New Challenges and Opportunities for the Electric Grid

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MIT Future of the Electric Grid Study

Sustainable Energy – Choosing Among Options
September 30, 2010

OUTLINE

- MIT Future of the Electric Grid Study
- "Smart Grid"
- New Challenges/Opportunities:
  - *Challenge:* more wind and solar, remote and distributed
  - *Opportunity:* new remote sensing & automation technologies
  - *Challenge:* electrification of transportation systems
  - *Opportunity:* technologies that can make demand more responsive to system conditions
  - *Challenge:* data communications, cyber-security, & privacy

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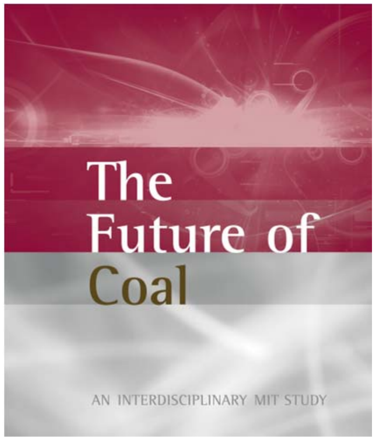
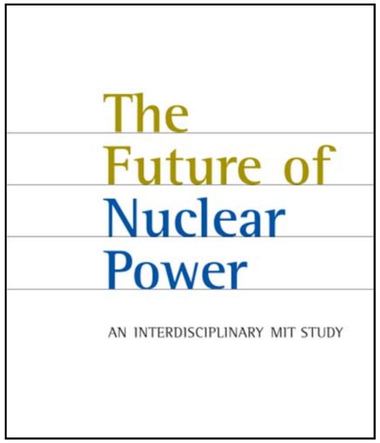
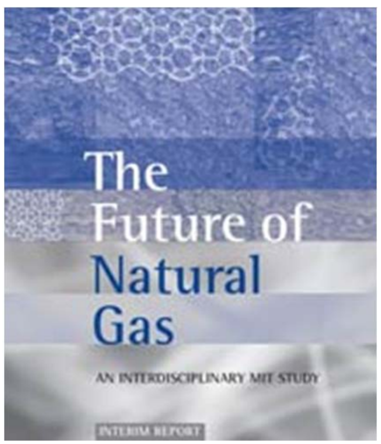
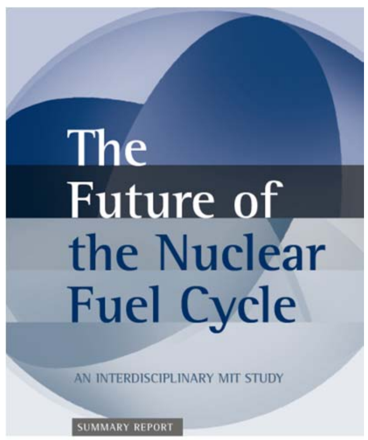
MIT "FUTURE OF…" STUDIES









- MIT faculty have, over the last several years, conducted several ***in-depth multidisciplinary energy studies*** designed to inform future energy options, research, technology choices, and public policy development.

- These studies — ***grounded in science, supported by objective economic/policy analysis, comprehensive in scope and input*** — underscore MIT's role as an "honest broker" on energy issues.

"THE FUTURE OF THE GRID" MOTIVATION

- The US electric grid, the system that links generation to load, is perhaps not "broken" at present, but
- It faces a number of new challenges and, because of advances in technology, new opportunities
- There is an enormous amount of hype around the "smart grid," much of it supplied by equipment vendors
- We aim to provide an objective analysis of the new challenges and opportunities the US grid faces, focusing on two questions:
  - *Can existing institutions and policies be relied upon to meet the new challenges and seize the emerging opportunities?*
  - *If not, what changes are required?*

STUDY BACKGROUND

- Study team recruited, work began in fall of 2009; initial focus was on narrowing the project scope.
- Recruited an Advisory Committee; met (on scope) in May 2010; will meet again in October and early in 2011.
- Have identified & studied key challenges & opportunities, but have not yet agreed on recommendations.
- Will finish study, with recommendations, by May 2011.
- Today: some thoughts on the challenges & opportunities on which we are working.
  - **Opinions in this talk are mine alone, not the research team's!**

RESEARCH TEAM

Co-Directors:

- Richard Schmalensee
  Howard W Johnson Prof. of Economics and Management
  Former Dean, Sloan School of Management
- John G. Kassakian
  Professor
  Electrical Engineering & Computer Science

Faculty/Staff:

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  Electrical Engineering & Computer Science
- Gary DesGroseilliers
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  MIT Future of the Electric Grid Study
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  Former Vice President
  Information Services and Technology, MIT
- Timothy D. Heidel
  Postdoctoral Associate / Research Director
  MIT Energy Initiative
- William Hogan
  Raymond Plank Professor of Global Energy Policy
  HEPG Research Director
  Mossavar-Rahmani Center for Business and Government
  John F. Kennedy School of Government, Harvard
- Henry D. Jacoby
  William F. Pounds Professor of Management Emeritus
  Professor of Applied Economics
  Center for Energy and Environmental Policy Research
- James L. Kirtley
  Professor
  Electrical Engineering & Computer Science
- Harvey Michaels
  Energy Efficiency Research Director/Lecturer
  Department of Urban Studies and Planning
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  Visiting Professor
  Engineering Systems Division
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  Associate Professor
  Electrical Engineering & Computer Science
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  Professor
  Department of Economics
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  Electrical Engineering & Computer Science
  Former Dean, School of Engineering

Students: Nabi Abudaldah, Minjie Chen, Samantha Gunter, P. Jordan Kwok, Vivek A. Sakhrani, Jiankang Wang, Andrew Whitaker, Xiang Ling Yap

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  - *Challenge:* data communications, cyber-security, & privacy

Figure showing leading companies by market segment for an "end-to-end" smart grid has been removed due to copyright restrictions. Please see Leeds, David J. "The Smart Grid in 2010: Market Segments, Applications, and Industry Players." GTM Research, July 13, 2009.

“We’ll fund a better, smarter electricity grid and train workers to build it…”

~ President Barack Obama

“To meet the energy challenge and create a 21st century energy economy, we need a 21^{st} century electric grid…”

~ Secretary of Energy Steven Chu

“A smart electricity grid will revolutionize the way we use energy…”

~ Secretary of Commerce Gary Locke

“[With] a new, American-built smart grid, the same people who work on killer apps for an iPhone will now help you know how much energy you use from your iFridge, iStove, or iToaster.”

