Advanced Grid Research
OFFICE OF ELECTRICITY
US DEPARTMENT OF ENERGY

SENSOR TECHNOLOGIES AND DATA ANALYTICS

DECEMBER 2018

ACKNOWLEDGMENT

The U.S. Department of Energy's (DOE's) Office of Electricity (OE) developed this multi-year program plan (MYPP) for a new program, **Sensor Technologies and Data Analytics**. Development of this MYPP builds on the technology review, assessment, and roadmapping that have been published by the DOE Grid Modernization Initiative (GMI) Sensing and Measurement Strategy project. Further, core team members of the Sensing and Measurement Strategy project were assembled to form the MYPP Working Groups, which were led by Mr. Eric Lightner of OE. The Working Groups and their individual lead members, as listed below, provided essential input on the respective MYPP technical areas.

- **Enhanced Power System Resilience**
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- **Incipient Failure/Fault Detection**
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  - Paul Ohodnicki, National Energy Technology Laboratory
- **Detecting and Forecasting Behind-the-Meter Distributed Energy Resources Impacts**
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- **Sensor Valuation**
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  - Vaibhav Donde, Lawrence Livermore National Laboratory

DOE also acknowledges the support provided by Tom King (Oak Ridge National Laboratory), who serves as lead for the Grid Modernization Laboratory Consortium (GMLC) Sensing and Measurement Technical Area. GMLC is a strategic partnership between DOE and 13 national laboratories to collaborate on research and development that supports GMI.

The initial draft of the MYPP was further reviewed by other federal and DOE national laboratory and industry collaborators for the GMI/GMLC Sensing and Measurement Strategy project. Their review comments have been incorporated into this document. Special acknowledgment goes to the U.S. Department of Commerce's National Institute of Standards and Technology and DOE's

Bonneville Power Administration for providing organization and staff support to both the Strategy and MYPP development. DOE also acknowledges the efforts of Energy & Environmental Resources Group, LLC, in producing this document through assembling and assimilating all input and review comments that serve as the basis of this MYPP.

EXECUTIVE SUMMARY

Major power system outages are often caused in part by lack of adequate situational awareness of grid conditions. Other contributing factors include an aging electrical infrastructure and increasing complexity and variability in electricity generation and demand. At the same time, threats to the power system have multiplied, including extreme weather events, cyber-attacks, terrorist attacks, and human and system errors. Due to the interconnected nature of electrical infrastructure to other critical infrastructures (for example, oil and gas, communications, water, and transportation), any power disturbance event has the potential for cascading into interruptions of critical facilities and services, which would have a debilitating impact on national security, national economic security, and national public health and safety.

To address these problems, and to provide utilities with new tools and critical information to mitigate and respond to potential issues and threats, the U.S. Department of Energy (DOE) Office of Electricity (OE) Advanced Grid Research and Development Division is proposing a new **Sensor Technologies and Data Analytics** Program. The Program will develop and integrate high-fidelity, fast acting sensor technologies and advanced data analytics into the power grid. The Program will also revolutionize the use of these technologies in electricity operations and delivery—from transmission to distribution to end-use load—for improved diagnostics, prediction, and prescription of all system variables and assets during normal and extreme-event conditions. Advances in data analytics are needed to enable utilizing an increasing number of heterogeneous data sources from the sensor technologies to infer complex underlying dynamics, diagnose system behavior and abnormalities, and provide situational awareness for operators to make informed decisions. The outcome of **Sensor Technologies and Data Analytics** research and development (R&D) will enable greater speed, accuracy, and precision in determining the state of the power system. This will meet the needs of managing grid assets and operations with their increased complexity, as well as monitoring and managing interconnected and interdependent effects among the nation's critical infrastructures—all under increasing levels of threat conditions.

This multi-year program plan (MYPP) lays out the technical areas and specific R&D activities that the Program intends to pursue. The MYPP builds on work being done by DOE's Grid Modernization Initiative (GMI) Sensing and Measurement Strategy project, including the gap analysis and technology recommendations as reported in the project's *Sensing & Measurement Technology Review and Assessment Document*[1] and *Technology Roadmap Document*,[2] respectively. Core team members for the Sensing and Measurement Strategy project were instrumental in developing the MYPP to ensure that Program activities align with the GMI vision of a smarter modern grid that delivers resilient, reliable, flexible, secure, sustainable, and affordable electricity to consumers.

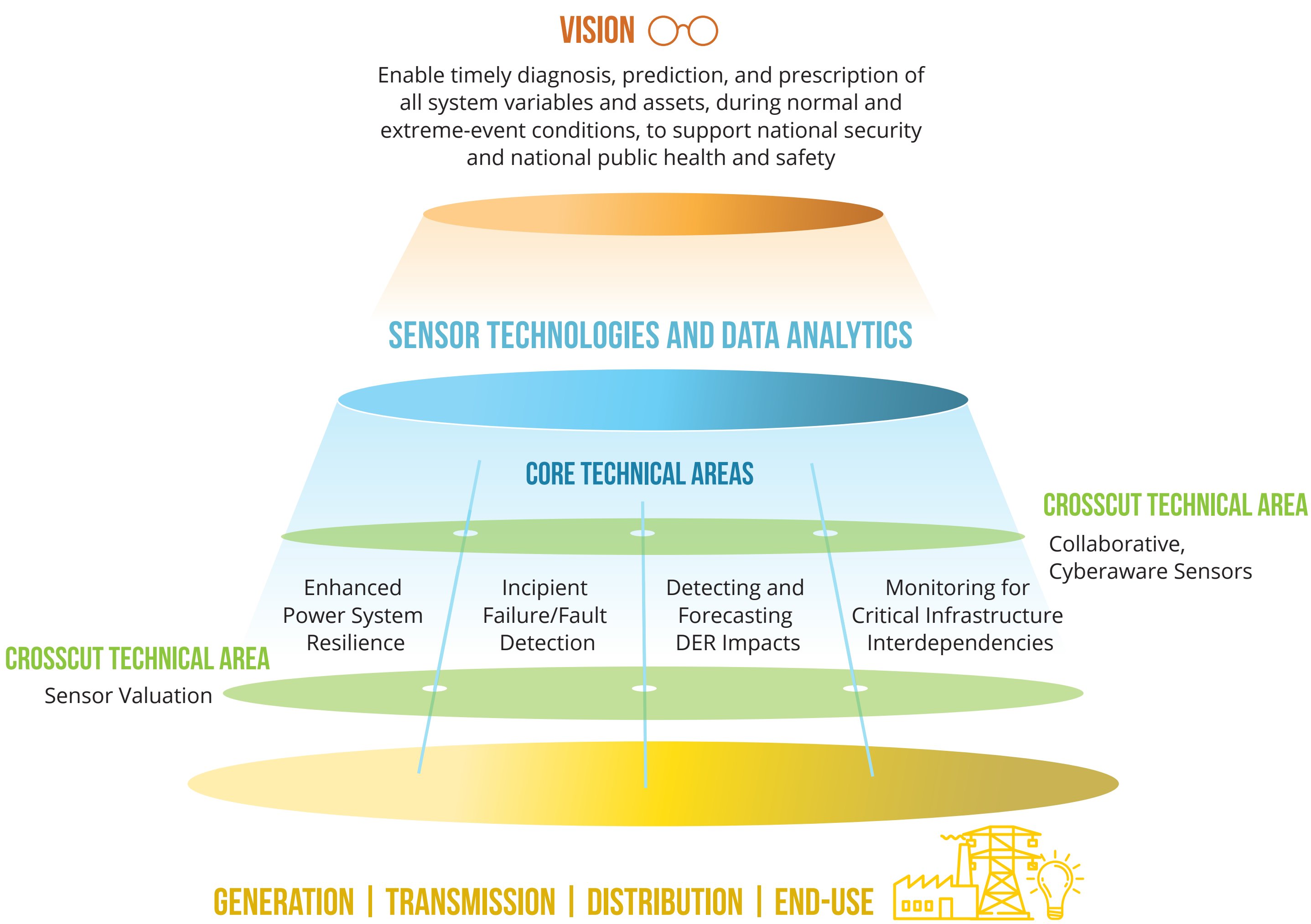
[1] Pending publication at https://gridmod.labworks.org/.

[2] Pending publication at https://gridmod.labworks.org/.

The Program's vision is to address the needs of achieving more resilient electricity delivery to counter increasing threats (natural and man-made) that could inflict greater damages to interconnected critical infrastructures. The Program has the following vision:

> *Develop and deploy high-fidelity, fast-acting sensing technologies and advanced data analytics that meet application, integration, cost, and cyber-physical security requirements throughout the nation's modernized, electric generation, transmission, and distribution systems to enable timely diagnosis, prediction, and prescription of all system variables and assets, during normal and extreme-event conditions, to support national security and national public health and safety.*

Section 1.2 of the MYPP identifies the key technical challenges to realizing the Program vision. The technical areas addressing these challenges consist of four core areas and two crosscut areas, which are summarized below and described in detail in Section 3.



Core Technical Areas

- **Enhanced Power System Resilience.** Develop a multifaceted, secure sensing system that is inherently resilient to extreme events and capable of distinguishing between outages resulting from man-made events and naturally, regularly occurring faults and failures; develop distributed communications architectures with dynamic networking features and a self-healing mechanism that are resilient to natural disasters; and develop robust data analytics integrated with network modeling and reconstruction techniques to provide viable damage assessment results when the data quality is largely impacted by natural disasters.
- **Incipient Failure/Fault Detection.** Research and develop new sensors that can measure indicators of incipient faults and failures with a focus on cost-effective and multi parameter, passive wireless, and optical platforms for compatibility with grid asset deployment. This will include developing new analytical algorithms that utilize real time sensor data from transmission and distribution systems—including multi-variate and multi-modal data from diverse sensor types—to diagnose asset health and predict imminent failure; conducting field testing and proof-of-principle validation of emerging sensor device and analytics platforms leveraging distributed communications architectures; and developing grid models and tools that optimize sensor placement in terms of monitoring effectiveness and cost.
- **Detecting and Forecasting Behind-the-Meter Distributed Energy Resources (DERs) Impacts.** Develop a suite of approaches and tools utilizing highly granular spatio-temporal data from networks of sensors that will accurately detect, characterize, and forecast DER behavior and its impacts on distribution and transmission systems. Two thrust areas include (1) improving the capabilities of existing sensor networks with enhanced analytics and/or increased communications network capabilities, and (2) developing new and improved sensors that complement existing commercially available sensor concepts or prototypes with significant leaps in capability.
- **Monitoring for Critical Infrastructure Interdependencies.** Investigate, develop, and demonstrate technologies capable of real-time monitoring of critical infrastructure interdependencies. R&D activities will include (1) providing early warning of deteriorating system conditions for operators of interconnected infrastructures to take corrective action, (2) establishing wide-area system visibility and improving resiliency and reliability of isolated and coupled systems, (3) developing and applying the decentralized communication network approach and data analytics, and (4) developing visualization tools to enable interconnected system diagnostics by operators.

Crosscut Technical Areas

- **Collaborative, Cyberaware Sensors**. Develop and apply the combination of multiple parameter, varying-measurement-resolution, IP-addressable, cyberaware sensors to augment the existing supervisory control and data acquisition sensors. The purpose is to provide a suite of physical, electrical, and ambient-condition parameters as needed for extended-grid-state[3] monitoring, while providing network communication information to a utility's (classic) information technology/operational technology (IT/OT) security system of the cyber state. R&D will also incorporate an artificial intelligence engine to correlate cyber status and grid operations and to distinguish between grid disruption(s) caused by a cyber-attack versus physical events (for example, weather- or human-based), as well as to identify the impacted network location and the geolocation of the event.

[3] The extended grid state (EGS) is a new architectural definition for the modern grid, which expands the reach of the power system to all of the modern assets interconnecting to the power system, including renewables, energy storage, electric vehicles, responsive loads, etc. More details about EGS can be found in the *Sensing & Measurement Technology Roadmap Document*.

- **Sensor Valuation**. Assess and develop valuation metrics and optimization approaches for advanced sensor technologies and associated analytics. This will include developing methods/tools that can integrate grid modeling with sensor placement and allocation capabilities, and the application of these tools to high-value use cases to determine and compare the valuation of different sensing and measurement technologies. Work will also include detailed value proposition analysis that considers multiple value streams for different stakeholders, as well as analyzing the impact of varying levels of sensing systems performance on grid economics and reliability.

Implementation of R&D activities described in the MYPP technical areas will support achieving the following Program goals:

- Develop sensors that meet the balanced requirements for application, integration, cost, and cyber-physical security.
- Define communications required to transfer sensing and measurement data in a timely and secure manner.
- Develop the ability to manage, analyze, and convert sensing and measurement data into actionable information for both operators and control systems.
- Develop sensors and advanced analytics for the high-priority use cases identified in the *Sensing & Measurement Technology Roadmap* report.
- Develop sensors and advanced analytics that enable improved information and situational awareness of grid state and asset conditions for a smarter modern grid.
- Develop sensor valuation assessment methodologies and tools to maximize the value of sensor deployment.
- Meet data needs for the North American Resilience Modeling initiative.

Benefits of the improved information and situational awareness, which will be achieved through the Program's R&D activities, will include the capability to assess the grid operational state in real time, to better predict grid behavior/condition and identify potential disruptions, to more quickly respond to disruptive events, and to better address future grid planning and operational challenges. Timely, actionable information about the grid state as well as asset health will give utilities and other stakeholders advanced warning so that responsive actions can be taken to prevent or mitigate potentially disruptive, costly, and even catastrophic failures before they occur. Additional benefits will include more effective asset utilization that leads to delayed build-out of new transmission and other grid assets. Furthermore, the nation's critical facilities and services that are dependent on the power grid will benefit from a more secure, reliable, and resilient electricity delivery system, under all-hazards incidents.

The **Sensor Technologies and Data Analytics Program** Program will coordinate with other related GMI projects and the OE North American Resilience Modeling effort to identify and meet data and associated communications and processing needs. The Program will coordinate and/or collaborate with the DOE Office of Cybersecurity, Energy Security, and Emergency Response for next generation tools and technologies to improve the cybersecurity and resilience of the nation's critical energy infrastructure. It will leverage advances made in sensor technologies and data analytics from DOE's Advanced Research Projects Agency-Energy projects in an effort to further develop and mature readiness levels for current and emerging applications. Furthermore, the Program will leverage existing partnerships with utilities, manufacturers, private-sector research institutions, and state and local government agencies for coordination on planning, development, and implementation.

Section 3 proposes specific R&D activities that the Program will undertake on an annual basis. The MYPP will be updated annually to reflect stakeholder feedback, current state of advances, priority needs, and resources availability.

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INTRODUCTION

The nation's electric power system is undergoing a major transformation stimulated by change across many areas: the increase and integration of new devices, such as distributed energy resources (DERs; for example, distributed generation, electric vehicles [EVs], and energy storage); a major shift in generation mix, including more renewable non-firm power resources; a significant reliance on just-in-time generation fuel delivery, notably natural gas and its pipelines; an aging infrastructure; and greater customer involvement, including demand-responsive systems and programs. This transformation has generated the need for greater determination ("visibility") throughout the electric power system to manage the capabilities of its increasing number and diversity of assets. At the same time, threats to the power system have multiplied, including extreme weather events, cyber-attacks, terrorist attacks, human and system errors, and more. Due to the interconnected nature of electrical infrastructure to other critical infrastructures (for example, oil and gas, communications, water, and transportation), any power disturbance event has the potential for cascading into interruptions in critical facilities and services, which would have a debilitating impact on national security, national economic security, and national public health and safety.

To address the needs resulting from grid transformation and to achieve more resilient electricity delivery to counter increasing threats (natural and man-made) that could inflict greater damages to interconnected critical infrastructures, the U.S. Department of Energy (DOE) Office of Electricity (OE) Advanced Grid Research and Development Division is proposing a new Program—**Sensor Technologies and Data Analytics**. This new Program is developing its first-ever multi-year program plan (MYPP) leveraging the work products (*Technology Review and Assessment Report and Technology Roadmap Report*[4]) of the DOE Grid Modernization Initiative (GMI) Sensing and Measurement Strategy project.

This MYPP herein describes the Program's plan to carry out key technical activities to fill identified technology gaps and provide needed technologies for the identified high-value use cases, both of which draw on the two GMI Sensing and Measurement Strategy project reports. Through implementing the MYPP, the Program aims to achieve greater determination ("visibility") throughout the electric power system to manage the capabilities of its increasing number and diversity of assets. Specifically, the Program seeks to develop advanced sensors and measurement systems, communications, and data management and analysis systems capable of determining the real-time state of the power system during normal operation and also capable of forecasting future states with enough accuracy and lead

[4] Both documents are pending publication at https://gridmod.labworks.org/.

time to avert deviations from normal operations (that is, self-heal for disturbances). Meeting this goal will require the capability to measure and characterize the state of the power system with greater speed, accuracy, and precision than ever before, spanning the Program's mission areas of transmission, distribution, and end-use load.

