Smart Grids with Distributed Energy Resources (DERs) to enhance Cybersecurity, Stability, and Resilience

by

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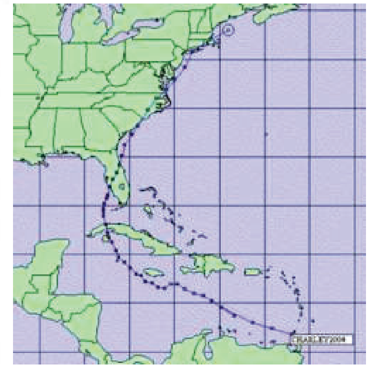
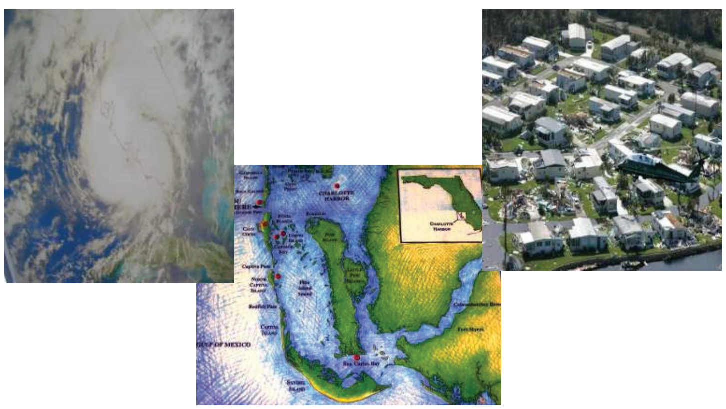
An Example: Hurrican ley

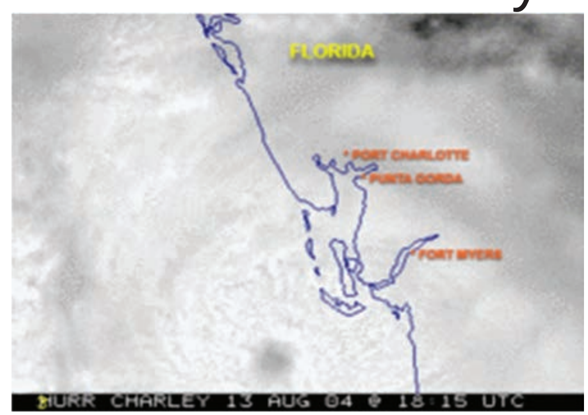
- Duration Aug. 9 - 14, 2004
- Highest winds 150 mph (240 km/h) sustained
- Areas affected Jamaica, Cayman Islands, Cuba, Florida, South Carolina
- Damages $15-17 billion
- Fatalities 15 direct, 20 indirect



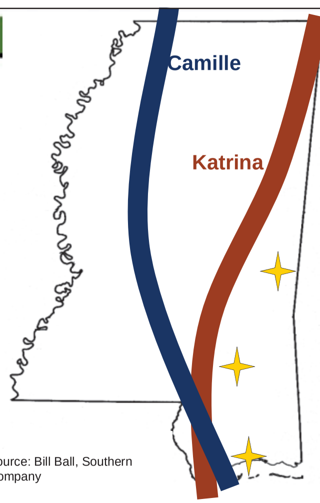
Hurricane Charley– August 13, 2004



Hurricane Charley



Peak Wind Speed Comparison (MPH)



Source: Bill Ball, Southern Company

	Katrina 08.29.05	Camille 08.17.69
Meridian	90	55
Hattiesburg	110	
Gulfport	140	190

	CAMILLE	IVAN	KATRINA
Landfall Date	08.17.69	09.16.04	08.29.05
Landfall	Waveland/BSL, MS	Eastern Mobile Bay	MS/LA State Line
Category at Landfall	Category 5	Category 3	Category 4
Wind Speed/Gusts	190 / 220 mph	115 / 135 mph	140 / 180 mph
Tidal Surge (Maximum)	20-28'	10-15'	35-40'
Hurricane Winds (Size of Storm)	60 miles	35-40 miles	125 miles
Forward Motion	NNW at 15 MPH Sustaining at Landfall	NNE at 12 MPH Weakening at Landfall	NNE at 15 MPH Strengthening & Expanding at Landfall
System Outages	104,000*	1.7 million	971,000
System Companies Most Affected	MPC - 77% Loss	Gulf - 90% Loss APC - 65% Loss	MPC - 100% Loss APC - 49% Loss
Others Impacted	APC	MPC, GPC	APC, Gulf, GPC
Service Restoration	15 days	2 weeks	2 weeks

Sandstorm

Wildfire

Drought

Hoover Dam turbines set for upgrade to cope with drought

April 19, 2010

The US Bureau of Reclamation has awarded a $3.4 million contract to Andritz Hydro Corporation to upgrade generating facilities at the Hoover Dam.

The Hoover Dam's water store, Lake Mead, has record low water levels because of the drought downstream

Andritz Hydro, which is based in Charlotte, North Carolina, will design and manufacture a new "wide head" turbine runner for the Number Eight generating unit at the power plant on the Nevada side of the Colorado River.

Drought & extreme temps

Drought could shut down nuclear power plants

Southeast water shortage a factor in huge cooling requirements

comments below

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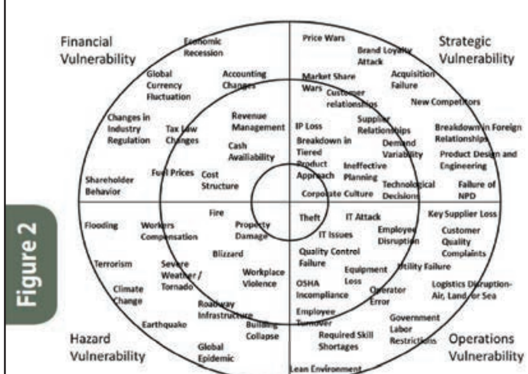
A man fishes next to the water outflows of the McGuire Nuclear Station near Lake Norman, N.C., on Monday. Lake Norman has dropped to about a foot above the minimum level needed for a backup system at the plant.

