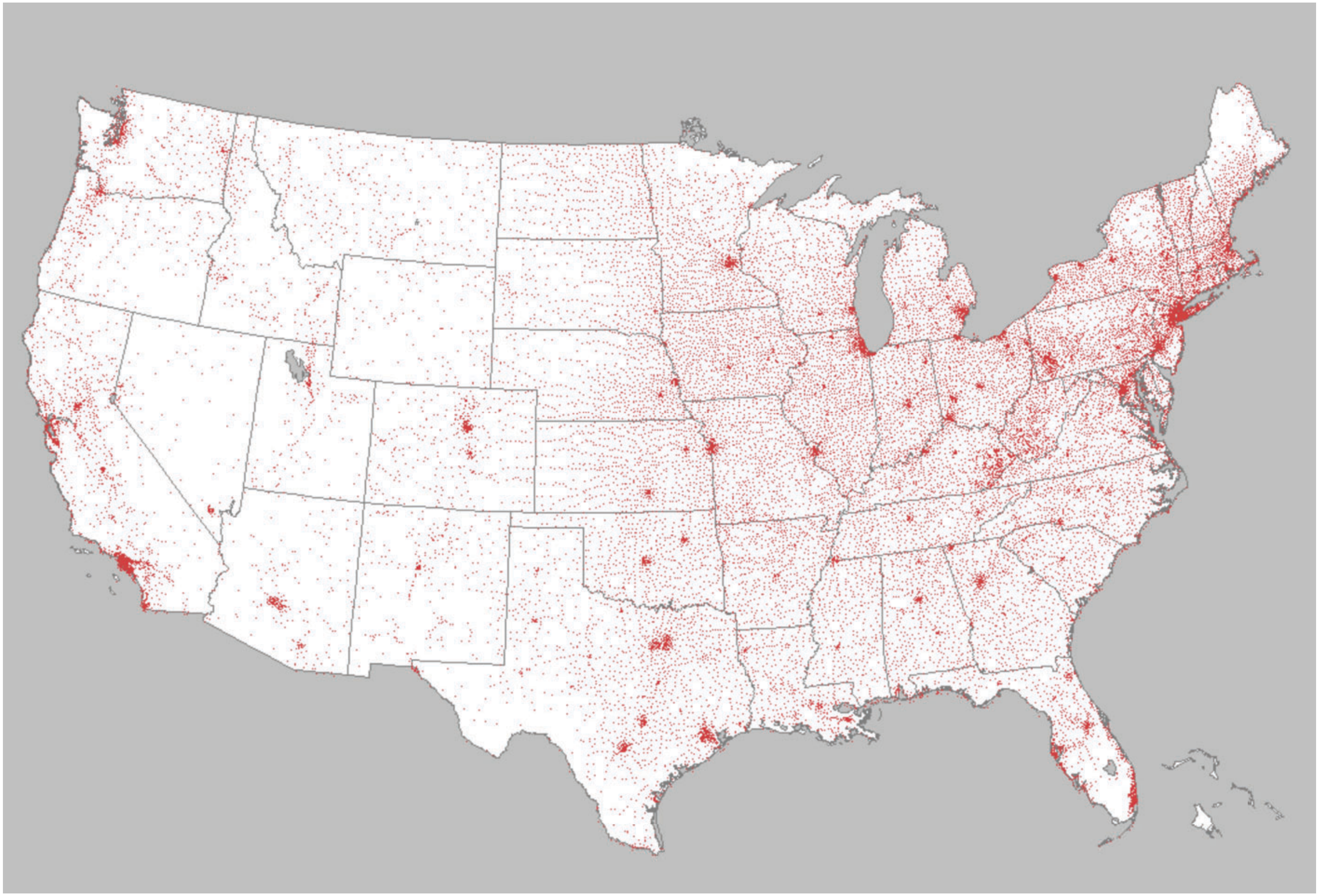
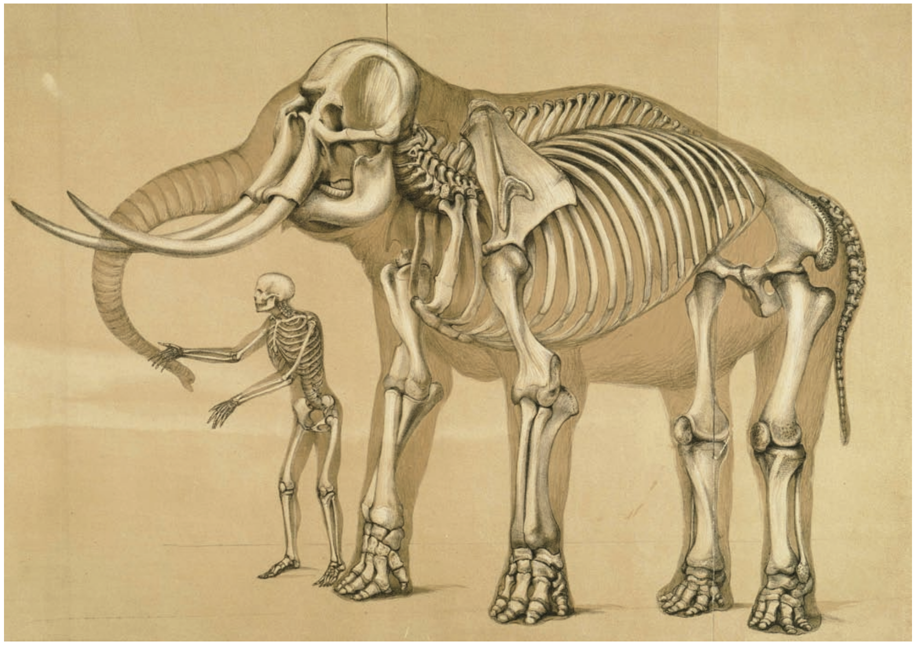


