Ninth Annual Carnegie Mellon Conference on the Electricity Industry
Role of Coordination in Resilient & Fine-Grain Control of Power Grids
February 4-5, 2014

Prosumer-Based Decentralized Cyber-Physical Architecture for Green Electricity Internetworks

Santiago Grijalva

Director, Power System Engineering Center, NREL

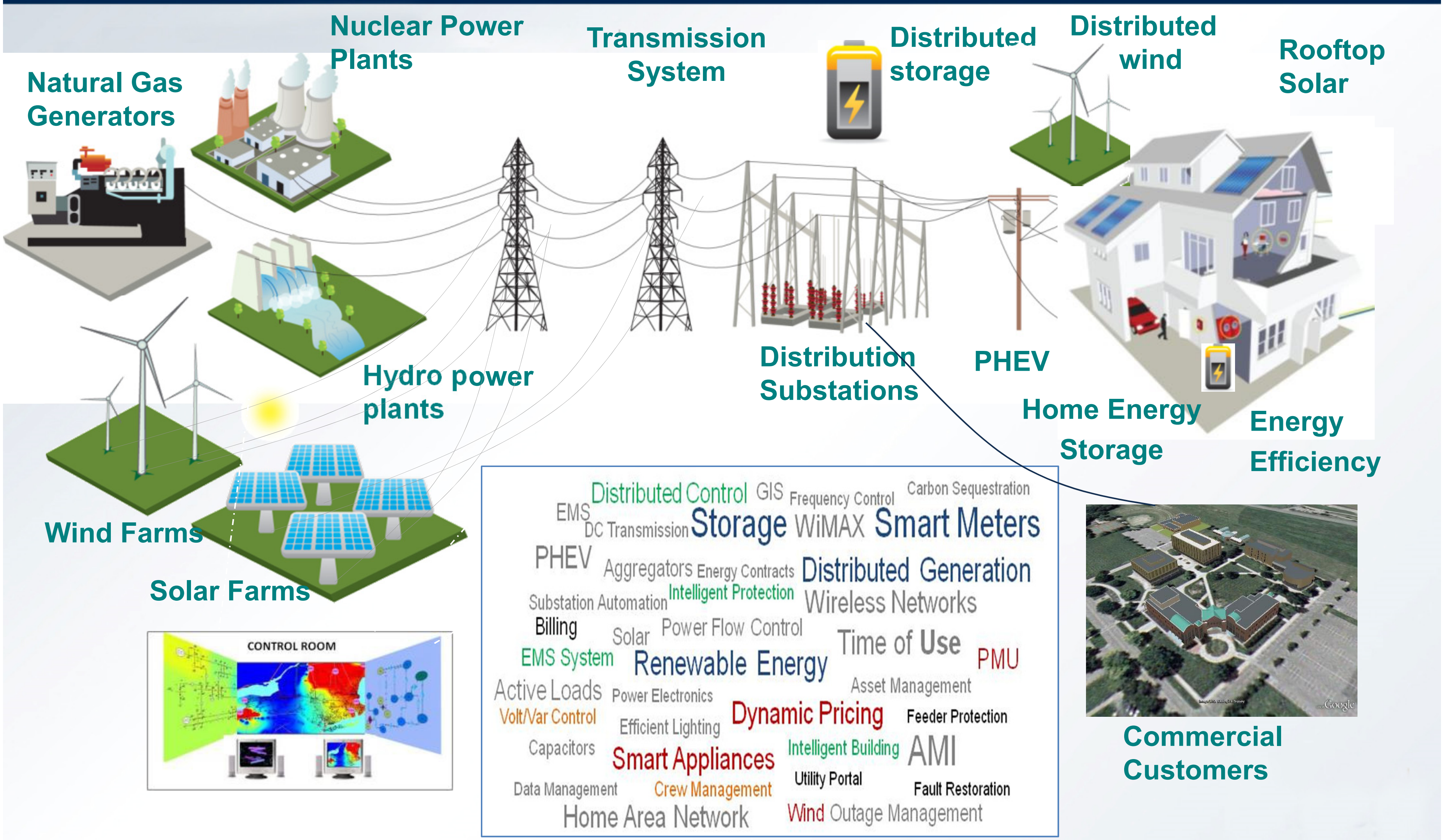
Associate Professor, Georgia Institute of Technology (on leave)

Georgia Institute of Technology

arpa·e Advanced Research Projects Agency • ENERGY

NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

The Emerging Grid



Core Trends and Paradigms

Domain	Trend or Paradigm Change	Future System
Objectives	• Reliability and Economy + Sustainability	Sustainable
Sources	• ⇒ From fossil fuel to renewable • From bulk centralized to distributed • Highly Variable	Renewable Distributed Stochastic
Information	• Can control entire system through SW • Increased digital control -> • Privacy and cyber-security issues	Cyber-Controlled Cyber-Physical Private
Actors	• Consumers can also produce and store • Consumers seek their own objectives • Massive number of actors and devices	Prosumers Smart Scalable
Carriers	• Interdependencies with other systems	Integrated

Prosumer-Based Decentralized Cyber-Physical *Control and Management Architecture* for Green Electricity Internetworks

Georgia Tech ARPA-E GENI Project

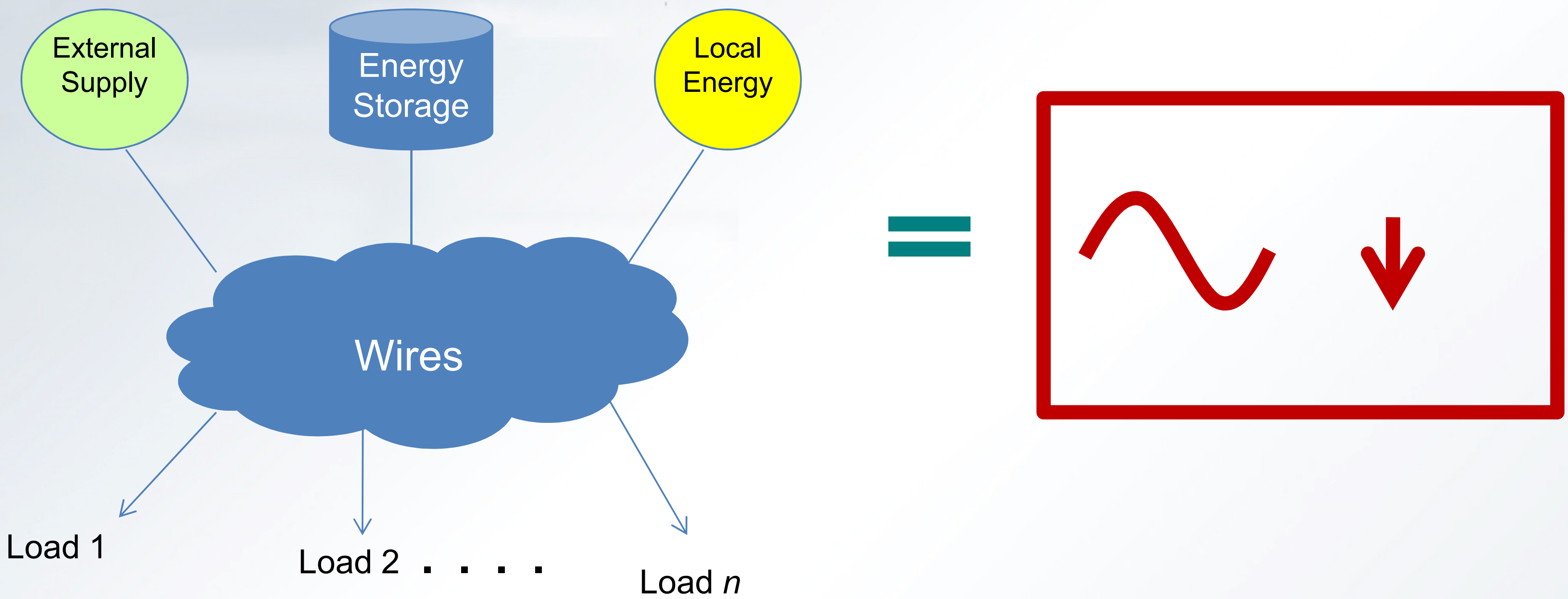
Investigators:

Santiago Grijalva, Magnus Egerstedt, Marilyn Wolf, Shabbir Ahmed.