~ Congressman Ed Markey

U.S. SMART GRID LEGISLATION

- **Energy Policy Act 2005 (EPACT 2005)**
  - Established a definition for Smart Metering / Advanced Metering

- **Energy Independence and Security Act 2007 (EISA 2007)**
  - Title XIII established Smart Grid concepts in law
  - Established program to provide matching grant money for Smart Grid investments
  - Directed NIST to come up with Interoperability Standards

- **American Recovery & Reinvestment Act 2009 (ARRA 2009)**
  - Provided funding for EPACT 2005 and EISA 2007 provisions

ARRA 2009 SMART GRID FUNDING

Smart Grid Investment Grants (100 projects) ($3.4 billion)

- 850 PMUs covering 100% of transmission
- 200,000 smart transformers
- 700 automated substations
- 40 million smart meters
- 1 million in-home displays

Smart Grid Demonstration Projects (32 projects) ($620 million)

- 16 storage projects
- 16 regional demonstrations

More Information: http://www.smartgrid.gov

"SMART GRID" DEFINITIONS

Europe (Eurelectric):

"*A smart grid is an electric network that can intelligently integrate the behavior and actions of all users connected to it — generators, consumers, and those that do both — in order to efficiently ensure sustainable, economic, and secure electricity supply*."

United States (Department of Energy):

"*A Smart Grid uses digital technology to improve reliability, security, and efficiency of the electric system: from large generation, through the delivery systems to electricity consumers and a growing number of distributed generation and storage resources*."

SO, WHAT IS A SMART GRID?

A. Anything a vendor tells you that Smart Grid is (it usually also happens to be what the vendor is selling)

B. Whatever Congress, the PUC, State Legislature, or DOE wants it to be (and is willing to pay for)

C. Anything that involves adding new technology to the electric grid

D. The merger of the Telecommunications and Electric Utility industries

E. All of the above

ENERGY INDEPENDENCE AND SECURITY ACT 2007
SEC. 1301 STATEMENT OF POLICY ON MODERNIZATION OF ELECTRICITY GRID

It is the policy of the United States to support the modernization of the Nation's electricity transmission and distribution system to maintain a reliable and secure electricity infrastructure that can meet future demand growth and to achieve each of the following, which together characterize a Smart Grid:

(1) Increased use of digital information and controls technology to improve reliability, security, and efficiency of the electric grid.
(2) Dynamic optimization of grid operations and resources, with full cyber-security.
(3) Deployment and integration of distributed resources and generation, including renewable resources.
(4) Development and incorporation of demand response, demand-side resources, and energy-efficiency resources.
(5) Deployment of `smart' technologies (real-time, automated, interactive technologies that optimize the physical operation of appliances and consumer devices) for metering, communications concerning grid operations and status, and distribution automation.
(6) Integration of `smart' appliances and consumer devices.
(7) Deployment and integration of advanced electricity storage and peak-shaving technologies, including plug-in electric and hybrid electric vehicles, and thermal-storage air conditioning.
(8) Provision to consumers of timely information and control options.
(9) Development of standards for communication and interoperability of appliances and equipment connected to the electric grid, including the infrastructure serving the grid.
(10) Identification and lowering of unreasonable or unnecessary barriers to adoption of smart grid technologies, practices, and services.

Energy Independence and Security Act of 2007, Public Law 110-140, 110th Congress.

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INSTITUTIONAL COMPLEXITY (US GRID)

- Began with municipal regulation of integrated private systems, then state regulation; federal role is limited; *no comprehensive national policy.*
- Generation: investor-owned firms (84% of generation), plus cooperatives and systems owned by city, state, and federal governments
- Transmission/Distribution: 3,200 government owned, cooperative, and (state-regulated) investor-owned entities (242 investor-owned, 65% of sales)
- Wholesale market deregulation began in 1990s, halted by the California meltdown of 2000-01:
  - Organized (ISO/RTO) wholesale markets serve about 2/3 of load, about 42% of generation nationally by investor-owned firms without retail customers;
  - Regulated integrated companies dominate in the southeast;
  - Federal hydro generation and transmission are important in the west.
- No two utilities/states/regions /countries are identical, historical evolution occurred differently and at different rates

ORGANIZED ISO/RTO MARKETS (U.S.)

Map of ISO/RTO operating regions removed due to copyright restrictions.

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CHALLENGE: RENEWABLE GENERATION

- 29 states & the District of Columbia have "renewable portfolio standards," requiring non-hydro renewable (NHR) generation.
- A national standard is possible, more state standards are likely, so expect requirements for more grid-scale and distributed NHR generation, **mainly intermittent wind & solar**.

Maps of U.S. Wind Resource (50m) and Annual Direct Normal Solar Radiation (Two-Axis Tracking Concentrator) removed due to copyright restrictions.

Graphs removed due to copyright restrictions. Please see p. 11 in "Implementation of Market & Operational Framework for Wind Integration in Alberta." AESO Recommendation Paper, March 2009.

→ More grid-scale renewable generation is likely to require more long-distance transmission.
→ More grid-scale renewable generation is likely to require system operation changes (due to intermittency and imperfect predictability)

CHALLENGE: RENEWABLE GENERATION

- Long-distance transmission for remote grid-scale renewables poses both technical and policy challenges:
  - Planning must now account for new goal ("policy lines")
  - Planning will need to reflect optimization under uncertainty
  - Planning and allocating costs of transmission across traditional regional boundaries is difficult (currently use ad hoc, case-be-case processes)

- Distributed renewables (e.g., rooftop solar) pose different technical and (harder) policy challenges
  - May need to configure distribution systems for two-way power flow & to maintain worker safety
  - Must provide incentives for the necessary investment – even though it will lead to lower sales; need sophisticated "uncoupling"?

OPPORTUNITY: SENSING / AUTOMATION

Recent technical advances offer the potential to dramatically increase the observability and controllability of transmission and distribution systems.

System Monitoring Today -> “Supervisory Control And Data Acquisition” (SCADA) systems

- **Functions:** system monitoring, state estimation, blackout detection….

- **Age:**
  - Have been in use for the past 40 years.
  - Have typically not kept pace with rapid advances in sensor technologies and information processing techniques.

- **Performance:**
  - Record data every 2-4 seconds, sufficient for voltage monitoring, but not sufficient for phase monitoring.
  - Can have 30+ second delay for detecting blackouts.
  - Measurements are not synchronized.