Image courtesy CAIDA

Similarities

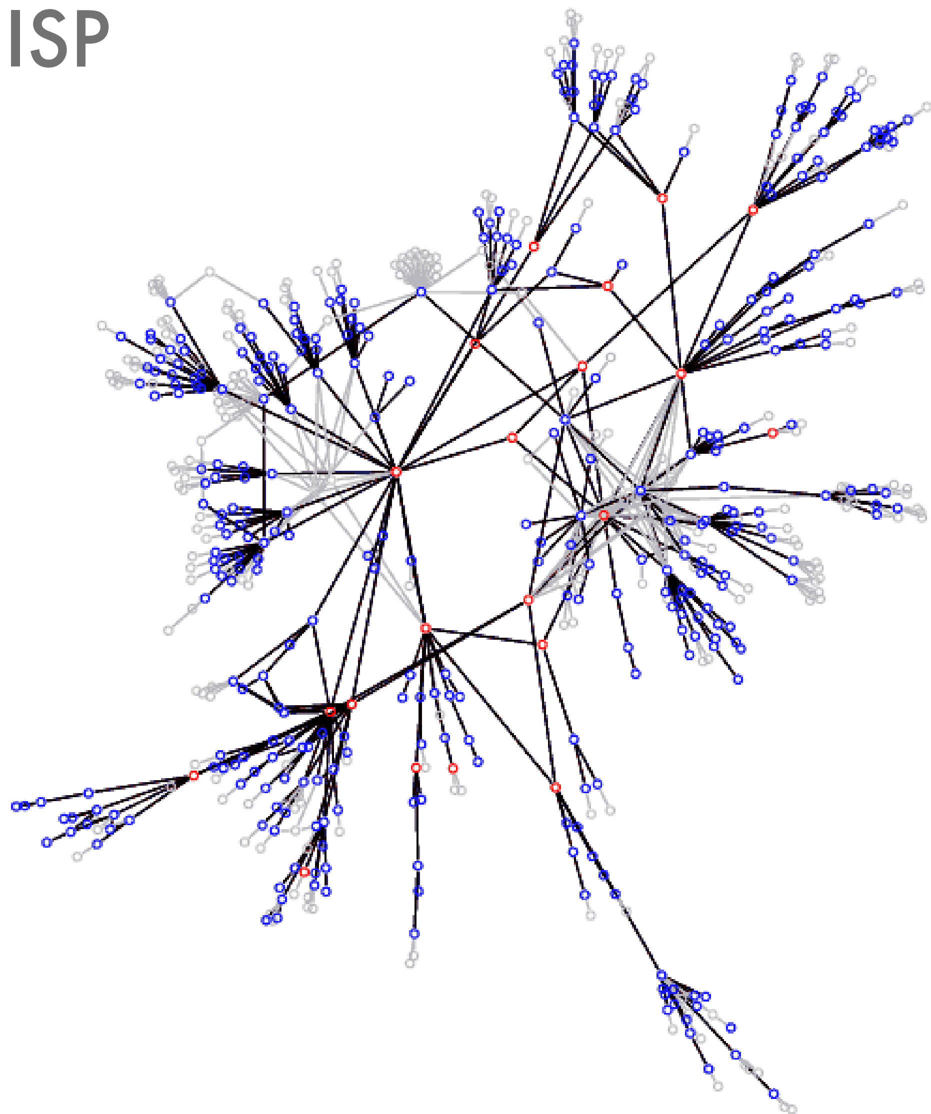
- Heterogeneous
- Critical to society
- **Ossified**



