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Advanced Electrical Power System Sensors

Workshop Report

Prepared for
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Executive Summary

Background

The objective of the Advanced Electrical Power Sensors Workshop was to provide input into planning processes being undertaken by the National Institute of Standards and Technology (NIST), Department of Energy (DOE), and the Grid Modernization Laboratory Consortium (GMLC). The workshop provided these entities with the opportunity to hear industry concerns and ideas regarding emerging and future electrical power system sensors, transducers, and transformer technologies.

As the grid continues to evolve, and as grid operation and planning support advanced functions, it may be necessary to measure aspects of the grid which have not been measured in the past, or to refine the way measurements, at present, are performed. This workshop explored various means by which grid related activities can be better informed.

High-Level Findings

Findings from the workshop cover key application areas for next generation sensing devices, future targets for sensor performance, challenges and barriers to achieving performance, and research activities to address the challenges. Exhibit E-1 provides a high-level summary of the results in these categories.

Application Areas. Grid planning, operations and event analysis were considered in terms of major challenges and information needs. Major challenges are related to managing dynamic and distributed generation/loads, modeling of resources, and evolving requirements for cybersecurity or specific applications. Information is needed to track loads, provide better situation awareness, and improve external inputs to planning/operations. Event analysis will require more robust sensors that yield useful, actionable data that is time-correlated.

Future Targets. Advanced sensors should have a greater range of functionality and yet be low cost, resilient, secure, self-calibrating and able to transmit useful data about both traditional and non-traditional key parameters, regardless of external conditions.

Challenges and Research Needs. Obtaining quality data, retrieving actionable, useful data, improving sensor performance, and increasing communication system capabilities are major challenges for development and use of advanced electrical power system sensors. Data fusion techniques, where large quantities of data are analyzed/fused so they are meaningful, is important for both operations and planning. A range of issues impact sensor performance, but most center around better testing and measuring and predicting performance (at lower cost). Standards are needed for performance including key factors such as interference and accuracy. The limits of present communication systems (bandwidth, speed, response to external conditions) could constrain the capability of advanced sensors.

Priority Research Areas. As shown in Exhibit E-1, the identified research priorities address the major challenges of performance testing, the need for new standards, increasing sensor functionality, sensor lifetime and maintenance, accuracy and other performance measures.

Exhibit E-1: High Level Findings for Advanced Electrical Power System Sensors

APPLICATION AREAS

Grid Planning	Grid Operations	Grid Event Analysis
Challenges – Managing generation challenges, such as the balance between time of supply and demand, energy storage, renewables – Dynamic resource models and modeling changing loads – Evolving requirements for cybersecurity, new threats, blurring lines between planning and operations **Information Needs** – Data to track changing loads, better load visibility and trends – Improved metadata for all types of conditions and component life – Societal and economic data that could aid in planning	**Challenges** – Technical and resiliency issues with islanding – Increased data flows from real-time sensors and good data analytics – Resiliency and security challenges with distributed systems – Intermittency of resources; lack of standardized sensors to provide both distributed/centralized control **Information Needs** – State information - data on active state of power electronics, availability, and capacity over multiple time scales – Better use of data, authentication of data, trusted data from distributed sources	**Challenges** – Lack of robust, high precision sensors for event analysis – Inappropriate information from sensors, i.e., non-actionable data, extracting out meaningful data, properly time correlated data – Observing state of equipment life **Information Needs** – Consistent and quality measurements between devices; observable controlled event data – Data from active sensors that perturb and observe – New types of data from wide-range dynamic sensors

FUTURE TARGETS FOR POWER SYSTEM SENSORS

- Low cost, high bandwidth, and dynamic range (frequency) with high accuracy and precision
- Self-calibrating, adaptive, and resilient
- Reporting of relevant metadata
- Capability for measuring traditional (voltage, current, harmonics, etc.) and non-traditional (partial discharge, interference, weather, human dynamics) parameters
- Self diagnostics for equipment health and life

MAJOR TECHNICAL CHALLENGES

Data Quality and Analytics	Sensor Performance	Sensor Communication
Retrieving usable information from data, lack of good data fusion techniques and metadata; complexity and increased processing time for advanced sensors with greater functionality, limited data processing algorithms	High costs for high performance, application-dependent accuracy and performance requirements, environmental factors, electromagnetic interference; lack of standards for performance, accuracy and external interference, limited sensor performance testing	Lack of low cost, ubiquitous, small scale, secure, high speed communications that can resist external conditions; Speed, bandwidth and other limited factors for existing communication systems

PRIORITY RESEARCH TOPICS FOR ADVANCED SENSORS

Interface Standards for Smart Sensors for Smart Grid	Testing Methods for New Sensors and Systems in a Federated Test Bed Environment	Wider Range Sensors for Enhanced Capture of Grid Harmonics	Rechargeable Batteries with Longer Life	Self-Calibrating Sensors and Testing for Accuracy in Field
Standards to support plug & play devices and interoperability, cyber security, self-identification, self-describing, self-configuration, self-calibration, and self-diagnostic/testing of sensors.	Broadly accessible capabilities to test and evaluate new sensor technologies, including connectivity and communication-related issues.	New sensors for enhanced capture of harmonics on the grid, including GMD-induced (electromagnetic pulse (EMP); electromagnetic environmental effects (E3)), inverter-induced, and equipment/switching transients.	Improved batteries with life times more comparable to the equipment they are powering (10-20 years).	Tests, standards and tools to verify and ensure the accuracy of the output of the sensor (needed for applications using sensor data) in the field.