Further, the Program will advance achieving a smarter modern grid, as envisioned by GMI; this smarter modern grid is characterized by broadly employing DERs, responsive loads, electric transportation, two-way power flow, and distributed intelligence. This grid will require developments in new sensor technologies and data analytics, as described in this MYPP, to enable better information and situational awareness of grid state and assets, in terms of health and capabilities, to allow more efficient, effective, and flexible grid control and operation and to improve long-term, short-term, and real-time power system reliability and resiliency.

PROGRAM VISION

Develop and deploy high-fidelity, fast-acting sensing technologies and advanced data analytics that meet application, integration, cost, and cyber-physical security requirements throughout the nation's modernized, electric generation, transmission, and distribution systems to enable timely diagnosis, prediction, and prescription of all system variables and assets, during normal and extreme-event conditions, to support national security and national public health and safety.

PROGRAM GOALS

Develop sensors that meet the balanced requirements for application, integration, cost, and cyber-physical security.

- Define communications required to transfer sensing and measurement data in a timely and secure manner.
- Develop the ability to manage, analyze, and convert sensing and measurement data into actionable information for both operators and control systems.
- Develop sensors and advanced analytics for the high-priority use cases identified in the *Sensing & Measurement Technology Roadmap report*, namely:
    - Fault detection, interruption, and system restoration;
    - Incipient failure detection in electrical grid assets;
    - Mitigation against impacts of cyber-attacks or man-made attacks;
    - Integrating advanced resource forecasts for transmission and distribution (T&D) grid operations;
    - Topology detection within the distribution system;
    - Mitigation against impacts of natural disasters, and enhanced grid resilience;
    - Optimizing grid operation with enhanced data spanning transmission, distribution, and generation; and
    - Detection of energy theft and unregistered DERs.
- Develop sensors and advanced analytics that enable improved information and situational awareness of grid state and asset conditions for a smarter modern grid.
- Develop sensor valuation assessment methodologies and tools to maximize the value of sensor deployment.
- Meet data needs for the North American Resilience Modeling initiative.

Challenges and Opportunities

Currently, the power system utilizes multiple layers of sensors (electrical, mechanical, chemical, etc.), potential and current transformers, and actuators (breakers, capacitor banks, voltage regulators, reclosers, etc.). These sensors detect and measure power flow, voltage level, and power quality from generation, through the transmission/distribution system, to end loads. However, these sensors are not integrated; are used in localized fashion, primarily due to communications challenges; and can be expensive, especially for distribution systems—thus, they are used only in critical applications where the value proposition is clear to the utility or other relevant stakeholder. New research and development (R&D) is therefore needed to overcome various technical and economic challenges of advanced sensor deployment and use.

The dynamic and interconnected nature of the power system requires monitoring of grid variables and assets at all levels. However, monitoring for generation, transmission, distribution, and end use involves different needs and challenges. Due to geographic extensions of the transmission system that can easily reach hundreds of miles, key power flow states are mostly measured at substations (that is, ends of lines). While these data points are largely sufficient for regular grid applications in a centralized system with predominantly one-way power flow, new and emerging applications require measurements with much higher spatial resolution, including in remote areas out of the reach of modern transportation and communication channels. These deployments face technical challenges, such as the need to operate sensors/devices in inclement operational conditions and requiring high reliability (low maintenance or maintenance-free), self-sustainability (harvesting energy from ambient environment), and localized action in coordination with other sensors in the network. Other challenges involve data transmission issues—such as delay, latency, and loss of data—for wide-area monitoring systems (WAMS), which hamper key functions of gathering measurements from phasor measurement units (PMUs) that are geographically dispersed. Until WAMS technology matures, power system monitoring and protection will be limited to being performed locally, not extending to wide areas or the entire power system.

Most of the current distribution system is "blind" in terms of monitoring and control capability beyond the distribution substation due to the complexity of network configurations and higher temporal/spatial resolution monitoring required by new and emerging applications of advanced distribution management systems (ADMSs). The requirements for higher-resolution monitoring are propelled in part by the increasing number of DERs employed in distribution systems and behind the meters that must be monitored to ensure safety of operators and optimal control of the complete system while maximizing benefit from DER assets. Other requirements include more granular data needed in applications, such as for distribution state estimation, distribution automation (Fault Location Isolation and Service Restoration [FLISR] and voltage optimization control), enhanced power quality for sensitive loads, and transactive control. Because sensing technologies need to be more ubiquitously deployed at distribution/end-use levels, they must be low cost and capable of multi-parameter measurements. Meanwhile, the influx of these heterogeneous data sources poses challenges to data analytics to infer complex, underlying dynamics; diagnose system behavior; and provide situational awareness for operators to make informed decisions.

Sensing technologies face common challenges at all levels. First, although sensors can be a critical instrument to detect and mitigate cyber-physical security threats, they are also vulnerable to cyber-physical attacks. Thus, cyber-physical security requirements need to be balanced with application, integration, and cost requirements for sensor development. Challenges relating to sensor adoption include lack of well-defined valuation metrics and analysis approaches for technical and economic risks and benefits from employment of new sensing technologies.

In addition, due to the increased dynamic nature of power flow in the modern power system, one challenge is redefining "normal" conditions for the assets and grid conditions being monitored to better understand the boundary between acceptable and "high risk" conditions. The increased variability of assets and loads could affect the range in which a monitored parameter is considered normal.

The MYPP technical areas present more detailed sensing and measurement challenges facing transmission, distribution, and end-use monitoring, respectively and collectively, along with specific R&D activities to address the listed challenges.

DOE Role

DOE and its national laboratories are uniquely positioned to engage with industry stakeholders to envision and prototype next-generation sensors for which investment from industries is infeasible, and to guide and facilitate the adoption of advanced sensors in utility or facility operations. They are also well positioned to validate technical and economic performance of advanced sensors, aiming toward accelerating use of advanced sensors for the modern grid and toward ensuring the security of both the grid and the sensor technology being deployed. The unique roles of DOE and the national laboratories include, but are not limited to, the following:

- Advancing sensor technology for the modern grid;
- Developing and implementing testbeds for validation testing;
- Developing methodologies and tools for valuing sensor technology;
- Making unbiased, open, and well-documented estimates of the synergistic benefits of sensors supporting multiple new technologies;
- Providing input to standards organizations (such as the Institute of Electrical and Electronics Engineers [IEEE] and the International Electrotechnical Commission) to promote development and documentation of interoperability standardization for new technology;
- Providing regulatory authorities with valid tools for valuation and input on technology adoption and deployment; and
- Ensuring cybersecurity.

Sensing technology is currently deployed across the electric power system. However, because of the disconnect between organizations responsible for covering the full costs of deployment and the full system-level value of newly deployed sensing and measurement technology across the electric power system, it is anticipated that the private sector alone will be unable to reduce the costs of new sensing technologies to the desired price point for the purpose of accomplishing the goals of the Program. To complement private-sector efforts, DOE and national laboratory efforts will emphasize scientific and engineering innovations in lower technology readiness level (TRL) R&D—from research to proving feasibility through technology demonstration.

With the noted exception of advanced metering infrastructure (AMI), sensors are under deployed and sensing data are under-utilized—from the distribution substation down to end use. This is largely due to a lower "per unit" value of a comparable sensor (than for generation and transmission systems) and a greater number of sensors required for temporal, geospatial, and topological awareness. DOE's R&D efforts to lower costs through innovation, enable technology platforms with multi-parameter capability, and develop valuation methods and the tools to assess technology placement for maximized benefits will allow fulfilling the objective of ubiquitously deploying low-cost sensors to gain visibility of distribution systems.

Program Coordination

The **Sensor Technologies and Data Analytics** Program will coordinate closely with the GMI Sensing and Measurement Technical Area to support R&D for a smarter modern grid. The two sensing and measurement reports, *Technology Review and Assessment Document and Technology Roadmap Document*, provide the technology review, gap analysis, and technology pathways on which this MYPP is based. Additionally, development of this MYPP involved support and input from the core team members of the Sensing and Measurement Strategy project to ensure continuity—from gap analysis, to roadmapping, to program implementation. Further, R&D activities in the Program's technical areas will build on the GMI Sensing and Measurement projects, notably the sensor placement optimization tool (SPOT) and early-stage, advanced sensor development.

As development and application of sensing and measurement technology are embedded in many of the projects in GMI's other five technical areas, the Program will engage related projects in the GMI portfolio for coordinated development. Examples of related GMI projects being carried out by the Grid Modernization Laboratory Consortium (GMLC) follow.

GMLC Project number	GMLC project title	GMLC project description
GMLC Project 1.2.2	Interoperability	To articulate general interoperability requirements along with methodologies and tools for simplifying the integration and cyber-secure interaction among the various devices and systems.
GMLC Project 1.4.1	Standards and Test Procedures for Interconnection and Interoperability	To help develop and validate interconnection and interoperability standards for existing and new electrical generation, storage, and loads—ensuring cross technology compatibility and harmonization of jurisdictional requirements.
GMLC Project SI-1695	Accelerating Systems Integration Codes and Standards	To update the standards and establish accelerated development of new interconnection and interoperability requirements and conformance procedures, focusing on the distribution systems.
GMLC Project 1.4.15	Development of Integrated Transmission, Distribution, and Communication (TDC) Models	To integrate simulators designed for separate TDC domains to simulate regional and interconnection-scale power system behaviors.
GMLC Project SI-1625– CyDER	A Cyber Physical Co-Simulation Platform for Distributed Energy Resources in Smart Grid	To develop a modular, scalable tool combining transmission/distribution system simulation to accommodate high levels of photovoltaic (PV) penetration.
GMLC Project 1.4.9	Integrated Multi-Scale Data Analytics and Machine Learning for the Grid	To develop the full capability of synchronized disparate data sources for distribution and building grid analysis and control to enable future distributed applications.
GMLC Project 1.2.4	Grid Services and Technologies Valuation Framework	To address the inconsistencies and lack of transparency across existing valuation methodologies by developing a comprehensive, transparent framework to value services and impacts of grid-related technologies.

GMLC Project number	GMLC project title	GMLC project description
GMLC Project 1.4.23	Threat Detection and Response with Data Analytics	To develop advanced analytics to help power operators detect complex cyber threats and differentiate between cyber and non-cyber incidents, such as physical attacks and natural hazards.
GMLC Project 1.2.3	Testing Network	To close the gap in accessibility to validated models for grid devices and simulation tools and corresponding full documentation.
GMLC Project 1.4.29	Future Electricity Utility Regulation	To assist states in addressing regulatory, ratemaking, financial, business model, and market issues related to grid modernization in the power sector.
GM0072	Suite of Open-Source Applications and Models for Advanced Synchrophasor Analysis	To develop a suite of software applications and libraries of PMUs and synchrophasor data for power system planning, modeling, and analysis. All applications will be based on the common open platform concept, have a common data format structure, and be released under an open-source license.
GM0077	Advanced Machine Learning for Synchrophasor Technology	To develop a suite of new machine learning tools to monitor the transmission grid during its normal operations and also localize significant frequency events seconds after they occur.

The Program will provide support to other DOE programs and initiatives. This includes working jointly with the North American Resilience Modeling team to identify and meet data and associated communications and processing needs for this DOE/OE priority initiative; it also involves engaging the Office of Cybersecurity, Energy Security, and Emergency Response's Cybersecurity for Energy Delivery Systems Division on coordinated and/or collaborative R&D for next-generation tools and technologies to improve the cybersecurity and resilience of the nation's critical energy infrastructure. Further, the Program will coordinate with or build on the projects funded by DOE Advanced Research Projects Agency-Energy (ARPA-E) programs, including its Generating Realistic Information for the Development of Distribution and Transmission Algorithms (GRID DATA) program, Saving Energy Nationwide in Structures with Occupancy Recognition (SENSOR) program, and Network Optimized Distributed Energy Systems (NODES) program.

Existing partnerships with utilities, manufacturers, private-sector research institutions, state and local government agencies, and the U.S. Department of Commerce's National Institute of Standards and Technology (NIST), will be leveraged for coordination on Program planning, development, and implementation. These partnerships include those established under GMLC projects (with more than 100 partners), through DOE user facilities (such as the Electricity Infrastructure Operations Center at Pacific Northwest National Laboratory and the Energy Systems Integration Facility at the National Renewable Energy Laboratory), and through other OE programs. Moreover, industry engagement will be further guided by the expanded ADMS/Sensor Steering Committee. The existing ADMS Steering Committee comprises recognized industry leaders or experts in the ADMS community who are well versed in sensing and measurement necessary to meet the needs for data-rich, data-driven ADMS applications.
The Committee will be expanded to strengthen expertise and industry linkages in data analytics.

PROGRAM BENEFITS

Fast, high-fidelity, and high-resolution measurements increase grid visibility and allow timely and precise grid event detection, protection, and control. Utilities will be able to assess grid operational state in real time, predict behavior and potential disruptions, quickly respond to events, and better address future challenges. Better information and situational awareness of the entire power system—including behind-the-meter DERs—allow more efficient, effective, and flexible grid operation and improve long-term, short-term, and real-time power system operational reliability and resiliency. Successful realization of incipient failure detection schemes along with associated condition-based maintenance programs ubiquitously throughout electric T&D systems will provide utilities and other stakeholders with sufficient warning time and specificity regarding the failure mechanism to enable predictive and prescriptive actions to prevent potentially disruptive, costly, and even catastrophic failures before they occur. Further, more effective asset utilization will result, allowing avoidance of unnecessary build-out of new transmission and other grid assets. Ultimately, sensor technologies and data analytics R&D will support achieving uninterrupted electricity delivery to the nation's critical facilities and services under all circumstances.

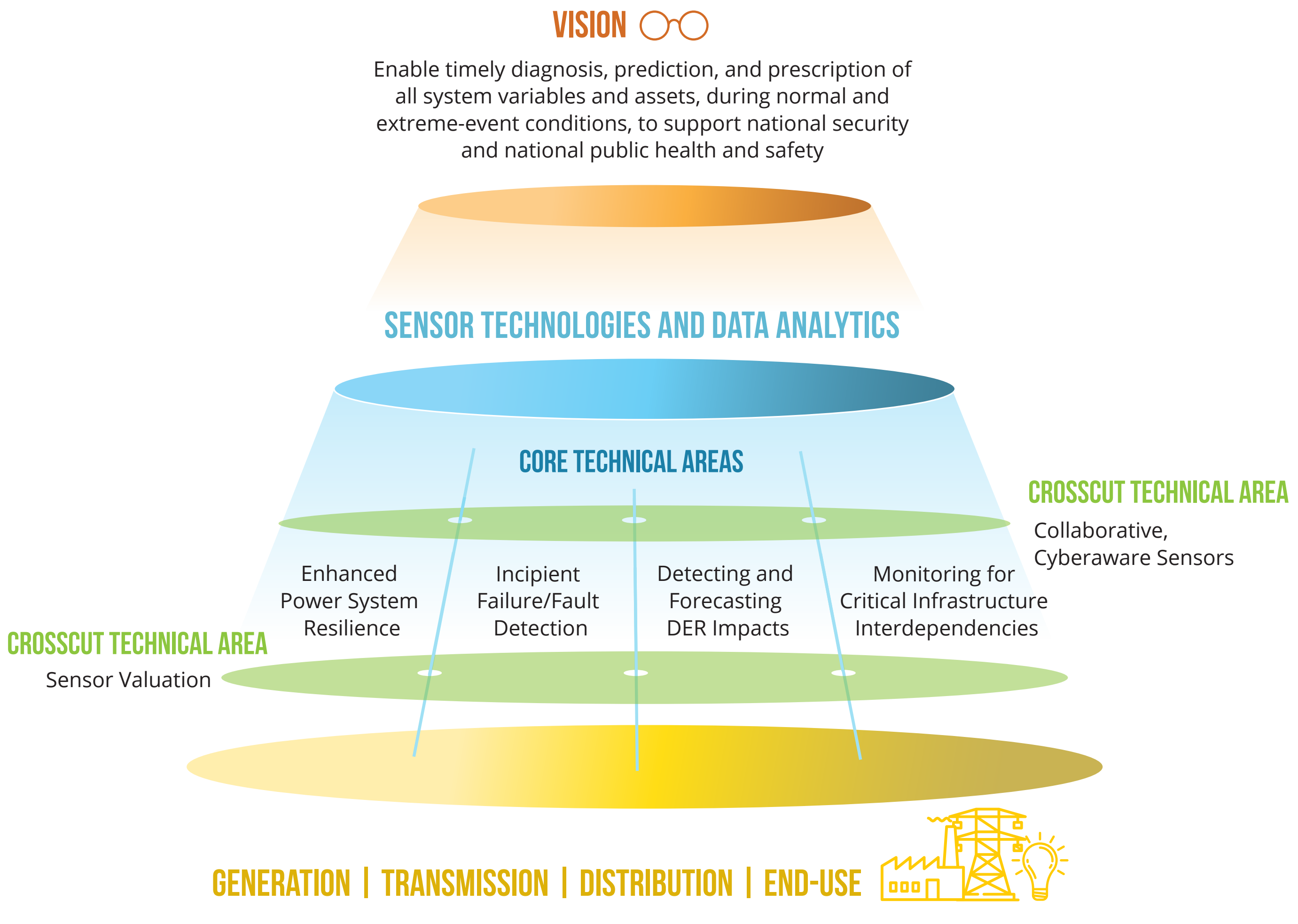
Outcomes of broad sensing technologies deployment made possible by Program R&D

- Improved situational awareness of incipient failure and anomalous behavior regarding grid assets and the operational state of T&D systems;
- Ability to distinguish outages resulting from man-made events and naturally occurring faults and failure mechanisms, improving system restoration speed and efficiency;
- Better forecasting of future states with enough accuracy and lead time to avert deviations from normal operations (or allow self-healing from disturbances);
- Better understanding of the capabilities and consequences of advanced control systems for dynamic grid operations and protection; and
- Extended visibility throughout the entire power system for dynamic grid control, operations, and protection meeting the performance metric of a modern grid.