Automatic Generation Control (Not centralized)

- Primary control methodology today, individual generators do not usually know system state

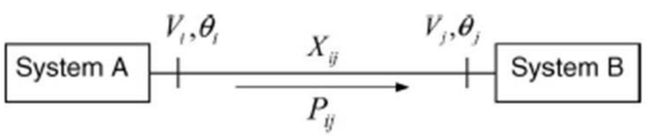
THE IMPORTANCE OF MEASURING PHASE

Calculating flows on a transmission line

$$X_{a,b} = \omega * L_{a,b}$$

$$P_{a,b} = \frac{E_a * E_b}{X_{a,b}}(\sin(\theta_a - \theta_b))$$

$$Q_{a,b} = E_a \frac{(E_a - E_b * \cos(\theta_a - \theta_b))}{X_{a,b}}$$



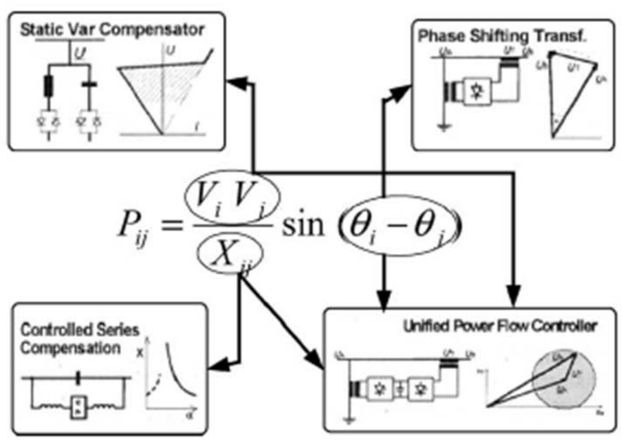


Fig. 2. Variables controlled by each FACTS device in active power flow.

Phase has not been used in the past

❖The active and reactive power flows on lines are determined by three parameters along the lines:

❑ line impedance
❑ voltages amplitudes
❑ phases

❖Only frequency and voltage are monitored in the current system control architecture.

New tech. could measure and control phase

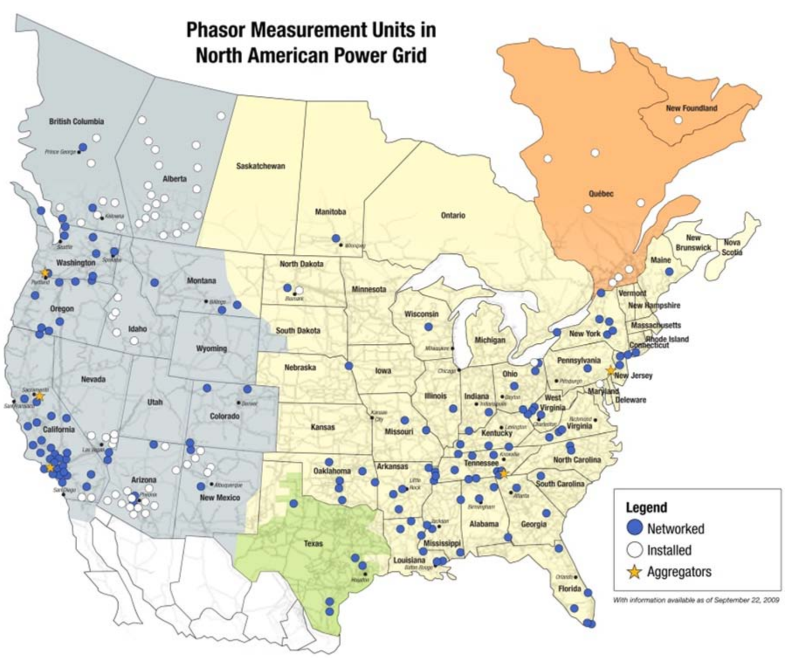
❖Synchrophasor measurement units (PMUs) make large scale synchronous phase measurement possible.

❖Flexible AC Transmission Systems (FACTS) make phase modification possible.

Source: Song, S.-H., J.-U. Lim, et al. (2004). "Installation and operation of FACTS devices for enhancing steady-state security." Electric Power Systems Research **70(1): 7-15.**

SYNCROPHASOR MEASUREMENT UNITS (PMUs)

- Measure instantaneous phase angle at their installed location
- Often can take and transmit >30 measurements per second
- Measurements are synchronized to a GPS time signal
- IEEE Standard C37.118
- 250 already installed in North America, 850 more on the way



Source: http://www.naspi.org/pmu/pmu.stm

Image by Pacific Northwest National Laboratory, operated by Battelle for the U.S. Department of Energy.

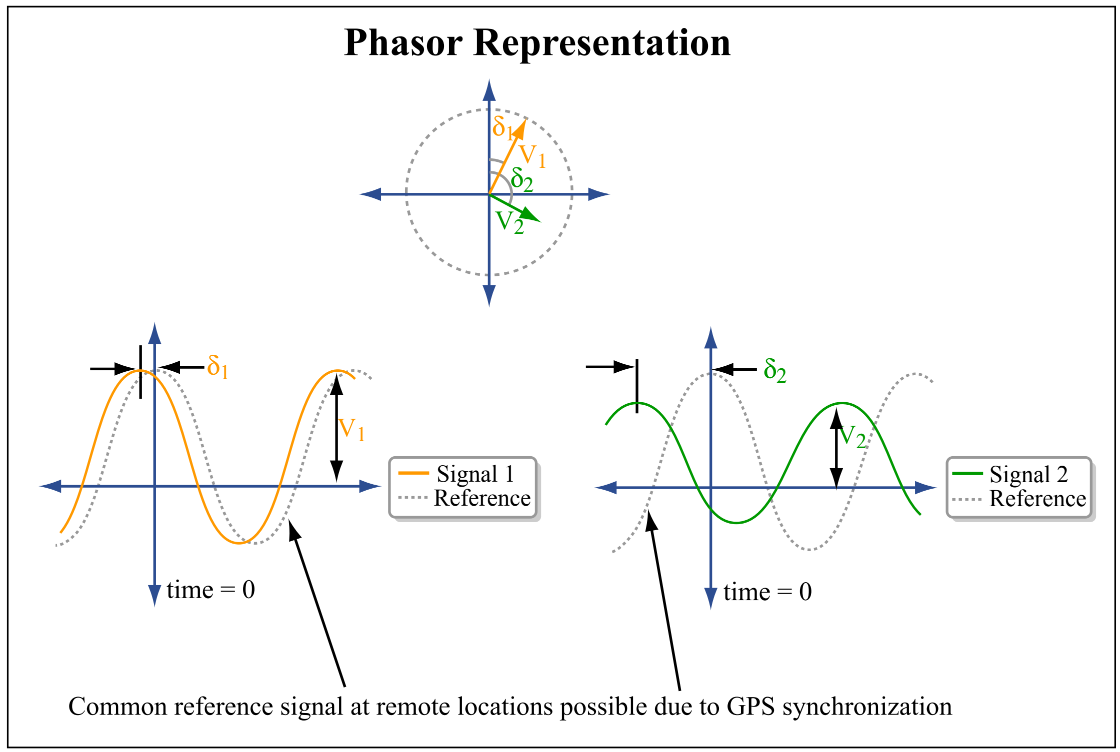


Image by MIT OpenCourseWare.
Adapted from "What is Phasor Technology?" Advanced Concepts FAQ, Phasor-RTDMS.