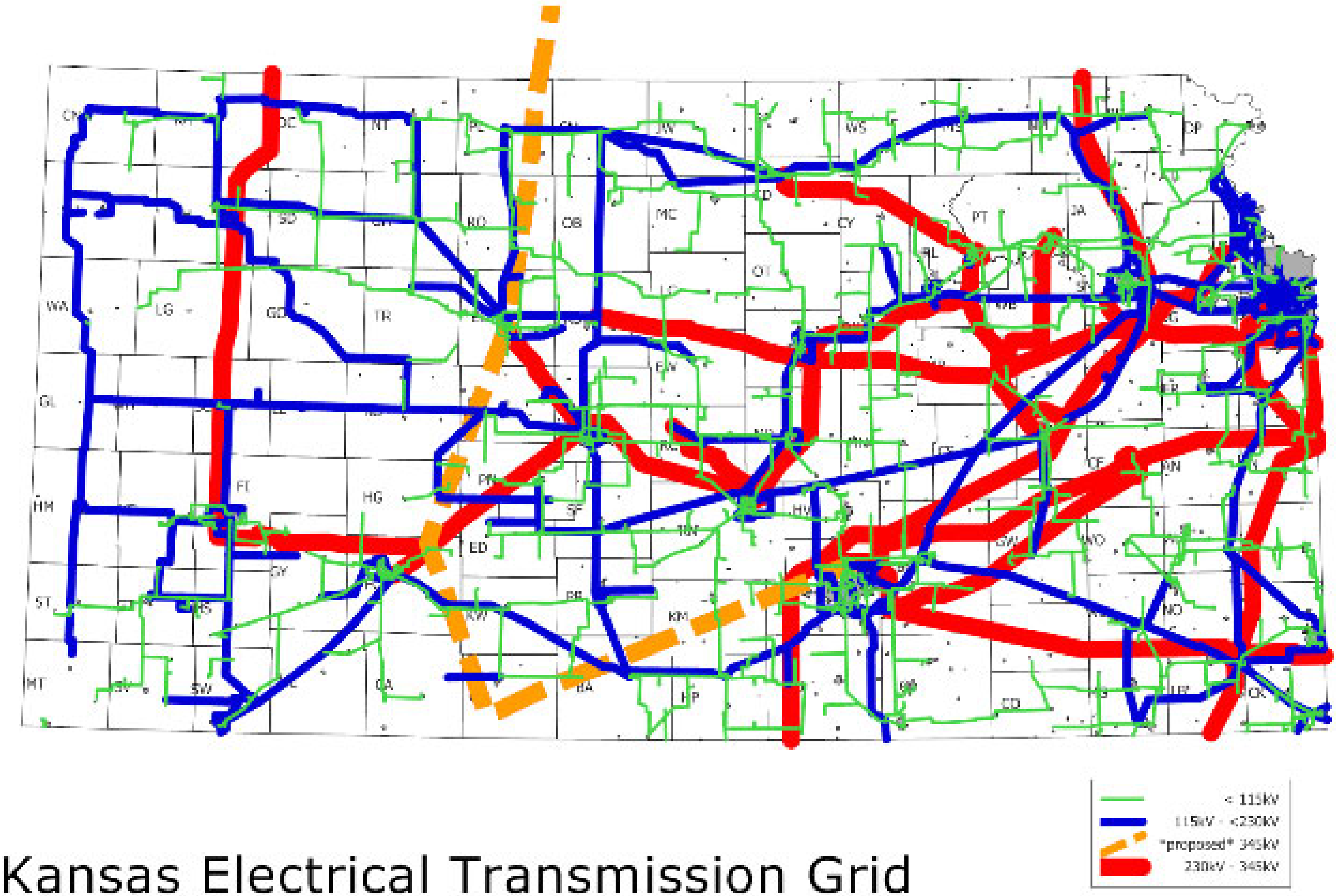
Similarities

- Hierarchical
  - mesh-like core designed for high capacity
  - tree-like access network

A mid-size ISP



By R. Govindan et al



Kansas Electrical Transmission Grid

From climateandenergy.org

Similarities

- Simple API

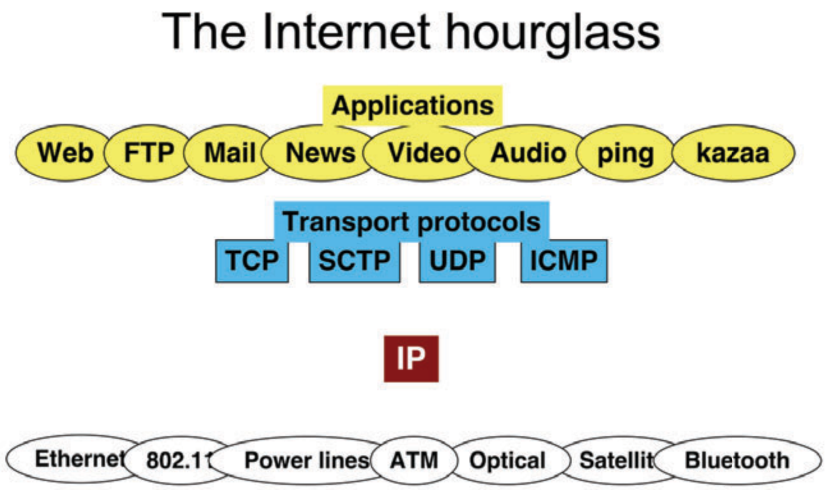
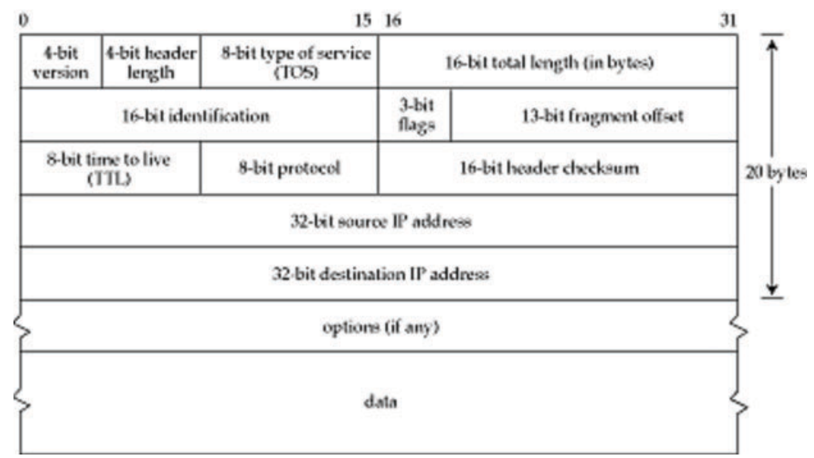


Image courtesy David Alderson, Caltech

Differences

- Electricity has no **headers**
  - no type
  - no destination



Differences

- Primarily one-way vs. primarily two-way flows

Differences

- Electricity loads are predictable

Differences

- Grid has practically no storage
  - Batteries not quite the same as DRAM!
  - $500/KWh

ISS4E vision

To apply our expertise in ***Information Systems and Sciences*** *to find* ***innovative solutions*** *to problems in* ***energy systems****.*

