A More Resilient Grid

The U.S. Department of Energy Joins with Stakeholders in an R&D Plan

By Dan T. Ton and W-T. Paul Wang

ELECTRIC DISTRIBUTION GRID RESEARCH AND DEVELOPment (R&D) has long focused on the reliability, affordability, flexibility, and efficiency of electricity delivery for end users; however, this focus has primarily been outside the realm of severe climate events. Due to the increasing frequency and intensity of weather-caused grid outages in recent years, the U.S. Department of Energy (DOE) has placed an added emphasis on R&D to enhance resilience to climate change and extreme weather. To forge a focused national R&D effort on grid resilience, the DOE is adopting a public/private partnership approach to join with key stakeholders in developing and implementing a resilient grid R&D plan. This article presents the plan development process and the R&D need areas identified for pursuit.

Weather and Climate Disasters and Grid Resiliency

From 1980 to 2014, a total of 178 weather/climate disasters occurred in the United States, with overall damages/costs reaching or exceeding US$1 billion for each event and US$1 trillion for all events. Eight of these events occurred in 2014, as shown in Figure 1. Both the frequency and intensity of these disaster events have been trending higher in recent years, with seven of the ten costliest storms in U.S. history occurring in the last ten years. These weather disaster events represent one of the most significant threats posed by climate change.

With increasing dependence on electricity for most daily activities and vital services (such as transportation, commerce, communications, health care, water, and emergency responses), an urgent need exists to

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enhance the resilience of our nation's electricity delivery infrastructure to reduce the impact from natural disasters and climate change events on our quality of life, economic activity, and national security. U.S. Energy Secretary Ernest Moniz recently stated, "Building in grid resiliency has gained greater urgency in recent years, as demonstrated by the economic and personal losses from electricity outages due to severe weather. Keeping the power on during extreme weather events and other electric grid disruptions is essential, particularly so that critical facilities such as hospitals and water treatment plants can continue operating." The term "resilience" used herein is defined in Presidential Policy Direction 21 (PPD-21) as "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents."

Smart Grid R&D Program Addresses Electric Distribution Grid Resilience

The DOE Smart Grid R&D Program has launched a national effort on electric distribution grid resilience. This effort not only responds to the increasing vulnerability of grid outages to climate change and extreme weather events but also supports Executive Order 13653 "Preparing the United States for the Impacts of Climate Change" and the goal of "building stronger and safer communities and infrastructure" in accordance with "The President's Climate Action Plan." The Smart Grid R&D Program resides within the DOE Office of Electricity Delivery and Energy Reliability (OE) and has the program objectives of

- ✔ modernizing the electric distribution grid through the adaptation and integration of advanced technologies (information, communications, and automation) and new operational paradigms (microgrids and transactive controls)
- ✔ supporting the increasing demand for renewable energy integration and grid reliability and resiliency at state and local levels.

Smart grid technologies, developed by the DOE OE, are being applied to customer-based, distribution, and transmission systems, as shown in Figure 2.

The DOE effort on resilient distribution grid R&D began with engaging its national labs and other key stakeholders in both public and private sectors to develop an initial resilient distribution R&D plan. This initial plan and its R&D need areas were further refined, via internal DOE deliberations, by incorporating input received through the DOE grid modernization efforts. Of note is that the resilient distribution

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grid R&D plan focuses solely on R&D for climate preparedness and climate impact resilience for electric distribution grid and customer-side assets and systems. R&D for the resilience of electricity supply and electric transmission grid is not within the scope nor is the resilience of electric distribution grid to physical and cyberthreats.

Initial Plan Development via Stakeholder Engagement

To begin framing the scope of R&D needed for enhanced resilience, the DOE Smart Grid R&D Program gathered experts from DOE national labs in meetings in late 2013 to better understand current capabilities and activities in grid resilience and to envision the extent of resilience enhancement that could be attained through a focused effort. This program conception and envisioning process laid the foundation for a workshop, held in June 2014 with the engagement of key stakeholders, which included the objective of identifying an initial set of R&D needs and associated R&D projects critical to enhancing electric distribution grid resilience to natural disasters. National lab experts provided the DOE with the names of experts and practitioners to be invited to the workshop, as well as facilitated discussions in the two concurrent breakout sessions: "Design, Preparedness, and Planning" and "Operational Response and System Recovery." In addition to the DOE invitees, workshop attendance was open to all interested parties. A total of 75 people attended the workshop, representing vendors, utilities, national laboratories, universities, research institutes, and end users.

