Sensing & Measurement
Grid Modernization Laboratory Consortium

Thomas J. King Jr.

Oak Ridge National Laboratory

Electricity Advisory Committee
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Industry Drivers and Context

- Nation's electric power system is going through a major transformation:
  - Major shift in generation mix - more non-firm renewable resources.
  - More connected devices: DG, electric vehicles, and energy storage.
  - Greater customer participation: transactive control, demand responsive loads/programs.
- The Grid transformation requires greater power system determination ("visibility") to manage assets ideally to:
  - Determine the real-time power system state of the power system
  - Forecast future states with enough accuracy and lead time to avert deviations from normal operations (i.e., self-heal for disturbances)
- Drives the need for better sensing and measurements of the grid:
  - Accurate measurements to characterize the power system state from generation, to transmission and distribution to finally end-loads.
  - At much higher fidelity and resolution than ever before.
- Meeting the objective of greater visibility requires advanced sensors, accurate measurements, communications, and data analytics. This effort addresses the development of low-cost sensors

Bottom line: You can not detect or control what you can not accurately "observe"

Sensing and Measurement Technical Area

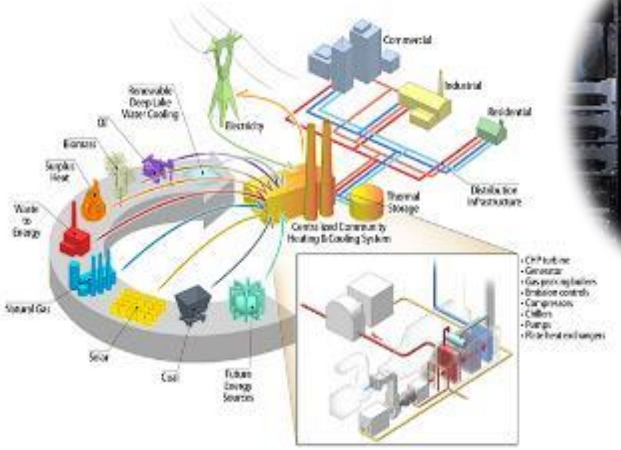
Objective: Sensor development and deployment strategies to provide complete grid system visibility for system resilience and predictive control

Expected Outcomes

- Advance and integrate novel, low-cost sensors to provide system visibility
- Develop real-time data management and data exchange frameworks that enable analytics to improve prediction and reduce uncertainty
- Develop next-generation sensors that are accurate through disturbances to enable closed-loop controls and improved system resilience

Federal Role

- Common approach across labs and industry test-beds for effective validation of emerging technologies
- Develop common interoperability and interconnection standards and test procedures for industry / vendor community



Grid Sensing & Measurement Activities & Technical Achievements

MYPP Activities	Technical Achievements by 2020
Improve Sensing for Buildings & End-users	Develop low cost sensors (under $10 per sensor) for enhanced controls of smart building loads and distributed energy resources to be "grid friendly" in provision of ancillary services such as regulation and spinning reserve while helping consumers understand benefits of energy options.
Enhance Sensing for Distribution System	Develop low cost sensors (under $100 per sensor) and ability to effectively deploy these technologies to operate in normal and off-normal operations Develop visualization techniques and tools for visibility strategy to help define sensor type, number, location, and data management. Optimize sensor allocation for up to 1,000 non-meter sensing points per feeder.
Enhance Sensing for the Bulk Power System: Develop Agile Prognostics and Diagnostics for Reliability & Asset Management	Develop advanced synchrophasor technology that is reliable during transient events as well as steady state measurement. Develop low cost sensors to monitor real-time condition of electric grid components. Using novel, innovative manufacturing concepts, develop low-cost sensors to monitor electric grid assets
Develop Data Analytic and Visualization Techniques	Provide real-time data management for the ultra-high velocities and volumes of grid data from T&D systems. Enable 100% visibility of generation, loads and system dynamics across the electric system through the development of visualization techniques and software tools Develop measurement and modeling techniques for estimating and forecasting renewable generation both for centralized and distributed generation for optimizing buildings, transmission, storage and distribution systems.
Demonstrate unified grid-communications network	Create a secure, scalable communication framework with a coherent IT-friendly architecture that serves as a backbone for information and data exchange between stakeholders and decision makers.

Sensing and Measurement Technical Area

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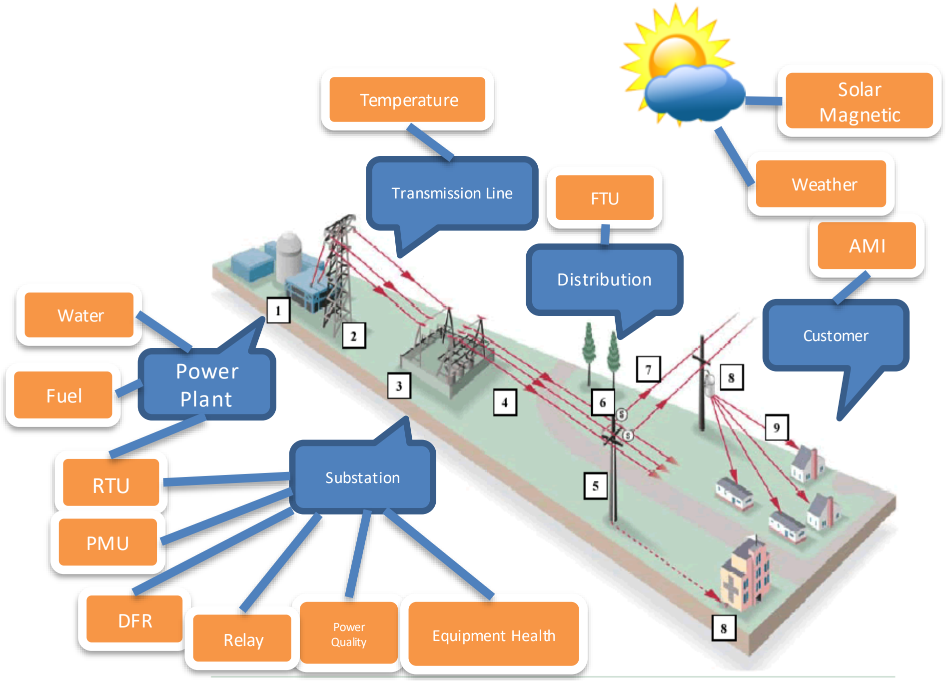
Objective: Sensor development and deployment strategies to provide complete grid system visibility for system resilience and predictive control

