Grid Modernization

Updated GMI Strategy 2020

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GRID
MODERNIZATION INITIATIVE
U.S. Department of Energy

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Acronyms

ADMS	advanced distribution management system
ARPA-E	Advanced Research Projects Agency–Energy
CESER	Cybersecurity, Energy Security, and Emergency Response
DER	distributed energy resource
DOE	U.S. Department of Energy
EERE	Energy Efficiency and Renewable Energy
EV	electric vehicle
GMI	Grid Modernization Initiative
GMLC	Grid Modernization Laboratory Consortium
HELICS	Hierarchical Engine for Large-scale Infrastructure Co-Simulation
HVDC	high voltage direct current
MYPP	Multi-year Program Plan
NAERM	North American Energy Resilience Modeling
NG	natural gas
OpenFMB	Open Field Messaging Bus
PUC	public utility commission
PV	photovoltaics
R&D	research and development
RD&D	research, design, and development
VRE	variable renewable energy

1.0 Introduction

The Grid Modernization Initiative (GMI) coordinates research and development (R&D) across the U.S. Department of Energy (DOE) to help set the nation on an affordable path to a resilient, secure, and reliable grid with a reduced environmental impact. The GMI focuses on developing new tools and technologies to measure, analyze, predict, protect, and control the grid and interdependent infrastructure. The results of this work will inform regulators and other oversight bodies, policymakers, industry and other stakeholders to facilitate widespread adoption of new technologies in generation, transmission and delivery. The GMI derives its statutory authority for carrying out electricity [delivery] activities from the DOE Organization Act of 1977 (42 U.S.C. 7101 et seq.) and other public law authorizations including:

- Public Law 109-58, Energy Policy Act of 2005
- Public Law 110-140, Energy Independence and Security Act, 2007
- Public Law 114-94, Fixing America's Surface Transportation Act, 2015

The GMI envisions a fully integrated energy system from fuel to generation to load, including interdependent infrastructures, and an emphasis on maintaining the reliability and resilience of the grid.

The GMI is a collaborative partnership of five DOE Offices: Fossil Energy; Nuclear Energy; Electricity; Energy Efficiency and Renewable Energy (EERE); and Cybersecurity, Energy Security, and Emergency Response (CESER). These five Offices and steering committee drive activities under the GMI that complement individual investments and programs that each Office implements separately. In addition, GMI past and future activities have been and will be coordinated with DOE's Office of Science, Advanced Research Projects Agency–Energy (ARPA-E), and crosscutting Energy Storage Grand Challenge, electricity delivery system, and artificial intelligence efforts.

GMI activities are supported by 14 national laboratories under the Grid Modernization Laboratory Consortium (GMLC), a structure established to enhance laboratory coordination and impact for grid modernization activities (Figure 1)[1]. In addition, national and regional organizations and private-industry participants have been and will continue to be partners in implementing GMI activities.

[1] https://www.energy.gov/grid-modernization-initiative

Figure 1. GMLC Participating Laboratories

1.1 State of the Grid

Our extensive and reliable power grid, connecting all generation to all end use, has been so critical to our nation's growth that the National Academy of Engineering named "electrification" the greatest engineering achievement of the 20th century. However, the existing power system cannot meet the evolving demands of the 21st century. Traditional grid architecture was based on large-scale generation remotely located from consumers, centralized control structures with minimal feedback, limited energy storage, and passive loads. A modern grid must be flexible, robust, and agile from end to end, spanning generation, delivery, and end-user segments (Figure 2).