Each workshop breakout session first identified several R&D needs and associated R&D projects for its assigned main topic. Votes cast by attendees were then used to determine the top three R&D needs in each main topic. Attendees in the session "Design, Preparedness, and Planning" determined the two top R&D projects for each top-voted need, through a similar voting process. R&D projects in the session "Operational Response and System Recovery" were discussed but were not prioritized through the voting

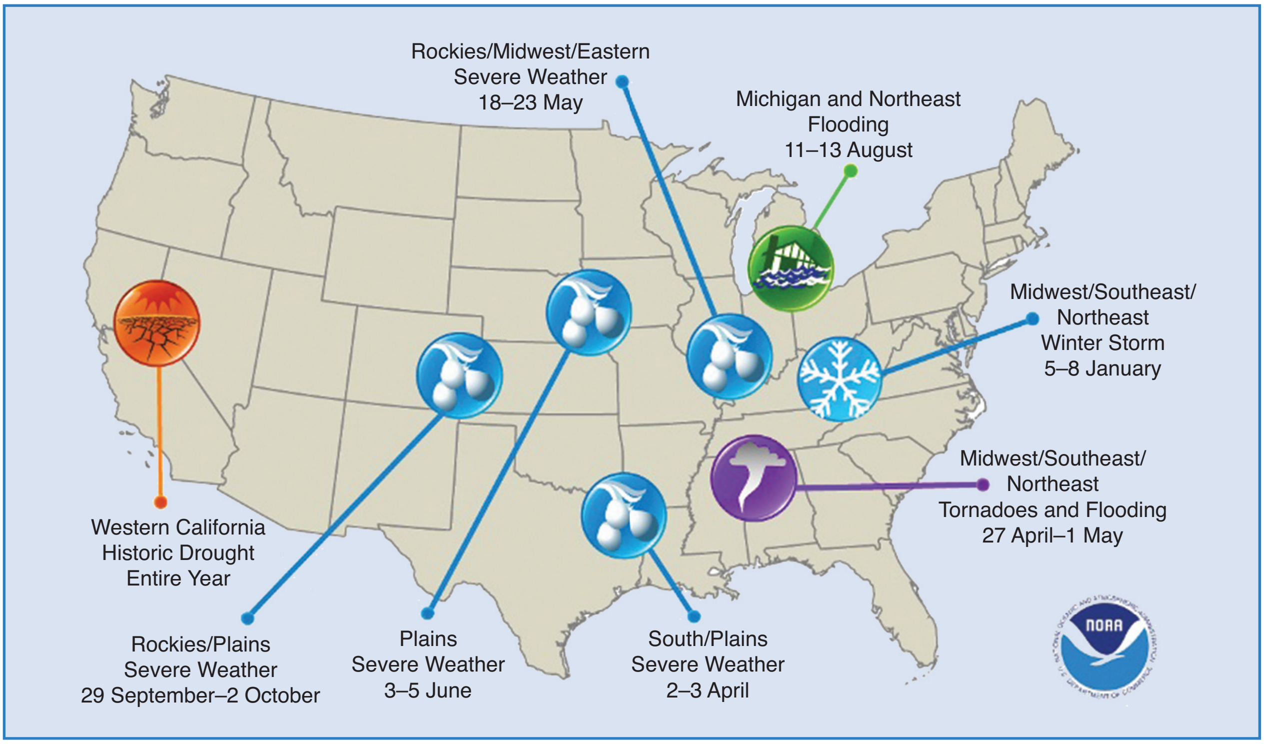

figure 1. The locations of eight US$1 billion weather and climate disasters in 2014 (picture courtesy of the National Climatic Data Center).

