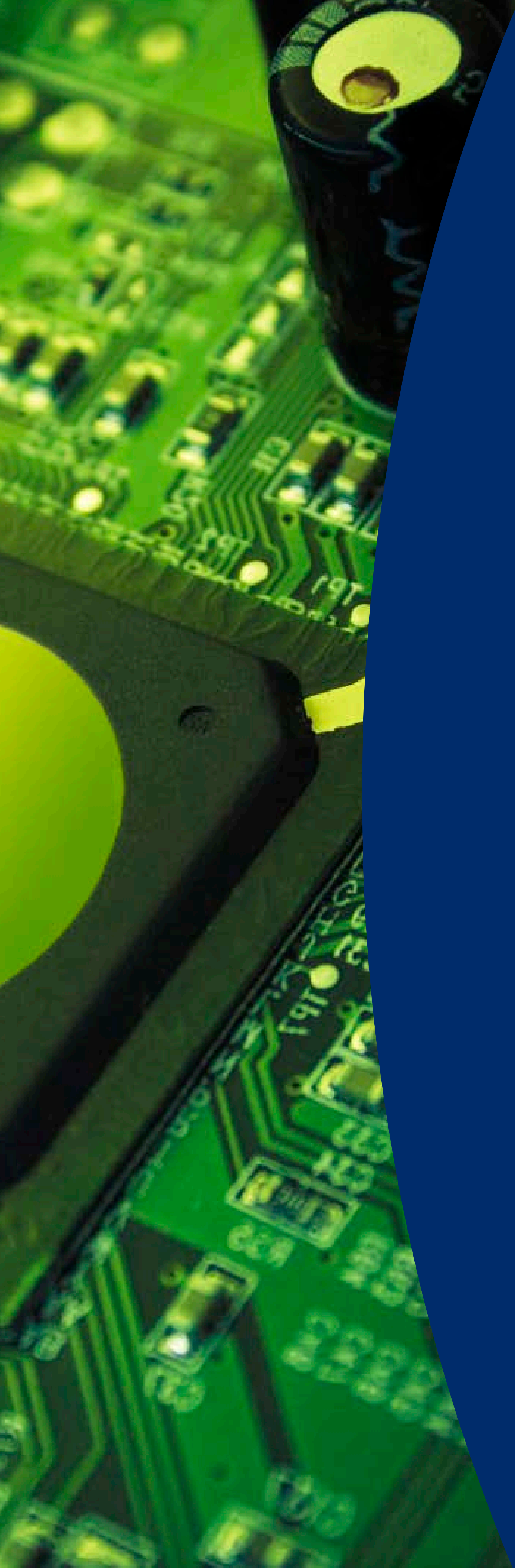
Foundations for Innovation

Strategic R&D Opportunities for the Smart Grid

Advancing measurement science and standards for smart grid technologies

March 2013

Report of the Steering Committee for Innovation in Smart Grid Measurement Science and Standards



STEERING COMMITTEE FOR INNOVATION IN SMART GRID MEASUREMENT SCIENCE AND STANDARDS

This report was prepared through the collaborative efforts of the individuals noted below. It reflects their expert contributions as well as the many insights generated at the *Workshop on Technology, Measurement, and Standards Challenges for the Smart Grid*, held August 13-14, 2012 in Boulder, Colorado.[1]

Committee Co-chairs

John McDonald, GE Energy

Mark McGranaghan, Electric Power Research Institute (EPRI)

Working Group Chairs

Don Denton, Duke Energy

Abraham Ellis, Sandia National Laboratories (SNL)

Carl Imhoff, Pacific Northwest National Laboratory (PNNL)

David Mooney, National Renewable Energy Laboratory (NREL)

---

1. Workshop Report: : Technology, Measurement, and Standards Challenges for the Smart Grid. December 2012

CONTRIBUTORS

Tom Acker, Northern Arizona University
Mark Ahlstrom, WindLogics/NextEra Energy
Venkat Banunarayanan, U.S. Department of Energy (U.S. DOE)
Frank Barnes, University of Colorado
Tom Bialek, San Diego Gas and Electric Company
Nisa Bradley, Honeywell
Cameron Brooks, Tendril
Tim Brown, University of Colorado
Angela Chuang, Electric Power Research Institute
Angela Cifor, RASEI
Larry Clark, Alabama Power, a Southern Company
Frances Cleveland, Xanthus Consulting
Karin Corfee, Navigant Consulting, Inc.
Jeff Dagle, PNNL
Brian Deaver, EPRI
Don Denton, Duke Energy
Jennifer Drake, Tri-State Generation and Transmission
Erik Ela, NREL
Abraham Ellis, SNL
Robert Erickson, University of Colorado
Paul Flikkema, Northern Arizona University
Ryan Franks, National Electrical Manufacturers Association (NEMA)
Erik Gilbert, Navigant Consulting, Inc.
Frank Goodman, San Diego Gas and Electric Company
Steve Hauser, New West Technologies, LLC
Jonathon Hawkins, PNM
Tim Heidel, U.S. DOE
Gregor Henze, University of Colorado
John Holmes, San Diego Gas and Electric
Marija Ilic, Carnegie Mellon University
Carl Imhoff, PNNL
Rebecca Johnson, Colorado Public Utilities Commission
Lawrence Jones, Alstom Grid
Landis Kannberg, PNNL
Mladen Kezunovic, Texas A&M University
Peter Klauer, California ISO
Ben Kroposki, NREL
Eugene Litvinov, ISO-NE
Dragan Maksimovic, University of Colorado
David Malkin, GE Energy
Art Mander, Tri-State G&T
Paul Molitor, NEMA
David Mooney, NREL
Karina Muñoz-Ramos, SNL
Russell Neal, Southern California Edison (SCE)
Damir Novosel, Quanta Technology
Terry Oliver, Bonneville Power Administration
Mark Osborn, Pacific Gas and Electric (PGE)
Brian Parsonnet, Ice Energy
Melissa Peskin, Dominion Voltage, Inc.
Jack Peterson, SCE
Jill Powers, California ISO
Rob Pratt, PNNL
Saifur Rahman, Virginia Polytechnic Institute and State University
Wanda Reder, S&C Electric Company
Adam Reed, University of Colorado
Roland Roesch, IRENA
Brad Rogers, Navigant Consulting, Inc.
David Rolla, Hawaiian Electric Co.
Mike Rowand, Duke Energy
Joe Schatz, Southern Company
Charlie Smith, GE Appliances
Frank Stern, Navigant Consulting, Inc.
Thomas Tobin, S&C Electric Company
Aidan Tuohy, EPRI
Joe Waligorski, FirstEnergy
Steve Widergren, PNNL
Lynn Worrell, Xcel Energy
Bob Zavadil, EnerNex

WORKSHOP ON TECHNOLOGY, MEASUREMENT, AND STANDARDS CHALLENGES FOR THE SMART GRID

To facilitate smart grid interoperability standards and advanced technology, NIST and the Renewable and Sustainable Energy Institute (a collaboration between the University of Colorado and the National Renewable Energy Laboratory) hosted a workshop in Boulder, Colorado, on August 13–14, 2012. This invitational event brought together technical experts and industrial leaders in fields directly related to the smart grid. The workshop was consensus-oriented and considered four fundamental areas of the smart grid (i) integration of large, utility-scale, renewable energy with the grid; (ii) integration of distributed generation and energy storage with the grid; (iii) energy efficiency, demand response, and load control; and (iv) grid efficiency, reliability, security, and stability. Discussions focused on the current state of the smart grid, future goals and vision, major technological and other challenges, and research and measurement science prioritization. A workshop summary technical report was issued in December 2012. Building on the workshop report, the Strategic R&D Opportunities for the Smart Grid provides a high-level perspective of the key challenges and strategic R&D opportunities for advancing the smart grid. The report will be used by public and private stakeholders to inform decisions about the technology R&D that should be pursued, as well as new measurement methods and standards that must be developed to realize the potential of the smart grid.

CONTENTS

INTRODUCTION 2

A CALL TO ACTION 3

BENEFITS TO THE NATION 4

BROAD CHALLENGES FOR THE SMART GRID 6

TECHNICAL CHALLENGES 6

INSTITUTIONAL, SOCIETAL, AND OTHER CHALLENGES 9

STRATEGIC R&D OPPORTUNITIES 10

PLANNING AND OPERATIONS 12

OPPORTUNITY 12
Optimize smart grid capabilities for system planning and operations 12

OPPORTUNITY 18
Develop Smart Tools and Technologies to Utilize Demand Response, Demand Load Control, and Energy Efficiency 18

ENABLING INFRASTRUCTURE 20

OPPORTUNITY 20
Expand and upgrade infrastructure to improve communications and interconnectivity

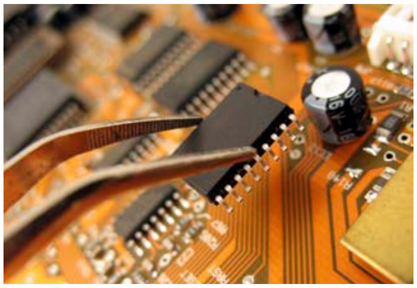
OPPORTUNITY 21
Develop infrastructure to assure cyber security and resilience

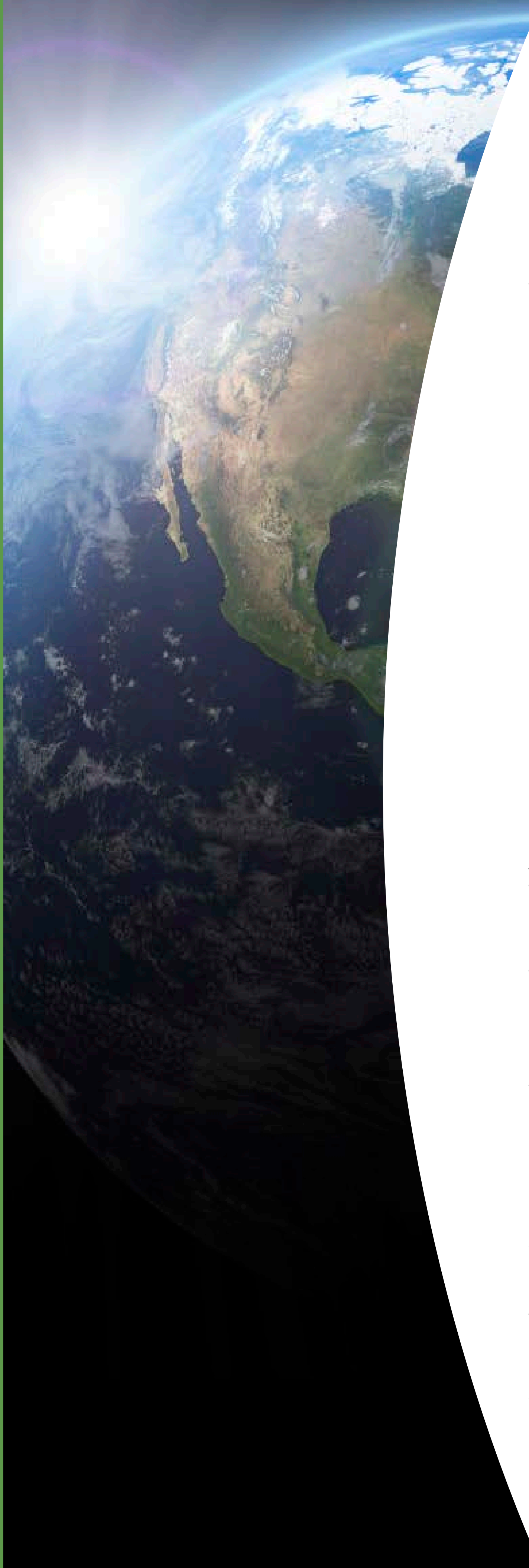
OPPORTUNITY 22
Create models to foster smart grid investment and inform regulatory frameworks

CONCLUSION 24

CITATIONS AND REFERENCES 26

ACRONYMS AND ABBREVIATIONS 28





INTRODUCTION

The U.S. electricity system, sometimes referred to as the "grid," is a vital national asset that powers homes, businesses, factories, and communication systems. It is a highly complex "system of systems," composed of thousands of conventional central-station power plants as well as a growing number of grid-tied renewable energy generating systems (primarily photovoltaics [PVs] and wind), plus the accompanying transmission lines and distribution systems. Much of this infrastructure has been in existence for many decades, and is burdened by aging equipment and control/monitoring systems that are increasingly susceptible to reliability failures and compromises of data security.