Objectives: Develop and demonstrate at large-scale:

1. A *control and management architecture* that will allow the electricity industry to operate with characteristics similar to the internet: Distributed, Flat, Layered, Scalable
2. A *distributed services cyber-infrastructure* that supports prosumer interaction. This cyber-infrastructure can be understood as an "*Electricity Operating System*".
3. A real-time decentralized *prosumer frequency controller*
4. A decentralized *prosumer energy scheduler*

Architecture: Prosumer Abstraction



- A generic model that captures basic functions (produce, consume, store) can be applied to power systems at any scale.
- The fundamental task is power balancing:

$$P_{INT} = P_G - P_D - P_{Loss} - P_{STO+} + P_{STO-}$$

- Energy services can be virtualized.

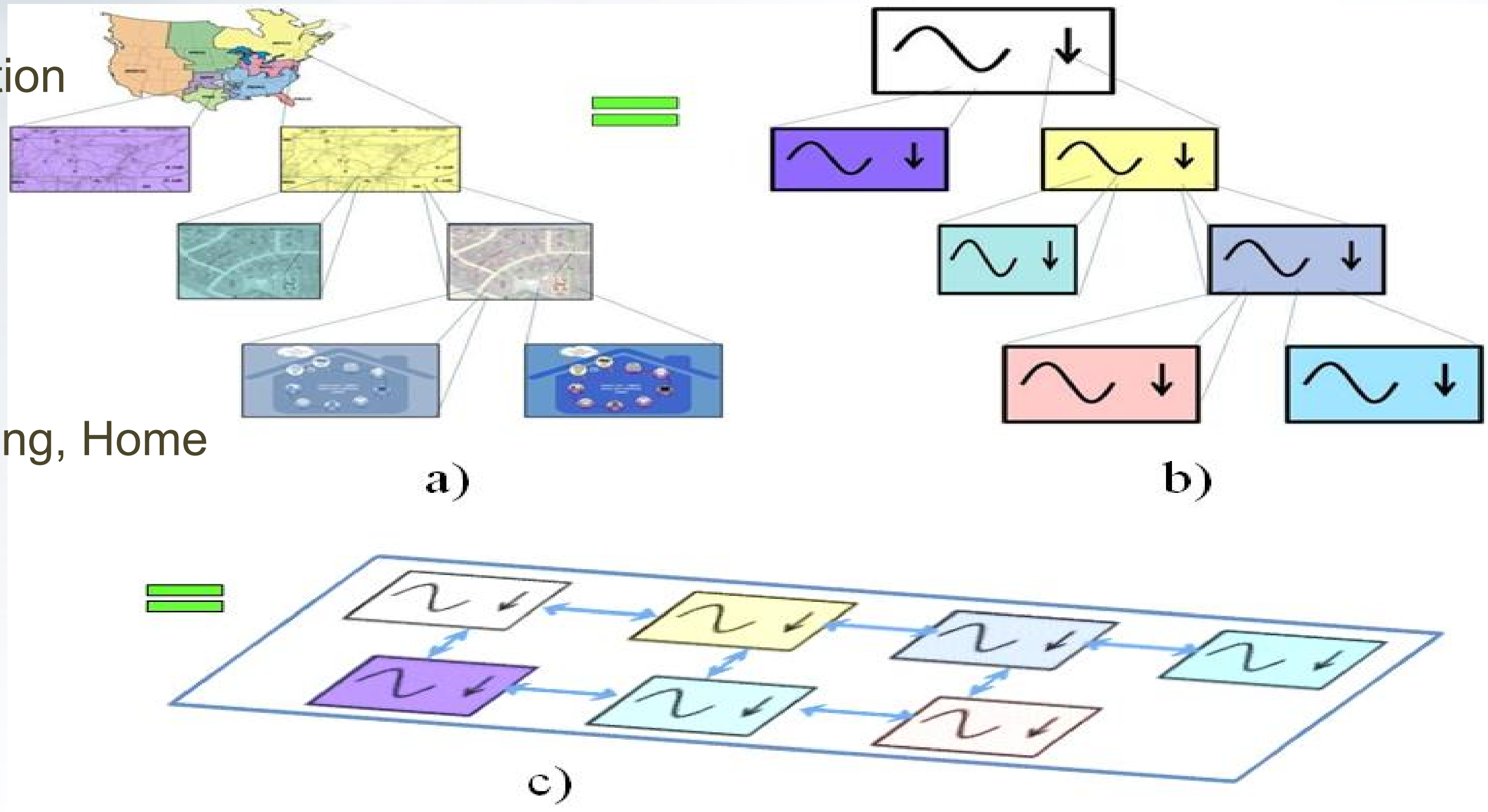
Architecture: Flat Electricity Industry

Interconnection

ISO

Utility

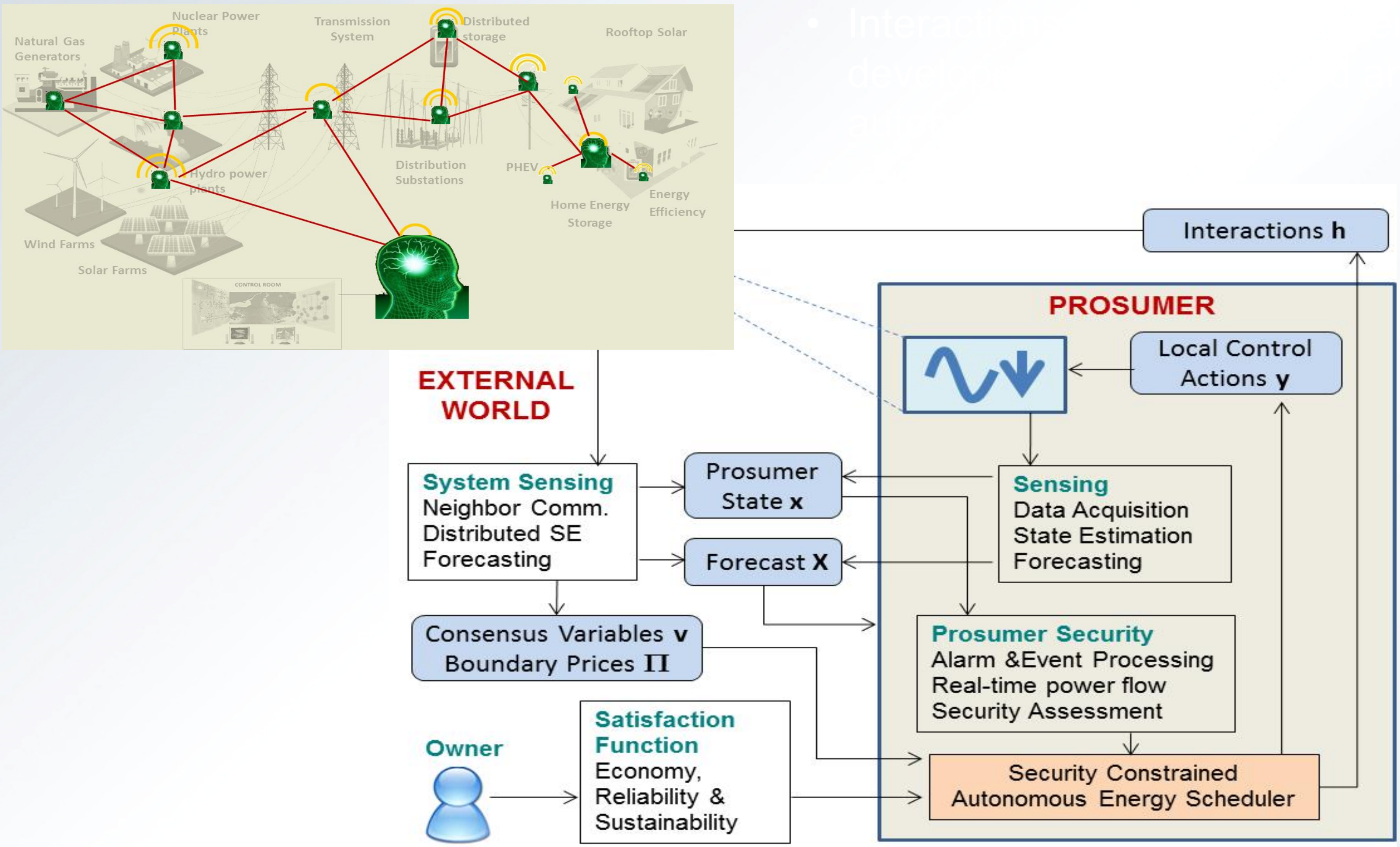
μGrid, Building, Home



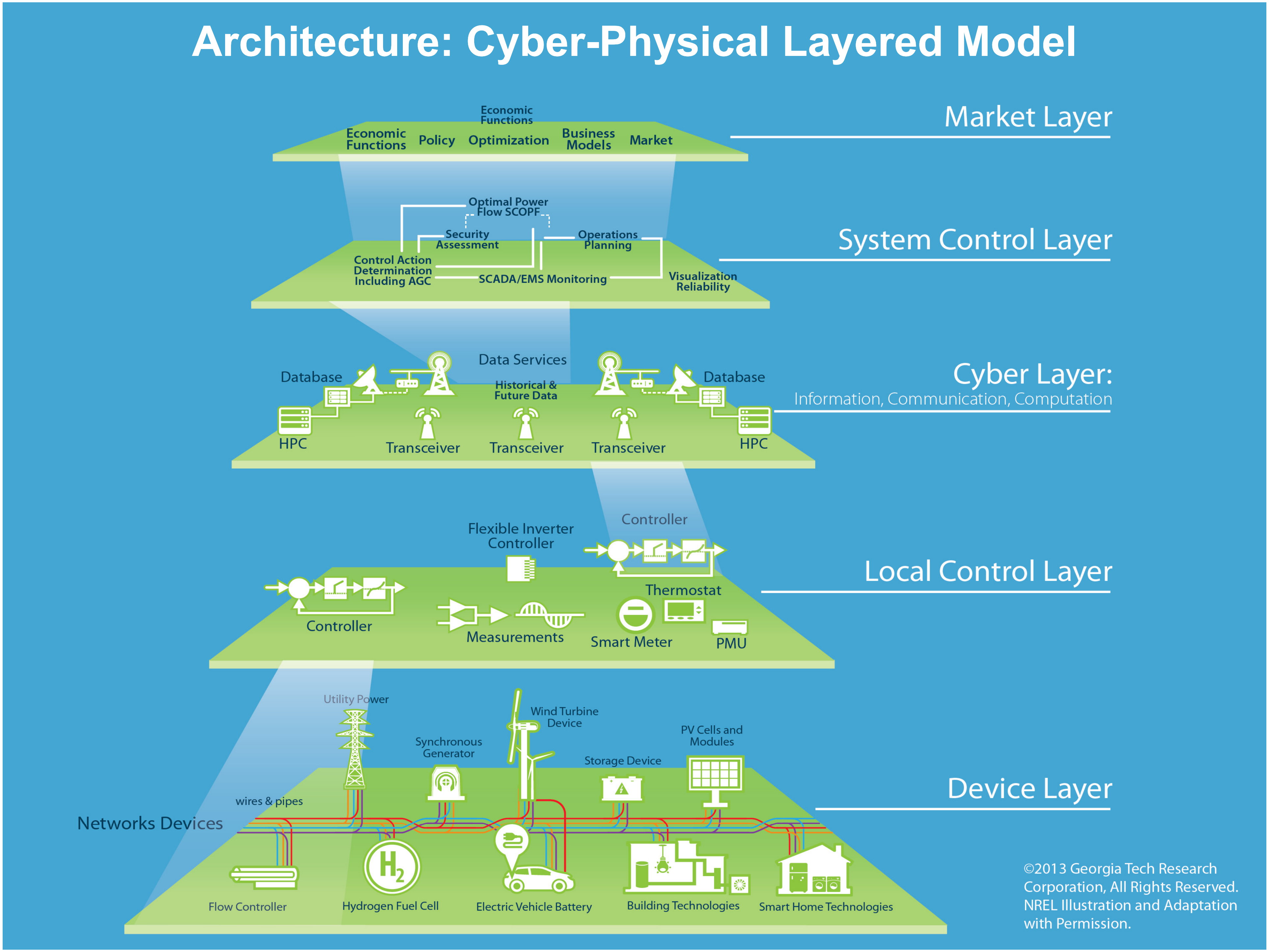
- Interactions occur among entities of the same type (prosumers)
- Can achieve "flatness"

S. Grijalva, "Multi-Scale, Multi-Dimensional Computational Algorithms for Next Generation Electric Power Grid", DOE Workshop on Computational Needs for Next Generation Electric Power Grid, Cornell University, Ithaca, NY, April 18-20, 2011.