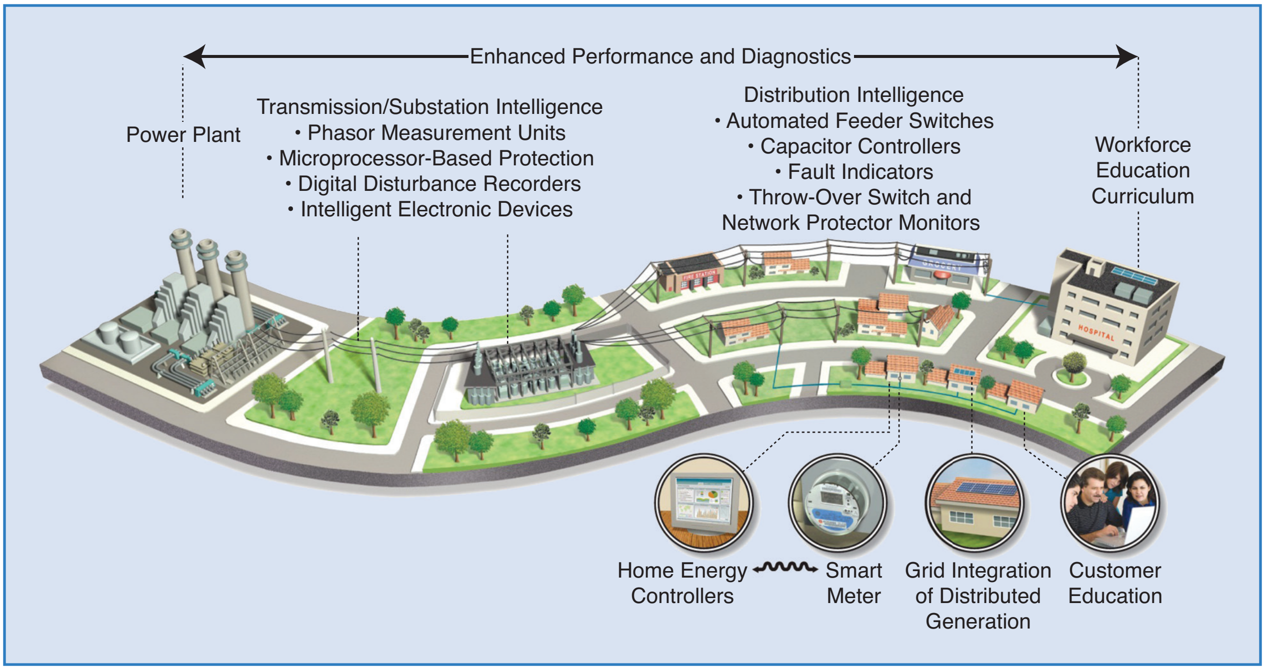

figure 2. Smart grid technologies that are applicable across the electricity delivery infrastructure (picture courtesy of the Florida Power and Light Company).

process to determine their relative priority. These key needs and projects are summarized and shown in Table 1.

Conclusions from the breakout session discussions and the resulting presentations from the workshop are documented in the DOE workshop summary report. All presentations from the workshop can be downloaded through Web links in the workshop report.

R&D Need Areas for a Resilient Distribution Grid

Grid resilience is a key attribute of the future of the grid and is thus central to the DOE grid modernization efforts. The DOE Grid Tech Team (GTT) has developed, through outreach and engagement with stakeholders, a vision of the future grid with key attributes shown in Figure 3 and a strategic framework that organizes grid modernization activities into interrelated focus areas (informational, analytical, and physical). The Grid Modernization Lab Consortium—a strategic partnership between the DOE and its national labs—was established to carry out an integrated approach to implement the DOE grid modernization multiyear program plan (MYPP). This MYPP, currently under review, expounds on key initiatives and outcomes for each of the six focus areas organized by the GTT, with the aim of achieving the DOE's vision of the future grid. Resilience R&D resides primarily in the focus area of security and resilience; it is interrelated to activities in the other five focus areas: devices and integrated systems, sensing and measurement, systems operations and control, design and planning tools, and institutional support. The DOE, acting as the Secretariat for the Quadrennial Energy Review (QER) Task Force, has been developing a working paper on grid modernization as part of a policy recommendation in the first-year QER report. The capacity of the nation's energy systems, including the electricity delivery infrastructure, to absorb, adapt, and recover from climate changes and extreme weather events is one of the key issues to address in the recommendation.

The DOE Smart Grid R&D Program analyzed all input received (from the stakeholder workshop in June 2014 and the DOE grid modernization efforts) and related publications to further consolidate them into the following five needs for resilient distribution grid R&D:

- ✔ develop resilience metrics
- ✔ enhance system design for resiliency
- ✔ improve preparedness and mitigation measures
- ✔ improve system response and recovery
- ✔ analyze and manage interdependencies.