Flood

Approach

- **Vulnerability mapping**



- **Scenario analysis**
  - **The green movement**
    - Resilience requirement for new suppliers
  - **Middle East embargo**
    - New projects require improved delivery
  - **Non-renewable energy abundance**
    - Supplier and product distribution will provide snapshot of product portfolio health

This illustration provides a target-and-crosshairs model for vulnerability mapping to prioritize risk factors across four sectors, including operational, hazard, financial and strategic vulnerabilities

Resiliency Metrics

TABLE 2.2 Example Resilience Metrics Proposed by the DOE-supported Grid Modernization Laboratory Consortium

Consequence Category	Resilience Metric
Direct	
Electrical Service	Cumulative customer-hours of outages
	Cumulative customer energy demand not served
	Average number (or percentage) of customers experience an outage during a specified time period
Critical Electrical Service	Cumulative critical customer-hours of outages
	Critical customer energy demand not served
	Average number (or percentage) of critical loads that experience an outage
Restoration	Time to recovery
	Cost of recovery
Monetary	Loss of utility revenue
	Cost of grid damages (e.g., repair or replace lines, transformers)
	Cost of recovery
	Avoided outage cost
Indirect	
Community function	Critical services without power (e.g., hospitals, fire stations, police stations)
	Critical services without power for more than N hours (e.g., N> hours or backup fuel requirement)

SOURCE: GMLC (2017).

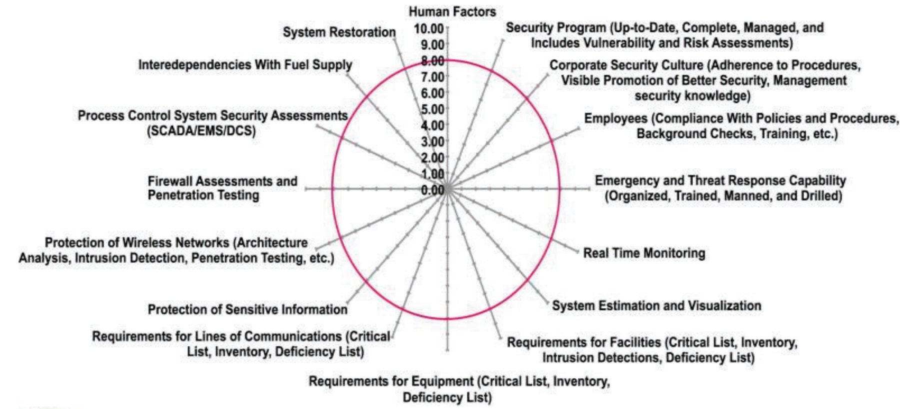
Source: Forthcoming "Enhancing the Resilience of the Nation's Electricity System," NAP, 2017

Prioritization: Security Index

General	Corporate culture
	Security Program
	Employees
	Emergency and threat response capability
Physical	Requirements for facilities, equipment and lines of communication
	Protection of sensitive information
Cyber and IT	Protection of wired and wireless networks
	Firewall assessments
	Process control system security assessments

Assessment & Prioritization:

A Composite Spider Diagram to Display Security Indices



The conference featured four parallel tracks:

- H3O – Smart Home, Hospital, Hotel & Office
- Microgrids, Rural Electrification and Renewables
- Smart Cities
- Humanitarian Impact of Smart Electricity

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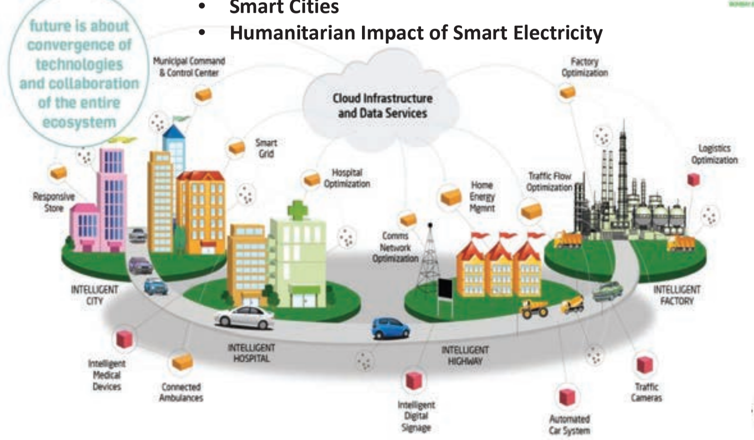
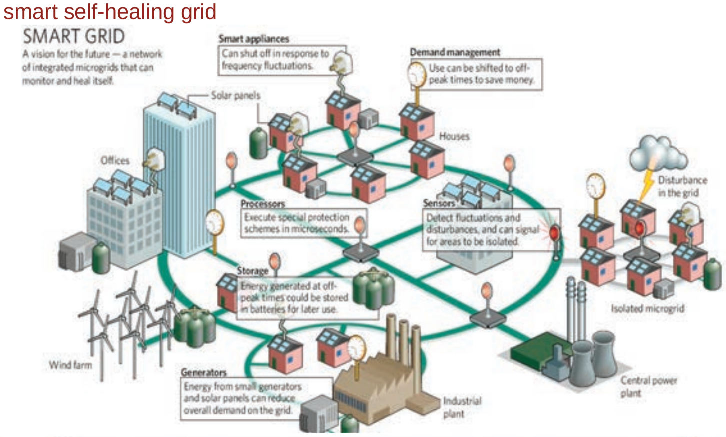
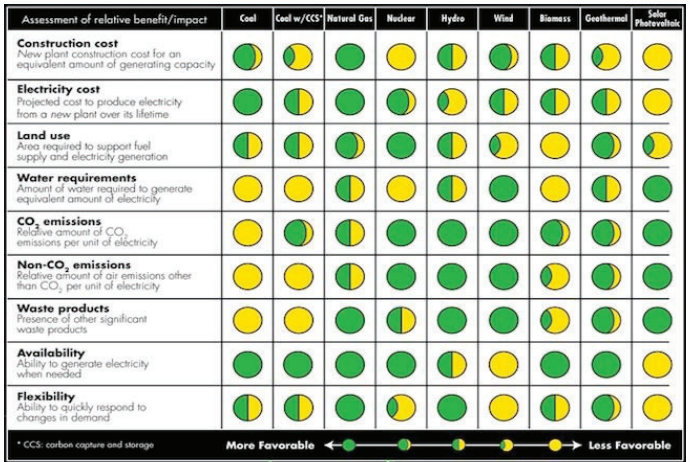


Enabling the Future

Infrastructure integration of microgrids, diverse generation and storage resources into a secure system of a smart self-healing grid