Key Projects and Accomplishments GMLC 2016

- Sensing & Measurement Strategy
  - Developed state of the art document, extended grid state, sensor placement tool and created roadmap providing a foundation for the multi-year plan
- Advanced Sensor Development
  - Advancement of 13 different technologies across end-use sector, transmission & distribution and asset monitoring; six invention disclosures and 5 patents, R&D100 award; 9 publications
  - Office of Nuclear Energy leveraging printed sensor work
- Integrated Multi Scale Data Analytics and Machine Learning for the Grid
  - Develop real-time data management and data exchange frameworks that enable analytics to improve prediction and reduce uncertainty; 12 conference journals, 3 technical reports and 2 patents filed on topology detection and event analytics



Modified from Duke Energy
https://www.progress-energy.com/florida/home/safety-information/storm-safety-tips/restoration.page?

Sensing & Measurement Strategy
Approach

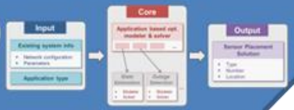
Sensor Roadmap & Tool

Extended Grid States

- Convergent Network States
- Ambient State
- Electrical State
- Building State
- Component State
- Topological State

✓ Low-Cost Sensors
✓ Communications
✓ Data Management & Analytics

✓ Sensor Placement Optimization Tool (SPOT)



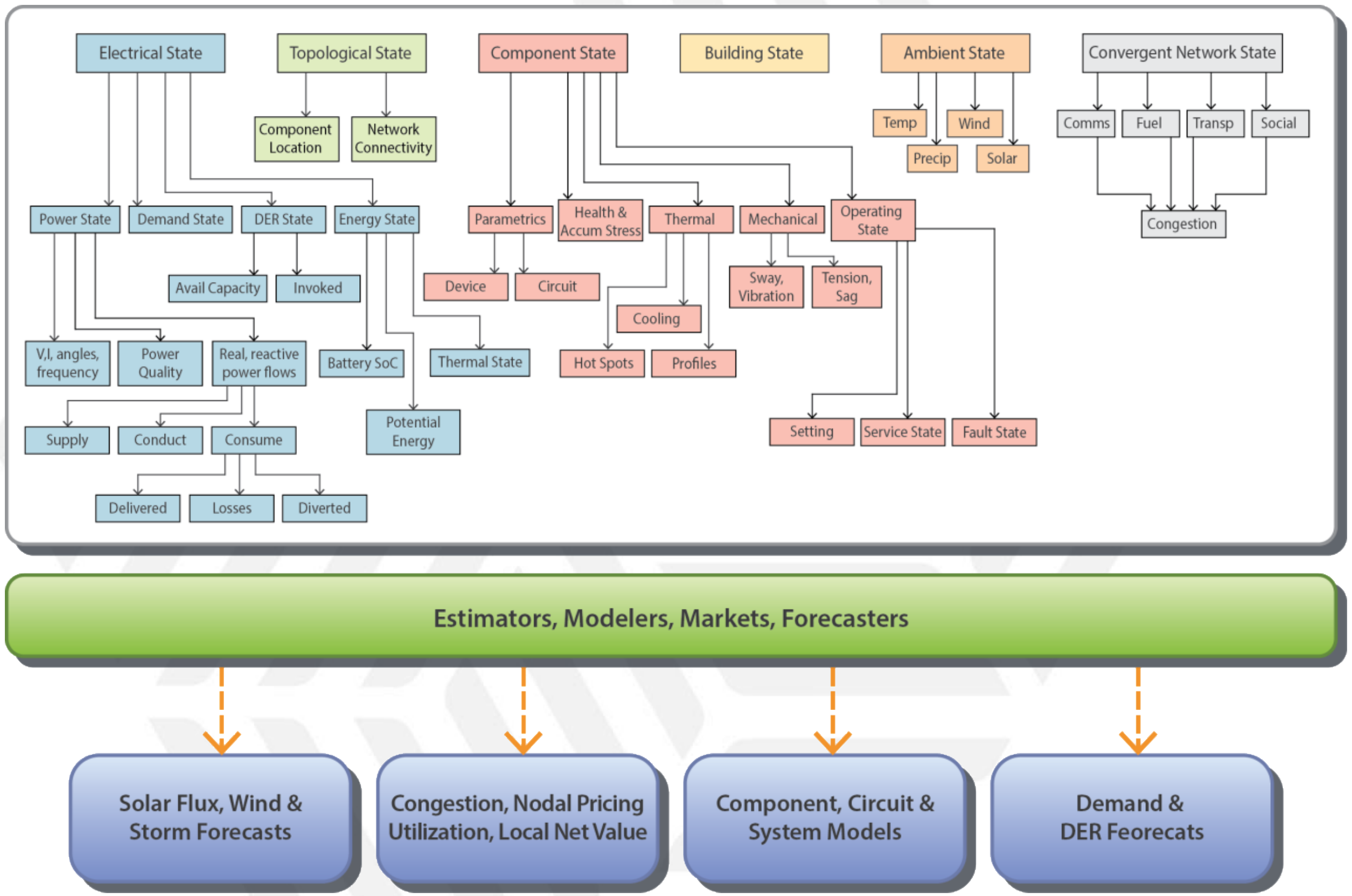
Sensor R&D Needs & Priorities including:
- Communication Requirements
- Data Analytics Requirements