In addition, major innovations in generation technology, grid topology, and producer-user interaction are now appearing. One significant example is the increasing integration of renewable energy deployments. It is anticipated that renewables will grow rapidly and become both widespread and an important part of the domestic electric supply in the next two decades. Because of the variable nature of solar and wind resources, the grid must be re-engineered to accommodate this nascent but inevitable trend. Another example is seen in plug-in electric vehicles (PEVs). These will require special grid capabilities and might afford needed energy storage to accommodate variability and peak load.

The grid must be overhauled to improve power delivery efficiency, integrate renewables, improve reliability, and enhance cyber security for producers and users. This effort, already underway, will be accomplished by the so-called "smart grid." The smart grid is a cyber-physical approach to power grid design and operation. It will be heavily dependent on a wireless environment for metering, fault detection, and power quality characterization. The smart grid will allow sophisticated bi-directional secure data transfer, and it will provide increased producer and user awareness and controllability of electric power in essentially real time.

The assurance of equipment interoperability and secure data transfer is essential to smart grid development, demanding a corresponding system of interoperability standards. The National Institute of Standards and Technology (NIST) plays a vital role in this regard. NIST is charged by the 2007 Energy Independence and Security Act with facilitating interoperability standards for the evolving smart grid. This task is pursued through in-house research and the creation and support of the Smart Grid Interoperability Panel (SGIP), a private-public partnership between NIST and the power generation and electric equipment communities.

There is broad consensus that substantial investments are needed to modernize the electricity system through new technology and other improvements. Between 2010 and 2030, estimated costs for modernization range from $340 billion to $480 billion (EPRI 2011); however, benefits are estimated at $1.3 trillion to $2 trillion over 20 years—roughly three to five times the investment. Despite the projected value, expenditures for improvements are expected to fall about $107 billion short by 2020 (Economic Development 2011). This growing investment gap is likely to increase the potential for electricity interruptions due to inadequate equipment and capacity bottlenecks. Both public and private expenditures could make an impact on the investment gap. Private investment in electricity infrastructure is affected by many factors, such as private capital loan and bond markets, perceived economic risks and uncertainties, public policies and regulation, electricity rate approval processes, and siting of facilities.

The smart grid uses monitoring, communication, control, and automation to improve the way electricity is generated, distributed, and consumed. A smart grid will be able to analyze, protect, and optimize the operation of its interconnected components, from electricity generation systems to high-voltage transmission and distribution networks to collaborating with consumer end-use systems. The same smart system will provide customers with the data and tools they need to manage their energy use and make energy choices and investments that meet their individual needs and increase efficiency. Through the smart grid, electricity providers and users can become partners in creating a sustainable and economical electricity system.

A CALL TO ACTION

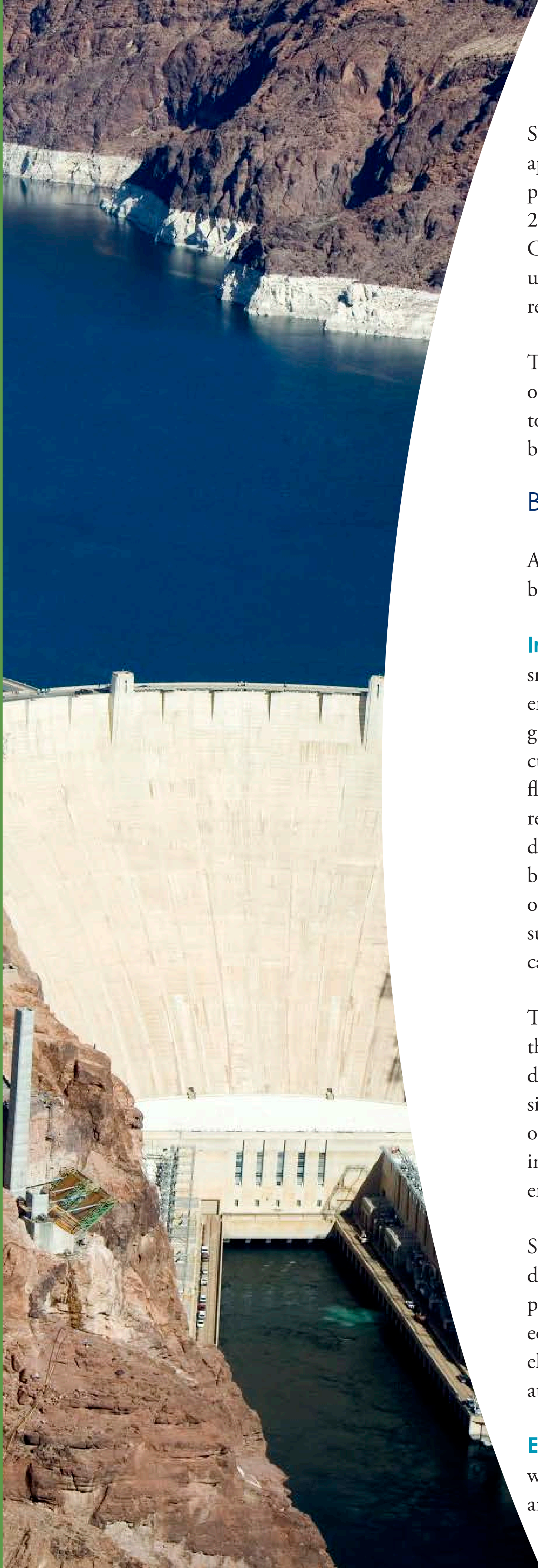
The smart grid will profoundly transform the generation, transmission, distribution, and consumer end-use of electricity in the United States. Reaching this potential will require development and integration of entirely new technologies, infrastructure, and computational systems. The integration of these technologies will require seamless interoperability; bidirectional communications; and the ability to exchange, parse, and act on many forms of data. In some cases, these systems will need to respond to unforeseen conditions and interact safely and securely with both humans and machines. New levels of cyber security and protection of privacy will overlay all of these requirements.

Achieving these capabilities presents complex and multidisciplinary engineering challenges. Science and engineering advances are needed to accelerate innovations in the design and development of leading-edge smart grid systems. Scientists and engineers working in the physical sciences will need to interact closely with their counterparts in computer and information science and agree on common languages and protocols to ensure robust, workable designs.

Smart grid technology is essential to electricity system modernization

"A 21st century electric system is essential to America's ability to lead the world and create jobs in the clean-energy economy of the future.... In the face of an aging grid, investing in the grid's infrastructure is crucial. Given this imperative, there is an opportunity to update the grid's efficiency and effectiveness through investments in smart grid technology."

Executive Office of the President, National Science and Technology Council, A Policy Framework for the 21st Century Smart Grid: Enabling Our Secure Energy Future. June 2011.



Several reports outline the technical challenges and potential approaches for overcoming key barriers to the smart grid, providing federal, state, industrial, and global perspectives (IEC 2010, Zpryme Research 2012, Schuler 2010, NIST 2012, California ISO 2010). Research and development (R&D) is underway on a number of fronts, but critical gaps in capability remain to be tackled.

This report is a call to action. It outlines a set of strategic R&D opportunities that must be addressed to enable the smart grid to reach its potential and deliver broad societal and economic benefits to the nation.

BENEFITS TO THE NATION

Adopting a smart grid will provide a multitude of lasting benefits.

Increased generation reliability and flexibility: A smart grid will more efficiently accommodate use of renewable energy resources, such as wind and solar, as well as enable greater use of storage and demand response (DR). While the current electric grid was originally designed to enable energy flows from large generators to consumers, a smart grid can more readily accommodate distributed generation (DG). To do this, distribution systems must accommodate bidirectional flows. This bi-directionality allows the grid to accommodate larger amounts of electricity provided by multiple, small, distributed sources, such as rooftop photovoltaic panels, fuel cells, and even electric car batteries.

Through sophisticated data collection and analytic capabilities, the smart grid provides operators with a broader and more detailed look at the power infrastructure and enables wide-area situational awareness. This knowledge enables rapid, informed operator decision making, which can optimize performance, improve reliability, and enhance use of renewable and distributed energy.

Smart grid tools and technologies will also improve fault detection and enable self-healing of the power network, potentially reducing manual field tasks to identify and resolve equipment failures. The result will be a more reliable supply of electricity and greater resiliency in the face of natural disasters or attack.

Economic growth: Constructing and operating a smart grid will grow the economy by creating demand for new products and services, such as advanced communications and equipment, mobile networks, smart appliances, and new software to support consumer participation. New revenue streams could arise from investments in DR, DG, and energy storage. Smart-grid-related technologies and services have been expanding rapidly; by 2014, they are projected to grow to nearly $43 billion in the United States, and to more than $171 billion globally (Zpyrme 2009). Through better market and operating efficiencies, reduced supply cost, and greater customer involvement, the smart grid will enable more efficient markets and lower electricity prices.

Engine for jobs generation: The smart grid can potentially create thousands of new jobs. A recent study shows that employment in Silicon Valley and the San Francisco Bay Area's smart-grid-related sectors rose 129% while total employment rose only 8% since 1995—persisting through the 2007 recession (SVSGT 2011). Other reports predict that as many as 140,000 permanent, high-paying jobs could be created between 2009 and 2018 due to smart grid investments (KEMA 2011).

Improved efficiency: Smart grid tools will empower suppliers and consumers to strategically monitor and control their energy production and consumption, particularly during high-cost, peak-usage periods. For example, a smart grid can help a large customer to reduce load and or increase local generation temporarily when resources are limited or prices are high. The smart grid would also allow utilities to increase reliability by communicating with devices directly to prevent system overloads. Using DR tools, customers will receive real-time information on electricity supply conditions, enabling them to reduce their consumption at critical times or in response to market prices. With a smart grid, both generators and demand can be controlled automatically in real time, avoiding the need to deploy additional transmission and generation capacity to deal with spikes or peaks in load. Eliminating spikes in demand reduces the cost of adding generators, extends equipment life, and allows users to cut energy bills by using energy when the cost is low.

Enhanced security: The smart grid's secure communication and decision-making interfaces will reduce the threat, vulnerability, and consequences of deliberate physical or cyber attacks. The greater robustness possible with the smart grid will also reduce the consequences of interruptions due to storms and other natural events. The result will be greater assurance that the grid is less likely to be vulnerable to terrorist or other threats.

More sustainable electricity system: The smart grid promotes sustainability and reduces environmental impacts by enabling more penetration of clean, renewable energy sources such as wind and solar. Efficiency gains possible through smarter management of electricity generation, delivery, and use will reduce emissions of air pollutants as well as greenhouse gases such as carbon dioxide. The smart grid will also make possible integration of electric-powered vehicles, which reduce tail pipe emissions and can serve as valuable energy storage units that can be drawn upon during peak loads and help ameliorate the effects of the variability of renewable energy resources.

