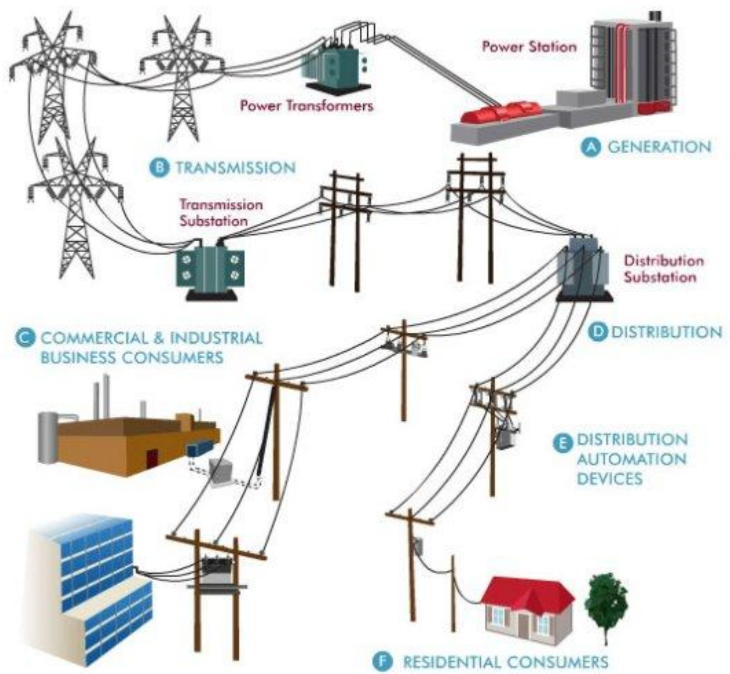
The Grid of the Future

Speaker: Ana Radovanovic
Google Energy Team

Today’s 20th Century Grid



ONE WAY POWER FLOW

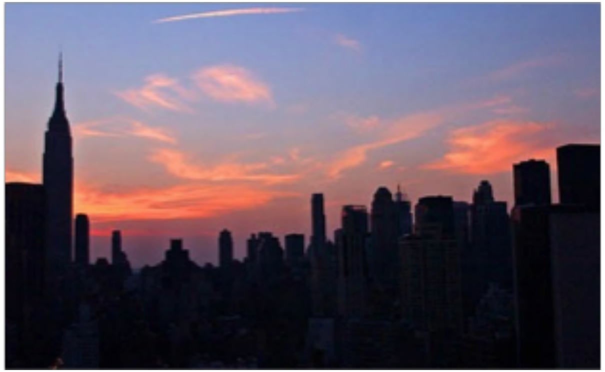
- Centralized generation
- Long distance transmission via mesh network
- Millions of homes on branched distribution network

Power distribution planning - ***NOT in real time***:

- Day ahead planning only robust to *small* fluctuations in demand/supply
- Integrating intermittent renewables (> 20%) very difficult due to:
  - Current dispatch process
  - Tight frequency tolerance 60 +/- 0.036 Hz

Challenges with Today's Grid

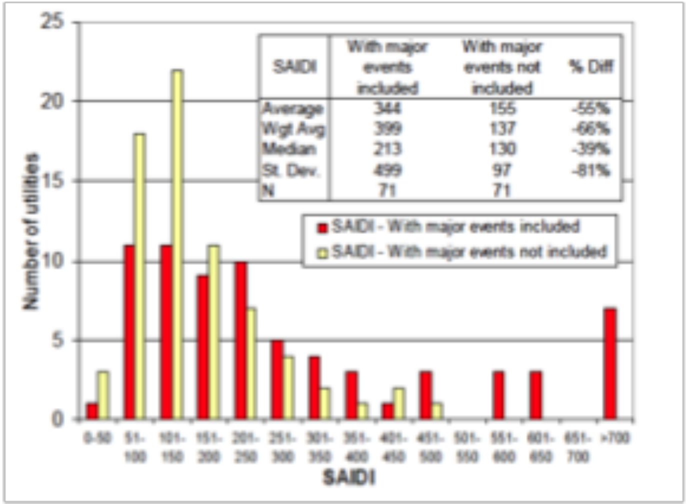
2003 Northeast Blackout



Lessons learnt?

Not much!