University of Waterloo

4 faculty
4 Master's
4 PhDs
1 postdoc position

WISE

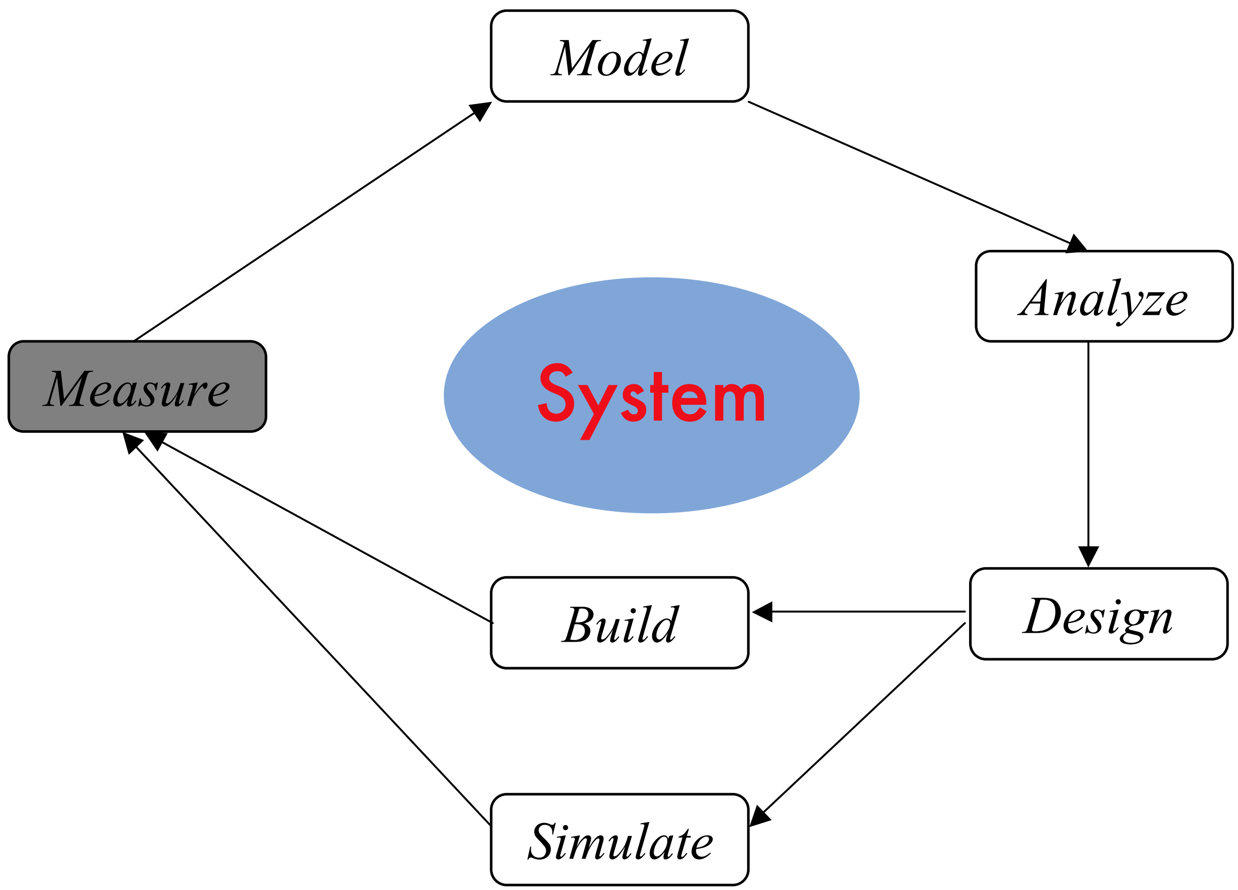
Focal point at UW for research in energy studies

- More than 70 faculty members with graduate students and postdoctoral fellows working as multi-disciplinary research teams
- Research areas:
  - Renewable Energy
  - Storage & Transport
  - Conversion Technologies
  - Emission Management
  - Power System Optimization
  - Sustainable Energy Policy
  - Conservation, Demand Mgmt, Energy Efficiency
  - Green Auto Powertrain
  - ISS4E

Lab facilities

- Sensors for building monitoring
- Smart power strips for home monitoring and control
- ENVI systems for home energy data collection
- Custom-built wireless sensors for solar panel monitoring

Data-driven approach



Measure

Fine grained (6 sec)

24 homes

1 year

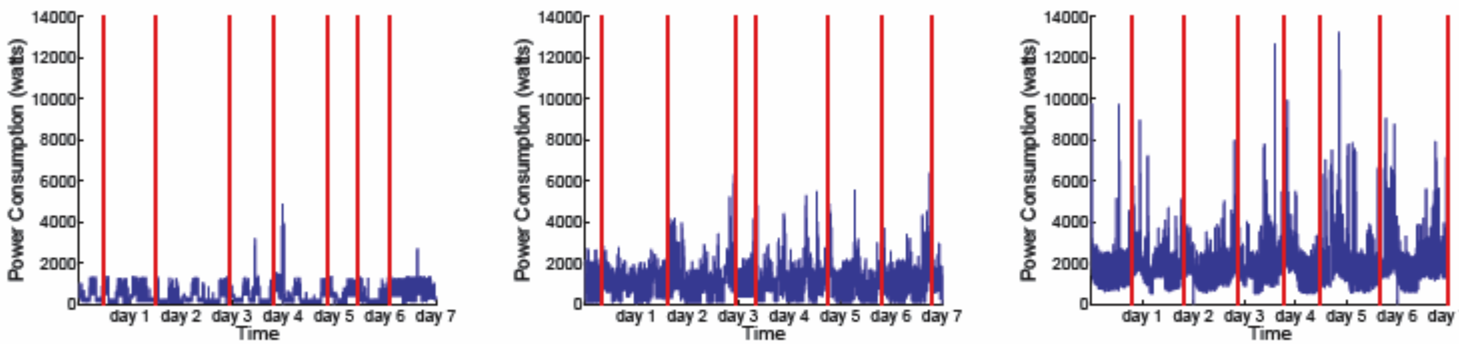


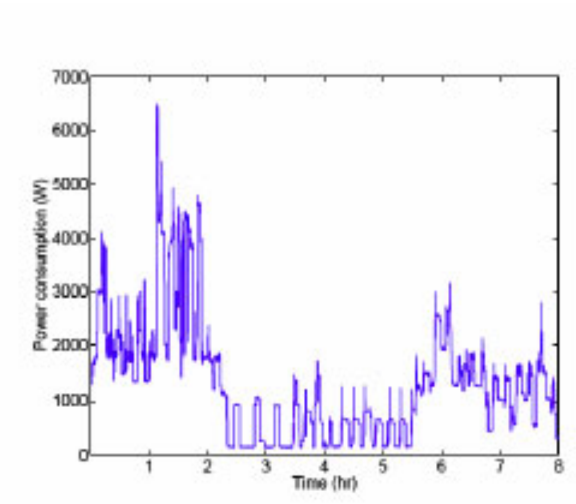
Figure 3: Load measurements from houses in three classes for one week with busy hours marked by vertical lines.