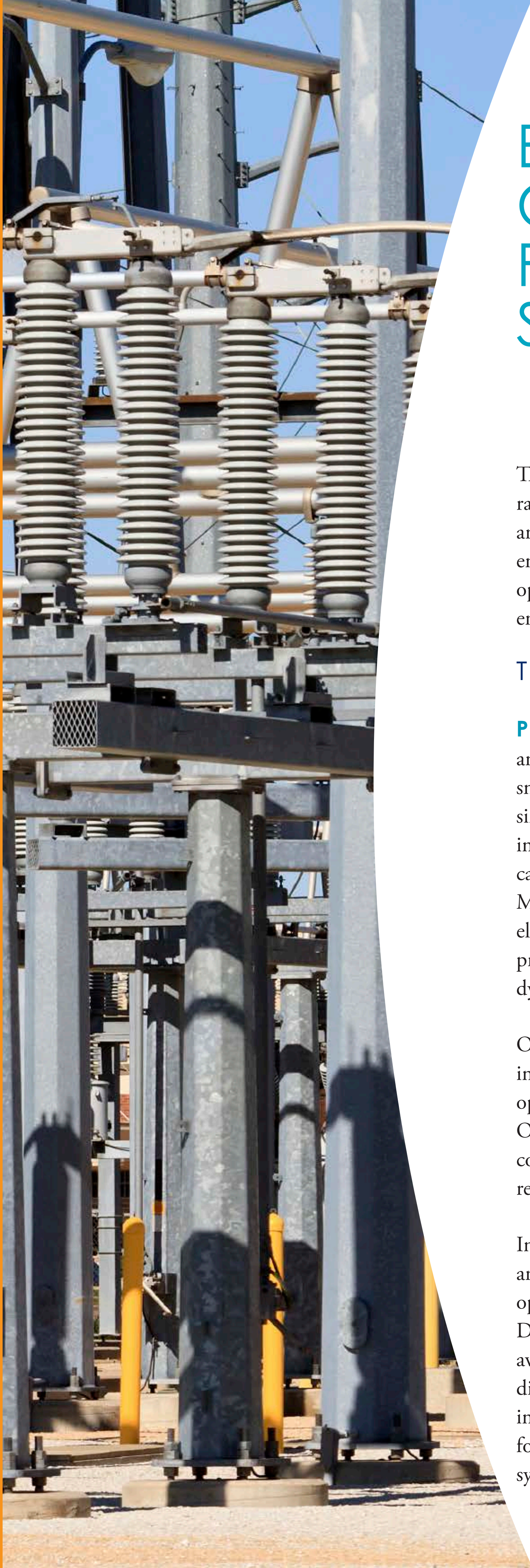
Smart grid technologies and applications give rise to cross-cutting benefits

"…enabling a clean energy economy with significant use of renewable energy, distributed resources, electric vehicles, and electric storage;

Creating an electricity infrastructure that saves consumers money through greater energy efficiency; and

Enabling technology innovation that creates jobs…and new opportunities for consumers to use energy wisely and reduce their energy bills."

Executive Office of the President, National Science and Technology Council, *A Policy Framework for the 21st Century Smart Grid: Enabling Our Secure Energy Future*. June 2011.



BROAD CHALLENGES FOR THE SMART GRID

The smart grid continues to face broad challenges reflecting a range of technical, institutional, and societal issues. Barriers arise at all stages of development, from fundamental science and engineering research through demonstration, deployment, and operations. Addressing the most critical of these will help to ensure that the future potential of the smart grid is realized.

TECHNICAL CHALLENGES

Planning and operations models: Simulation models are currently lacking to evaluate the performance of the future smart grid. Models also lack the sophistication needed to simulate the impacts of cyber infrastructure and markets, and interconnections with physical devices. High-fidelity forecasting capability is also lacking for improving dispatch decisions. Modeling, analysis, and valuation related to residential price elasticity of demand are often hindered by a lack of consistent probabilistic modeling methods for load forecasting under dynamic pricing.

Operators also lack sufficient visibility of situational awareness; increasing visibility, including uncertainties, would improve operational decisions while ensuring reliability and optimization. Operators are unable to adjust decision logic based on changing conditions created by dynamic data and in step with rapid responses required by the increased resource choices.

In distributed energy resource (DER) systems, communications are not clearly articulated between DERs and system grid operation. System operators are generally not familiar with DER dispatch at the system level and lack effective situational awareness of these sources (e.g., changes in performance, disruptions, etc.). This impacts the ability of operators to incorporate large amounts of DERs while still accurately forecasting loads and maintaining grid reliability. Optimizing system operations for large penetrations of DERs is a substantial challenge requiring advanced control system architectures to coordinate decision making on distribution networks.

Appropriate metrics are not currently available for evaluating the performance of the smart grid, including the impact of renewable energy and load uncertainty, DERs, storage, and new smart grid capabilities. These metrics should be quantifiable and useful to drive operations and planning decisions.

Information management: Data generation has grown exponentially, and this trend is expected to continue. With the pending deployment of billions of advanced sensors that enable communication among devices, enormous amounts of data will be available. This creates new challenges in mining, analyzing, storing, and managing large data sets so that meaningful information can be extracted for grid optimization, load balancing, business planning, and other purposes. While central sharing of data repositories, data usage information, and applicability of data increases each year, compatibility of data sets continues to be an issue.

Cyber security: Uncertainty in the security and privacy of data as well as information access (e.g., data access rights) hinders the adoption of some smart grid solutions. The smart grid information technology (IT) perimeter has expanded to include systems outside the grid, generating beneficial data but also creating new security issues. Good security foundations and models must be in place to ensure data security, grid safety, and advancement of smart grid technologies.

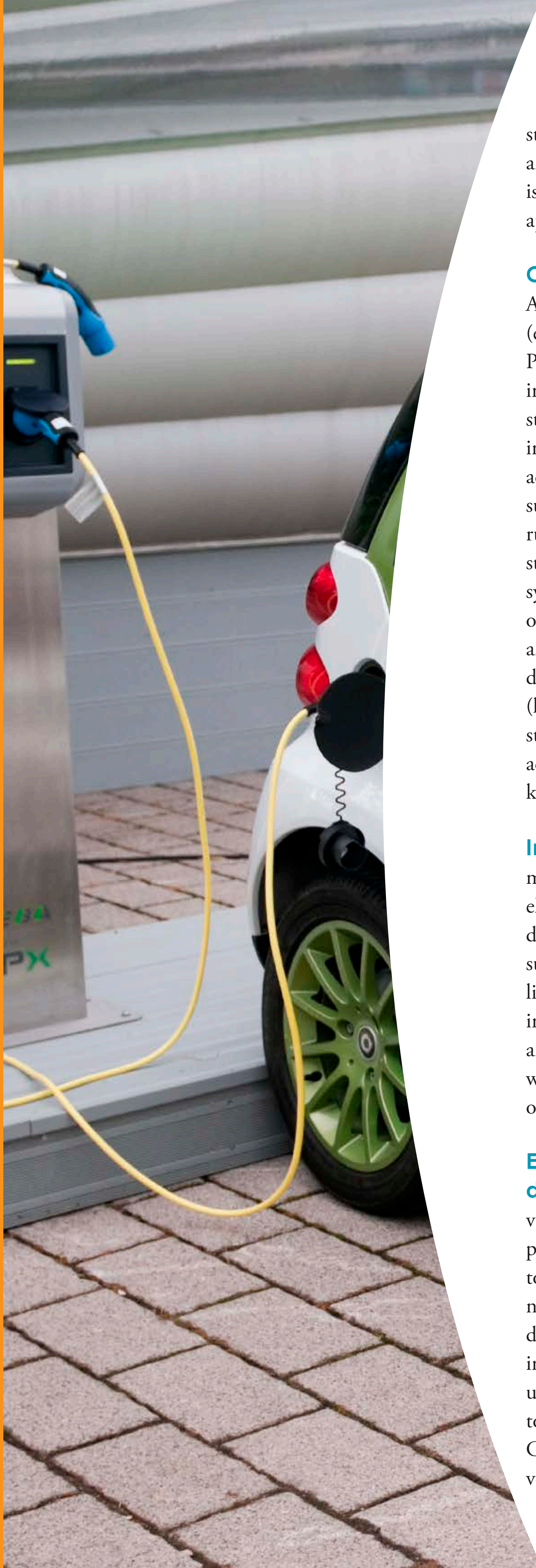
Load and resource scheduling and dispatch: Today's operating practices do not adequately support voltage scheduling and real power generation with renewables in the mix. While there is a trend toward increasing application of power electronics and inverter-based renewable generation, grid compatibility standards (grid codes) vary greatly and must be revised to address the management of inverter-based renewable generation versus conventional generation. Balancing authorities currently manage load and resource dispatch for DERs, which does not encourage or enable broad deployment. In addition, good models for incorporating DERs and identifying how to determine optimum load and resource balance are limited. This creates a significant challenge when trying to incorporate a large number of DER installations.

Infrastructure: Existing infrastructure is aging, and replacement with new technologies could be impeded by cost, risk, and learning curves. Efforts are underway to expand the grid measurement infrastructure (e.g., smart meters, phase measurement units [PMUs]), but it is still uncertain how this will support transmission planning and operation. A clear direction for future grid architectures has yet to be defined.

Energy storage: Energy storage is at a nascent stage of development and deployment, and it is underutilized due to the limited versatility and high costs of current technology. For example, different control regimes require a range of cycling types that are largely unanticipated by storage manufacturers. As a result, storage devices must be operated in a limited

"...The smart grid will depend on interfaces that allow home appliances, electric cars, homeowners, building operators, electricity generators, distribution network operators and many other participants to interact with the grid and make efficient energy choices."

(PCAST 2010) Report to the President and Congress. Designing a Digital Future: Federally Funded Research and Development in Networking and Information Technology. December 2010.



state of charge range, which makes evaluation of storage difficult and creates implications for guarantees and warranties. There is a lack of consensus on which storage technologies are most applicable for the smart grid.

Communications standards and protocols: Although some communications standards are being developed (e.g., 61400-25, SGIP Priority Action Plan 16 for Wind Plant Communications), gaps in both communications and interconnection standards for renewables and DERs are still significant. For example, current communications and interconnection standards and regulations are inadequate to address data interfacing requirements. Regulations for grid support functions are relatively undefined and data exchange rules among enterprise applications are lacking. Lack of standardization creates system inefficiencies, prevents full system optimization, and inhibits data exchange between all operational units (e.g., distribution, transmission, generation, and consumers). In many cases, systems have progressed at different rates, employing both new and old technologies (legacy) with different communication capabilities, making standardization more problematic. For DERs, the lack of adequate communications between DERs, loads, and utilities is a key factor inhibiting large-scale integration.

Interoperability standards: Standards for interoperability make coordination possible between all components of the electric system. Significant effort has been made toward development of these standards (NIST 2012). In some areas, such as DERs and energy storage, standards exist but are limited. For example, practical realizations of “plug and play” interoperability for DERs do not exist from technical, economic, and business perspectives. DERs interconnect with the system without a means to coordinate functionality, and therefore they operate on a local, autonomous basis.

Energy efficiency, demand response, and demand load control: Real-time measurement and visibility of non-generation resources is currently limited, partially because market structures are incapable of reacting to these resources. As a result, there are few incentives and no avenue to provide visibility of these resources down to the distribution level. Data best practices for distribution-level instruments and systems are thus lacking (types of data, data users, and purpose). Stakeholders will require data visibility to implement effective DR and efficiency customer programs. Current methodologies for evaluation, measurement, and verification (EM&V) for energy efficiency (EE), DR, and DLC currently vary across proponents, markets, organizations, and regulatory bodies and lack sufficient credibility. A drop in electricity prices generally de-emphasizes DR and dynamic pricing. The uncertainty in payback due to low prices creates a difficult planning environment for businesses that are focused on DR and causes uncertainty in investment.