1. Introduction

1.1. Workshop Scope

The National Institute of Standards and Technology hosted the *Advance Electrical Power System Sensors Workshop* at its Gaithersburg campus, MD on March 24, 2017. The event brought together over 60 electric power sector experts from industry, government, national laboratories, and academia to identify measurement science challenges and associated research and development (R&D) needs for the future of the electric grid.

The objective for the workshop was to better understand industry concerns, challenges, and R&D needs regarding Advanced Electrical Power System Sensors. This proceedings document represents the output of the workshop. This document identifies high priority research pathways for consideration by NIST, DOE, National Laboratories, academia, and the private sector.

The ideas presented here are a reflection of the attendees and not necessarily the entire industry. As such, they should be viewed as a good snapshot of the important perspectives, but not all-inclusive. The participants were carefully selected based on their high level of technical knowledge related to planning, operations, and event analysis for the electric power sector.

1.2. Workshop Process

To guide the discussions that took place during the workshop, several focus areas and key questions were identified beforehand. These were introduced to the participants in a series of breakout sessions, where participants provided responses. Those responses were recorded and synthesized, and are summarized in this report. The focus areas and questions utilized during the workshop are shown in Table 1-1.

Figure 1-1. Workshop Focus Areas

Application Areas

- What aspects of electric grid planning, operations, and event analysis, can be enhanced by measuring new or different variables, quantities, or phenomena?

Future Targets for Power System Sensor Performance

- Envision an ideal grid of the future. What power system sensors will be presented?

Challenges and Barriers for Achieving Sensor Advances

- What challenges or barriers must be addressed to enable the desired future state discussed earlier?

Priority R&D Topics for Power System Sensors

- What research and development efforts are needed to address the top priority barriers identified?

Pathways to Realizing Solutions

- What are the R&D activities, standards, and approaches for addressing priority challenges?

During the challenges and barriers discussion, participants were asked to rank the items identified. As a criterion for ranking, participants considered the extent to which each item impacted realization of the envisioned future grid. Each group used a real-time voting scheme (5 votes per person, same value for each vote) to indicate which challenges were of most priority to address.

The results of this process are outlined in the following sections, organized by focus topic.

2. Applications for Next-Generation Sensors

The first focus area explored applications on the grid that may require new or enhanced sensing. These potential application areas include:

- Grid planning
- Grid operations
- Event analysis

In each of these cases, information is needed to ensure the stability of the grid and its continued operation, to ensure that the grid will continue to operate given the demands of the future, and to diagnose why faults and outages occur, so that changes can be made to either operation or planning processes.

2.1. Grid Planning

Planning for the electric grid is a complex process that considers changes in the type and amount of generating resources available, changes in the topology and equipment in the transmission and distribution system, and changes in the amount and characteristics of customer load on the system. These considerations are accounted for over multi-year, and often decadal, time scales. Accurate planning requires trustworthy information to reduce uncertainty. As wide-area protection and control, distributed generation, and distributed automation becomes more prominent, equipment on the grid acquires enhanced features, and customer devices become more dynamic, planning for the future of the grid may require new and different sensing and information sources.

2.1.1. Challenges in Planning

A number of challenges were identified in grid planning, and these fell within three broad categories: generation-related challenges, modeling challenges, and evolving requirements (Table 2.1).

On the generation side of planning, there are many dynamics to consider. Participants noted that the non-traditional characteristics associated with variable renewable generation sources adds a layer of complexity to the planning problem. It is difficult to plan for randomness. Moving from a centralized resource environment to one where consumers and other non-utilities source energy into the grid adds to planning challenges due to the lack of available energy storage. Often, these renewable sources are not available when there is demand on the system and the lack of energy storage to compensate for their unavailability makes exacerbates the challenge of maintaining generation/demand balance. Adding energy storage to the generation side of the grid could drastically change the operating characteristic of generators, making them more flexible. It is difficult to foresee future technologies or capacities of energy storage on distribution and transmission systems, and how quickly these solutions will be deployed.

Transmission and distribution system planners utilize models to better understand the dynamics of the grid at various points in the future. Participants noted a number of modeling related challenges, mostly related to the information uncertainty that comes with dynamic sources and loads. Participants also noted a lack of visibility in relation to identifying equipment on particular phases in the distribution network.

It was noted that a number of challenges impact the environment in which planning take place. Planners must now account for new types of threats. Planning cycles are shortening, leaving less time for decision making. Traditional system boundaries are being transcended, causing more uncertainty.