Architecture: Prosumer Interactions



S. Grijalva, M. Costley, "Prosumer-Based Smart Grid Architecture Enables a Flat, Sustainable Electricity Industry", *IEEE PES Conference on Innovative Smart Grid Technologies (ISGT)*, Anaheim, California, January 17-19, 2011.


Architecture: Cyber-Physical Layered Model
Market Layer
Economic Functions
Policy
Economic Functions
Optimization
Business Models
Market
System Control Layer
Optimal Power Flow SCOPF
Security Assessment
Operations Planning
Control Action Determination Including AGC
SCADA/EMS Monitoring
Visualization Reliability
Cyber Layer:
Information, Communication, Computation
Database
Data Services
Historical & Future Data
Database
HPC
Transceiver
Transceiver
Transceiver
HPC
Local Control Layer
Flexible Inverter Controller
Controller
Thermostat
Controller
Measurements
Smart Meter
PMU
Device Layer
Utility Power
Wind Turbine Device
Synchronous Generator
PV Cells and Modules
Storage Device
wires & pipes
Networks Devices
Flow Controller
Hydrogen Fuel Cell
Electric Vehicle Battery
Building Technologies
Smart Home Technologies

Prosumer Power Agreement

Prosumer States

$\hat{p}_i$: Desired Power

$\tilde{p}_i$: Agreed Upon Power

p_i : Actual Power

Given desired power levels, how to agree on power outputs?