TECHNICAL AREAS

Sensor Technologies and Data Analytics Program activities are structured into four core areas and two crosscut areas, as depicted in Figure 1. Crosscut areas cover technologies, methods, and tools for which application cuts across each and every core area. In total, these six technical areas address sensing and monitoring needs for electric T&D systems and end-use loads to achieve the Program vision and goals.

Figure 1. *Vision and six technical areas of the Sensor Technologies and Data Analytics Program.*



A detailed description of each technical area is provided in the respective sections below, which cover technical goal and objectives, technical challenges, technical scope, status of current development, DOE role, technical activity descriptions, and milestones.

Enhanced Power System Resilience

Achieving electric grid resilience and protection under natural, man-made, or cyber disasters is challenging due to the following factors: lack of timely, comprehensive, situational awareness; lack of trusted information regarding equipment damage or state, or operational status of the grid; or lack of state estimation for the distribution system in particular. Distinguishing between naturally occurring failure mechanisms and a cyber or physical event is a significant challenge for responding grid operators. This challenge affects reliable operations of multiple infrastructures, including electric, gas, transportation, and communications, as well as operations involving mission-critical facilities and lifesaving services. Addressing the challenges and threats to the electric power system from these events is, thus, critical to national security.

TECHNICAL GOAL AND OBJECTIVES

This technical area aims to investigate and demonstrate technologies that will enable power systems to better predict, respond to, and recover from critical events, achieving improved system visibility and operational awareness.

The effective management of power systems requires both access to and measurement of data and parameters needed to evaluate system performance, along with the timely ability to share information to multiple, potentially geographically distributed parties. At present, performance of power system analytics occurs primarily at centralized control centers, with real-time data sets unavailable to other locations in the system. Distribution-level measurement and analysis are often used to understand events in the past, as opposed to real-time and look-ahead analyses. The limited practice of the latter reflects the lack of application of a suite of new distribution sensing technologies and also constraints relating to the ability of software and utilities to handle increasing volumes of data in real time.

However, the number of controllable devices composing today's power systems is growing and expected to increase exponentially. The traditional centralized control center paradigm, pragmatic in the past, was not designed to handle communication and analytics for data from this number of controllable devices. To utilize resources such as DERs in restoration, the stochastic behavior associated with these devices (for example, variable generation of PV and stochastic availability of EVs) must be modeled and visualized for effective dispatch.

Power system operators, especially distribution system operators, are looking to visualize system status without wading through a vast amount of raw data but still have fast access to raw data during wide-scale events, if needed. Operators would benefit from a user-friendly visualization tool that provides an overview of the true system state—damaged, protected, and availability of restoration resources—to decide how best to respond. For example, a distribution operator has little need to see phase angle data. However, analytics stemming from phase angle data, such as behind-the-meter PV output on a feeder basis, is considered extremely valuable. An integrated and effective sensing and analytics infrastructure is key to improved situational awareness and also toward more automated grid operations.

TECHNICAL CHALLENGES

The current practice for response, repair, and restoration still mostly relies on damage assessors to patrol the feeders to identify trouble spots and evaluate the extent of damage, which is a slow process. In regions that recently experienced significant events, such as hurricanes, there are examples of significantly improved response times from introduction of new sensing and evaluation technology, but there are also examples of this technology having limited usefulness due to lack of intelligent analytics of gathered data.

Large-scale events—such as severe weather, cyber-attacks, or natural disasters—put the nation's electric grid at risk. When the local or regional system includes a high penetration of DERs, it can be challenging to identify which resources are still available to help restore services efficiently after a disruption. The same event that caused the grid to fail often results in a loss of communications, making the sensor data needed to understand grid state unavailable and utilization of behind-the-meter resources not possible.

In addition, most current distribution systems are "blind" in terms of monitoring and control capability beyond the distribution substation. Even with some observability enabled by AMI or distribution automation, measurement data during and after an outage may be unavailable, unreliable, or untrusted (from a cybersecurity point of view) because the devices and the underlying communications network may be impacted. To pinpoint the faulted areas, today's outage management systems usually depend on customer trouble calls, which are slow and inaccurate. Furthermore, the data silos among different data sources impact the ability to achieve situational awareness in a timely manner.

Balancing application, integration, cost, and cyber-physical security requirements drives innovation in sensor development to meet targets in performance, cost, and deployment. Technologies developed for resiliency applications cannot generally be made as robust and reliable as required during high-impact, low-probability scenarios, while remaining within normal cost structures.

Such development inherently includes the device-transducer, embedded computing for data processing, and end-to-end communication. These novel sensor technologies must be developed with scalability and reliability for utility adoption. By understanding vital parameters throughout the electric infrastructure, from generation through end use, utilities will be able to assess grid health in real time, predict behavior and potential disruptions, quickly respond to events, and better address future challenges.

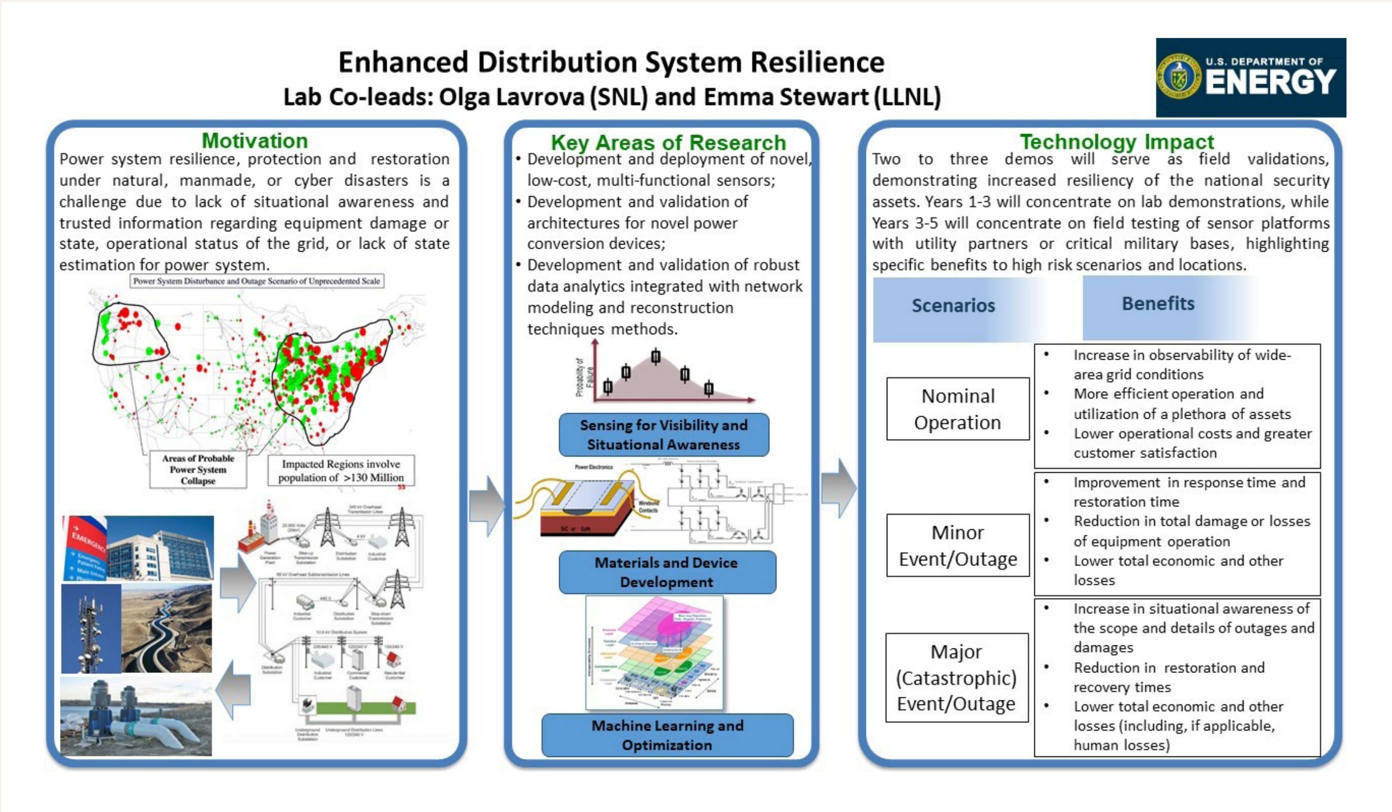
Development of high-fidelity, affordable (with reference to value of added situational awareness and resilience), and multi-parameter sensing and measurement technology has the potential to improve situational awareness after natural disasters and thus can improve distribution restoration practice for utilities. Sensors in themselves must have adequate survivability and resilience and be able to detect dynamic, fast-moving, real-time event signatures—as is required for improved resilience—but yet enable ongoing analytics for reliability. Value streams for a resilient distribution sensing architecture are layered from normal operation to resilient and worst-case scenario performance.

For example, from the device-level perspective, development of low-cost, multi-parameter sensors to monitor asset status (for example, via asset monitoring sensors) as well as grid condition (for example, smart meters, PMUs, and distribution automation sensors) could provide additional measurements to estimate damage status, increase redundancy, and achieve observability under severe conditions. From the communication-level perspective, development of distributed communication architectures and an associated self-healing mechanism could achieve resilient communications and data streams to mitigate and respond to the impact of infrastructure damage due to disasters. From the data management and analytics perspective, integration of distributed analytics and peer-to-peer communication could enable the efficient fusion of multiple data sources from different types of sensors to improve situational awareness; the development of data analytics methods to estimate the damage status could be robust to missing or erroneous measurement data due to the impact of natural disasters.

TECHNICAL SCOPE

To achieve the goals outlined above, key areas of research have been identified. These areas, along with their underlying motivation and technology impact, are depicted in Figure 2.

Figure 2. *A graphical summary of motivation, key R&D areas, and technology impact relating to T&D resilience.*



The technical scope encompasses a broad range of system operator needs, including the following:

- **System sensors**. Develop a novel, multi-faceted sensing system to support restoration, resiliency, and reliability—spanning condition assessment, grid state, and weather.
- **Performance sensors**. Develop multi-tiered metrics to balance performance/cost tradeoffs. Dramatically reduce cost for existing performance and enable new lower-cost sensors to meet targeted performance. Develop frequency-selective, high-bandwidth, and low-latency electrical current measurements with sufficiently low cost for ubiquitous deployment. Develop new set of transducers capable of providing accurate information about frequency content and total harmonic distortion (THD).

- **Novel behind-the-meter transducers**. Monitor the performance of several devices and broadcast this information to the utility. A possible "smart outlet" that can collect power and power-quality information is another example. A complete solution would be a smart meter that not only provides revenue information but also provides power and power-quality information for all devices at the customer interconnection locations.
- **Novel parameter sensors**. Develop a new set of transducers capable of providing fundamentally new information for electric grid state and assets, such as frequency selective current sensing, fault-current detection, fault-location detection, optical current transformers and voltage transformers, accurate harmonics and THD measurement, accurate pulse-width-modulation diagnostics, voltage derivative sensors, current derivative sensors, frequency derivative sensors, and other information that may be useful for dynamic system protection.
- **Multi-modal, multi-variate, real-time, and historical analytical frameworks**. Develop a real-time streaming analytical framework that leverages new sensing technologies and historical data sources across modalities and time frames. Perform data integration and synchronization with network models and known conditions.
- **Distributed and local analytics**. Detect major local events, data distribution, and local data processing to determine damage and attack pathways. Integrate analytics framework with resilience modeling efforts for validating and verifying results.
- **Communication**. Prioritize secure data transport in degraded conditions, helping to move all data out of the path of damage with the highest volume/precision possible. Ensure reliable communication in response to hazardous conditions.

STATUS OF CURRENT DEVELOPMENT

Regarding data management and various technologies for dealing with data, many commercial entities and government/non-government research institutions have ongoing, synergistic R&D.

The proposed R&D activities, more broadly, are being addressed to some extent by the GMLC and GMI. For example, an existing effort under GMLC's Advanced Sensor Development project targets passive microwave sensor technology, referred to as MagSense, for ubiquitous grid asset fault-current monitoring. Despite the ongoing efforts within GMI, clear opportunity exists to expand on the area of developing novel transducers capable of sensing and communicating actionable information that is significantly value-added and will lead to more informed and robust electric grid and assets controls.

Current efforts within GMLC's analytics areas have focused on identifying existing analytics as well as artificial intelligence (AI) and machine-learning techniques that could be applied to the grid space. A key limitation of this work is the unavailability of significant volumes of historical data to create learning models of the network. High-value use cases were evaluated for application of combinations of supervised, unsupervised, and deep machine-learning techniques. These cases included disaggregation of behind-the-meter resources and incipient failure detection. Key gap areas are identified that can be addressed by DOE in the use of multi-modal, multi-variate data streams, and limitations of communication and data analytics pathways during resilience events.

DOE ROLE

Addressing the business and physical case for sensors and analytics focusing on T&D resiliency is a challenge. Resiliency has traditionally differed from reliability in that it deals with low-probability, high-consequence scenarios as opposed to continual system assessment. While industry has moved toward sensing and measurement throughout the grid, development of sensors and analytics that have high survivability with layered value streams is a challenging prospect that should be addressed by DOE. The resilience problem for sensing and measurement is also one spanning infrastructure areas and utility/balancing authority boundaries, along with dealing with data silos from different sources. The DOE role would be to develop vendor-agnostic technologies, focusing on needed capabilities for improved resilience and cost bands, which could be rapidly transitioned in five years to useful application. Sensor and analytics testing in low-probability scenarios is also uniquely addressed by national laboratories with the supercomputing capabilities required for AI solutions in complex, comprehensive national security-level events.

TECHNICAL ACTIVITY DESCRIPTIONS

The following R&D activities are proposed for enhancing T&D resilience:

- Develop and validate cross-infrastructure analytics capabilities that will be able to distinguish between outages resulting from man-made events (such as cyber-attacks or other malicious attacks) and naturally, regularly occurring faults and failures (such as those resulting from extreme weather, or slow aging or degradation of equipment). Develop a high-fidelity, dynamic behavior model for wide-area transients with increased fidelity and computation speeds of state estimators.
- Develop and deploy cost-effective sensor devices that could provide observability of asset status and grid condition, as well as withstand certain natural or man-made threats. Develop optimal sensor placement strategies to ensure a certain level of redundancy for observability under severe conditions. Develop sensor platforms with (a) multi-parameter capability, (b) compatibility with deployment internal to electrical and generation assets, and (c) capability for spatially distributed measurements.
- Develop distributed communications architectures with functionalities that do not rely on infrastructure availability and provide dynamic networking features that are resilient to natural disasters. Develop a self-healing mechanism to recover a certain level of communication to mitigate the impact of damages.
- Develop a data management scheme to achieve efficient integration of multiple sources of the sensors information to enhance damage assessment. Validate robust data analytics integrated with network modeling and reconstruction techniques, which provide viable damage assessment results when the data quality (for example, erroneous data or missing data) is largely impacted by natural disasters.
- Conduct cross-device validation and verification of measurement.