Table 2.1. Challenges in Grid Planning

Generation-Related Challenges	Imbalance between time of supply and when there is demand	Randomness of supply in renewable generation; move from centralized to distributed non-utility sources	Availability of viable energy storage
Modeling Challenges	Generation resource models that change frequently (e.g., wind models)	Ability to measure which phase a customer is connected to (in modeling)	Changing loads
Evolving Requirements	Ability/need to plan for grid resilience (e.g., cyber-attack, electromagnetic pulse, terrorism)	Requirement for better understanding of interactions between transmission and distribution	Half-life of plans that is shrinking with lines blurring between planning/ operations

2.1.2. Information Needs

New information sources were identified that would benefit electric grid planning, as shown in Table 2.2. A number of new data sources were also suggested which would better inform grid planning. It was generally observed that the electrical and mechanical measurements taken on the grid itself do not provide sufficient information for planning purposes. It is of value to provide additional information pertaining to the context in which the physical measurements are taken. For instance, renewable generation data should be coupled with meteorological data. Fault information should be coupled with time and location information. This coupling of data would help system planners better understand root causes of incidents and better plan for incident avoidance.

It was noted that some of the desired metadata pertained to the operating environment of the equipment, while an entirely different set of metadata pertained to the societal context in which the equipment operated. Large social events, for example, can impact electrical demand (e.g., sporting events or others with major changes to loads) and create demand spikes at unusual times that utilities typically do not plan for. Regulatory environments also impact planning decisions, as do plans for large consumers of energy such as data centers or industrial expansion. The information derived from grid planning could be used to better inform the regulatory decision-making process.

Apart from the metadata described, load information was generally considered as a category where existing information sources were deemed insufficient. A need for improved model information, both on the generation and load side was noted as important. Additional information about the true load and possible generation behind the meter will also aid planning. Lastly, it was determined that additional cost-benefit information would improve grid planning.

Table 2.2. New Information to Improve Grid Planning

Load	Modelling to rack dynamically changing load	Technologies developed that help to even out load	Better visibility into true load (actual customer consumption)	Better predictive models about load trends (e.g. electric vehicle charging, energy storage availability)
Metadata	Temporal, location, distance between data pairs tags	Better predictions about component remaining life	Environmental conditions, especially for renewables. Good characterization of predictions.	Localized hazard information down to system, component level
Societal Information	External factors beyond the grid (e.g., major sporting events, major load changes)	Use of information to inform regulatory decision-making	Improved information about bad actors (cyberphysical attacks)	Better predictions about regulatory environment, economic factors, new technologies
Economic	Data on benefits that go beyond cost; better cost/benefit tools and inputs		Societal cost/benefit analysis	
Generation	Improved generation predictive models for existing generation (component level)			

2.2. Grid Operations

Grid operations involve the realtime monitoring and control of electrical equipment to ensure stable and reliable execution of system objectives. Grid operations require accurate information pertaining to the state of the system and the condition of its equipment. This information must be reliable, and must be available when decisions need to be made. While grid planning takes place over a long time horizon, grid operations occur on a scale from minutes down to fractions of a second.

2.2.1. Challenges in Operations

A broad array of challenges in grid operations were identified. Many of the challenges fell into distinct categories, while others were more general, as shown in Table 2.3. Major challenges for operation center around tactical issues that arise with islanding, control strategies, and load balancing, particularly with microgrids or where distributed energy resources (DER) are in play. Resilience and security are issues that are becoming increasingly important and require greater situational awareness and shorter response times.

Table 2.3. Categorical Challenges in Operations

Islanding	Real-time Control/ Sensors	Short Circuit Currents	Resilience/ Security	Resource Availability	Other
Challenges for islanding - connection, adaptive protection, safety, frequency management Need to dynamically connect/ disconnect islands	Increasing complexity introduces increased volume of information that needs to be addressed in a short time frame Limitation of response time of human operator DER dynamically challenge safety methods; need real-time methods (e.g., for relay settings) Predictive control - where is system going in the future? Lack of standardized sensors to provide centralized and distributed control Load control management using cost-effective sensors Four quadrant control (i.e., ability to regulate both real and reactive power)	Challenges with low/high current Microgrids could cause short circuit current to be very hard to measure	Black start capability of large grids Cybersecurity-requirement to keep resilience throughout distributed systems, but also be careful when centralizing control	Intermittency, lack of predictions about renewables Lack of "guarantee" that resources will be available; need real-time availability insight Present interconnection standards limit full potential of using power electronic devices on the grid	Education challenge – planning is more "open" to new ideas, operations less open due to overriding emphasis on reliability and minimizing risk. Benefit to managing loads, but difficult to coordinate

2.2.2. Information Needs

Consideration was given to new information sources that would benefit electric grid operations. Table 2.4 below displays the results of discussions. Information needs generally fell into three categories: state information about all devices, data quality and use, and sensing.

With regard to state estimation, many items were discussed. Of primary concern was the ability to know the capacity and availability of resources on the grid. This is especially of concern as more distributed energy resources are added at different points in the grid. This also applies to the dynamic rating of transmission and distribution assets such as overhead lines and cables, as well as transformers.