2011 San Diego Blackout



SAIDI	With major events included	With major events not included	% Diff
Average	344	155	-55%
Wgt Avg	399	137	-66%
Median	213	130	-39%
St. Dev.	499	97	-81%
N	71	71	

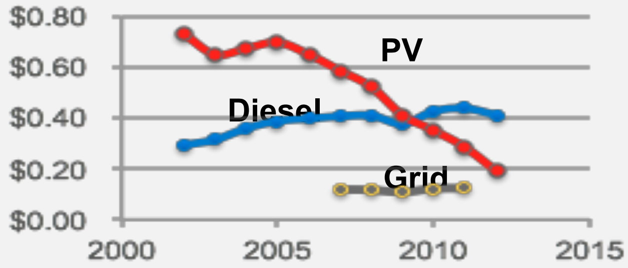
Outage statistics - $20-30 billion lost annually from outages

Source: "Tracking the Reliability of the US Electric Power System," J. Eto, K. Hamachi La Commare, LBNL Report 1092E (2008)

Novel Trends in Technology and Economics

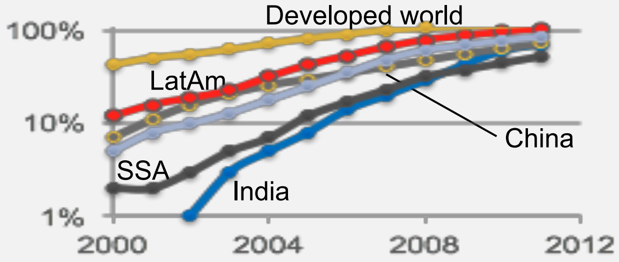
PV SOON TO BE THE CHEAPEST ELECTRICITY SOURCE

Electricity cost
2011$/kWh delivered, residential



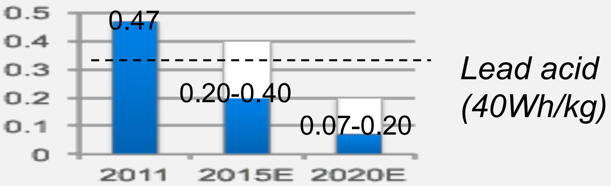
DISTRIBUTED COMPUTING WIDELY AVAILABLE

Mobile penetration
Subscriptions per capita



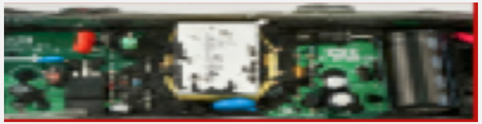
BATTERY STORAGE GETTING CHEAPER

Li-ion storage cost ($/Wh delivered)
200-400 Wh/kg (cell); 100-200 Wh/kg (pack)



ELECTRONIC POWER CONVERSION: CHEAP AND UBIQUITOUS

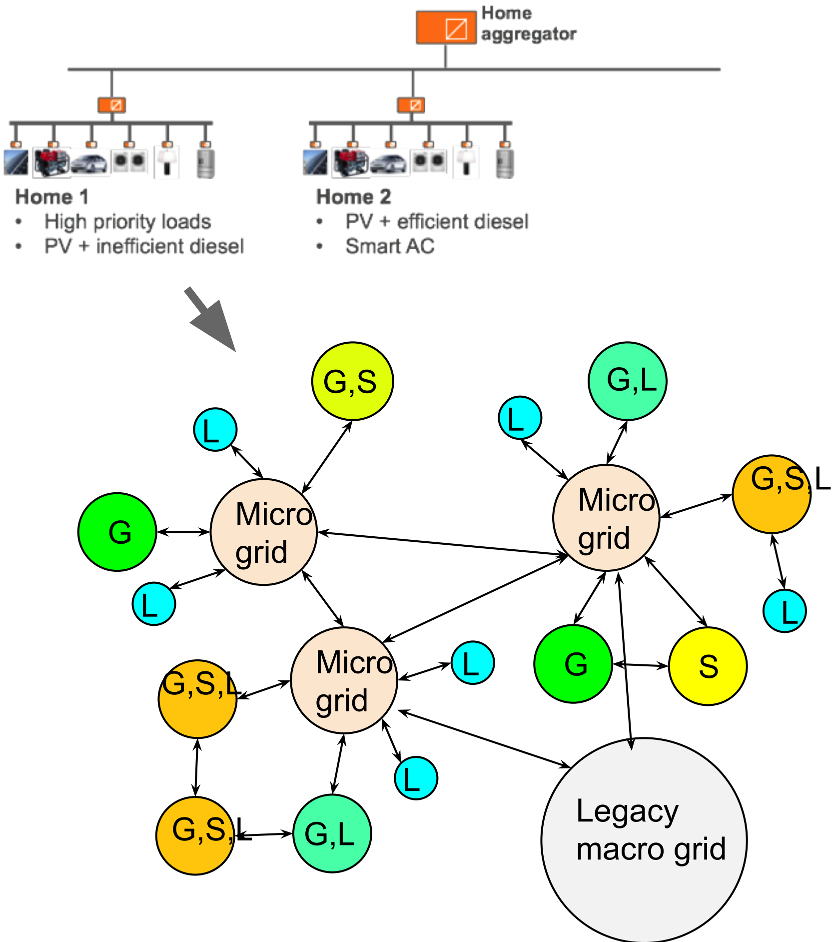
WBG Power Electronics
300x size reduction in 25W AC-DC SSL Driver