MILESTONES

Key milestones involve two to three demonstrations of increased resiliency of national security assets that also serve as field validations. Years 1 to 3 will concentrate on lab demonstrations, while Years 3 to 5 will concentrate on field testing sensor platforms with utility partner(s) or critical military base(s), highlighting specific benefits to high-risk scenarios and locations.

- **Scenario 1: Nominal Operation** – Increase observability of wide-area grid conditions, operation efficiency, and utilization of a plethora of assets, resulting in lower operational costs and greater customer satisfaction.
- **Scenario 2: Minor Outage** – Improve detection/isolation/response/restoration time and reduction in total damage or losses of equipment operation, resulting in fewer total economic and other losses.
- **Scenario 3: Major (Catastrophic) Event and/or Outage** – Increase situational awareness of scope and details of outages and damages and reduction in restoration and recovery times, resulting in fewer total economic and other losses (including, if applicable, human losses).

Incipient Failure/Fault Detection

Health monitoring of the components within the electric power system is currently limited, and the operating model of the industry today remains largely reactive. Utilities, for example, have operating and maintenance processes, but they tend to focus on maintenance schedules as opposed to predictive maintenance. While the lack of predictive capabilities is due to a combination of factors, it is primarily a result of not having effective methods for monitoring incipient failure of relevant components and, in many cases, the high cost of currently available technologies. Needs are also emerging for health monitoring of grid-connected devices, such as power electronics converters and energy storage. In all cases, sensor technologies should avoid complex installation procedures, a need for expert interpretation, and frequent servicing to simplify the time and cost associated with their use, and they should be compatible with the unique requirements imposed for electrical asset monitoring. Due to the large areal extent in the electric power system and the large number of components involved—especially in the functioning of the distribution system—sensor placement and selection in terms of geospatial information content and the ability to maintain the sensor network are important considerations.

TECHNICAL GOAL AND OBJECTIVES

This effort aims to investigate technologies and approaches that enable real-time health monitoring, and determination of the probability of failure and the estimated time-to-failure, of critical grid assets at the T&D levels rather than relying on run-to-failure and schedule-based maintenance. Realization of these capabilities will enhance overall grid reliability by reducing system outages and significantly improving system maintenance capabilities. Specific benefits associated with development of incipient failure and anomaly detection include the following:

- Reduced maintenance cost and effort based on proactive as opposed to reactive component maintenance;
- Reduced in-field failures that produce outages;
- Sensor-enabled, novel dynamic protection schemes to limit impacts of component failure; and
- Improved energy efficiency and grid performance by early detection of component degradation.

Ultimately, new sensing and measurement technologies must be demonstrated in terms of their impacts and benefits at the system level. As the effort progresses in future years, the research task validation should focus on two primary objectives, namely (1) integration of sensor device platforms onto operational grid assets and application of analytics techniques to supervisory control and data acquisition (SCADA) systems and WAMS, in addition to newly enabled measurements from PMUs and other emergent sensor platforms; and (2) demonstration programs involving the deployment of analytics, devices, and modeling/valuation techniques on a number of regionally diverse systems through close collaboration between DOE national laboratories and utility partners in close geographical proximity.

TECHNICAL CHALLENGES

Incipient failure and fault detection solutions that meet the goals of this thrust area should address the following challenges:

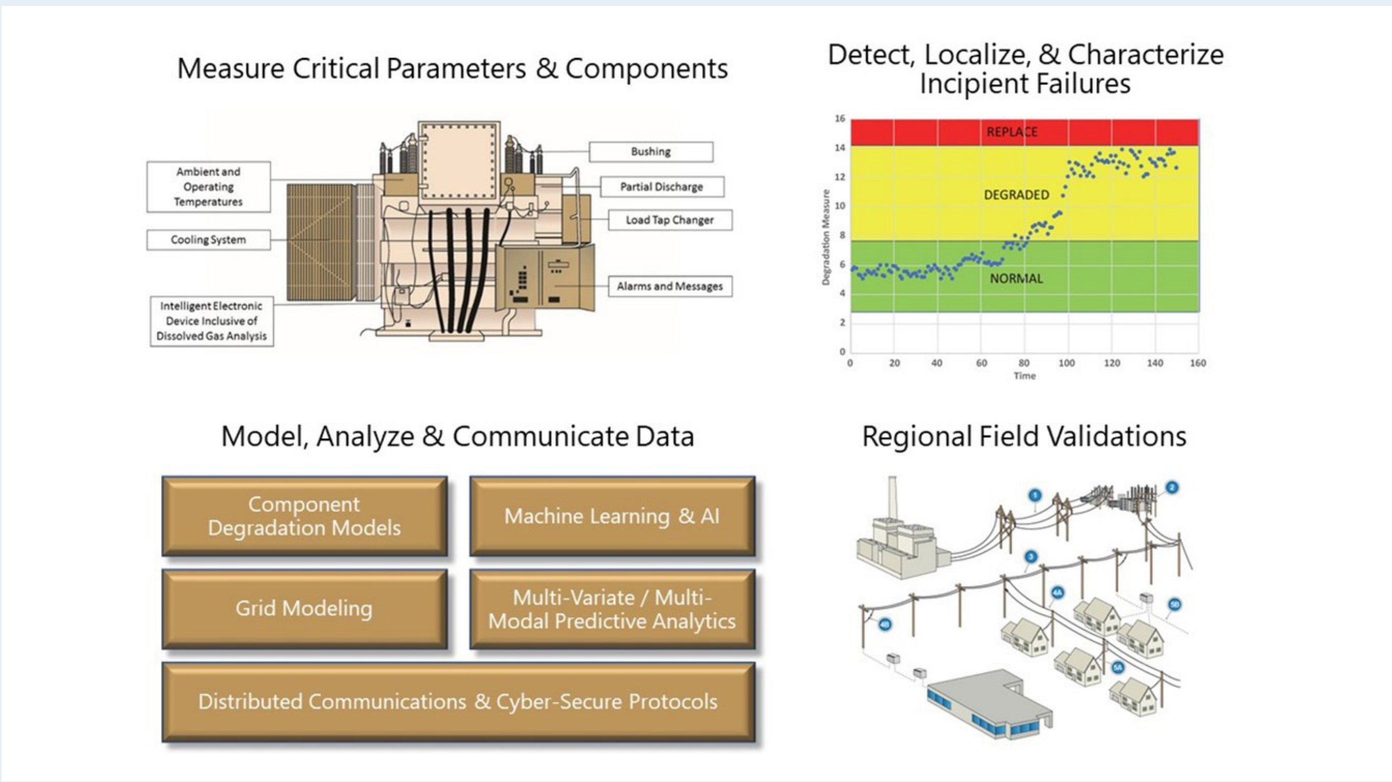
- Health monitoring must be risk-based, encompassing all critical and impactful power system assets. Efforts should provide clear value proposition justifications.
- Sensor detection approaches must be based on a sound understanding of underlying material and component degradation processes of grid assets, as well as component loading histories.

- Grid system sensors should be simple to install and maintain, including self-diagnosis of sensor health and accuracy to mitigate against installation, calibration, and drift/long-term reliability issues.
- System failures can occur at many locations within a vast area, and monitoring technologies must address technical challenges and costs of deployment, communication, and maintenance—particularly when installed beyond the substation.
- Sensor selection and placement should be optimized to meet “grid visibility” requirements for monitoring incipient failure subject to deployment, operation, and maintenance cost constraints.
- Sensor detection schemes capable of operating internal to electrical assets are needed for certain failure mechanisms, such as the monitoring of high impedance faults or outgassing within enclosed structures.
- Sensor data processing at the device or “edge computing” may in some instances be needed to reduce communication burdens.
- Some failures are associated with event recovery, so some sensors may have to assess health prior to energizing.

TECHNICAL SCOPE

The scope encompasses four technical areas, which are described below. Key R&D activities are shown in Figure 3.

Figure 3. *Scope of R&D activities for incipient failure/fault detection.*



- **New sensor technology development**. Sensors for monitoring incipient failure and anomalies may cover individual components or the collective behavior of components. They should be based on a measurable understanding of the degradation mechanism leading to incipient failure or empirically validated indicators leading to failure, and they should represent dominant or critical failure modes within the grid. Example applications of interest include the following: transformer oil degradation, transformer winding impedance, insulation degradation and current leakage, mechanical switch degradation, circuit breaker reliability, switchgear humidity, high impedance fault detection (including buried lines), intermittent faults, conductor condition (including sag and swing), and lightning mitigation. A key enabler for the successful detection of incipient failures of grid assets is real-time measurement and cost-effectiveness. Prospective sensing technologies should consider total cost of ownership. Multi-parameter and low cost sensing platforms are of particular value and must be compatible with deployment on or near electrical grid assets without introducing additional potential sources of component system failure.

  Electrical parameter measurements can provide evidence for fault currents, undesired harmonics, geomagnetically induced currents, power quality fluctuations, and related signatures of incipient failures on the electrical system. Measurements of physical and chemical parameters can provide evidence for thermal faults and overtemperature conditions, insulation breakdown and arcing, loose electrical connections and terminations, line or pole tilt/sag, and more. In addition, lower-cost alternatives with reduced—but adequate—functionality can enable ubiquitous deployment throughout the distribution system.

- **New analytics algorithm and technology development**. Advanced analytics approaches that can more effectively convert sensor data into actionable understanding offer the potential for improved capabilities for incipient failure monitoring without significant additional investments in new sensing technology hardware. Analytics approaches should be applicable to development of real-time, data-driven models that achieve specific operational goals, such as diagnosis of dysfunctions and prediction of asset condition. These analytics tools should be applicable to both novel sensors for monitoring T&D assets and existing data sources that are underutilized. Approaches can include physics-based, statistical, and AI and machine-learning methods. As new, cost-effective sensing devices compatible with system requirements become available, the ability to integrate disparate data from a wide variety of devices incorporating unique characteristics (geospatial, temporal, and information content) of data in a holistic analytical platform can provide early indications of incipient failures that would not otherwise be possible. Within existing analytics platforms, there are numerous instances of siloed data sources and techniques, and the analytics developed are often specific to the grid and sensor architecture. Research is required to implement both multi-modal and multi-variate techniques for present and future grid data sources.
- **Field testing and proof-of-principle validation**. New sensing and measurement technologies are only valuable to the extent that they can meet functional requirements, as well as acceptable levels of deployment and operating/maintenance costs. Advanced sensing hardware and analytics methods and techniques must first be demonstrated under controlled laboratory conditions, followed by testing in representative and relevant field conditions. Testbeds at DOE national laboratories and commercial facilities will be leveraged for early demonstrations. Analytics methods must be benchmarked using available data sets, both historic and current, to confirm efficacy for predictive identification of incipient failures. Furthermore, demonstrations of newly developed sensing devices and analytical platforms should focus on two primary objectives, namely (1) integration of sensor device platforms onto operational grid assets and application of analytics techniques to SCADA systems and WAMS, in addition to newly enabled measurements from PMUs and other emergent sensor platforms; and (2) a number of regionally diverse grid installations through collaborations between DOE national laboratories and utility partners in close geographical proximity.

- **T&D models and tools for sensor allocation**. Successful deployment of advanced sensing and measurement technologies for incipient failure detection within the grid requires models and tools that can maximize the impact while optimizing the total cost of ownership of deployed technologies. This includes analysis tools that allow the optimization of sensor placement to meet reasonable, cost-effective system visibility requirements. Grid component and system models, along with correlation modeling and AI, are required to understand how incipient failures at the component level can translate into measurable signatures within the system. Sensor selection, placement, and allocation tools that can be applied for various grid system and component models are also needed to clarify the value proposition of emergent technologies in the context of current and future, high-value grid applications.

STATUS OF CURRENT DEVELOPMENT

Commercial technologies for grid asset health monitoring are available on the market and are deployed regularly on the largest, most expensive, and critical grid assets—such as dissolved gas analyzers and associated analytics platforms deployed in large power transformers. However, costs of such real-time asset health monitoring systems are one to two orders of magnitude greater than required for ubiquitous deployment, especially throughout the distribution system.

The GMLC Advanced Sensor Development project includes three complementary asset monitoring technologies focused on both passive wireless (surface acoustic wave and engineered resonant magneto-elastic devices) and optical-fiber-based sensor platforms. The surface acoustic wave and optical-fiber sensor projects are seeking to develop platforms for low cost "dissolved gas analysis" and internal temperature sensing for power transformer health monitoring. The resonant magneto-elastic devices ("MagSense") enable low-cost, real time frequency selective monitoring of fault currents impacting transformers, as well as inverters and DERs such as solar PV. In all cases, a field validation effort is being carried out in FY 2018–2019 to demonstrate technologies under relevant operational environments. The GMLC Data Analytics project (#1.4.9) places emphasis on application of advanced analytics techniques, including machine learning, with one of the project's use cases aligning directly with grid asset incipient failure detection by leveraging electrical parameter measurements in conjunction with advanced analytics. Several related projects were also awarded and initiated through a recent DOE OE funding opportunity announcement (FOA).[5] The GMLC Sensing and Measurement Strategy project (#1.2.5) developed the SPOT tool for sensor placement and optimization, along with several use cases—including distribution state estimation (DSE) and FLISR.

DOE ROLE

To complement private-sector R&D efforts, DOE efforts should focus on achieving required cost reductions through lower-TRL scientific and engineering innovations that are enabled by emerging technologies and technology platforms. DOE efforts should also promote development and documentation of necessary interoperability standards early in sensor technology development efforts to ensure that technologies under development can be readily deployed as they mature. DOE efforts will also promote integration of multi-modal and multi-variate data sets into integrated analytics platforms compatible with distributed sensing and communications networks from a wide array of sensor devices, including existing technologies such as PMUs. To promote rapid and widespread adoption of newly developed technology platforms, DOE efforts will also support regional demonstrations and field validations, as well as development of relevant grid models and sensor allocation tools—including quantitative, defensible methods for assigning valuations to new technologies.

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[5] FOA: Sensor and Modeling Approaches for Enhanced Observability and Controllability of Power Systems with DERs, Number: DE-FOA-0001616 (award announcement available at https://www.energy.gov/oe/articles/oe-announces-investment-new-research-improve-grid-reliability-and-resilience-through).

TECHNICAL ACTIVITY DESCRIPTIONS

Technical activities will involve a combination of novel sensor development, analytics methodology and platform development, sensor placement valuation assessment, and regional field validation demonstrations. The R&D maturity levels of interest will span early stage, for emerging technologies and platforms, to later stage, for demonstrations on actual grid assets.

Sensor device R&D efforts will place a significant focus on platform technologies that can be optimized for and applied across the wide range of applications relevant for incipient failure monitoring within the system. Analytics technologies and platforms will place emphasis on multi-modal and multi-variate methodologies for integrating disperse and disparate data sets into a unified framework to successfully identify incipient failures.

The activity will engage relevant stakeholders—including vendors, utilities, and standards development organizations—through establishment of an industry advisory group. One goal of these interactions will be to ensure that tools and techniques under development through the activity address recognized gaps in commercial offerings and are compatible with existing and emerging standards and interoperability requirements. Another goal will be to obtain feedback on proposed field demonstration activities and review conclusions of sensor placement and allocation tools for technologies being developed.

YEAR 1

ACTIVITIES

- Establish an industry partnership group—that includes vendors, utilities, and standard development organizations—specifically focused on incipient failure monitoring.
- Review GMLC 1.4.4 (advanced sensor development) and 1.4.9 (advanced analytics) project activities specifically relevant for incipient failure to determine which technologies should proceed in collaboration with the industry partnership group.
- Establish new sensor development efforts focused on high-priority needs identified in the *Sensing & Measurement Technology Roadmap Document* and in collaboration with industry partners.
- Establish a new project activity focused on sensor placement and allocation, as well as valuation methodologies for incipient failure use cases.
- Establish a new project activity focused on component and grid-scale models to understand the relationship between incipient failures and measurable parameters.

YEAR 1

MILESTONES

- Establish industry advisory group.
- Review platform technologies under development with industry advisory group; obtain feedback and revise development plan as appropriate.
- Document detailed use cases for at least three incipient failure detection scenarios relevant to novel detection methods under development.
- Initiate development of sensor placement valuation tool.

YEAR 2

ACTIVITIES

- Continue R&D efforts on selected technology platforms and continue development of sensor placement, allocation, and valuation tools.
- Continue development of multi-modal, multi-variate analytics platform.
- Conduct early-field investigation of developed technologies.
- Engage with standards development organizations to understand relevant interoperability and standards requirements for technologies under development.
- Perform application and further development of sensor network optimization and valuation tool.
- Perform application of component-level models to highlight key parameters relevant for incipient failures.