Measure

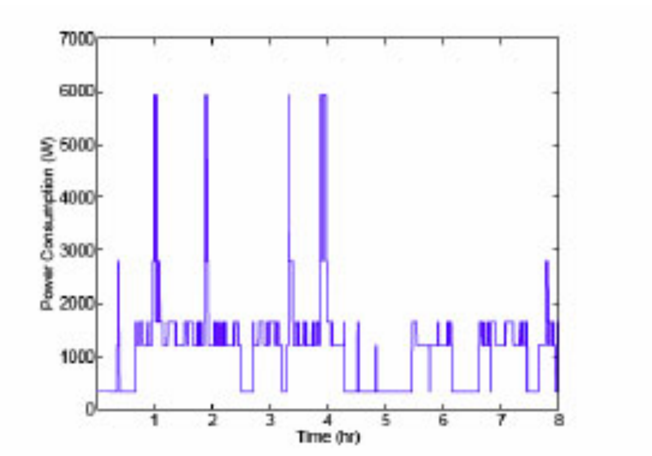
Other datasets

- appliance energy use (SmartA, IBM)
- commercial building energy use over 2-4 years (Pulse)
- taxi driving records (Cabspotting)
- car fleet records (CrossChasm)
- electricity prices (IESO, UK, India)
- weather records
- …

Model



P =	0.90264	0.00192	0.01080	0.00834	0.07630
	0.00103	0.97198	0.00006	0.02210	0.00481
	0.06325	0.00110	0.91737	0.00183	0.01645
	0.00336	0.01929	0.00028	0.94352	0.03355
	0.02448	0.00166	0.00108	0.03038	0.94239
R =	2252	500	4355	1077	1614



Markov models for home energy use

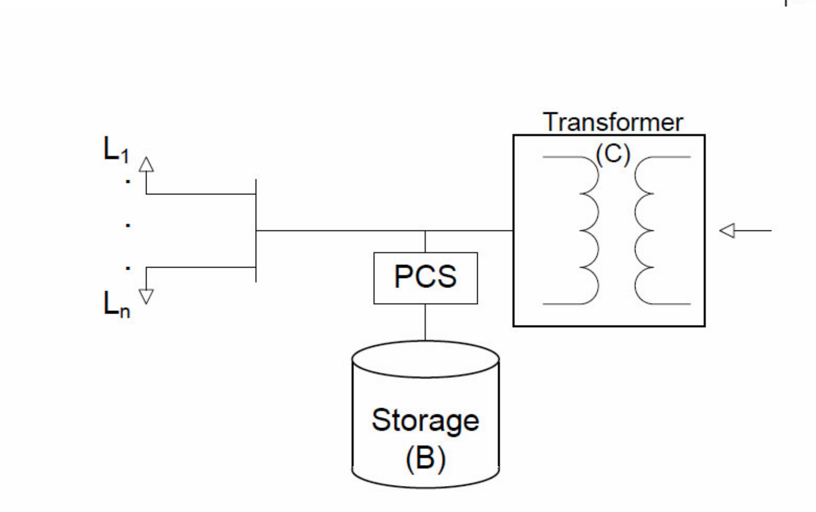
Model

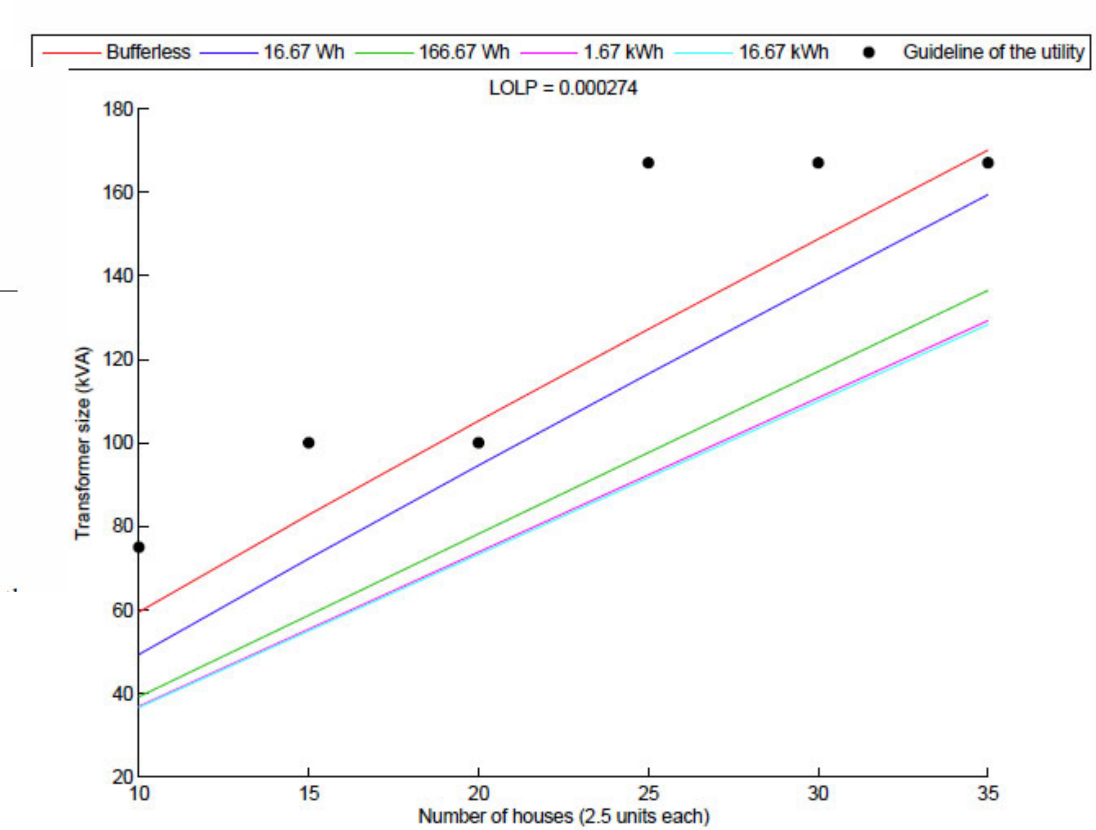
Other models

- appliance elasticity model
- transformer loading model
- aggregate electricity load model
- EV fleet charging model
- data center load model
- grid regulation model
- storage sizing model
- …