Perfect Storm

- Affordable electricity
- Local/distributed generation
- Modern power electronics
- Access to communication/distributed computing for real-time price adjustments
- Increasing demand (both flexible and non-controllable)

Grid of the Future



Plug-and-play for distributed generation, storage and load

Automate <u>real-time</u> operation via networked distributed computing

- Real-time dispatch of generation & load curtailment for dynamic balance
- Fault tolerance and resilience via real-time control and optimization
- Dynamic stability
- Voltage & frequency regulation
- Economically optimized
- Enables trading between buyers and sellers
- Security

Flexible architecture, bidirectional flow, and scalable

- Large penetration of intermittent resources

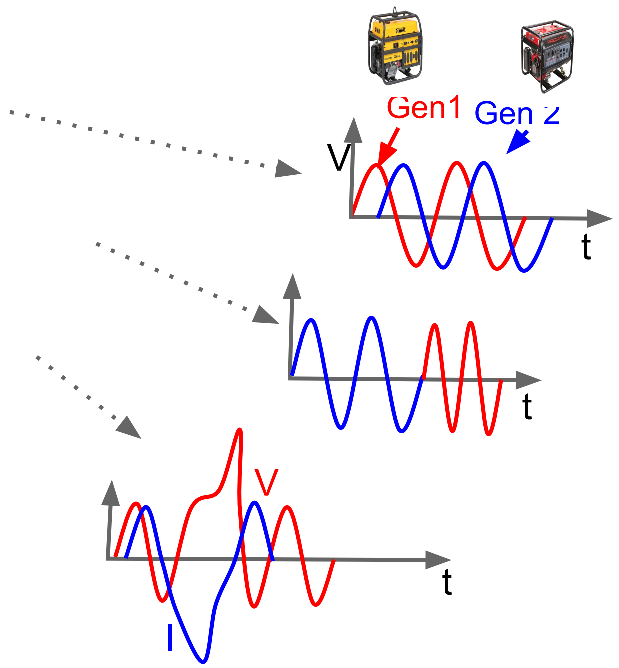
New "Intelligent" Interface to the Grid

Necessary capabilities provided in today's grid

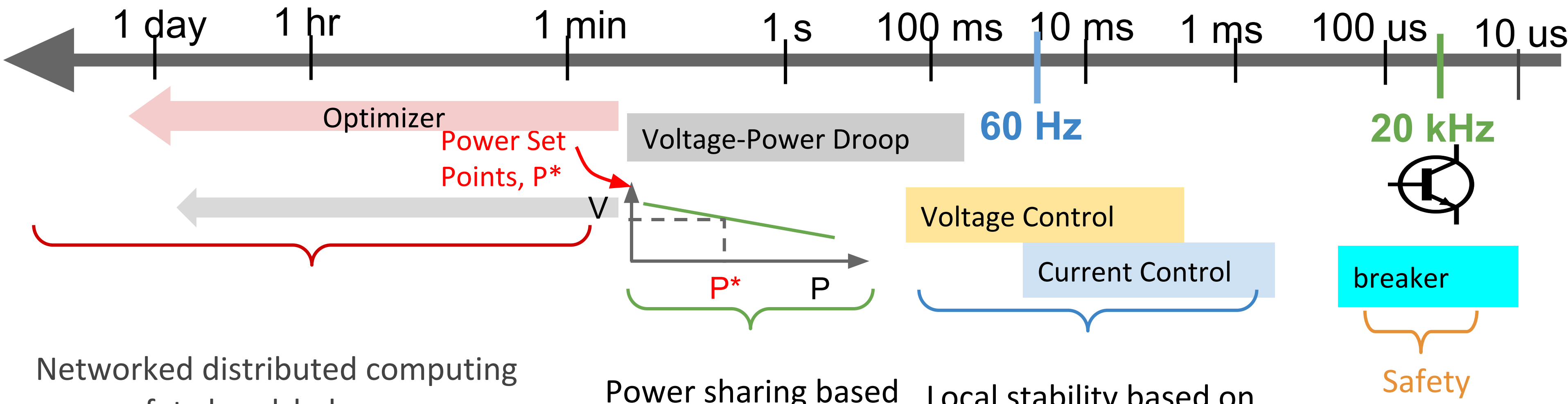
- Synchronizing generation
- Frequency regulation (60+/-0.036Hz)
- Voltage and current regulation
- Reactive power control

New features

- *Ultrasafe*
- *Lack of inertia*
- *Real-time generation-load balance*
- *Smooth plugging and unplugging*
- *Robust to large fluctuations*
- *Morphing topology*



Time Scales for Control, Communication and Computation



Networked distributed computing

- safety handshake
- economically optimized real-time dispatch & curtailment
- system-level monitoring & diagnostics
- economic transactions, ….

