Physical and Cyber Infrastructure to Support the Future Grid

Final Report on an Executive Forum and Workshop
Held May 4-5, 2015

Co-sponsored by PSERC and the National Science Foundation

Power Systems Engineering Research Center

Empowering Minds to Engineer
the Future Electric Energy System

Physical and Cyber Infrastructure to Support the Future Grid

Unresolved Research Problems and Technology Requirements for the Next 10 Years

May 4-5, 2015
Waterview Conference Center, Arlington, VA

Final Report

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Power Systems Engineering Research Center

The Power Systems Engineering Research Center (PSERC) is a multi-university Center conducting research on challenges facing the electric power industry and educating the next generation of power engineers. More information about PSERC can be found at the Center's website: http://www.pserc.org.

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Preface

The Power Systems Engineering Research Center (PSERC), an NSF Industry/University Cooperative Research Center, and the National Science Foundation Directorate for Computer and Information Science and Engineering invited leaders from the utility industry, vendors, government, and the academic community to participate in a PSERC/NSF Executive Forum and Workshop on Physical and Cyber Infrastructure to Support the Future Grid. The Forum and Workshop were held at the Waterview Conference Center in Arlington, Virginia, on May 4-5, 2015.

The first day was the Executive Forum on Near-Term Research Needs for the Physical and Cyber Infrastructure that Supports the Future Grid. The Executive Forum had five panels with panel members from industry, academia, and government identifying problems and challenges associated with the future grid, and offering some research ideas or issues. On the second day the participants convened in a workshop to discuss research directions and propose research ideas over the near-term, 5-10 year horizon.

With close to 100 participants, and with a day and a half of intensive interaction through presentations and discussions, the participants identified many research challenges and opportunities related to unresolved problems and technology requirements for the future grid over that 5-10 year horizon. This report summarizes key conclusions from the forum panels and outcomes of the workshop discussions. The appendices provide notes taken by the forum note-takers, and a categorization of research issues and ideas identified during the Forum and by workshop participants along with the results of voting by workshop participants on what research priorities.

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Executive Summary

The Executive Forum and Workshop on Physical and Cyber Infrastructure to Support the Future Grid, held on May 4-5, 2015, was a co-sponsored event organized by Power Systems Engineering Research Center and National Science Foundation. The main objective was to assess emerging research issues and pave research directions for resolving them in the next ten years. To get balanced perspectives, the Executive Forum on the first day featured speakers from various stakeholder groups: utility industry executive officers, technology executives responsible for technology applications, technology and solution providers, and representatives of government research organizations, and leaders of academic and government research centers and labs. The second day was devoted to discussions among participating researchers trying to identify research directions that were motivated by the forum presentations and discussions. This report communicates views expressed by around 100 attendees from industry, government, and academia.

The keynote address provided the following high level perspectives:

- The top challenges and uncertainties in the utility industry today include levels of electricity demand; extreme earth and space weather; world's largest fuel switch to low-carbon fuels; natural gas operations coordination, including security of pipelines; integration of intermittent and demand-side resources.
- Need to move from extra high voltage (EHV) AC flow to high voltage DC (HVDC) for controllability; high performance scientific computing and analysis of big data; computer models moving from DC power flow to AC power flow; integrating storage and smart inverters as integral parts of the future grid.

A panel of executive officers raised the following industry issues that need resolution:

- *Renewables and Distributed Generation*: how to deal with the ramp rates that are created; determining how much inertia is needed in a power system; defining ancillary services more appropriately; determining how storage can fit into the grid and markets.
- *HVDC*: how to create a business case which will lead to appropriate cost allocations; where HVDC is best deployed and how it should be implemented; convincing regulators to use HVDC.
- *Demand Response*: how to enable increased visibility into the distribution system; better forecasting tools; expanding definition of ancillary services.
- *Planning*: longer-term with a more strategic approach to planning the system; better wind and solar forecasting in real-time and day-ahead; approaches and tools to address

uncertainties in the planning process; faster computing to solve operation and planning models.

A technology application perspectives panel with lead technology executives among technology user organizations focused on the following problems and research needs:

- Centralized vs. decentralized control, and who decides was recognized as a concern particularly as microgrids and other flexible loads are incorporated in the future grid with their interface requirements for on- and off-grid operating modes.
- How to justify the grid expansion investments was also emphasized, which includes issues of how much distributed generation and energy storage is justified, and where to locate them in the system as well as geographically.
- The need for large-scale testbeds was identified since evaluation of new grid solutions will have to be performed in more realistic test and evaluation environments other than by using pilots and laboratory tests.
- Market efficiency was emphasized, and in that context, options for centralized vs. decentralized markets will need to be evaluated along with formation of new designs for distribution service provider participation in the market.
- Water heaters as a thermal storage was singled out as an underutilized energy storage opportunity. It was suggested that both thermal storage in buildings and water heaters should be explored for various demand side management along with combined heat and power (CHP) options.
- Understanding the weather impacts in real-time was pointed out as a new concern as the seasonal changes in weather affect both load and generation, and hence can significantly impact electricity markets and power system operation.
- How to incorporate policy implications of technology remains an ever challenging task, so it was suggested that new ways of demonstrating technology benefits, such as risk analysis and elaborate testbed demonstrations, be offered to policy makers.

A panel on technology and solution provider perspectives focused on the following topics:

- The construction of a composite representation of the flexible loads, be they either of passive or active market participants, in the balancing of supply and demand, together with a detailed representation of consumer behavior, including the impacts of policies and incentives
- Energy storage modeling, management, and solution methodologies including storage participation in markets, the economic value of storage in investment decision analysis, the development of new schemes to enable the application of inventory management to energy storage
- PMU deployment for enhanced protection, control of storage devices, and transition from local to system-wide control together with the development of tools that effectively

assure fidelity and security of PMU data, and software for PMU data verification with operational models
- Assessment of cyber security technologies to meet the requirements of current and planned standards.

The representatives from government research organizations provided perspectives on the following topics:

- Scalable hybrid data-driven control strategies
- Integrated risk management tools; enhanced modeling and simulation capabilities
- Composable, reconfigurable test beds to address interoperability challenges
- Increased capabilities for demonstration, testing and assessment of new technologies
- Address barriers to entry of new applications, and find solutions, such as open models
- Better understanding of complex systems; newer risk methodologies
- Education of policy makers regarding critical need for R&D.

Invited leaders of selected academic and government research centers and labs focused on the following research needs:

- Controls options (generation, transmission, distribution, and load) as an alternative to infrastructure expansion (transmission, distribution, and storage)
- Integration of traditionally-independent planning, operations, and markets functions
- Integrating and coordinating transmission and distribution systems, including distributed resources and loads
- Integrated planning and operation of the grid with other energy systems (e.g., liquid fuels, natural gas, transportation)
- Integrated models of transmission and distribution, including uncertainty and power electronics
- New power electronics applications and models for reliability, distributed resource dispatch, and other needs
- Optimal communications systems for distributed resource control and demand response
- Behavior analysis to better understand consumers, their interests, and how they integrate with the grid.

There were two workshop sessions organized around research ideas and issues. The first breakout session titled "Modeling and Analysis" resulted in the following top-ranked research ideas and issues:

- Characterize uncertainty and develop analytical tools that incorporate uncertainty for operations and planning decision-making in the presence of renewable resources
- Develop better short term forecast methods to enable more effective scheduling of variable generation
- Incorporate PMU and other synchronized real-time measurements in control algorithms for enhanced grid operation

- Determine the impact of reduced inertia on system dynamic performance and develop methods to mitigate detrimental impacts of low inertia
- Develop techniques for high-resolution identification of load composition to facilitate effective demand side management.

The second breakout session titled “Technology and Supplemental High Priority Research Ideas” prioritized several topics:

- Create real-time scalable and reconfigurable test beds based on multiple hardware-in-the-loop (HIL) technologies
- Create simulation and testing tools for architecture and device large-scale testing
- Develop resiliency models and metrics with multiple weighted indicators based on electrical, economic, and social factors for rate of return assessment of resilience improvements, for investment analysis, or for establishing incentives for adoption of resiliency measures.
- Increase resiliency of the grid through smart control and smart protection, centralized data, large dynamic data sets, model validation and operations, “no regrets” and best transmission system configurations
- Study how should we reconfigure the electric power grid to rely more on microgrids; redefine the technical interface between transmission and distribution systems to coordinate both systems and integrate distributed energy resources efficiently; design the architecture for integrated T&D operation.

Table of Contents

1 Introduction

On May 4 and 5, 2015, an executive forum and workshop were convened in Arlington, VA on ”Physical and Cyber Infrastructure to Support the Future Grid.” The Forum and Workshop were intiated by the Power Systems Engineering Research Center (PSERC) as part of its long-running executive forum series on timely subjects of industry and government interest. The initiative was also supported by the National Science Foundation thorugh a Travel Grant 1450738 titled ”Workshop on Research Directions for Cyber Physical Systems Related to Future Energy and Power Grids”. For the Forum, five panels were convened, with panel members from principally from industry, but also from government, national labs, and universities. In the Workshop, forum participants discussed the forum outcomes, and prioritized research ideas and issues.