In reference to data quality, participants identified a number of critical factors. Verifying the accuracy and authenticity of the data was of top concern. Control, data, and metadata going to the sensor, if any, should also be secure and authenticated. Participants also stressed the importance of having vetted methods for best utilizing the available data. With regard to sensors themselves, participants agreed that each sensor should be low-cost, precise, and authenticated.

Table 2.4. Information Needs to Inform Grid Operations

State Information on All Devices	More information about active state of power electronics on the grid	Knowledge about availability and capacity	State information over wide time-scale (from microseconds to weeks to tens of years), and at low cost
Data Quality and Use	Fusion and better use of available information (e.g., information on harmonics produced by devices that could be better used by operators)	Identification and authentication of source of information	Consider using power system information for communications (if analysis is available)
Sensing	Outputs from low-cost, high-precision, frequency sensors	Trusted data from all of these distributed sensors - origin, has data been modified, authorization	Four quadrant controls (information to support regulation of supply of both real and reactive power)

2.3. Grid Event Analysis

Events on the grid can occur in fractions of a second. It is often necessary to record events that cause disruptions, disturbances, or outages. By analyzing the events, operators can find ways to prevent their reoccurrence.

2.3.1. Challenges in Event Analysis

A number of challenges were identified in grid event analysis, as illustrated in Table 2.5. At a high level, these event analysis challenges dealt with the idea of appropriateness. It was stressed that appropriate sensors must be developed to measure the appropriate information on the grid. Then, an appropriate conclusion must be derived, to inform actions by operators or planners. For this to happen, only the appropriate data must reach the person needing it. It is not necessary that all data be transmitted.

Table 2.5. Challenges for Event Analysis

Appropriateness of Sensors	General purpose sensors don't offer robust sensing required for analysis	Lack of high-precision sensors for system	Taking information from sensors never designed to provide that information
Appropriateness of Information	Lack of data - sensors exist but information doesn't always get communicated back	Operators require actionable information, not reams of data (applies across planning, operations, analysis)	Ensuring meaningful data is returned for analysis rather than sending ALL the raw data
General Concerns	Properly time-correlated data; time stamped to occurrence on the circuit, not at a distant sensor	State of equipment life	

2.3.2. Information Needs

New information sources were identified that would benefit electric grid event analysis, as shown in Table 2.6. These required information sources stress the importance of improving sensing devices, and delivering high quality event data.

Table 2.6. New Information to Inform Event Analysis

Event Data	Ensuring measurement quality and structuring it properly	Measurements are consistent between devices; based on standards or user agreement	Observable, controlled event information
Improved Sensing	Self-calibrating, self-identification sensors	Active sensors – perturb and observe	Optimize and utilize wide dynamic range sensors in ways that may not have been previously conceived

3. Future Needs for Power System Sensors

When asked to imagine an ideal grid of the future and describe the characteristics of sensing devices in the future grid, a number of common themes emerged. Table 3.1 provides highlights of the future desired characteristics that were identified. Sensors are needed to measure a wide range of traditional physical parameters, external phenomena (both environmental and societal), and non-traditional phenomena such as electromagnetic pulses (EMPs) and geomagnetic disturbances (GMDs).

Table 3.1. Desired Future Characteristics for Grid Sensors

Common Themes

• Sensors that measure important physical parameters
  – Voltage, current, power, power factor, frequency, harmonics
• Sensors that exhibit high bandwidth, and/or a wide dynamic range
  – Frequency measurements from DC – 10 MHz
• Sensors that are low cost, but provide high accuracy and precision
• Sensors that are self-calibrating, adaptive, and resilient
• Sensors that measure non-traditional electrical phenomena, like partial discharge, EMPs, and GMDS
• Sensors that measure external phenomena, like weather and important human social dynamics (traffic, events)
• Self-diagnostic sensors that measure equipment health and lifetime
• Sensors that report relevant metadata
  – Synchronized timestamp when measurement was taken
  – Physical location where measurement was taken

4. Challenges for Advanced Sensors

A number of challenges and barriers were identified that prevent grid sensing from providing the desired data and information needed to inform planning and operations. The challenges revolve around using and interpreting sensing data, transmitting data, and ensuring the quality of data. Table 4.1 provides highlights the technical and non-technical challenges categorized by major topic area.

Data Use and Quality – Sensors can provide vast amounts of data – the challenge is retrieving information that is usable and interpretable. A number of challenges impact use of sensor data for operations and planning, particularly algorithms that retrieve useful information, and the ability for good data fusion. Data quality needs to be assured to enable operators to act based on information received. Standards and better methods for determining accuracy are needed.

Communication of Data – One challenge is the lack of low-cost and secure high-speed communications for transmitting data from sensors. The distance over which data must be transmitted can also be a limiting factor, as well as ensuring sufficient bandwidth at the sensors.

Sensor Performance – Accuracy is critical for sensor data to be actionable. Currently, high-performance sensing comes at higher cost. In addition, sensor performance, accuracy, and precision requirements may be different depending upon the application – how much accuracy and precision is really needed? While precision is a design choice, the accuracy of sensors can also be impacted by many environmental factors, such as temperature, humidity, electromagnetic interference, and equipment age.

