Smart Grid: Toward a stronger, smarter, and more secure energy infrastructure

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Director, Technological Leadership Institute
Honeywell/H.W. Sweatt Chair in Technological Leadership
Professor, Electrical & Computer Engineering
University Distinguished Teaching Professor

Context: US Energy Supply Since 1850

End-to-End Energy Inefficiency
End-to-End Energy Inefficiency
Losses as high as 98.4%

Opportunities to improve the situation:
- Use more efficient power plants, energy storage, modern transmission systems
- Use co-generation plants where useful (electricity and heat or desalination)
- Upgrade efficiency of use (change to many times more efficient LED or fluorescent lamps)

Capital Invested as % of electricity revenue

Utility construction: Overharvesting

Less Reliable Grid
Power Outages have steadily increased

Source: NRC, 2009
Long Term Choices: Solar and Nuclear

Emerging Supply and Demand Patterns

A Multi-layer Grid System in need of Strengthening and Protection

Goals and Recommendations

- Build a stronger and smarter electrical energy infrastructure
  - Transform the Network into a Smart Grid
  - Develop an Expanded Transmission System
  - Develop Massive Electricity Storage Systems
- Break our addiction to oil by transforming transportation
  - Electrify Transportation: Plug-In Hybrid Electric Vehicles
  - Develop and Use Alternative Transportation Fuels
- Green the electric power supply
  - Expand the Use of Renewable Electric Generation
  - Expand Nuclear Power Generation
  - Capture Carbon Emissions from Fossil Power Plants
- Increase energy efficiency

Source: Massoud Amin’s Congressional briefings, on March 26 and Oct. 15, 2009
Enabling the Future
Infrastructure integration of microgrids, diverse generation and storage resources into a secure system of a smart self-healing grid


Smart Grid Definitions

FERC: “Grid advancements will apply digital technologies to the grid and enable real-time coordination of information from both generating plants and demand-side resources.”

DOD: “A smarter grid applies technologies, tools, and techniques available now to bring knowledge to power – knowledge capable of making the grid work for more efficiently...”

GE: “The Smart Grid is in essence the marriage of information technology and process automation technology with our existing electrical networks.”

IEEE: “The term ‘Smart Grid’ represents a vision for a digital upgrade of distribution and transmission grids both to optimize current operations and to open up new markets for alternative energy production.”

Wikipedia: “A Smart Grid delivers electricity from suppliers to consumers using digital technology to save energy, reduce cost, and increase reliability.”

Functionality
Common themes: Efficiency, Demand response, Consumer savings, Reduced emissions

Technology
Two-way communication, Advanced sensors, Distributed computing

Reliability
Interconnectivity, Renewable integration, Distributed generation

Efficiency
Demand response, Consumer savings, Reduced emissions

Smart Grid Components & Devices

Highly Instrumented with Advanced Sensors and Computing

• Engaging Consumers
• Enhancing Efficiency
• Ensuring Reliability
• Enabling Renewables & Electric Transportation

Secure Smart Grids are architected with standards (source: Gridnet)

Smart Meters

Smart Grid

Control’s EMS-100

Google Power Meter

Smart Charger Controller

Source: IBM Smart Grid

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End-to-End Smart Grid Players/Opportunities

Opportunity: $130B in US alone?

Storage and DG can play these roles...

5-15% from consumer behavioral change or...efficiency could shrink by 50%

This is what many utility commissions focus on

May grow...

West Virginia Business Case

Consumers resistant to costs

...who decides, who pays?
Overview: Challenges/Opportunities for sensing, estimation, control & management of Smart Grids

1) End-to-end Communication Overlay & Advanced Metering Infrastructure (AMI):
- Inside the home... manage electric usage and take advantage of time-of-use pricing. Many devices can be home-network connected, including smart thermostats, appliances that could move with the family to another utility's service area.
- Outward facing — collection & distribution of data by the utility to and from the meter
  - IEEE 802.15.4g describes the utility-to-meter communications link of the ZigBee Smart Energy (ZSE) Profile, leading standard for smart metering and the home area network.
  - ZSE provides the capability needed for the utility to interact in a defined way, through the meter, with the consumer and the devices in the home for status monitoring and load control — especially needed in the emerging era of electric vehicles and plug-in hybrids.