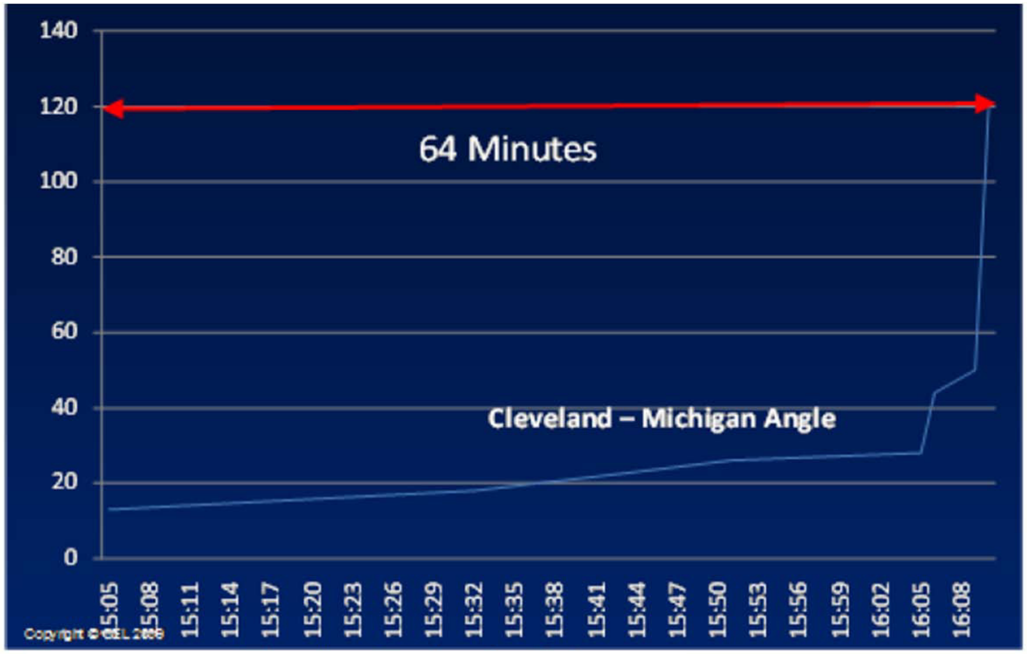
SYNCROPHASOR MEASUREMENT UNITS (PMUs)

Phasor measurement units (PMUs) and other sensors can provide detailed, real time information on transmission system status, potentially enabling increased capacity & enhanced reliability

Example:

Phase angle monitoring applications could give system operators early warning of potential system instability

Relative phase angle between two locations during August 2003 blackout



SYNCROPHASOR MEASUREMENT UNITS (PMUs)

Phasor measurement units (PMUs) and other sensors can provide detailed, real time information on transmission system status, potentially enabling increased capacity & enhanced reliability

Example:

PMUs could be used to calibrate and/or improve system models (used for operations, planning and reliability studies)

OPPORTUNITY: SENSING / AUTOMATION

A variety of recent technical advances offer potential to automate portions of the distribution system

Source: ABB

CHALLENGE: TRANSPORTATION ELECTRIFICATION

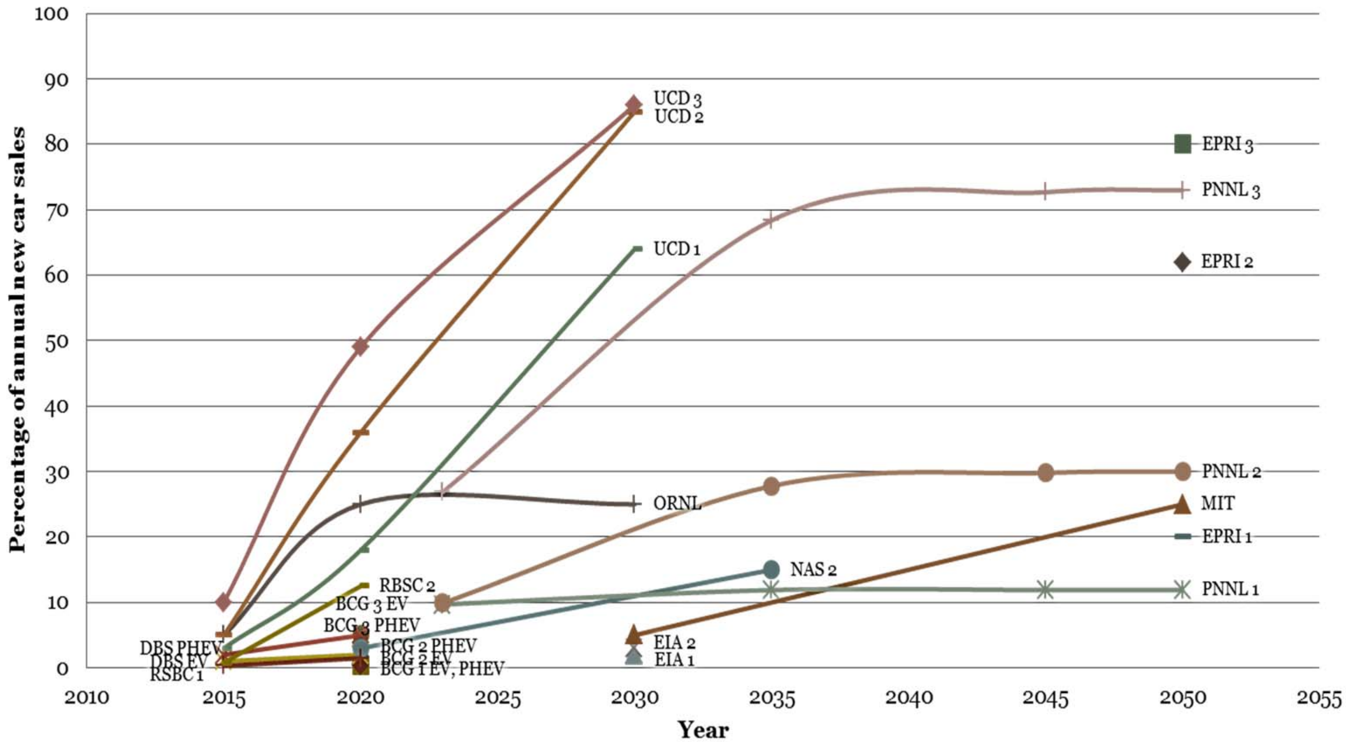
Energy security & other concerns have led to state & federal incentives for electric vehicles (EVs) and plug-in hybrids (PHEVs)