Cost and Market Factors – Lack of market drivers and the high risk of developing new products in general limits the introduction of new sensors for grid planning and operations. Sufficient volume and scale will be needed to drive new sensor development for grid planning and operations. Information is currently not readily shared among competing market players, making it more difficult to find common ground for sensor development.

Table 4.1. Technical and Non-Technical Challenges/Barriers for Advanced Sensors
TECHNICAL CHALLENGES
Retrieving Usable Information from Data
• Data processing algorithms • Data fusion, i.e., integrating multiple data sources to produce more consistent, accurate, and useful information than that provided by an individual source • Complexity and processing time increases as sensors provide increased functionality
Communication
• Lack of low cost, ubiquitous, small scale, secure, high speed communications that are resilient to adverse weather conditions and cyber attacks • Limitations of existing communication systems, including speed, bandwidth, and other factors • Limited communications and bandwidth availability at the sensor • Remote sensors able to communicate to operations centers

Table 4.1. Technical and Non-Technical Challenges/Barriers for Advanced Sensors
Data Quality
• Lack of metadata • Environmental conditions that affect measurement quality • Measurement methods to ensure accuracy of generated data
Sensor Performance
• High cost for high performance • Accuracy needs that change for different applications • Lack of standards for quantifying external interference • Lack of standards to define minimum performance and accuracy requirements in the context of the grid • Lack of performance testing for sensors • Unknown performance requirements for different applications • Tradeoff between accuracy and dynamic range • Electronics need power to operate, even during a fault • Environmental impacts due to extreme temperatures, humidity, wind and solar radiation • Electromagnetic interference (EMI) • Size, safety, and insulation requirements that limit the performance of sensors (physically challenging)
NON-TECHNICAL CHALLENGES
Market and Policy Factors
• Small market size • High risk of developing new products • Lack of urgency to develop new features • Market players that are unwilling to share data • Current net metering policies that mask information about local generation and load
Sensor Cost Drivers
• Number of devices manufactured • Personnel and labor needed for installation • Communication capability • Effort to install must be minimal • Maintenance cost (e.g. rechargeable battery lifetime in remote sensors)

5. R&D Areas for Advanced Sensors

5.1. Broad Research and Development Needs

R&D areas were identified with the potential to address a number of the technical challenges. Table 5.1 provides a summary of R&D needs, categorized by topic area and prioritized based on the importance and urgency of the outcomes.

Broad R&D topics focus on the need for greater testing facilities and methods; development of new algorithms and platforms for effective processing and interpretation of sensor information; and standards that will allow for better sensors tailored to smart grid requirements. R&D is also needed to improve sensor capabilities and functionality; and enhance security and resilience.

Table 5.1. R&D Topics for Advanced Sensors
(numbers in parentheses indicate priority votes)

Testing	
Highest Priority	• Test bed for testing and demonstrating new sensors (4)
Medium Priority	• Methods to test sensors for accuracy in the field under actual operating conditions without an outage (3) • Testing for plug-and-play interoperability (2) • Testing pilot projects for prototype sensors (2) • Identification of performance test conditions, i.e., all the practical situations where a sensor needs to meet its performance specifications (1)
Low Priority	• Enhancements in labs to provide sensor testing capability • Accurate models to inform sensor R&D
Algorithms	
High Priority	• Configuration tool for sensor networks (2)
Medium Priority	• Identification/invention of new data processing algorithms for sensors (1) • Intelligent development of algorithms for distributed sources (1) • Integration of sensors into real-time control systems (1)
Low Priority	• Algorithms for self-validation and location awareness • Algorithms for identification and location
Standards	
High Priority	• Develop a smart sensor standard, for smart grid specifically (3)
Medium Priority	• Balancing of sensor device innovation with new sensor standards development (2) • Sensor communications standards (2) • Low-cost reliable timing source with high accuracy, resolution and stability for sensor (2) • Interface standards to connect sensors to other intelligent electrical devices (1)

Table 5.1. R&D Topics for Advanced Sensors
(numbers in parentheses indicate priority votes)

Low Priority	• Standards to require power converter to provide time synchronized measurements of its status • Development of a "health index" and reporting standards (self-reporting sensors)
Sensor Characteristics and Capabilities	
High Priority	• Sensor security – self-validation and anti-intrusion (4)
Medium Priority	• Calibration-free sensors (3) • Wider dynamic range sensors (3) • Clip-on, or other types of non-contact voltage sensors (2) • Flexible, self-configuring, self-calibrating sensors, configuration tool (1) • Sensor network performance measurement and analysis tools (1) • "Nano" mass sensors – very small, light sensor (1) • Flexible sensors that take many types of measurements and output what is needed for a specific application(1)
Low Priority	• Miniaturization of sensors
Business Case	
High Priority	• Use case focusing on future applications of sensors addressing barriers (3)
Medium Priority	• Investigation of potential for adding fiber for bandwidth and improved communications (1)
Low Priority	• Quantify risk and cost of failure of sensor
Safety, Security, and Protection	
High Priority	• Harmonic sensors to pick up impacts of geomagnetically induced currents (GICs) or power electronics (3)
Medium Priority	• Data "Switzerland' – secure method for sharing data, with classification levels; a data-sharing environment with stakeholders under NDA (2) • Quantum key distribution techniques for security in communications (2) • Future shielding for advanced EMI immunity (room/high temperature superconductors) (2) • Data source authentication and message tampering detection, with the following characteristics: cyber-secure, low overhead, low latency, standardized (2) • GMI/GMD wide-area sensor array (1) • National repository of power grid sensor data (1) • Identification of safety impact of new sensors on grid and mitigation methods (1)
Low Priority	• Sensor data authentication • Integrated measurement assurance built in to sensor
Sensor Power Requirements	
High Priority	• Rechargeable batteries (small or large) that never wear out (charge using energy harvesting) (4)
Medium Priority	• Other means to power sensors with little or no user-service requirements (3)
Low Priority	• Energy harvesting and scavenging for sensors • Sensors with low-power usage