2) Interconnection standards: Consensus standards needed in cybersecurity, data networking, demand response, distribution, electric-vehicle support, information modeling, metering infrastructure, renewables integration, sensor networking, storage and wide-area situational awareness...

3) Efficiency: Improving the grid's efficiency by 5 percent would be equivalent to permanently eliminating fuel and greenhouse emissions from 53 million automobiles.

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Context: Better Situational Awareness and Automation

- **Increasing Dependence on ICT, Computation and Communications.**

- **Increasing Complexity:** System integration, increased complexity: call for new approaches to simplify the operation of complex infrastructure and make them more robust to attacks and interruptions.

- **Centralization and Decentralization of Control:** The vulnerabilities of centralized control seem to demand smaller, local system configurations. Resilience rely upon the ability to bridge top-down and bottom-up decision making in real time.

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Overview: Challenges/Opportunities for sensing, estimation, control & management of Smart Grids

4) Consumers remain skeptical: Smart meter deployments in California and Texas have been followed by complaints over increased utility bills, potential health and safety impacts, and privacy concerns. Engage and educate consumers about the opportunities offered by the global smart grid, specifically by honoring the following principles:
  - **Venue is important.** Customer education initiatives should use channels that consumers find most comfortable, such as email, the Internet or town hall-style meetings.
  - **Feedback comes first.** If consumers are given the chance to register their concerns early in the process, utilities and regulators will have time to construct a targeted response during hands-on demonstrations of smart meters and other technologies.
  - **Participation should be incentivized.** Successful appliance rebate programs have a message: Consumers will be more likely to accept smart meters and smart grid technologies when there is a direct financial benefit.
  - **Consumer acceptance is essential:** Proactive outreach can help create a cadre of consumers who are actively engaged proponents, rather than opponents.
  - Despite more than two decades of attempts to develop technologies for a smarter power grid, only now has the concept become a priority.
  - As the world's power grid infrastructures continue to age and deteriorate, the reality is that this is the "make or break" time.

5) R&D Thrusts: Sensing, Estimation and Control... Data and Measurements... Communications and Signal Processing... Security

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What are we working on at the University of Minnesota?

- Integrating PHEVs into the grid
- Grid agents as distributed computer
- Fast power grid simulation and risk assessment
- Secure Smart Distribution Systems Control
- Security of cyber-physical infrastructure

University of Minnesota Center for Smart Grid Technologies
Dept. of Electrical & Computer Engineering
Faculty: Professors Massoud Amin and Bruce Wollenberg
PhD Candidates/Research Assistants: Anthony Giacomoni, Laurie Miller, and Sara Mullen
PI: M. Amin (support from EPRI, NSF, ORNL, SNL and University of Minnesota funding)
Objectives

- Our strategic goal is to better understand the true dynamics of complex interdependent energy/communications/economic networks in order to enable stronger, greener, more secure and smarter power grids.

- The objective of this project is to model, design and develop a reconfigurable smart distribution management system supported by secure sensing/wireless communication network and fault-resilient real-time controls.

Areas and Foci

- Interconnection of Distributed Energy Resources (DER)
- Connecting Plug-in Hybrid Vehicles (PHEV) to the grid
- Smart Grid as a Distributed Computer: State estimation
- Transmission system actions in an emergency
- Substation component modeling
- Smart metering
Transmission Limits

- High dimensional problem
  - Large interconnection models (1/5 of the North American system) require ~40,000 buses & ~50,000 lines, and ~3,000 generators with ~120 control areas
  - Each line has a capacity limit
  - N-1 Contingency Criteria: The system must withstand the loss of any one line or generator (~53,000 contingencies)
    - 53,000 x 50,000 = 2,650,000,000 possible constraints
- Reliable operation requires an operating point that satisfy these 2.65 billion constraints!