1.1 Forum/Workshop Goals and Objectives

In light of the developments affecting the electric power industry, a central question is where research can help with finding solutions in the near-term. Specifically, what research can be done to make a tangible difference in the next ten years? The Executive Forum held on May 4 identified unresolved problems facing industry and government that need to be addressed in the near-term to meet expectations of the grid and of the energy industry in general. The focus was on those problems with the potential for engineered solutions either created by engineers or by interdisciplinary research efforts. Based on the forum conversations on May 4, the Workshop on May 5 focused on brainstorming research with deliverables over the next ten years.

Therefore, the goal of this event was to gather a group of thought leaders from the utility industry, vendors, government organizations, and academia, to discuss research needs and directions for the future grid over for a 10 year horizon. By so doing, the objective was to identify specific high priority research topics of high priority and the direction needed to achieve the next steps in future grid development for the next 10 years.

1.2 Forum Panels

The Forum featured a keynote speaker and five panels:

- Keynote address by Terry Boston, President and CEO, PJM Interconnection, entitled“21st Century Power Grids: What Engineering is Needed”
- Panel #1: Executive Perspectives
  - H. B. “Trip” Doggett, President and CEO, ERCOT
  - Bob Mitchell, CEO, Atlantic Wind Connection and Trans-Elect Development Co.
  - Tony Montoya, Executive Vice President and Chief Operating Officer, Western Area Power Administration
  - A. Wade Smith, CEO, AEP Texas
- Panel #2: Technology Application Perspectives
  - Valentine Emesih, Manager, Division Vice President, CenterPoint Energy
  - James Gallagher, Executive Director, NYS Smart Grid Consortium

  - David Mohre, Executive Director, Energy & Power Division, National Rural Electric Cooperative Association
  - Matt Wakefield, Director, Information and Control Systems, EPRI
- Panel #3: Technology and Solution Provider Perspectives
  - Jovan Bebic, Managing Director, GE Energy Consulting
  - Jay Giri, Director, ALSTOM Grid
  - Ralph Masiello, Innovation Director and Senior VP, DNV GL
  - Doug Voda, Smart Grid Segment Leader, ABB Inc.
- Panel #4: Government Perspectives
  - Chris Greer, Senior Executive, Cyber Physical Systems, NIST Engineering Laboratory
  - Timothy Heidel, Program Director, Advanced Research Projects Agency-Energy
  - Pramod Khargonekar, Assistant Director, Directorate of Engineering, National Science Foundation
  - Jalal Mapar, Director, Resilient Systems Division, Department of Homeland Security
  - David Ortiz, Deputy Assistant Secretary, U. S. DOE's Office of Electricity Delivery & Energy Reliability
- Panel #5: University and National Lab Perspectives
  - Jeff Dagle, Chief Electrical Engineer and Team Lead, Pacific Northwest National Lab
  - Iqbal Husain, Director, The Future Renewable Electric Energy Delivery Systems Center
  - Mark O'Malley, Director, Electricity Research Centre, University College Dublin
  - Kevin Tomsovic, Director, Center for Ultra-Wide-Area Resilient Electric Energy Transmission Networks
  - Vijay Vittal, Director, Power Systems Engineering Research Center

1.3 Workshop Breakout Sessions

Two breakout sessions were convened in the morning on May 5:

- Modeling and Analysis
- Technology and Supplemental High Priority Research Ideas.

1.4 Report Organization

This report has an executive summary and three chapters, corresponding to the forum keynote and panel sessions, the Workshop with its two breakout sessions, and the conclusions. For the panel sessions, the chapter provides a background of the panels is explained, the summaries are provided, and key takeaways are highlighted. For the chapter on the Workshop, besides the background, prioritized research ideas and issues are listed, the identified categories of all the research ideas and issues are presented, and key takeaways are presented. Two appendices provide the notes from the Executive Forum taken by participants who volunteered to be note-takers, and the categorized and prioritized list of research ideas and issues covered in the Workshop.

2 The Keynote and Panel Discussions

2.1 Background

The keynote was delivered by Terry Boston, the President and CEO of PJM Interconnection. The five panels covered different points of view: Utility industry CEOs, utility industry technology end-users, technology providers, government agencies, and federal labs and universities.

2.2 Keynote and Panel Discussion Summaries

For his keynote address, Terry Boston offered his perspectives on important challenges and uncertainties in the utility industry today. These included levels of electricity demand; extreme earth and space weather; world's largest fuel switch – switching to low-carbon fuels; natural gas operations coordination, including security of pipelines; integration of intermittent and demand-side resources; 21st century expectations of the grid; and investments in more high voltage direct current (HVDC) transmission in the grid. He identified such research needs as moving from extra-high voltage (EHV) AC flow to HVDC for controllability; using high performance scientific computing and analysis of big data; developing computer models that model AC flows rather than using DC flow approximations; and integrating storage and smart inverters as integral parts of the future grid.

Following the keynote address, the panel of executives covered a wide range of perspectives with representatives from an independent transmission developer (Atlantic Wind Connection & Trans-Elect), Regional Transmission Organization (ERCOT), a federal power authority (Western Area Power Authority), and an energy delivery (wires) company (AEP-Texas). The panelists discussed the need for inertia on the system and how the inertia would be obtained with increasing amounts of renewables and distributed generation. High Voltage Direct Current (HVDC) was discussed, focusing on the need to replace the four back-to-back HVDC links interconnecting the Western and Eastern Interconnections as well as the need to reduce barriers to the use of HVDC. Cost-effective demand response was an issue for some of the panelists as well as the recognition that there is a great opportunity to do more with demand response by customers. Finally, planning issues were identified with the need to take a longer-term view than most planning today, and the need for faster computing and new tools. Many problems and challenges facing industry were identified.

- Renewables and Distributed Generation: how to deal with the ramp rates that are created
- Determining how much inertia we need on the system
- Defining ancillary services more appropriately
- Determining how storage can fit into the grid and markets
- HVDC: how to create a business case which will lead to appropriate cost allocation
- How to determine where HVDC is best deployed and how it should be implemented
- How to convince regulators to consider construction of HVDC
- Demand Response: increased visibility in the distribution system
- Better forecasting tools
- More defined ancillary services
- Planning: need for a longer-term and more strategic approach to planning out the system
- Better wind and solar forecasting in real-time and day ahead
- Approaches and tools to address uncertainties in the planning process
- Faster computing to solve large, complex operation and planning models.

A technology end-user applications panel gave views from different organizational entities: a large transmission and distribution operator (CenterPoint Energy), a public-private consortium (New York State Smart Grid Consortium), rural utility organizations (National Rural Electric

Cooperative Association), and a non-profit utility research organization (Electric Power Research Institute). The panelists discussed the following topics:

- grid resiliency
- real-time customer interaction
- cost-effective demand response
- distribution visibility and automation
- integration of renewables and distributed generation
- role of Distribution Service Providers (DSP)
- granular pricing of demand-side management: hourly, sub-hourly
- resiliency of ICT and enabling technologies
- standardization for decoupled functionalities
- cyber-physical security and privacy.

During the discussion with the technology end-user application panel, the following research needs were identified:

- centralized vs. decentralized generation, and who decides
- how to justify the grid expansion investments
- how much distributed generation is justified
- the need for large-scale testbeds
- market efficiency: centralized vs. decentralized
- use of water heaters for thermal storage
- understanding of weather impacts in real-time
- market design for participation of distribution service providers
- how to incorporate policy implications of technology.

The very lively Technology and Solution Provider Perspectives panel session benefitted extensively from the diversity of views articulated by the four knowledgeable panelists. Topics discussed ranged from the importance of research on storage and its effective deployment to the need for the improved understanding of the representation of the behavior of customers (and their loads) and from the criticality of improved management of cyber security of the grid to the formulation of effective policies for various aspects of renewable, energy storage, and demand resources. The discussion in response to the numerous audience questions led to the identification of four major research areas:

- The construction of a comprehensive load model with improved composite load representation of the flexibility of loads as they morph from passive to active participants in the balancing of supply and demand; detailed representation of consumer behavior including the impacts of policies and incentives; and the capability to represent the operational needs for load visibility at each point in time and its flexibility characterization.
- Energy storage modeling, management and solution methodologies including the development of models for effective participation of storage in markets for the provision of commodity and ancillary services; the construction of tools to assess the economic

value of storage in investment decision analysis; and the formulation of operational paradigms and the development of new schemes to enable the deployment of inventory management to storage and the formulation of computational procedures that overcome scalability issues in mixed integer programming algorithms.

- PMU deployment and data utilization, including PMU deployment for enhanced protection; the development of tools that assure fidelity and security of PMU data; the formulation of procedures for PMU data verification with operational models; the deployment of PMU data for inertial response estimation for control of storage devices; assessment of how far synchronized sampling rate of PMU needs to be pushed; the investigation of PMU data use beyond monitoring to formulate control actions to ensure the health of the system for eventual decision-making and to lead to the transition from local to wide area control.
- Assessment of cyber security technology to meet the requirements of current and planned standards.

A government perspectives panel included a diverse set of panelists including staff from Advanced Research Projects Agency-Energy (ARPA-E), Department of Homeland Security (DHS), National Institute of Standards and Technology (NIST), National Science Foundation (NSF), and the Office of Electricity Delivery & Energy Reliability in the U.S. DOE. The panelists discussed research needs regarding the following topics:

- scalable hybrid data-driven control strategies
- integrated risk management tools
- enhanced modeling / simulation capabilities
- composable, reconfigurable test beds to address interoperability challenges
- increased capabilities for demonstration and testing/assessment of new technologies
- address barriers to entry for new applications, e.g., open models
- better understanding of complex systems
- new risk assessment and decision-making methodologies
- education of policy makers regarding the critical need for R&D.