YEAR 2

MILESTONES

- Complete study of T&D system failure modes and identify high-value incipient failure detection applications.
- Complete performance specification for T&D system multi-modal sensor data analytics platform.
- Initiate field validation of at least one incipient failure detection technology under development in an energized distribution transformer.
- Expand incipient failure detection methods to include priority measurements identified in the T&D system failure modes study.
- Develop conceptual architecture for distribution system multi-modal sensor analytics platform.
- Complete and document field evaluation of incipient failure detection technology, including benefits analysis.

YEAR 3

ACTIVITIES

- Continue R&D efforts on selected technology platforms.
- Continue engagement with industry group and standards development organizations.
- Continue field investigation of developed technologies.
- Perform application of developed modeling and sensor placement and allocation tools for simulated deployment within standardized T&D system applications in preparation for regional field validation efforts to be pursued in subsequent years.

YEAR 3

MILESTONES

- Complete development of T&D system multi-modal sensor data analytics platform.
- Demonstrate at least one new sensor technology relevant for incipient failure detection in grid asset health monitoring.
- Integrate information derived from new sensor technologies into analytics platforms.
- Identify at least three regional field validation sites and strategies for incipient failure monitoring of various grid assets.
- Release sensor placement valuation tool for public use.

YEAR 4

ACTIVITIES

- Continue development and demonstration of new technologies.
- Select regional demonstration sites and applications in consultation with industry.
- Perform application of sensor placement, allocation, and valuation tools to regional demonstration sites.
- Select one technology platform or a collection of platforms for large-scale incipient failure field validation in the context of regional demonstrations.
- Conduct smaller-scale field validation to prepare for future full, large-scale field validation.

YEAR 4

MILESTONES

- Select at least one incipient failure detection technology for large-scale field demonstration (> 100 monitoring units deployed).
- Release T&D system multi-modal sensor data analytics platform for public use.
- Complete initial field validation to prepare for future, large-scale validation.

YEAR 5

ACTIVITIES

- Undertake commercial technology transfer activities of newly developed technologies.
- Continue R&D to expand capabilities of developed sensing platforms for a broader array of relevant grid parameters and grid asset applications.
- Complete full, large-scale regional demonstrations of networked sensors.
- Engage with standards development organizations and industry partners.
- Develop estimates of valuation and benefits for developed sensor network solutions

YEAR 5

MILESTONES

- Transition at least one new sensor technology to a commercial partner through licensing.
- Release updated version of T&D system multi-modal sensor data analytics platform that is interoperable with available industry data analytics applications.
- Release updated version of sensor placement and valuation tool that is interoperable with ADMS and utility planning software.
- Complete large-scale, regional field validation.
- Complete documentation of results of large-scale field testing.

Detecting and Forecasting Behind-the-Meter DER Impacts

DERs such as rooftop solar PV systems, EVs, batteries, and demand response from end-use loads offer savings for energy costs and opportunities for providing valued flexibility services increasingly recognized by electricity markets and utilities. However, these DERs also introduce a high degree of uncertainty around their electricity usage patterns, ranging from both increasing and decreasing net loads; introducing rapid changes in net load; and injecting power locally that can reverse power flows, raise local voltages, and introduce harmonics from inverters, EV chargers, variable-speed drives, and other power electronics.

As customer-side DER technologies become a growing part of the grid landscape, and as distributed controls become prevalent, utilities have a critical need to understand the electrical connectivity and interaction of these highly dispersed, variable components to ensure that sufficient visibility and control can be maintained. It will not be possible to operate the electric power system with high levels of active DER participation without substantially increased ability to sense their impacts on the system and predict their behavior.

This technical area will advance sensor technology and analytics for DER applications through understanding and improving capabilities of existing sensors and developing new, cost-effective sensor packages and deployment strategies. In addition, a significant opportunity exists to identify addressable operating parameters of many of these new, largely 'smart' devices to sense and react positively to specific grid events.

TECHNICAL GOAL AND OBJECTIVES

The Program's goal in this area follows:

> *New and improved sensors, optimally deployed with advanced analytics and enhanced sensor networks, will be able to detect, characterize, and forecast DERs and their impacts to enable their integration into electric power systems at high penetration levels.*

To meet this goal, the following objectives must be achieved:

- Real-time observation of DER states with data collection that will enable characterization and reliable forecasts of their outputs at resolutions required for grid control and protection;
- Detection of unknown, behind-the-meter DERs to enable safe and reliable operation of distribution systems;
- Characterization of DERs and end-use loads for effective planning, operations, and market integration;
- Real-time, on-demand visualizations of net-load and renewable energy ramp forecasts in distribution and bulk system operations; and
- Update of topology-specific distribution network models, in the presence of large numbers of DERs, for online/real-time analysis that estimates distribution system states for operational decision-making.

TECHNICAL CHALLENGES

Wide-spread adoption of DERs can make the distribution system's behavior volatile and make existing issues worse (for example, phase unbalance and high-impedance faults). Therefore, DERs make the distribution system more challenging to manage. Power system decision support tools—including market dispatch tools, transmission Energy Management Systems, and Distribution Management Systems—all need fast and accurate estimates of current and forecasted distribution system states. These states are also needed to guide proper action of controls and protective equipment (for example, voltage regulators, capacitor banks, reactive power sources, breakers, switches, and reclosers).

Sensing and measurement of DERs are needed for T&D applications, which include, but are not limited to, volt-var control and optimization; FLISR; managing reverse power flows; forecasting net loads, cold-load pickup, and blackstart loads; and participation in energy and ancillary services markets at the bulk system level. With advanced DER sensors and sensor analytics, these applications will be able to make more effective decisions and will lead to better planning for distribution grids, including DER-hosting capacity.

Further, this will allow more effective market participation that could otherwise be challenging as variable DER penetration increases. Data are needed on actual and forecasted DER performance for participation in day-ahead and real-time markets, as well as for after-the-fact financial settlements with customers and DER owners. Forecasting net loads and net-load uncertainties is critical to determining the reserve and ramping requirements in the day-ahead and real-time market operations. Currently, procurement of spinning and non-spinning reserves is based on an ex-ante, preventive planning process. Having low-latency, highly-accurate, and real-time forecasts will enable reserves to be procured on a corrective paradigm using the latest forecasts, allowing reductions in reserve quantities and costs.

High spatiotemporal granularity measurements from extensive DER sensor information will greatly improve the performance of distribution system state estimation processes that are foundational to many of the applications listed above. The primary challenges involved are to obtain the accuracy and resolution required while keeping hardware and installation costs low. Also required is a comprehensive examination of the potential for a given sensor to support multiple applications—for DER management and, more broadly, reliability and resiliency.

TECHNICAL SCOPE

This DER technical area intends to develop a suite of approaches and tools that utilizes highly granular spatiotemporal data from networks of sensors for accurately detecting, characterizing, and forecasting DER behavior and its impacts on T&D systems. Emphasis will be on behind-the-meter and distribution-connected DERs, including demand response. Inclusion of demand response in this definition of DERs is significant in that it involves the need to characterize major end-use loads involved in demand response. By extension, this provides critical information that aids in load forecasting and planning applications, as well.

The R&D activities undertaken by the DER technical area fall into two basic tracks:

1. Improved capabilities for existing sensor networks—based on improved analytics and/or increased communications network capabilities. This includes leveraging the intrinsic capabilities of many new, grid-connected devices to behave constructively during varying grid conditions.
2. New and improved sensors that complement existing commercially available sensor concepts or prototypes with significant leaps in capability.

Each of these activity tracks is discussed further, with examples, in the subsections that follow.

In addition, the DER technical area will coordinate closely with the Program's crosscut activities in cybersecurity and sensor valuation. It will work closely with the cybersecurity crosscut to ensure that all sensors and analytics associated with DERs developed by the Program are integrated with the Program's strategy to secure sensors and sensor networks from cyber intrusion and sensor data spoofing. It is critical to ascertain the measurements required for various applications and assess the balance between costs and benefits of various options for obtaining them. Therefore, the DER technical area will also work closely with the sensor valuation crosscut to develop detailed use cases and determine that (1) the value of improved sensors, sensor networks, and analytics justifies the associated marginal costs of deployment; and (2) the sensor networks are co-optimized across applications that extend beyond those in the DER technical area itself.

Track 1: Improved Sensor Networks and Analytics

One prominent example of how improved analytics and sensor communication networks present significant opportunities is evidenced in understanding the full potential of AMI to support characterization of DERs. Analyzing AMI data intelligently can result in detection and characterization of PV power profiles and hence can enable better estimation of real-time load demand. Understanding of loads decomposed into different types of end use can help with finer control and management of demand-responsive DERs.

The current state-of-the-art and more advanced analytics for this must be assessed, both in ex post and real-time modes (the latter enabled by potential upgrades to AMI bandwidth). Similarly, the potential to obtain data from inverters needs to be assessed in conjunction with developing requirements for new DER-oriented sensors. Understanding the potential of these sources of sensor data is critical, as an improved capability in its own right, but it is also important to establish a baseline against which the marginal benefit of developing and adding new, low-cost sensors for DERs can be compared with respect to the number, location, and quality needed.

Examples of activities in this track include the following:

A. Address the detection and forecasting problem associated with PV deployments by modeling PV customer loads using AMI data against solar radiation intensity. Correlating the residual errors of net loads with solar intensities indicates the likely presence of PV systems and, to a first order, indicates the size of the arrays. Long-term correlations of the residuals with sun angles may further suggest probable orientations and tilt. This potentially forms a powerful, low-cost forecasting capability to support applications to manage distribution and transmission system operations with interacting DERs in real time.

B. Situational awareness of DERs, in particular the inverter operational states, is needed for optimal T&D operations, particularly when large quantities of DERs may become isolated or disabled and operators must anticipate the sudden increase in net load. Inverters typically have mechanisms for sensing events like voltage or frequency excursions as part of controls that manage their response. The activity will examine the value of gaining access to such information by interfacing with DER inverters at interconnection points. Similarly, interfaces with smart inverters and EV chargers to leverage their sensing, measurement, and networking capabilities will be done, if access is given by the customers and/or manufacturers.

Track 2: New and Improved Sensors

Under this track, the Program will develop low-cost, high-resolution sensors for monitoring DERs, distribution transformers, and end-use loads, along with greatly enhanced analytic capabilities. Use cases and associated sensor requirements will be developed. After their value is justified, the Program will develop, bench test, and then prototype the sensors and sensor packages utilizing novel manufacturing techniques.

Activities that fall under this track include the following:

A. Develop a range of sensor packages for measuring power flows and other variables at the circuit panel in a home or business—the point of common coupling of most customer-owned DERs. Multiple sensor packages may be developed so that they offer a range of sensing capabilities.

B. Develop low-cost, easy-to-mount (for example, refrigerator magnet or peel-and-stick) sensors based on detecting noise, vibration, electric or magnetic fields, current, voltage, frequency, and temperature to determine the state of the end-use device. This can be the basis for achieving good resolution of end-use loads (spatial and temporal, including high-order harmonics) from readily available interval AMI consumption data to support end-use load and demand-response monitoring and characterization at very low cost. Characterizing end-use loads is essential for utility planning, energy efficiency management, and demand response.

C. Develop sensors for measuring electrical and non-electrical parameters as identified in the use cases and sensor requirements for accurate DSE in the presence of significant penetration of DERs. The use cases include adaptive relay protection, fault localization, network reconfiguration, and cold-load pickup for restoration. This development, in turn, can support adaptive control for DERs to inject real and reactive power based on an online distribution power-flow model (with current state inputs), as well as forecast load for optimal operations.

D. Develop sensors and analytics suitable for dynamic phase identification using network configuration information and operational data fed by a range of sources and sensors for better management of unbalances.

E. Develop a transformer secondary circuit modeling tool using low-cost sensor measurements and AMI data.

F. Develop circuit-level power measurements with embedded analytics that use disaggregation to detect the EV-specific consumption and enable forecasts for distribution planning and operation. This is necessary because high penetrations of EVs have the potential to disrupt the traditional expected load shapes in time and magnitude.

STATUS OF CURRENT DEVELOPMENT

Sensors between the substation and customer meters are generally sparse, and in many distribution systems they are absent entirely. Sensor telemetry may exist to capacitor banks and voltage regulators, but many of these are adjusted autonomously or manually and hence do not contribute any sensor data to other operational processes. Where FLISR systems have been deployed, sectionalizing switches with networked status indications may be available. Many modern switches and reclosers come with advanced sensing capabilities approaching that of PMUs, but these capabilities are often dormant due to lack of communications networks along distribution feeders.

A majority of U.S. electricity customers are metered with AMI, and this remains the most granular data available in most distribution systems. Many AMI meters have capabilities to provide instantaneous values for current, voltage, and power factor measurements (in addition to interval consumption), but they generally lack enough memory to record time series of these readings. In the current generation, AMI meters often have computational capabilities sufficient to host at least modest applications, but these are seldom utilized at present. However, due to the design of AMI communications networks for billing applications, they have too much latency for real-time applications. Little progress has been made toward utilizing ex-post facto consumption data to check power-flow models of the infrastructure, perform state estimation, or detect and model PV system outputs. The value of adding networks of sensors to support real-time state estimation has not been established.

Many PV system inverters contain power measurements for diagnostic purposes, but these data are generally the property of the manufacturer or system provider and not made available to the utility (or customer).

This state of lack or absence of sensor applications for distribution systems is also driven by the fact that the benefits of more extensive sensor networks have not been well enough established to overcome utility management and regulatory oversight. Installation and communication network costs are perhaps more of a barrier than the cost of sensors themselves. As a result, many relevant quantities are not monitored, important new applications are not supported, and distribution-level problems remain unaddressed. Some of these are described below.

DOE ROLE

Sensors are largely absent below the substation level with the exception of AMI and inverters (PV and batteries). This is primarily because the benefits of the advanced technology are not well established with utilities. Hence, industry is slow in developing new technology for lack of active market uptake.

DOE and its national laboratories are uniquely positioned to engage with industry stakeholders to guide and facilitate the adoption of advanced sensors in utility or facility operations, as well as to envision and prototype next-generation sensors in which vendors are not in a position to invest. DOE and DOE laboratories are especially well positioned to make unbiased, open, and well-documented estimates of the synergistic benefits of sensors supporting multiple new technologies, which are key to spurring deployments.

TECHNICAL ACTIVITY DESCRIPTIONS

YEAR 1

ACTIVITIES

First-year activities will focus on establishing a baseline and ensuring the maximum utilization of existing sensors through improved analytics. In parallel, technical requirements for new sensors will also be defined. Technical activities are as follows:

1. Perform a baseline study to define the range of information needed or desired for DER applications now and in the future as a function of DER location (for example, T&D), penetration level, and type of application (for example, planning and operation).
2. Catalog the capabilities, costs, and installation requirements of existing and near-term, commercially available sensors.
3. Conduct system integration and deployment tests to:
   a. Understand existing data availability and options thereof.
   b. Understand the existing state of analytics; develop improved, advanced analytics.
4. Develop open-source, state-of-the-art algorithms that maximize use of currently deployed sensors and data sources, including ex-post, non-real-time analytics.
5. Initiate development of low-cost, new sensor packages for various DER-related applications based on the cost targets determined by analysis of value addition.
   a. Define new sensor requirements based on:
      i. Fidelity,
      ii. Accuracy,
      iii. Deployment environment,
      iv. Physical characteristics, and
      v. Installation requirements.
      vi. Conduct bench tests of various sensor options with respect to requirements in (5a).
      vii. Develop primary use cases for advanced sensors.

YEAR 1

MILESTONES

- Establish industry advisory group.
- Review platform technologies under development with industry advisory group; obtain feedback and revise development plan as appropriate.
- Document detailed use cases for at least three incipient failure detection scenarios relevant to novel detection methods under development.
- Initiate development of sensor placement valuation tool.

YEAR 2

ACTIVITIES

After exploring the existing and near-term sensor capabilities in Year 1, activities in Year 2 will focus on improving existing sensors to generate data with more real-time performance and better communication capabilities. Sensor development activities will progress to the prototyping stage. The technical activities are as follows:

1. Improve existing sensors via retrofitting or other feasible options in a cost-effective manner to incorporate better real-time capabilities and communication features.
2. Develop algorithms/analytics for effective use of the improved real-time capabilities and network features.
3. Conduct system integration and deployment tests, including bench and field tests of sensors with improved capabilities.
4. Develop prototype of new sensor packages.