Intelligent Agents and Functionalities

<table>
<thead>
<tr>
<th>Layer</th>
<th>Agent Locations</th>
<th>Control Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactive</td>
<td>-Smart Meters</td>
<td>- Demand response</td>
</tr>
<tr>
<td></td>
<td>-Substations</td>
<td>- Load management</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Connect/disconnect load</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Send alarm signals</td>
</tr>
<tr>
<td>Coordination</td>
<td>-Switches</td>
<td>- Connect islands</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Connect substations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Disconnect compromised sections</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Send alarm signals</td>
</tr>
<tr>
<td>Deliberative</td>
<td>-Microgrids/Feeder Systems</td>
<td>- Determine system objectives</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Optimal radial reconfiguration for each island (e.g. min. losses)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Determine electricity price</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Calculate power flows</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Send alarm signals</td>
</tr>
</tbody>
</table>

Smart Grid as a Distributed Computer
the State Estimator
State Estimation:

\[ Z = h(X) + V \]

where:
- \( Z \) = The measurement vector
- \( X \) = The state vector
- \( V \) = The measurement error vector
- \( h(X) \) = Non-linear observation function, the set of electrical equations relating MW and MVAR values to bus voltages and angles
- \( R \) = The measurement error covariance matrix

Extended to Advanced Topology Estimator:
- determine unknown substation switch settings from voltages, power flows, and current measurements

Building a super computer from many small processors

- The IBM Blue Gene computer

Fast Power Systems Risk Assessment

Doctoral Dissertation: Laurie Miller (June 2005-present)
- ORNL contract, the U of MN start-up fund (2005-2008), and NSF grant (2008-2009), PI: Massoud Amin

Connection Machine 2: $5 million in 1987, only a few dozen made
- NVIDIA Tesla C870: $1300 in 2009, over 5 million sold

Fast Power Grid Simulation

- Use Nvidia GeForce GPU card to gain 15 times faster power flow calculation on PC (Laurie Miller)
Distributed State Estimation & System Identification → Look-ahead Simulation

- Process of using a set of over determined, noisy measurements to estimate the system state
  - $V$ and $\theta$ are the state variables in our problem
  - We use measurements that are functions of $V$ and $\theta$ to form our estimate

- One of the first milestones in moving towards a Smart Grid is demonstrating that distributed state estimation is workable

Central computer control system

Using the grid agents to do power system state estimation calculation

Relevant Equations

- PQ node (typical load node):
  \[ P_i = V_i \sum_{k=1}^{n} V_k (G_{ik} \cos \theta_{ik} + B_{ik} \sin \theta_{ik}) \]
  \[ Q_i = V_i \sum_{k=1}^{n} V_k (G_{ik} \sin \theta_{ik} + B_{ik} \cos \theta_{ik}) \]

- PV node (typical generator node) has same $P$ equation and trivial $V$ equation

- Line Flow Equations
  \[ P_{ij} = -G_{ij} V_i^2 + V_i V_j (G_{ij} \cos \theta_i + B_{ij} \sin \theta_i) \]
  \[ Q_{ij} = -B_{ij} V_i^2 + V_i V_j (G_{ij} \sin \theta_i - B_{ij} \cos \theta_i) - V_i^2 B_{ij_{copy}} \]

- In our case, each bus has six measurements so we write 6 equations
Algorithm

1. Choose Slack Bus
2. Make initial guess for voltages and phases
3. Determine measurement error
   \[ \text{error} = (z_{\text{meas}} - f(V, \theta)) \]
4. Calculate Jacobian as a function of \( V, \theta \)
5. Compute correction
6. Determine if a component of the correction vector exceeds \( \varepsilon \)
7. If so, apply correction, repeat steps 3-6
8. Share state variables with adjacent nodes
9. Repeat

\[
\Delta x = (J^T R^{-1} J)^{-1} J^T R^{-1} \left[ z_i - f_i(V, \theta) \right] \text{ for all } i \]