INSTITUTIONAL, SOCIETAL, AND OTHER CHALLENGES

Privacy: Consumers generally want to protect or have control over the release of personal information that may reveal their behavior or habits. In smart grid deployment, this desire manifests as a resistance to the installation of smart meters that allow the consumer to better understand their energy use and enable utilities to gather usage data. In spite of the potential benefits, some communities are banning the use of smart meters rather than embracing them. Misinformation and/or inadequate education of the general public about smart grid technologies are major contributing factors.

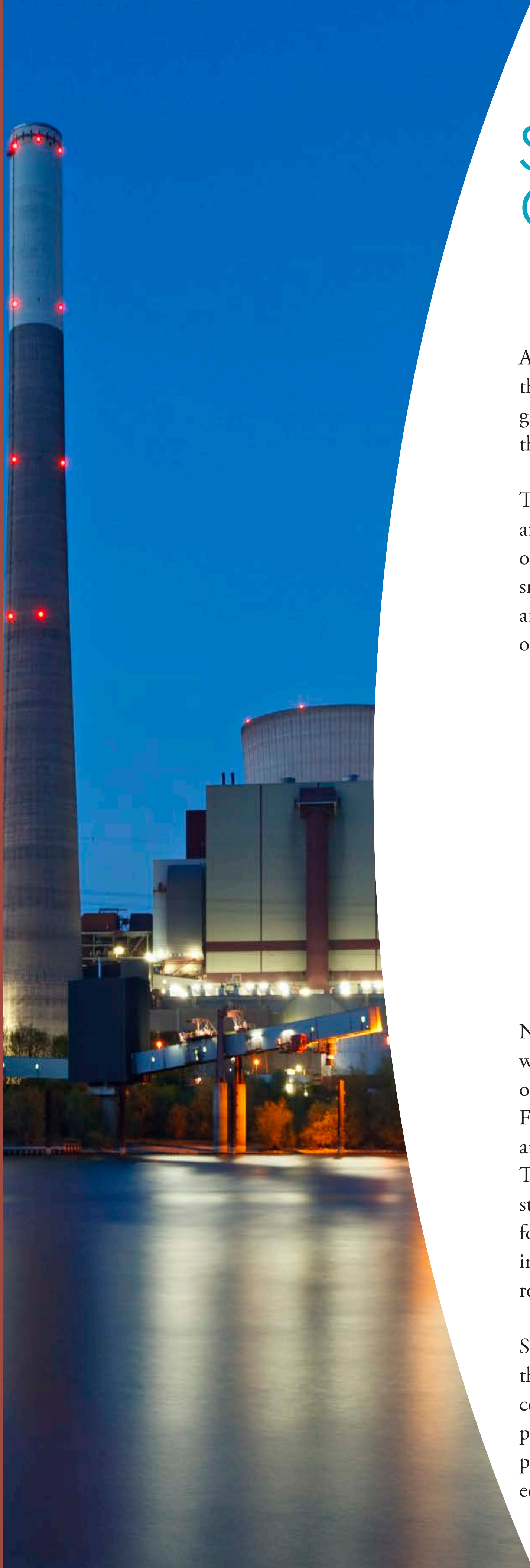
Policy and regulation: Managing the grid can involve navigating a complex patchwork of protocols and policies that are issued by multiple entities. In addition, coordination at the federal level and among states and utilities on smart grid policies is insufficient, creating uncertainty and a business environment that is not supportive of risk-taking and innovation. Complex jurisdictional and policy issues, permitting, and differences among state, federal, and interstate policies create impediments. Thousands of utility companies operate under more than 50 regulatory bodies and rate structures. Coordinated policies and regulations among stakeholders and regions are important to stimulate investment and growth in the smart grid.

Regulatory practices also do not appropriately value DERs, creating significant limitations to widespread integration of DG and storage technologies. More flexible regulatory models that go beyond dollars per kilowatt-hour to include innovative rate structures and decoupling would create greater incentives for broader deployment of these sources. Utility regulations also currently do not allow private distribution of DG to customers.

Regional planning and coordination: Effective communication among the diverse stakeholders involved with the smart grid presents planning and operational challenges. For example, the existence of many small balancing authorities across large service areas (each operating its own infrastructure) can delay operational optimization. The lack of communication standards and protocols for information exchange among balancing authorities and other entities exacerbates this problem. Market agility also varies widely by region; intra-hour transactions are not supported in some areas, which results in balancing performed with more expensive generation sources. While many (but not all) regions are beginning to coordinate operational scheduling and cross-state transmission planning, it is not happening as rapidly as the growth of wind and solar generation, particularly in geographic areas with greater potential.

Market fragmentation: The marketplace for smart grid technology is highly fragmented. The lack of a common vision between utilities and independent system operators (ISOs) for the smart grid and the residential sector in particular has led to manufacturers having to address many different solutions. Current utility and ISO requirements are heterogeneous, making broader applicability of devices a challenge. No two utilities have the same solution and devices must be able to be integrated into unique systems.

Business case for smart grid technologies: New technology can be costly to implement. Investments in smart grid are complicated by uncertainties over who should pay for upgrades (e.g., consumers, utilities) and how and when these costs will be recouped. One of the underlying issues is that the distribution of monetary benefits (e.g., cost savings from smarter electricity) has not been clearly defined. The lack of clarity on the ability to recover costs continues to limit incentives to invest in smart electricity technologies. Making a strong business case also requires pulling information from multiple entities, which can be difficult because of information boundaries. Current rate structures and utility revenue models are not designed to promote or capture the value of DERs; very few models for the time value of energy pricing exist. Good business models are important because they provide the justification and rationale for investments into capacity planning and grid operations.



STRATEGIC R&D OPPORTUNITIES

A number of strategic R&D opportunities have been identified that are essential to development and deployment of the smart grid. While these emphasize measurement science and standards, they also include many other technological components.

The strategic R&D opportunities are summarized in Table 1 and described in depth on the following pages. They cover some of the areas where advances are needed to fully implement the smart grid, including key aspects of planning and operations and enabling infrastructure developments. The following are the objectives of the R&D opportunities outlined in this document:

- Optimize smart grid capabilities for system planning and operations
- Develop smart tools and technologies to utilize DR, DLC, and EE
- Expand and upgrade infrastructure to improve communications and interconnectivity
- Develop infrastructure to assure cyber security and resilience
- Create models to foster smart grid investment and inform regulatory frameworks

Needed advances in measurement science and technology, as well as standards development, are woven throughout these opportunities and impact nearly all aspects of the smart grid. For example, effective communication for system optimization and efficiency is hindered by a lack of standards and protocols. The ability to effectively take advantage of EE, DR, and DLC strategies is impeded by inadequate EM&V methods. Metrics for security, grid performance, and planning are insufficient, inconsistent, or do not exist. All of these challenges have strong roots in measurement science and technology.

Some of the R&D opportunities described are recurring themes that cut across multiple technology areas and consequently could have far-reaching impacts if addressed. They represent the priority research that has been identified as essential to advancing progress toward the smart grid and reaping the potential energy, economic, environmental, and societal benefits.

TABLE 1. STRATEGIC R&D OPPORTUNITIES FOR THE SMART GRID

Optimize Smart Grid Capabilities for System Planning and Operations		PLANNING AND OPERATIONS
Comprehensive models and tools for robust operations and planning	• Standard models to connect transmission, distribution, and communications • Comprehensive grid models and methods for load and resource balancing with consideration of DER, demand response and energy storage • Probabilistic models for load forecasting under dynamic pricing • Stochastic methods for operations and resource planning to enable optimization in the presence of high uncertainty • Improved variable generation forecasting • Visualization and analysis tools that provide situational awareness and other actionable information to operators	
Standards, procedures, and protocols	• Standards and associated metrics for equipment performance • Standards for communications interoperability • Efficient procedures for generator interconnection as well as transmission/distribution network expansion • Standardized methods for collecting and managing distribution-level operations data	
Control architectures and voltage management in distributed networks	• Scalable, reliable, secure control system architectures for coordinated, distributed decision-making • Hierarchical distribution-level voltage controls and communication	
Develop Smart Tools and Technologies to Utilize Demand Response, Demand Load Control, and Energy Efficiency		
Evaluation methods and frameworks for EE, DR, and DLC	• Evaluation, measurement, and verification (EM&V) methods • Frameworks to relate demand response to business objectives	
Expand and Upgrade Infrastructure to Improve Communications and Interconnectivity		ENABLING INFRASTRUCTURE
Communication and interconnection methods and technologies	• Communications infrastructure for multiple interconnections • Communications to optimize ancillary services • Methods for managing and extracting information from large and disparate data flows	
Develop Infrastructure to Assure Cyber Security and Resilience		
Models and topologies for improving security and resilience	• Cyber-physical design methods, metrics, and analytical tools • Flexible power system topologies and communications/control architectures	
Create Models to Foster Smart Grid Investment and Inform Regulatory Frameworks		
Cost-benefit and life cycle models for smart grid	• Economic models and uniform business metrics • Standard methods for life cycle analysis	

PLANNING AND OPERATIONS

Opportunity
Optimize smart grid capabilities for system planning and operations

The smart grid has the potential to streamline and improve the efficiency of the generation, transmission, and distribution of electricity—with major improvements possible in both planning and operations. Electric system planning is a complex process encompassing local, regional, and sub-regional perspectives. It includes a range of components such as peak load forecasting, risk management, reliability analysis, system steady state and dynamic responses, resource and load analysis, incorporating demand-side resources, and many other elements.

Grid operators incorporate aspects of planning to make daily decisions about resource and grid management, control, and performance. They also rely heavily on real-time information to be able to respond effectively to changes in demand or system availability. Through highly networked, computer-based monitoring, control, and automation of electric system components, the smart grid will provide better data for both planning and operations—while improving communications between the two.

COMPREHENSIVE MODELS AND TOOLS FOR ROBUST OPERATIONS AND PLANNING

The ability to comprehensively model all of the domains of the electric system will be necessary to take advantage of efficiency and other benefits possible through the smart grid. Better tools will help to ensure grid reliability and stability under dynamic conditions. While not all capabilities are needed immediately, some will be critical to effective planning and operations that incorporate more renewables and other flexible resources in the mix. The target outcomes are standardized, trusted models that are accepted and used by the industry for assessing the dynamics of performance and operations over all time scales and granularity.

Tools for improving situational awareness will help operators better anticipate, manage, and/or recover from interruptions or events (e.g., storms, equipment failure, or high demand), and make decisions about when and how to best integrate renewable and DG. Grid visibility and analytical decision tools are two integral and interrelated aspects of situational awareness. Visibility (i.e., how operators see what happens on the grid) occurs via data from sensors placed around the grid, reports from field crews dispatched to conduct manual inspections, or customer calls about outages or other issues. The smart grid can enhance real-time operator visibility by providing more and better data, automated reports and analysis, and advanced feedback and controls for decision support. New forecasting tools and advanced analysis that translate data into actions will be needed to fully realize smart grid capabilities.

Standard models to connect transmission, distribution, and communications: Unification of planning and optimization for the electric system will require construction of a standard, all-inclusive library models and the development of common vocabularies and taxonomies for use in model building. New tools and software interfaces are needed to enable the combination of domains in a unified modeling approach. Carefully constructed domain-connected models would improve overall system planning and management and have direct positive impacts on system reliability.