Develop Resilience Metrics

A review of the state of metrics for the resilience of electric power, natural gas, and oil distribution systems revealed that the metrics generally are not standardized, consensus on core required capabilities and how to measure those capabilities for resilience to extreme events is lacking, and relating capabilities to desired outcomes is not well understood. Quantitative, risk-based metrics are needed to assess and measure the progress of the ability to plan, operate, and recover from weather disasters. Metrics are useful, as the decision context and criteria in decision-support processes or tools, to manage trade-offs and make decisions for policy, planning, investments, and operations. Decision-support tools incorporating resilience metrics are helpful, for example, to public utility commissions and other regulators in making infrastructure investment and rate recovery decisions.

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Enhance System Design for Resiliency

The development of new materials and designs for electric systems and components to be more resilient to extreme events is needed. This development includes "hardening" the existing electricity delivery infrastructure (e.g., distribution lines, poles, substations). Design and construction standards for higher performance will be required but dependent on the local conditions of the facilities. An industry study on the myriad hardening measures concluded that widespread system hardening is cost prohibitive. Innovative R&D is needed for developing and implementing cost-effective strengthening measures (such as those for lines and poles, hydrophobic coatings, dynamic circuit reconfiguration and microgrids) as well as for resilient design tools to enable grid designers to prioritize cost-effective system upgrades and expansions.

Improve Preparedness and Mitigation Measures

Simulation tools, equipped with environmental forecasting and damage prediction models, need to be developed to provide high-fidelity system performance predictions under extreme event scenarios. R&D on monitoring predictive failure modes of electric equipment is needed to provide timely information on maintenance, repair, and replacement actions before failures occur. New tools for resilience assessments that address technical, organizational, social, and economical dimensions are needed to determine what key aspects of resilience measures are lacking (at the facility, sector, community, and regional levels) and their corresponding resilience-enhancing measures to mitigate against system risks. R&D is also needed for improved flexibility and robustness, which includes power electronic-based controllers to enable the routing of power around damaged/impacted areas to continue delivery of electricity to critical loads, energy storage to support renewable energy integration and improve system stability, and microgrids with the ability to continue operating and to serve as a grid resource during grid disturbances.

Improve System Response and Recovery

Improved situational awareness and its prerequisite of a more resilient communications infrastructure are two key

table 1. The top R&D needs and projects identified at the 2014 DOE resilient electric distribution grid R&D workshop.

Area	R&D Needs	R&D Projects
Design, preparedness, and planning	Design of segmented and agile distributed system	• Emergency controls, segmentation, and communications • Microgrid to feeder integration
	Big data and analytics	• Multiscale modeling: distribution and transmission • Real-time database with speed and accuracy
	Stochastic and uncertainty	• Robust control to uncertain data • Predictive models
Operational response and system recovery	Proactive assessment of damage (automated calls to customers, smart meters)	• Damage assessment • Unmanned aerial vehicles to support real-time Google Maps • New devices to support degradation identification • Hardening of communications
	Situational awareness	• Development of architecture • State estimation with new data and new devices • Cyberphysical degradation and the necessary understanding to respond to it when it occurs • Three-phase state estimation
	Decision support to determine restoration priorities	• Development of technologies to find alternative restoration strategies • Cost-effective resilient control systems • Coupling of electric restoration models to other infrastructure models • Integration of microgrids to distribution management system • Advancement of standardization of microgrid resources such as inverters and distributed generation

areas needed for strengthening electric grid resilience over the next ten years. New distribution management systems that integrate advanced visualization and situational awareness, along with look-ahead capabilities, to provide viable control solutions need to be developed to help utility operators respond to the range of threats and mitigate and recover from damages. Moreover, faster, more accurate, and metrics-based optimization tools for restoration prioritization will be needed to support faster disruption recovery for damaged systems. Targeted applications include optimal repair scheduling, utility and communications crew logistics, control system restoration, and resource coordination and allocation decisions.