Exchange of data

Gives rapid reliable algorithm convergence

Smart Grid Protection Schemes & Communication Requirements

<table>
<thead>
<tr>
<th>Type of relay</th>
<th>Data Volume (kb/s)</th>
<th>Latency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Present</td>
<td>Future</td>
</tr>
<tr>
<td>Over current protection</td>
<td>160</td>
<td>2500</td>
</tr>
<tr>
<td>Differential protection</td>
<td>70</td>
<td>1100</td>
</tr>
<tr>
<td>Distance protection</td>
<td>140</td>
<td>2200</td>
</tr>
<tr>
<td>Load shedding</td>
<td>370</td>
<td>4400</td>
</tr>
<tr>
<td>Adaptive multi terminal</td>
<td>200</td>
<td>3300</td>
</tr>
<tr>
<td>Adaptive out of step</td>
<td>1100</td>
<td>13000</td>
</tr>
</tbody>
</table>

Smart Grid: Tsunami of Data Developing

Tremendous amount of data coming from the field in the near future - paradigm shift for how utilities operate and maintain the grid
Data and Measurements

Wide-Area Measurement System (WAMS)
Integrated measurements facilitate system management

“Better information supports better - and faster - decisions.”

Source: DOE/EPRI WAMS project—BPA & PNNL

Real-Time System Data
Collected from various monitors throughout the grid

Example: BPA’s Phasor Data Concentrator

Three-phase WAMS application in China

Source: DOE/EPRI WAMS project—BPA & PNNL
Last Episode of the TV series “Survivor”

Source: Jim Ingleson (NYISO) and Joe Chow (RPI)

Disturbance records for WSCC breakup of August 10, 1996

Source: DOE/EPRI WAMS project

Disturbance records for WSCC breakup of August 10, 1996

Source: DOE/EPRI WAMS project

Initial Conditions on August 14, 2003

Source: DOE/EPRI WAMS project

Star 345 kV Bus Voltages (Aug 8-14, 2003)
Smart Grid Vulnerabilities

• Cyber:
  – Existing control systems were designed for use with proprietary, stand-alone communications networks
  – Numerous types of equipment and protocols are used
  – More than 90% of successful cyber attacks take advantage of known vulnerabilities and misconfigured operating systems, servers, and network devices
  – Possible effects of attacks:
    1) Loss of load
    2) Loss of information
    3) Economic loss
    4) Equipment damage
Vision for the Smart Grid U™

- **Goal:** transform the University of Minnesota’s Twin Cities’ campus into a SmartGridU.
  - Develop system models, algorithms and tools for successfully integrating the components (generation, storage and loads) within a microgrid on the University of Minnesota campus.
  - Conduct “wind-tunnel” data-driven simulation testing of smart grid designs, alternative architectures, and technology assessments, utilizing the University as a living laboratory.
  - Roadmap to achieve a “net zero smart grid” at the large-scale community level — i.e., a self contained, intelligent electricity infrastructure able to match renewable energy supply to the electricity demand.

### Minnesota

#### General
- Population: 5.2 million
- Per Capita Personal Income: $37,373
- Gross Domestic Product: $234.6 billion

#### Reserves
- Crude Oil: —
- Dry Natural Gas: —
- Natural Gas Liquids: —

#### Production
- Crude Oil: —
- Coal: —
- Natural Gas: —

#### Consumption by Sector
- Residential: 410,193 billion Btu
- Commercial: 344,757 billion Btu
- Industrial: 529,178 billion Btu
- Transportation: 511,640 billion Btu

**Source:** EIA 2003 State Energy Data

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**Estimated Energy Consumption**

- **Coal:** 28%
- **Natural Gas:** 22%
- **Petroleum:** 41%
- **Hydro:** 1%
- **Nuclear:** 3%
- **Other Renewables:** 0%

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Smart Grid U™

- Control algorithms and interfaces for turning individual energy components (storage, generation and loads) into an integrated, optimized energy system.
  - E.g., demand surface plots of raw data for demands, emissions, & efficiency

**Next steps:** demonstrate ability to integrate renewables/storage, cogeneration and achieve NZE status.
UM Morris Net Energy Balance