The Federal Labs and Universities Panel included panelists from one national lab, one European university research center, and the three NSF centers on electric energy. The main topics discussed were:

- controls technologies
- integration of planning, operations, and markets
- integrating transmission and distribution systems
- integrating electricity with other energy systems
- simulating the grid and other supporting infrastructure, including communications systems
- power electronics
- communications
- consumer behavior.

The panel identified these research needs:

- controls (generation, transmission, distribution, and load) as an alternative to infrastructure (transmission, distribution, and storage)
- integration of traditionally-independent planning, operations, and markets functions
- integrating and coordinating transmission and distribution systems, including distributed resources and loads
- integrated planning and operation of the grid with other energy systems (e.g., liquid fuels, natural gas, transportation)
- integrated models of transmission and distribution, including uncertainty and power electronics
- new power electronics applications and models for reliability, distributed resource dispatch, and other needs
- optimal communications systems for distributed resource control and demand response
- behavior analysis to better understand consumers, their interests, and how they integrate with the grid.

2.3 Key Takeaways

The takeaways below were compiled by the report authors the based on the panel presentations.

- The combination of increasing uncertainty and new technologies is creating additional risks and opportunities in the development of the future grid. Increasing uncertainty stems from levels of demand growth; the changing generation mix, including more natural gas and intermittent sources of generation including renewables and distributed generation; the changing load shape with the potential for much steeper ramps; threats from extreme earth and space weather; and threats from cyber and physical attacks.
- Both existing and new technologies are available to provide more visibility into grid operations and more control of the grid. These technologies include PMUs, HVDC and increased computing power.
    - PMUs can provide much more visibility into grid operations but need to be more widely deployed; data verification and PMU operations protocols need to be developed and tested so operators can depend on the information provided.
    - HVDC can provide much more control of the power grid but is expensive and, as a non-traditional transmission option, planners and operators are not as familiar with it as AC transmission. A better business case is needed to understand all the benefits of the technology and for proper cost allocation, and planners need to become more familiar with the technology and its abilities.
    - Increased computing power provides opportunity to better understand and model what is happening on the grid.

- Increased integration of grid planning and operations is needed. This includes:
    - Integration of traditionally-independent planning, operations, and markets functions
    - Integrating and coordinating transmission and distribution systems
    - Integrated planning and operation of the grid with other energy systems (e.g. liquid fuels, natural gas, transportation).
- Increased security and resilience are needed on the grid.
    - Increased cyber and physical security are needed within appropriate cost ranges
    - Increased resilience involves being able to recover from incidents more quickly.
- The future electricity grid will expand in both the primary (network) as well as secondary (information technology) infrastructure. A key question is what should be the design of the future expanded grid cyber-physical architecture.
- Due to the introduction or renewables, flexible load, storage devices, and the grid controls, the dynamics of the grid operation will change. What are the new control algorithms that need to be developed to manage the future grid?
- The future grid will be characterized by abundance of data coming from within the grid (smart meters, PMUs, protective relays, etc.) and from outside the grid (markets, weather, behavioral aspects); hence, new data analytic solutions are needed
- Improving grid resiliency will require development of new risk assessment metrics for cyber-physical security, operational modes, customer participation, expansion investments, and policy considerations
- The future grid implementation will require development of new testbeds with both physical and virtual (modeling and simulation) capabilities that will allow evaluation of new solutions in a real-time environment reflecting the production complexity and scale.
- The construction of a comprehensive load model requires the explicit representation of the load flexibility, consumer behavior, and the impacts of new policy directives.
- System operators require the representation of the operational needs for load visibility, including its flexibility characterization, at each point in time.
- Energy storage investment and deployment require modeling, management and solution methodologies that include models for effective storage participation in commodity and ancillary service markets, tools for storage valuation, and the application of inventory management schemes to storage with computationally efficient algorithms.
- Broader PMU deployment and data utilization that include enhanced protection, the assurance of fidelity and security of PMU data, procedures for PMU data verification with operational models, control of storage devices, assessment of limits of PMU synchronized sampling rates and control actions to ensure the health of the system for eventual decision-making to lead to the transition from local to wide area control.

3 Workshop Discussions

The thesis for the Executive Forum on May 4 was that researchers and research funding agencies needed a better understanding of the immediate problems affecting the future grid. With that knowledge, they would be better able to set research directions and propose research projects over the near-term, 5-10 year horizon. The Forum's focus was on those problems with the potential for engineered solutions as opposed to problems required resolution in policy-making processes. Thus, panelists and discussions in the Executive Forum identified unresolved problems facing industry and government that need to be addressed in the near-term to meet expectations of the grid and of the energy industry in general.

The Workshop on Research to Support Development of the Future Grid on May 5 was then used to brainstorm research questions and directions with deliverables over the next ten years, and to get feedback from the participants on what research should be given priority.

3.1 Workshop Background

During the Forum, selected university participants served as note-takers for recording problems, challenges, and research ideas or issues that came from panelists or other participants, or from their own thoughts. Research ideas were then combined and edited for use in the Workshop.

There were two workshop breakout sessions: (1) Modeling and Analysis and (2) Technology and Supplemental Research Ideas. There were approximately 30 participants in each breakout session. The Forum Coordinating Team members categorized the edited research ideas provided by selected university participants in the Forum according to the workshop session topics. Breakout session participants also added their own research ideas and issues to the list for their particular breakout session. Then, the session moderators facilitated identification of high priority research ideas by the participants in their session. Each attendee was invited to vote for up to five "high priority" research ideas that:

- were likely to produce a useful solution within ten years
- would be of high value whether to industry or society at-large due to cost savings, new services, reliability improvement, higher system flexibility and resiliency, greater profitability, operational improvements, environmental improvements, or any other measure of value that the participant preferred to use.

3.2 Breakout Session Summaries

This section summarizes the top ideas identified by the session moderators based on the voting and discussions that occurred in each workshop breakout session. The first breakout session entitled “Modeling and Analysis Research Ideas” resulted in the following top-ranked research ideas:

- Characterizing uncertainty and developing analytical tools which incorporate uncertainty for operations and planning in the presence of renewable resources
- Developing better short term forecast methods in order to enable more effective scheduling of variable generation
- Incorporating Phasor Measurement Unit and other synchronized real time measurements in control algorithms for enhanced grid operation
- Determining impact of reduced inertia on system dynamic performance and develop methods to mitigate detrimental impacts of low inertia
- Developing techniques for high-resolution identification of load composition to facilitate effective demand side management.

In the second breakout session entitled “Technology and Supplemental Research Ideas,” the highest ranked research need was testing and evaluation of future solutions. This topic included creating:

- real-time simulation-based test beds shared between multiple universities
- scalable and reconfigurable large scale, test beds based on multiple hardware-in-the-loop (HIL) technologies
- simulation and testing tools for architecture and device large-scale testing.

The second most highly rated research topic was related to resiliency modeling and metrics. It included:

- Modeling power system resilience with multiple weighted indicators based on electrical, economical, and social aspects
- Creating metrics for resilience and investment criteria (such as rate of return) for resilience improvements
- Studying use of resiliency measures for investment analysis or to provide incentives to operators to consider resiliency in decision-making.

There were a number of research topics in the Technology and Supplemental Research Ideas session that were ranked third in priority. They included:

- Increasing resiliency of the grid through smart control and smart protection
- Centralized databases for analysis
- Large dynamic data sets for analysis
- Model validation testing
- No regrets and best transmission system configurations
- Reconfiguring electric power grid to rely more on microgrids

- Redefining the interface between transmission (i.e., high voltage) and distribution (i.e., low voltage) systems to coordinate both systems and integrate distributed energy resources efficiently. Relatedly, designing the needed information architecture for integrated Transmission and Distribution operation.

3.3 Categorization of Research Ideas Discussed in the Workshop

The suggested research ideas for the Workshop were wide-ranging so members of the Forum Coordination Team created ten categories for the ideas and issues, and then placed the ideas and issues into appropriate categories, sometimes assigning them to multiple categories. The following gives the categories that Team created along with examples of research ideas that fit into the categories. The research ideas tended to be the ones that were most frequently rated as high priority by the workshop participants. The complete list of ideas and issues by category is given in Appendix 2.

1. Real-time Measurements for Control and Situational Awareness
    - Enhanced grid operation and control
2. Resiliency: managing extreme events and security risks
    - Physical and cybersecurity, metrics for assessment/valuation
    - How to increase resiliency?
3. T&D System Modeling, Simulation, and Test Beds
    - Collaborative test beds for testing new strategies, hardware, business services, controls, reliability and resiliency actions
4. Electricity Markets
    - Simulation test bed/platform for assessing market mechanisms
    - Future of ancillary services: models and frameworks
5. Integrated Transmission and Distribution Operations and Control
    - Accounting for uncertainty in operations and planning
    - Designs for operating/coordinating an integrated transmission and distribution system
6. Information and Computational Technology Needs and Architectures
    - Framework for secure/efficient communication of smart grid data
7. Distributed Energy Resource Modeling and Integration
    - Improve wind/solar forecast accuracy (including ramping)
8. Distribution Systems and Microgrids
    - How to reconfigure the grid for more microgrids?
    - Expand uses of PMU data
9. Power Electronics/FACTS/HVDC/Grid Hardware
    - Advance hardware development
    - Improve modeling such as for power flow control
10. Business/Research Models and Technical-Economic Analysis
    - Create incentives for resilience improvement

3.4 Key Takeaways

Taking the number of votes given to high priority research ideas, two key takeaways appear to dominate the collective thinking of the workshop participants: the need to quantify resiliency and to account for uncertainty in operations and planning, particularly in the presence of renewable resources.