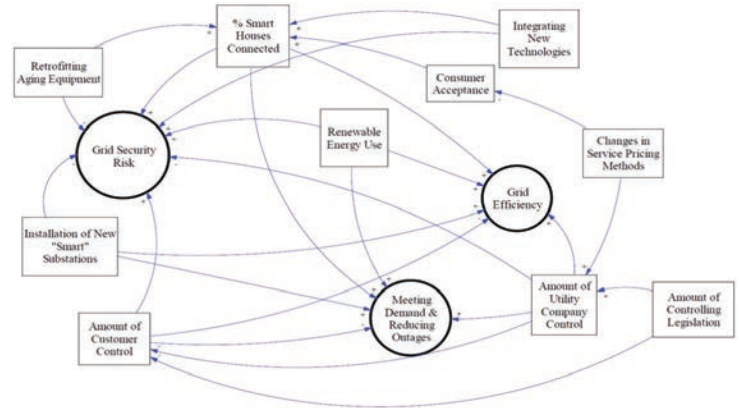


Source: Interview with Massoud Amin, "Upgrading the grid," *Nature*, vol. 454, pp. 570–573, 30 July 2008



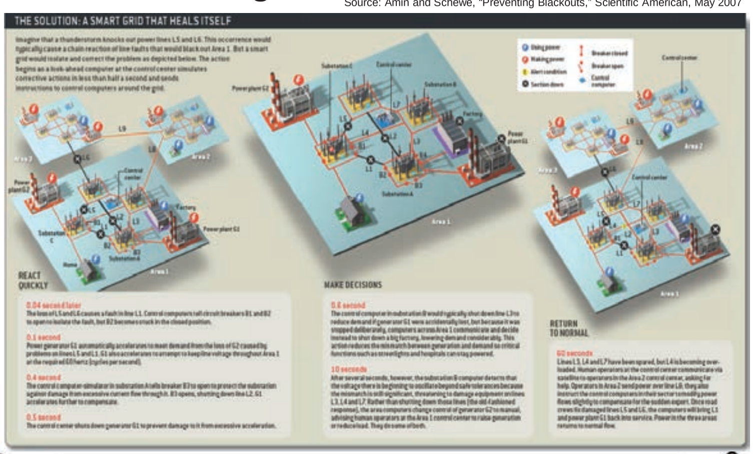
Source: EPRI http://sites.epri.com/refcard/comparison.html

Smart Grid Interdependencies: Security, Efficiency, and Resilience



Smart Self-Healing Grid

Source: Amin and Schewe, "Preventing Blackouts," Scientific American, May 2007



Distribution Systems
Consumers
Micrograds

Pivotal and Emerging Technologies

1. Energy storage
2. Micrograms
3. Cyber-Physical Security
4. Advanced Controls with Secure Communications
   - Operating Platform – Advanced EMS/DMS
   - Sensors, Monitoring, and Diagnostics
   - Smart Breakers
5. In-home Technologies

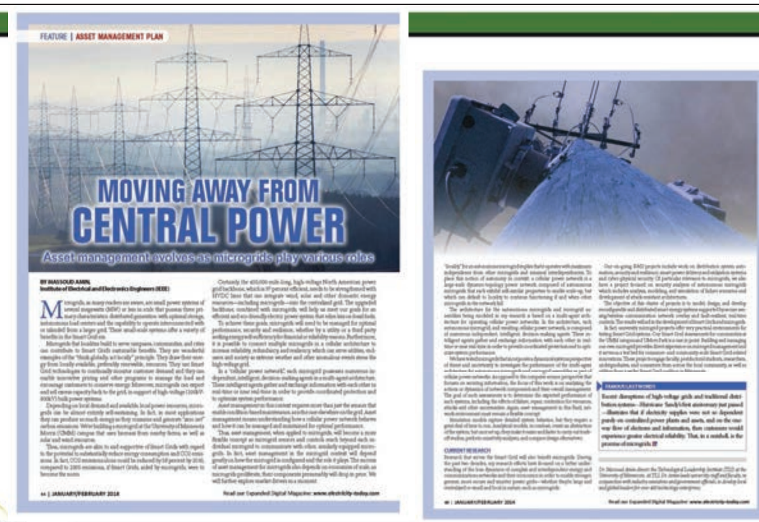
The next phase of power grid evolution is managing demand through consumers as part of a well-managed, secure, and smarter grid

The Microgrid Revolution

- Nearly all Utilities now see Microgrids as an important business opportunity.
- Utilities and Independent Power Producers both are viewing Microgrid Partnerships as the best ownership model.
- Regulations must be changed to better incentivize Microgrids and allow them to cross public rights-of-way.

The Role of the Microgrid

– Optimize distribution performance and service value
– Maximizing DC Power
– Seamlessly integrate electricity supply and demand
– Convert buildings from Power Pigs to Power Plants
– Provide user-friendly consumer empowerment
– Open the door to entrepreneurial innovation
– Enable local green enterprise zones



Smart Grid Assessment for UMore Park

Smart Grid assessment for UMore Park

Can the application of smart grid technologies, and more broadly, smart systems provide a better method and designs for managing the energy needs of the community?

Massoud Amin and his team of graduate MOT assistants, Eric Bohnert, Andrew Fraser, Hope Johnson and Shanna Leeland

UMore Park: Smart Grid Technologies for Homes

- Photovoltaic inverters
- Smart meters, in-home displays
- Grid-ready appliances
- Electric vehicle power charging station
- Battery storage backup
- Estimated costs: $10,670 to $27,190 per home
- About 4-5% of total cost

Estimated Prices for Energy-Efficient, Smart Grid Ready Homes in a Micro Grid – the UMore Park

Estimates for Lot Sizes and Home Prices in UMore Park (Maxfield Research, Inc., 2010)

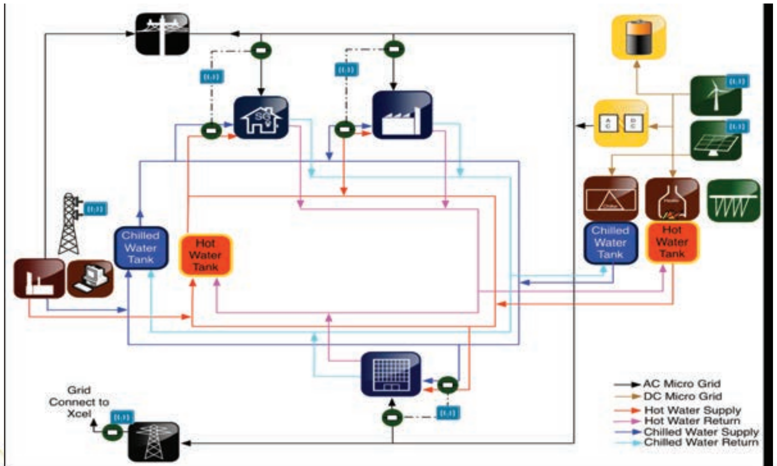
	Square Foot Range			Estimated Home Pricing		
	Low	High	Average	Low	High	Average
Small Lot	1,600	2,500	2,050	$225,000	$350,000	$287,500
Traditional	1,800	2,800	2,300	$225,000	$410,000	$317,500
Large Lot	2,800	4,500	3,650	$450,000	$725,000	$587,500