Power sharing based on local measurements & between communication

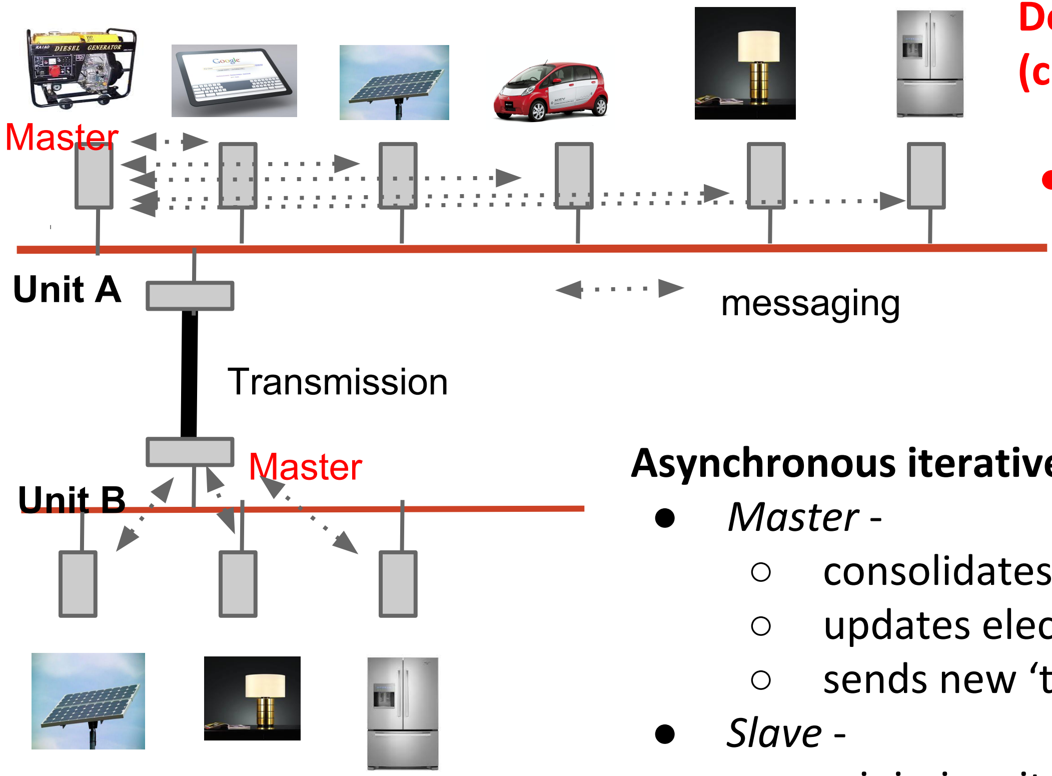
Local stability based on local measurements & between communication

Networked Microcomputer

Digital Microcontroller

Power Conversion Circuit

Large-Scale Distributed Optimization Algorithm



Decentralized optimization algorithm (consensus messaging):

- provides operating point (P*, Q*, V*) for each device:
  - economically optimal
  - respects laws of physics
  - provides optimal electricity price

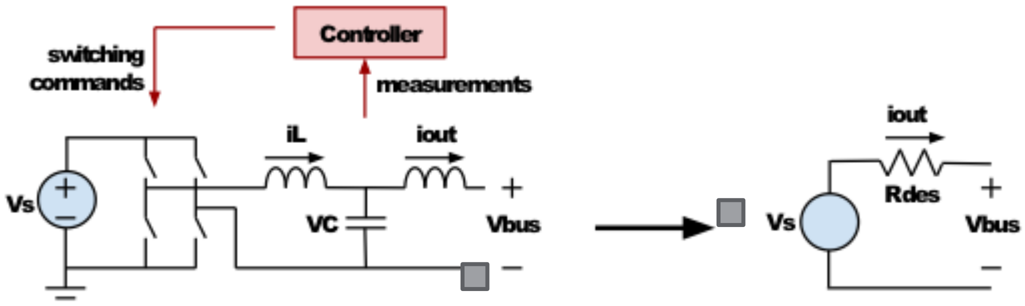
Asynchronous iterative message updates:

- *Master* -
  - consolidates device schedules to preserve laws of physics
  - updates electricity price
  - sends new 'target' schedule to each device
- *Slave* -
  - minimizes its private cost function:
    - subject to operational constraints (private data!)
    - keep close to the target schedule sent by the master

Messaging is local within each bus!