$$\min_{\tilde{p}} \sum_{i=1}^{N} w_i \| \tilde{p}_i - \hat{p}_i \|^2$$

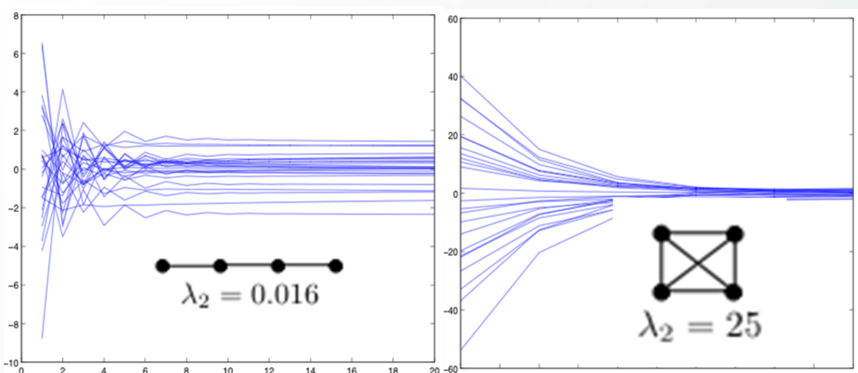
An agreement dynamics, incorporating constraints, weights, and trust, is used to agree on the power levels across the network in a decentralized fashion.

$$q(t+1) = q(t) - \Delta t[LWLq(t) - WL\hat{p}]$$

$$q_i(t+1) = q_i(t) - \Delta t\left[\sum_{j\in N_i}\left(w_i \sum_{k\in N_i}(q_i(t)-q_k(t)) - w_j \sum_{\ell\in N_k}(q_k(t)-q_\ell(t))\right) - w_i \sum_{j\in N_i}(\hat{p}_i - \hat{p}_j)\right]$$

$$\tilde{p}_i = \sum_{j\in N_i} p_{ij}$$

Converges asymptotically to the global minimizer (exponentially in the algebraic connectivity of the network)



Ramachandran, Costello, Kingston, Grijalva, Egerstedt. "Distributed Power Allocation in Prosumer Networks", *NecSys*, 2012.

Malicious/Malfunctioning Prosumer

- Linearize dynamics: $$M_i \Delta\ddot{\delta} + \tilde{D}_i \Delta\dot{\delta} + \sum_{j \in N_i} T_{ij}(\Delta\delta_i - \Delta\delta_j) = d + \Delta P_{M_i}$$

??

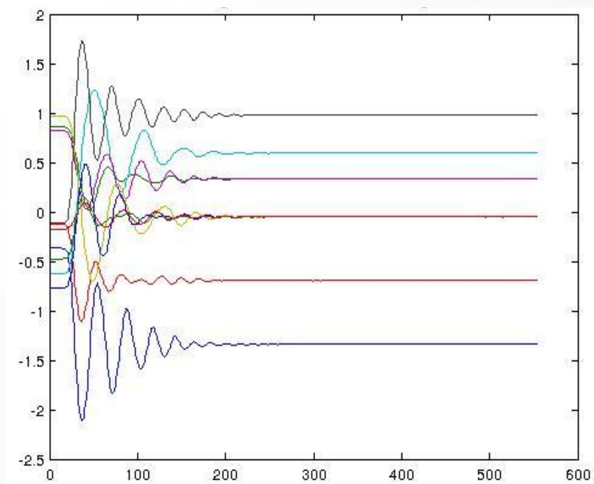
- On state-space form: $$\dot{x} = \begin{bmatrix} 0 & I \\ -M^{-1}L_t & -M^{-1}\tilde{D} \end{bmatrix} x + \begin{bmatrix} 0 \\ M^{-1}d \end{bmatrix}$$

Unstable!

- Project the (asymptotically stable) dynamics and evaluate *z* "after a while" and solve for *d*: $$z = \begin{bmatrix} L_t & 0 \\ 0 & I \end{bmatrix} x \qquad \begin{bmatrix} 0 \\ d \end{bmatrix} = \begin{bmatrix} 0 & -ML_t \\ I & \tilde{D} \end{bmatrix} z_\infty$$

- Can evaluate *x* in a distributed way: $$d = \begin{bmatrix} L_t & \tilde{D} \end{bmatrix} x_\infty$$

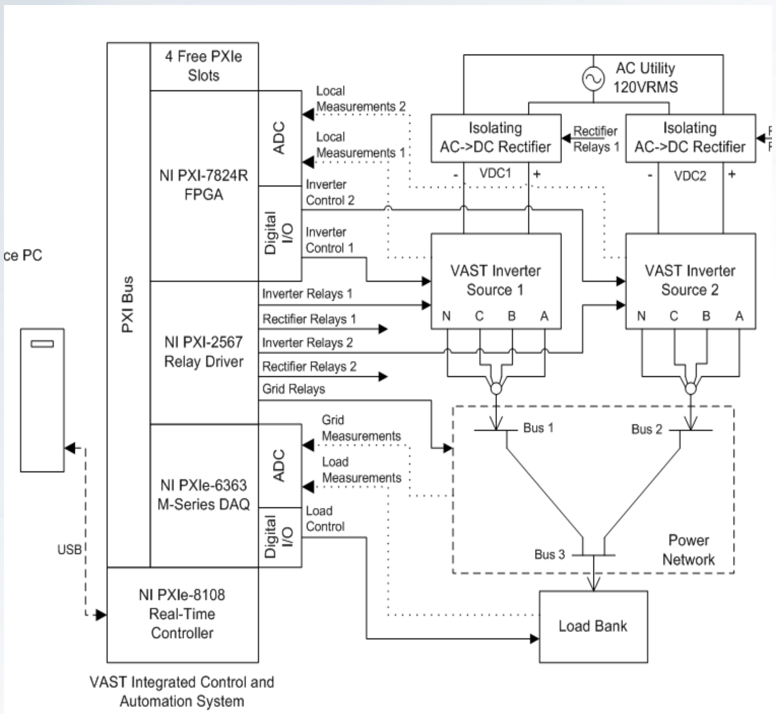
$$d_i = \sum_{j \in N_i} T_{ij}(\delta_{\infty_i} - \delta_{\infty_j}) + \tilde{D}_i \dot{\delta}_{\infty_i}$$

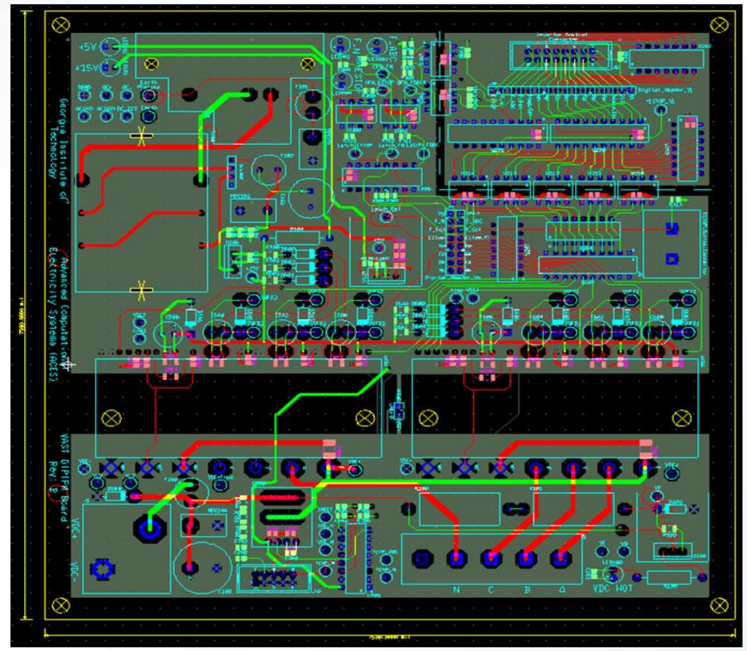


$$d_{recovered} = \begin{bmatrix} -0.1000 \\ 0.0300 \\ -0.0501 \\ 0.0500 \\ 0.0300 \\ 0.0000 \\ 0.0800 \\ -0.0000 \\ 0.0000 \\ 0.0000 \end{bmatrix}$$