Comprehensive grid models and methods for load and resource balancing with consideration of DER, demand response, and energy storage: Currently, a balancing authority manages load and resource dispatch; a paradigm that does not enable or encourage broad deployment of DERs. Understanding how to optimize power flows among DERs and loads is generally lacking. Because DER power flows can be volatile, maintaining power quality and stability while maximizing efficiency is a significant challenge as DER penetration levels increase. Capabilities for modeling and analyzing current load and resource balancing methods and the application of DERs need to be developed to better assimilate distributed sources. This will require understanding common DER performance attributes, evaluating various architectures of load and resource measurement, and incorporating the effects of market forces (i.e., price) versus engineering optimization into models. The targeted outcome is a comprehensive model that covers any number, size, and type of load and resource. The benefits would be greatly improved reliability, increased effectiveness of DER, and potentially a reduction in the need for additional capital-intensive traditional generation.

Probabilistic models for load forecasting under dynamic pricing: New models will support utility system and resource planning and smart decision making under conditions of uncertainty, and could provide a distribution of expected outcomes based on local characteristics and thus create a framework for decision making amid uncertainties. A universal model could be applied to planning scenarios using local data and uncertainties to improve the forecast of load profiles based on a utility's unique characteristics (e.g., climate, historical loads, and demographics). The overall desired outcome is a standardized model for characterizing the expected load profile in a given territory or service area under conditions of dynamic pricing.

Stochastic methods for operations and resource planning to enable optimization in the presence of high uncertainty: Power system planners and operators are faced with maintaining effective operations regardless of the type of generation on the grid, whether it is variable or traditional. The overall system must

The Role of Measurements and Standards

Measurement science and standards play a key role in many of the technical challenges related to the smart grid. For example, science and standards are needed to support effective communication and interoperability across all equipment connected to the grid, including the complex infrastructure that serves the grid. Numerous measurement and standards challenges also confront key technologies supporting the grid, such as power electronics, power metering, and energy storage.

be balanced and operated reliably and efficiently; and generation and transmission capacity must be planned for and made operational to meet demand. Wind and solar generation are variable sources, which complicates the planning process. The more simplified assumptions possible with traditional thermal generators must be combined with probabilistic methods to effectively incorporate the stochastic nature of variable generators into planning. Stochastic methods will be needed to enable optimization of resources in the presence of these uncertain and variable energy sources.

Improved variable generation forecasting: Renewable resources exhibit greater variability and uncertainty in generation than traditional energy sources. Variable generation concerns include established sources such as run-of-river hydro, wind, and solar, and emerging sources such as wave energy. Better forecasting methods are needed to address challenges created by the integration of these sources into the grid. Most sources of variable generation share similar characteristics, as variability is driven by weather or other non-anthropogenic phenomena. Load is also influenced by the weather, so integrated forecasting models for demand and generation forecasting could be needed.

Visualization and analysis tools that provide situational awareness and other actionable information to operators: *Forecasting and probabilistic* tools will improve operators' visibility and ability to adjust decision logic in response to changing conditions. High-fidelity forecasting capability for renewables, DERs, and other flexible sources will help to improve dispatch decisions and optimize resource choices. New forecasting models should be capable of correlating a high density of weather sensors, improved computational methods, and renewable or flexible source characteristics to create high-resolution, localized, advance forecasts of events that impact load. Probabilistic (stochastic) tools and models, as well as effective ways to integrate forecasting tools, must be developed to enable advance forecasting. Better understanding of human factors will be needed to ensure that information can be consistently processed and acted on. The objective is the ability to forecast operating conditions and understand the options in advance (e.g., one day ahead) for achieving operating objectives.

Advanced decision support such as fusion of advanced data (e.g., energy management systems DR, and high-speed aggregation of PMU data) could improve operator decision logic. Automatic logic approaches should also be explored, such as the automatic activation of remedial action schemes or other control schemes, and the feasibility and extent of autonomous operation. A desired outcome is the ability to switch between control schemes quickly for more resiliency and flexibility. Control architectures for DERs that support operator responses are discussed in the section on control architectures and voltage controls for distribution networks, below.

Visualization tools and analytics are needed for converting smart grid data into operator actions. High-performance computing, graphics, and visualization interfaces will need to be developed to process data and create visualization tools for operators. This will require new algorithms along with advanced computing and parallel processing approaches to rapidly extract knowledge from smart grid data. The performance targets are production of actionable outputs from operational data, as well as automatic detection and mitigation of cascading events. The benefits will be overall robustness of decision making, improved reliability, reduced uncertainty, and greater assurance of system control and response.

STANDARDS, PROCEDURES, AND PROTOCOLS

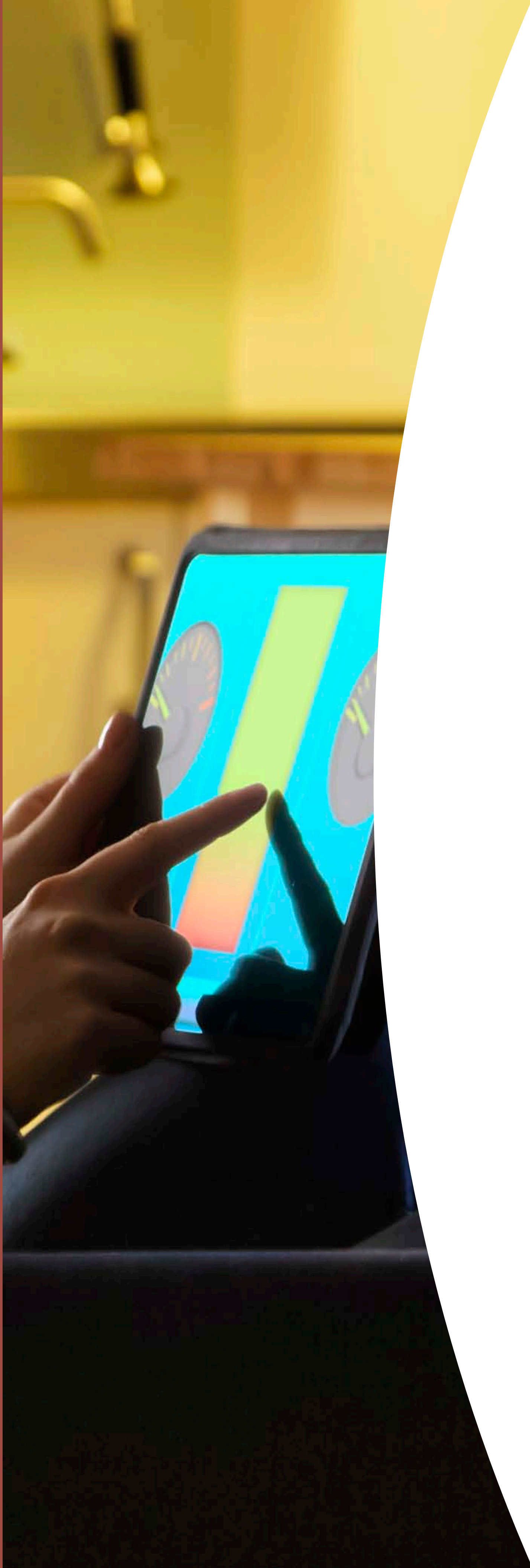
Standards are needed to ensure seamless and efficient exchange of data between various domains in the electric system. Standardized ways to measure performance are also needed to ensure that smart grid objectives are realized and to demonstrate the benefits of new technologies.

Standards and associated metrics for equipment performance: Performance metrics and new measurement methods are needed at the component and interconnection level to predict and evaluate the impacts of renewables, DERs, and smart grid applications on overall system performance. Metrics would help to define performance objectives and clarify how to balance multiple objectives (e.g., efficiency, cost, and environment), especially when integrating renewables and DERs. For example, grid-level performance metrics (temporal, spatial) could provide a quantifiable response based on a given percentage of renewable energy penetration. To be effective and gain widespread use,

NEW TECHNOLOGIES AND SYSTEMS VIA THE SMART GRID INVESTMENT PROGRAM

TThe Smart Grid Investment Grant (SGIG) program is a $3.4 billion initiative focused on accelerating the modernization of the nation's electric grid through development and deployment of smart grid technologies and systems (OE 2012). The U.S. Department of Energy (DOE), Office of Electricity Delivery and Energy Reliability (OE) manages the SGIG program, which was first authorized by the Energy Independence and Security Act of 2007 and funded by the American Recovery and Reinvestment Act of 2009. As of March 31, 2012, the combined level of federal and grant recipient investments in smart grid modernization totaled about $4.6 billion. Projects are ongoing to develop:

- **Electricity transmission** – phasor measurement units (PMU), line monitors, and communications networks
- **Electricity distribution** – automated sensors and controls for switches, capacitors, and transformers
- **Advanced metering** – smart meters, communications systems, and meter data management systems
- **Customer services** – in-home displays, programmable communicating thermostats, web portals, and time-based rate programs



performance metrics would need to be flexible for differing industry needs, as well as be accepted by industry stakeholders, regulators, and other decision makers. Universally accessible, consistent, and comparable metrics for a range of smart grid technologies would also help inform discussions of future regulation and policy.

New measurement methods and standards will be required to collect and verify a wide spectrum of data for use in model development and validation. Standard test cases, data sets, and metrics would aid in construction of models that encompass and connect different electric system domains. Better measurement and data collection methods will provide a solid foundation for building new, more accurate models that enable planners and operators to take full advantage of smart grid capabilities.

Standards for communications interoperability: Standards are needed to address information exchange and interfacing requirements between legacy and new communication systems. A robust, real-time data structure will be required for both real-time communication and application interfacing to enable seamless data exchange between generation, transmission, distribution, and customer applications. Rules and standards for data exchange among enterprise applications are needed to allow detailed information exchange among various entities. This includes general data and communications standards as well as rules for privacy and security. The desired outcome is a set of established communication protocols that can be adopted industry-wide to enable better interconnections with both new and legacy systems. Standards for communication interfaces and compliance testing for interfaces are also needed to reduce discrepancies between multiple communication protocols and data models. Standard interconnection protocols would reduce operator error and increase operators' ability to detect system problems, increasing system assurance and security.

Efficient procedures for generator interconnection as well as transmission/distribution network expansion: Standards for interconnection of hardware and devices are needed to provide a better interface between new and existing systems. Economical, secure, and reliable utility-grade communication hardware will be needed to enable disparate systems to work together effectively and securely and enable network expansion. System redesigns will be required that incorporate, for example, hyper-secure wireless, high-bandwidth programmable logic controllers or fiber-optic-based technologies. Universal standards are also needed for device interfacing, which requires full use of existing standards (e.g., International Electrotechnical Commission 16850 and mappings).

Hardware will need to be developed that utilizes current communication standards and mappings and also incorporates all communication functionality. This will aid in reducing uncertainties introduced when implementing new standards and technologies in legacy systems. Adaptors will be needed that can translate information from legacy systems while ensuring that device security is maintained. Overall, the targeted outcome is the capability for all devices to utilize a standard communication protocol in a utility-run, hierarchical-controlled, plug-and-play environment that manages both system operations and markets. Enabling disparate systems to work together will increase reliability and security, while reducing the potential for system losses.

Standardized methods for collecting and managing distribution-level operations data: Implementation of customer programs in DR and EE requires measurement technologies and methods that can provide uniform data. Technologies will need to be able to integrate low-cost, intelligent sensors and aggregate sensor data at the levels of granularity useful for program implementation. Data best practices for determining data collection accuracy, frequency, and quantity are also needed for distribution-level instruments and systems. Specifications and/or standards are needed for the measurement and instrumentation systems that will provide input to control methods for DR and EE. This requires identifying performance objectives and criteria and the formal role of DR and energy efficiency (EE) in reliability. The targeted outcomes are consistent visibility of data methods for DR and EE, determination of appropriate data levels and access for program implementation, and data best practices of distribution-level measurement methods. The benefits will be a uniform environment for program development, as well as new options for assuring reliability.