The future grid needs to significantly move towards incorporating real-time tools and technologies in operational planning and controls to address uncertainty and resiliency challenges that impact the entire value chain from consumer level to bulk power generation. An example challenge cited often is the ability to measure system inertia including centralized and distributed energy resources in real-time, determine the limits, and mitigate low inertia effects. The key enablers are real-time simulation platforms and test beds, including the hardware-in-the loop, that can be used to develop and validate models, and data, and assess new potential applications that will address problems and challenges identified by industry. Such simulation and testing tools will be of paramount importance to test new strategies, market mechanisms, new hardware, business services, controls, and reliability and resiliency investments.

Improving or simply maintaining power system resiliency has become an urgent concern given the growth in small-scale distributed energy generation resources and in demand resources with customer participation. Workshop participants identified the need for resilience metrics with multiple weighted indicators based on electrical, economical, and social aspects. Such metrics, when coupled with resiliency models, could be used to analyze and provide incentives for adoption of resiliency enhancing approaches perhaps such as the use of microgrids.

4 Conclusions

New technologies and their increased pace of adoption are creating a significant amount of the overall change on the electric system.

- Horizontal drilling for oil and natural gas has substantially reduced the price for natural gas, and changed the generation mix and dispatch.
- Falling prices of renewables, including wind and solar, mean these are being adopted more quickly than in the past.
- Distributed generation and microgrids are emerging, partially in response to more extreme weather events.
- Increased computing power and the ability to process large amounts of data have encouraged the deployment of many PMUs around the country and this deployment has created a host of research issues related to verification, communication, and interoperability.
- Smart meters and demand controllability have created need to unbundle the services provided by generators so Demand Response can participate in markets.
- Energy efficiency technologies creating less demand growth overall.
- The combination of all the generation and load technologies have created the need for much more sophisticated planning and operations tools; increased computing power will allow the industry to use more sophisticated and complex tools.
- Improvements in modeling and simulation, as well as hardware- and system-in-the loop evaluation tools has created an opportunity to evaluate largescale implementation of proposed solutions

New technologies, extreme weather, and emerging energy and environmental policies have combined to create a host of new uncertainties and risks to the electric grid. New technologies are both bringing more uncertainty for operators and planners than in the past while also providing new options for mitigating that uncertainty. Extreme weather events are occurring with much more frequency and severity than is normally seen, creating the need for a more resilient grid. Emerging energy and environmental policies have encouraged the adoption of many of the new technologies, most notably wind, solar (utility-scale and rooftop), energy efficiency, demand response, and the shift from coal to cleaner fuels.

The changes are taking place much more quickly than electric utility technology changes have occurred historically, challenging an industry that is used to planning conservatively and deliberately. This increased pace is one of the reasons why the Forum and Workshop focused on short-term, 5-10 years, research. In addition, the focus was intended to bridge the gap between fundamental research and very short-term demonstration projects.

The first breakout session entitled "Modeling and Analysis Research Ideas" resulted in the following top-ranked research ideas:

- Characterizing uncertainty and developing analytical tools which incorporate uncertainty for operations and planning in the presence of renewable resources
- Developing better short term forecast methods in order to enable more effective scheduling of variable generation
- Incorporating Phasor Measurement Unit and other synchronized real time measurements in control algorithms for enhanced grid operation
- Determining impact of reduced inertia on system dynamic performance and develop methods to mitigate detrimental impacts of low inertia
- Developing techniques for high-resolution identification of load composition to facilitate effective demand side management.

In the second breakout session entitled "Technology and Supplemental Research Ideas," the highest ranked research need was testing and evaluation of future solutions. This topic included creating:

- real-time simulation-based test beds shared between multiple universities
- scalable and reconfigurable large scale, test beds based on multiple hardware-in-the-loop (HIL) technologies
- simulation and testing tools for architecture and device large-scale testing.

The second most highly rated research topic was related to resiliency modeling and metrics. It included:

- Modeling power system resilience with multiple weighted indicators based on electrical, economical, and social aspects
- Creating metrics for resilience and investment criteria (such as rate of return) for resilience improvements
- Studying use of resiliency measures for investment analysis or to provide incentives to operators to consider resiliency in decision-making.

There were a number of research topics in the Technology and Supplemental Research Ideas session that were ranked third in priority. They included:

- Increasing resiliency of the grid through smart control and smart protection
- Centralized databases for analysis
- Large dynamic data sets for analysis
- Model validation testing
- No regrets and best transmission system configurations
- Reconfiguring electric power grid to rely more on microgrids
- Redefining the interface between transmission (i.e., high voltage) and distribution (i.e., low voltage) systems to coordinate both systems and integrate distributed energy resources efficiently. Relatedly, designing the needed information architecture for integrated Transmission and Distribution operation.

Appendix 1: Session Notes

This appendix provides notes taken by selected forum participants. For each panel session there were two note-takers. The notes represent the note-takers' understanding of what the panel members and members of the audience. Since the notes were intended to capture problems, challenges, and research needs about the future grid identified during the Executive Forum, there is no attribution of the notes to particular panel members or participants (except the key note address). No one as reviewed and approved the notes so these notes may not exactly reflect what was said. There also has not been an extensive effort to clean-up the notes and convert them into a narrative of the ideas and perspectives expressed during the Executive Forum. Thus, by in large they do simply communicate what the note-takers heard, interpreted, and recorded. Also, since no effort was made to integrate the notes from the two note-takers for each panel session, there may be differences between the two sets of notes for each panel session.

Keynote (one note-taker) {Presentation slides are available on the PSERC website.}

- Challenge: electricity demand (in particular, integrating energy storage capabilities of electric vehicle batteries). Energy storage: need to explore multiple uses.
- Microgrids: Efficiency can be an issue. Synchronous or asynchronous attributes?
- Challenge: extreme earth and space weather
- Need to improve grid resiliency to high impact/low frequency events such as through storm hardening, improving transmission infrastructure, and improving generator availability and performance through better fuel availability, dual fuel capability, coordination with gas pipeline and neighboring grids). Need for ring-bus network structure which integrates microgrids and diverse resources.
- Cybersecurity threats are real. Responses may include greater use of intranets.
- Uncertainty about how to harden the grid against extreme weather conditions.
- Cold weather issues: SF6 liquification. Another example of needing to reengineer the grid for extreme weather.
- Need to secure the infrastructure to human actions (physical security). Is it possible to build the grid that minimizes physical risk to substations?
- Need to advance grid-scale energy storage and how to control it to support integration of renewables.
- Challenge: reliably managing switch to low-carbon fuel sources
- Challenge: natural gas operations coordination
- Challenge: integration of intermittent and demand side resources
- Need an international standard for smart inverters to account for such requirements as frequency, voltage, droop requirements for asynchronous generation.
- Need to improve usefulness of PMU data
- Need to advance modeling performance using private cloud networks using high performance scientific computing. System becoming more voltage limited so analytics/modeling becoming even more important to allow the system to operate closer to the edge. This also affect day-ahead planning and unit commitment. Need to

move from DC load flow to AC models using faster computers for optimization. Modeling accuracy will be an issue. For example, model parameters used in existing models may be inaccurate (such as generator models)

- Need to move from EHV AC to HVDC for controllability and to integrate renewables.

Executive Perspectives Panel (first note-taker)

Notes:

- Cost effective demand response, with limited devises
- Renewables: Improve forecast accuracy on icing of blade, availability, ambient temperature etc.
- Distributed resources: Distribution level resources how to integrate into bulk system operations
- Cyber security: prevention of attacks
- Demand response with residential consumer participation through aggregation along with bulk system interface
- Implementation of future HVDC and the challenges
- Distribution level storage: how to make it cost effective
- Future active control devices to meet the grid needs, with higher controllably
- New solutions to increase resiliency and smart control
- From large generation to distributed generation – how much inertia behind inverters? How to ensure enough inertia behind inverters?
- Reliability of the CPU-based equipment. How do they interface?
- Harmonics would it be a problem if more control at the distribution level. Will the current models reasonable in capturing the harmonic events?
- Better grid model for future needs
- Reliability and resiliency: meeting the consumer expectations? How to model?
- System observability (visibility) modeling for demand response
- Philosophy behind operating system: Operate for worst contingencies (n-1) vs. high probability contingencies – standards
    - Limitations behind operating with worst contingencies, will move towards risk-based operations is a possibility
- Reliability-based consumer operation for demand response
- Resiliency: Coordination of multiple resources (how to combine multiple layers: for example: (i) gas-electric-cyber, (ii) water-electric interface - not only hydro, usage in fossil based (iii) cyber-relay-power
- New auxiliary services to improve the future needs for generation demand balance
- Market-based requirements - need to identify what they are
- Energy Management Systems: Operation is based on weather conditions. Little weather data for power system operations
    - Short term (5 min.) economic dispatch (security constraint) vs. weather based