Decentralized Control

Hardware Demonstrations





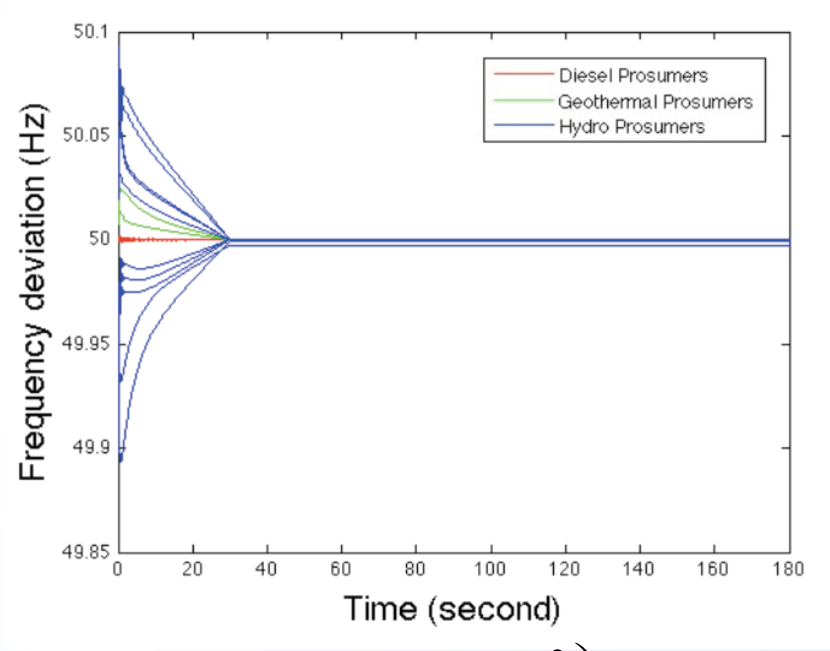
N. Ainsworth, M. Costley, J. Thomas, M. Jezierny, S. Grijalva: "Versatile Autonomous Smartgrid Testbed (VAST): A Flexible, Reconfigurable Testbed for Research on Autonomous Control for Critical Electricity Grids", in *Proceedings of the North American Power Symposium*, Champaign, IL, September 9-11, 2012.

Decentralized Frequency Regulation

- Model Predictive Control solvable in a distributed manner.
- Each prosumer solves its sub-problem and shares its optimal control strategy with its neighbors.

$$\min_{u_1,\ldots,u_n} \sum_{i=1}^{n} \left(p_i x_i (t_c + 1)^2 + r_i u_i^2 \right)$$

$$s.t.: x_i(t_c + 1) = a_{ii} x_i(t_c) + b_{ii} u_i(t_c) + \sum_{j \in N} \left(a_{ij} x_j(t_c) + b_{ij} u_j(t_c) \right)$$

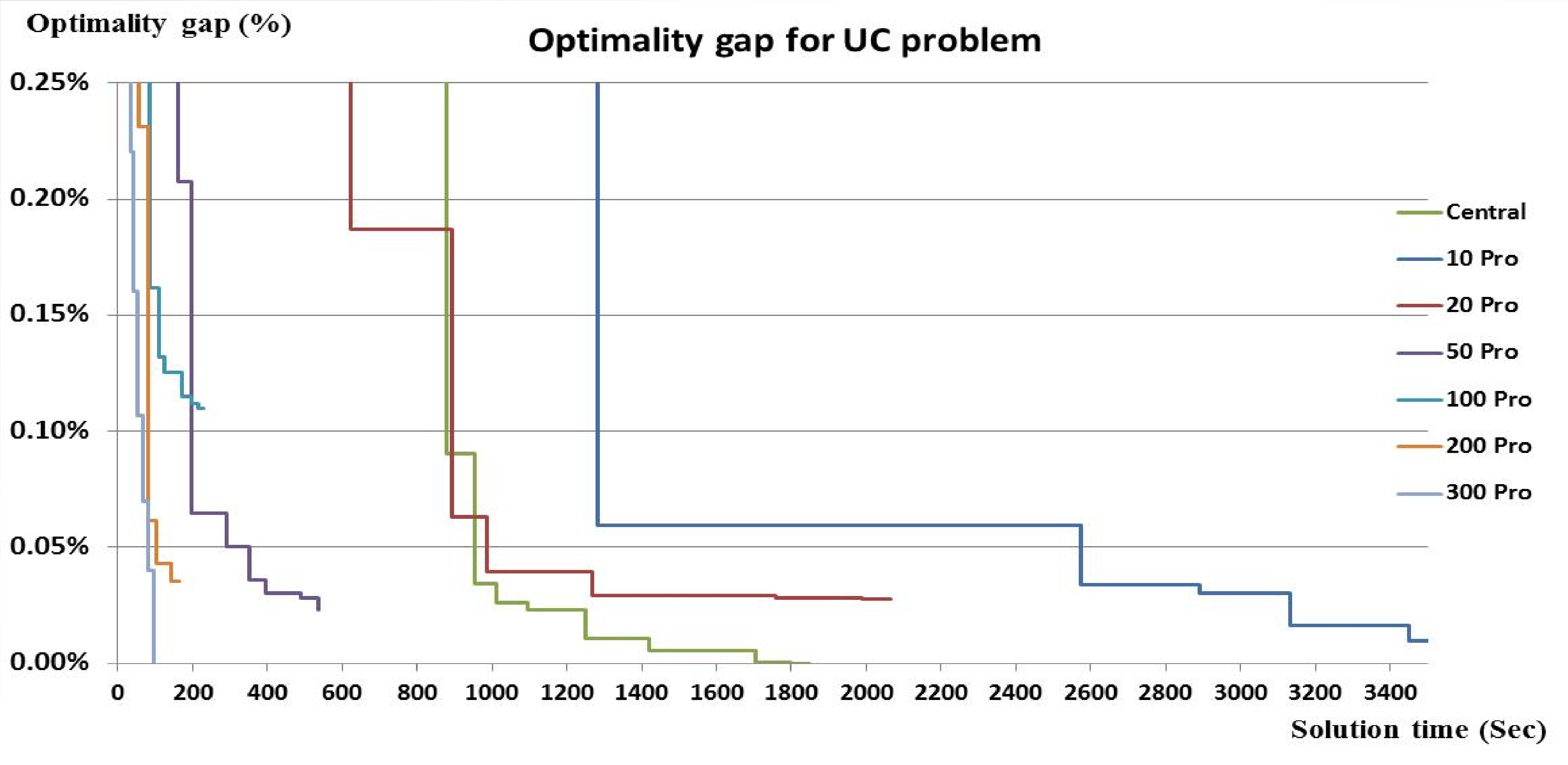


- Prosumer *i* strategy:

$$u_i^{k+1} = \arg\min \left(r_i u_i^2 + p_i \left(a_{ii} x_i + b_{ii} u_i + \sum_{j \in N_i} (a_{ij} x_j + b_{ij} u_j \right)^2 \right)$$