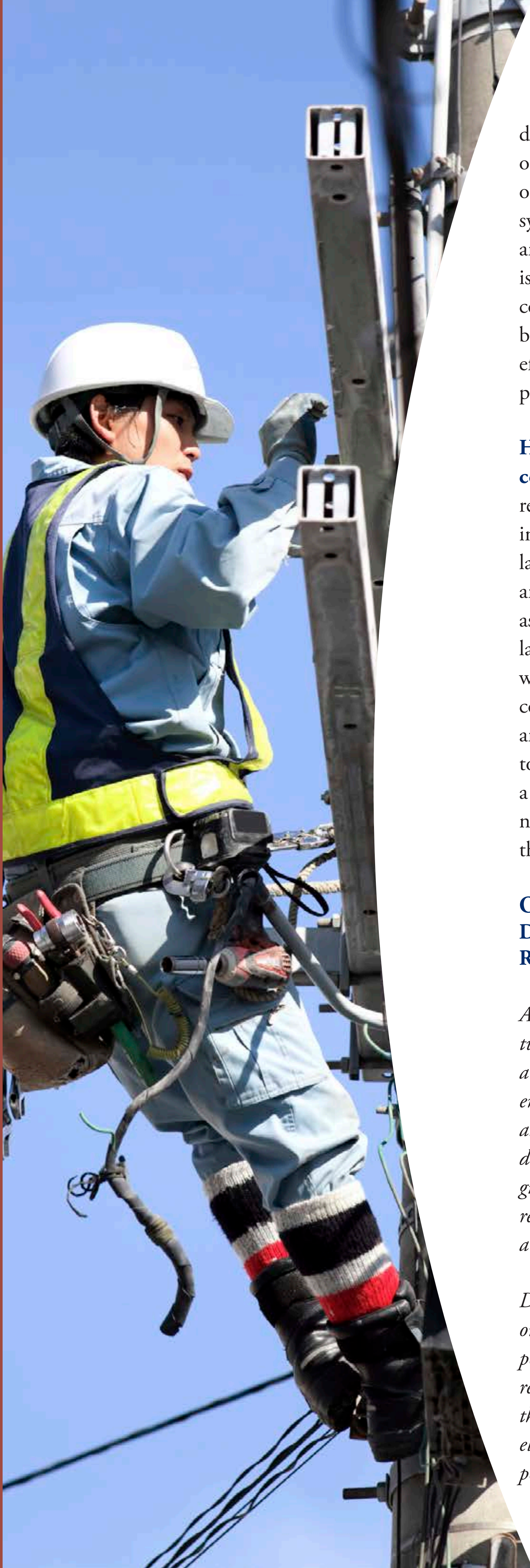
CONTROL ARCHITECTURES AND VOLTAGE CONTROLS FOR DISTRIBUTED NETWORKS

DERs are small, modular, energy generation and storage technologies that can provide electric capacity or energy where it is needed. They include small-scale renewable systems, fuel cells, micro-turbines, reciprocating engines, combustion turbines, cogeneration, and various energy storage systems (e.g., batteries, compressed air, flywheels, and super capacitors). DERs can reduce peak power requirements, provide a more resilient energy supply, and relieve transmission congestion by replacing electricity delivered by long-distance power lines.

Optimizing system operation with wide-scale penetration of DERs will require new control architectures and strategies. Methods are needed to manage DER power output and avoid transformer overloads and/or reverse power flows, and minimize impacts from voltage and frequency deviations and renewable resource variability.

Scalable, reliable, secure control system architectures for coordinated, distributed decision-making: Both centralized and

Electric vehicles (EV) that plug in to the electric grid have the potential to revolutionize transportation. Widespread EV adoption will require a modern electrical grid with accessible, quick, and easy-to-use charging stations. The smart grid will enable vehicle charging stations like the one above to become widely available to power future generations of plug-in electric vehicles. As larger numbers of EVs hit the roads, the smart grid could also connect with vehicles to store and supply electricity, tapping this resource as needed to ease the ebb and flow of electricity on the grid.



distributed control models should be evaluated to enable system optimization with distributed sources, with attention to issues of scaling and coordination between clustered assets. Analysis of system control architecture for real-time situational awareness and automated or system operator response is needed to address issues of stability and security. Interoperability of sensor and communication technologies across all network layers must be addressed. The objective is to make it easier and more cost effective to integrate DERs into the grid at larger scales, while providing safe, reliable, and robust operations.

Hierarchical distribution-level voltage controls and communication: Hierarchical approaches to voltage regulation that support DERs can be cost effective and improve resilience to failures, important factors in achieving large-scale DER integration. New voltage-control schemes are needed to overcome some of the current challenges, such as higher-speed voltage regulation devices; high-speed, low-latency communication infrastructures; and low-cost sensors with standardized communication interfaces and high-speed communication. Efficient control strategies must be adaptable and flexible for power electronic inverter-based DERs to connect to each other as well as to existing power systems (covering a range of voltage). The target is maintenance of a specified nominal voltage within a specified tolerance range, with DERs in the mix.

Opportunity
Develop Smart Tools and Technologies to Utilize Demand Response, Demand Load Control, and Energy Efficiency

Advances in communication infrastructures and the creation of a two-way channel for real-time communication between consumers and the utility operator made possible via the smart grid will better enable use of DR, DLC, and EE as sources of energy supply. DR allows energy users to act as a power plant by voluntarily lowering demand for electricity during peak times or critical events—users are given incentives for providing DR capacity. A tapestry of consumer response programs now exist that offer real-time pricing, real DR, and demand bidding.

DLC is a way to balance electricity supply with load by adjusting or controlling the load rather than the electricity generated by the power plant. DLC can occur via direct utility intervention, by relays that trigger circuit breakers (ripple control), by time clocks, or through consumer tariffs. Load management can reduce demand for electricity during peak times and decrease requirements for peaking power plants.

EE improvements can reduce energy demand and provide a passive source of electricity. Advances in IT and networking are already allowing consumers to make better decisions and change the way they use energy. New, efficient technology and best energy management practices, when applied to major uses of electricity in the buildings, industrial, and agricultural sectors, can provide efficiency improvements that result in significantly lower demand.

EVALUATION METHODS AND FRAMEWORKS FOR EE, DR, AND DLC

Good data collection and analysis mechanisms are essential for taking advantage of non-generation sources of electricity. A strong data foundation (e.g., measurement tools, data standards and protocols, verification methods, data mining and interpretation, and knowledge frameworks) will provide the information needed by industry, markets, regulators, and consumers to actively incorporate DR and other strategies into current electric system business and operations.

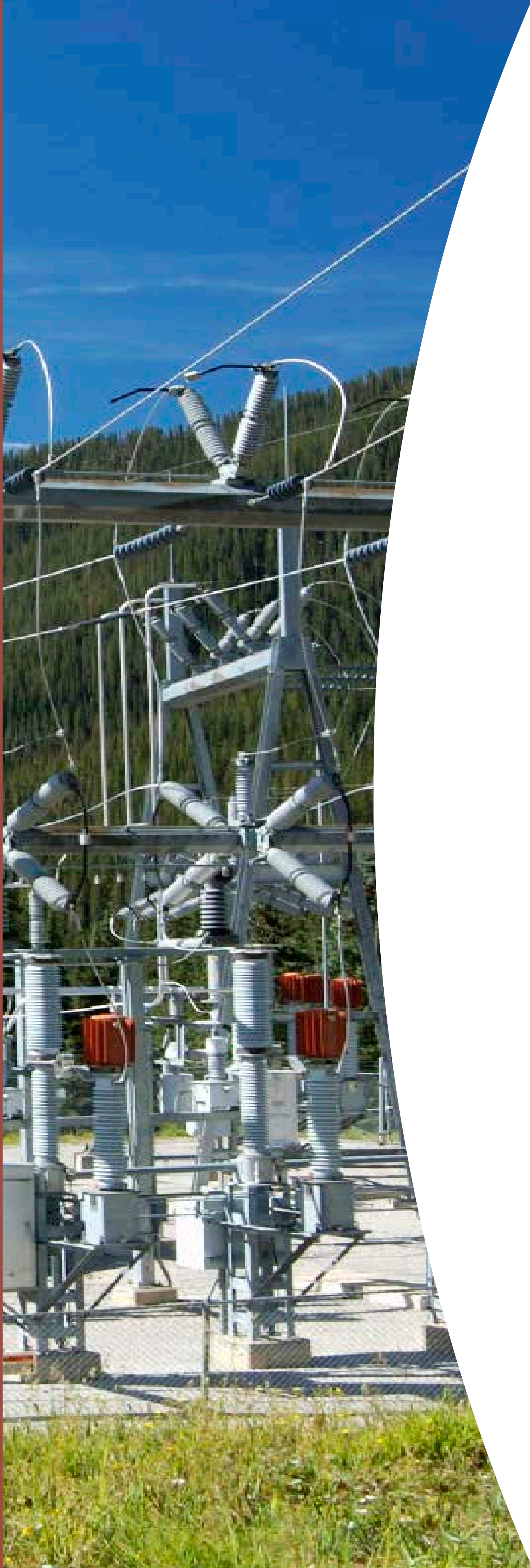
Evaluation, measurement, and verification methods: EM&V methods are needed that can be broadly deployed and accepted (e.g., conservation voltage regulation/ dynamic voltage regulation). This will require analysis and development of new methods, including econometrics, behavioral science, field instrumentation, spot measurement capabilities, continuous power measurement, calibrated simulation models, and billing. Resource characteristics critical to identifying the best EM&V methods, as well as available data sources (e.g., substation supervisory control and data acquisition [SCADA] and advanced metering infrastructure), will need to be categorized and evaluated. One objective is to establish a standardized protocol framework that can be widely used to identify the best EM&V methods for EE, DR, and DLC based on an individual system's unique resources and attributes. The benefits will be greater confidence in the reliability of DR, DLC, and EE from wholesale to distribution; optimization of existing assets; automated capability to use these sources; and greater adoption of relevant programs.

Devices capable of DR calculations will be an integral component of EM&V, including the ability to measure actual loads and compare them to model loads to improve voltage conservation regulation. Methods such as in-meter billing, advanced meters, and model-based methods must be developed and validated in the field to ensure acceptable levels of accuracy and cost. Accepted methods are also needed to forecast and measure device communications and responses and then connect these to rewards, incentives, or benefit programs.

Frameworks to relate demand response to business objectives: Mapping DR technical capabilities (e.g., loads, DERs, storage, PVs, PEVs) by sector to the specific requirements of utilities and grid operators requires a broad understanding of DR business and customer needs and technologies available, and would enable better business mapping, improve and optimize dispatch of resources, and help inform relevant policies. Existing frameworks and resources for DR should be identified and consolidated,

Standards for an interoperable smart grid

The *NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 2.0* provides a framework for transforming the nation's aging electric power system into an interoperable smart grid—a network that will integrate information and communication technologies with the power-delivery infrastructure, enabling two-way flows of energy and communications. It reflects input from a wide range of stakeholder groups, including trade associations, standards organizations, utilities and industries associated with the power grid (NIST 2012).



and incremental improvements should be made to the framework as needed to successfully map capabilities. New models are needed to incorporate elements of this framework and key variables (e.g., utility and operator geography and customer differences) to allow customization of DR for specific utility or operator requirements. A DR taxonomy will be necessary for characterizing the full spectrum of DR business and customer needs. Standards or guidelines are also needed so that third parties can develop consistent tools to enable smart dispatch of DR and DERs.

ENABLING INFRASTRUCTURE

Opportunity
Expand and upgrade infrastructure to improve communications and interconnectivity

An integrated, modern two-way communications and networking infrastructure is essential to the smart grid, enabling monitoring and scheduling of electricity use in real time. Many types of communications and networking technologies can be used to support the smart grid. These include, for example, traditional copper phone lines, cable lines, fiber optic cables, cellular, satellite, microwave, and broadband over power lines, as well as short-range in-home technologies such as Wi-Fi and ZigBee. Smart grid applications of communications technologies could include home area networks, networks for wide area situational awareness, SCADA systems, DG monitoring and control, and DR and pricing systems.