- Modeling consumer participation and the value of demand response
- Modeling the value of HVDC including the control, cost of outage of HVDC (n-1), and controllability of AC in the presence of DC network
- Privacy: Demand response and consumer based data
    - Data belongs to the consumer, but the utility needs only the aggregated information
    - Need to get the data with minimum consumer concerns
- EV as storage
    - Delivery vehicles as storage. It is growing at a slow rate
- Longer planning period?
- Ramp rates?
    - CA: new products are introduced
    - TX: The issue is reduced over last three years
- Storage at transmission level with increased control

Executive Perspectives Panel (second note-taker)

Notes:

- There is a need for research on cost effective demand resources. Peak and near peak demands are only encountered for 25-75 hours. Need to utilize automated meters. Loads such as pool pumps offer a solution to Scarcity Pricing if implemented in effective demand response programs.
- 40% penetration of wind generation exists today in ERCOT. There is continuing strong growth in wind generation and penetration will go higher. This requires improvements in forecasting for load and equipment availability – more specifically forecasting for icing on wind turbine blades.
- Research assistance is needed for distributed resources, standby generators and interfaces with distribution systems.
- Physical and Cyber Security is a big risk and research help is needed in that area. Firewalls are generally around an RTO and not customer/generator concerned.
- There are barriers to development of HVDC and offshore wind generation. Research should focus on the benefits of HVDC and cooperative effects of utilities, RTOs, and users to provide these benefits.
- There is a need for a longer planning perspective for analyzing solutions. The biggest issues to overcome are cost allocation issues.
- Devices that are reaching the end of their useful lives require evaluation to determine if or how these devices are to be upgraded? In kind replacement is not necessarily the best answer.
- For resiliency, there is need for increased smart control.
- Shifting characteristics of generation fleet mix has created issues that need research. How much inertia is needed on the interconnected system? What voltages sources and responses are available behind the inverters?

- CPUs on equipment need to work cooperatively: interface nicely. There is a need for faster computing to improve modeling capability interfacing the distribution systems and distributed resources.
- Reliability is still the greatest customer expectation. How is good power quality assured to meet customer expectation?
- There is a need for standards requirements for voltage response, frequency response and droop control for intermittent and distributed generation.
- There is a research need for cloud computing to handle the increasing quantities of data. Models need to be more AC capable while system equipment needs to transition to more DC supply and delivery.
- Gas-electric coordination needs to improve and gas delivery problems need to be avoided as future generation to 2030 is largely gas fueled.
- Can speed of inverters compensate or substitute for retirement of thermal generation unit contributions to inertia?
- Research is needed to develop/utilize storage at the transmission level.
- Security- including cyber on relay systems, control systems and communications is a concern.

Technology Applications Perspectives Panel (first note-taker)

Notes:

- Distribution utilities have developed a number of smart grid investments on the distribution system.
- DER is a matter of reliability and resiliency.
- Grid has evolved and the following are in need to be improved: reliability, real time customer interaction, privacy, affordability, and security.
- Inclusion of distributed generation (DG) creates concerns regarding safety and reliability of the distribution system.
- Need to develop products on local distribution level that can be added to the power system to improve pricing on the distribution level. The key is that these markets should be adding to, and not duplicating the existing products.
- There is a need to quantify the actual value of the distributed generation on the system and show what technologies are needed to realize their benefits.
- It is an important research area to identify the type of the information that is required to be gathered from the system to be able to allow distributed market.
- Rural electric cooperatives operate 40% of distribution systems. Grid operations can be more cost effective, and therefore smart grid technology and distribution system automation are effective in reducing the cost of operation.
- It is essential to integrate DER into distribution systems in an economical manner.

- There is a disconnect between the research ideas related to advanced analytics and the actual economic analogy and needs of the power industry. Cost-benefit analysis is required to ensure customers are provided with an affordable service.
- How do we enable the applications to make sure we have the right standards in place?
- Our road map for research is not aligned with the pace the DER enabling technology is evolving.
- Having accurate data is essential for transmission and distribution system operation. Distribution system is much more connected than transmission system
- The communication system needs to be more reliable than the grid. The ability to update the data accurately can improve actions taken during outage restoration and improves the speed of power restoration.
- With more connected devices cybersecurity has become an emerging issue. Being able to detect events and coordinate actions is needed for reliable system operation.
- For a safe, reliable and yet environmental friendly system, a balance between distributed generation and conventional generation is required.
- We have well-developed models and communication systems for the transmission system. However, lack of behind the meter information and poses a challenge to the power system operators.
- Inability to perform experiments on physical power system is a challenge for power system researchers. Rural cooperatives can serve as potential benchmarks for implementing research ideas due to their nature.
- Inefficiencies at the local level in distribution system operator environment can propagate to bulk power system and impact overall system efficiency.
- Technology to track the weather and tie that into existing EMS systems can have a significant impact on system operation.
- There is a need to define metrics of how a research idea and solution fits the needs of the industry.

Technology Application Perspectives Panel (second note-taker)

Notes:

- Posed the question on how to improve reliability and resiliency of the system while keeping the system cost-effective
- Problems with the grid open to cyber attacks
- Predictive modeling of extreme weather impact leading toward effective deployment of resources to restore outages
- Use market-based price signals at distribution level to monetize distributed resources based on where they are located
- We use advanced analytics to show cost and benefits of proposed projects such as developing distributed generation.

- Automating a process to collect data accurately with the growing challenges of a more connected grids (i.e., cellphone, computers, etc.)
- Detection of cyberattacks
- Application of good computer science fundamentals in any integration or enhancement efforts to the grid. For example, the concept of "separation of concerns" applied to the design of an electric outlet where one outlet should not be aware of what is connected to other outlets.

Technology and Solution Provider Perspectives Panel (first note-taker)

Notes:

- Improved composite load models are needed that can better address the flexibility of loads.
- Evaluate new and current policy mechanisms and rate designs to determine if they effectively encourage new behavior.
- There is a need for improved grid operator control center tools that reduce manual decision making in grid control centers.
- Incorporate increased load flexibility into operations as loads change from passive to active.
- Research is needed to discover innovate ways of dealing with loads as they change from resistive to constant power.
- Research ways to transition from local area control (LAB) to wide-area control (WAC) by utilizing PMU and FACTS devices.
- Participation of smaller and smaller resources into wholesale markets will challenge mixed integer programming solutions.
- New methods will be needed to address issues managing inventory with energy storage.
- How to address governor response and inertial response in ancillary service markets.
- Utilities need new economic models and business cases for the value of energy storage with increased distributed energy resources.
- There are no methods to qualify emerging cybersecurity technologies to determine if they meet standards.
- Ways to enhance protection with PMUs.
- Labs are needed to study PMU data to verify accuracy.
- Research how far synchronized sampling rate of PMU needs to be pushed.
- There is a need to verify PMU data with operational models.
- There is a need for an end to end business model that provides incentives to customers for demand resources and allows the system operator to take useful actions.

Technology and Solution Provider Perspectives Panel (second note-taker)

Notes:

- Energy storage technology is now prevalent in electric vehicles as well as in households. Research on storage, therefore, is becoming more and more important.
- The new generation of society is becoming more and more aware of the energy crisis, and the needs for energy efficiency and carbon footprints, which in turn is giving a lot of momentum to green energy technology. At the same time, what we are lacking is a good and visible knowledge of current and future policy changes, and how they may impact storage facilities such as the 1500 MW storage installation plan by 2020.
- Another area that needs attention is visibility of loads. What is the load at any point, what part of it can be deferred, and what part of it is flexible?
- There is also a pressing need to understand the impact of policies and incentives on the behavior of consumers.

- From a control center point of view, operators are gradually losing control of the proactive actions that need to be taken on the grid, mostly due to decentralization of monitoring and control. This can be useful for grid efficiency, but also poses several research challenges.
- Transmission and distribution substations are gradually becoming smarter and more active. Loads are also not as supportive during emergency conditions as they used to be in the past. There is an inherent challenge posed by that for monitoring and control.
- Another topic is wide-area measurement systems (WAMS). It is not enough to just monitor the grid using PMU data, but also take proactive control actions on the grid within fractions of seconds without jeopardizing the health of the system.
- Besides wide-area control, operators are also interested in taking regional or local control actions using static VAR compensators (SVCs) and FACTS devices. The challenge is to take control actions without harming the neighboring utilities.
- The final challenge is to take academic research to industry, and implement pen and paper designs to actual devices on the field.

- Electric storage will make the real impact if storage can also be made to participate in the market, perform ancillary service such as PV smoothing, instead of just serving the customers from behind the meter. How can storage technology be improved to make this leap?
- Participation of storage in the wholesale market will promote research problems on mixed integer programming. The challenge is scalability
- With more renewable penetration the importance of AGC, governor response and inertial response will increase. We need more research on these topics, and how PMU data can be used for estimating inertial response, especially for control of storage devices.

- Three main topics of research - cyber security, protection and control and its transition to digital technology, and energy storage.