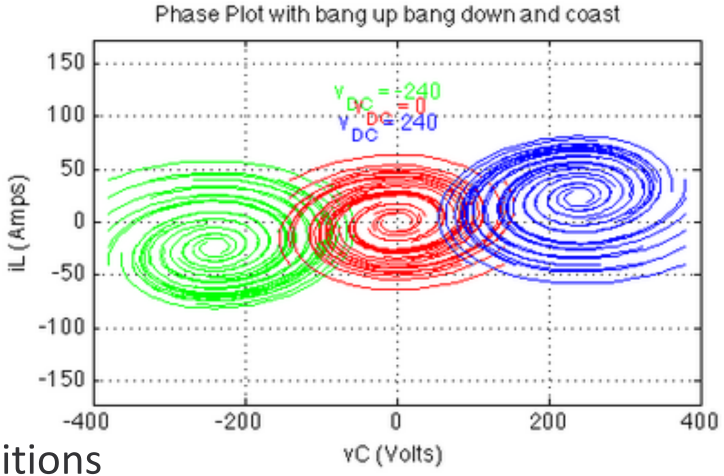
Faster Controls

- Handle perturbations by performing optimized voltage/current control



The H bridge "emulates" desired inverter behavior, and uses its internal grid model objectives for inductor current and capacitor voltage.

Interface to the smart grid,
that should allow energy source to
be connected in parallel!

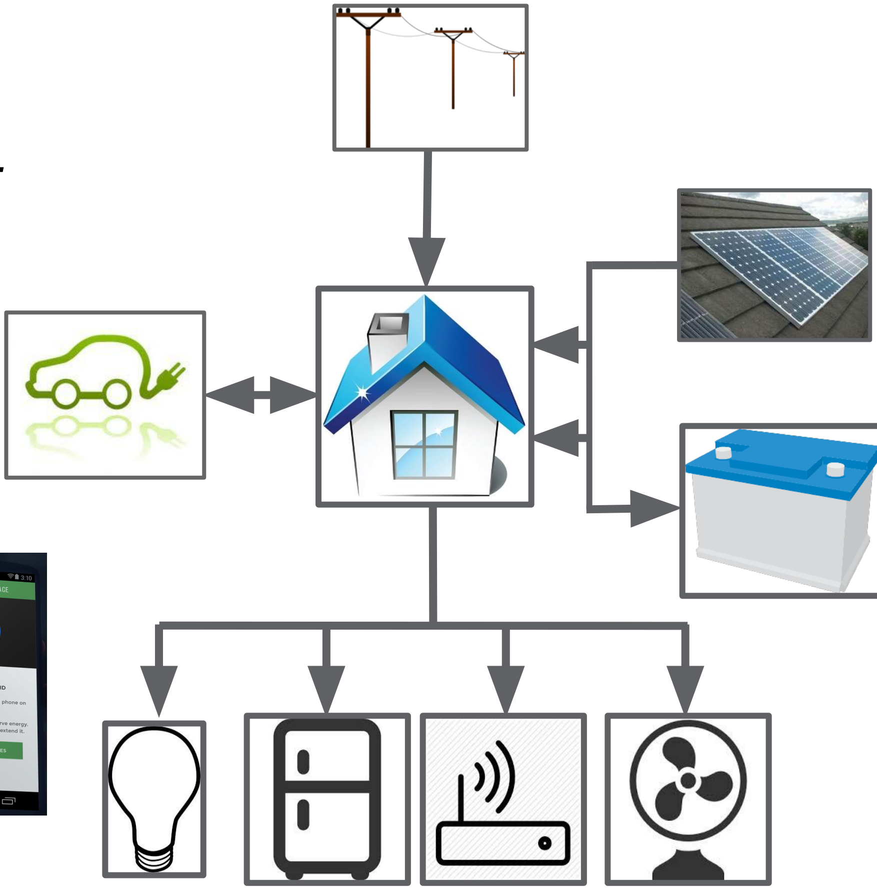


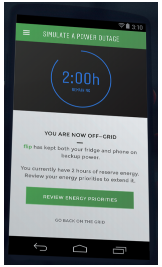
240VDC H-Bridge driving a 10 Ohm load - varied initial conditions