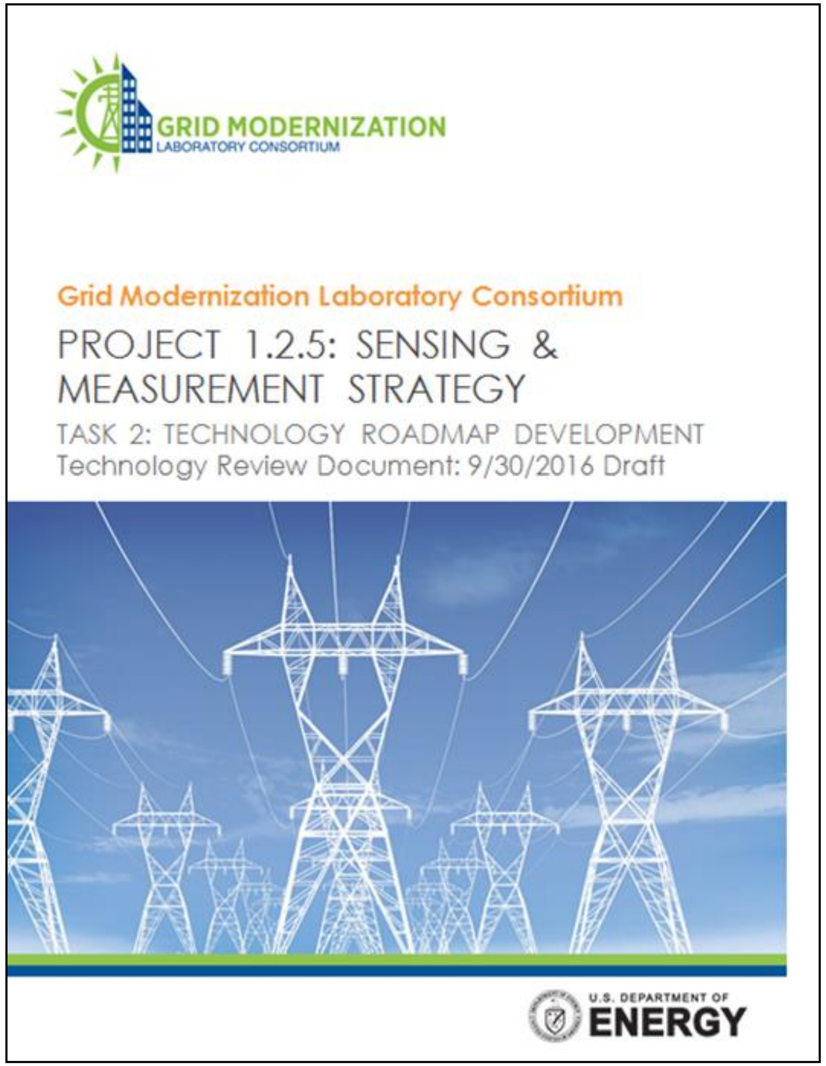
Sensor Allocations
- Types
- Quantity
- Locations

Sensing & Measurement Strategy

Technology Review

Extended Grid State framework and definitions

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PROJECT 1.2.5: SENSING & MEASUREMENT STRATEGY

TASK 2: TECHNOLOGY ROADMAP DEVELOPMENT

Technology Review Document: 9/30/2016 Draft

U.S. DEPARTMENT OF ENERGY

Sensing & Measurement Strategy Roadmap Elements

Sensing & Measurement Devices

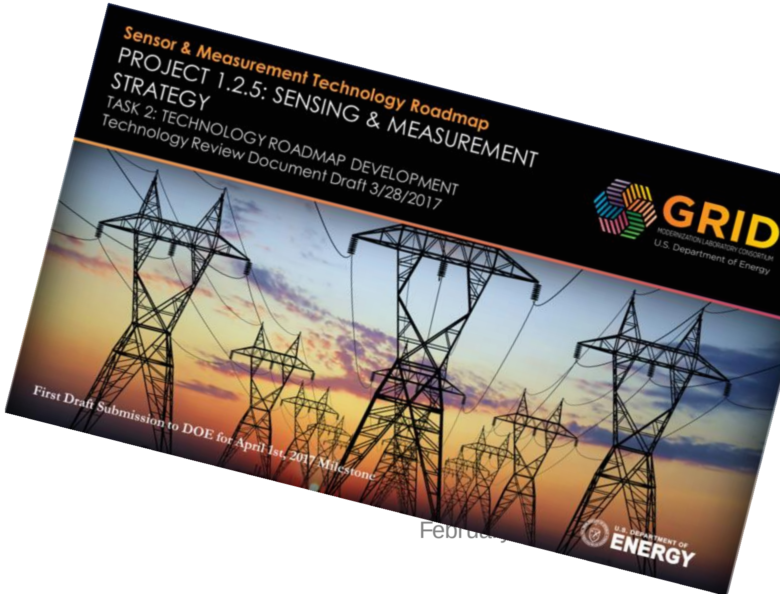
- Harsh Environment Sensors For Flexible Generation
- Sensors to Enable Advanced Generation Controls
- Grid Asset Health Performance Monitoring
- Grid Asset Functional Performance Monitoring
- Sensors for Dynamic System Protection
- Phasor Measurement Units for Grid State and Power Flow
- Sensors for Weather Monitoring and Forecasting
- Novel Voltage and Current Transducers for T&D
- End-Use / Buildings Monitoring