<table>
<thead>
<tr>
<th>Year</th>
<th>Net Campus Energy Balance, MWh</th>
<th>Net Campus CO2 Footprint, Metric Tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>20,000</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>20,000</td>
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<td>2006</td>
<td>20,000</td>
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<td>2007</td>
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<td>2008</td>
<td>20,000</td>
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<td>2009</td>
<td>20,000</td>
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<tr>
<td>2010</td>
<td>20,000</td>
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<tr>
<td>2011</td>
<td>20,000</td>
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<tr>
<td>2012</td>
<td>20,000</td>
<td></td>
</tr>
</tbody>
</table>

... power electronics sub-system?

1 MW wind “converter”: huge=expensive

1900’s transformers

... pathways forward?

... SECURITY

... Self healing & adaptive

... Local “power quality”: locally self adjusting

... Evolvable architecture, open, predictive

... Power Electronics (control, quality, locality...)

... Modularity/flexibility & Management

Research Challenges

Sensing/Measurement → Analysis/Visualization → Automation/Self-healing Systems

• Complex Dynamical Systems: Systems Science and Applied Mathematics
  - Modeling: Idealized models, consisting of static graph-theoretic models, and interactive dynamic models, such as interconnected differential-algebraic systems; Hybrid Models.
  - Robust Control: Design of self-healing systems requires the extension of the theory of robust control in several ways beyond its present focus on the relatively narrow problem of feedback control.
  - Complex Systems: Theoretical underpinnings of complex interactive systems.
  - Dynamic Interaction in Interdependent Layered Networks: Characterization of uncertainty in large distributed networks: Multi-resolutional techniques where various levels of aggregation can co-exist.
  - Disturbance Propagation in Networks: Prediction and detection of the onset of failures both in local and global network levels.
  - Forecasting, Handling Uncertainty and Risk: Characterizing Uncertainties and Managing Risk; Hierarchical and multi-resolutional modelling and identification; Stochastic analysis of network performance; Handling Rare Events.

• Mathematical/Theoretical Foundation is Fragmented: Computational complexity, information theory, dynamical systems and control science… need for a new science of interdependent complex networks and infrastructure security.
Strategic R&D Challenges

- **Planning**: Develop a theoretical framework, modeling and simulation tools for infrastructure couplings and fundamental characteristics, to provide:
  - An understanding of true dynamics and impact on infrastructure reliability, robustness and resilience
  - Real-time state estimation and visualization of infrastructures—flexible and rapidly adaptable modeling and estimation
  - An understanding of emergent behaviors, and analysis of multi-scale and complexity issues and trends in the future growth and operations.

- **Security**: Integrated systems assessment, monitoring, and early warning:
  - Vulnerability assessment, risk analysis and management
  - Underlying causes, distributions, and dynamics of and necessary/sufficient conditions for cascading breakdowns (metrics)
  - Impact: “If you measure it you manage it, if you price it you manage it even better”
  - Infrastructure databases, data mining and early signature detection

New Challenges for a Smart Grid

- **Need to integrate**:
  - Large-scale stochastic (uncertain) renewable generation
  - Electric energy storage
  - Distributed generation
  - Plug-in hybrid electric vehicles
  - Demand response (smart meters)

- **Need to deploy and integrate**:
  - New Synchronized measurement technologies
  - New sensors
  - New System Integrity Protection Schemes (SIPS)

Sensors

- Phasor measurement units (PMUs) providing time-stamped magnitude and phase of fundamental voltage/current, frequency, harmonics, ...
- Other sensors (temperature, sag)? e.g. to monitor key components and permit dynamic rating (transient overloads)
- New sensors?
- “Sensors” for market data
Issues and Problems in Wide-Area Sensing

• What mix of sensors?
• Where to deploy them?
• Economic and performance justifications
• Communication
• Data management

Communication & Data Management

• Flexible and robust communication architectures (wireless to optical backbone? wireline schemes?), protocols
• Dealing with latency, variable time delay
• Data management, calibration & validation (bad or missing or malicious data), sharing and distribution, archiving, hierarchical aggregation
• Dynamic, distributed databases
• Appropiate computer network architectures

Smarter about education, safety, energy, water, food, transp., e-gov, ... Innovative Cities:

• Smarter transportation
  Stockholm, Dublin, Singapore and Brisbane are working with IBM to develop smart systems ranging from predictive tools to smart cards to congestion charging in order to reduce traffic and pollution.