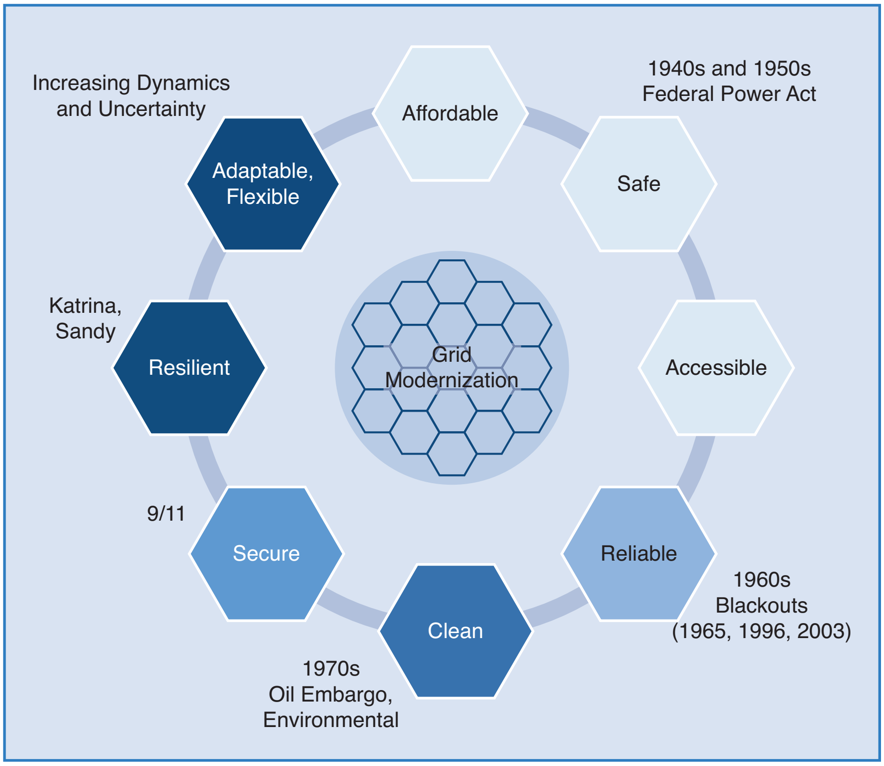

figure 3. The eight key attributes of a future electricity system, defined by the DOE GTT.

Analyze and Manage Interdependencies

Electricity delivery and other critical infrastructures (e.g., communications, water, and transportation) are interconnected and mutually dependent. The interdependencies among critical infrastructures and the potential for cascading effects of disruptions from one infrastructure to others are complex to analyze and manage. Although models and simulation tools are available to address aspects of individual infrastructures, a comprehensive framework for interdependency modeling and simulation is needed to allow for coupling or integrating multiple disparate models and simulations to conduct cross infrastructure analysis to address the threat assessment, preparedness, mitigation, response, and recovery issues.

Ongoing Resilient Grid R&D Projects

To address some of these near-term needs, the DOE Smart Grid R&D Program has launched several projects over the last two years. These projects and their progress, achieved or planned, are highlighted as follows.

Conceptual Framework for Developing Resilience Metrics

In response to the need for quantitative, risk-based resilience metrics, Sandia National Laboratories has introduced an iterative process for resilience analysis and a conceptual framework for developing metrics. This framework would result in representing the developed metrics as probability density functions (PDFs) of consequences from one or more threats to a system such as the electric distribution grid. A notional example of a PDF, expressed as probability of consequence versus consequence, is shown in Figure 4. The metrics are used to not only measure an existing system's resilience to extreme events but also analyze alternative investment scenarios for resilience improvements. The analysis process and conceptual framework were presented in a stakeholder workshop convened by the DOE in June 2014. A report was published by Sandia, stating that continued research is needed in the following areas, among others:

- ✔ improved quantification of human/societal consequences based on reduced system performance in a disruption

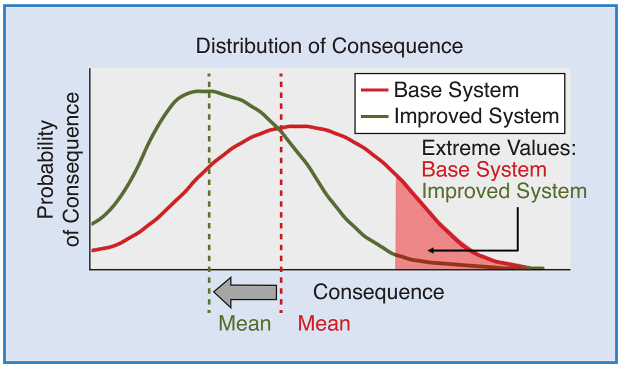

figure 4. The resilience metric, represented as a PDF, and its use to compare the improved resilience of the system with an investment alternative (red trace) to an existing, unimproved system (green trace).