Communications

- Distributed Communication Architecture Development
- Low Latency, Rapid, Robust, and Secure Communication Technologies Development for Sensing in Distributed System Environments
- New Networking Technologies to Tackle the Challenges of Scalability, Diverse Quality of Service Requirements, Efficient Network Management, and Reliability
- Input into Standardization Efforts for Interoperability among Diverse Equipment and Standards

Data Management & Analytics

- Support for Advanced Applications for Visibility
- Big Data Management for Grid Applications
- Distributed Analytics Support
- Advanced Data Analytics Techniques & Applications



Sensing & Measurement Strategy

Roadmap Example and Structure

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Suggested Focus Area with Description

Phasor Measurement Units for Grid State and Power Flow

The transmission and distribution (T&D) systems of the power grid are used to transfer electric power from the generation sites to loads. To ensure this power transferring task is accomplished in a reliable, secure, and efficient manner, the system operator must know the states of the systems at all times during the operation. That knowledge requires a number of system states and parameters, which describe different physical characteristics of the systems, to be measured and monitored accordingly.

Power flow includes the information of the amount and direction of the real and reactive power flowing in the T&D networks. It is one of the key grid states that are crucial to the grid operation and must be continuously monitored and controlled over the entire grid to achieve optimal operation of the systems. The generation and consumption of real power have to be balanced at any given time in the grid to maintain a stable system and stable frequency. Reactive power is due to energy which is stored in the electric and magnetic fields in the whole systems (generators, T&D, and loads) and does not do actual work, but it enables the transfer of real power in the grid.

With the maturation of the technology of Phasor Measurement Units (PMU), the phasor measurement capability is widely enabled in modern power systems to measure and time-stamp basic electrical parameters.

Key Parameters

Key measurement parameters: Voltage, current, frequency, phase angle, real and reactive power

Individual Research Thrusts

Research Thrust #1

Improve the dynamic response of PMU technologies in order to significantly improve dynamic grid state measurement and enable high-speed, real-time control applications. This research area seeks to provide a 1 to 2 order of magnitude performance improvement over the current state of the art.

Key measurement parameters: voltage and current phasors

Metrics Goal = Quantitative

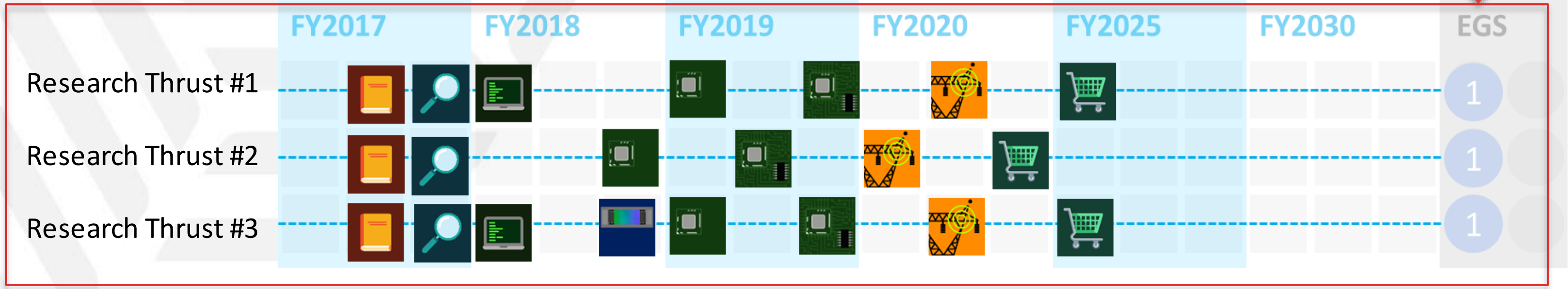
Key metrics:
Current spec: 5-6 cycles time window
Target spec: < one cycle time delay