Estimates for Energy-Efficient, Smart Grid Ready Homes in UMore Park

	Price Ranges			Cost Over Traditional Home		
	Low	High	Average	Low	High	Average
Small Lot	$244,920	$379,920	$312,420	$19,920	$29,920	$24,920
Traditional	$244,920	$444,720	$344,820	$19,920	$34,720	$27,320
Large Lot	$487,920	$784,920	$636,420	$37,920	$59,920	$48,920

Average prices are within range of the low-high estimated home prices for UMore

Microgrid: A District Energy Model



UM-Morris Potential Smart Grid projects

- Location: Morris, MN
- Size: 1,800 student residential campus
- Energy Sources:
  - Biomass gasification plant
  - Solar thermal panels
  - Solar photovoltaic system
  - Two 1.65MW wind turbines (provides ~70% of campus's electricity needs)
- Load 300,000-750,000 kWh/month

… pathways forward?

… SECURITY

… Self healing & adaptive

… Local "power quality": locally self adjusting

… Evolvable architecture, open, predictive

… Power Electronics (control, quality, locality…)

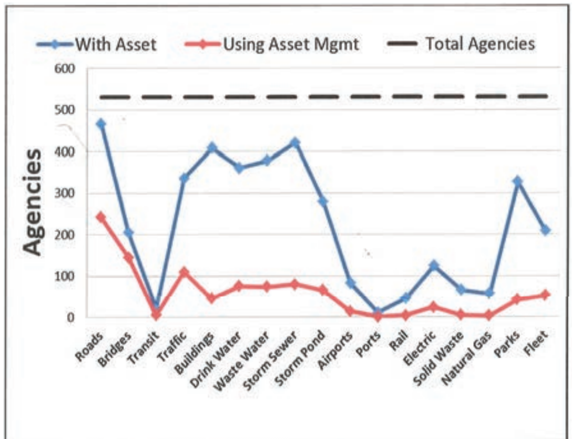
… Modularity/flexibility & Management

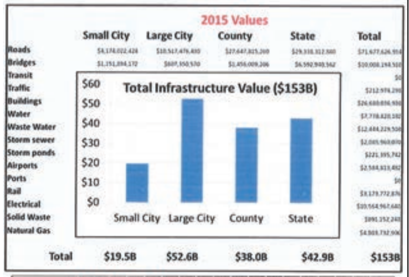
Not Just Utilities … Our Role in Minnesota: 2015 MN2050 Survey

	2015 Values				
	Small City	Large City	County	State	Total
Roads	$4,174,022,424	$10,517,476,430	$27,647,815,260	$29,338,312,840	$71,677,626,954
Bridges	$1,151,894,172	$807,350,570	$1,456,009,206	$6,592,940,562	$10,008,194,510
Transit	$0	$0	$0	$0	$0
Traffic	$14,168,440	$138,820,460	$59,985,398	$0	$212,974,298
Buildings	$7,583,657,510	$13,724,959,690	$4,869,723,674	$501,696,056	$26,680,036,930
Water	$1,499,020,952	$6,279,799,230	$0	$0	$7,778,820,182
Waste Water	$1,704,463,332	$4,244,983,540	$0	$6,494,782,638	$12,444,229,510
Storm sewer	$0	$2,085,960,070	$0	$0	$2,085,960,070
Storm ponds	$150,185,464	$65,757,060	$5,453,218	$0	$221,395,742
Airports	$1,240,446,922	$1,344,366,560	$0	$0	$2,584,813,482
Ports	$0	$0	$0	$0	$0
Rail	$0	$0	$3,173,772,876	$0	$3,173,772,876
Electrical	$0	$10,564,967,640	$0	$0	$10,564,967,640
Solid Waste	$0	$94,982,420	$796,169,828	$0	$891,152,248
Natural Gas	$2,056,549,066	$2,747,183,840	$0	$0	$4,803,732,906
Total	$19.5B	$52.6B	$38.0B	$42.9B	$153B

MN 2050 Infrastructure planning, long term success

Not Just Utilities — Our Role in Minnesota: 015 MN2050 Survey





Assets Managed by Cities, Counties and State Agencies

	Assets Managed	Road	Bridge	Transit	Traffic	Buildings	Drink Water	Waste Water	Storm Sewer	Storm Pond	Airports	Ports	Railways	Electrical	Solid Waste	Natural Gas	Total
Small Cities	14	97	11	1	55	71	92	92	89	54	15	0	7	18	5	9	616
Large Cities	15	187	88	4	112	109	128	139	137	133	19	2	9	54	9	7	1137
Counties	14	132	99	4	64	45	7	5	36	18	8	0	4	4	18	3	447
State Agencies	7	9	3	0	3	7	0	4	2	2	0	0	0	0	0	0	30
Totals =		425	201	9	234	232	227	240	264	207	42	2	20	76	32	19	2230

IT interdependencies and impact

source: Massoud Amin, EPRI, January 27, 1998

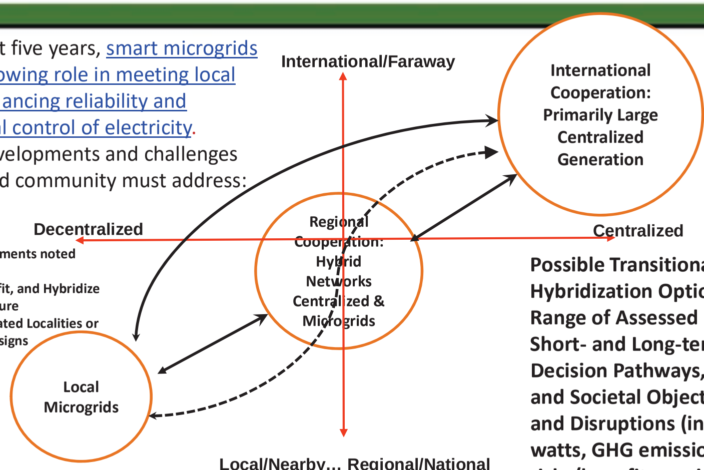
Dependence on IT
- Today's systems require a tightly knit information and communications capability
- Protecting the system will require new technology to enhance security of power system command, control, and communications.

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.

Assessing the most Effective Security Investments
- Probabilistic assessments can offer strategic guidance on where and how to deploy security resources to greatest advantage.