First, Enable a Single Home to Operate Efficiently

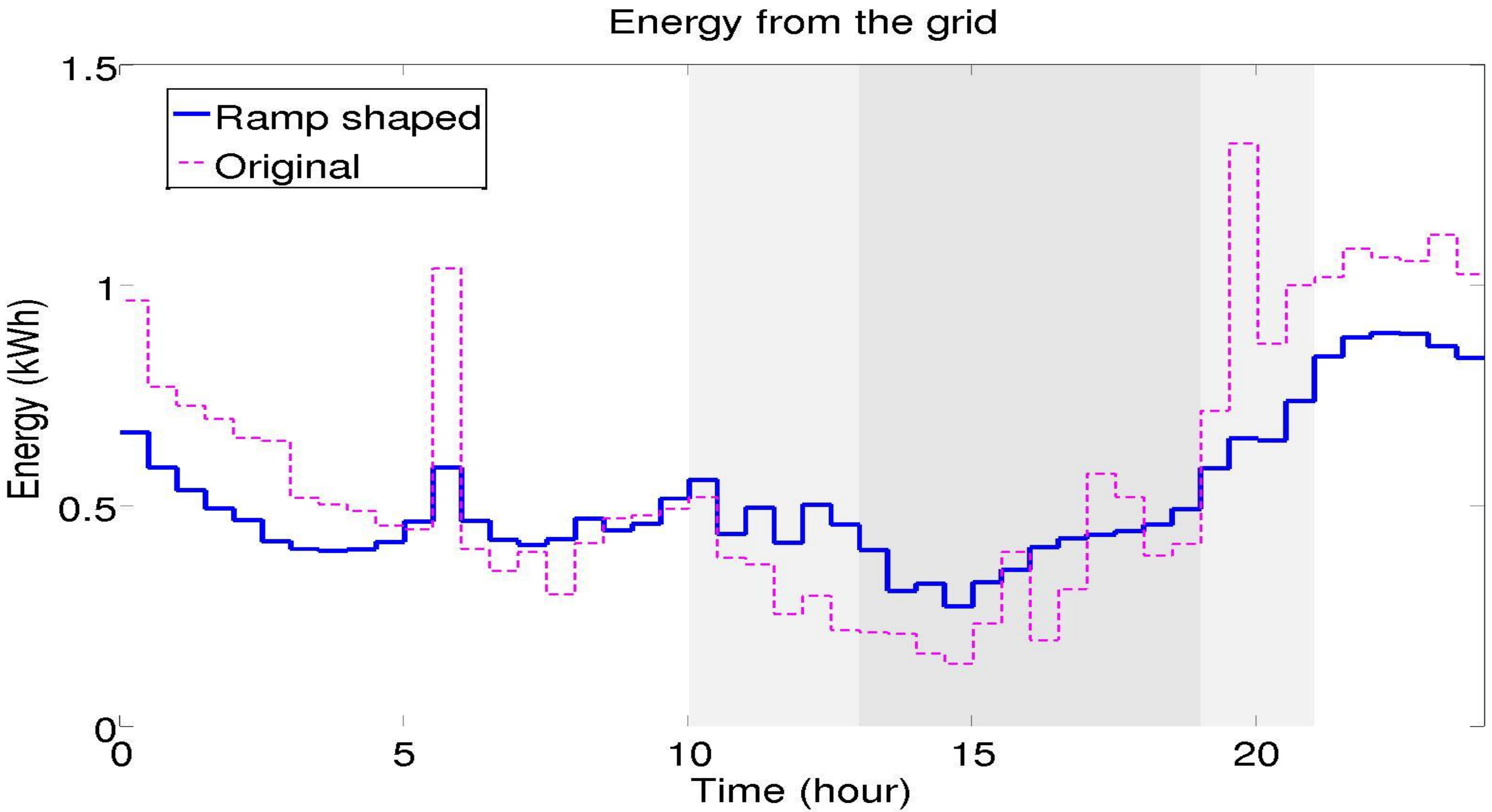
Distributed load, generation and storage control:

- *Simple/plug-and-play*
- *Knowledge-based*
- *Real-time*
- ***Cost-efficient*** - exploiting:
  - Loads' deferrability (EV, pool pump, WH, A/C,...)
  - Price diversity (PV, utility, generator)
  - Storage cost/efficiency (battery)