Drivers: Resiliency, Flexibility
EGS Level: Electrical State

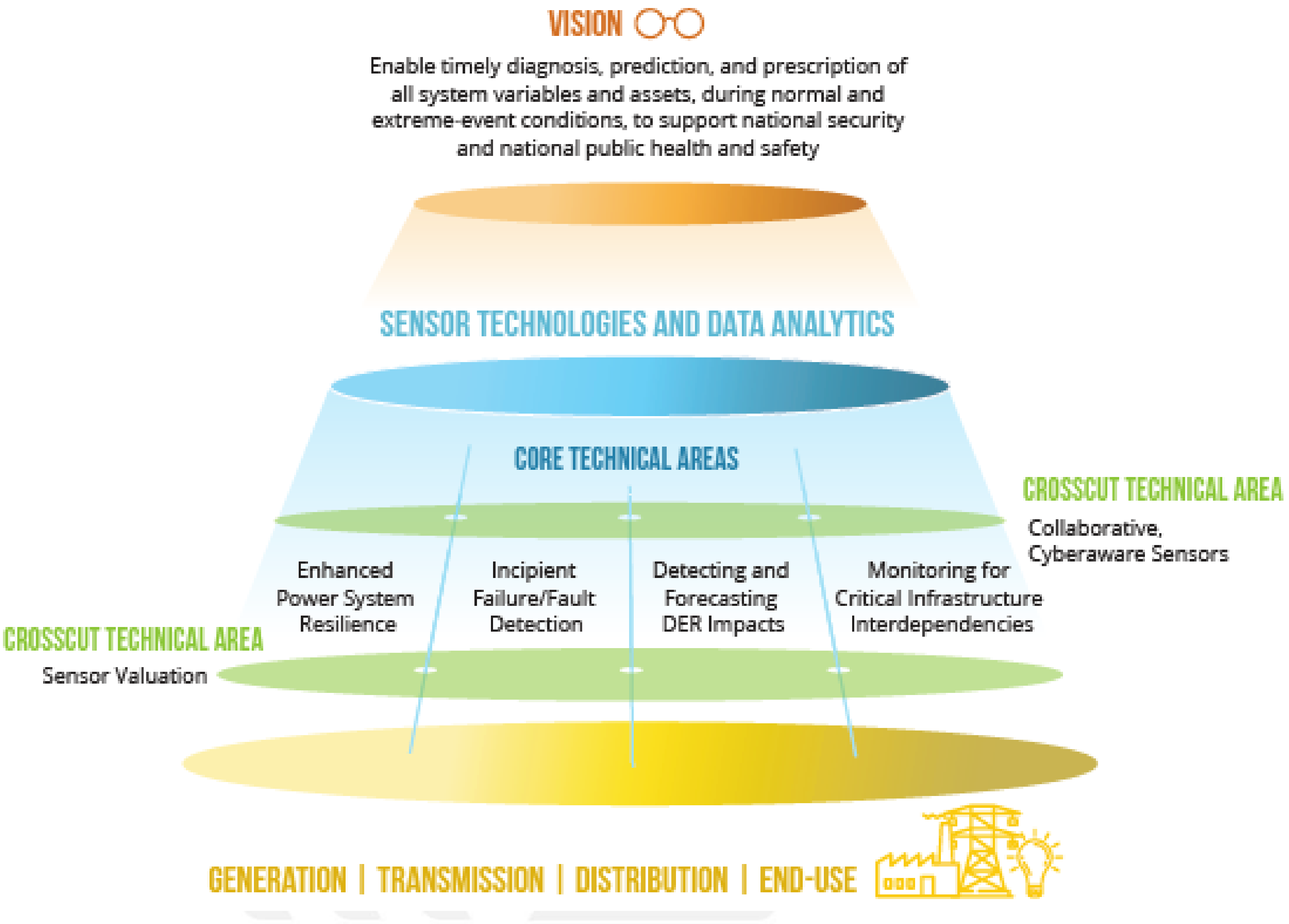
Direct Links to GMI MYPP and EGS

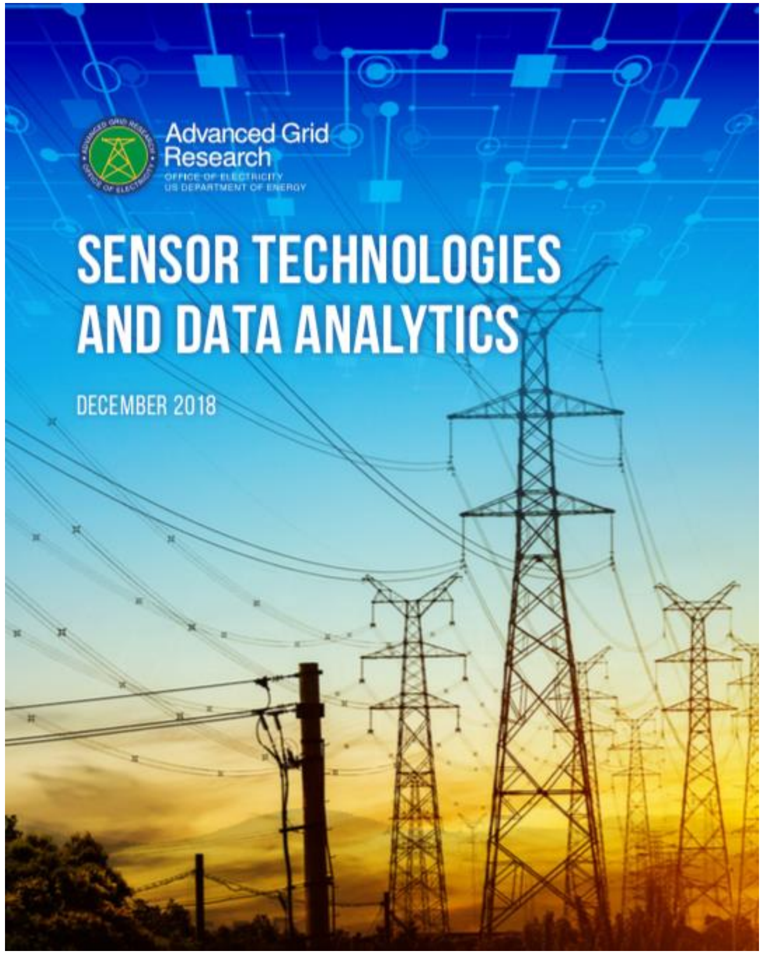
Scope of Activity: Develop robust, cost-effective PMU with fast dynamic response with pilot scale deployment and testing by FY2020.

Graphical Timelines with Icons



ADVANCED SENSORS AND DATA ANALYTICS PROGRAM PLAN





Industry Engagement

Utility Industry, EPRI, & NASPI

- ✓ Two industry meetings hosted by EPB and ComEd; 30 industry reps attended meetings in Chattanooga and Oak Brook, IL
- ✓ AEP, Ameren, BPA, CAISO, Duke Energy, Dominion, Entergy, EPB, EPRI, ComEd, ISO-NE, National Grid, NRECA, MISO, NY-ISO, PacificCorp, Peak, PJM, SMUD, Southern Co., Southern California Edison, TVA
- ✓ EPRI – provided update on their current sensor activities
- ✓ NASPI Synchrophasor Task Teams: Performance, Standards & Verification, Distribution Systems

