Smart Grid: Status and Challenges

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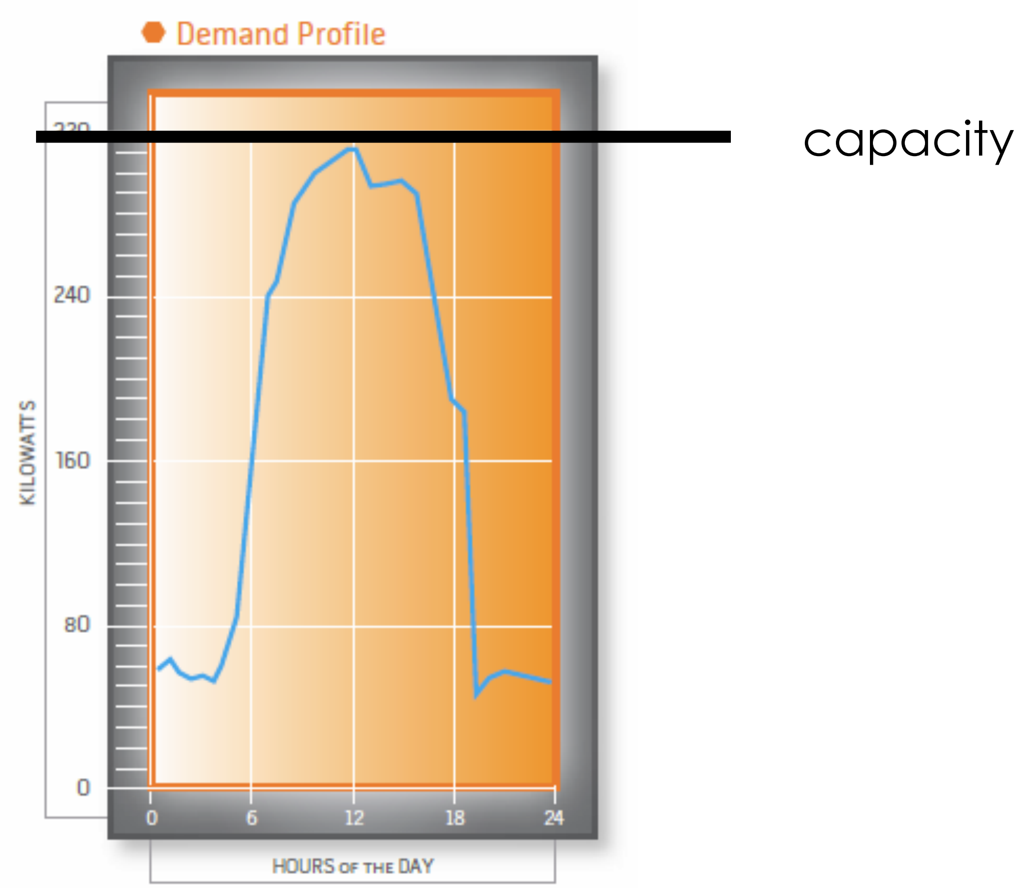
CCSES Workshop
April 28, 2014

Outline

- The grid has real problems
  - that smart grids can solve
- These problems are intrinsic and difficult
  - so progress has been slow
- Three areas where changes are imminent are solar, storage, and sensing
  - I'll give some examples of my work in these areas

The grid has some real problems

1. Overprovisioned



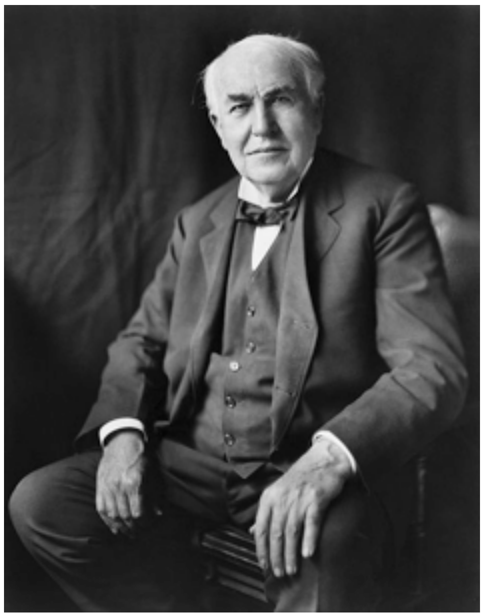
2. Inefficient

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

	TWh generated	Daily W/capita (2012 est.)
China	4,938	395
US	4,256	1402

Wikipedia

5. Poorly measured

6. Poorly controlled

- Electrons are not addressible

7. Huge carbon footprint

Smart grid vision

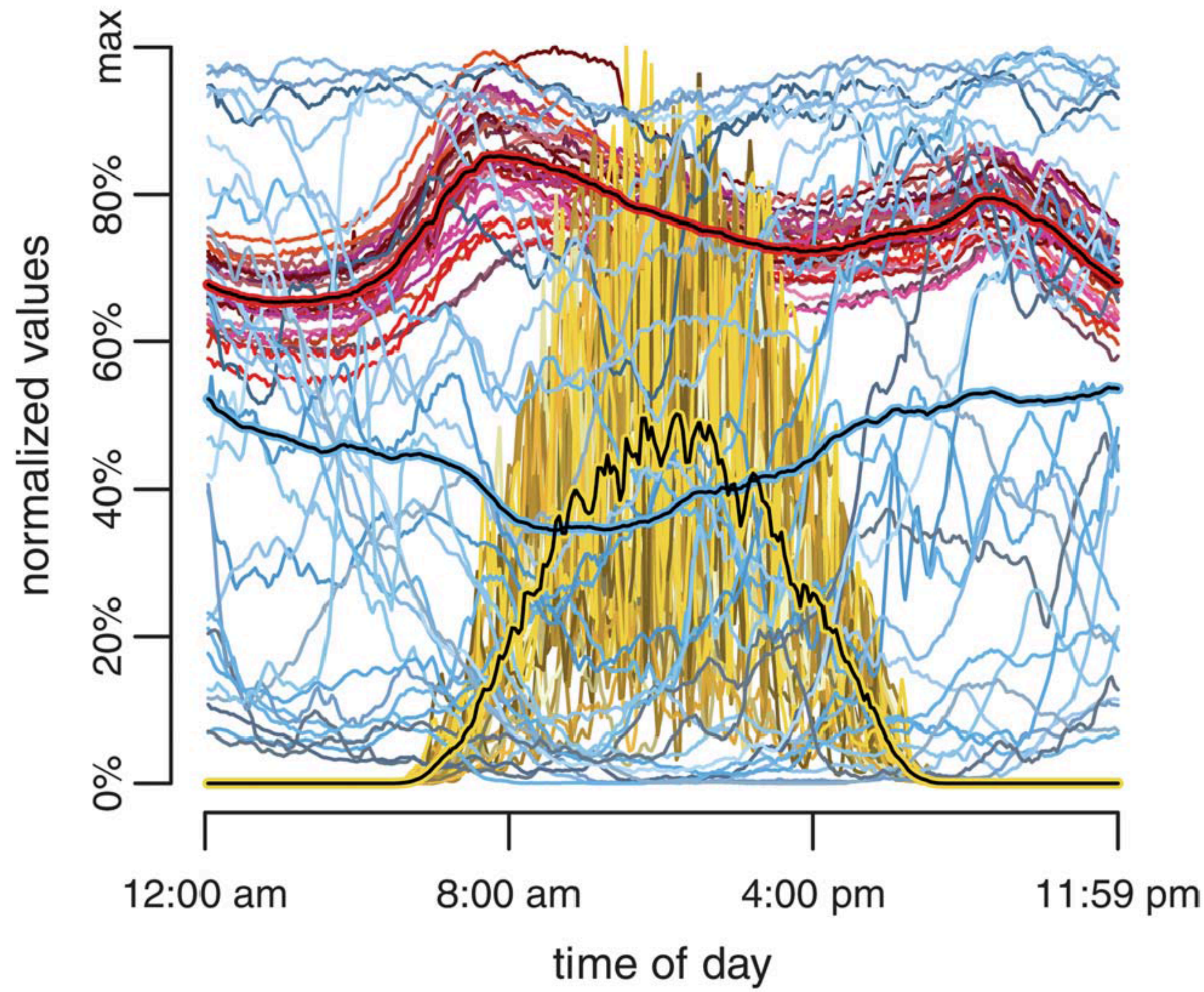
Current grid vs. "Smart" grid

Current grid	"Smart" grid
High carbon footprint	Renewables/low carbon
Little to no storage	Storage rich
Poorly measured	Sensing rich
Poorly controlled	Control rich
Ossified	Flexible
Inefficient	Energy frugal
Centralized generation	Decentralized generation