Nissan Leaf

Tesla Roadster

GE WattStation Charger

U.S PHEV/EV Penetration Goals, Targets, Projections, Forecasts, & Dreams

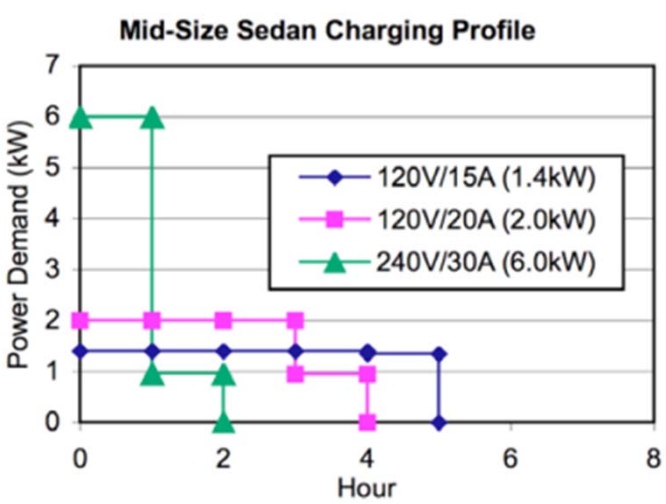


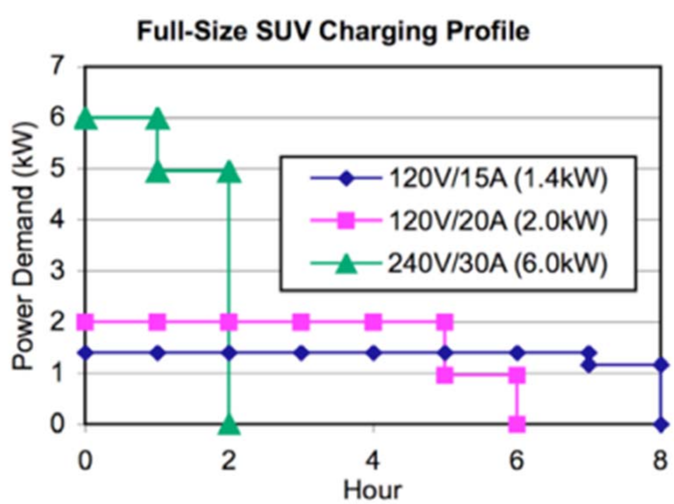
Source: Various (Contact me for original data sources).

PHEVs/EVs COULD BE LARGE NEW LOADS

	Voltage (VAC)	Current (Amps)	Power (kVA)	Freq. (Hz)	Phase	Standard Outlet
Level 1	120	12	1.44	60	Single	NEMA 5-15R
Level 2	208/240	32	6.7/7.7	60	Single	SAE J1772/3
Level 3	480	400	192	60	Three	N/A

Pack size:
5.9 kWh





Pack size:
9.3 kWh

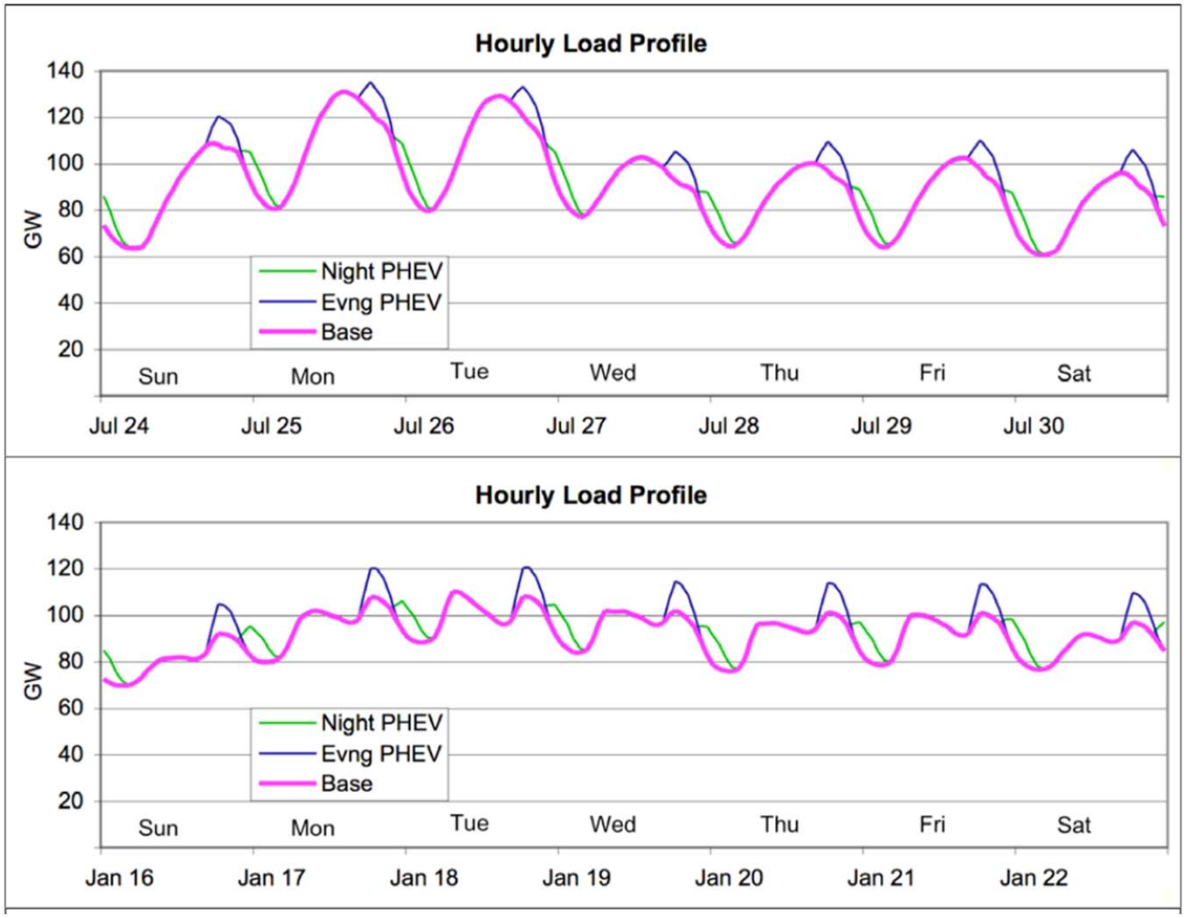
Potential hourly demand for a PHEV20 Vehicle

S.W. Hadley and A. Tsvetkova, "Potential Impacts of Plug-in Hybrid Electric Vehicles on Regional Power Generation," 2008.

Figures by Oak Ridge National Laboratory for the U.S. Department of Energy.

PHEVs/EVs COULD BE LARGE NEW LOADS

On-peak (late afternoon) charging could increase peak load, requiring substantial additional generation investment.