• Smarter policing and emergency response
  New York, Syracuse, Santa Barbara and St. Louis are using data analytics, wireless and video surveillance capabilities to strengthen crime fighting and the coordination of emergency response units.

• Smarter power and water management
  Local government agencies, farmers and ranchers in the Paraguay-Paraná River basin to understand the factors that can help to safeguard the quality and availability of the water system. Malta is building a smart grid that links the power and water systems, and will detect leakages, allow for variable pricing, and provide more control to consumers. Ultimately, it will enable this island country to replace fossil fuels with sustainable energy sources.

• Smarter governance
  Albuquerque is using a business intelligence solution to automate data sharing among its 7,000 employees in more than 20 departments, so every employee gets a single version of the truth. It has realized cost savings of almost 2,000%.

Source: IBM and Economist

“Computers are incredibly fast, accurate, and stupid; humans are incredibly slow, inaccurate and brilliant; together they are powerful beyond imagination.”

Albert Einstein
An Example: Smarter I-35W bridge

Just after 6:00 p.m. on Aug. 1, Prof. Massoud Amin was at work in his office on the University of Minnesota’s West Bank, where he heard and watched the unthinkable happen—the collapse of the I-35W bridge about 100 yards away.

“As an individual, it was shocking and very painful to witness it from our offices here in Minneapolis,” says Amin, director of the Center for the Development of Technological Leadership (CDTL) and the H.W. Sweatt Chair in Technological Leadership. Amin also viewed the tragedy from a broader perspective as a result of his ongoing work to advance the security and health of the nation’s infrastructure.

In the days and weeks that followed, he responded to media inquiries from the BBC, Reuters, and the CBC, keeping his comments focused on the critical nature of the infrastructure. He referred reporters with questions about bridge design, conditions, and inspections to several professional colleagues, including Professors Roberto Ballarini, Ted Galambos, Vaughan Voiles, and John Guille in the Department of Civil Engineering and the National Academy of Engineering Board on Infrastructure and Constructed Environment.

For Amin, Voiles, and many others, the bridge collapse puts into focus the importance of two key issues—the tremendous value of infrastructure and infrastructure systems that help make possible indispensable activities such as transportation, waste disposal, water, telecommunications, and electricity and power, among many others, and the search for positive and innovative ways to strengthen the infrastructure.

Enabling a Stronger and Smarter Grid:

• Broad range of R&D including end-use and system efficiency, electrification of transportation, stronger and smarter grid with massive storage

• Sensing, Communications, Controls, Security, Energy Efficiency and Demand Response if architected correctly could assist the development of a smart grid

• Smart Grid Challenge/Opportunity areas include:
  – Distributed Control
  – Grid Architectures
  – Cyber Security

Source: Massoud Amin, Congressional briefings, March 26 and October 15, 2009

To improve the future and avoid a repetition of the past:

Sensors built in to the I-35W bridge at less than 0.5% total cost by TLI alumni

THANK YOU
Appendix

Context and the Global Macro-Environment: Cities with 10 million people

By 2020, more than 30 mega cities* in the now less-developed world. By 2050, nearly 60 such cities.

The Energy Gap

- Half the world's population subsists on agrarian or lower levels of energy access, and
- Their population density generally exceeds the carrying capacity of their environment

Note: *Mega city 10 million population or greater

Global Energy Consumption 2030

- World's electricity supply will need to triple by 2050 to keep up with demand, necessitating nearly 10,000 GW of new generating capacity.