Source: European technology platform: Smart Grids

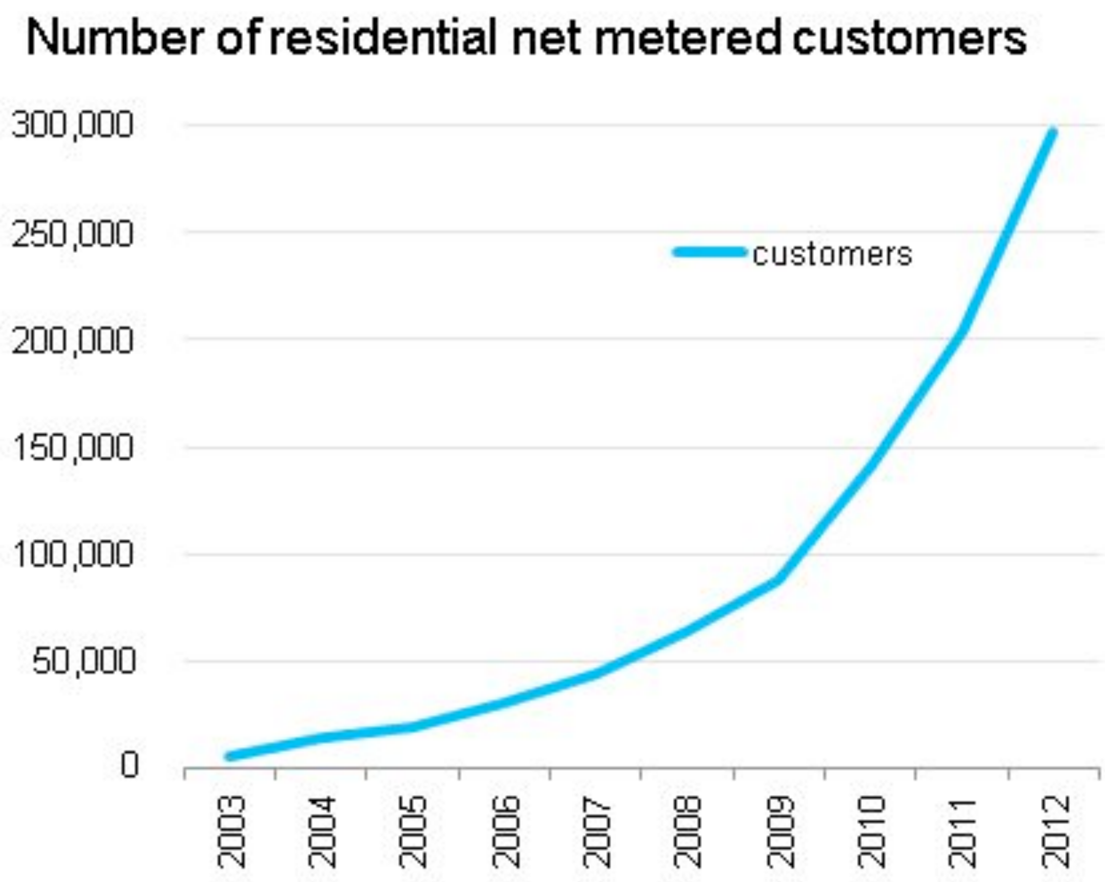
Intrinsic challenges

1. Matching demand and supply



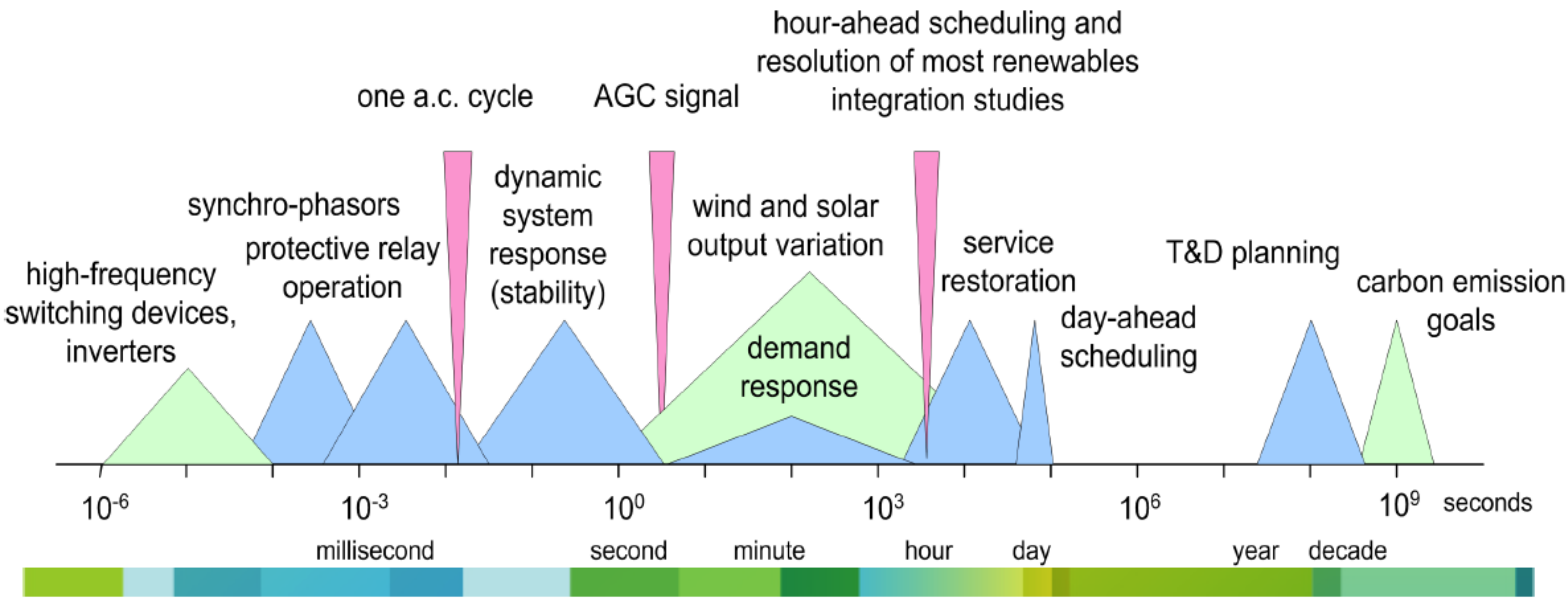
Barnhart *et al*, Proc. Energy and Environment, 6:2804, 2013