Analyze

Use teletraffic theory to analyze effect of storage on distribution networks



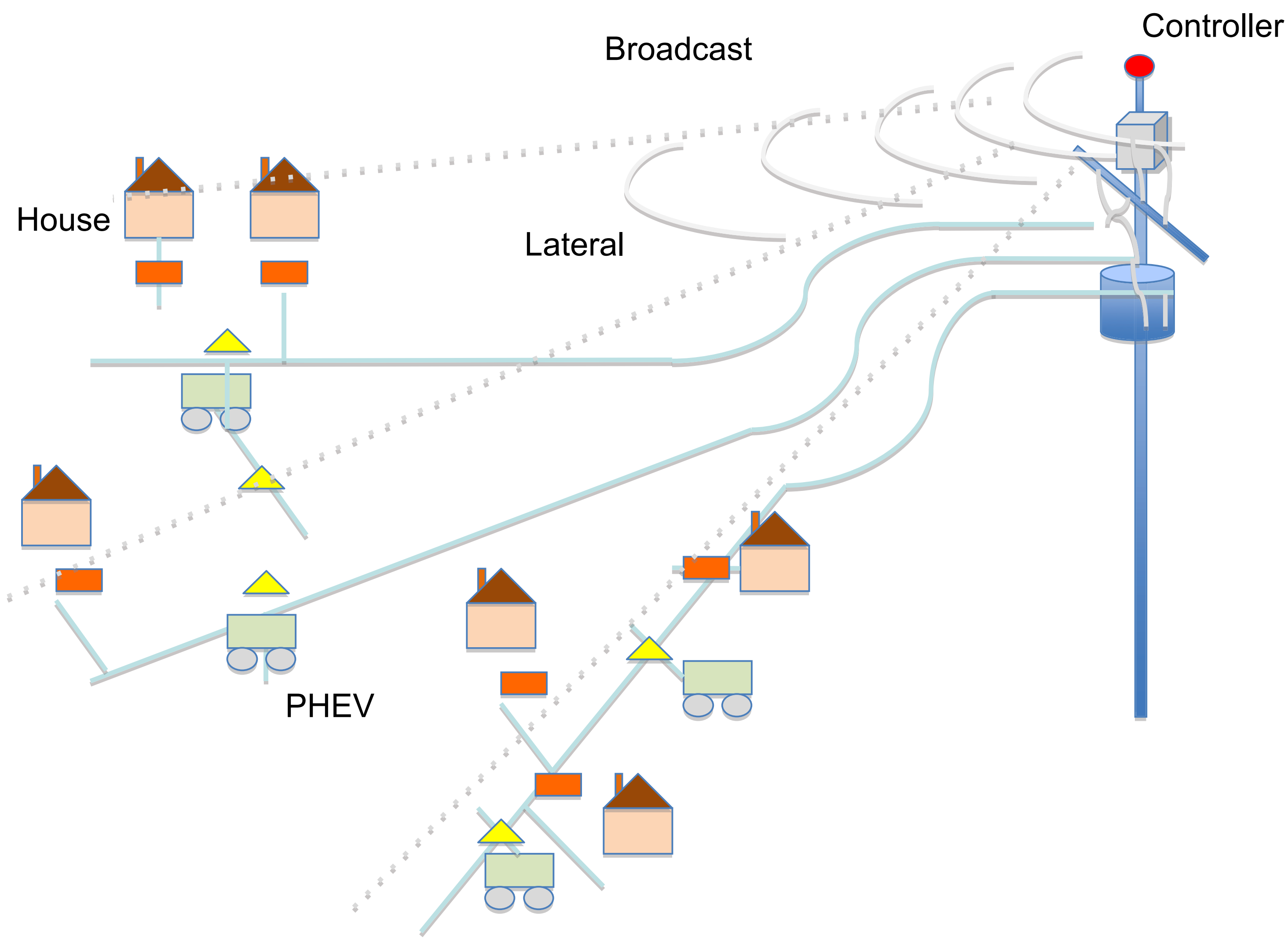


Analyze

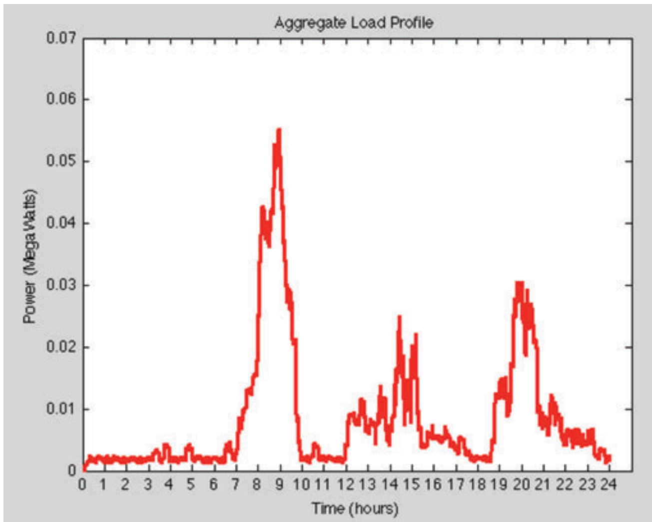
Other analysis

- effect of smart appliances on peak energy
- cost-effectiveness of storage for homes
- regulation services provided by fleet charging
- benefit of EVs to taxi fleets
- carbon-footprint reduction of CDNs by request routing
- effect of smartphones on user behaviour modification
- solar cell anomaly detection
- …