- For energy storage systems, where generation will become more disintegrated into smaller and decentralized entities, existence of a viable business model is still not very well understood.
- For security, industry and academia must work together to determine how the resilient designs for grid monitoring and control can really help the control room operations.
- Most importantly, what we need most is high-quality education in power systems so that the next generation of students are well qualified in difficult topics such as protection and control of power systems.

- How to develop end to end business models for different kinds of demand response?
- How can market control inertial responses?
- How much data should be shared with neighboring utilities?
- How can big data analytics, such as compressed sensing, data mining, etc., can help power system operators deal with large data volumes?
- How to model loads accurately?
- How to guarantee fidelity and security of PMU data?
- Four final topics of current and future interest - understanding consumer behavior, promoting power system education in protection and control, interaction with other energy infrastructures such as water and natural gas, and finally understanding load models and market mechanisms.

Government Perspectives Panel (first note-taker)

Notes:

- Need research at grid speed & not science speed –pace of change is pretty high
- New asset classes – on both sides of meters, fly by wire
- New services and actors – external players aggregators (like Uber)
- Grid as a component – like a smart city's resilience
- Scalable hybrid control strategy – e.g., communication
- New threat vectors and confidentiality (Cyber Security –Physical)
- Realistic models and simulations
- Composeable, reconfigurable, scalable test beds
- Optimization and advanced computing hardware
- T & D –combined goals
- Use of high powered power-electronics
- Flexible demand management
- Manage uncertainty
- Demonstration platforms
- Remove barriers to entry to outsiders to the industry
- Ten yrs. is long term for this industry because of changes going on.

- Harness atypical power research community – almost 300 EE departments with no power system programs
- Robotics lab at Georgia Tech – make it open to all students. Similar test bed open to community in grid technology.
- Consumer behavior, scalability
- Resilience
- Energy is one of the life-line sectors.
- Water, finance, etc., are others
- Cascading and inter-dependencies within each sector
- Designed by humans – we solve things in isolation
- Threat levels and risks are multidimensional
- Requires strong correlation
- How to measure resilience
- What are the Incentives for improving resilience
- Return on investment for resilience investments/improvements
- DOE Quadrennial Energy Review & Quadrennial Technology Review
- Grid Modernization consortium
- What research? Very little POWER and lots of other areas
- Cyber security
- Data to information
- Closing loops - Measurement to Control, Supplies to Demand
- Across boundaries
- Lower barriers to entry – engage the community at an early stage
- Need Infrastructure to evaluate new ideas and solutions:
    - Some of them are open models, test beds, high performance computers (HPCs), but in addition, not just stuff, but also need communities
    - Get all PIs together – 2 min. lightening talks to improve communications
    - Smart Grid Interoperability Panel is an example.
    - How do we figure out what works and what does not.
- How do we increase govt. involvement
    - Make noise. Government is more reactionary.
    - Policy and decision makers see value when they see research being used – demonstrate how research contribute and make difference
- How can we get field data to test out ideas (e.g., NASPI data repository)?
    - Smart Cities – engaging stakeholders in solving their problems
    - Transition is always a challenge
    - We have to share our success stories.

Government Perspectives Panel (second note-taker)

Notes:

- The number of power experts in this country is small.
- Therefore, how to harness online resources (e.g., online courses) to educate community at large is a challenge.
- NSF is community-driven. We need to make efforts to disseminate the message that power/energy is a crucial area.
- Workshop such as this one is a great opportunity for networking.
- Fly by wire is needed in response to new asset classes.
- Business models more like Uber would change the traditional economic models in traditional utilities.
- Grid and components need to be examined jointly.
- Scalable hybrid data-driven control strategies are needed.
- Integrated risk management with both physical and cyber layers.
- We need realistic models at scale.
- We need composable, reconfigurable testbeds at scale.
- Interoperability challenges are significant.
- Integrated transmission & distribution planning is much needed.
- High power electronics
- How do we integrate T&D, as well as dispatchable demand, all at once?
- We need to think through the uncertainty in the industry. So much could change in ten years.
- We need new systems for demonstration.
- There is high entry barrier for power systems. We should try to engage other communities.
- Industry needs to make more “value proposition” to enable a broader energy picture.
- Energy is one of the lifeline sectors.
- We need to understand the multidimensional risks.
- How do we embed resiliency into the grid?
- The measure and value proposition of such resiliency/risk concepts need to be clearly communicated.
- There is a lot of new dimension to add to the traditional view of “power engineering”.
- Cyber security is of significant importance for the grid.
- We need to use the data more appropriately (in particular big data).
- A major challenge is how to close the loop throughout the system in real-time.
- Inter-agency coordination and management could better streamline the research portfolio and communicate the message.

University and Lab Perspectives Panel (first note-taker)

Notes:

- Synchrophasor project has done a good job of bringing together government, researchers, and industry; building a community around synchrophasors.
- Grid Modernization Architecture Consortium: This is a new initiative and we are looking for the research community to be a technical resource working with DOE.
- Another area which should be supported by the research community is the Future Power Grid Initiative. It has three main focus areas (fusions) 1) Fusion between planning, operations, and markets; 2) Fusion between Transmission and Distribution; 3) Simulating power grid and other supporting infrastructure, especially communications systems.
- Open source software will be key for research community.
- Renewables are being integrated into the distribution side of the power equation so we need to focus research on that aspect in order to understand it.
- We need to make DG power electronics plug-and-play and understand how to utilize DG to make the grid more reliable
- Power electronics will make DG and storage dispatchable
- Communication is needed to make the power system more reliable by enabling the control of DG and storage technology
- We need to leverage other technologies to advance the research to full scale use time. Automotive sector has already integrated some of the power electronics that are needed for the distribution system.
- Understanding the evolving consumer behavior is important. Consumer may be willing to accept lower levels of reliability.
- Try to understand how the electrical system integrates with the rest of the energy system.
- The US can learn from other places in the world on integrating low inertia energy sources.
- Challenge to coordinate funding agencies especially for research across different countries with different funding agencies
- Controls are cheaper than infrastructure reinforcement/improvements for integrating multiple power sources. Focus on research to advance the controls and how to implement them in the grid.
- Controls can be placed at the generator, load, or transmission infrastructure; there is benefit of placing the controls on the infrastructure itself.
- Penetration of renewables and the impending large impact of DR have introduced uncertainty in power models. Need to develop models to remove that uncertainty or uncertainty needs to be included in planning.
- Capturing uncertainty in load modeling needs to be captured and historic data leveraged.
- Research has discovered that capturing wind speed information is difficult, but capturing wind farm output is a better metric for wind uncertainty.
- We need to revisit standards used for operations and planning. Risk-based standards may replace first contingency standards.

- Simple positive sequence models cannot adequately model the new grid with high penetrations of renewables and power electronics.
- Need to develop predictive models for the new dynamic control devices currently introduced or to be introduced in the near future. Research community should be focused on it.

University and Lab Perspectives Panel (second note-taker)

Notes:

- Grid modernization consortium – DOE seeking increased budget authority – working to get labs to be a technical resource to work hand in hand with DOE HQ – group of 6 labs
- System operations, power flow and control: operations and control theory, coordinated system controls (link EMS and DMS), improved analytics and computation, advanced power flow control devices and decreasing costs for these → these topics already discussed a lot today
- Future Power Grid Initiative– three fusions
  - 1) fusion between planning, operations and markets
  - 2) transmission and distribution – historically there has been a stable boundary condition between these two, but going forward there will not be such a boundary.
  - 3) simulating power grid with … time based network with event based network
- Need to approach and use open source software – the research community needs to embrace this. Open source will drive future developments.
- Much here has also already been addressed today.
- Focus on wide area control of the power grid – networking over large areas will facilitate low cost and reliable power even if the sources (e.g., wind) are 'unreliable'.
- Make the case for large research centers and engineering research centers
  - 1) Modeling and estimation
  - 2) Actuation / affecting power flows in the grid
  - 3) Control
- Aspects of how we will control the grid
  - Options: lots of transmission, or storage, or lots of controls
  - Can trade these off, but propose that controls are cheaper than expanding the infrastructure.
- We could push control onto the generation side, or onto the demand side, or push it into the infrastructure and let people do whatever they want and have enough storage to handle whatever happens. There is a good argument for pushing the control into the grid itself which will facilitate expansion of new resources
- Newer ideas/options – control at the 'edge' or transmission with HVDC
- Understanding and involving the consumer: in how the consumer integrates with the rest of the electricity system.
- We might very well lower the reliability of the system with all the changes coming.