YEAR 2

MILESTONES

- Develop improved sensors.
- Develop and test analytics for improved sensors.
- Complete prototype of new sensors.

YEAR 3

ACTIVITIES

Year 3 activities will focus on understanding the impact of wide and deep deployment of existing and improved sensors for better detection, characterization, and forecast of DER output and its impacts. In addition, prototyped sensors will be developed for bench testing. The technical activities are as follows:

1. Develop large-scale deployment schemes for existing and improved sensors based on the catalog of sensors created in Year 1.
2. Develop algorithms/analytics for effective use of the large volume of data with better spatiotemporal granularity.
3. Conduct system integration and deployment tests, including field tests of large-scale deployment schemes.
4. Develop analytics for new sensor packages and perform bench or simulation testing.

YEAR 3

MILESTONES

- Develop and test analytics for utilization of data from large-scale deployment of existing/improved sensors.
- Develop and bench test analytics for new sensors.

YEAR 4

ACTIVITIES

By the end of Year 3, existing and improved sensors will be field tested and new sensors will be developed and tested. In Year 4, analytics will be advanced for combined application of existing, improved, and new sensors. Additionally, the new sensor packages will be matured through field testing. Commercialization and outreach activities will also begin in Year 4. The technical activities are as follows:

1. Integrate and tune algorithms/analytics for combined application of existing, improved, and new sensors.
2. Conduct system integration and deployment tests, including field tests of new sensor packages.
3. Engage in commercialization and outreach activities for advanced analytics.

YEAR 4

MILESTONES

- Refine analytics for integrated application of sensors of different capabilities.
- Field test new sensor packages and analytics.

YEAR 5

ACTIVITIES

Year 5 activities will focus on finalizing development of planned sensors and analytics, reviewing performance, and setting directions for future development. The technical activities are as follows:

1. Conduct integrated field demonstrations with all types of sensors and analytics through complex applications or use cases, including resilience.
2. Review results, identify shortcomings, and develop future directions.
3. Engage in commercialization and outreach activities for advanced analytics.

YEAR 5

MILESTONES

- Demonstrate sensors of different capabilities and analytics in the field through complex use cases (for example, resilience).
- Identify gap analysis and future directions.

Monitoring for Critical Infrastructure Interdependencies

The nation's critical infrastructures do not operate in isolation; rather, they are closely coupled. The U.S. Department of Homeland Security defines 16 critical infrastructure sectors as energy; communications; water and wastewater systems; dams; chemical, transportation; financial services; information technology; nuclear reactors, materials and waste; food and agriculture; commercial facilities; chemical; critical manufacturing; government facilities; defense industrial base; healthcare and public health; and emergency services.[6] The electricity sector is the backbone of the nation's economy, with all 16 critical infrastructure sectors dependent on electricity for their operations. The interdependencies of these infrastructures exhibit spatial, temporal, operational, and organizational characteristics. For example, the tight coupling between critical infrastructures can depend on their geography, simultaneously directly affecting or influencing their operations by location and inducing wide-area cascading failures.[7]

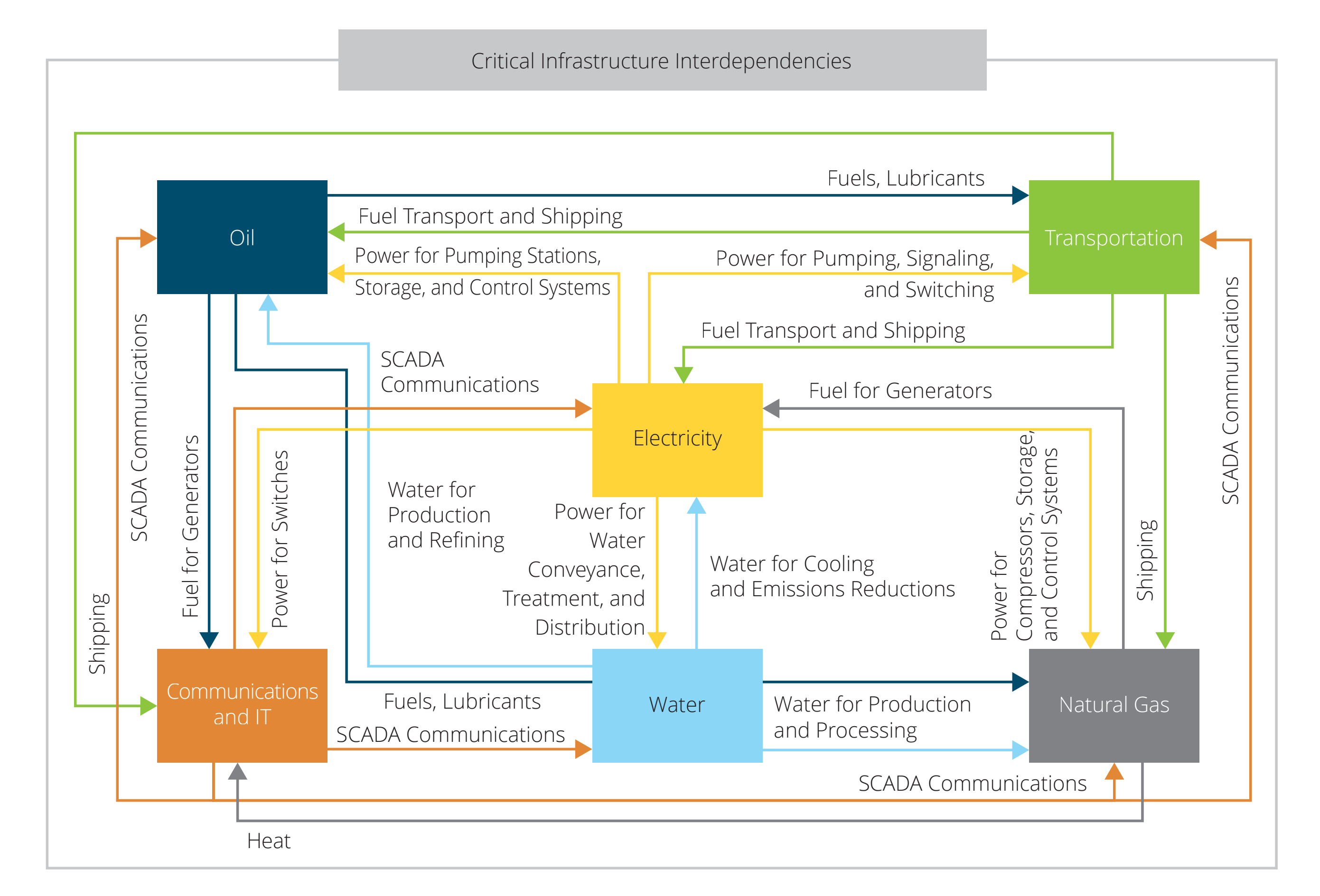
A recent example of these interdependencies was evidenced in Puerto Rico after Hurricane Maria. The hurricane severely damaged the region's power infrastructure, causing a cascading effect of collapsing coupled infrastructure systems, such as water and wastewater systems, transportation, communication networks, and fuel delivery. The cascading failures of these critical infrastructures caused billions of dollars in damages.

Figure 4 illustrates the interdependencies of the core critical infrastructures and the relationships among the systems associated in energy delivery. These multiple systems can be monitored and evaluated in isolation from other infrastructures or as an integrated system. The latter, as proposed herein, will offer critical information that can assist in planning for reliability and resiliency of the integrated system.

[6] "Critical Infrastructure Sectors," U.S. Department of Homeland Security, last published August 22, 2018, https://www.dhs.gov/critical-infrastructure-sectors.

[7] Steven M. Rinaldi, James P. Peerenboom, and Terrence K. Kelly, "Identifying, Understanding, and Analyzing Critical Infrastructure Interdependencies," *IEEE Control Systems Magazine* 21, no. 6 (2001): 11–25.

Figure 4. *Core critical infrastructure interdependencies. [Source: U.S. Department of Energy, Office of Energy Policy and Systems Analysis, Transforming the Nation's Electricity System: The Second Installment of the QER (Washington, DC: DOE, January 2017)].*



TECHNICAL GOAL AND OBJECTIVES

This effort aims to investigate, develop, and demonstrate technologies applicable to the real time monitoring of critical infrastructure interdependencies. Multiple benefits result from establishing a real-time system for the monitoring of critical infrastructure interdependencies. The technical goal and objectives of this effort include the following:

- Provide early warning of deteriorating system conditions for operators of interconnected infrastructures to take corrective action;
- Establish wide-area system visibility and improve resiliency and reliability of isolated and coupled systems;
- Develop and apply decentralized communication network and data analytics; and
- Develop visualization tools to enable interconnected system diagnostics by operators.

TECHNICAL CHALLENGES

Several challenges are associated with sensor development for infrastructure interdependencies monitoring:

- No specific correlation between sensing activities in the core critical infrastructure areas shown in Figure 4;
- Dissimilar SCADA systems, ranging from various protocols and interfaces to no clear means of achieving interoperability (or interchangeability) between various vendors' sensors and systems;
- Significant implementation barrier to information sharing; this occurs even within each infrastructure area, not solely across or throughout all infrastructures shown in Figure 4;
- Communications and computational challenges to integrate complex dynamic data from different sensors under different conditions at different locations;
- Operations and maintenance of such a system; and
- Inadequate communication links, bandwidth, scalability, latency, and reliability to determine the various applications.

TECHNICAL SCOPE

This technical area addresses monitoring of the interconnected critical infrastructure sectors and their interdependencies. In this context, the technical area looks at the large interplay between electricity (generation, transmission, and distribution) and other core infrastructures depicted in Figure 4. It specifically examines the roles that advanced sensors play in many/all of these domains.

Many parameters (including electrical, mechanical, chemical, etc.) can be measured to provide situational awareness about the interconnected system of critical infrastructures. The scope of this technical area encompasses the following:

- Develop low-cost, multi-parameter sensor agents[8] to provide detailed characterization of the state of the system at a particular location;
- Develop autonomous hardware/software agents and integrate them as sensors networks for deployment at different locations within a utility's service area to provide situational awareness for a particular utility system;
- Combine sensor networks for deployment to a much larger area covering multiple utilities (for example, water, communications, and electricity) to provide information about the state of interconnected critical infrastructures for early detection of faults to avoid cascading effects; and
- Perform application of the decentralized network approach, combined with data analytics and visualization tools, to provide multiple utilities with real-time information about the state of different systems for accelerating corrective actions.

[8] Within the context of this document, an "agent" is defined as: "a hardware or (more usually) software-based computational system that inhabits some complex dynamic environment, senses and acts autonomously in this environment, and by doing so realizes a set of goals or tasks for which it is designed."

[9] Emiliano Casalicchio and Emanuele Galli, "Metrics for Quantifying Interdependencies," in *Critical Infrastructure Protection II*, vol. 290, The International Federation for Information Processing Book Series, Boston: Springer (2008).

STATE OF CURRENT DEVELOPMENT

Over the years, researchers have developed different approaches to understand and analyze the interdependencies of the different critical infrastructure sectors. These approaches have been qualitative (for example, mathematical formalisms, hierarchical holographic modeling, and graph theory) and quantitative (engaging discrete simulation or agent-based modeling simulation[9]). In water-infrastructure systems, reliability and risk management are widely used for engineering and management. Considering the negative impact disruption of critical infrastructure has on our society, resiliency based approaches are also considered to study the interdependencies across sectors.[10]

In the electricity sector, recent efforts have focused on applications of PMU in WAMS for wide area monitoring and visualization of the power grid. WAMS provide much better awareness of system states across a large portion of the transmission system in real time. Besides improved state estimation and power-flow analysis, the operation and control functionalities that can be realized by WAMS are expanding, especially in real-time power-flow control and protection areas. In addition, interest is increasing in applying PMUs in the distribution system (for example, MicroPMU) for similar applications, as in transmission systems as well as applications specific to distribution systems.

The NASPI network (NASPInet), an effort by the North American SynchroPhasor Initiative (NASPI), allows synchrophasors from different utilities to be time-aligned (or "synchronized") and combined to provide a precise, comprehensive view of the entire interconnection. The NASPInet effort has also set a baseline to enable a redundant communication network for utilities sharing synchrophasors data. This effort can be leveraged and expanded to different critical infrastructure sectors, such as water, communications, oil and gas, and transportation.

The DOE-OE Advanced Modeling Grid Research Program has modeling projects related to the study of monitoring critical infrastructure interdependencies, with the aim of developing dynamic models and controls of the electrical grid and natural gas transmission systems. Similarly, the DOE OE North American Resilience Modeling initiative aims to study the robustness, adaptability, and recovery strategies of the interconnected electrical systems in an effort to increase resiliency and identify future investments. Within this scope, the models intend to predict responses to systems disruption and outage prediction, analyze risks, improve resource planning, and assess the impact of interdependencies across multiple infrastructure systems. This technical area develops relevant sensing techniques, measurements, and analytics that complement and refine the modeling efforts.

The ability of the nation to effectively respond to and facilitate restoration of energy systems during disasters relies on the ability of local, state, and federal government agencies and private sector electricity and fuel providers to have access to timely, accurate, and actionable information about the status and potential impacts of energy sector disruptions. This information is provided by DOE via its Environment for Analysis of Geo-Located Energy Information (EAGLE-I) system. This real-time situational awareness tool for the nation's energy infrastructure provides capabilities for monitoring energy infrastructure assets, reporting energy outages, displaying potential threats to energy infrastructure, and coordinating emergency response and recovery. Currently, EAGLE-I is utilized as a service to other federal, state, and local agencies and departments, as well as first responders, in accordance with DOE's Emergency Support Function #12 mission.

[10] Sangmin Shin, et al., "A Systematic Review of Quantitative Resilience Measures for Water Infrastructure Systems," *Water* 10, no. 2 (2018).

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DOE ROLE

Monitoring critical infrastructure interdependencies involves agreement among multiple public and private partners to use existing sensing technologies, incorporate new sensing technologies in their areas, and share systems operations data among organizations. These utilities share their infrastructure across different critical infrastructure sectors. For example, telecommunications networks utilize electricity T&D systems and gas pipelines to support their infrastructure. Applying the same approach, sensors and data networks can be established and deployed to monitor critical infrastructure interdependencies. While federal entities—including DOE, the National Science Foundation, and the Defense Advanced Research Projects Agency—have been involved with sensor R&D for decades, these efforts have often resulted in sensors and systems tailored to a specific application. DOE and its national laboratories can expand research initiatives to develop new sensors, data networks, and data-sharing mechanisms for real-time monitoring of critical infrastructure interdependencies that directly support the North American Resilience Modeling effort. Such cross disciplinary initiatives will allow multiple federal agencies to engage and coordinate with multiple stakeholders to develop and implement technology, cybersecurity practices, and policies compliant with critical infrastructure protection.

TECHNICAL ACTIVITY DESCRIPTIONS

R&D activities are organized as follows: (1) to provide early warning of deteriorating system conditions for operators of interconnected infrastructures to take corrective action, (2) to establish wide-area system visibility and improve resiliency and reliability of isolated and coupled systems, (3) to develop and apply the decentralized communication network and data analytics, and (4) to develop visualization tools to enable interconnected system diagnostics by operators. Detailed descriptions are provided below.

YEAR 1

ACTIVITIES

Provide early warning of deteriorating system conditions for operators of interconnected infrastructures to take corrective action:

1. Determine sensing and measurement requirements, hardware/software agents, and data collection approaches. Incorporate project concepts into existing sensor systems (for example, optical potential transformer/current transformer [PT/CT], dissolved gas, and PMUs) and related sensor focused R&D for demonstration of integration.
2. Develop a plan and strategy for sensors deployment and data analytics, concentrator, storage, and display, as well as user interface.
3. Design and develop communication architectures to monitor single infrastructure (for example, energy systems) and interdependencies of the critical infrastructures (for example, energy, water, communications, oil and gas, etc.).

YEAR 1

MILESTONES

- Assess key monitoring points for the interconnected critical infrastructure interdependencies within a region and scaling up to a larger area (for example, within a city, to multiple cities, to statewide).
- Review and evaluate sensing requirements, including, but not limited to, PMUs, PT/CT, and all sensing parameters related to the extended grid state defined by GMLC initiatives.
- Design communication architecture and data analytics.