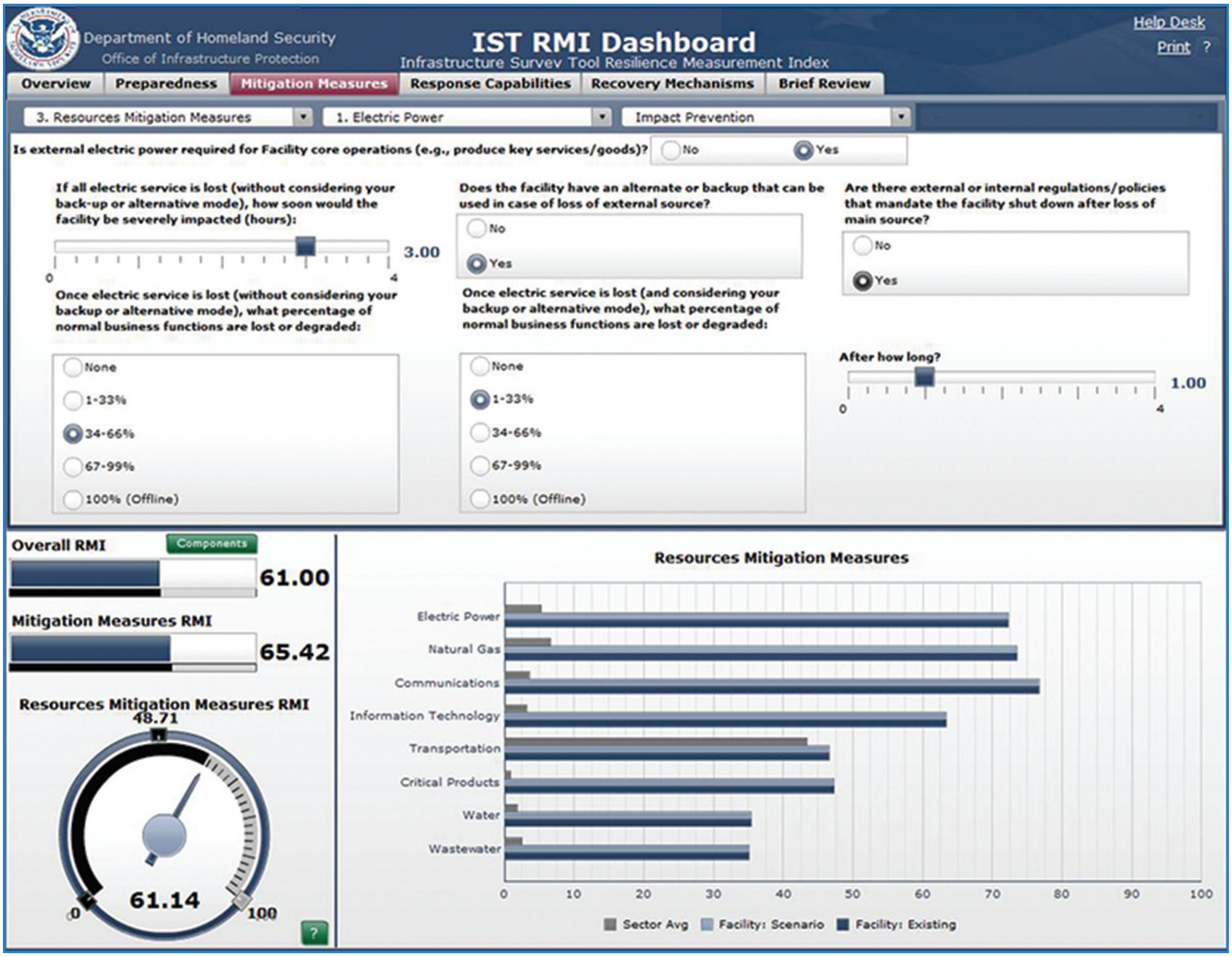

figure 5. A notional IST RMI dashboard with its component indices for transportation facilities.

- ✔ the development of a library of suggested capabilities and recommended methods for translating those capabilities and system performance to common consequence measures
- ✔ definitions of the decision types that will use resilience metrics
- ✔ the standardization of metrics with consensus among stakeholders.