2. Controlling distributed generators



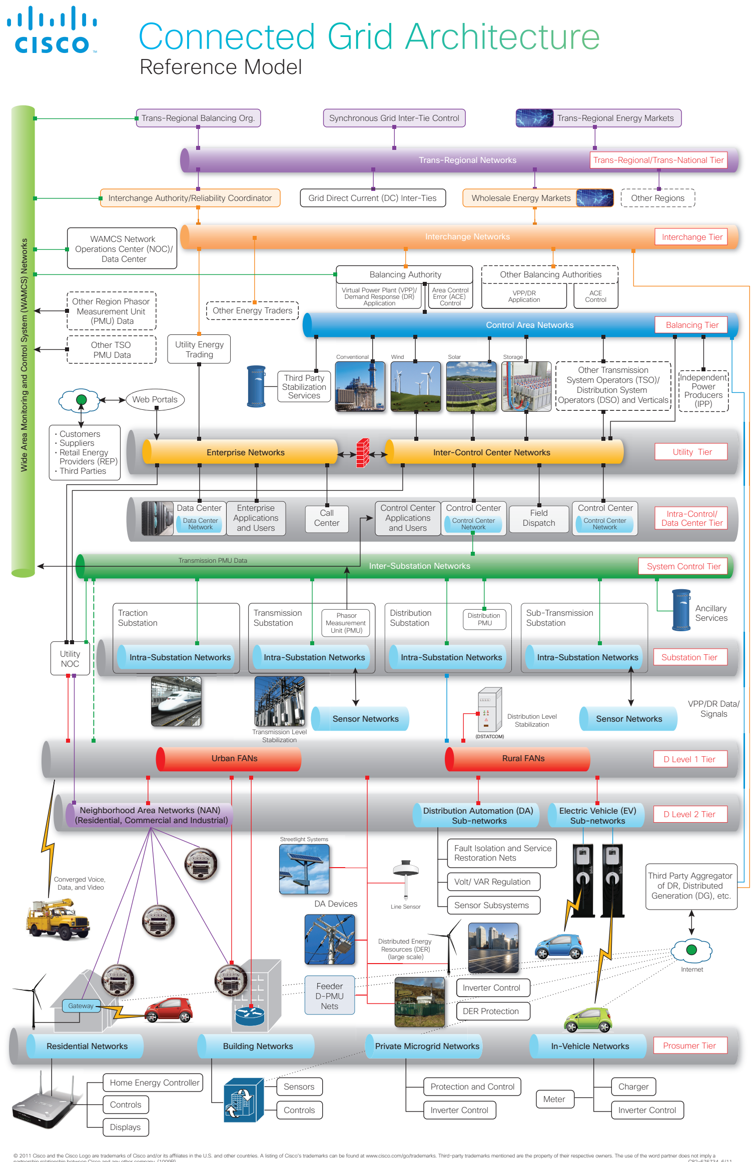
US EIA

3. Control over many time scales



Jeff Taft, Cisco

4. Complex control architecture



Cisco

5. Consumers lack incentives

- Energy savings of 10%
  - $10/month

6. Utilities also lack incentives!

7. Huge legacy infrastructure

8. Storage is complex and expensive

- No clear winner in terms of technology
- Need to balance energy and power

Status

Depressing…

A. Demand response – only time of use pricing
B. Storage - tiny
C. Smart buildings and homes – demo stage
D. Microgrids – rare
E. Electric vehicles – early stage
F. Security and privacy – mostly missing

Three inflection points

- Solar
- Storage
- Sensing

Global cumulative installed PV capacity in MW

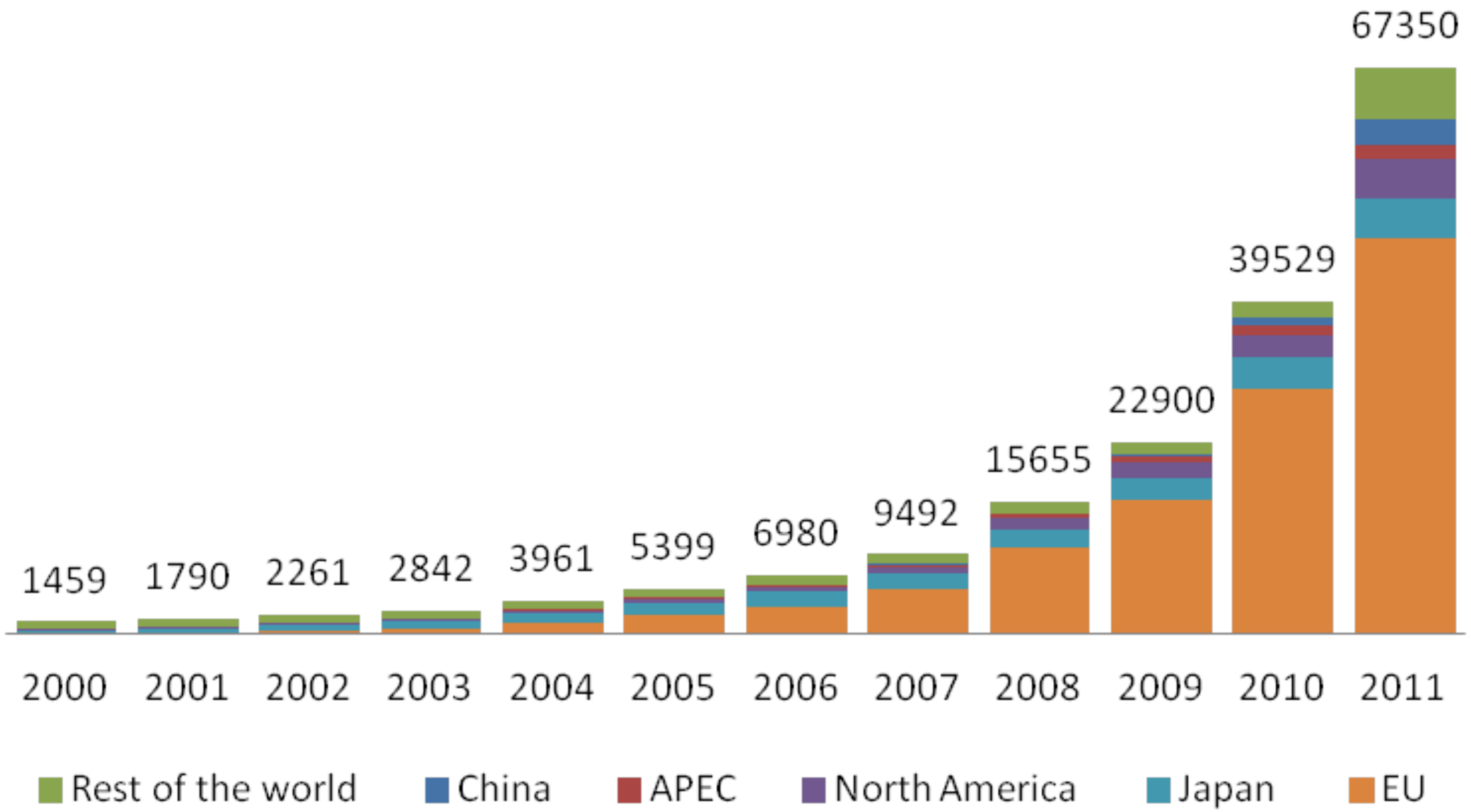
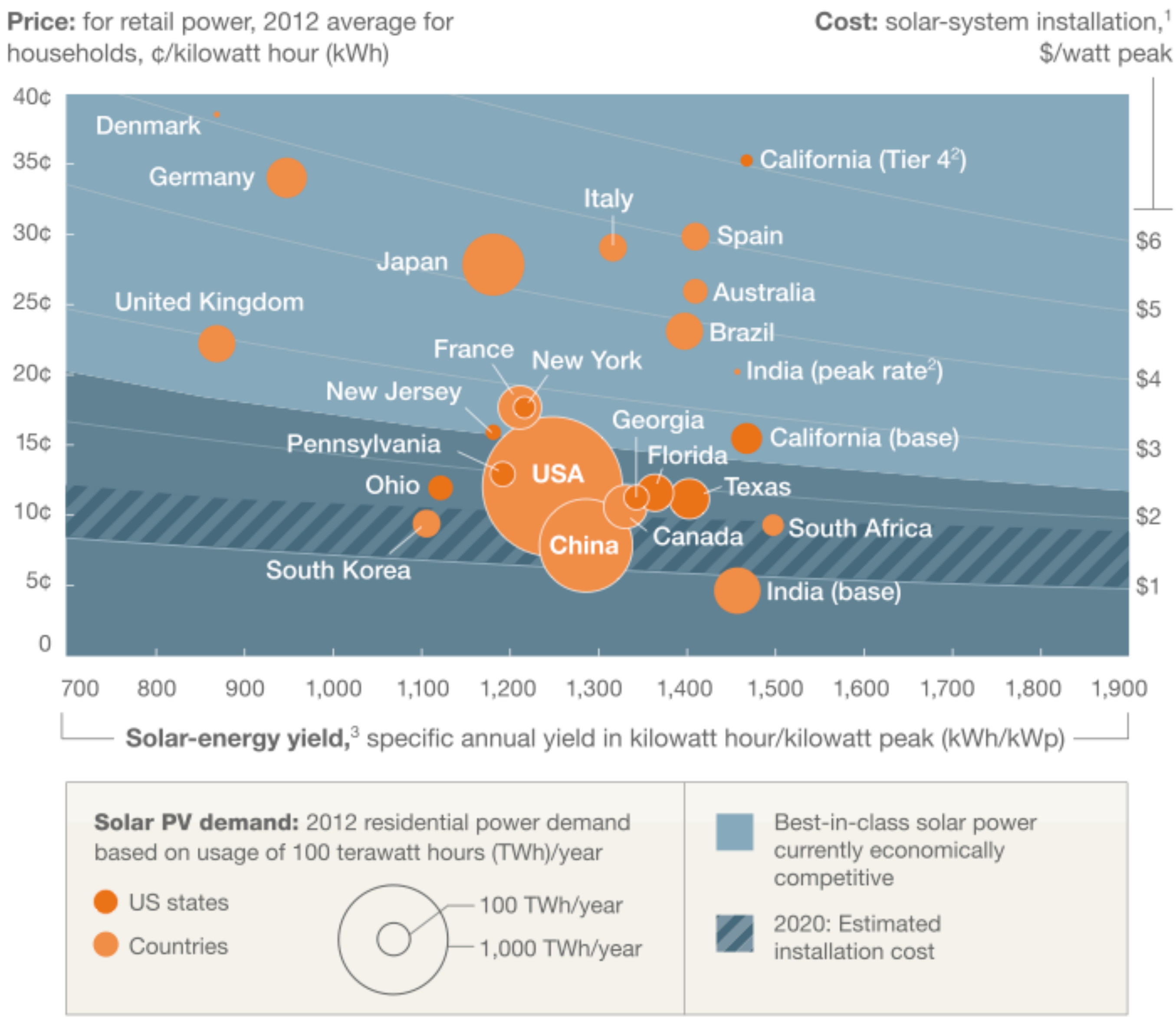