Decentralized Energy Scheduling

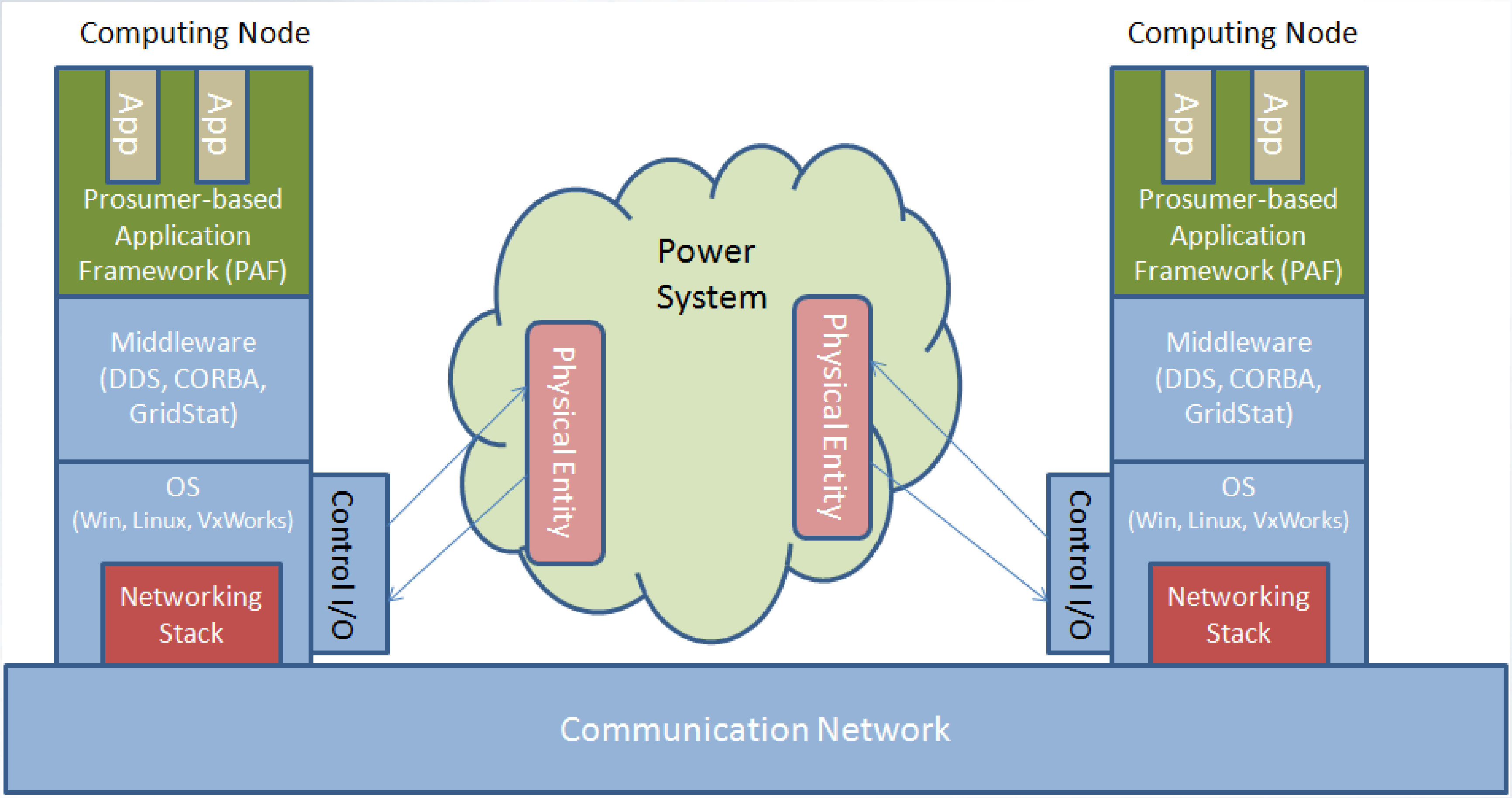
- 1,500+ Generator case
- Full UC realistic data.



Further Elements for De-centralized Control

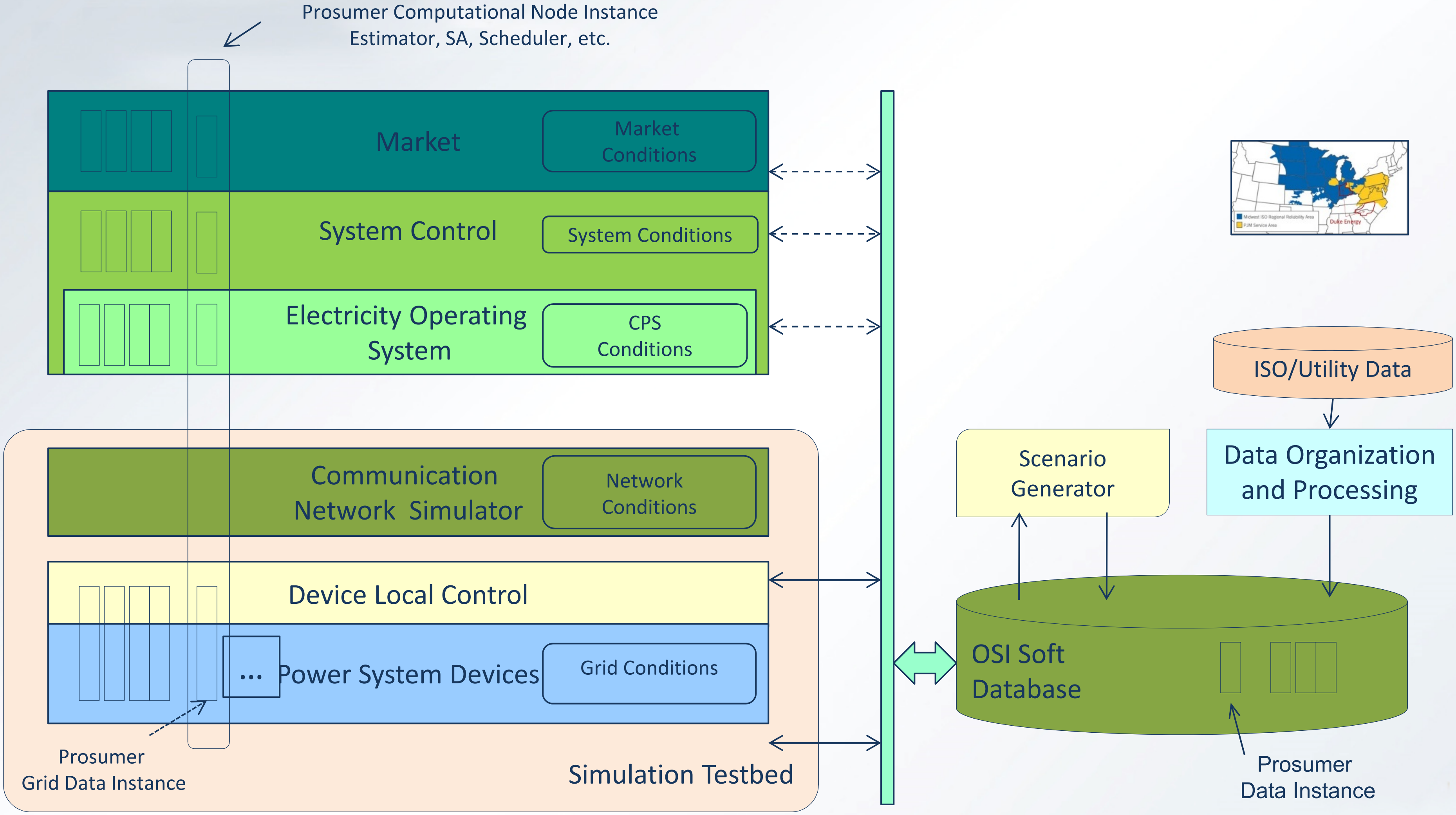
Requirement	Theory
Synchronization/ stabilization	Decentralized controller for nonlinear coupled oscillators
Effect of losses	Bi-directed graphs and non-odd functions
Voltage Stability	Locally enforceable necessary condition
Transient Stability	Locally enforceable sufficient condition
Flow Constraints	Distributed enforcement of coupling constraints