- Need to better understand the consumers, perhaps with behavior analysis
- Understanding and modeling the consumer interests in the electric power system
- Will probably need to build more HVDC, and so inertia will be an important topic.
- Asynchronous grid of the future
- Maybe all of us EEs should talk with other people!
- With DG and DER becoming more prevalent – energy storage will also become more prevalent – sites will have load, generation and storage (dispatchable storage).
- This will require improved power electronics – each of those three elements will require more and improved power electronics, for smooth integration into the grid without compromising reliability

- Two Hardware Technologies:
    a. Solid state transformer
    b. Isolation devices to help manage the power system
- Need to ensure the reliability and resiliency of the power system
- Focus on the control aspects
- Cyber physical aspects of the modeling – this is where the research challenges are.
- There is a lot of commonality with other sectors, such as transportation, in terms of storage and understanding/modeling storage.
- Also ship propulsion systems
- We should leverage technologies and knowledge from these other sectors.
- Some analysis areas
    - Large penetration of renewable resources and with future in which will be able to deal with demand response, we need to bring uncertainty into our analysis tools
    - Will require robust stochastic power flow, stochastic OPF and stochastic transient stability analysis
    - Capturing uncertainty in load modeling will be/is a critical area. We have LOTS of historical data and can use this to capture the uncertainty in load.
    - Compare to previous focus on wind speed data that has now shifted to analysis of wind power output.
    - Do we need to revisit standards associated with operations and planning – historically focused on worst case contingencies. Should we turn to risk-based standards instead.
    - For this need to quantify what is an acceptable level of risk.
    - Power electronics – includes single phase devices – variable speed drives, wind and solar generation –these dynamics change the dynamics of the power system in a fundamental way, as these are inconsistent with historical positive sequence modeling/assumption.
    - Need high speed simulation tools in which we can model these new devices accurately in our a-b-c time domain sequence analyses
- Conversation about needs for utilities to understand what the customer wants – we have been talking about this for 30 years. Small customers are not unhappy enough with current prices to change their behavior. Larger customers are seeking out other solutions – we have

a poor track record of understanding customers – perhaps WE SHOULD leap-frog this and anticipate what customers WILL want and present it / propose it to them.

- Note that we do not want or need every customer to be responsive. A percentage of response is what is best and what will give us a good demand curve.
- We (power sector) seem to have given up on the notion of reliability and quality of service – in other sectors people accept the notion of reliability at a price. There really is no 'one size fits all' and power sector needs to come back to this.
- We need to look for mechanisms to move from the public good concept of reliability to reliability as a private good – this will neutralize the concept of reliability by giving people choices, determining how much they are willing to pay for different classes of reliability.
- What is the next big breakthrough in power electronics?
    - Hybridized circuit breakers with electronic and mechanical switches
    - Transformer technology and better anticipate and control transformer failures – quantify the benefits of putting controls into the transformer systems
- Need to be able to measure resilience and flexibility – need to develop measures to be able to quantify resilience and flexibility – especially to quantify in terms of dollars is difficult.
- Is industry ready to adopt our new algorithms and software that academia is developing because it is fun. Could there be a roadmap from government to help move industry to adopt the new tools.
- Need regional demonstration projects, field proven, in order to get these into industry. But demos necessary but not sufficient – need many demos to convince industry to truly adopt. Need to build entire system around the new analysis technologies to provide necessary support
- At microgrid level, people start with the droop characteristic and forget about the fast dynamics – we need to be careful with the fast phenomena, modeling and understanding these – that are being introduced by the power electronics and their increasing presence on the grid.
- Research question: need to balance robust switches vs. solving problems with software
- Need to do research into dynamic observability and dynamic controllability – *e.g.,* how many controllers do we need to ensure stability?
- Could we go back to tubes rather than acres of silicon, to control power flow – can we investigate very high power electronic tubes?
- Facilitating collaborations will come through open source software and technologies.

Appendix 2: Categorized Research Ideas and Issues

This appendix presents the complete list of research ideas discussed in the workshop sessions. The ideas have been categorized according to categories selected by the Forum Team. Some ideas were assigned to multiple categories because they crossed-over those categories. The tables have three columns:

1. statements of research ideas or issues
2. a number assigned to each idea for tracking purposes where research ideas beginning with M were discussed in the Modeling and Analysis session and the ideas beginning with S and T were discussed in the Technology and Supplemental High Priority Research Ideas session
3. the number of high priority votes given to that research idea by participants in that workshop session.

Category 1: Control and Situational Awareness Using Real-time Measurements

Research Idea or Issue	Assigned No.	High Priority Votes
Develop control algorithms based on real time measurements such as synchrophasors for enhanced grid operation and control	M105	10
Measure system inertia including centralized and distributed energy resources in real-time, determine inertia limits, and mitigate low inertia effects (inertia)	M109	10
Centralized data: large dynamic data sets (e.g., of normal operation and of abnormal operation) for model validation and modeling of realistic operations	T338	8
Develop cheaper (much cheaper) PMU technology to be deployed in the distribution level for cost-effective and fast linear state estimation on the distribution level, line impedance identification, time-domain load modeling, adverse event identification (such as faults), DER coordination, etc.	T309	7
Develop early warning methods and situational awareness tools based on PMU data along with mitigation strategies based on such information	M103	6
Develop big data driven methods for better controlling and operating the power grid (big data)	M106	4
Large area situational awareness (related to M123) on an interconnection and/or national scale with real-time visualization, real-time analytics, and real-time reporting	T339	2
Specify how much inertia is needed	M113	0
Develop methodologies for the use of real time PMU data to help system operators to go beyond monitoring of grid to actual decision-making and control	M123	0
Investigate grid operator control center tools that reduce operator decision-making when appropriate to maintain grid reliability	M139	0
What are the research issues, challenges, and value proposition for the application of big data analytics to smart grid? What is the specification of "big data"?	S218	0
Develop scalable hybrid (electric power, weather, traffic, etc.) data-driven control strategies that enable new infrastructures	S219	0

Category 2: Resiliency - Managing Extreme Events and Security Risks

Research Idea or Issue	Assigned No.	High Priority Votes
Model power system resilience with multiple weighted indicators based on electrical, economical, and social aspects	S220	11 (w/ S221)
Create metric(s) for resilience and rate of return for resilience improvements. Possible use: investment analysis or to provide incentives to operators for adoption of resiliency measures.	S221	11 (w/ S220)
Increase resiliency of the grid through smart control and smart protection	T307	10
No regrets and best bets transmission system configurations. Useful for creating a grid road map/development plan.	T342	8
How to harden the grid against extreme weather conditions	T327	7 (w/ T333)
Harden grid (resiliency) vs. redundancy, which is more appropriate?	T333	7 (w/ T327)
Smarter security in the grid, advanced heuristics and analytics. Next generation technical standards.	T337	6 (w/ S202, S210)
Cybersecurity: Identify security risks such as digital relays, control center firewalls, etc.	S202	6 (w/ T337, S210)
Investigate methods for quantifying the impact of cybersecurity investments	S210	6 (w/ T337, S202)
Model coupling of infrastructures in reliability studies	M119	5
Framework/model for secure and efficient communication of smart grid data	M154	5
How should we manage extreme risks so as to minimize their adverse system wide impact?	M101	4
Formal methods to analyze/verify behavior of power system as cyber/physical system/designs	M149	1
Explore system vulnerability to interdiction and develop ways to make the grid more resilient to such attacks	T302	0
Physical security: Identify weak links in the grid	T304	0
Develop standards related to the use and implementation of cyber security technologies	S217	0
Create risk models that also capture the inter-dependencies of subsystems	S222	0

Category 3: T&D System Modeling, Simulation, and Test Beds

Research Idea or Issue	Assigned No.	High Priority Votes
Need to create real-time simulation-based test beds shared between multiple universities	T317	12 (w/ T318,T341)
Create scalable and reconfigurable large scale test beds based on multiple hardware-in-the-loop (HIL) technologies	T318	12 (w/ T317,T341)
Simulation and testing tools of new architecture and devices for testing new strategies, hardware, business services, controls, reliability and resiliency assessment, etc.	T341	12 w/ (T317,T318)
Improve real-time power system models, particularly by expanding use of AC models, to allow expanded utilization of the grid	M140	3
Create an open source full scale simulation model for transmission/distribution systems	M126	3
Create and solve models that capture the cascading effects due to inter-dependencies of subsystems	M129	3
Create cross discipline simulation models (physics, economics, society studies) for power system analysis	M125	2
Power system dynamics with fast-acting and single-phase components – hybrid simulation and analysis	M133	2
Create models that integrate transmission and distribution as one entity for flexible coordination and control	M127	1
Models for integrated analysis of transmission and distribution systems	M135	1
Apparatus libraries with operational data and validated models	M143	1
Models for evaluating dynamic stability consequences of dispatcher actions	M144	1
Research already proven and tested models used by other industry to see if there is applicability to power systems analyses	M128	0
Robust stochastic models and algorithms for power flow, stability, etc.	M136	0
Develop hybrid models, analytics, and simulation tools for new devices	M137	0
Modeling demand response for operational decision-making and situation awareness	M138	0
Develop enhanced models of power system operations to incorporate diverse demand, generation and storage resources	M141	0

Category 3: T&D System Modeling, Simulation, and Test Beds (continued)

Load Modeling and Demand Response		
High-resolution identification of the load composition, especially with respect to quantifying its flexibility potential, and in what ways it can be provided	M118 (merge M118, M122, M132)	9 (only M118)
Develop a high fidelity load model with specific flexibility for the effective implementation of demand response technologies	M122 (merge M118, M122, M132)	6 (only M122)
Develop techniques to dynamically extract load data	S216	4
Load modeling and uncertainty bounding from historic data	M132 (merge M118, M122, M132)	1 (only M132)
Modeling demand response for operational decision-making and situation awareness	M138	0