Table showing average cost in cents/kWh over 20 years for solar power panels

Cost	Insolation								
	2400 kWh/kWp·y	2200 kWh/kWp·y	2000 kWh/kWp·y	1800 kWh/kWp·y	1600 kWh/kWp·y	1400 kWh/kWp·y	1200 kWh/kWp·y	1000 kWh/kWp·y	800 kWh/kWp·y
200 $/kWp	0.8	0.9	1.0	1.1	1.3	1.4	1.7	2.0	2.5
600 $/kWp	2.5	2.7	3.0	3.3	3.8	4.3	5.0	6.0	7.5
1000 $/kWp	4.2	4.5	5.0	5.6	6.3	7.1	8.3	10.0	12.5
1400 $/kWp	5.8	6.4	7.0	7.8	8.8	10.0	11.7	14.0	17.5
1800 $/kWp	7.5	8.2	9.0	10.0	11.3	12.9	15.0	18.0	22.5
2200 $/kWp	9.2	10.0	11.0	12.2	13.8	15.7	18.3	22.0	27.5
2600 $/kWp	10.8	11.8	13.0	14.4	16.3	18.6	21.7	26.0	32.5
3000 $/kWp	12.5	13.6	15.0	16.7	18.8	21.4	25.0	30.0	37.5
3400 $/kWp	14.2	15.5	17.0	18.9	21.3	24.3	28.3	34.0	42.5
3800 $/kWp	15.8	17.3	19.0	21.1	23.8	27.1	31.7	38.0	47.5
4200 $/kWp	17.5	19.1	21.0	23.3	26.3	30.0	35.0	42.0	52.5
4600 $/kWp	19.2	20.9	23.0	25.6	28.8	32.9	38.3	46.0	57.5
5000 $/kWp	20.8	22.7	25.0	27.8	31.3	35.7	41.7	50.0	62.5

Grid-parity potential of solar PV (photovoltaic) power in major markets, residential-segment example



[1]Full cost estimated, based on residential 5-kilowatt c-Si system; levelized cost of energy accounts for solar insulation and assumes 5% weighted average cost of capital, 25-year lifetime, 0.3% annual degradation, and fixed 1% operating and maintenance costs.