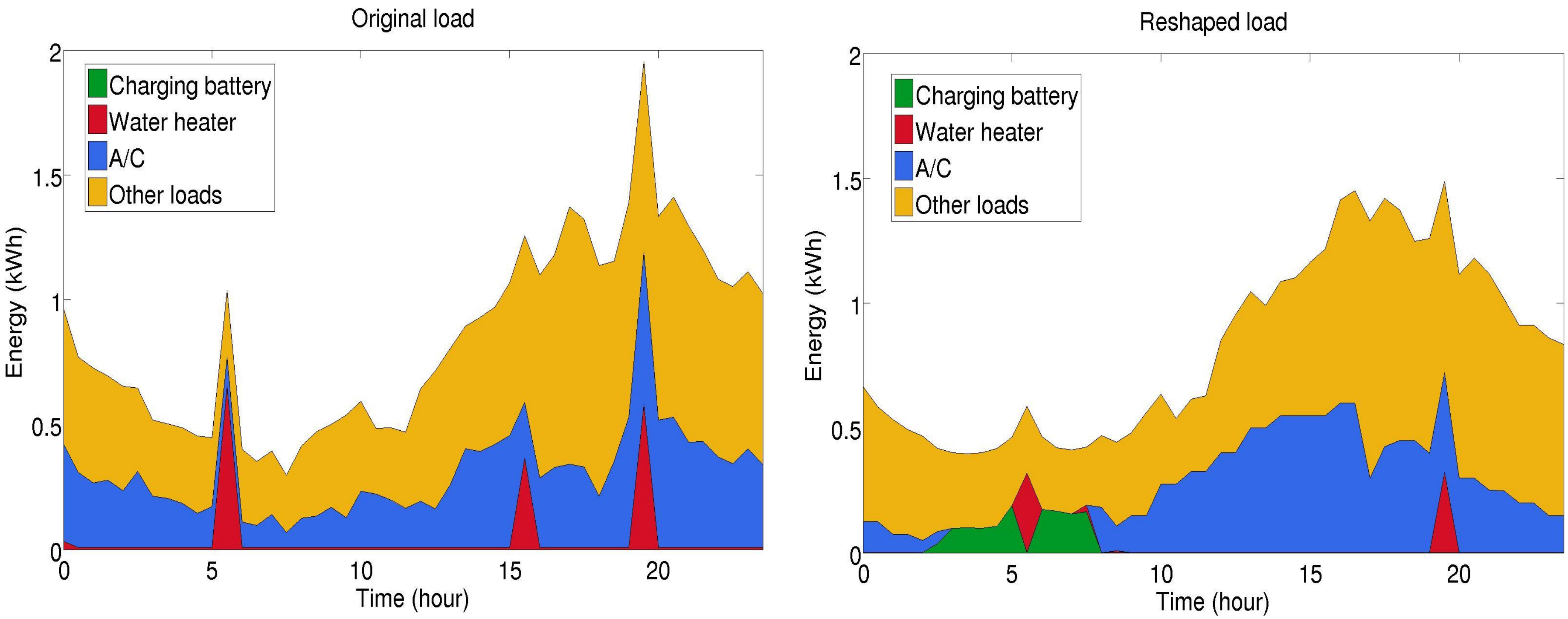




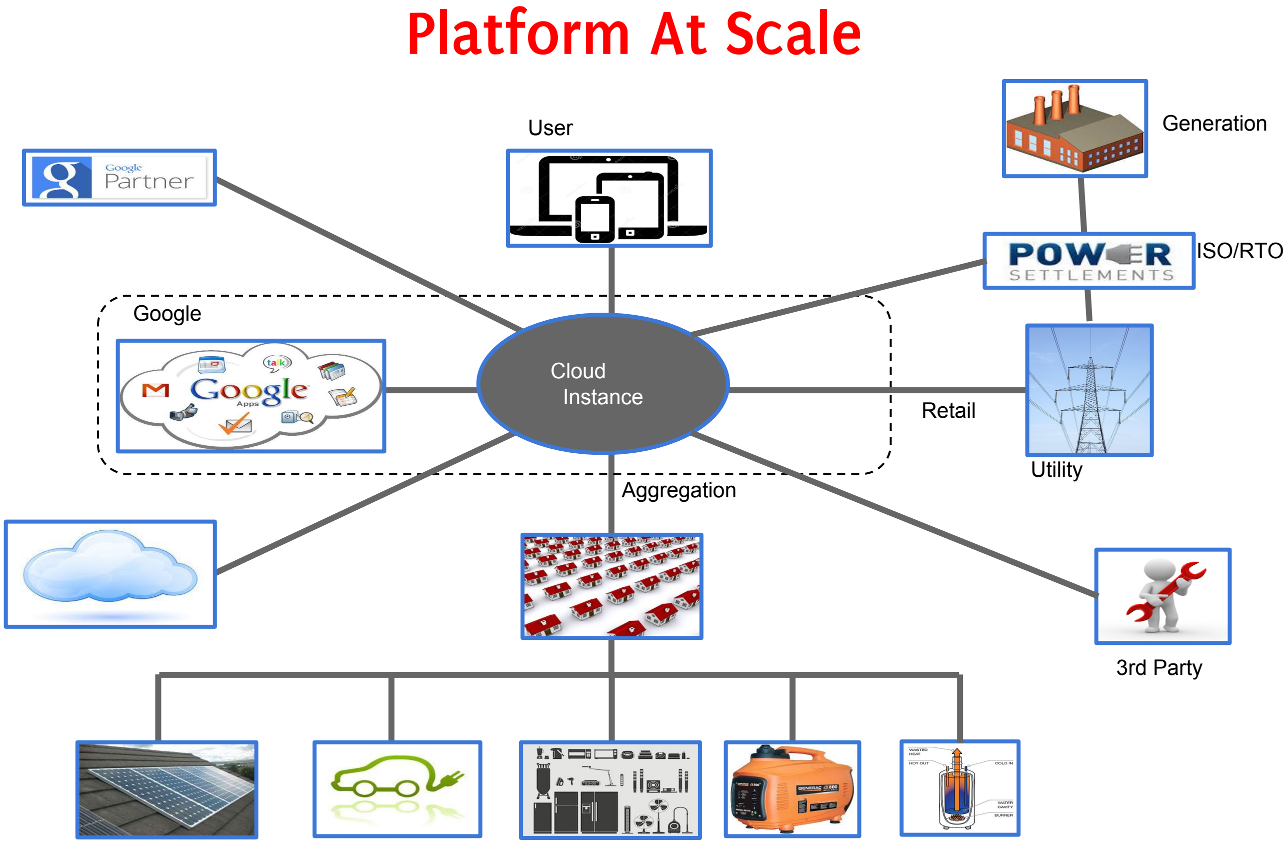
Example: Optimized Demand Shaping



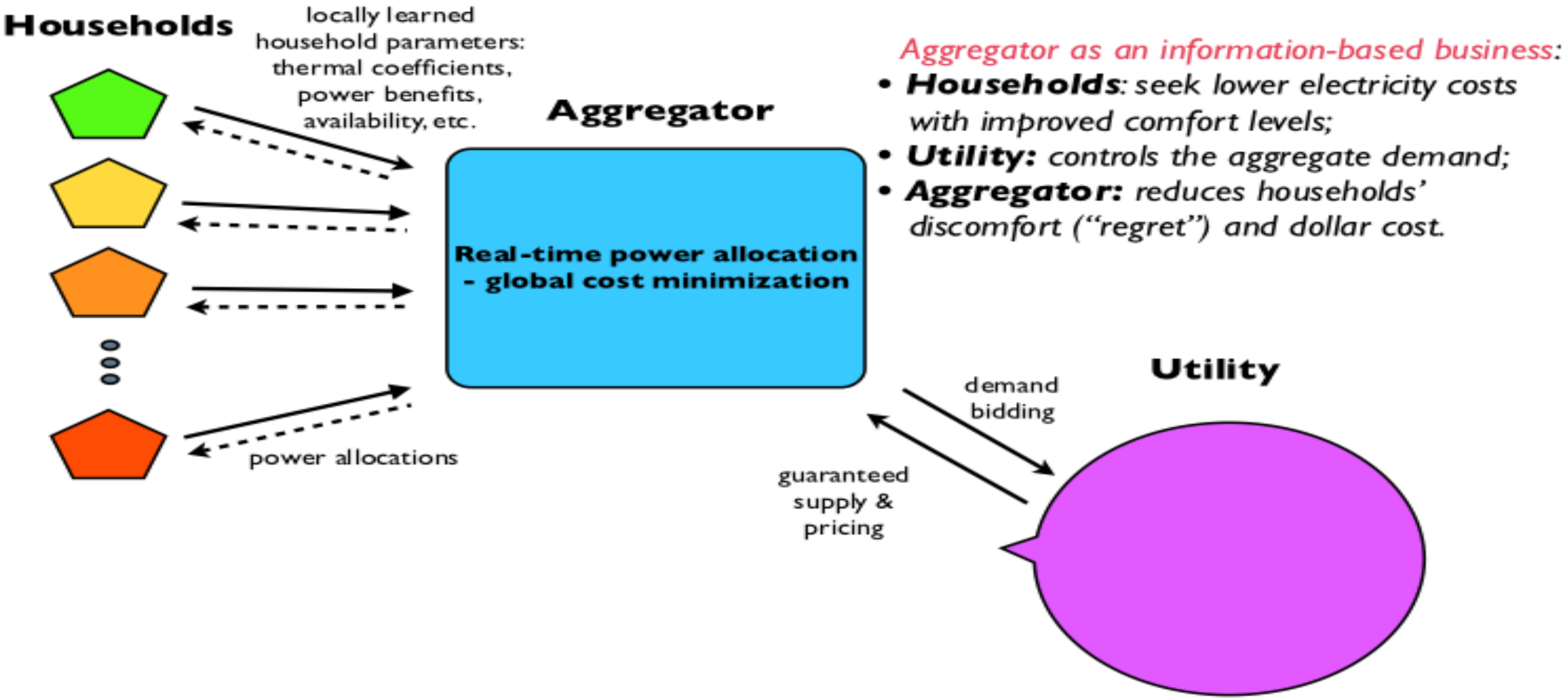
Example: shaping due to flexible loads



Operate at Scale - Control Aggregated Flexible Loads



Monetizing Loads’ Flexibility at a Large Scale



Deliver more reliable, affordable, and clean electricity to everyone in the world using innovative technologies and business models