Vendors

- ✓ ABB, Bosch, Eaton, Opal-RT, Alstom, OSIsoft, Quanta, GE

IEEE PES

- ✓ IEEE Smart Distribution Working Group

Standards & Testing Organizations

- ✓ GridWise Alliance
- ✓ Smart Grid Interoperability Panel (SGIP)
- ✓ National Institute of Standards and Technology (NIST)

Research Thrusts for Sensing & Measurement Devices

Attributes of a Modern Electrical Grid	Harsh Environment Sensing for Real-Time Monitoring	Advanced Electromagnetic Diagnostic Techniques	Electrical Parameter Measurements for More Flexible Centralized Generation Controls	Electrical Parameter & Topological Measurements for Distributed Generation Controls	Large Power Transformer Health Performance Monitoring	Distribution Grid Asset Health Performance Monitoring	Transmission and Distribution Substation Health Monitoring	Transmission Line Health Monitoring	Centralized Thermal Generator Health Monitoring	Distributed Generation and Energy Storage Monitoring	Broadband Frequency-Selective Sensors	Derivative Sensors	Sensors for Next Generation Power Elect	Low Cost Sensors for PMU Mon	Rapid Abnormality Detec	Integration of Se	Optimizin	In
Reliability			■	■	■	■	■	■	■	■								
Security					■	■	■	■										
Affordability																	■	■
Flexibility	■	■	■	■							■	■	■	■	■	■		■
Resiliency	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■
Sustainability	■	■	■	■														

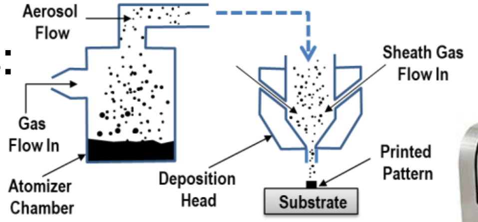
Matrix – How R&D Thrusts Impact High Level Objectives

Project Highlights: Direct-Write Printed Electronics

- **Description**: Sensor development and deployment strategies to provide complete grid system visibility for system resilience and predictive control
- **Deliverable**: Advanced sensor platforms for energy applications
- **Status**: Currently working on applications for low-cost sensors for nuclear generation
- **Opportunity for Engagement**: collaborative development and field validation

Direct-Write Inkjet and Aerosol Jet Printing

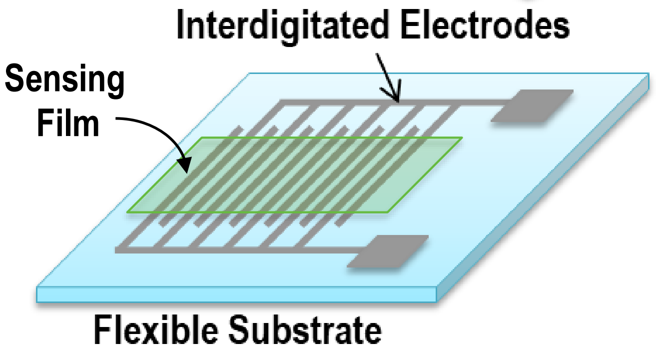
Printing Challenges:
– Resolution
– Process tolerance
– Defect density
– Printing yield



Fujifilm Dimatix

Optomec Aerosol Jet

Line Width/Spacing Control
- Down to 10μm



Direct-write Printing
– Sensors
– Active/Passive Layers
– Antennas
– Electrical Contacts

Project Highlight: Asset Monitoring

Innovative SAW-Based Online System for Dissolved Gas Analysis for Power Transformers

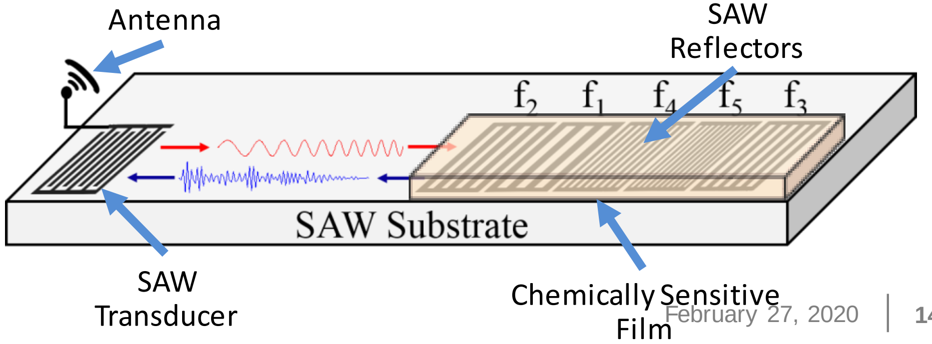
Description: Develop a low cost, in situ, dissolved gas analyzer for incipient failure monitoring of power transformers

- Dissolved Gas Analysis (DGA) of power transformers typically employs offline methods and takes a relatively long time. Online methods exist, but costs ~ $30-50K per (DGA) system.

Deliverable: An in-situ DGA system that costs an order-of-magnitude lower than the state of the art

Status: Currently in the lab demonstration phase and moving to field demonstration

Opportunity for Engagement: collaborative development and field validation



Project Highlight: Development of Sensor Suites

GMLC Developed Sensors being deployed in utilities

- **Description:** An integration of sensors and systems that cross multiple technological boundaries addressing the need from both cyber-physical and cybersecurity perspectives.
  - Interacting in a singular or collaborative mode to “report” to (classic and avantgarde) cybersecurity systems while also reporting to local-, regional-, national-scale SCADA, inter-control center, and situational awareness systems.
- **Deliverable:** A coordinated interplay of dual/multi-use sensors providing measurements for extended grid state monitoring thru applications embedded within the devices and systems.
- **Status**: Licensed technologies and currently being deployed
- **Opportunity for Engagement**: Field testing and validation and data analytics