COMMUNICATION AND INTERCONNECTION METHODS AND TECHNOLOGIES

Network infrastructures will need to be improved and expanded to take full advantage of smart grid capabilities. This requires developing the infrastructure needed to enable effective communication between multiple devices, technologies, and across different organizations and business units—as well as with the consumers of electricity.

Communications infrastructure for multiple interconnections: The utility industry needs an improved infrastructure to manage and control the larger number of interconnected devices possible with the smart grid. Communication performance standards (design and operation) will be needed for different smart grid applications to ensure effective communication and optimization of capabilities. Standards will also be needed for developing service-level agreements between utilities and communication providers.

To scale up to many interconnected devices, utilities need to be able to compare the many communications solutions that are available (e.g., mesh networks, 4G, fiber optic cable directly to the site, and Internet protocols). This includes understanding the practical requirements for high bandwidth and low latency, and developing metrics appropriate for utility-grade quality of service. A database of emerging technologies (e.g., with performance comparisons) could be a useful tool for making decisions about the many communication options available. Models are needed to simulate the interaction between communication system performance and grid/smart grid performance. Developing reference communication and grid performance models will enable utilities to adopt cost-effective solutions and leverage communications industry infrastructure investments.

Communications to optimize ancillary services: In addition to energy generation capacity, ancillary services (e.g., regulation, load following, and spinning and non-spinning reserves) give system operators the resources to maintain balance between generation and load under normal operation and when contingencies arise, improving reliability while increasing the cost effectiveness of maintaining the electric system. Markets have been created for some ancillary services to lower the cost of maintaining reliability, and they can also increase profitability for generators. Optimizing the provision of ancillary services such as regulation and spinning reserves will require development of low-latency, time-synchronized communication technologies. Methods will be required that can provide rapid, high-speed communication of simple regulation and spinning reserve signals to devices. The overall objective is an approximate four-second latency signal approach that is accepted and widely adopted by the industry.

Methods for managing and extracting information from large and disparate data flows: Effectively managing and extracting information from large data flows is necessary for taking full advantage of smart grid capabilities. Systems originally designed for handling much smaller data volumes are quickly becoming outdated and need to be replaced. Methods will be needed to enable data concentration and consolidation without losing trends, statistics, and context. New ways to apply and use data will be needed that incorporate visualization tools (user interface), data navigation (user interface), context application, relational data building, and advanced search capabilities.

Correlation tools will be needed to bring apparently unrelated large data sets into a more relational approach. Mining, analyzing, and managing the data can deliver meaningful and actionable information for model inference and state-based control. Data analytics can help inform planners, operators, and business units regarding the value and use of renewables and DERs, in addition to supporting autonomous control of operations, reducing losses, and providing better asset utilization.

Opportunity
Develop infrastructure to assure cyber security and resilience

Dependable electricity distribution depends on a resilient power infrastructure. Infrastructure resilience has been defined as "the ability to reduce the magnitude and/or duration of disruptive events" (NIAC 2010). Recent intrusions on U.S. computer systems, both government and commercial, illustrate the current vulnerabilities of the Internet and the rationale for addressing the security of cyberspace. Cyber security is a strong national priority and much progress has been made in ensuring protection from cyber attacks. However, systems such as the smart grid create new challenges because they possess a combination of cyber and physical components with different vulnerabilities. Securing both the cyber and physical components may require protecting against fundamentally new, more complex attack models. Maintaining privacy and confidentiality is another important aspect. Ensuring the confidentiality of information and controlling the access and use of data will be a priority as smart grid communication systems continue to evolve.

MODELS AND TOPOLOGIES FOR IMPROVING SECURITY AND RESILIENCE

Cyber-physical design methods, metrics, and analytical tools: Ensuring the security of the smart grid includes development of cyber-physical models and performance metrics that can be used to simulate and test the cyber security of the system and various components. Exploratory work on the multidisciplinary fundamental science of cyber-physical systems will be needed to lay the foundation for new models. The desired outcome is a holistic conceptual framework that can be

demonstrated for incorporating new smart grid technologies as well as new cyber-physical design and analytical tools. Holistic system models and tools that are accepted by the industry would improve grid reliability as well as system assurance and security.

Flexible power system topologies and communications/control architectures: Ensuring grid security and resilience requires power system topologies and communications and control architectures that go beyond legacy technologies and designs. These include microgrids, storage, DG, and other alternative generation methods. Security-related performance metrics will need to be established to enable comparison of alternate topologies.

Securing data integrity for control and coordination of distributed sources and storage, including protection of owner-operator information, is challenging. The stability and security of distributed control approaches and fail-safe rules and operations will need to be assessed, and optimization objectives will need to be identified (e.g., energy, voltage, and frequency). The desired outcomes are the development of standards for the behavior of decentralized controllers to ensure security and privacy, and protocols for performance and behavior of distributed controllers and their devices. New approaches would also allow for participation of local decisions in optimizing the overall system operation.

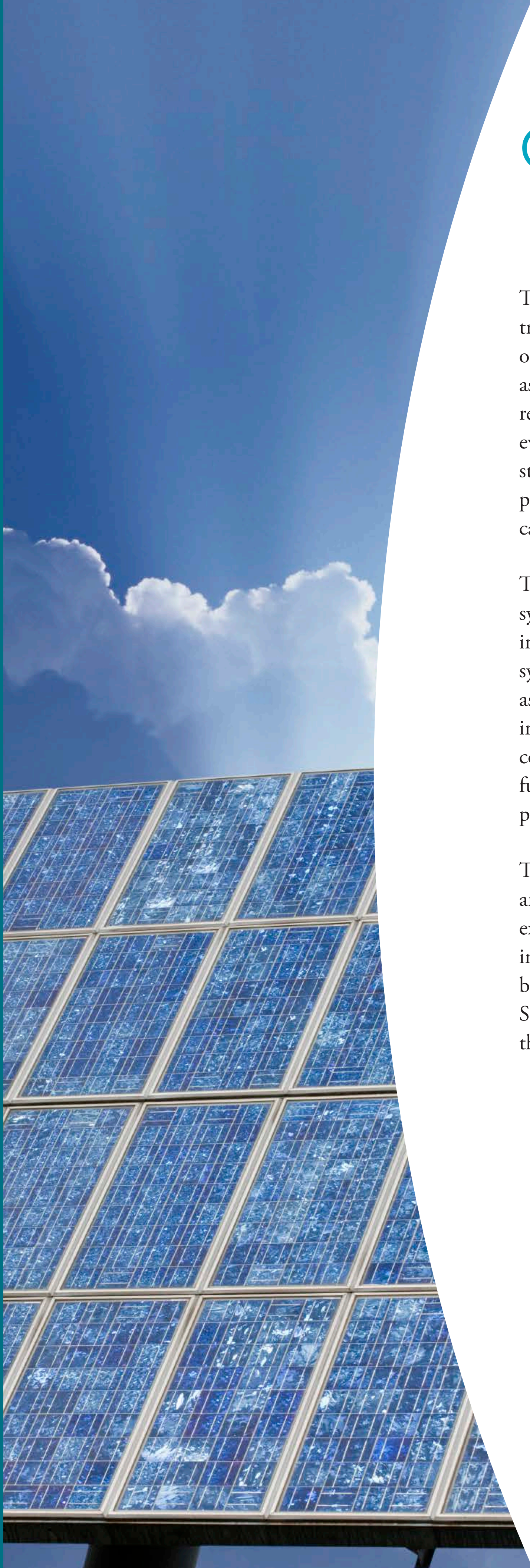
Opportunity
Create models to foster smart grid investment and inform regulatory frameworks

Broad-based economic models will provide tools for building a strong business case for the smart grid and help to stimulate investments. They will provide a means for comparing the economics of a variety of resource and technology scenarios. Life cycle analyses (LCA) provide information about the energy, economic, environmental, and other impacts of smart grid systems, from development through implementation and end of life. In addition to business planning, economic models and LCA are valuable for the development and evaluation of regulatory practices and emerging policies.

COST-BENEFIT AND LIFE CYCLE MODELS FOR SMART GRID

Economic models and uniform business metrics: Capturing the full picture of the costs and benefits of the smart grid (e.g., societal, environmental, and reliability) requires economic models and business metrics. By incorporating pricing structure alternatives and other market factors, such models would be able to estimate the possible economic impacts of smart grid implementation on customers, markets, institutions, and other stakeholders. Economic models will require development of uniform cost and business metrics to enable comparison of various technology and system options. Sufficiently robust economic cost-benefit models would also be useful for capturing the outcomes and potential impacts of current or future regulatory models and approaches.

Standard methods for life cycle analysis: To support economic models and aid in assessing the costs and benefits of these systems over their useful life, benchmarking of existing methods for LCA, analysis of best practices, and the development of new methods as well as performance metrics are required. For such methods to be useful and widely applied, consistent performance metrics will need to be tied to economics and other relevant factors. This would allow comparison of the business aspects of different smart grid applications and ancillary services and drive utility investments toward the most cost-effective solutions. Industry consensus will be needed on best practices for LCA as well as business performance metrics.



CONCLUSION

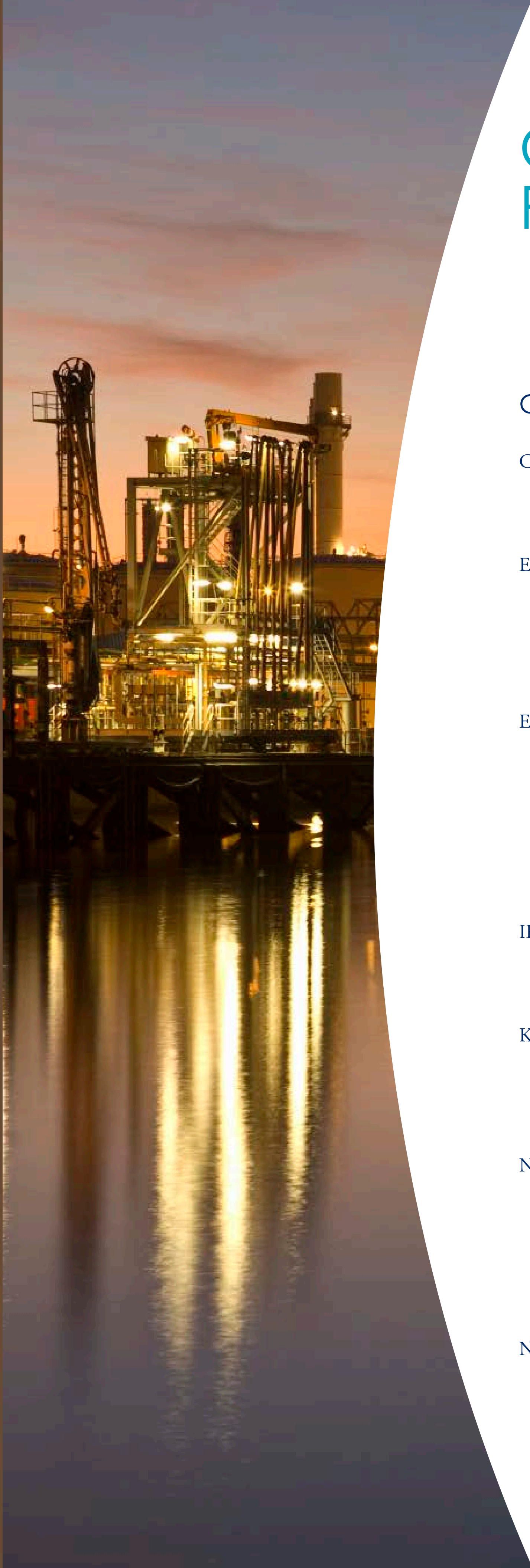
The smart grid has enormous potential to modernize and transform our electricity system, producing positive impacts on the economy, the environment, energy security, and many aspects of everyday life. Realizing the potential of the smart grid requires new technologies, measurement science, standards, and even new market paradigms. Collaborative efforts of multiple stakeholders are also essential to these efforts. The result will be planning and operations that take full advantage of smart grid capabilities.