Over the next five years, smart microgrids will play a growing role in meeting local demand, enhancing reliability and ensuring local control of electricity.
Emerging developments and challenges the smart grid community must address:



Depending on assessments noted herein, we:
- Modernize, Retrofit, and Hybridize Legacy Infrastructure
- Leap-Frog for Isolated Localities or for Clean Slate Designs

Possible Transitional and Hybridization Options in a Wide Range of Assessed Scenarios: Short- and Long-term Strategies, Decision Pathways, ROI, Economic and Societal Objectives, Policies, and Disruptions (including dollars, watts, GHG emissions, risks/benefits – private and public)

What to do? Pathways forward

1. Create National Infrastructure Banks:
   - ➢Focused on addressing both the much-needed repairs today (to modernize existing aging infrastructure) AND also to bridge to more advanced, smarter, more secure and sustainable lifeline infrastructures envisioned for the next 10-20 years.
   - ➢Created as public/private partnership enterprises that lend money on a sustainable basis and has clear cost/benefit, performance metrics and include fees for quality of services provided by the modernized infrastructures.
2. Retool/re-train our best and brightest for this call to action:
   - ➢Some of the best talents to help rebuild our critical infrastructure are our veterans of the Armed Forces.
3. Renew/Update the American Model:
   - ➢**Align innovation and policy: Focus, Alignment, Collaboration, and Execution to revitalize leadership in education, R&D, innovation and entrepreneurship.**

Smart Grids with Distributed Energy Resources (DERs) to enhance Cybersecurity, Stability, and Resilience

S. Massoud Amin, *Fellow, IEEE and ASME*

***Abstract*—Key questions we are addressing include: 1) What key distributed energy technologies can disrupt the power sector? Impacts of DG and DER on reliability, resilience and need for end-to-end transparency; 2) How might distributed energy resources, such as solar panels or plug-in vehicles in garages, affect power system operations, markets, and regulations? 3) What business models may develop, and how will they successfully serve both upstream electricity market actors and energy consumers? 4) What effects could these new business models have on incumbent utilities, and what opportunities may exist for other industry sectors to capitalize on these changes? 5) How will regulation need to evolve to create a level playing field for both distributed and traditional energy resources? 6) What are plausible visions of the future of the power sector, including changes for incumbent utilities, new electricity service providers, regulators, policymakers, and consumers? And 7) Issues concerning critical infrastructure protection (CIP) and the security of cyber physical infrastructure will persist, necessitating vigilance and proactive counter measures.**

I. Introduction

To answer these questions, we address a number of new challenges, such as how to integrate large-scale stochastic (uncertain) renewable generation, electric energy storage, distributed generation and DERMs, plug-in hybrid electric vehicles, and demand response (smart meters). We must also realize methods to deploy and integrate new types of micro synchronized measurement technologies, new sensors, and new system integrity protection schemes.

Such advances contribute toward the development of an effective, intelligent, distributed resilient control of power system networks to achieve the overall objectives of efficiency, robustness, security, and reliability.

Customized and cost-effective advancements to address the above questions are both possible and essential to enable smarter, more secure and resilient electric power infrastructures. For example, advanced technology now under development or under consideration holds the promise of meeting the electricity needs of a robust digital economy. The potential exists to create an electricity system that provides the same efficiency, precision, and interconnectivity as the billions of microprocessors that it will power.

From a strategic viewpoint, long-term developments and research issues relating to the defense of cyber-physical interdependent infrastructure networks must also be considered. The driving scientific motivation is to further our understanding of adaptive self-healing and self-organizing mechanisms that can be applied to the development of secure, resilient, and robust overlaid/integrated energy, power, sensing, communication, and control networks. In addition to the above, further research and development needs include the following areas:

1. Enabling Technologies for an end-to-end secure system of Sensing/Measurement ➔ Analysis/Visualization ➔ Automation/Self-healing Systems
    - Monitoring and analysis, automation/control, materials science, power electronics, and integrated distributed energy resources (DERs)
    - Sensing, communication, data management, and mathematical/theoretical foundations to support a better, faster and higher-confidence understanding of what is going on: improved state and topology estimation, and fast look-ahead simulation
2. Enabling a Stronger and Smarter Grid: Complex Dynamical Systems, Systems Science, Controls, and Applied Mathematics
    - Modeling, robust control, dynamic interaction in interdependent layered networks, disturbance propagation in networks, and forecasting and handling uncertainty and risk
    - Overall systems science and dynamics (including infrastructure, ecology/environment, markets, and data-driven policy designs)
3. Strategic R&D
    - Digital control of the energy infrastructure
    - Integrated energy, information, and communications for the user
    - Transformation of the meter into a secure two-way energy/information portal
    - Robust advanced power generation portfolio

Awareness, education, and pragmatic tool developments in this vital area also continue to remain challenges. Educating stakeholders and colleagues in the cyber-physical interdependencies has often been difficult, as those who are distinguished members of the community and understand power systems well, but not the cyber threats, routinely minimize emphasis on these persisting novel threats.

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In addition, a growth area in recent years has been smart microgrids that will play a growing role in meeting local demand, enhancing reliability and ensuring local control of electricity, where financially viable. Microgrids are small power systems of several megawatts (MW) or less in scale with three primary characteristics: distributed generators with optional storage capacity, autonomous load centers, and the capability to operate interconnected with or islanded from a larger grids. Storage can be provided by batteries, supercapacitors, flywheels, or other sources.

Microgrids can serve as ideal platforms for realizing combined goals of a Smart Grid, including reliability, integration of renewables, DER, diversification of energy sources, and flexible demand response. Because of their scale, they facilitate systematic, yet innovative, approaches to solve local as well as global energy needs. They can also provide facilities and communities a certain level of independence from grid disruptions while providing grid operators and utilities an additional resource for improving their operations.

Wide integration of microgrids can be achieved by means of evolving control and communication systems in engineering. Besides providing greater reliability of supply, microgrids will have several other advantages, including the opportunity to integrate some "greener" but smaller-capacity electricity sources, such as photovoltaics, in the grid. Microgrids are providing the basis for new operating philosophies such as virtual power plants, where many small consumers of electricity can be aggregated to reduce consumption and sell unused electricity into the grid at times of peak demand.

However, this vision also presents challenges. One is socio-economic. History suggests that fundamentally redesigning any critical infrastructure requires subsidies and government involvement. Active participation of the for-profit private business sector is also required. There will have to be heavy initial investment in information technology infrastructure, updated or novel sensing and protection technologies, and in personnel training.