Electric Resilience Assessment Program–Distribution (ERAP-D) Tool

Under the support of the Department of Homeland Security's (DHS) Regional Resilience Assessment Program (RRAP), Argonne National Laboratory has developed the infrastructure survey tool (IST), which is designed to be applicable to collect and assess protection and resilience information from facilities in all 16 critical infrastructure sectors. The IST involves the use of a Web-based survey tool to collect protective and resilience measures at a facility, as well as a developed procedure to use the collected data to estimate a resilience measurement index (RMI) to facilitate comparisons among the surveyed facilities. To date, more than 1,800 assessments have been conducted using the methodology across the United States.

The development of the ERAP-D tool is building upon the current IST by revising the questions used to survey electric utility operators and by determining weighting factors for each resilience question and topic to calculate an index for the four resilience domains (preparedness, mitigation measures, response capabilities, and recovery mechanisms). The indices will then be combined into an overall measure of resilience (i.e., RMI) for distribution utilities. An illustrated example of the RMI and its four component indices for transportation facilities is shown in Figure 5.

This project is eliciting the information (questions and weighting factors) required to assess the resilience of electric distribution utilities. Once the tool is fully developed in 2016, it is intended to be used by distribution utilities to conduct self-assessments using a holistic approach to grid resilience that includes assessing physical infrastructure and company plans, policies, and procedures. The DOE Smart Grid R&D Program plans to provide technical support to electric utilities and other entities interested in using the tool.

> An urgent need exists to enhance the resilience of our nation's electricity delivery infrastructure to reduce the impact from natural disasters and climate change events.

Distribution Resilience Design Tool

This object of this project by Los Alamos National Laboratory (LANL) is to create a decision support tool for designing resilient distribution grids and selecting optimal resilience upgrades for existing distribution grids. This tool will enable distribution grid designers to discover and prioritize cost-effective system upgrades and expansions that enable the utility to minimize future damage to their grid and outages to customers through improved, cost-effective designs. The project is leveraging many existing modules developed under the DHS National Infrastructure Simulation and Analysis Center at LANL for predicting infrastructure impacts of major natural disasters. In fiscal year (FY) 2014, LANL adapted a probabilistic damage model for distribution grid components under ice/snow storm conditions and integrated the component damage models and a distribution power solver into a network optimization tool to predict distribution system impacts as well as provide decision support analysis. The tool capabilities for modeling the fragility of key distribution grid equipment to ice/snow storm hazards, distribution system impacts resulting from the damage, and the design of system upgrades to improve resilience were presented.

Ongoing project activities include testing, evaluating, and demonstrating a prototype of the optimal resilience tool for multiple hazards (ice and flooding). Out-year work will include incorporating restoration models and optimization into the design tool, following the design process flow shown in Figure 6.

Microgrids Enhancing the Resiliency of Distribution Systems

Pacific Northwest National Laboratory and Washington State University are working together to examine the use of microgrids as a resiliency resource. Dynamic simulation capabilities and a power system model have been developed and used to examine reconfiguration and restoration strategies that will allow microgrids to operate as a resiliency resource at the customer and community level. The former involves having generation assets within a microgrid serve only local loads, while the latter involves serving critical loads outside of the boundaries of the microgrid as well. An extended application of having microgrids act as a black start resource is being studied in FY 2015, such as supporting the auxiliary systems (e.g., feed water pumps and condensate pumps) necessary to bring a thermal plant online during grid outages. This will include examining the impact on existing protection schemes and expanding the existing dynamic system model to include portions of the local serving utility's subtransmission system so that additional system constraints such as subtransmission charging inrush and generator reactive power limits can be studied.

In addition, the DOE recently awarded more than US$8 million to seven microgrid projects to help cities and towns better prepare for extreme weather events and other potential electricity disruptions, in support of President Obama's Climate Action Plan and the Administration's commitment to improve