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Economists estimate, that all systems carry inefficiencies of up to $15 Tn, of which $4 Tn could be eliminated

Analysis of inefficiencies in the planet’s system-of-systems

Global economic value of

System-of-systems $54 Trillion 100% of WW 2008 GDP
Inefficiencies $15 Trillion 28% of WW 2008 GDP
Improvement potential $4 Trillion 7% of WW 2008 GDP

How to read the chart:
For example, the Healthcare system’s value is $4,270B. It carries an estimated inefficiency of 42%. From that level of 42% inefficiency, economists estimate that 34% can be eliminated ($4,270 x 0.34).

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Foresight

Integration of Renewables, Infrastructure, and the Electrification of transportation

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Full Fuel Cycle Efficiency Comparison

- **Plug-in Hybrid**: 0.29–0.47, 2116 Btu/mile, 1631 – 2185 miles Per Barrel
- **Conventional**: 0.84, 4115 Btu/mile

Why the Interest in Hybrids:

**Vehicle Efficiency**

- **Gas tank**: Engine, Transmission, Driveline
- **Gasoline**: 15-20% 90-95% 95%
- **Electric**: 85-90% 85-95%

Why the Interest in Hybrids:

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Two huge industries are transforming and a new one is emerging...

Battery Industry

Scaling up an End-to-End System

- **Worldwide shipments of Solar Cells in 2008 (Megawatts)**
- **Lithium-ion battery manufacturing volumes in 2009 (millions of cells/year)**

Strategy -- Commit to a few innovation/growth vectors -- Speed

eSTEM: Put “entrepreneurship & innovation” in STEM for inclined students/postdocs
Aggregate PHEV as Energy Storage

- Technical potential with 5% PHEV penetration in Minnesota
- About 235,000 vehicles based on vehicles registered in 2007 [1]
- Assuming 10 kWh usable state-of-charge

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<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>AC Level 1</td>
<td>1.4 kW</td>
<td>0.33 GW</td>
<td>1.88 GWh</td>
<td>5 h 43 min</td>
</tr>
<tr>
<td>AC Level 2</td>
<td>7.7 kW</td>
<td>1.81 GW</td>
<td></td>
<td>1 h 2 min</td>
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<tr>
<td>Level 3</td>
<td>160 kW</td>
<td>37.6 GW</td>
<td></td>
<td>3 min</td>
</tr>
</tbody>
</table>

*MN retail electricity sales in 2007: 187 GWh/day
MN installed generating capacity in 2007: 14 GW

[4] Total-energy divided by the total power.

Renewable Energy Cost Trends

Levelized cost of energy in constant 2005$¹

![Graphs showing cost trends for various renewable energy sources.](source: NREL Energy Analysis Office (www.nrel.gov/analysis/docs/cost_curves_2005.ppt))

¹These graphs are reflections of historical cost trends NOT precise annual historical data.


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Distributed PV: Japan

Japanese policies have emphasized distributed rather than centralized solar power production, as illustrated by residential developments in Sapporo, a designated “Solar City.”

Sapporo established a goal of reducing per capita carbon dioxide emissions in 2012 by 10% compared to 1990 levels. The city has active programs to increase public awareness, stimulate citizen initiatives, provide incentives, and host city-sponsored activities. Local schools are hosting five 10-kW solar power demonstration projects, and a suburban residential complex with 500 homes will be equipped with 1,500 kW of rooftop PV (3 kW per house) when completed in 2008. In addition to encouraging solar power, Sapporo has installed several large cogeneration projects that utilize waste heat from steam turbines, thereby increasing the overall efficiency of energy production.

Many other “Solar Cities” have instituted similar goals and programs, including Copenhagen, Denmark; Barcelona, Spain; Guangzhou, China; Adelaide, Australia; Freiburg, Germany; and Portland, Oregon.

Utility-Scale PV: Germany

Due to the structure of its incentive policies, Germany is a world leader in centralized PV deployment, with several megawatt-scale plants in operation or development.

The 10-MW Bavaria Solarpark, dedicated in June 2005, includes ground-mounted PV systems at three sites: the 6.3-MW Solarpark Mühlhausen, the 1.9-MW Solarpark Günching, and the 1.9-MW Solarpark Münchhof. All together, the three projects comprise 57,650 solar panels over 62 acres of land. Cumulatively, they make up the largest PV plant in the world.