So far, microgrids and DERs have been realized at the distribution voltage level, but they may be extended to higher voltage levels too, where they have the potential to comprise large fractions of power grids. With enhanced information technology to improve sensing, control and monitoring, it is easier to imagine the larger grid being sectionalized into self-sustaining microgrids whose electrical boundaries may be defined by expected levels of reliability. Thus, microgrids may evolve from being a niche application to encompass large portions of the interconnected grid. Understandably, this vast transformation in the operation of future power systems needs to be achieved through a series of pilot projects to study and overcome technical, economic and social challenges.

The United States Department of Defense, through the Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) program, was engaged in investigations on supplying various U.S. bases by means of microgrids. Europe is also investing significantly in a modernized electricity grid, for example in the context of the European Union's More MicroGrids project. Besides illuminating technical issues, such projects also will shed light on social challenges—reactions of large corporate and small residential consumers; their receptiveness to the next generation of the smart grid, and the net social benefits microgrids can yield.

So how would this improve reliability, security and efficiency?

For reliability's sake, multiple automated microgrids could be built with similar properties and arrayed in a "cellular power network" in which each microgrid possesses numerous independent, intelligent, decision-making agents in a multi-agent architecture. These intelligent agents gather and exchange information with each other in real-time or near real-time in order to provide coordinated protection and to optimize system performance. Asset management in this context requires more than sensors that enable condition-based maintenance, as is the case elsewhere on the grid. Asset management means understanding how a cellular power network behaves and how it can be managed and maintained for optimal performance.

Localities should build microgrids because these facilities can meet community energy demands in an eco-friendly way that also provides cost advantages to consumers and families. I also believe that local commitments to microgrids will help the country overall by highlighting their capabilities and just proving that it can be done. Cities, communities, and universities are great candidates for microgrids because their microgrid projects can be manageable in size and the local participants are passionate about the opportunity and want their programs to succeed.

Local entities can use their microgrids as well to develop and test innovations for consumers, such as smart homes, and the results of these programs can be used in developing other smart grid projects around the country.

Security, which includes privacy and cybersecurity, is fundamentally necessary for reliable grid operations and for customer acceptance of smart grids, and many in IEEE and the smart grid community are developing technologies and standards addressing this issue. What is most important, however, is that security is incorporated into the architectures and designs at the outset, not as an afterthought. For the microgrids that I am involved with, we employ security technologies for each equipment component we use and for each customer application we develop and we do this in a way that cannot be reverse engineered. We use an architecture that cannot be taken down. If any part of the system is compromised, the system reconfigures to protect itself, localize and fend off the attacks.

In some respects, microgrids with DERs can be significantly more complex—for example, they might include DC elements and inverters for conversion, they can exert greater control over a wider variety of loads, and the connection with the grid can be flexible. On the last point, microgrids can enable uninterrupted operation where grid supply might be unreliable. In this case, the *islanding* capability of a microgrid comes into play. Intelligent microgrids have to optimally manage interconnected loads and distributed energy resources (including renewables) both in grid-connected and islanded modes.

An autonomous microgrid is a microgrid operated and coordinated by intelligent automatic controls without significant reliance on human intervention. The principle of locality for an autonomous microgrid implies that it operates with maximal independence from other microgrids (i.e. minimal interdependencies among microgrids) subject to meeting its goals for reliability and cost limits on storage. A cellular power network is a large-scale dynamic-topology power network composed of autonomous microgrids that each exhibit self-similar properties to enable scale-up.

The architecture for the autonomous microgrids and microgrid assemblies being modeled are based on multi-agent architecture for operating cellular power networks. In the architecture, each autonomous microgrid, and resulting cellular power network, is composed of numerous independent, intelligent decision making agents. These intelligent agents gather and exchange information with each other in real-time or near real-time in order to provide coordinated protection and to optimize system performance.

We have tested microgrids that incorporate a dynamical systems perspective of threat and uncertainty to investigate the performance of the multi-agent architecture for autonomous microgrids and microgrid assemblies as part of cellular power networks. As opposed to the computer science perspective that focuses on securing information, the focus of this work is on analyzing the actions or dynamics of network components and their overall management. Therefore, threats and uncertainties are viewed as undesirably modifying the dynamics.

The primary question that is answered is "what is the expected resilience and performance of such systems that are augmented with DERs, including the effects of failure, repair, contention for resources, attacks, etc.?" Simulation models are able to capture system behavior in as much detail as desired by the modeler, but they can take a significant amount of time to run. Analytical models, on the other hand, are generally more of an abstraction of the system, but once they are set up, it is easy and fast to carry out trade-off studies, answer "what if" questions, perform sensitivity analyses, and compare design alternatives.

Moreover, in case of an emergency, such as the failure of a critical node or loss of utility power, an intelligent microgrid has to make critical decisions urgently—islanding might need to be in effect within sub-second timescales to avoid damaging equipment.

With increased penetration of DERs and renewable sources, such as solar generation, there are ramifications in some electrical distribution systems, putting stress on devices traditionally used to handle voltage variability. To address the impacts of intermittent generation effectively, the hitherto largely separate disciplines of power electronics and power system automation need to be integrated.

As residential solar photovoltaics (PV) reach high levels of penetration on the grid's distribution system, the grid will become more susceptible to voltage variability. This issue has been documented by several utilities including some in California and Arizona, on the frontline of this trend and they have begun the search for solutions, which include power electronics.

This foundation for a new approach is being laid today. The large-scale deployment of a sensing, control, and two-way high-speed communication infrastructure including GPS-synchronized Phaser Measurement Units (PMUs) and Advanced Metering Infrastructure (AMI) is currently under way around the world. In addition, the rapid and continued advances of power electronics will provide the needed platform for ubiquitous sensing, computation, communication and control. For instance, unlike traditional distribution devices that are switched only a few times a day, the inverters that connect photovoltaics (PV), wind turbines, or batteries to the grid can pull or push reactive power at a much faster timescale and with a much finer resolution.

Existing and planned information and communication technology (ICT) infrastructure, if integrated with the power system, will allow us to monitor and control 1,000 times faster than done today. Indeed, in 2010 the International Energy Agency forecast $6.9 trillion in electric grid modernization globally through 2030; of that amount, Cisco estimates about 25%, or about $1.7 trillion, will be in related ICT infrastructure. As infrastructure deployment proliferates, the new bottleneck in the exploitation of ICT on a massive scale will be the need for overarching frameworks, foundational theories, and practical control algorithms to manage a fully ICT-enabled power network.