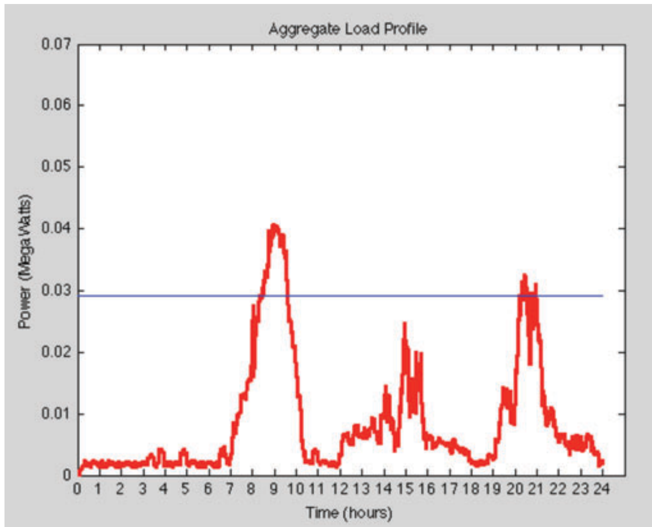
Design



Design



Aggregate Load Profile
Power (MegaWatts)
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time (hours)



Aggregate Load Profile
Power (MegaWatts)
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time (hours)

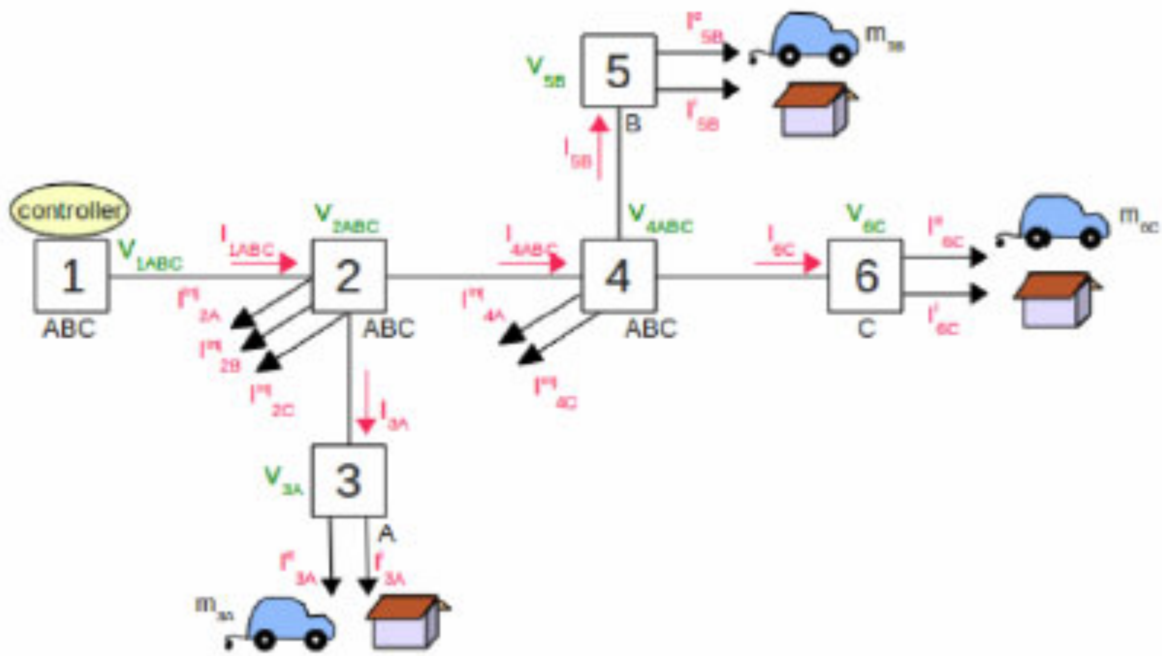
Design

Other control mechanisms

- fleet charging control
- home storage control
- CDN request routing and data placement
- …