Decentralized Computing Infrastructure



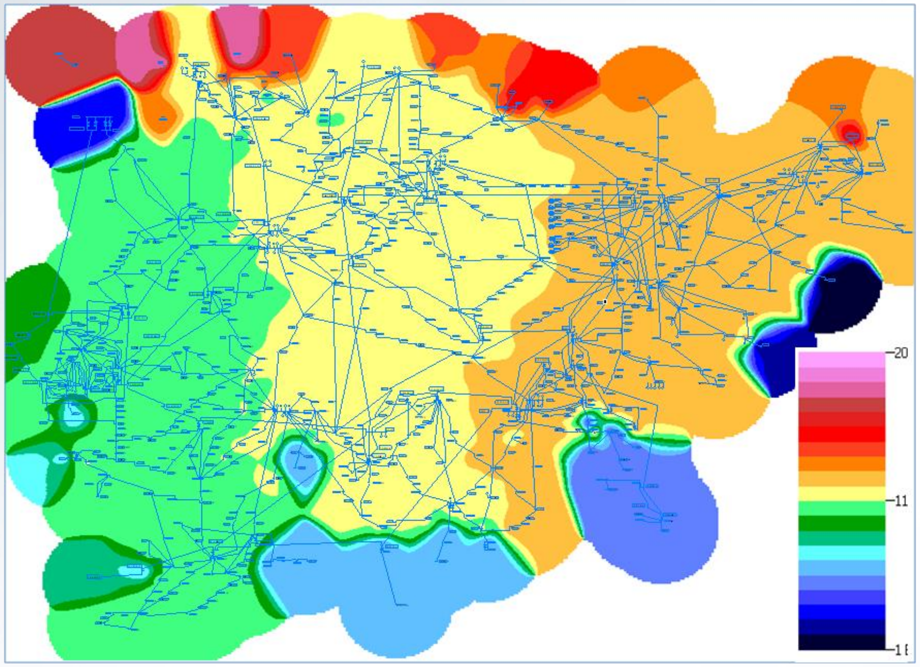
M.U. Tariq, S. Grijalva, M. Wolf, "Towards a Distributed, Service-Oriented Control Infrastructure for Smart Grid", *ACM/IEEE Second International Conference on Cyber-Physical Systems*, Chicago, IL, April 11-14, 2011.

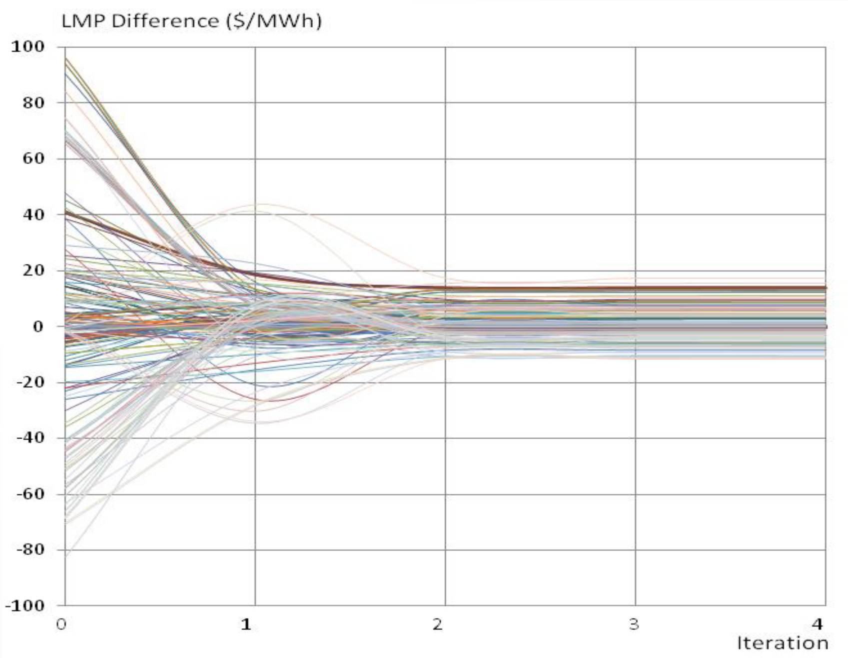
Demonstration System



Decentralized Control: Large-Scale Systems

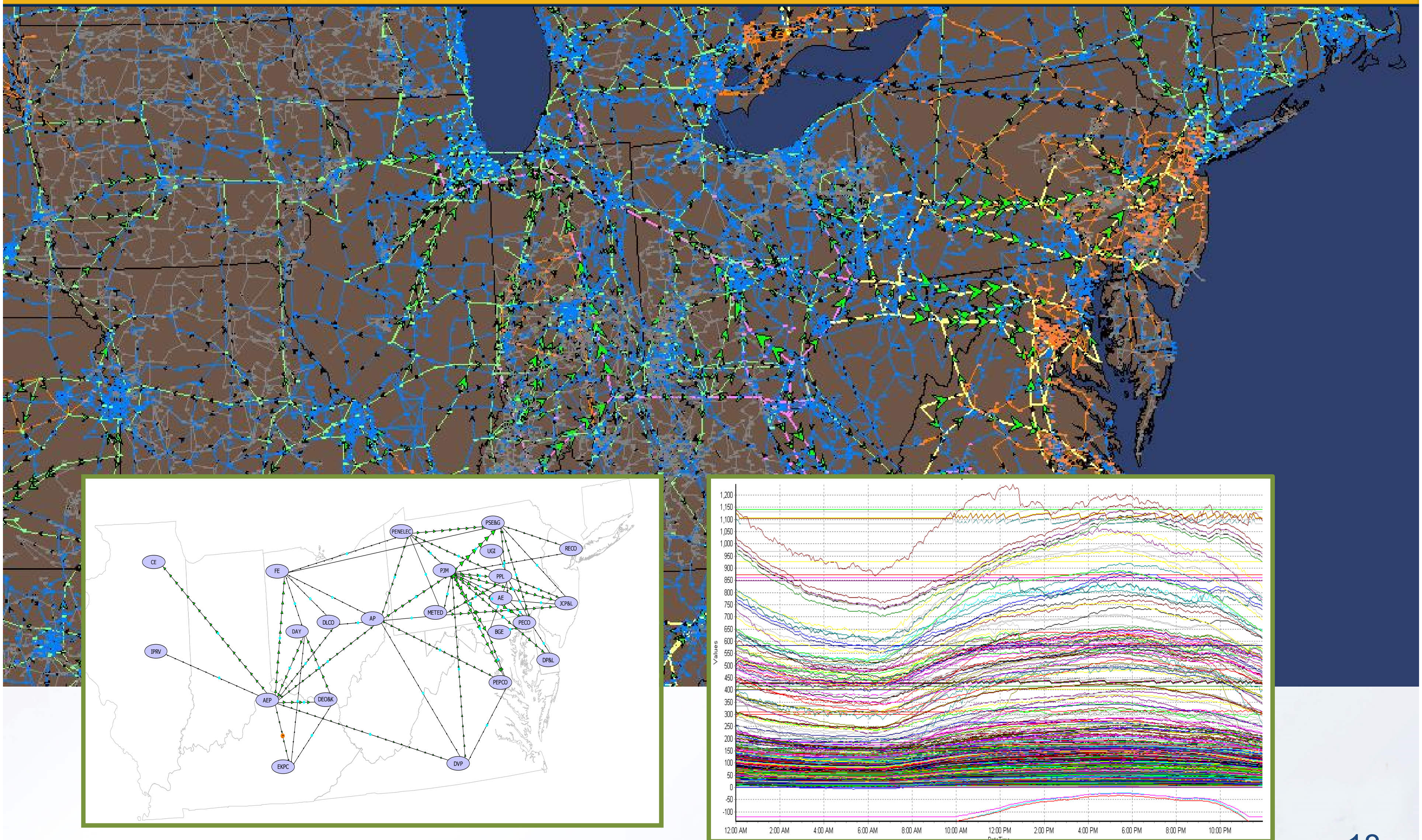
- 20 Self-Optimizing Regions in a Large-Scale RTO System.
- Non-fictitious Tie-Line Bus LMP Difference Convergence obtained using Distributed Optimization.