Category 4: Electricity Markets

Research Idea or Issue	Assigned No.	High Priority Votes
A new simulation testbed or platform for modeling, simulating, quantifying new markets, market mechanisms, that provides valuable information on a unified system all the way from the ISO-level to end-user distributed assets	M117	8
What is the potential expanded portfolio of ancillary services?	S212	4
Forecast ramping requirements	M145	2
Market constructs for variable energy resources to compete with conventional producers and loads	M148	2
Framework for valuation of grid support services	M151	2
Evaluate flexible resource adequacy	M153	2
Assess revenue sufficiency viability of low capacity factor resources	M146	1
Model/framework for establishing the value of DER	M152	1
Develop a new mathematical paradigm that will enable participation of thousands of smaller resources in wholesale markets, including stochastic effects	M120	0
What is the right mix of fast and conventional frequency response?	M121	0
Develop stochastic-based optimization strategies with the incorporation of storage and distributed resources in retail market and various sources of system uncertainties	M124	0
Change markets to have inertia based service to provide incentives for renewables to then provide synthetic inertia	S205	0
Improve cost-effective demand response (i.e., pool pumps, air conditioning)	S200	0

Category 5: Integrated T&D Operations and Control

Research Idea or Issue	Assigned No.	High Priority Votes
Develop methods for scheduling all available resources including traditional generation, intermittent energy resources	M104	18
Redefine the technical interface between transmission and the distribution systems to coordinate both systems and integrate DERs efficiently	S201	8 (w/ T328)
Design the information architecture needed to support integrated transmission and distribution operations	T328	8 (w/ S201)
How restrictive do operating standards have to be in power systems? How much flexibility can be permitted?	M116	2
How much competitive vs. cooperative efforts should be within an integrated system?	S207	0
To achieve better coordination across transmission and distribution systems, explore how to coordinate EMS – DMS	S224	0
In response to new asset classes in the system, including those behind the load, how can the power system be converted to a better fly-by-wire system?	T320	0
Integrated controls as an alternative to hardware redundancy	T324	0
Closed loop control technologies that are implemented on physical apparatus based on high dimensional data	T344	0
Transactive controls at various levels of aggregation through price and bid flows.	T332	0
Model the interaction between microprocessor controlled equipment and develop control strategies to ensure cooperation	S203	0
New control paradigms that will achieve the same goals (in terms of stabilization, variability mitigation, etc.) as transmission assets that are too expensive (and time intensive) to build	S227	0
System Operations Under Uncertainty		
How can we better account for uncertainty in operations and planning, especially in the presence of renewable resources	M100	22
Stochastic control algorithms with approximation guarantees	M147	3
Include uncertainty into basic tools – power flow, OPF	M131	0
Explore ways to incorporate detailed weather model data into power system operations	T329	0
System Operations with No or Less Inertia		
Measure system inertia including centralized and distributed energy resources in real-time, determine inertia limits, and mitigate low inertia effects (inertia)	M109	10
Specify how much inertia is needed	M113	0
Investigate power system operations in systems with no synchronous inertia at all	M130	0
What control paradigms will allow newer power electronic devices to make up for the relative reduction of inertial response with increased penetration of variable resources?	S226	0

Category 6: Information and Computational Technology Needs and Architectures

Research Idea or Issue	Assigned No.	High Priority Votes
Framework/model for secure and efficient communication of smart grid data	M154	5
Approaches to model the communication and computation of information and platforms (e.g., networks, processes)	T336	3
Develop efficient approaches such as parallel computing to take advantage of supercomputers/clusters for tackling power system problems	M107	1
How to design the information architecture and supporting communications system to achieve a fault-tolerant grid management system? What should the information architecture be for the future grid?	T311	0
Design the information architecture needed to support integrated transmission and distribution operations	T328	0
What information is needed between different layers of industry in order for the system to balance objectives of reliability, resiliency and efficiency?	S206	0
What are the better ways of handling, storing, and protecting data?	S213	0
Address architectural issues: (1) design goals (such as distributed management) and (2) design principles that enable the system to achieve these goals (e.g., the division of functionality, the placement of intelligence, etc.)	T347	0

Category 7: Distributed Energy Resource (DER) Modeling and Integration

Research Idea or Issue	Assigned No.	High Priority Votes
Develop a new dynamic underfrequency load shedding scheme that accounts for the contribution of power generation at the distribution feeder level and how this varies over time.	T334	4
Evaluate flexible resource adequacy	M153	2
Change IEEE 1547 for integration of DERs	M150	2
Model voltage sources behind inverters and develop closed and open loop control strategies to improve the security and reliability of the grid	M110	0
Analyze and compare the economic consequences of local storage versus system upgrades for the integration of PV at the residential and commercial level	M112	0
How should we integrate EV's into the grid so as to exploit their flexibility in managing the system	T301	
How many DERS under 10MWs would it take to require new distribution grid management?	T312	1
How can distributed resources assist grid operators?	T314	0
Design of new topology (ring-based) for distributed resources, distributed optimization and controls	T343	0
What control paradigms will allow newer power electronic devices to make up for the relative reduction of inertial response with increased penetration of variable resources?	S226	0
Wind and solar forecast accuracy		
Improve wind/solar forecast accuracy for system operation	M108 (merge M108, M145)	9 (only M108)
Forecast ramping requirements	M145 (merge M108, M145)	2 (only M145)
Need for improved wind forecasting and forecasting of ramp rates	M115	0
Exploit Renewables and Storage		
Explore how to exploit complementarity between renewables and storage in operations and market structure	M102	1
Develop higher energy storage density technologies and batteries	T313	0
Investigate the lifecycle of energy storage	T316	0

Category 8: Distribution Systems and Microgrids

Research Idea or Issue	Assigned No.	High Priority Votes
How should we reconfigure the electric power grid to rely more on microgrids?	T300	8
Develop cheaper (much cheaper) PMU technology to be deployed in the distribution level for cost-effective and fast linear state estimation on the distribution level, line impedance identification, time-domain load modeling, adverse even identification such as faults, DER coordination, etc.	T309	7
Develop real-time black start algorithms for dynamic restoration of the distribution system with DER in order to close the control loop for secure and adequate restoration	S204	4 (w/ S212)
What is the potential expanded portfolio of ancillary services?	S212	4 (w/ S204)
Optimal location and sizing of switching devices in distribution systems	T326	2
What information should be required to be provided by users for a distribution system operator to be able to maintain reliability and efficiency?	S209	1
New distribution sensors to address DER altered power flows – for planning and design	T340	0
Is decentralized control in distribution systems “good” or “bad” from the perspective of a system operator?	S215	0
Model power quality, particularly at the distribution level. Improve modeling of power flows and harmonics between generation and end-use customers instead of stopping at the substation	M111	0
How do we ensure that power quality is maintained, particularly with DER	T308	0
Develop a home energy system to collect and visualize data. Develop pricing, timing or other curtailment strategies for more efficient residential end use	T310	0

Category 9: Power Electronics/FACTS/HVDC/Grid Hardware

Research Idea or Issue	Assigned No.	High Priority Votes
Design the next generation of power electronic based solid state generators and transformers via an integrated hardware and software approach	T319	3 (w/ T321)
Build, demonstrate, and use high power electronics models capitalizing on recent material advances, and create algorithms that work with real data (this applies to all areas).	T321	3 (w/ T319)
Fast-acting electronic and mechanical switches	T323	2
Develop high performance power electronics based on new material such as diamond	T303	0
HVDC active control devices are at the end of their service life. What's next?	T306	0
Develop UPFC & substation automation controls that are enabled from PMU data	T315	0
Load, generation, and storage with power electronics – creating a plug and play operating environment	T322	0
Can HVDC systems and other fast-acting power electronics help with mitigation of variability from renewables?	T325	0
What control paradigms will allow newer power electronic devices to make up for the relative reduction of inertial response with increased penetration of variable resources?	S226	0
Power Flow Controllers		
Models and coordination algorithms are needed for advanced power flow control devices recently developed	M134	3
Flexible power flow control assets must be integrated into software	M114	0
Explore methods for allowing operator control actions with SVCs, FACTs devices, and new flow control technologies without adversely affecting neighboring systems.	M142	0
Magnetic amplifiers for controlling power systems	S225	0

Category 10: Business and Research Models, and Technical-Economic Analysis

Research Idea or Issue	Assigned No.	High Priority Votes
Create metric(s) for resilience and rate of return for resilience improvements. Possible use: investment analysis or to provide incentives to operators for adoption of resiliency measures.	S221	5
Assess revenue sufficiency viability of low capacity factor resources	M146	1
Long-term financial justification of important/critical projects. Technical justification can take a lesser role than financial implications. How can large projects requiring significant financial resources be justified when decision-makers are incentivized to make short-term/least-cost solutions?	T330	0
Value of distributed resources to the system. How to incorporate consumer behavior into traditional grid operations.	T335	0
Development of complex analysis tools for technology, policy, societal, and public perspectives in development of resilient power systems	T345	0
What is a systematic method for evaluating cost-effective investments in distribution lines and comparison with investing in local DERs?	S208	0
Develop detailed business model for energy storage that will enable large scale deployment	S211	0
How can we transition to a generation-following model (instead of the conventional load-following mode), where load is more flexible than generation?	S214	0
Explore opportunities to improve gas-electric coordination for reliable grid operations	S228	0
Research and Education Collaboratives		
Design and run competitions similar to “DARPA” challenge to drive large-scale engagement of students. Use artificial but representative data to set it up.	T346	1
Establish a consortium of stakeholders (policy, government, academic, utility) to define obstacles/barriers to implementation of research and potential solutions to remove those roadblocks.	T331	0