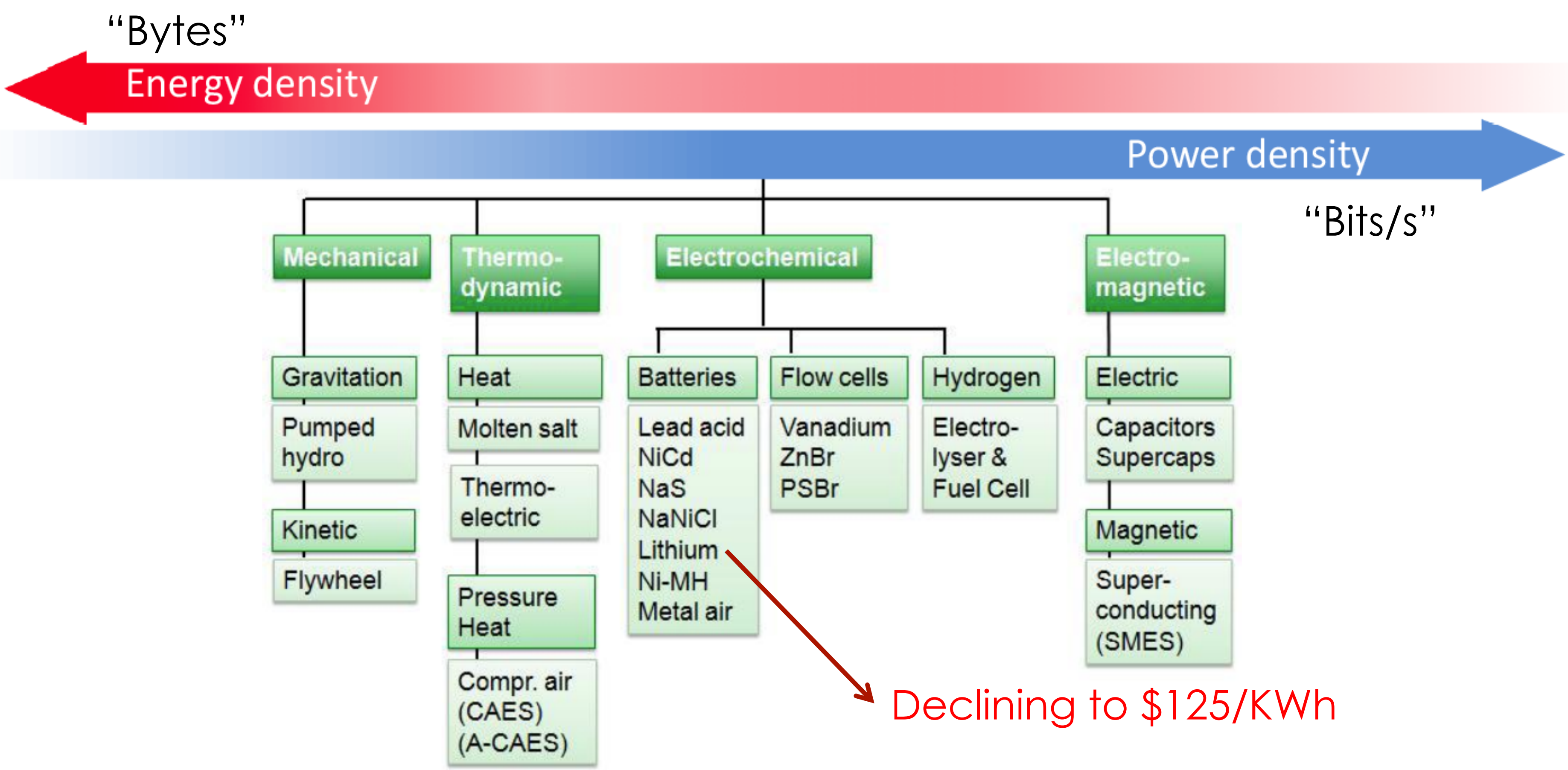
McKinsey, 2014

Storage

- Global investment to reach $122 Billion by 2021

Pike Research

Storage alternatives

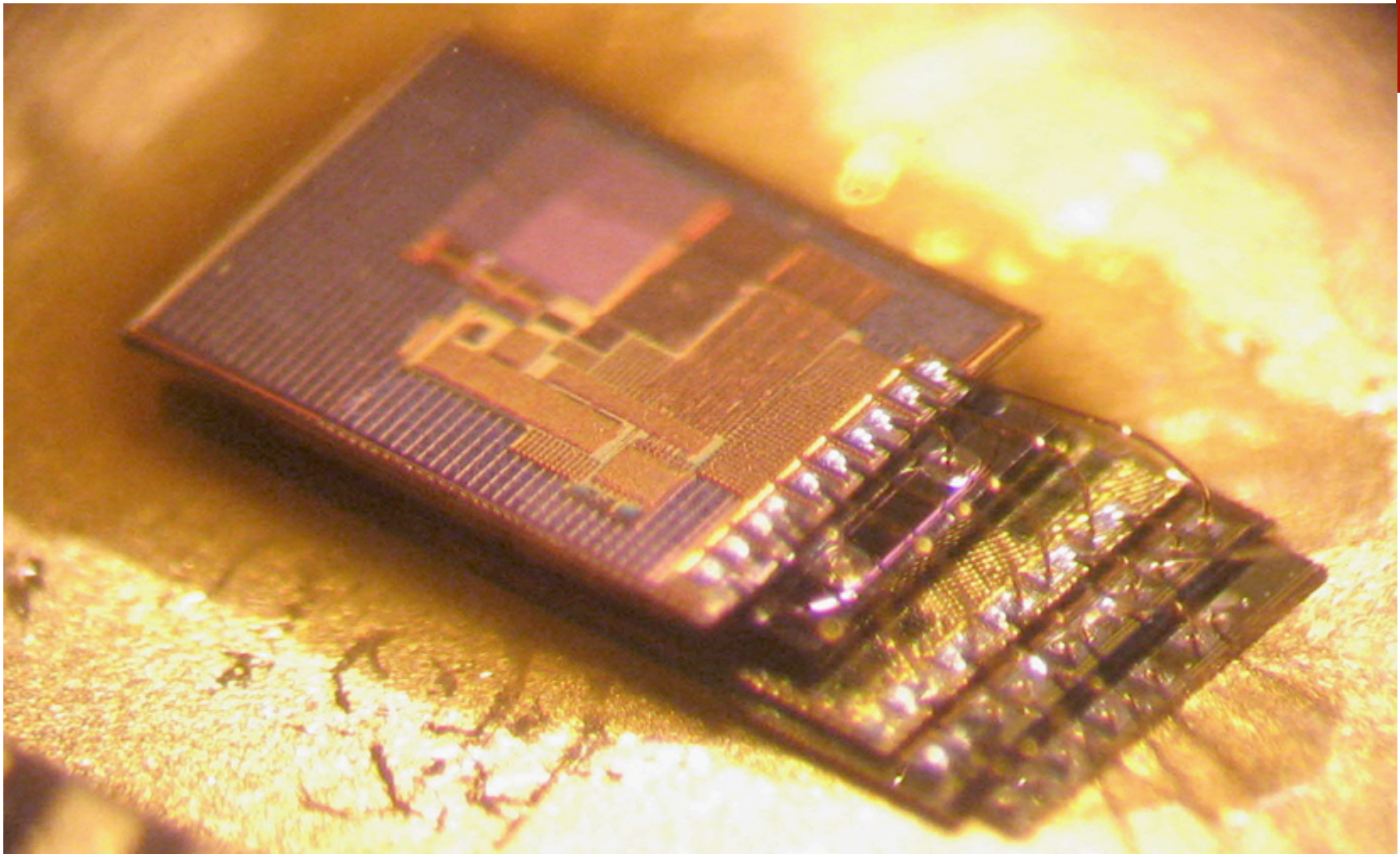


Graphs adapted from: A. Oudalov, C. Yuen and M. Holmberg, "Energy Storage is a Key Smart Grid Element" |
Cigré Symposium The Electric Power System of the Future, Sept. 13-15, 2011, Bologna, Italy

Process storage

Thermal storage

Sensing

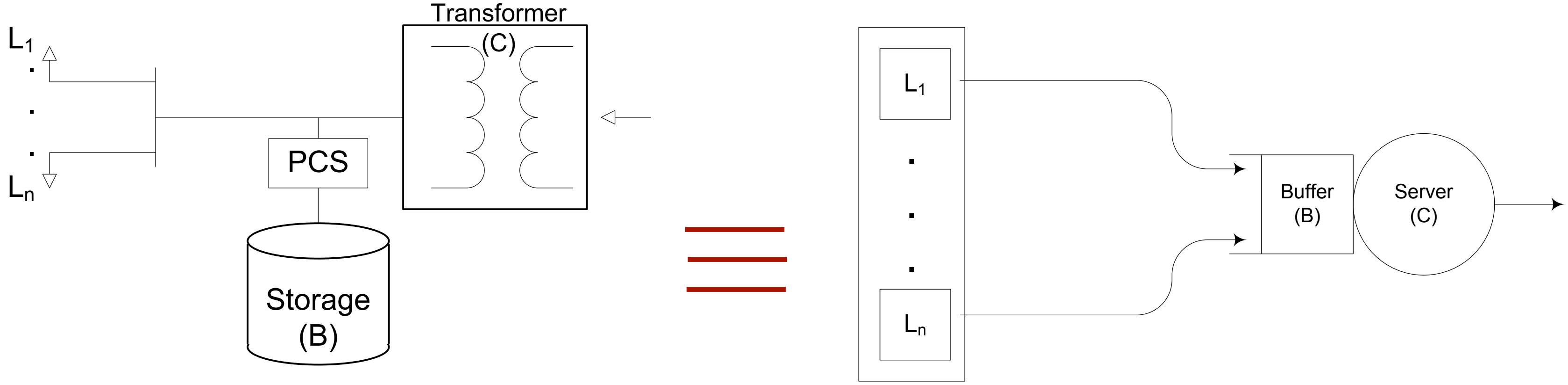


Michigan Micro Mote

So what?

Grid	Internet
Solar	= Variable bit-rate source
Electrons	= Bits
Storage	= Buffer
Transmission line	= Communication link
Transmission network	= Tier 1 ISP
Distribution network	= Tier 2/3 ISP
Demand response	= Congestion control

Equivalence theorem

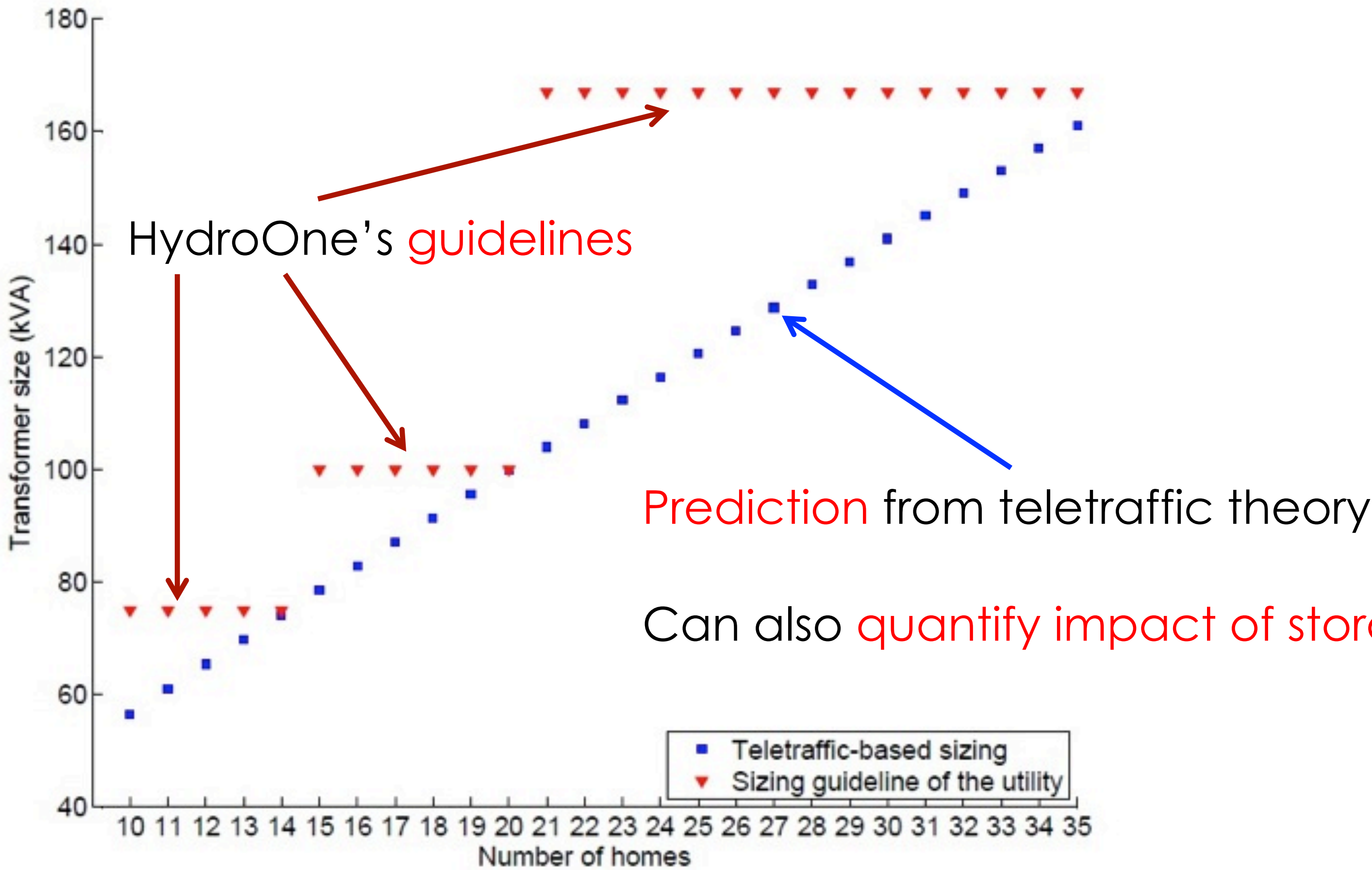


Every trajectory on the LHS has an equivalent on the RHS

- can use teletraffic theory to study transformer sizing

O. Ardakanian, S. Keshav, and C. Rosenberg. On the Use of Teletraffic Theory in Power Distribution Systems, e-Energy '12.