Project Highlight – Integrated Multi-scale Data Analytics and Machine Learning for the Grid

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- **Description**: Develop and demonstrate distributed analytics solutions to building-grid challenges, leveraging multi-scale data sets, from both sides of the meter. Evaluate and demonstrate the application of machine learning techniques to create actionable information for grid and building operators, and derive customer benefits from disparate data

- **Deliverable**: Deploy local analytics integration at the grid edge, with a bridge to supervisory grid layers

- **Next steps:** Initiating next phase of GMLC project to understand incipient failures in transformers

- **Opportunity for Engagement**: Provide data ingestion feeds to perform machine learning and analytics

Use Case	DR & DER Local Availability & Verification	Incipient Failure Detection in Distribution	Topology & Parameter Estimation
Present State of Art	Estimated forecast and manual communication	Local sensing, smoke signals, outage management	Successful applications in highly sensed environments,
Present Granularity	Sub or Individual Customer, Day+	Limited prior to outaged component	Sub or Individual Customer, Day+
Future Requirement	Cust & Dist XFRMR Real time and Hrs Ahead	Dist XFRMR/ component level Real time, Months and Hrs Ahead	Switch, Distribution Component Planning and Event Driven
Useful Data	AMI, Irradiance, Green/Orange Button, PMU, model	AMI, Model, PMU, GIS	AMI, Model PMU, GIS, Model

smarter grid solutions
PSL
Hawaiian Electric
Maui Electric
Hawai'i Electric Light
WATER | ENERGY | LIFE
CITY OF RIVERSIDE PUBLIC UTILITIES
PG&E
DUKE ENERGY.
OSIsoft.
PingThings
PECAN STREET

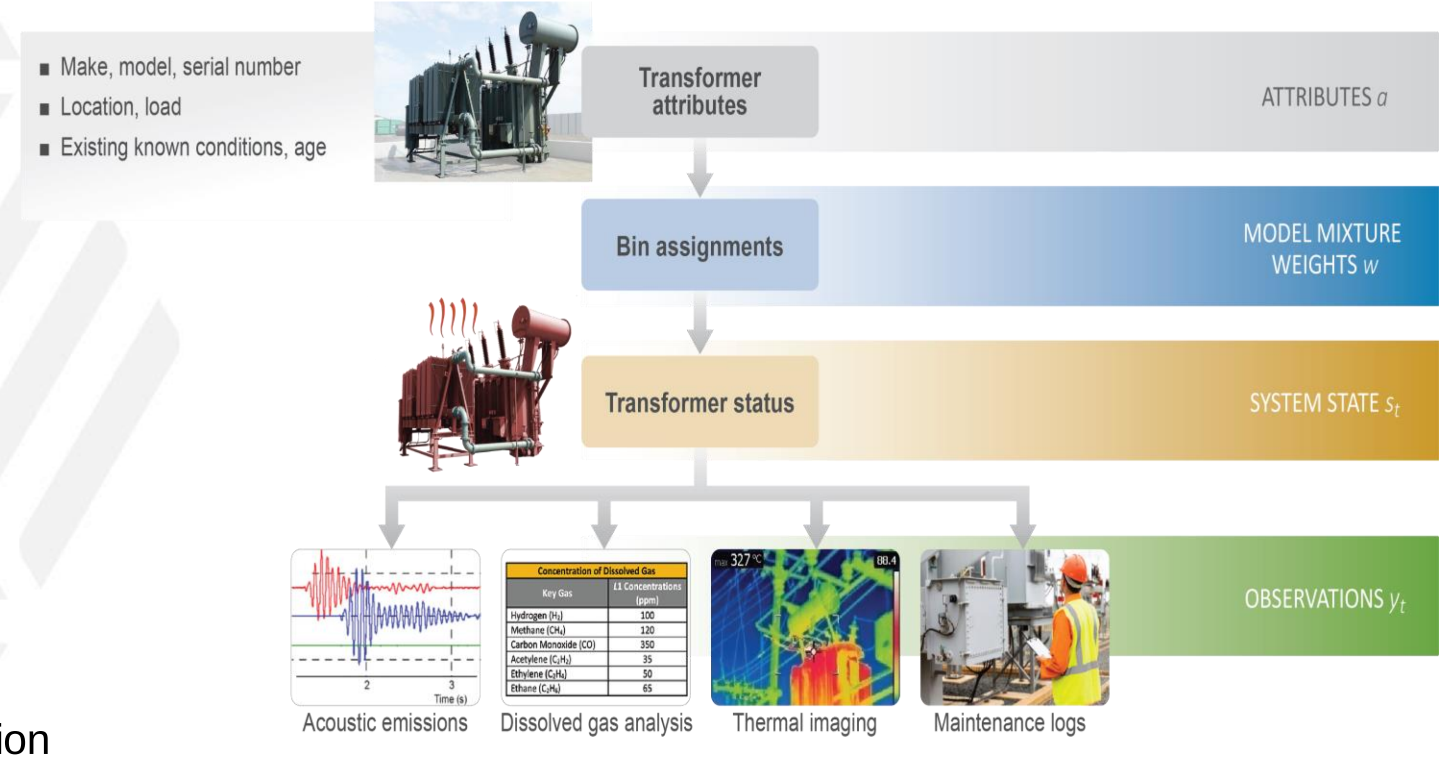
New Project: Incipient Failure Identification for Common Grid Assets

Lead: LLNL Lab Team: ORNL, NETL, SNL

Need: Individual sensing of all components on the grid is a challenge, the grid is aging, and the approaches to identifying critical failures on so many components are limited by data silos and specific analytics for each component

Approach: operationalize a multi variate, multi modal approach to diagnose and prescribe remediation pathways for both short term but critical failures locally and incipient growing problems centrally in commonly utilized equipment throughout the country