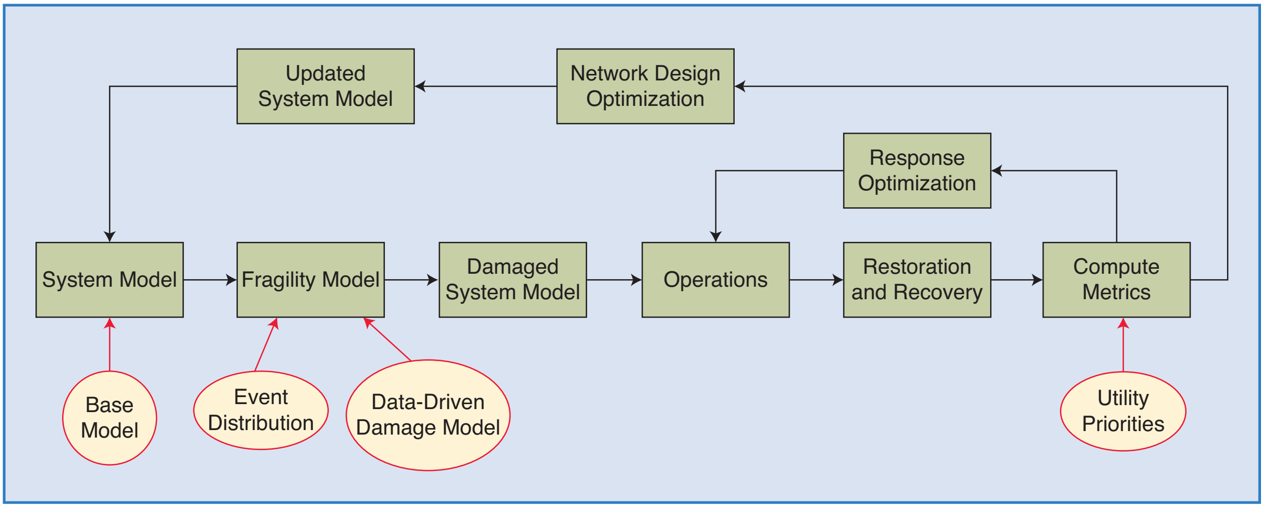

figure 6. A resilience design process flow for the development of the distribution resilience design tool.

> The development of new materials and designs for electric systems and components to be more resilient to extreme events is needed.

national power grid resiliency. The projects will bring together communities, technology developers and providers, and utilities to develop advanced microgrid controllers and system designs for microgrids fewer than 10 mW in capacity.

Conclusions and the Path Forward

As the nation's energy infrastructure is primarily owned and operated by the private sector, partnerships across all levels of government and the private sector are required for the pursuit of the R&D identified in this article. Tools, technologies, and methodologies developed through public/private partnerships will then need to be implemented, such as through select pilots in regions with diverse characteristics (e.g., energy sources and issues, and climate-related threats) to provide valuable data and feedback for improvements and build confidence for national replication.

The DOE will continue its public/private partnership approach—from planning and development to technology transfer to industry and end users for implementation—to help communities better prepare for the impact of severe climate events. Smart grid technologies deployed under the DOE Smart Grid Investment Grant Program have helped utilities in improving service reliability and strengthening resilience to major storm events. Following the climate action champions announcement, the DOE issued a funding opportunity announcement (FOA), "The Resilient Electricity Delivery Infrastructure (REDI) Initiative," to local and tribal governments to help deploy smart grid technologies/tools to improve climate preparedness and resiliency in their communities. Project selection criteria include, but are not limited to, measurable and tangible improvements in resiliency, robustness, and recovery; replicable and scalable for national deployment; and leveraging investments from the private, public, and/or philanthropic organizations. The DOE anticipates making the REDI FOA selection announcement by the end of June 2015.

Going forward, the DOE is planning for a stakeholder workshop in June 2015 to seek further feedback on the R&D need areas for a resilient distribution grid. The Resilient Distribution Grid R&D plan will then be finalized after feedback is incorporated. The priority needs and projects identified in the plan will be implemented by the DOE Smart Grid R&D Program under public/private partnerships beginning in FY 2016. Finally, the DOE Smart Grid R&D Program will continue the path of expanding partnerships with additional states on microgrid deployments. These partnerships could include collaborative projects with the state of Connecticut's microgrid program, which offered US$45 million in three rounds to study microgrid design, engineering, and interconnection challenges; the US$40 million NY Prize Competition to protect and strengthen the electrical system in the face of major storms; and the state of Maryland's Resiliency through Microgrids Task Force to study the statutory, regulatory, financial, and technical barriers to the deployment of microgrids in Maryland.

For Further Reading

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Biographies

Dan T. Ton is with the U.S. Department of Energy, Washington, D.C.

W-T. Paul Wang is with the Energy & Environmental Resources Group, LLC, Pittsburgh, Pennsylvania.