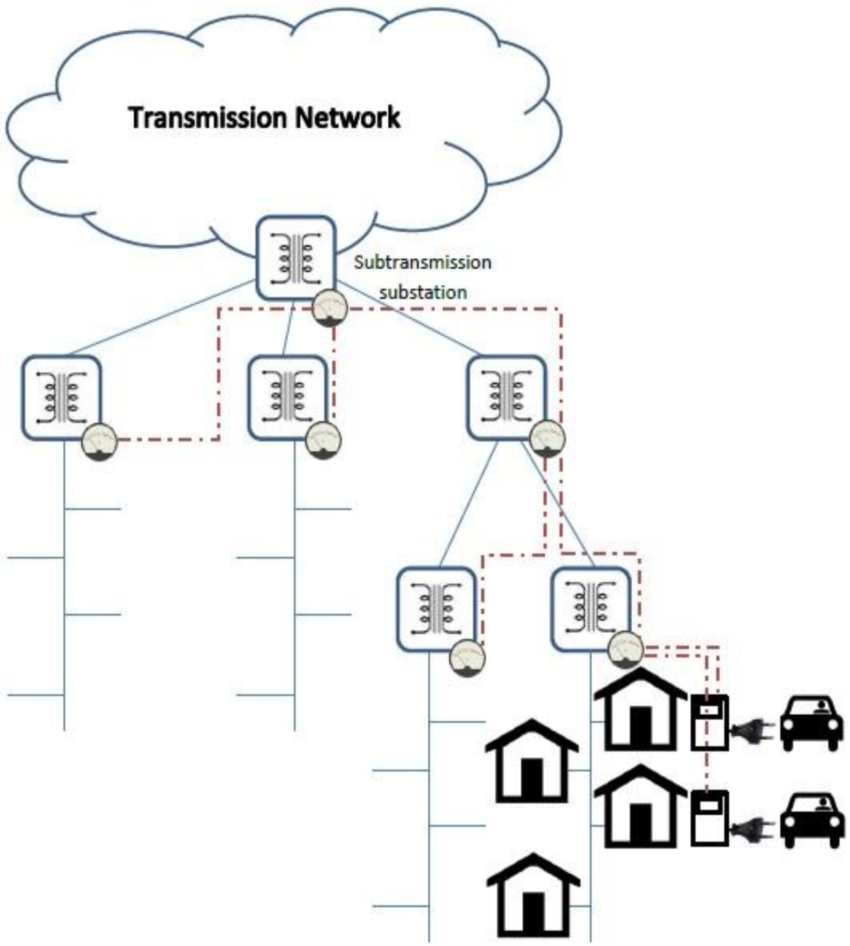
Guidelines for transformer sizing



Can also quantify impact of storage

O. Ardakanian, S. Keshav, and C. Rosenberg. On the Use of Teletraffic Theory in Power Distribution Systems, e-Energy '12.

"TCP" for EV charging



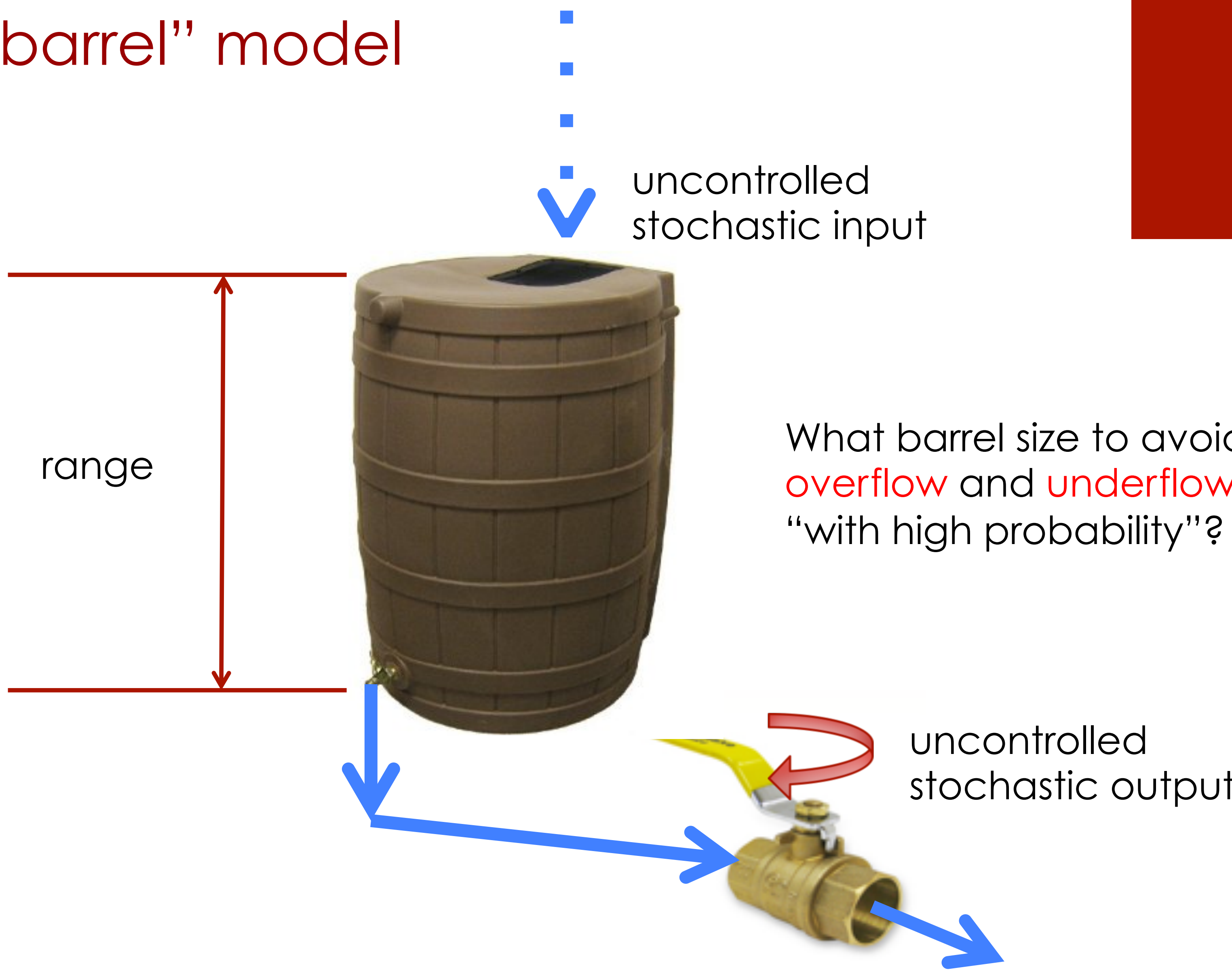
- 1 EV = 5 homes
  - Creates hotspots
- Real-time AIMD control of EV charging rate
- Solution is both fair and efficient

O. Ardakanian, C. Rosenberg and, S. Keshav, "Distributed Control of Electric Vehicle Charging". e-Energy '13

Stochastic network calculus

Joint work with Y. Ghiassi-Farrokhfal and C. Rosenberg

“Rainbarrel” model



What barrel size to avoid overflow and underflow “with high probability”?