M. Costley, S. Grijalva, “Efficient Distributed OPF for De-centralized Power System Operations and Electricity Markets”, IEEE PES Conference on Innovative Smart Grid Technologies, Washington D.C., January 17-19, 2012.

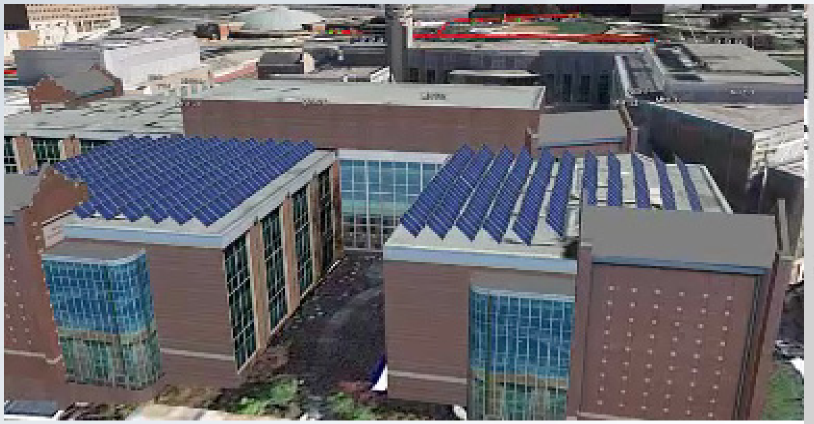
Decentralized Control: Large-Scale Systems

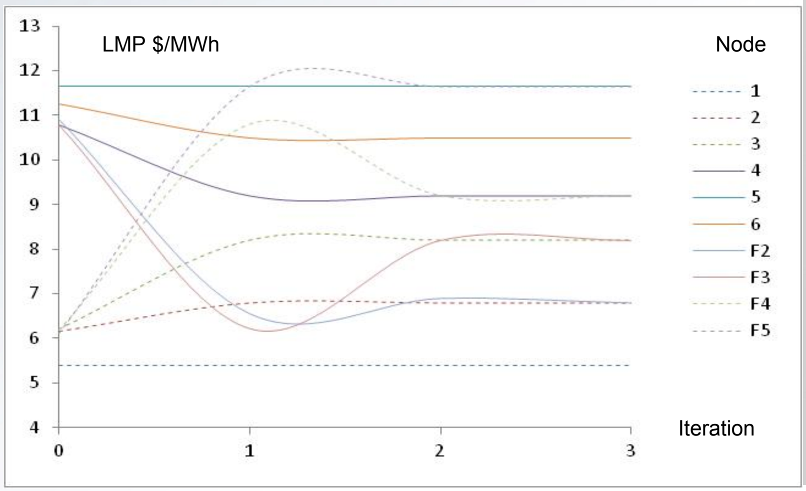


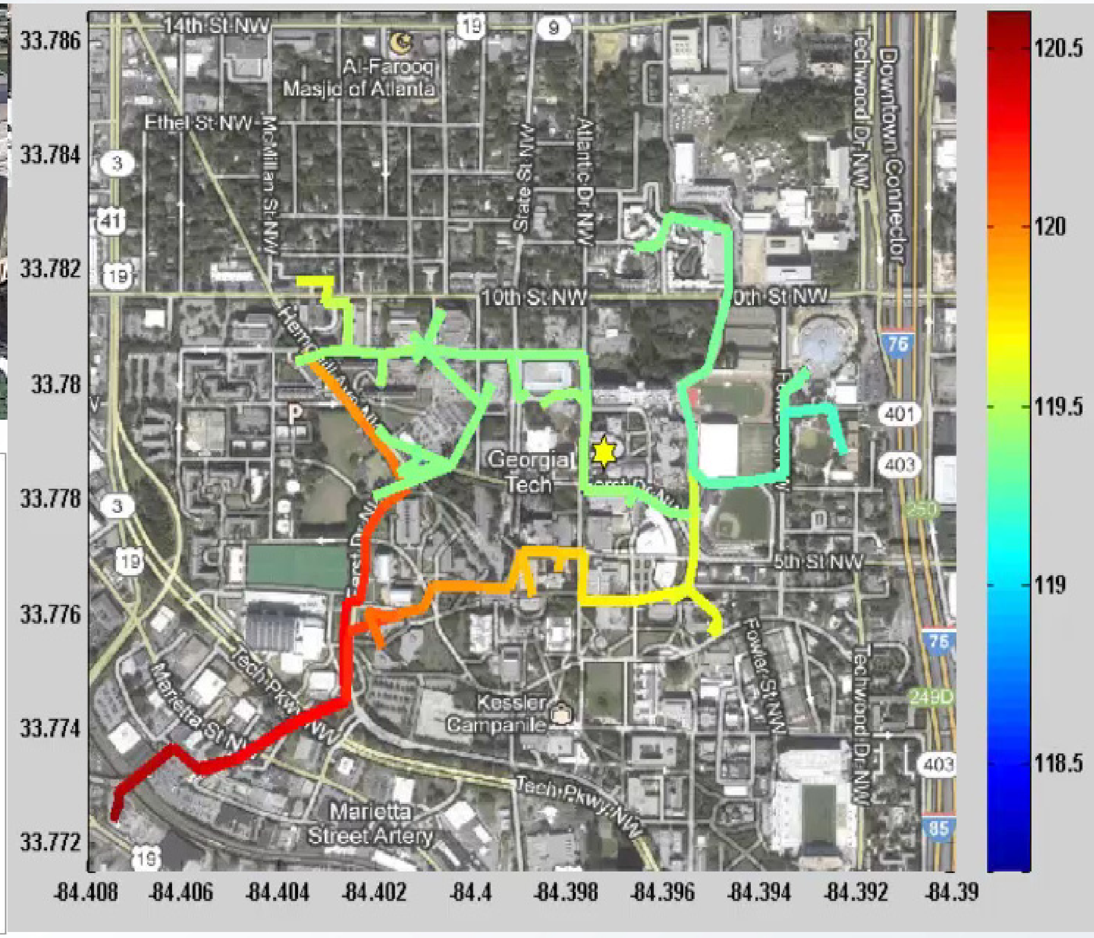
Multi-Scale Prosumer Behavior

- Prosumer exposes standardized services
  - Energy balancing
  - Frequency regulation
  - Reserve
  - Sensing and Information
  - Forecasting
  - Security

Decentralized Building Control







a) Building prosumer interaction at transformer connection point for a constrained grid.

b) Voltage contouring for PV variability

Summary

- Future electricity systems will consist of billions of smart devices and millions of interconnected decision makers.
- Only a decentralized control and management architecture will be able to support the objectives and requirements of the future electricity industry.

THANKS!