YEAR 2

ACTIVITIES

Establish wide-area system visibility and improve resiliency and reliability of single infrastructure sector and interconnected infrastructures:

1. Incorporate multi-measurement domain sensors operating in a collaborative manner.
2. Design a scalable sensor platform framework for integration of "traditional" and non traditional sensor measurement parameters consistent with utility performance and security requirements. Minimize operational impact on the utility during installation. Develop coordinated data architecture for secure software/data integration. Develop (nearly) plug-and-play, low-cost sensors in an operational environment (substations, network communications).
3. Demonstrate cybersecure Internet of Things (IoT) sensors, mobile and stationary, deployed in an operating utility network with seamless data integration and data management. Combine improved sensing capabilities with cyber-responsiveness and collaborative sensing capabilities to support monitoring of critical infrastructure operations and overall cybersecurity, while providing the information necessary for a robust, geographically and temporally scalable, local/regional/national situational awareness.

YEAR 2

MILESTONES

- Engage stakeholders to validate sensing needs and existing communication infrastructure.
- Design scalable, plug-and-play hardware/software sensor agents compliant with utilities' performance and security requirements.
- Conduct laboratory and field demonstrations of cybersecure IoT sensor agents.
- Determine communication architecture requirements to establish a collaborative localized sensor network.

YEARS 3 & 4

ACTIVITIES

Develop and apply the decentralized communication network and data analytics:

1. Apply the distributed ledger, decentralized network approach to provide a unique solution in the form of "black box" capabilities with a distributed information exchange ledger. An example application is to have the blockchain associated with networked sensors retain information from all information exchanges being transmitted in the network in case of disrupted or severed substation connectivity with the SCADA historian. This provides system information—independent of the SCADA historian—that can be used locally (or combined with similar clustered information sets from other blockchain-equipped networks) to determine the system state from stored (distributed ledger "accounting") sensor measurements.
2. Develop wide-area collaborative sensor network architectures that will provide partial and aggregate system state with fusion of temporal, spatial, and multi parameter data to improve situational awareness. Enable real-time, post disturbance analysis capabilities to provide information to establish the necessary automatic controls for a self-healing system. Employ prioritization of data schemes during an event to determine the state of local systems and cascading effects, if any.

YEAR 3

MILESTONES

- Report, with full details, on the requirements for secure data exchange between critical infrastructure interconnected sectors.
- Design and develop a decentralized network approach with a distributed data information exchange ledger between multiple participants.

YEAR 4

MILESTONES

- Perform laboratory-scale demonstration and deploy in a utility service area.
- Conduct feasibility studies on scalability of such networks and optimization.
- Develop data analytics tools for collaborative sensor networks.

YEAR 5

ACTIVITIES

Develop visualization tools to enable operators to perform interconnected system diagnostics:

1. R&D of tools capable of organizing data generated from different monitoring points at the interconnected critical infrastructure sectors. These tools must support data sources ranging from short bursts at rates of several kilohertz to one-off, manual entry data. Research efforts must identify applicable schemes to successfully manage and archive the wide range of existing and future data sources, as well as develop advanced applications for use by grid operators.

Demonstrate the collaborative sensor networks technology within the lab, within the region, and nationwide.

YEAR 5

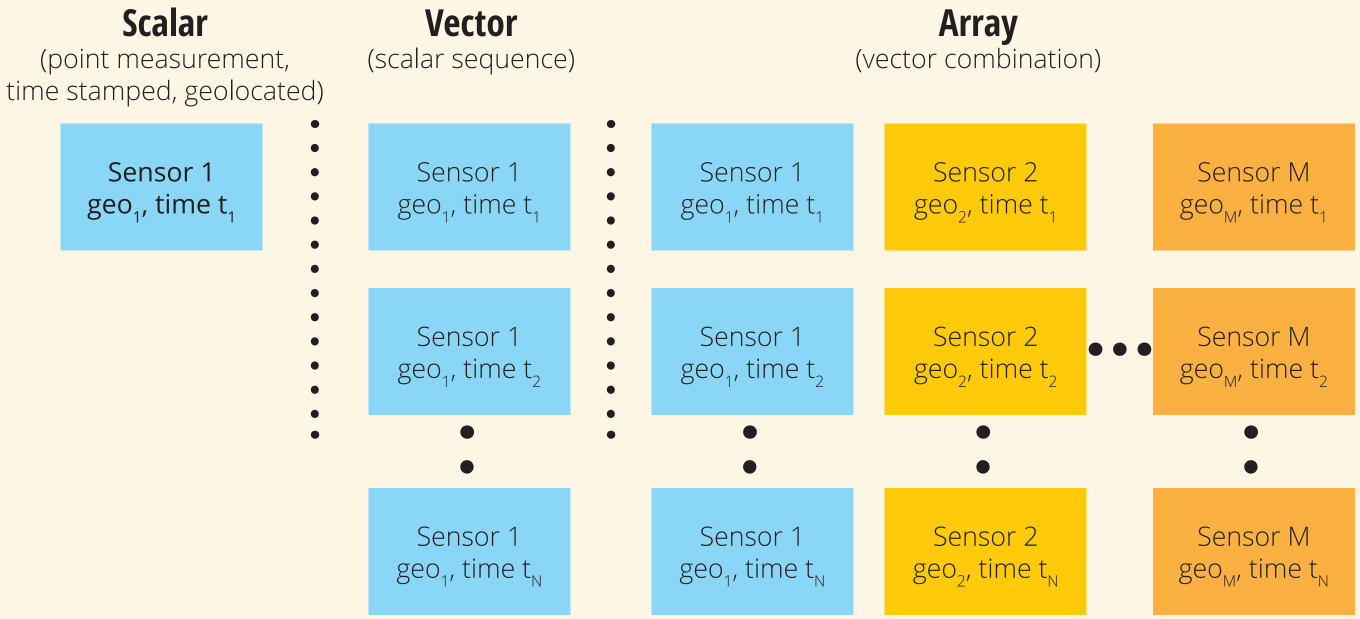
MILESTONES

- Develop a visualization tool integrating all sensing parameters and sensor networks that will provide situational awareness.
- Demonstrate collaborative sensor networks technology in utility service areas.
- Produce final report and documentation of the collaborative sensor networks technology, metrics, and implementation.

Collaborative, Cyberaware Sensors

Sets of discrete (scalar) measurements from individual sensors may be combined to form vector fields that, when combined with other vectors, may form information arrays, upon which parameter waves may be constructed and analyzed. As more vector fields are correlated, a more refined picture of parameter waves may be formed, as illustrated in Figure 5.

Figure 5. *From discrete, point measurements to vectors of measurements from a single sensor to an array of measurement vectors formed from spatially diverse sensors.*



The fidelity of such a parameter wave moving through an operational electrical grid is based on the measurements taken and mathematical, analytical processes applied. The convergence of advancements in microcontrollers, software tools, and “sensors-on-the-edge” to perform local signal processing capabilities that include IP or similar network addressing and responding to network-centric cybersecurity queries provides the framework upon which such collaborative, cyberaware sensors may be built, and, depending on implementation, capable of performing varying levels of responsiveness.

Development and application of the combination of multiple-parameter, varying measurement-resolution, IP-addressable, cyberaware sensors with flexibility to direct their measurement capabilities toward specific parameters of interest in grid applications is the focus of this technical area.

TECHNICAL GOAL AND OBJECTIVES

A secure and resilient electric grid that protects its assets and critical functions and can withstand and recover rapidly from disruptions is a national priority. Protecting against and mitigating cyber and physical risks while improving the electric grid’s operational resiliency require continued collaboration between public and private-sector partners.

Specifically, the goal of this technical area is to combine use of multiple-parameter, varying-measurement-resolution, IP-addressable, cyberaware sensors for monitoring the extended grid state (EGS). This suite of sensors for physical, electrical, and ambient-condition parameters will augment existing SCADA while also providing the cyber state of network communication information to a utility’s (classic) IT/OT system. The companion goal is to distinguish between grid disruption(s) caused by a cyber-attack and “traditional” means (for example, weather or humans) by incorporating an AI engine that ingests sensor measurements and information and allows for a correlation between cyber status and grid operations to identify the network/geo-positioning location of events such as an operational anomaly. In the broader sense, complex questions associated with parameter waves interacting with local, regional, national-scale, interconnected grid operations involving connected utility systems are inherently easier to answer with collaborative, multiple-parameter sensors.

TECHNICAL CHALLENGES

While sensor protocol standardization—or harmonization—has been a topic of considerable activity for over a decade,[11,12] and the focus of the European Union Inspire program,[13,14,15,16,17] what is being presented in this document is development of collaborating sensors. Similarly, New Vistas[18] stated:

> *The problems of the next decade are to identify the relevant databases, to devise methods for collecting, analyzing, and correlating them, and to construct the needed communication and distribution architectures.*

The extensive work performed by the Open Geospatial Consortium and others in sensor standardization and/or sensor protocol harmonization through efforts such as IEEE 1451, SensorWeb, SensorML, Semantic Sensor Networks, IFTTT, and Common Data Models[19] attempts to address the more general issue of sensor interoperability. The need for a clear, consistent sensor "language" will accelerate the collaboration of sensors.

A significant technological gap exists between discrete single parameter sensors and devices constructed with a multisensory suite. A clear technical challenge in the use of the latter class of sensors is the need for software within the device and at the network (or above) layer to provide the collaborative operation described previously. The capability of providing on-demand sensing of a single parameter and/or multiple-parameter sensing providing the measured values in a readily usable protocol must be addressed.

Other operational concerns, such as deployment within an electrical grid of such envisioned sensors, lead to the challenge of defining varying-scale communications requirements that need to transport information from one sensor to another in various networking topologies. A clear examination of such requirements is needed.

Guidance for issues to be further examined in collaborative sensors may be found in similar studies conducted for wireless sensor networks.[20]

[11] Kang Lee, "Sensor Standards Harmonization-Path to Achieving Sensor Interoperability," 2007 IEEE Autotestcon 71 (2007): 381–388.

[12] Kang Lee, "Sensor Standards Harmonization," Sensors Expo Chicago (June 2006).

[13] Inspire (2014). "Draft Guidelines for the Use of Observations and Measurements and Sensor Web Enablement-related Standards in Inspire Annex ii and iii Data Specification Development." Inspire Guidelines.

[14] INSPIRE, *Guidelines for the Use of Observations and Measurements and Sensor Web Enablement-related Standards in Inspire* (INSPIRE Maintenance and Implementation Group, December 2016), https://inspire.ec.europa.eu/id/document/tg/d2.9-o%26m-swe.

[15] "INSPIRE Principles," INSPIRE, accessed October 10, 2016, http://inspire.ec.europa.eu/inspire-principles/9.

[16] "Data Specifications," INSPIRE, accessed August 5, 2016, http://inspire.ec.europa.eu/index.cfm/pageid/2.

[17] "INSPIRE Principles," INSPIRE, accessed October 11, 2016, http://inspire.ec.europa.eu/inspire-principles/9.

[18] U.S. Air Force (USAF), *New World Vistas: Air and Space Power for the 21st Century*, Chapter 3 (USAF, December 1995), http://www.au.af.mil/au/awc/awcgate/vistas/vistas.htm).

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TECHNICAL SCOPE

The operational goals and envisioned scenarios associated with collaborative, cyberaware sensors can be realized through a coordinated development process. Rather than an entirely sequential research process, it is envisioned that core technologies can be rapidly transitioned over the five year period to useful application by the private sector. A proposed development scheme involves the following areas:

- **Development of cyber-physical sensors (hardware [HW])**. Leverage ongoing private, public, and academic sector development of IoT sensors to measure parameters—such as temperature, irradiance, chemicals, and radio frequency—that have been identified as needed for EGS information and modeling. These sensors must be agile in performance; for example, they should allow variability in the frequency of data acquisition and volume needed for optimized grid operations and enhanced cyber-physical security.
- **Development of a cyber sensor (software [SW]) for the HW as a cyber defense**. Develop HW/SW agent based on a micro-computational IoT platform programmed to perform (a) blockchain distributed ledger, and (b) Internet Control Message Protocol/Simple Network Management Protocol response to IT security applications and queries with integration of physical sensors. Implement and test SW for single HW solutions.
- **Develop collaborative sensor controlling applications to achieve high-resolution sensing with aggregated measurements**. Use techniques and mathematics similar to those found in stellar interferometry to achieve high-resolution parameter sensing using correlation-based collaborative sensing. Compare measurement resolution for varying collaborative sensor configurations and parameter measurement domains.
- **Develop a selectable platform to combine various measurements to achieve a more complex information set**. Determine a cross-listing of measurement parameters that, when combined, can address a more complex grid operations question. Upon automation, a controlling AI/machine learning engine (or application) can select the parameters to be measured and then direct a set of collaborative, multi-parameter-capable sensors to tailor their measurements. Such measurements are then combined (geolocation, temporal location, parameter being measured) and processed.
- **Develop analytics on SW and HW data to produce real-time alerting**. The proliferation of sensors enables application of new, more data-intensive approaches monitoring normal behavior, detecting and locating anomalies, and evaluating the analytics. A number of correlations are expected to be present both with and across physical and IT data. These correlations will be discovered and leveraged to produce real-time operational alerts using both unsupervised training (for example, probabilistic modeling and outlier detection) and supervised training (for example, classification of synthetically generated data degradation attacks).
- **Sensors as botnets for SCADA**. Develop a communication system for the intercommunication of multiple, reconfigurable sensors capable of directing their sensing capabilities onto a single parameter of interest, sensors as botnets. Predominant communication technology in distribution automation and substation automation is distributed network protocol 3. Develop a mechanism with a hierarchical network abstraction to detect correlations in physical and cyber aspects of the networked sensor data from distribution-level electric grid network. This data will be utilized to identify various attacks, including sensor spoofing and malware. Authentication of transactions that occur in the distribution-level grid enable trusted communications. Blockchain provides a unique mechanism for authenticating transactions or decisions made by autonomous grid devices. The proposed concept of "sensors as botnets" will combine blockchain for communication to the unified threat management/intrusion detector sensor/intrusion prevention sensor. Implement and test single and multiple SW/HW simultaneously.

- **Develop blockchain (distributed ledger) protocols**. Implement the technology in microcontrollers within sensor node using local cryptography. Document the time-series ledger of transactions using blockchain to authenticate the decision-making process in the hierarchical sensor network.
- **Integration and testing on a software defined grid**. Testing of the devices and systems described above will be "subjected" to cybersecurity scrutiny within a software-defined grid/real-time power distribution system. Execute a suite of cybersecurity and grid operation tests (SCADA and IT security) on a network of developed devices.

STATUS OF CURRENT DEVELOPMENT

Many advancements continue in product design and software application development associated with the IoT and Industrial Internet of Things (IIoT) areas. Groups such

as the Industrial Internet Consortium ([IIC], https://www.iiconsortium.org) and IEEE (http://iot.ieee.org) are working to define guidance for members and member companies on IoT/IIoT device development. The aforementioned sensor standardization/harmonization activities are in varying stages of activity. Market analysts highlight the confusion within IoT developments[21] that has led to minimal and inconsistent cybersecurity activities and developments.

While sensor collaboration, or the companion area of sensor fusion, is primarily an area of research in academic circles,[22] it has broad application areas. No discernible research related to cybersecurity of collaborative sensors—let alone cyberaware and responsive sensors—is underway within the private, public, or academic sectors.

Numerous development platforms for AI software are available.[23] Similarly, machine learning tools and AI coding languages are maturing, providing stable code bases.[24] While the use of AI for cybersecurity is of considerable interest,[25] a thorough examination of cybersecurity vulnerabilities within developed AI applications is lacking.[26]

DOE ROLE

The DOE role in this area is to develop designs and implementation strategies for collaborative, cybersecure, and cyberaware sensors and systems. It is anticipated that DOE R&D would result in validated devices and systems, which would then be transitioned to practice with the private sector commercializing the design. By providing guidance on market needs, DOE will help orient private sector R&D investments in the commercialization of developed systems. In this role, DOE should focus R&D efforts specifically on electric grid needs and provide demonstration sites/integration platforms with operational utilities.

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TECHNICAL ACTIVITY DESCRIPTIONS

1. Develop and validate the achievement of high-resolution, high-fidelity sensing using low/modest resolution, yet collaborative, sensors. Develop in-network, mathematical tool sets for distributed applications that allow segmentation of sensing performance without relying on a centralized database or computer, thereby forming the sensing + computational equivalent to an electrical microgrid that allows for continued grid operation in the presence of varying types of electrical grid outages.
2. Develop a decentralized data structure to accommodate simple and complex, structured and unstructured, and raw and processed measurements for deployment on low cost microcontrollers with limited computational and storage capabilities.
3. Develop a repository of processing and analytics engines for various workloads and information sets. Identify AI trends in software development applicable to sensor collaboration and performing mathematics in distributed, decentralized HW.
4. Develop software tools to allow ease of code integration and migration onto resource-limited HW, yet achieve distributed edge analytics, aspects of decentralized machine learning (specifically, sensor network tuning), and historical analysis.
5. Develop a data management scheme to achieve efficient integration of multiple sources of the sensor's information to enhance damage assessment. Validate robust data analytics integrated with network modeling and reconstruction techniques methods, which provide viable damage assessment results when the data quality (for example, erroneous data or missing data) is largely impacted by natural disasters.