5.2. Priority Research Pathways

Five of the high priority R&D topics identified were explored further to gain understanding on the path forward for addressing the associated challenges. Table 5.1 to 5.5 show the proposed methodologies for implementing the R&D recommendations selected. Each table describes the goal of the R&D effort, an approach to reaching the goal, anticipated barriers to be overcome, and the stakeholders who can inform, or participate in the process. Selected R&D topics include:

- **Interface Standards for Smart Sensors for Smart Grid –** Development of standards to support plug & play devices and interoperability, cyber security, self-identification, self-describing, self-configuration, self-calibration, and self-diagnostic/test of sensors.
- **Testing Methods for New Sensors and Systems in a Federated Test Bed Environment –** Broadly accessible capabilities to test and evaluate new sensor technologies, including connectivity and communication-related issues.

Wider Range Sensors for Enhanced Capture of Grid Harmonics – New sensors for enhanced capture of harmonics on the grid, including GMD-induced (EMP; Electromagnetic Environmental Effects E3), inverter-induced, and equipment/switching transients.

- **Rechargeable Batteries with Longer Life –** Improved batteries with lifetimes more comparable to the equipment they are powering (10-20 years).
- **Self-calibrating Sensors and Testing for Accuracy in Field –** Tests, standards and tools to verify and ensure the accuracy of the output of the sensor (needed for applications using sensor data) in the field.

Table 5.1. Interface Standards for Smart Sensors for Smart Grid

Desired Capabilities/Enhancements

- Plug & play/interoperability
- Cyber security
- Self-identification, self-describing, self-configuration, self-calibration, self-diagnostic/test
- Future-proof, extensible
- Technology agnostic
- Focus only on interface, improved standards

Technical Barriers

- Today's proprietary interfaces that make interoperability impossible
- No uniform set of requirements
- No uniform interface terminology, data format, etc.
- Today's standards are "vertical", specifying devices and all their requirements; standards are needed that are "horizontal" and layered, specifying functions with device requirements specific to the environment in which the function resides..
- A general model of smart sensors for smart grid is lacking and would be helpful in standardization efforts.

Outcomes

Desired Results

- New standards

Performance Metrics

- Certification, conformable, interoperability
- Metrics: 1) standard issued, 2) number of sensors in industry that comply with this standard

Applications

- All uses of sensors

Required Innovations/Science

- Will require a certification consortium/lab

Approach

Activity	Required Resources	Expected Time to Complete
Industry study group	Participants	1 to 6 months
Form standard working group	IEEE, IEC, others	6 months
Develop standard	Working group	**1 to 3 years – parallel**
Approve standard	IEEE, IEC, others	6 months
Testing method in parallel	Working group (different)	**1 year - parallel**
Testing consortium	Industry	6 months
Certification	Testing consortium	1 to 3 years

Stakeholders	Roles
Industry, Utilities, End users	**Identify the need for new standards, participate in standard setting**
Senior Developer	Early implementation of new/draft standards, Feedback into standards process.
Standards Organization	Standards drafting/publishing
National Laboratories	Initial testing
NIST	R&D and tests for standards development

Table 5.2. Testing Methods for New Sensors and Systems in a Federated Test Bed Environment

Desired Capabilities/Enhancements	Technical Barriers
• Capabilities to test/evaluate new sensor technologies • Connectivity and communication-related issues • Third party (academics/NIST/national labs)	• Identifying appropriate sensor technologies for further improvement or test as a pilot project • Interoperability • Plug-and-play capability • Merging measurements • Limited availability of intelligent algorithms

Outcomes

Desired Results
- Testing procedures
- Standards
- Performance matrix
- New sensor models

Performance Metrics
- Verify test results with field performances
- Verify against real-time simulation

Applications
- Optimization of system operation
- Advanced protection and metering
- Cyber security issues
- Allows real-time system operation and control
- Improves system analysis and system development

Required Innovations/Science
- Real-time simulators
- Accurate sensor models
- Higher resolution testing
- Higher resolution measurement devices
- Distributed measurement across large geographic area