The Bürstadt Plant in Bürstadt is a 5-MW system incorporating building-integrated and roof-mounted systems. It was completed in February 2005. Solarpark Leipziger in Espenhain is a 5-MW system built in August 2004. The facility has both stand-alone and grid-connected PV elements. The Solarpark Geiselreuth/Mersburg employs 25,000 mono- and polycrystalline modules from BP Solar to generate 4 MW of electricity. At the time of its completion in September 2004, it was the fifth largest PV plant in the world.

Building-Integrated PV: New York City

Reconstruction of New York’s Stuyvesant Avenue subway station provided an opportunity to integrate amorphous silicon thin-film PV into a semi-opaque roof canopy that, upon its completion in 2005, was one of the largest building-integrated PV (BIPV) structures in the world.

The station’s canopy roof was constructed with ASI solar modules from Schott Solar to provide the station with electricity as well as shade. Some 2,800 thin-film modules covering 76,000 square feet (7,060 m²) generate approximately 210 kW while permitting 25% to 26% of daylight to pass through. During summer, the system provides approximately two-thirds of the station’s power needs (not related to powering the trains). Its annual output is about 250,000 kWh.

Planning and design took more than four years, and the station’s design process was done in conjunction with an educational component that included a large-scale industry workshop involving several major companies in the photovoltaics industry. The station was designed so its architecture would evoke the historic architecture of nearby Coney Island and provide passengers with a grand sense of arrival, elegance, and civic pride.
Technology Scanning Process - Evaluation

Strategic Selection in Technology Space

Power Zone

Information Science
- Leading
- Strong
- Capable

Physical Science
- High
- Medium
- Low

Life Science

Examples of industry’s technology strengths today

Examples include:
1. Power Electronics
2. Adv. Electric motors
3. Wind generation
4. Nuclear Power
5. Solar power
6. Systems integration
7. Real-time systems control
8. Personal storage devices
9. Power conditioning
10. Efficient illumination
11. Emission control
12. Turbine generation
14. Security technology

Industry’s Power Zone™ in Technology Space

Physical Science

Bio- and Life Sciences

Industry Application Status
- Leading
- Strong
- Capable
Expanding the Power Zone

A. Distributed control
B. Electronic power commerce
C. Distributed generation/storage
D. Integrated common infrastructure
E. Integrated/Embedded PV

F Wireless backup
G Granular Semi-autonomous Architecture
H Fractal Grid Lego Model
I Lego Model
J Plug and play appliances

Expanding and Transforming the Power Zone

Technology Map for Bio-fuel Systems, Distributed Gen and Storage systems integrated with Advanced Information Systems for Network Management

The Energy Crises Taught Us Interdependency

National Security

Environmental Security

Economic Security

System of Systems:
No “magic bullets” but there are many innovative bullets, including:
1) Green the power supply,
2) Energy systems & end-use efficiency,
3) Electrify transportation,
4) Build a stronger & smarter grid with massive storage integrating greener electrical energy.

Awareness, Costs and Benefits

Awareness:
~68% of consumers in the U.S. don’t know what “Smart Grid” is...
- what is the “Smart Grid”?
- what are the range of new consumer-centered services enabled by smart grids?
- what are the smart grid’s potential to drive economic growth?

Costs:
EPRI: $165 billion over 20 years ($8 to $10 billion per year).
Energy consulting firm Brattle Group: $1.5 trillion spread over 20 years (~$75 billion per year) for an overhaul of the entire electricity infrastructure.
My work, 1998-present: $150 to $170 billion ($10 to $13 billion per year for 10 years or longer).
... Awareness, Costs and Benefits

Smart grid benefits:

- Increases efficiency by 5% ($20.4 billion in savings annually)
- Reduces costs of outages by about $49 billion per year
- Reduces emissions by 12-18%
- Increases overall energy security, and can spur economic growth

- Our $14 trillion economy depends on reliable, disturbance-free access to electricity.

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