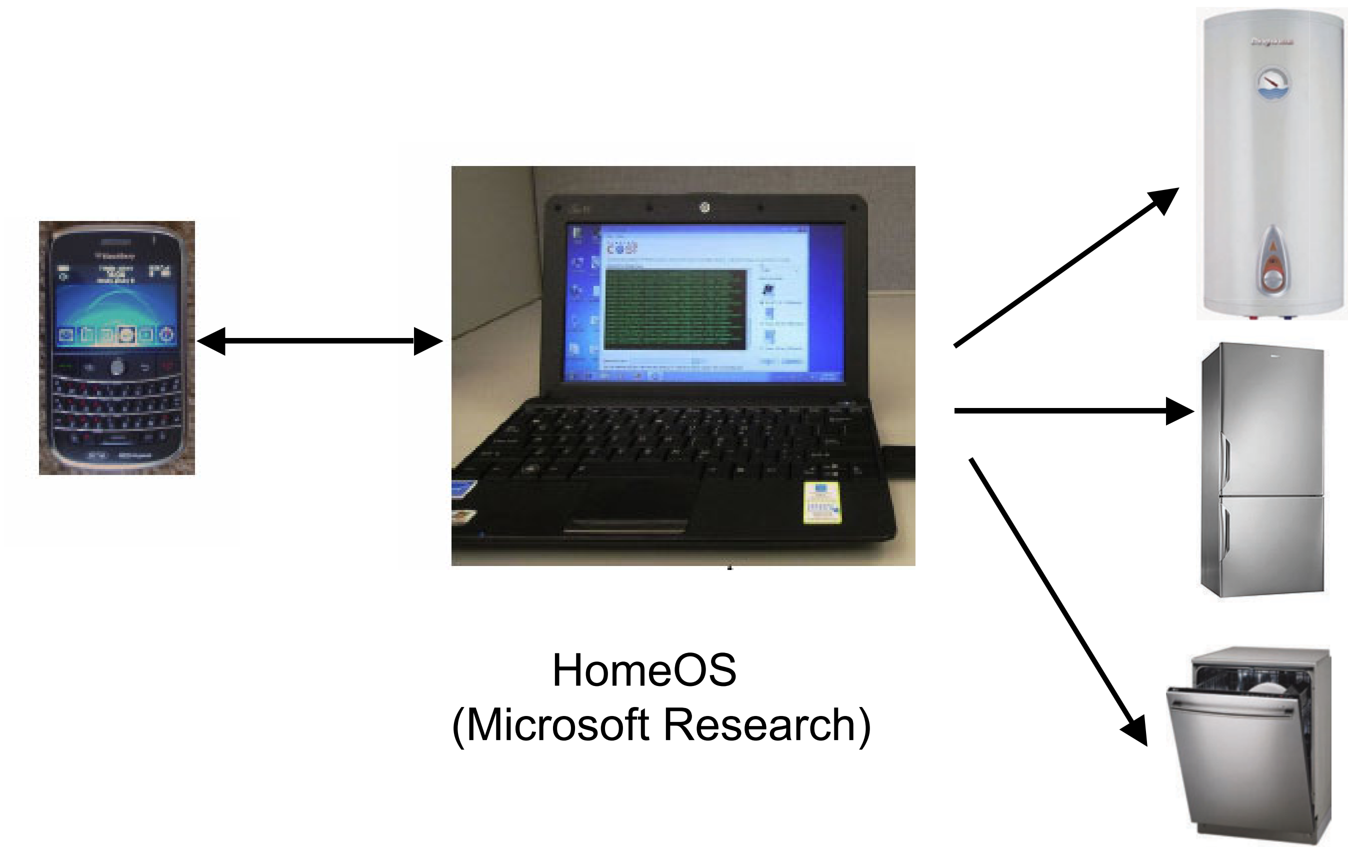
Simulate

Gridlab-D for detailed grid simulation



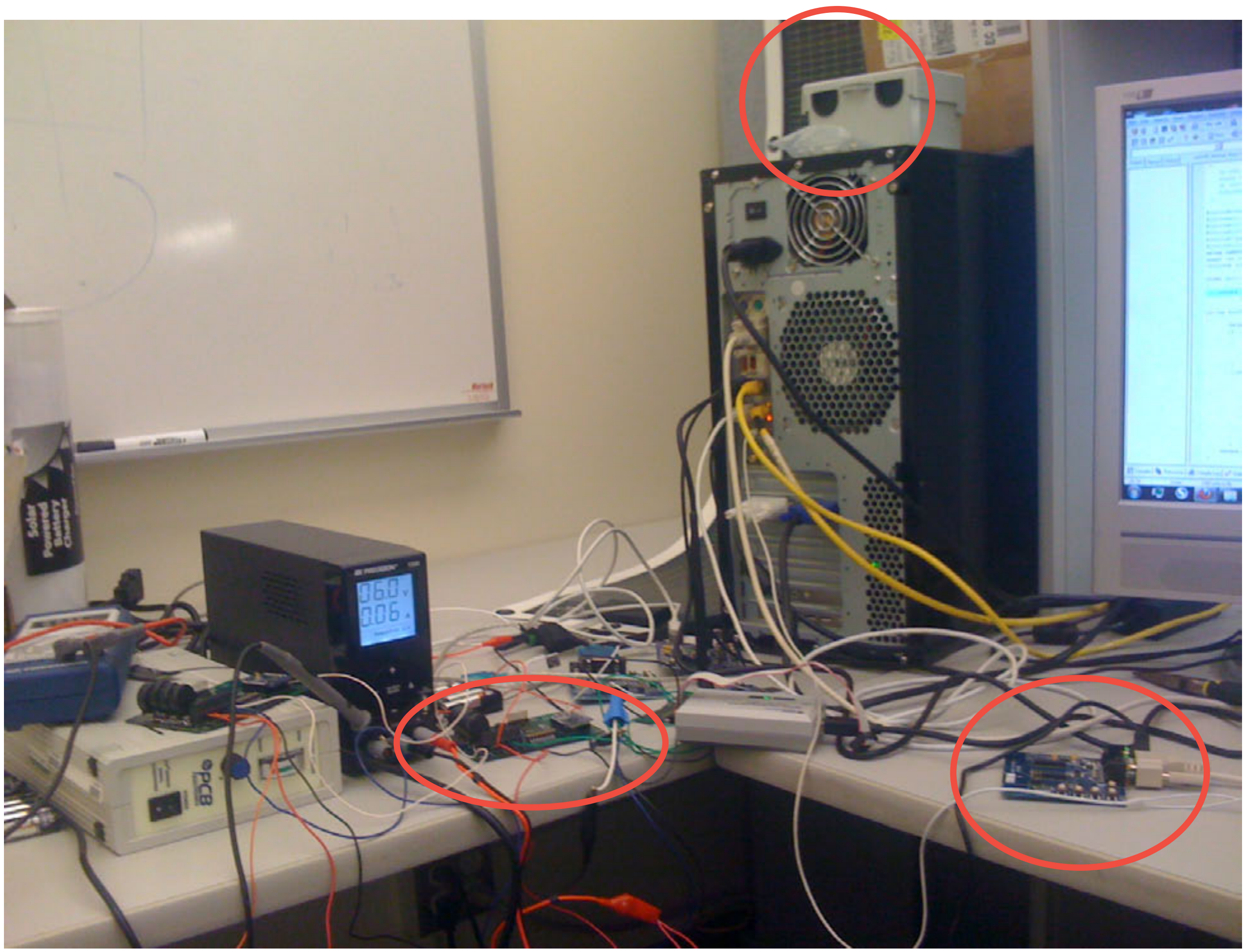
Build

Smartphone-based application architecture



Build

Prototype system for solar panel anomaly detection



Conclusions

- The next decade will decide the grid of 2120
- Internet ~= Grid
- 40 years of Internet research {could, should, may} help
- Rich area for research

More information

http://blizzard.cs.uwaterloo.cs/iss4e