Approach

Activity	Required Resources	Expected Time to Complete
Education/outreach	Researchers, academics, professional organizations	1 Year
Gov't/other funding	Grant writers, govt funding specialists	1 Year
Research engineering and acquire systems for measurement	Engineers, academics	1.5 to 2 Years
Build and validate roadmap	Standards setting organizations, smart grid laboratories	2 years
Test high priority sensors	Testing laboratories (Govt, Academic, National Labs)	3 Years
Iterate over test methodology	Testing laboratories (Govt, Academic, National Labs)	4 Years
Publish results	Standards setting Organizations, test labs, academics, govt, national labs	3 to 5 Years
Education/outreach	Professional organizations, academic institutions	

Stakeholders	Roles
Utilities	Beneficiaries
Sensor Developers	Test their equipment
National Labs, ORNL, PNNL, NRELNIST	Hosts
Academia	Independent Research
National Metrology Institutes, National Resources Council (NRC) Standards setting organizations, academic institutions	Test contributor

Table 5.3. Wider Range Sensors for Enhanced Capture of Grid Harmonics

Desired Capabilities/Enhancements

- Enhanced capture of harmonics on grid
  - GMD-induced (EMP; electromagnetic environmental effects (E3))
  - Inverter-induced
  - Equipment/switching transients
  - More than 50 harmonics

Technical Barriers

- Dynamic range vs. accuracy
- Low cost
- More precise timing
- Range (DC to applicable harmonic - 3000 Hz) for most equipment
  - Range up to 10 MHz for some specialized sensors

Outcomes

Desired Results

- Prototype
- Product functional requirements
- Standard/standard revision
- Demonstration
- Testing procedures
- Installation design
- Proposed maintenance requirements

Performance Metrics

- Accurate physical measurements from grid or grid simulator
- Meet expectations of test plan

Applications

- Extended situational awareness
  - GIC/E3
  - High penetration of renewables
- Improved industrial power quality standards and monitoring
- Identify source/cause of harmonics
- Improved protection

Required Innovations/Science

- Improved timing
- New measurement techniques for high bandwidth/dynamic range
  - Amps or kiloamps
  - Wide, disparate frequencies (DC → 10MHz)
  - Low signal-to-noise ratio (SNR)
- Improved standards

Approach

Activity	Required Resources	Expected Time to Complete
Develop sensor algorithm	Math, computing resources, staff	**1 year (0-1) Parallel**
Sensing equipment to detect DC → 10MHz	Materials, sensors specialist, metrologist	**1 year (0-1) Parallel**
Integration to prototype	Power supply, prototype based, timing service, protection engineer, environmental engineer	18 months (2.5 years elapsed)
Lab test	Technicians	6 Months (3 years elapsed
Field test (inverter-based)	Technicians, integrators, weather evaluation	1 Year (4 years elapsed)
Final report (updated standard reports)	Technicians, facilities, writers, staff	6 Months after (4 to 5 years elapsed)

Stakeholders	Roles
Academic Institutions	Develop algorithm, lab test, field test, report writing
NIST	Develop sensor, lab test, field test, report writing
National Labs	Integration to prototype, lab test, field test, report
Utility Partner	Field test, report writing
Vendor	Develop algorithm, develop sensor, lab test, field test, writing report

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Table 5.4. Rechargeable Batteries with Longer Life

Desired Capabilities/Enhancements	Technical Barriers
• Sensors can be low-power, but need energy to report after outage and during restoration • Storage is needed to ride through outages, but battery replacement is expensive, limiting deployment	• Batteries must be replaced and are not comparable to the expected life of the equipment (10-20 years)

Outcomes

Desired Results

- Small, low capacity (1 mA-hr to 1 A-hr) battery with 20 (to infinite) year life (very large number of recharge cycles), low self-discharge. (-40 ˚C to +50 °C temperature range)

Performance Metrics

- Accelerated life testing for performance
- Performance testing of above requirements

Applications

- Wide area distribution monitoring
- Distributed resource penetration and power-flow management
- Islanding and microgrids (enabling) (sensing needed on both sides of an interconnection during separation/reconnection)
- Charging period may not need to be higher than discharge and may be much lower (research needed)

Required Innovations/Science

- New chemistries, nano-material research, packaging

Approach

Activity	Required Resources	Expected Time to Complete
Use Cases:	**Market Specialists:**	
Possible chemistries	Chemists, physicist, nano-material scientist	0 to3 Years 3 to 5 Years
Electrode design	Nano-materials scientist	0 to3 Years 3 to 5 Years
Package design	Materials specialist, mechanical engineering	1 Year
Applications/market research/use cases	Product experts from various application areas	1 Year
Prototype build/test	Engineering manufacturing	2 to 3 Years
Pilot test/higher volumes	Manufacturing engineering	2 to 3 Years
Technology transfer	Engineering, IP, all the above	1 to 3 Years

Stakeholders	Roles
NIST	Nano-materials research physics, chemistry
Academia	Physics, chemistry
National Labs	Design, testing
Industry Partners	Manufacturing, prototype, pilot testing
Standard Setting Organization	Specification/standardization
Safety Testing Labs (UL, telecommunication network voltage (TNV) circuits)	Safety conformance testing

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Table 5.5. Self-Calibrating Sensors and Testing for Accuracy in Field