Envelope idea

lower envelope ≤ Σ input ≤ upper envelope

Envelopes are computed from a dataset of trajectories

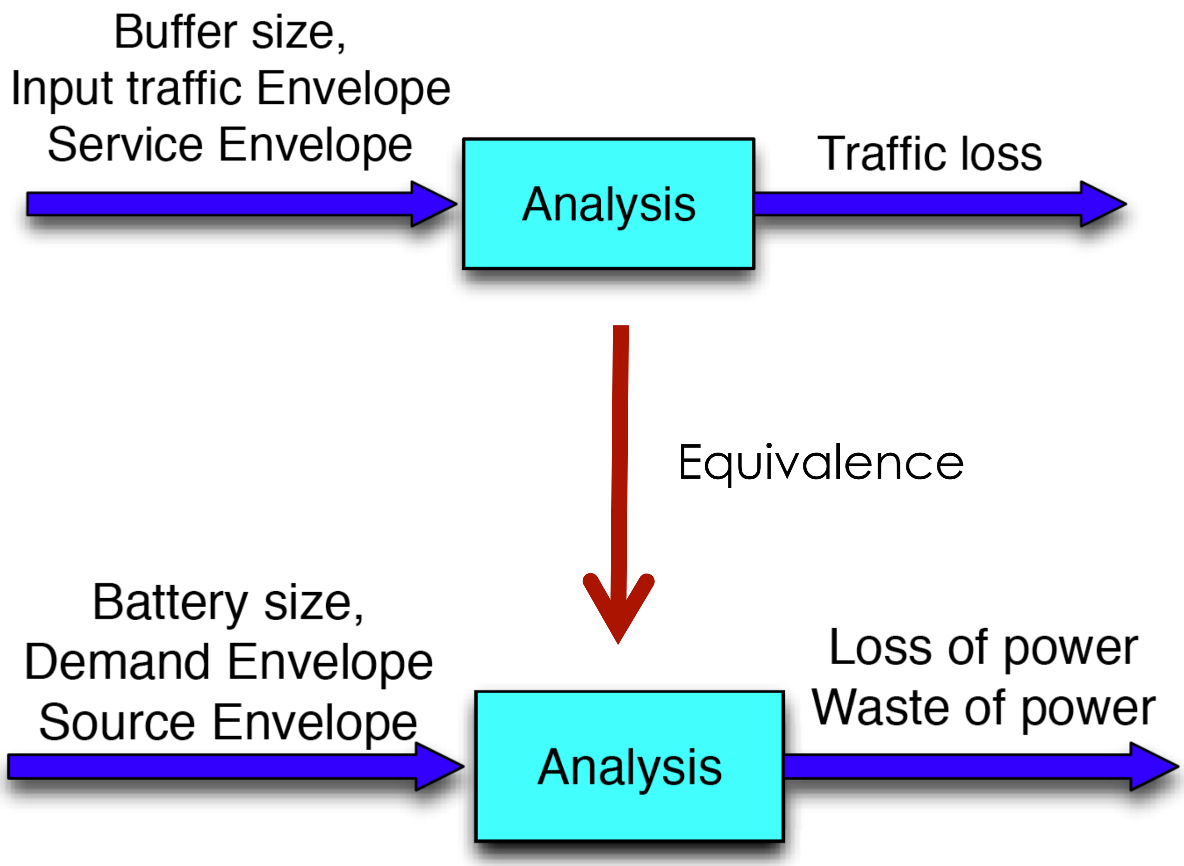
lower envelope ≤ Σ output ≤ upper envelope

Stochastic envelopes

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

$P((\text{upper envelope} - \Sigma\,\text{input}) > x) = be^{-x}$

Stochastic network calculus



Wang, Kai, et al. "A stochastic power network calculus for integrating renewable energy sources into the power grid." *Selected Areas in Communications, IEEE Journal on* 30.6 (2012): 1037-1048.

Analytic results

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

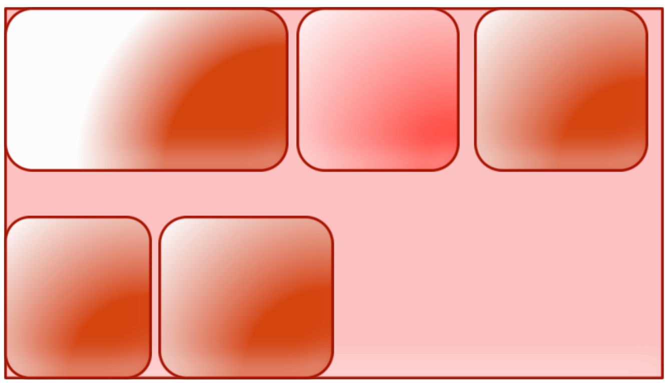
Joint work with Y. Ghiassi-Farrokhfal, S. Singla, and C. Rosenberg

Load reduction using extreme sensing

Smart Personal Thermal Comfort

Fine-grained thermal control of individual offices

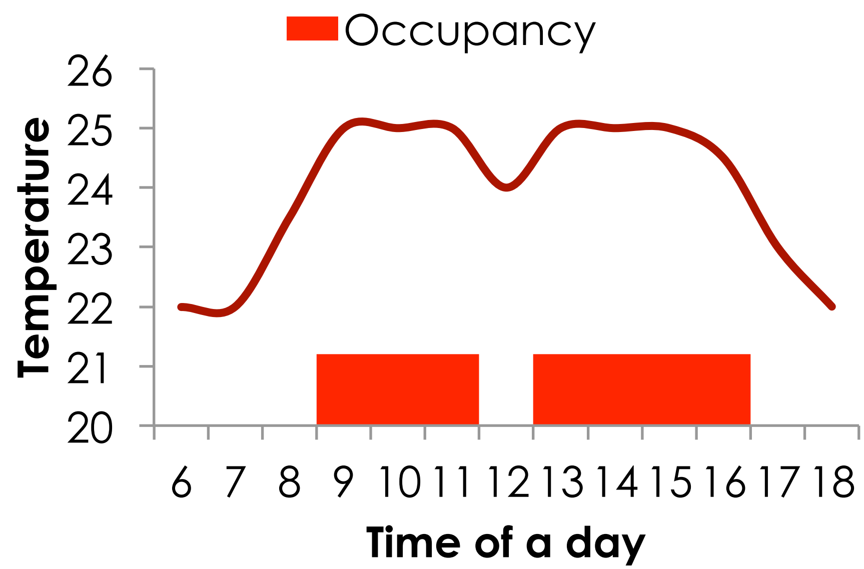
P.X. Gao and S. Keshav, Optimal Personal Comfort Management Using SPOT+, Proc. BuildSys Workshop, November 2013.
P. X. Gao and S. Keshav, SPOT: A Smart Personalized Office Thermal Control System, Proc. ACM e-Energy 2013, May 2013.