We note also that dynamic adaptation by hundreds of millions of end users on a sub-second control timescale, each contributing a tiny fraction of the overall traffic, is being practiced every day on the Internet in the form of congestion control. Even though both the grid and the Internet are massive distributed nonlinear feedback control systems, there are important differences in their engineering, economic, and regulatory structures. Nonetheless, the precedence of the Internet augurs for a highly scalable, dynamic, and distributed control architecture for the Smart Grid. A central task for the Smart Grid, as it was for the

Internet, is the development of architectures that support up to billions of active endpoints.

To achieve this goal, closer to customers and consumers, localities are starting to build microgrids to serve campuses, communities and cities, and many of those microgrids will draw their power from locally available and preferably renewable sources like wind and photovoltaics. Microgrids can be almost entirely self-sustaining. In fact, they can produce as much energy as they consume and generate "zero net" carbon emissions. We have shown this at the University of Minnesota, where we are building and demonstrating a microgrid on one of our campuses. Using biomass from nearby farms, as well as solar and wind resources, it will soon be energy-self-sufficient. It has been zero-net-carbon since 2008.

The microgrids and DER concept may eventually be extended to higher voltage levels, to create self-contained, self-sufficient systems (http://smartgrid.ieee.org/november-2013/1004-harmonizing-edison-and-tesla-with-hvdc-and-microgrids)

Utility executives must not only look to upgrade the existing power infrastructure, but must open their business plans to incorporating alternative energies and alternative ways to generate and provide energy. Certainly, the power grid backbone also needs to become increasingly efficient, integrating renewable resources that reduce society's need for fossil-based resources, among other approaches. The upgraded backbone, combined with microgrids, will help us meet our goals for an efficient and eco-friendly electric power system achieving major energy/national security and economic growth milestones.

Practical Decision Template: What is needed to proactively account for and manage/ameliorate sources of uncertainty:

1. Track and Understand What Is Driving Uncertainty and the Industry
   - Future demand for electricity supplied by grid resources
   - Future price of natural gas
   - The extent to which environmental and energy policy, laws

2. Flexibility and Proactive Adaptivity
   - Energy efficiency (end-to-end)
   - Long-term operations
   - Near-zero emissions
   - Renewable resources and integration
   - Smart grid
   - Water resource management

3. Connectivity is Critical (handling and collating the Tsunami of Data with full cybersecurity); gain actionable intelligence from data streams.

4. Resiliency based on situational awareness and actionable intelligence for prevention, recovery, and survivability

For example, to address uncertainty about the location, size, and schedule of new power plants coming on line, as well as uncertainties about interregional power transfer patterns, which may change from season to season and year-to-year, probabilistic transmission planning methods and tools are needed. In order to provide the market signals for investors to build new transmission projects, where the market needs them, an online congestion monitoring system would be useful.

At the macro-level, the ability to:

- Organize perceptions about future alternatives
- Remove biases in visioning
- Focus debates about technology needs
- Challenge the view that little will change
- Enable development of alternative technology portfolios
- Foster a probabilistic versus a deterministic view of the future

One sample case:

- Is the perceived resurgence of this industry plausible and if so, how much of a market does it constitute?
- Are nuclear capacity addition forecasts accurate?
- Are cost estimates for plant construction and operation reasonable?
- How does the cost of electricity from these new designs compare with alternative sources of electricity?

Another example is the development and deployment of bulk energy storage that plays a key role in supporting the power delivery system infrastructure needed for consumer services and enables integration of intermittent renewable sources. Despite these important roles, electricity cannot be easily stored today. Without an "inventory" to access, utilities have little flexibility in managing electricity production and delivery. Likewise, intermittent renewable resources – such as solar and wind – cannot be relied upon for hourly electricity supply. Although some commercially-proven technologies can store electricity by converting and storing it in another energy form – such as in flywheels, pumped storage, and batteries – only 2.5 percent of North American generation capacity, for example, uses such plants. This is because most storage options (except pumped hydro and compressed air) are relatively unproven; their value proposition is complex and poorly understood; and the uncertainties of changing regulatory rules makes storage options too risky for most investors.

Public and private organizations need to collaborate to analyze the costs and benefits of existing storage options, including pumped hydro, compressed air, and battery plants. Additional recommended work includes considering the potential return-on-investment (ROI) of enhancing existing storage options and building new ones. Achieving these goals will involve the development of sophisticated tools to predict the costs of producing large-scale storage systems 5-20 years in the future. It will also require new models to simulate the economic characteristics of future power delivery system conditions to predict the potential benefits of storage options to generation, transmission, and distribution owners as well as end-use consumers. Once accurate cost, benefit, and ROI estimates are available, the next step will be a series of RD&D projects designed to build large-scale, lower-cost storage modules and demonstrate them at appropriate utility sites under real-world conditions. During these demonstrations, the collection and analysis of cost and performance data will be a high priority. To address investor concerns about existing or new storage options, high-end communications to key stakeholders will be essential.

Here are some frequently asked questions, which I hope assist you as you chart the course for your organization:

What factors are hindering improvements to the U.S. grid? One of them is that, on any given day, there are half a million people in America without electricity for two or more hours per day. However, outages are not always in the same location, and because of that, we have a very short attention span. However, coping as a primary strategy is ultimately a defeatist strategy.

Second, there is a lack of leadership in the public and private sectors. There is a lot of uncertainty, and that hinders the development of the smart grid. Congress should incentivize investment in the infrastructure. We can create jobs in this area—very high-paying jobs. Just to integrate distributed resources such as wind power, we need to add about 42,000 miles of high-voltage line, and that would create over 210,000 jobs.

Third, there is a divide between federal jurisdiction and local jurisdiction. The high-voltage grid, for the most part, is under federal jurisdiction, but the distribution systems are under the local jurisdiction—mostly public utility commissions. That kills the incentive for any utility group to do regional work and upgrade on a regional basis. We need coordination in the investment in the grid and in the research and development areas. As noted earlier, we only invest 0.17 percent of net sales back into R&D and innovation. Yet all of society, our quality of life, fundamentally depends on reliable electricity.

Why do we need a smart grid?
Grid modernization is a global phenomenon, but in any day in the U.S., about a half million people are without power for two or more hours. The number of weather-caused, major outages in the U.S. has risen since the 1950s, from between two and five each year by the 1980s to 70–130 between 2008 and 2012. Two thirds of weather-related power disruptions have occurred in the past five years, affecting up to 178 million customers (meters), as changing weather patterns impact aging infrastructure.