Potential impacts on:

- Generation mix
- Load forecasting ability
- Distribution network

How to provide incentives for off-peak charging?

 Hourly Load Profiles (Lots of underlying assumptions)

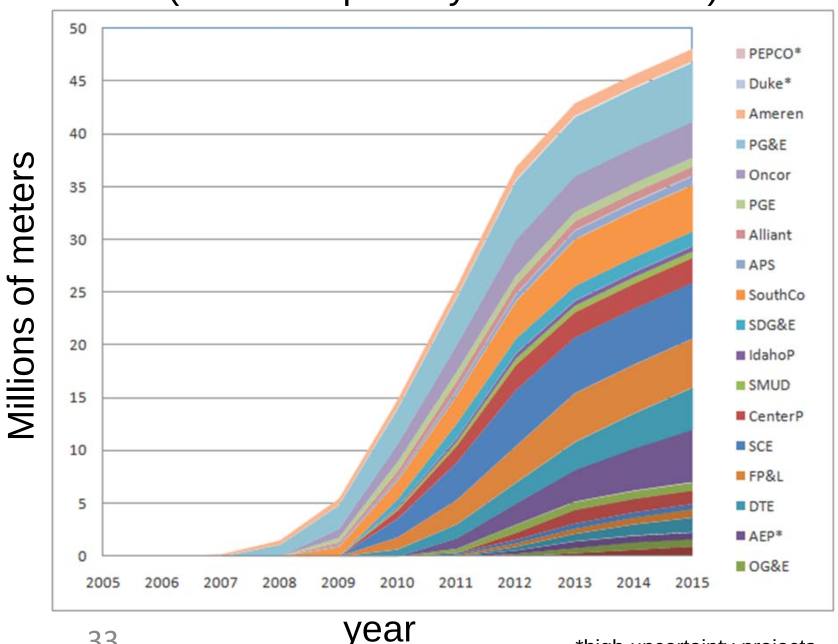
S.W. Hadley and A. Tsvetkova, "Potential Impacts of Plug-in Hybrid Electric Vehicles on Regional Power Generation," 2008.

Figures by Oak Ridge National Laboratory for the U.S. Department of Energy.

OPPORTUNITY: RESPONSIVE DEMAND

- Traditionally, residential customers have not been responsive to system conditions. (Customers do not know when electricity is cheap vs. expensive, clean vs. polluting, etc.)
- The potential costs of enabling residential customers to be more responsive have come down significantly (given advances in IT)

Largest ongoing/proposed AMI projects
(based on publicly available data)

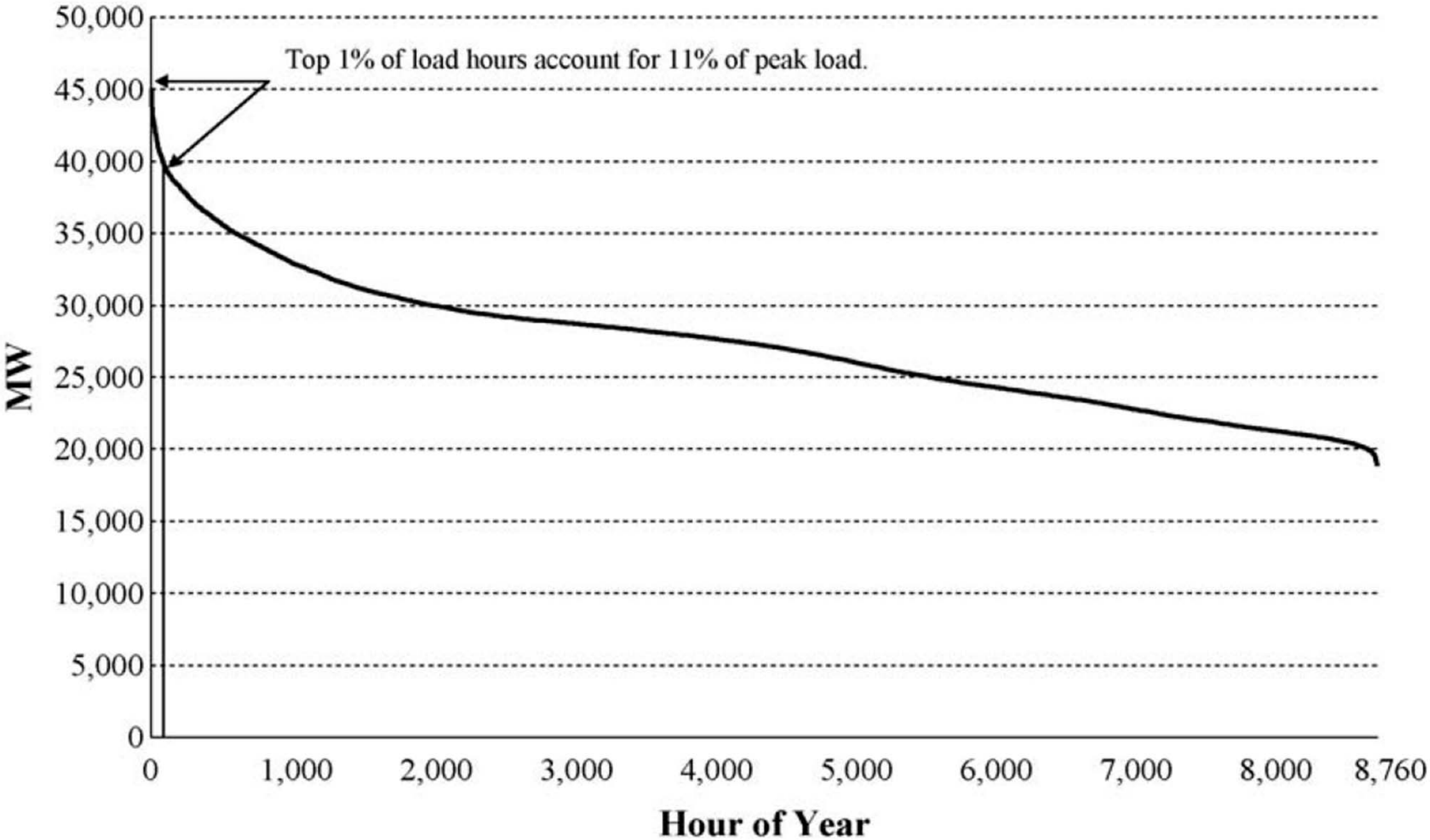


*high uncertainty projects

Images of a computer, smart phone, washer and dryer, power meter, and A/C thermostat have been removed due to copyright restrictions.

OPPORTUNITY: RESPONSIVE DEMAND

Peak demand occurs rarely (and is very expensive for the system)



OPPORTUNITY: RESPONSIVE DEMAND

Customers can reduce peak demand (given the right incentives.)