The smart grid will rely heavily on a central computational system that is tightly linked and coordinated with components in the physical world. Achieving this system requires advances in systems science and engineering that will enable effective design as well as improvements to communication and networking infrastructure. Multidisciplinary R&D efforts will encompass computer science, mathematics, statistics, engineering, and a full spectrum of physical sciences—even extending into ethics, psychology, and a broad array of human factors.

This report is a call to action. Progress has been made, but there are many challenges ahead. Overcoming these challenges creates exciting opportunities to ensure that the United States is a leader in the design, development, and adoption of a smart grid. The benefits to the nation from a modernized grid will be immense. Significant opportunities outlined in this call to action include the following:

- **Optimize smart grid capabilities for system planning and operations**—essential for utilizing the capabilities of the smart grid to streamline and improve the efficiency of generation, transmission, and distribution.
- **Develop smart tools and technologies to utilize DR, load control, and EE**—key to the greater and more efficient use of alternative sources of energy and balancing the ebb and flow of power on the grid.
- **Expand and upgrade infrastructure to improve communications and interconnectivity**—makes possible real-time monitoring and scheduling of electricity, collection and dissemination of massive amounts of data, and pervasive networking of multiple components.

- **Develop infrastructure to assure security and resilience**—secures the grid against cyber and physical attacks, while ensuring the protection of information.
- **Create models to foster smart grid investment and inform regulatory frameworks**—essential for spurring future investment, understanding the costs and benefits of the smart grid, and creating effective regulations.



CITATIONS AND REFERENCES

CITATIONS

California ISO. 2010. *Smart Grid Roadmap and Architecture*. Palo Alto, CA: Electric Power Research Institute, December. www.smartgrid.epri.com/doc/cal%20iso%20roadmap_public.pdf.

Economic Development Research Group, Inc. 2011. *Failure to Act: The Economic Impact of Current Investment Trends in Electricity Infrastructure*. Reston, VA: American Society of Civil Engineers. www.asce.org/uploadedFiles/Infrastructure/Failure_to_Act/SCE41%20report_Final-lores.pdf.

EPRI (Electric Power Research Institute). 2011. *Estimating the Costs and Benefits of the Smart Grid: A Preliminary Estimate of the Investment Requirements and the Resultant Benefits of a Fully Functioning Smart Grid*. Palo Alto, CA: EPRI, March. http://ipu.msu.edu/programs/MIGrid2011/presentations/pdfs/Reference%20Material%20-%20Estimating%20the%20Costs%20and%20Benefits%20of%20the% 20Smart%20Grid.pdf.

IEC 2010. Smart Grid Roadmap, International Electrotechnical Commission, 2012. Accessed 1/3/13. http://www.gpo.gov/fdsys/pkg/BILLS-110hr6enr/pdf/BILLS-110hr6enr.pdf

KEMA. 2011. *The U.S. Smart Grid Revolution: Smart Grid Workforce Trends 2011*. Washington, DC: The GridWise Alliance, July 25. www.gridwise.org/documents/GWA_2011_SG_Workforce_Trends_Overview.pdf.

NIAC (National Infrastructure Advisory Council). 2010. *A Framework for Establishing Critical Infrastructure Resilience Goals: Final Report and Recommendations by the Council*. Arlington, VA: U.S. Department of Homeland Security, October 19. www.dhs.gov/xlibrary/assets/niac/niac-a-framework-for-establishing-critical-infrastructure-resilience-goals-2010-10-19.pdf.

NIST (National Institute of Standards and Technology). 2012. *NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 2.0*. NIST Special Publication 1108R2. Gaithersburg, MD: NIST, February. www.nist.gov/smartgrid/upload/NIST_Framework_Release_2-0_corr.pdf.

OE (Office of Electricity Delivery and Energy Reliability). 2012. *Smart Grid Investment Grant Program: Progress Report*. Washington, DC: U.S. Department of Energy, July. http://energy.gov/sites/prod/files/Smart%20Grid%20Investment%20Grant%20Program%20-%20Progress%20Report%20July %202012.pdf.

PCAST (President's Council of Advisors on Science and Technology). 2010. *Report to the President and Congress Designing a Digital Future: Federally Funded Research and Development in Networking and Information Technology*. Washington, DC: Executive Office of the President, December. www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-nitrd-report-2010.pdf.

Schuler, Richard E. 2010. "The Smart Grid: A Bridge between Emerging Technologies, Society, and the Environment." *The Bridge* (40) 1:42–49. www.nae.edu/Publications/Bridge/TheElectricityGrid/18895.aspx.

SVSGT (Silicon Valley Smart Grid Task Force). 2011. "Smart Grid Deployment and the Impact on Silicon Valley." http://svlg.org/docs/smartgrid_sv_2011.pdf

Zpryme 2009. "Smart Grid: United States and Global Hardware and Software Companies Should Prepare to Capitalize on This Technology," Zpryme Research and Consulting, Dec. 14, 2009.

Zpryme Research and Consulting and Clasma. 2012. *Energy 2.0: Smart Grid Roadmap, 2012–2022*. Austin, TX: Zpryme Research and Consulting, Aubrey, TX: Clasma, May. http://en.calameo.com/read/000414633706521e203b1.

REFERENCES

The White House. "American Recovery and Reinvestment Act: Moving America Toward a Clean Energy Future." Washington, DC: The White House, February 17, 2009. www.whitehouse.gov/assets/documents/Recovery_Act_Energy_2-17.pdf.

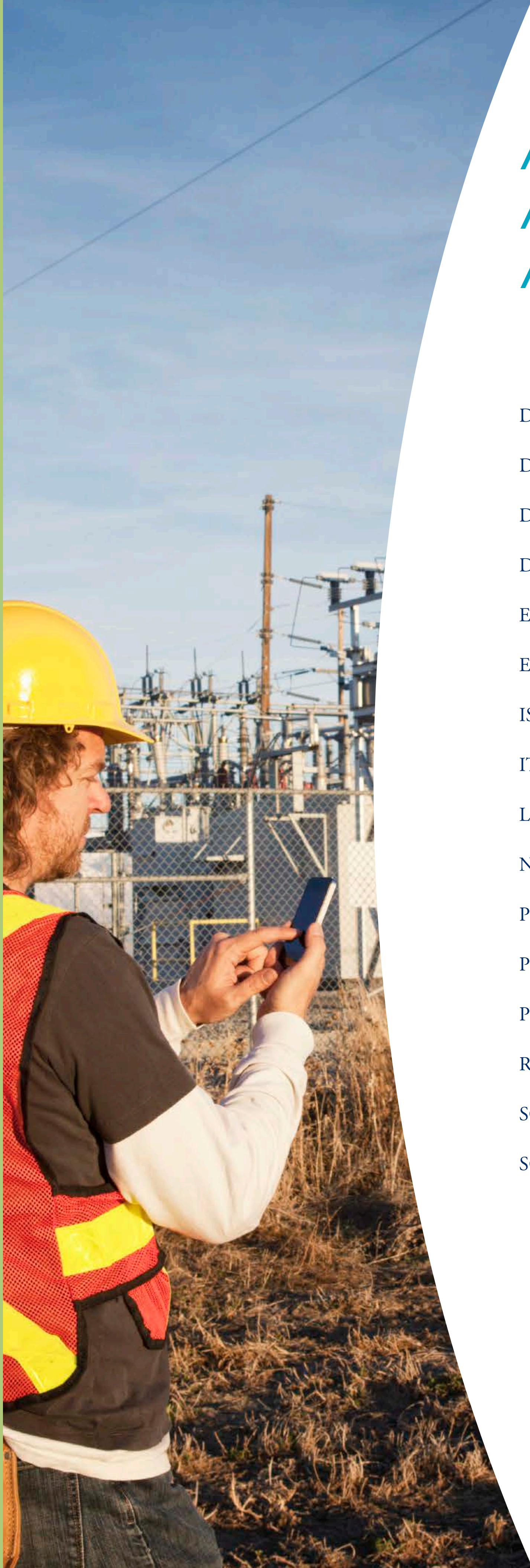
Report Card for America's Infrastructure. "Report Card." American Society of Civil Engineers. Accessed December 22, 2012. www.infrastructurereportcard.org/report-cards.

Energy Independence and Security Act. Pub. L. No. 110-140. 121 Stat. 1492 (2007). www.gpo.gov/fdsys/pkg/BILLS-110hr6enr/pdf/BILLS-110hr6enr.pdf.

SMB Smart Grid Strategic Group. *Smart Grid Roadmap*. Geneva: International Electrotechnical Commission, June 2010. www.gpo.gov/fdsys/pkg/BILLS-110hr6enr/pdf/BILLS-110hr6enr.pdf.

National Science and Technology Council. *A Policy Framework for the 21st Century Smart Grid: Enabling Our Secure Energy Future*. Washington, DC: Executive Office of the President, June 2011. www.smartgrid.gov/sites/default/files/doc/files/Policy_Framework_for_21st_Century_Grid_Enabling_Our_Secure_201110.pdf.

Silicon Valley Smart Grid Task Force. *Smart Grid Deployment and the Impact on Silicon Valley*. San Jose, CA: Silicon Valley Smart Grid Task Force, 2011. www.coecon.com/Reports/GREEN/SmartGridSiliconValley_OCT2011.pdf.



ACRONYMS AND ABBREVIATIONS

DER	distributed energy resource
DG	distributed generation
DLC	demand load control
DR	demand response
EE	energy efficiency
EM&V	evaluation, measurement, and verification
ISO	independent system operator
IT	information technology
LCA	life cycle analysis
NIST	National Institute of Standards and Technology
PEV	plug-in electric vehicle
PMU	phase measurement unit
PV	photovoltaic
R&D	research and development
SCADA	supervisory control and data acquisition
SGIP	Smart Grid Interoperability Panel

ACKNOWLEDGMENTS

Advisors

National Institute of Standards and Technology

Clare Allocca, NIST

Kevin Doran, RASEI

Danielle Tanner Felix, RASEI

Michael Janezic, NIST

Jeffrey Mazer, NIST

Cuong Nguyen, NIST

Diane Stultz, RASEI

Report Preparation
Energetics Incorporated

For more information contact:

Jeffrey A. Mazer
U.S. Department of Commerce,
National Institute of Standards and Technology
Smart Grid Program
Jeffrey.mazer@nist.gov

Photos provided by: iStockphoto

Above, a consumer uses a smart energy controller to check and see how efficient her household energy usage is. Smart systems like these are empowering energy users to monitor and control their energy use and become partners in energy efficiency. Tens of millions of households could adopt smart energy solutions for their homes within the next few years, giving them the ability to control energy use from virtually anywhere. Systems coming onto the market today provide connectivity to Wi-Fi, with seamless integration into home networks and devices, such as smart phones and tablets. In the future these could extend into cloud-based services and other technologies. With these systems consumers can use personal and mobile devices to control smart appliances, lighting, and other energy-consuming systems within the home.

FOR MORE INFORMATION CONTACT:

Jeffrey A. Mazer
U.S. Department of Commerce,
National Institute of Standards and Technology
Smart Grid Program
Jeffrey.mazer@nist.gov

National Institute of Standards and Technology
U.S. Department of Commerce

Renewable & Sustainable Energy Institute