The U.S. electric power system still relies on 1960s and 70s technology. The sector is second from the bottom of major industries in terms of research and development (R&D) spending as a fraction of revenue; only pulp and paper is worse. Electricity R&D received just 0.17 percent of net sales from between 2001 and 2006, and has not risen since.

Meanwhile, electricity needs are changing and growing fast. Tweeting, and the devices and infrastructure needed to operate the underpinning communication network, data centers and storage alone adds more than 2,500 megawatt hours (Mwh) of demand globally per year that did not exist five years ago**.** Kilowatt hour (kWh) is commonly used by power companies for billing, since the monthly energy consumption of a typical residential customer ranges from a few hundred to a few thousand kilowatt hours. One Mwh is equal to 1,000 kilowatts of electricity used continuously for one hour. One Mwh is the amount of electricity used by approximately 330 homes in one hour. On average 2500 Mwh is equivalent to the electricity used by about 825,000 homes**.** Factor in Internet TV, video streaming, online gaming and the digitization of medical records, and the world's electricity supply will need to triple by 2050 to keep up.

What forms should hardening and improved reliability and resiliency take? Hardening, for instance, might mean that substations in flood-prone areas should be optimized for location and design and construction standards against floods – especially for underground substations in, say, New York City. The design standards for feeders should be improved to the level applied to higher voltage lines. Selective undergrounding for critical lines may be cost effective. New materials can make power poles sturdier and cables more resilient.

What are we doing about this?
During the past two decades the strategic goal for my teams' R&D and the resultant services and technologies have focused at better understanding the true dynamics of complex interdependent energy/communications/economic networks in order to enable stronger, greener, more secure and smarter power grids. We develop and apply analytical and multi-domain modeling, simulation and testing methodologies to assess the effects of smart grid technologies on distribution system operations and performance. Our results integrate aspects of cyber-physical security, dynamic price and demand response, mix and placement of storage devices, integration of wind, solar and intermittent distributed energy resources, combined with sensing, communications, and dynamic optimization and reconfiguration. Applying this comprehensive systems approach, performance results for several distribution system test cases have been performed. Our on-going recent R&D projects include:

- **Distribution System Automation, Security and Resilience:** Integration and optimization of storage devices and PHEVs with the electric power grid. Assessments performed on several IEEE test cases as well as on the UM-Morris Campus, combined with practical costs, risk and reliability analyses.
- **Smart Power Delivery and Utilization Systems:** a) Fast power grid simulation and risk assessment, and b) Distributed state estimation and implementation of smart software agents as distributed computer.
- **Cyber-physical Security:** The objective of this cluster of projects is to model, design and develop reconfigurable and distributed smart energy systems supported by secure sensing/wireless communication network overlay and fault-resilient real-time controls. Projects include: a) Security of cyber-physical infrastructure, development of resilient real-time system for a secure and reconfigurable end-to-end power system; and b) Security analyses of autonomous Microgrids: Analysis, Modeling, and Simulation of Failure Scenarios, and Development of Attack-Resistant Architectures.
- **Smart Grid and DERs Assessments for communities, UM-Morris, and UMore Park**: Due to its size, complexity, and cost, the transformation of the existing electrical grid to a smart self-healing system will need to occur in several stages over time with equipment being gradually replaced as it reaches the end of its operating life. Focusing on smart grids for communities and at a college campus level, university microgrid projects offer very practical environments for testing Smart Grid systems. We employ a holistic systems approach for all of our work on this project. It engages faculty, postdocs, researchers, undergraduates, consumers from across the local community, as well as utilities from the wider Smart Grid coalition in Minnesota to build consensus on issues such as microgrid configuration, cost-effectiveness, and security.

Concluding Remarks and Next Steps

Energy and power infrastructure stakeholders, and the broader society, face challenges such as: Aging assets, severe weather events and billions of dollars in damage annually, physical and cyber attacks, interdependencies with other infrastructures (gas, telecommunications, transportation, water, etc.), investment recovery, and policy.

All infrastructures impacted by age and external forces must be viewed as capital equipment and critical strategic assets, which possess capabilities and characteristics that can, and must be revolutionized to improve reliability and resilience in face of a broad array of destabilizers. Therefore, a holistic quality management approach which weighs the relative risks and economics of maintenance, repair and replacement (or retirement) of the infrastructure's various elements is needed to advance grid resilience and modernization. This article addresses the areas noted above and provides options for addressing these challenges; it is based in part on the author's contribution, chapter 4 in the IEEE Joint Task Force to Quadrennial Energy Review (QER), on aging infrastructure and the overall asset management.

In summary, public and private organizations need to collaborate to analyze the costs and benefits of existing storage options, including pumped hydro, compressed air, and battery plants. Additional recommended work includes considering the potential return-on-investment (ROI) of enhancing existing storage options and building new ones. Achieving these goals and integration of DERs will involve the development of sophisticated tools to predict the costs of producing DERs and large-scale storage systems 5-20 years in the future. It will also require new models to simulate the economic characteristics of future power delivery system conditions to predict the potential benefits of storage options to generation, transmission, and distribution owners as well as end-use consumers. Once accurate cost, benefit, and ROI estimates are available, the next step will be a series of RD&D projects designed to build large-scale, lower-cost storage modules and demonstrate them at appropriate utility sites under real-world conditions. During these demonstrations, the collection and analysis of cost and performance data will be a high priority.

Finally, to modernize the whole end-to-end system, the smart grid represents a remaking of the electric power system encompassing all aspects of generation, delivery, and consumption. Benefits will accrue to individuals, societies, and industry: better use of renewable sources, reduction in carbon emissions from fossil plants, improved efficiencies across the power system, broad-based integration of electric and plug-in hybrid vehicles, real-time feedback to consumers on their electricity consumption, improved grid reliability, and more.

Nevertheless, several challenges must first be addressed. Intermittent renewables and greater variability in load profiles will result in high uncertainty in both generation and consumption. Dynamic pricing and demand response will intricately couple economic factors and power flow. With communication technologies providing a system-wide integration infrastructure, the smart grid will represent a prototypical "system of systems." Multiple and often conflicting criteria will need to be coordinated: profits, grid reliability, environmental impacts, equipment constraints, and consumer preferences. Environmental and Energy Policy need to be supportive of this transformation.

Development of operating standards is crucial, if utilities are to be convinced that intentional islanding of the larger grid into microgrids during system crises is useful and non-detrimental. The IEEE 1547.4 is one such forward-looking standard. Accounting for and managing uncertainties at all levels can be and must be addressed in a transparent dashboard at the level of detail (think of it as a "Google-Bloomberg" dashboard) that consumers, regulators, decision-makers and investors demand.