Graph removed due to copyright restrictions. Please see Fig. 6 in Farugui, Ahmad, Ryan Hledik, and Sanem Sergici. "Rethinking Prices." *Public Utilities Fortnightly* 148 (January 2010): 30-39.

Source: Faruqui, Hledik Sergici (2010)

POTENTIAL BENEFITS OF ADVANCED METERING

Text removed due to copyright restrictions. Please see Table 1 in Abbott, Ralph E., Stephen C. Hadden, and Walter R. Levesque. "Deciding on Smart Meters." *Electric Perspectives* 32 (March/April 2007): 52-65.

Source: Plexus Research, Inc., 2005

CHALLENGE: COMMUNICATIONS, CYBER-SECURITY, AND INFORMATION PRIVACY

Most of the new technologies involve more data transmission from the network (PMUs) & end users (AMI) to control centers

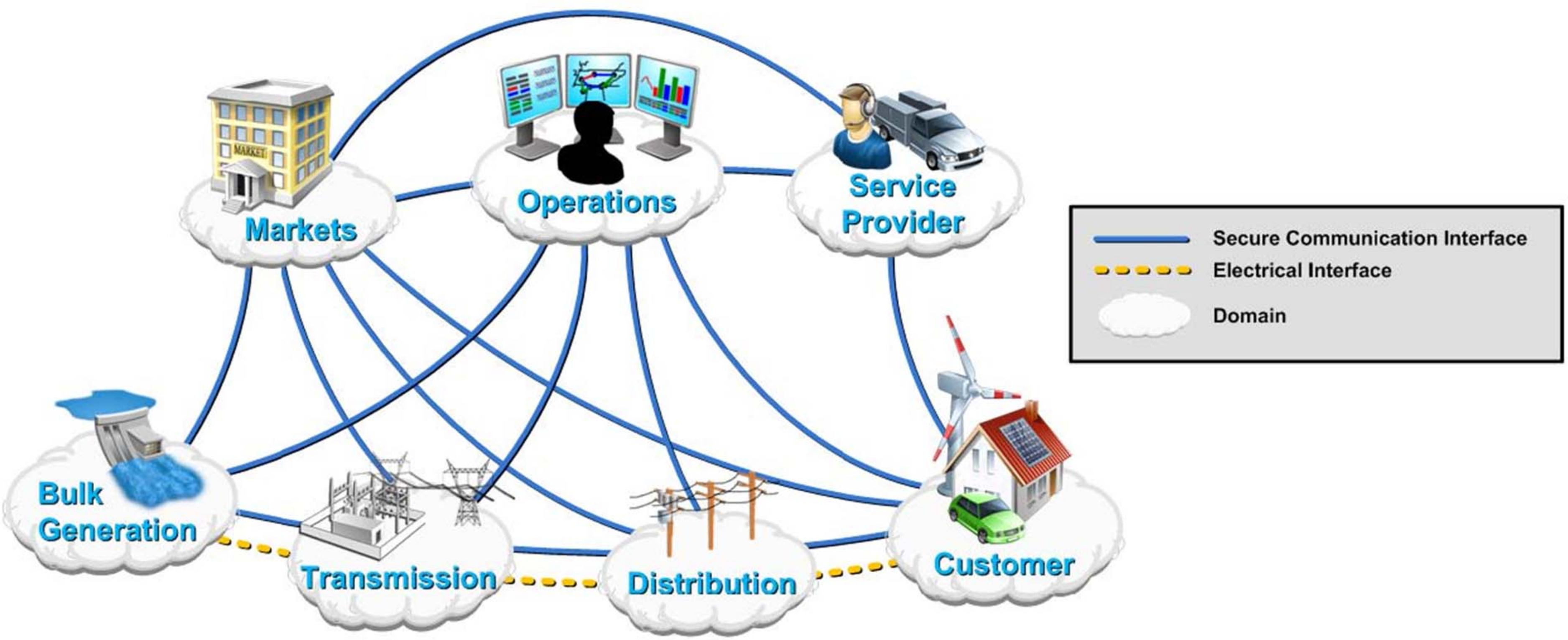


Image by the National Institute of Standards and Technology (NIST). See www.nist.gov/smartgrid.

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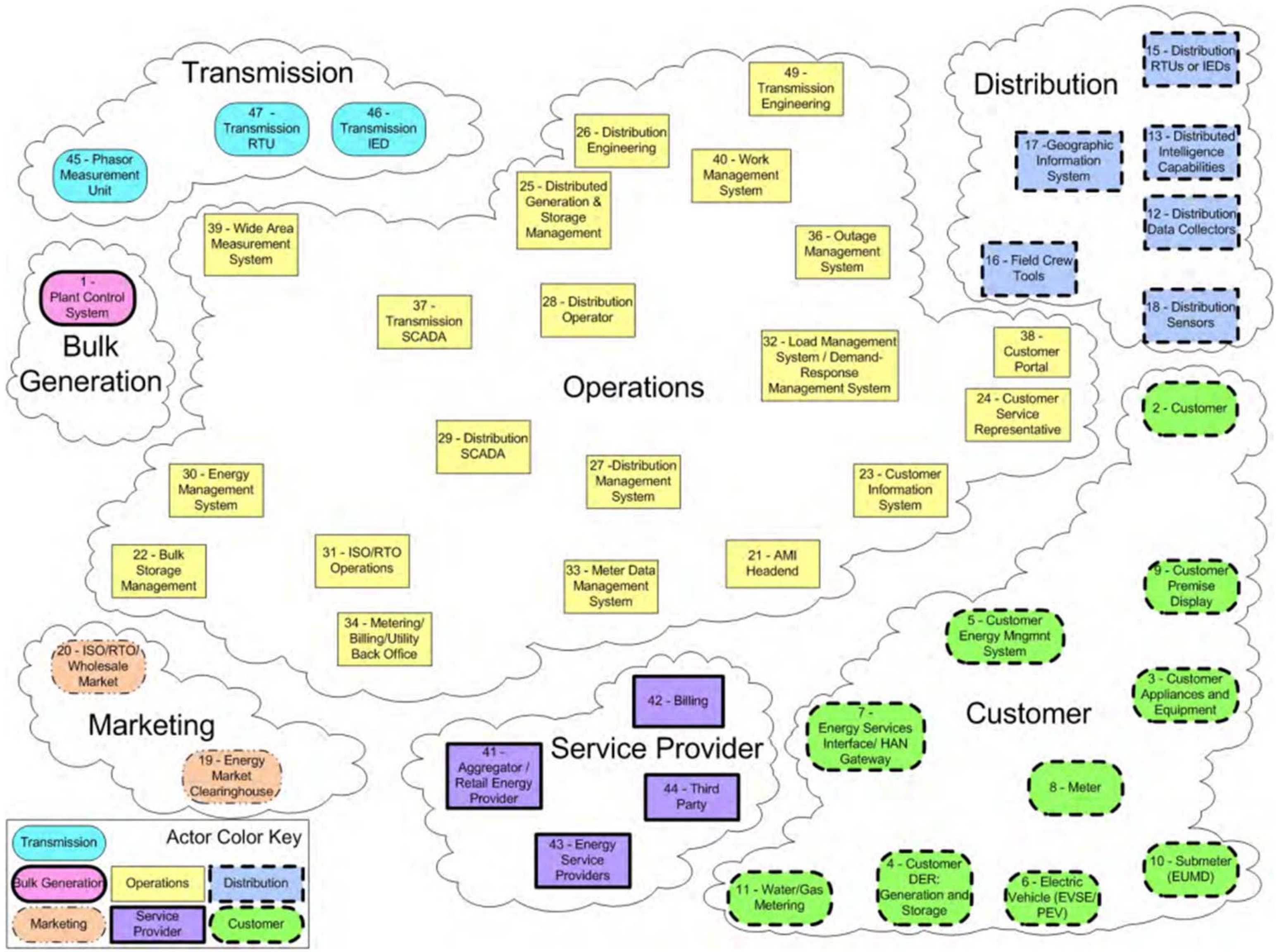