MILESTONES

Two to three demonstrations of varying TRL devices will progress from laboratory-based validations to field validations, demonstrating increased grid performance assets. Years 1 to 3 will concentrate on lab demonstrations. Demonstrations in Years 3 to 5 will concentrate on field testing of sensor platforms with utility partner(s). Specific parameter waves will be used for higher-level, proof of-principle tests. Scenarios associated with the T&D sensor development effort are relevant in this cross-disciplinary area.

- **Scenario 1: Nominal Operation** – Increase observability of wide-area grid conditions, operation efficiency, and utilization of a plethora of assets, resulting in lower operational costs and greater customer satisfaction.
- **Scenario 2: Localized Outage** – Improve response time and restoration time and reduce total damage or losses of equipment operation, resulting in fewer total economic and other losses.
- **Scenario 3: Major (Catastrophic) Event and/or Outage** – Increase situational awareness of scope and details of outages and damages and reduce restoration and recovery times, resulting in fewer total economic and other losses (including, if applicable, human losses).

Sensor Valuation

Valid and accurate valuation and risk/uncertainty analyses are among the defining factors needed by industry to adopt emerging sensing and measurement technology in the power grid. Technology valuation usually involves extensive analysis and quantitative modeling of technical and economic risks and benefits. However, major barriers to promotion of new sensing and measurement technology exist. They include the lack of comprehensive capabilities and sophisticated tools to conduct valid technology valuation and maximize the value of the technology in terms of high-value use cases. In addition, regulatory requirements and activity can significantly impact technology adoption and deployment and make the analysis even more complicated. Regulatory incentives tend to encourage adoption of new technologies, while regulation requirements and restrictions can induce extra costs and delays and even discourage adoption of the new technology.

TECHNICAL GOAL AND OBJECTIVE

The purpose of the sensor valuation crosscut area is to support the adoption of sensing and measurement technologies in the power grid. The objective is to promote capabilities and methodologies for improved valuation assessment, as well as sensor selection and allocation tools for maximizing desired metrics. This technical area will support the establishment of expertise and capabilities both internal and external to DOE's national laboratory system to facilitate technology optimization valuation, regulatory analysis, and risk evaluation of sensor deployment projects. Relevant methods, tools, research efforts, and best practices will be identified and categorized with up-to-date contact information, and the results will be made accessible for industry stakeholders.

TECHNICAL CHALLENGES

A key capability gap related to ubiquitous deployment of advanced sensing and measurement technology lies in the challenges associated with providing a clear valuation of the new technology. This includes being able to delineate the advantages that can be derived from deployment of a specific technology or even a full network solution. Well-defined valuation metrics and analysis approaches are key to accomplishing wide-scale adoption of new sensor and measurement technology. The significant importance of proper valuation to the power industry is recognized across DOE and the national laboratory system and is evident from the many ongoing valuation efforts under the GMLC. Valuation is relevant for all aspects of sensor and measurement technology application, including devices, architecture/network design, communications, analytical methods, advanced data management approaches and techniques, reliability and resiliency, deployment, maintenance and support, and regulatory requirements.

Successful valuation usually involves extensive analysis and quantitative modeling of the technical and economic risks and benefits of the technology. However, significant challenges exist in determining accurate equipment and deployment cost estimates for new or even existing technologies, as they may not be readily accessible. Also, these costs may be different for retrofits as compared to new installations. The costs and benefits due to some of the factors, such as sensor reliability and resiliency, are even more difficult to quantify, but they could have a significant impact on the ability to clearly demonstrate the value of advanced technology deployment. Furthermore, value proposition hinges heavily on end-use applications and business models considered. There is not a clear blueprint as to which utility applications should be assessed, what the metrics of interest are to various stakeholders, and under what business and local policies the evaluations should be performed. For technology adoption, businesses may also want to ascertain the temporal evolution of values (that is, short term versus long term) as the grid and policies evolve. Another challenge is to estimate the risks due to uncertainties, a vital aspect of the value proposition discussion. In current practice, the lack of comprehensive capabilities and sophisticated tools to conduct valid valuation analysis is a major barrier to promotion of a new technology. In addition, regulation and associated uncertainties may affect the valuation process of the technology for adoption and deployment, making the analysis more complicated. Regulatory policies can be greatly supported through the availability of clear valuation methods and tools that can quantify values at various stages of sensor technology adoption and grid evolution.

TECHNICAL SCOPE

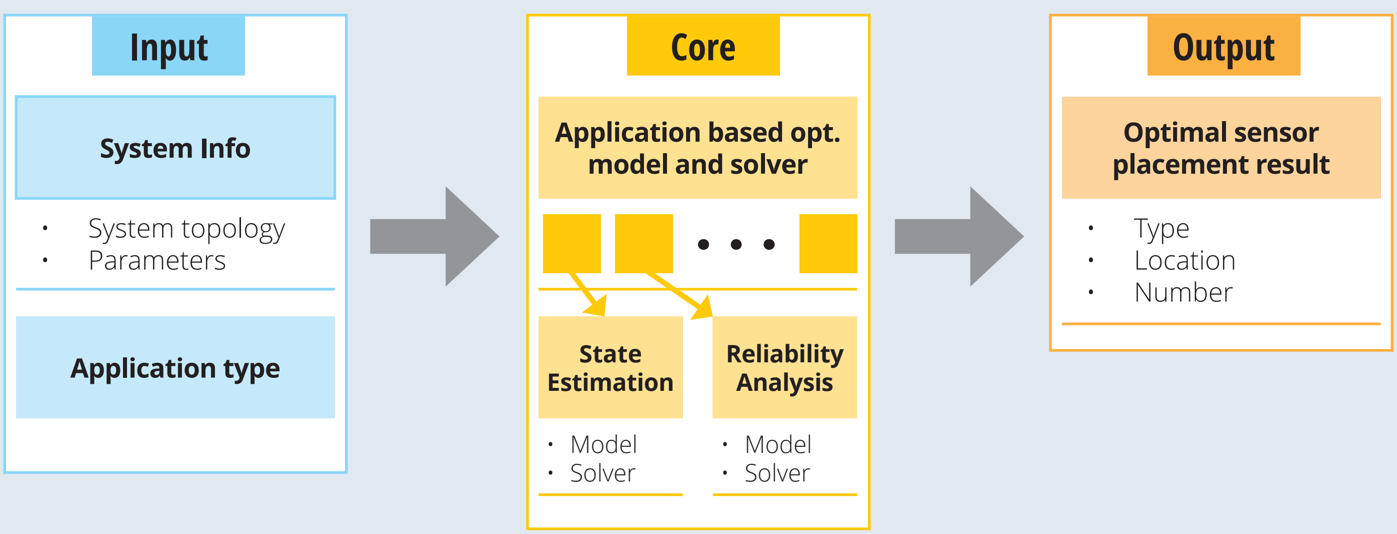
The scope of the sensor valuation crosscut area includes assessing and developing metrics and analytical approaches for the valuation of advanced sensor technologies and analytics under the core areas of the MYPP. The scope will be addressed through standardized testing approaches; by improving the understanding of full sensing and measurement costs through industry surveys; and by maintaining a database with information about costs, including details of installation, operation and maintenance, etc. Additionally, this will include developing standardized and well-accepted methods for the valuation of innovative technologies. These methods may include grid modeling in conjunction with sensor placement and allocation tools applied to high value use cases for which different sensing and measurement technologies and approaches can be compared on an equal basis. Consideration of evolving grid scenarios and related uncertainties will help in characterizing both the short-term and long-term values, as well as the risks associated with deployment. Such methods and tools can address sensor reliability and resiliency, in addition to performance and cost, to provide a convincing, relative valuation for benchmarking. Reliability or resiliency can be difficult to estimate and quantitatively represent, but they are critically important for the acceptance and deployment of advanced sensor and measurement technology.

STATUS OF CURRENT DEVELOPMENT

The GMLC Sensing and Measurement Strategy project (#1.2.5) developed two reports (EGS framework and sensor technology roadmap) that identify and define the EGS of the modern grid and the sensing and measurement technology requirements needed for the modern grid.

The SPOT tool developed under the GMLC Sensing and Measurement Strategy project (#1.2.5) and depicted in Figure 6 is an example of a sensor valuation tool. It is an application-based tool to optimize the placement (type, number, and location) of sensors subjected to application specific objectives (for example, reliability improvement) and constraints (for example, physical placement and cost/budget limitations). The effort of developing a sensor placement tool was identified as a key need of the GMI's sensing and measurement research area.

Figure 6. *Architecture and current state of the Sensor Placement Optimization Tool (SPOT).*



Two distribution system applications and optimization methods have been developed for SPOT, namely the DSE and recloser placement application modules. For the DSE module, it can handle a three-phase system with asymmetrical topology and unbalanced loads. The sensor placement problem is addressed with improved DSE accuracy and solver algorithms. For the recloser placement (and system reconfiguration) module, a distribution system reliability analysis program has been developed, which also considers integration of DERs and microgrids. Both modules have been tested in several different sized IEEE distribution test systems and an actual utility distribution feeder. Results show that the sensor placement objectives can be better achieved with optimal sensor locations suggested by SPOT. Furthermore, an interface between SPOT and the commercial distribution system analysis package of CYMDIST has been developed, allowing for the export of utility distribution system data files from CYMDIST to build system models for sensor placement studies in SPOT. The value proposition portion of SPOT leverages the Interruption Cost Estimator, or ICE program, developed by Lawrence Berkeley National Laboratory. Future work for this area of the MYPP will leverage and significantly expand on SPOT capabilities developed to date, focus on broadening the tool as an open-source program, and transition various functions to vendors for supporting use of the tool beyond DOE.

Other existing projects within GMI, such as GMLC projects #1.2.4 and #1.4.29, are also related to the topic of this initiative, and findings and results of those projects are relevant for this area.

Projects that look into utilizing sensor data for advanced use cases for the future, beyond what is listed in the GMLC *Sensing & Measurement Technology Roadmap*, will also become important to this technical area as the system evolves and DER penetration increases. Other DOE initiatives, including the OE sensor project portfolio, with collaborative efforts across academia, national laboratories, and industry will also be leveraged to inform the valuation approach and factors.

DOE ROLE

DOE and its national laboratories are in a unique position to provide support to the utility industry in valuing sensor technology and its peripheral technology (for example, communications and data analytics) needed for improving grid operations, planning, reliability, and resiliency. This support can lead to development of methodologies and tools for technology valuation. Through this support—including funding of projects, development and implementation of testbeds, and interaction with industry stakeholders—the general industry community will obtain clear valuation methods and tools for assessing sensor technology allocation. This will accelerate use of advanced sensors for the modern grid, as well as ensure the security of both the grid and the deployed sensor technology.

In addition, DOE and its national laboratories are also in a unique position to provide input to both standards and regulatory organizations. Standards, such as those of IEEE and IEC, are important to ensure standardization for new technology and methods. Regulatory activity can play a leveraging role that could significantly affect technology adoption and deployment; providing regulatory authorities with valid tools for valuation can assist in intelligent policymaking, leading to accelerated deployment of new sensing and measurement technology.

TECHNICAL ACTIVITY DESCRIPTIONS

The scope of activities will include the following:

- Identify and categorize relevant capabilities, tools, research efforts, and best practices for technology valuation with up-to-date contact information, and make these results accessible to stakeholders;
- Promote the development of methods/tools that can integrate grid modeling with sensor placement and allocation capabilities to address valuation of sensor technology for grid reliability and resiliency;
- Conduct detailed value proposition analysis that considers multiple value streams for different stakeholders, various sensing technologies to ensure grid and resource visibility, and a Pareto front of solutions that varies in costs and benefits; and
- Analyze the impact of varying levels of sensing systems' performance on grid economics, reliability, and resiliency.

More specifically, the following tasks will be pursued each year:

YEAR 1

ACTIVITIES

- Review existing tools and valuation methods for assessing sensing and measurement technology and its allocation on the grid, including the SPOT tool and other tools internal and external to DOE. The review must provide a comprehensive understanding of factors, end-use applications, optimization methods, and uncertainty modeling that will be important in assessing optimal allocation solutions. Studying the correlations and synergies across multiple types of sensors will also be a key piece for optimal allocation.
- Engage industry stakeholders, most specifically utilities, to identify their perspective and current state-of-the-art for identifying valuation needs and opportunities of sensor technology. This will include identifying the metrics, criteria, and methods they are using for valuing sensor technology and other grid-related technology.
- Begin developing quantitative metrics for valuation of the desired grid attributes of sensor technology, peripheral technology, and performance requirements (for example, resiliency and reliability).
- Begin developing a framework—including optimization methods, database, etc.—for use cases that are aligned with the core research areas of the MYPP and are identified by the GMLC Sensing & Measurement Strategy project. Other use cases will also be reviewed and considered through industry and other stakeholder engagement.

YEAR 1

MILESTONES

- Form an industry partnership group.
- Identify a preliminary list of use cases in collaboration with MYPP core areas.

YEAR 2

ACTIVITIES

- Identify key opportunities for development of new valuation methods and tools beyond SPOT. Identify both model-driven and data-driven methods that can account for short term and long-term system needs.
- Work with core areas to prioritize relevant use cases and identify at least one in each area to be pursued during Year 2.
- Develop a report on valuation metrics and optimization tools available in terms of the state-of-the-art as a reference for this crosscut area.
- Initiate the process of developing an open-source version of the SPOT tool.
- Begin interfacing with technical standards development organizations around the subject of valuation tools for sensor and measurement technology.

YEAR 2

MILESTONES

- Complete a report on the “state-of-the-art” in valuation metrics and optimization tools.
- Hold an industry meeting to discuss use cases, existing metrics, tool sets, and gaps.
- Complete a report on identified needs for an open-source version of the existing SPOT tool.

YEAR 3

ACTIVITIES

- Identify standardized “use cases” and apply tools developed for prioritized use cases within each research thrust.
- Identify real-world “use cases” in collaboration with industry partners and identify T&D systems where tools can be applied and validated in subsequent years.
- Complete an initial rollout of the open-source SPOT tool with limited functionality.
- Pursue development of new valuation metrics, methods, and tools to address gaps identified in the first two years of this crosscutting effort.
- Initiate development of a project authorization request (PAR) with technical standard organizations around the subject of valuation tools under development.

YEAR 3

MILESTONES

- Create a list of prioritized real-world use cases in collaboration with industry.
- Develop online availability of the SPOT tool for industry partners.
- Initiate development of a PAR with technical and standards development organizations.

YEAR 4

ACTIVITIES

- Develop a report based on the benchmarking of SPOT and related tools on standardized use cases.
- Apply tools to the identified real-world "use cases" in collaboration with industry partners.
- Expand capability of the open-source SPOT tool and work with industry partners to understand requirements for integration with their existing tools.
- Integrate new valuation methods and tools into SPOT and related optimization toolkits.

YEAR 4

MILESTONES

- Complete a report on SPOT and related tools benchmarked to standard use cases for each area.
- Complete an upgraded version of SPOT and related tools and provide availability via the internet.
- Hold a meeting with industry to understand commercial packages that need to be interfaced with SPOT.

YEAR 5

ACTIVITIES

- Develop a report based on sensor technology valuation tools applied to identified, real world "use cases" in collaboration with industry partners.
- Further expand the capability of the open-source SPOT tool and collaborate with industry partners to develop required interfaces for commercial packages.
- Develop a consolidated report that describes overall metrics, methods, and tool development over the course of the project and identifies areas for further development through future programs.

YEAR 5

MILESTONES

- Complete a report on the application of SPOT and related tools to real-world use cases for each area.
- Complete a final version of the open-source toolkit.
- Complete a consolidated report describing improved metrics and tools.
- Demonstrate success in developed interfaces of SPOT and related tools with commercial packages.

America's security, economy, and sustained global leadership depend on a secure and resilient power grid. **The Office of Electricity** (OE) provides national leadership to ensure that the Nation's energy delivery system is secure, resilient and reliable. OE works to develop new technologies to improve the infrastructure that brings electricity into our homes, offices, and factories, and the federal and state electricity policies and programs that shape electricity system planning and market operations. Through a mix of technology and policy solutions and in partnership with the private and public sectors, OE will harness innovation for a stronger, more reliable North American energy system and a path forward to energy independence. Visit https://www.energy.gov/oe/office-electricity to learn more.

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