Desired Capabilities/Enhancements	Technical Barriers
• Ability to verify and ensure the accuracy of the output of the sensor (needed for applications using sensor data) on the field	• Understanding and quantifying error-causing mechanisms • Moving away from labor-intensive and disruptive methods • Dealing with live-line work • Lack of non-intrusive testing technology

Outcomes

Desired Results

- New products
- New testing procedures/techniques
- New standards (performance standard)
- New sensors
- New tools

Performance Metrics

- How long a sensor keep its accuracy with self-calibration (performance over time)
- Technique to be deployed live in field for device accuracy verification
- Inclusion of disturbances/troubles and assessment of self-calibration effectiveness

Applications

- All application areas
- Cyberphysical reliability
- Higher confidence protection
- Higher accuracy energy metering and theft detection
- Better understanding and, if possible, control of the dynamic system/grid interactions

Required Innovations/Science

- Temperature sensitivity isolation from sensors
- Possibly, optical test techniques
- Non-intrusive test standard
- New digital test techniques
- Integration of sensor-injected calibration signal into what is being measured

Approach

Activity	Required Resources	Expected Time to Complete
Example: provide field calibration technique in a lab (e.g., NIST lab for medium-voltage (MV) voltage transformers (VTs) to 0.5% and 0.2% accuracy)	• Lab facility • MV sources and references	0 to 2 Years
Optical technique (non-intrusive); Calibration development	• Optical physicist • High voltage (HV) expertise • Electronic/optical components	0 to 5 Years
Detailed barriers and gaps analysists	• HV testing expertise • Industry application experts	0 to1 Year

Stakeholders	Roles
Utilities	End user, pilot location
Industry	Develop technology/ commercialize
Energy Users	End user (possibly)
Government/National Labs	R&D, create a lab to prove the techniques first
Academic Institutions	R&D
Standard Organization	Standardize test techniques

6. Path Forward

6.1. Overarching Themes

The results of this workshop illustrate the need for advanced sensors for electric power and many of the challenges that need to be addressed. Some of the overarching themes that emerged include the following:

- Advanced sensors will need to be able to better accommodate and interpret the nuances of new dynamic loads integrated into the grid and measure/sense their impacts on grid behavior to aid in planning and operations.
- A much higher degree of resilience and security will be necessary, given the evolving cyber and threat scenarios and the increasing use of distributed, random, and intermittent resources on the grid, and future scenarios where larger number of consumers generate power from variable sources.
- Future sensors need to be lower cost, more resilient and secure, able to self-regulate, and also exhibit higher performance and greater functionality, as well as longer life under multiple external conditions and dynamic loads.
- The increasing volume of data from today's sensors and advanced sensors will need new data platforms, algorithms and data fusion techniques to ensure data is interpreted, useful, and actionable for operators and those involved in planning and event analysis.
- Standards will play a key role in advanced sensing capabilities; new standards and measurement methods will be needed to ensure higher sensor performance under future distributed and non-centralized grid conditions. Interoperability reduces overall costs and improves data integration. Standards aim to ensure data is consistent and usable by multivendor equipment and applications.

6.2. Path Forward

This report was co-sponsored by NIST, the Department of Energy (DOE), and the Grid Modernization Laboratory Consortium (GMLC). NIST and some of the national laboratories have ongoing programs in advanced timing and related topics, and this report will be used to inform both strategic and tactical planning for these programs. The report shall be used to provide guidance for R&D in the NIST Smart Grid Testbed and also as input to the next revision, R4, of the NIST Smart Grid Framework and Roadmap[1].

The report will be sent directly to all workshop participants and made publicly available online. Notification of the report publication will be sent to members of the North American Synchrophasor Initiative (NASPI), Smart Electric Power Alliance Smart Grid Interoperability Panel (SEPA SGIP), IEEE Standards Association members, members of IEC Technical Committees 37 and 94,

[1] NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 3.0, NIST Special Publication SP 1108r3, October 1, 2014, available online at: https://www.nist.gov/publications/nist-framework-and-roadmap-smart-grid-interoperability-standards-release-30

and members of the IEEE Power Systems Instrumentation and Measurment (PSIM) Committee Sensors Working Group. Many of these members are equipment vendors or policy makers the report may help inform their research and development plans.

7. Appendices

Appendix A. Contributors

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Appendix B. Acronyms

CPI	Communications & Power Industries
DC	Direct current
DER	Distributed energy resources
DOE	U.S. Department of Energy
E3	Electromagnetic environmental effects
EMI	Electromagnetic interference
EMP	Electromagnetic pulse
GIC	Geomagnetically induced currents
GMI	Geomagnetic interference
GMLC	Grid Modernization Laboratory Consortium
GMD	Geomagnetic disturbance
HV	High voltage
Hz	Hertz
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IP	Intellectual property
MV	Medium voltage
NDA	Non-disclosure agreement
NIST	National Institute of Standards and Technology
NRC	National Resources Council
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
R&D	Research and development
SNR	Signal-to-noise ratio
TNV	Telecommunications network voltage circuit with specific voltage and current limits
UL	Underwriters Laboratories