Figure from "Guidelines for Smart Grid Cyber Security: Volume 1, Smart Grid Cyber Security Strategy, Architecture, and High-Level Requirements." NIST Smart Grid Interoperability Panel (August 2010): NISTIR 7628.

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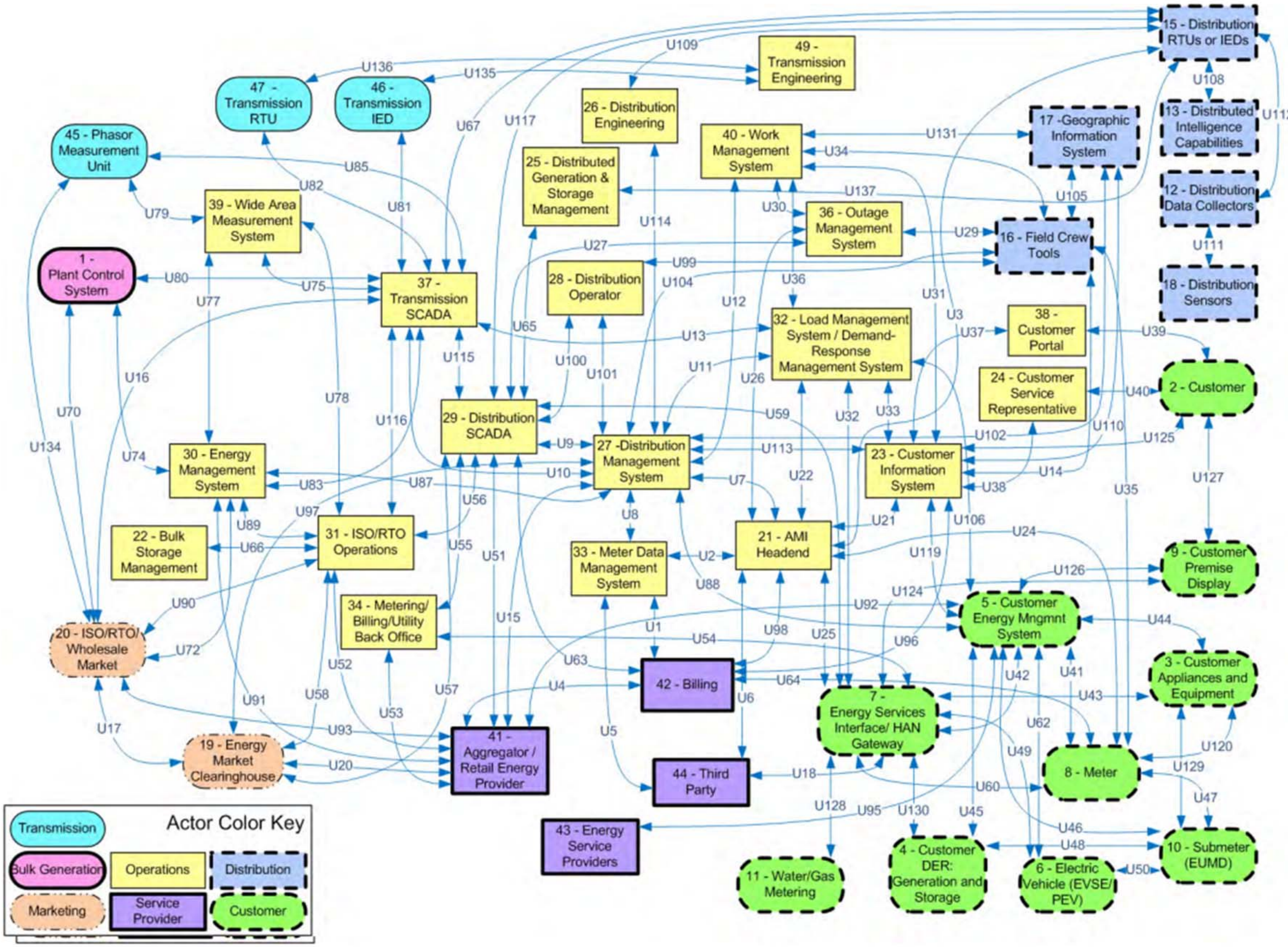

39 Figure from "Guidelines for Smart Grid Cyber Security: Volume 1, Smart Grid Cyber Security Strategy, Architecture, and High-Level Requirements." NIST Smart Grid Interoperability Panel (August 2010): NISTIR 7628.

COMMUNICATIONS, CYBER-SECURITY, AND INFORMATION PRIVACY

- Debates about communications architecture – internet plus encryption v. telecom networks vs. private networks
- Concern that AMI will tell utility personnel details of household activities, especially absences
- New technologies may bring greater vulnerability to errors or sabotage that can induce automated responses that produce service disruptions or (worst case) large blackouts

Conclusions

- Despite relatively slow expected load growth, the next few decades will see major changes in the US electric grid.
- However, there is a lot of hype right now so do not believe everything you hear.
- Despite the hype, the electric grid will face many new challenges and opportunities over the next few decades.
- Some of those changes will occur naturally, as grid participants pursue their self-interest under existing policies
- But there seem to be a few areas where increased R&D support or changes in regulatory policy could facilitate desirable changes
- And we hope to identify those areas in our report next spring!!

Thanks for Your Attention!

Tim Heidel

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Introduction to Sustainable Energy
Fall 2010