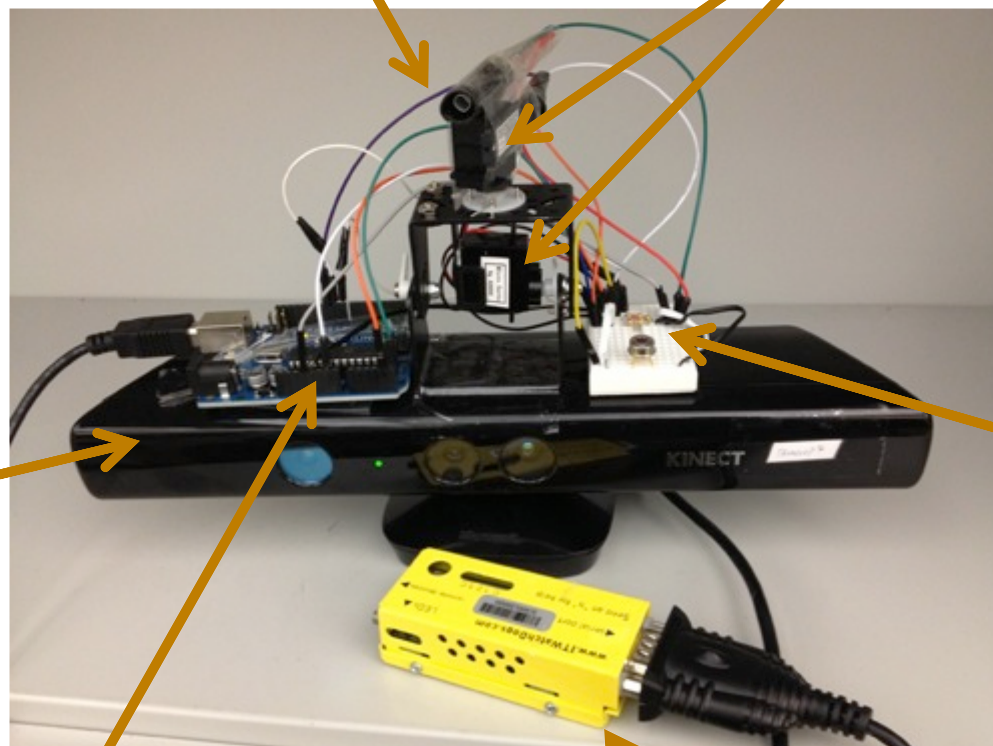
Our insight

In a nutshell

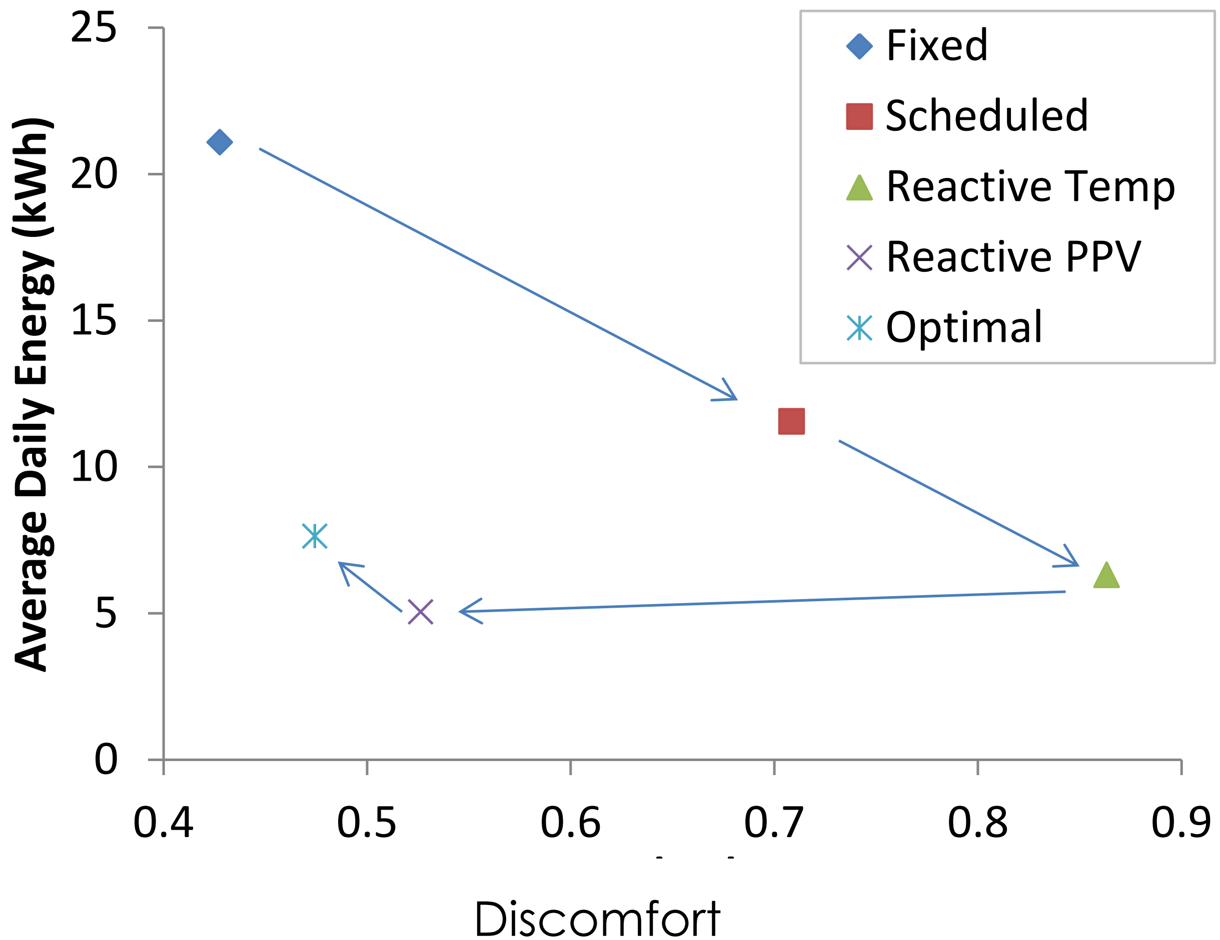
- Mathematical comfort model
- When occupied, reduce comfort to the minimum acceptable level
- When vacant, turn heating off
- Pre-heat
- Optimal model-predictive control



Extreme sensing



Comparision of schemes



Reflections on the research area

Energy research

Pros

- Rapidly growing 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

- Renewables 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

Many publication venues

Conferences/workshops

- ACM eEnergy
- IEEE SmartGridComm
- ACM Buildsys
- ACM GreenMetrics
- IEEE CCSES
- ACM Sustainability
- AAAI AAMAS

Journals

- IEEE Trans. Smart Grid
- IEEE PES magazine
- Energy and Buildings
- J. Solar Power
- J. Power Sources
- Transportation

ACM e-Energy 2014

- Premier conference at the intersection of Internet technologies and energy systems
- Sponsored by ACM SIGCOMM
- June 11-13, 2014 in Cambridge, UK
- Early registration deadline is Wednesday!

Conclusions

- The grid has some real problems
- Smart grid offers solutions, but it is still early days
- Three areas to watch out for
  - Solar
  - Storage
  - Sensing

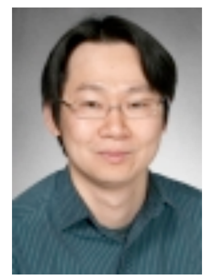
Acknowledgements

ISS4E

Co-Director

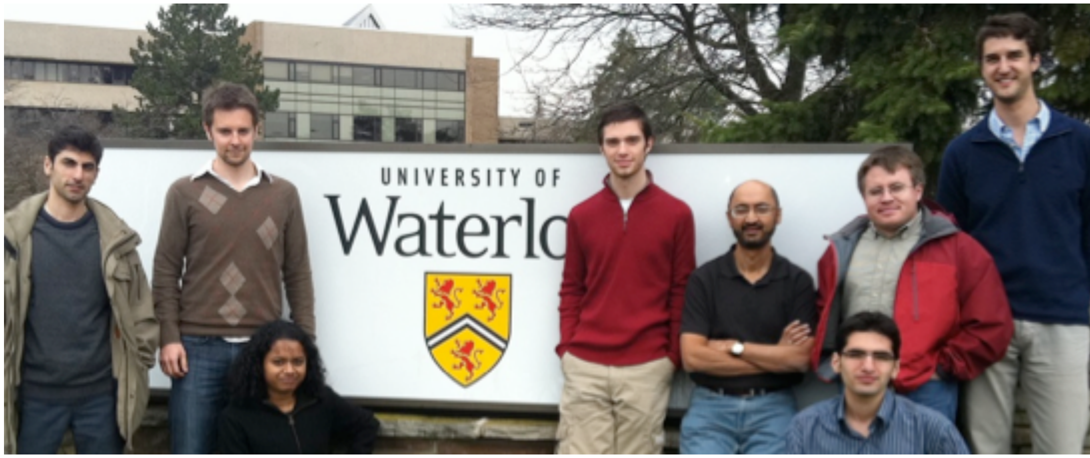




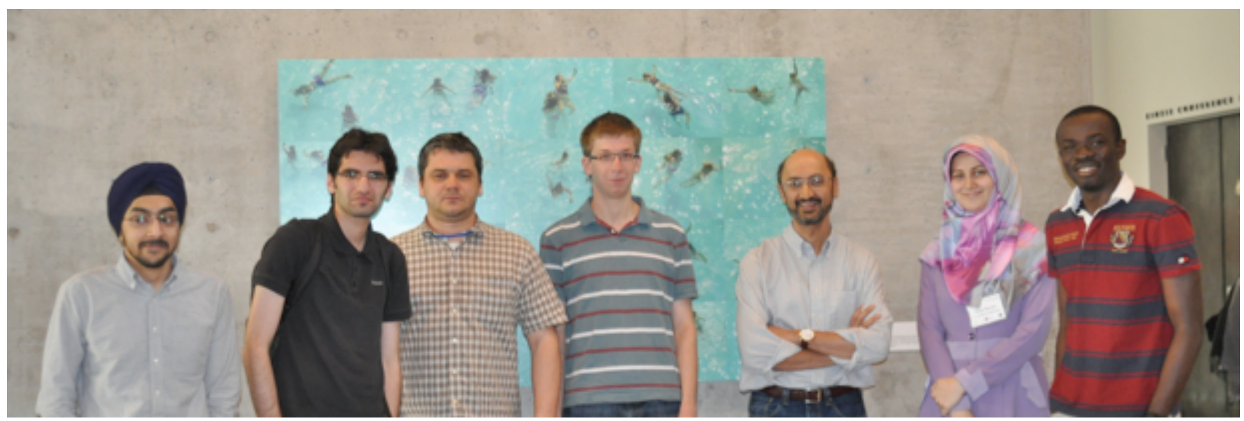



Affiliated faculty

http://iss4e.ca



ISS4E students



Our next project