DOE Office Relevance: Application for incipient and instantaneous failure analysis is applicable on any infrastructure, with multi modal data available, application is portable, generators, transmission all can utilize



New Project: GridSweep Frequency Response of Bulk Low-Inertia Grids

Lead: LBNL Lab Team: LLNL

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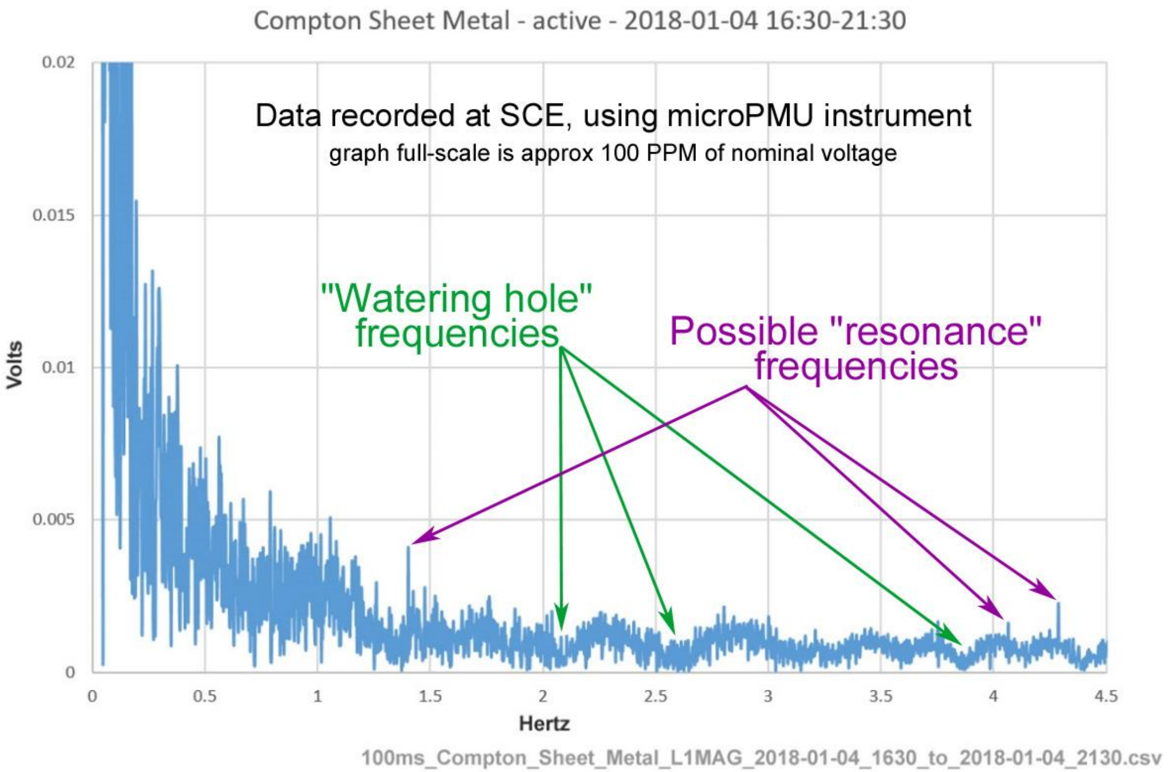
Need: The bulk grid has incipient instabilities that are known but not easily measured: reduced system inertia, vulnerability to forced oscillations, and adverse interactions from inverter controls

Approach: Develop a network of new class of measuring instruments that will be installed quickly and easily.

Probes inject a tiny signal and analyzes the response with ultra-high precision, applying novel devices and techniques

Outcomes: Provide visibility and situational awareness of grid status and grid frequency response behavior, to mitigate the risk of blackouts and to support intelligent decision making for critical infrastructure.



Team Partners

- ✓ LBNL, team lead Sascha von Meier
- ✓ LLNL
- ✓ McEachern Laboratories Inc.
- ✓ Idaho Power, Hawaiian Electric Co., et al.

GridSweep Innovation and Impact

- ✓ GridSweep will force a tiny, low-frequency (0.5 Hz to 10 Hz) signal onto the live grid, then measure the grid's response, then extract the signal from the background noise in the measurements.
- ✓ GridSweep's parts-per-billion measurement resolution will be a **100x** improvement over the state-of-the-art DARPA funded Grid Thumper technology, at **1000x** reduction of disturbing power.
- ✓ GridSweep will create a novel, low-cost method for revealing and quantifying grid stability.
- ✓ Within two years, the project will identify local and bulk grid vulnerability specific to sub-synchronous disturbance frequency and control loop parameters, informing utilities where nascent instabilities need to be curbed.

		Grid stimulus source	Stimulus size	Measurement devices	Measurement resolution	Noise extraction method
1980's – present		Chief Joseph Brake *Impulse*	1 GW	Fault recorders	1000 PPM 0.1%	None
2015 – present		Grid Thumper *Impulse*	1 MW	Micro PMU's	10 PPM 0.001%	Time-synchronous demodulation
2020 –		**GridSweep (new)** *Swept sine*	**1 kW**	**quasiPMU's (new)**	**100 PPB 0.00001%**	**Single-frequency vector-synchronous demodulation**

Summary

- Sensing & Measurement team has developed a strategy and roadmap that builds off state-of-the-art understanding
- Advanced sensor development in the initial GMLC phase emphasized end use, asset management and system analysis measurement devices
- Advancement of 13 different technologies across end-use sector, transmission & distribution and asset monitoring; six invention disclosures and 5 patents, R&D100 award; 9 publications
- Important to align new GMLC sensing projects with other related activities
- Industry engagement has been strong but continue to evaluate further opportunities

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Questions?