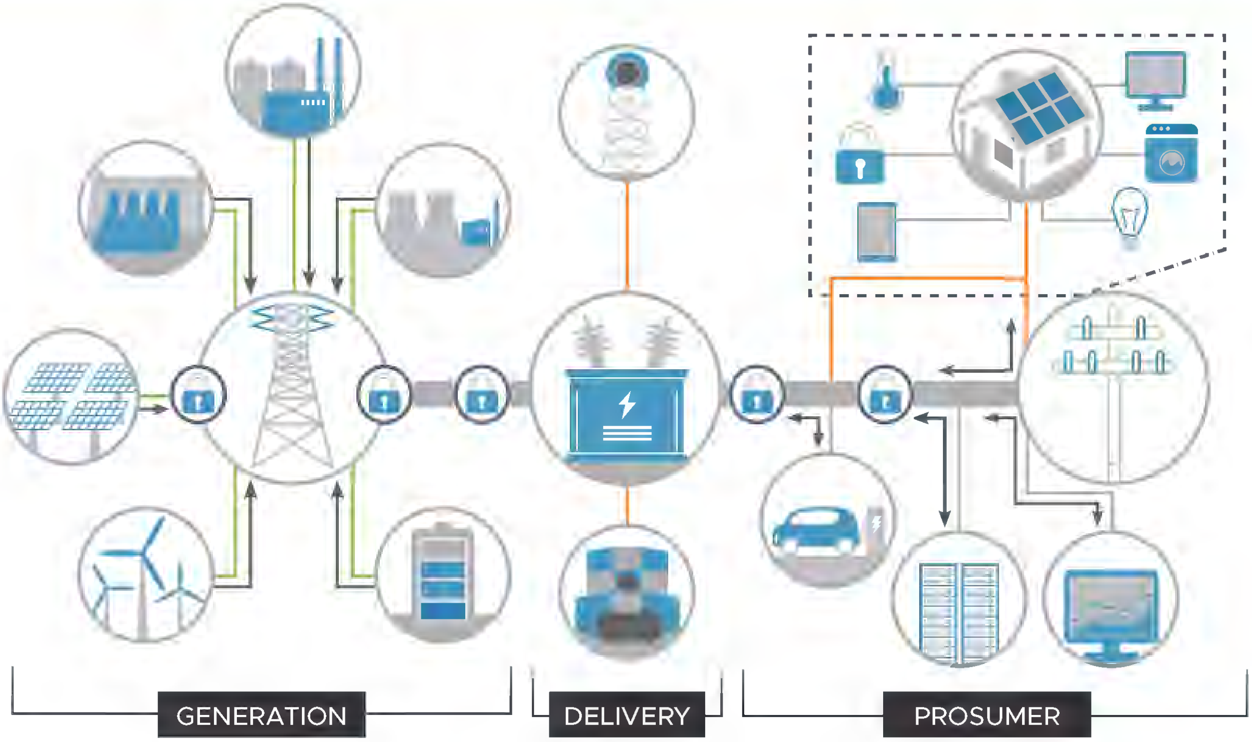

Figure 2. The Power Grid—Generation to Prosumers

Six key trends are driving a transformation that challenges the capacity of the grid to provide the services we need, but also the opportunity to transform our grid into a platform for greater prosperity, growth, and innovation.

- Changing mix of types and characteristics of electricity generation
- Growing demands for a more resilient and reliable grid, especially due to weather impacts
- Growing threat of cyber and physical attacks
- Opportunities for customers to provide grid services and participate in electricity markets
- Increased use of digital and communication technologies in the control of power systems.

Vulnerabilities to cyber and physical attacks have emerged as an important risk. Cyberattacks on key infrastructure—and on the electric grid—are increasing both in frequency and sophistication. It is important to have security designed into components and systems and not just rely on security measures after threats are identified. As shown in the *Worldwide Threat Assessment of the US Intelligence Community,* presented to Congress by the Director of National Intelligence in January 2019, threats to U.S. national security will expand and diversify in the coming years. The development and application of new grid technologies will introduce both risks and opportunities across the U.S.

economy, and the energy sector has been identified by the Department of Homeland Security as one of 16 critical infrastructure sectors in the nation.[2]

Changes in demand-side capabilities are also affecting electricity delivery. Growing installations of rooftop photovoltaics (PVs) and more energy efficient and grid-responsive appliances, buildings, and industrial equipment reduce the amount of peak power capacity needed. In addition, consumers are increasingly becoming "prosumers," managing their usage and interacting with the system as producers of electricity. The number of controllable devices in the system is rising sharply, challenging current control paradigms. DOE Electrification Futures also forecasts the potential for significant growth in an electrified transportation infrastructure.[3]

The emergence of interconnected electricity information and control systems provides both cybersecurity threats and opportunities for real-time control, information, and data exchange to optimize system reliability, asset utilization, and security. The information and communication technology that is now tightly integrated with our electric grid is changing all aspects of grid planning and operations, including new requirements for interoperability, cybersecurity, and the management of massive quantities of data from new meters and sensors.

The electric grid was designed to deliver one-way electricity, from centralized power plants to customers, with high reliability at a moderate cost. Today's electricity delivery system architecture is based on the principles developed back in the 19th century. As infrastructure is replaced, and smart meters and other digital communication and control devices proliferate, operators will require advanced control systems and distribution management systems that can securely manage new digital technology and use the new data to inform system operations.

Meeting the challenges of a resilient electricity delivery system, the core of a modernized grid, will require fully integrating the energy system from fuel to generation to delivery to load, including interdependent infrastructures (e.g., communications systems, natural gas (NG) pipelines, CO_2 management systems). Efforts will include flexible and small-scale generation technologies introduced into the current generation mix as well as increased growth in renewable energy technologies on both sides of the electricity delivery system.

The complexity of the electric grid and its interconnection with other critical systems can accentuate the risk of cascading failures. As a result, it is paramount that the grid be reliable and resilient against all malicious threats, natural disasters, and other systemic risks such as human error or dependence on other critical systems. Modernization efforts will strengthen, transform, and improve the resilience of the energy infrastructure while enabling all possible future scenarios and ensuring access to reliable and secure sources of energy.

[2] See Presidential Policy Directive (21) -- Critical Infrastructure Security and Resilience, February 12, 2013. See also Executive Order (EO) 13920, May 1, 2020, "Securing the United States Bulk-Power System," which authorizes the U.S. Secretary of Energy to work with the Cabinet and energy industry to secure the U.S. bulk-power system.

[3] https://www.nrel.gov/analysis/electrification-futures.html

The future modernized grid will need to balance six attributes. These attributes are all important and system designers should seek solutions that provide multiple benefits. Policymakers, regulators, grid planners, and operators should ensure that all are given appropriate consideration.

- **Resilient** – Recovers quickly from any situation or power outage
- **Reliable** – Improves power quality and fewer power outages
- **Secure** – Increases protection to our critical infrastructure
- **Affordable** – As measured by a reduction in electricity generation and delivery costs.
- **Flexible** – Responds to the variability and uncertainty of conditions across a range of timescales, including a range of energy futures
- **Environmentally Sustainable** – Reduces environmental impact of energy-related activities

1.2 Updated GMI Strategy

In 2015, after extensive analysis and collaborative work, DOE published its GMI Multi-year Program Plan (MYPP). In 2016, DOE announced the first Grid Modernization Lab Call—an extensive $220M, three-year program of 87 projects across the country, bringing together DOE and the national laboratories with more than 100 companies, utilities, research organizations, state regulators, and regional grid operators (Figure 3) to pursue critical R&D in advanced storage systems, clean energy integration, standards and test procedures, and a number of other key grid modernization areas.

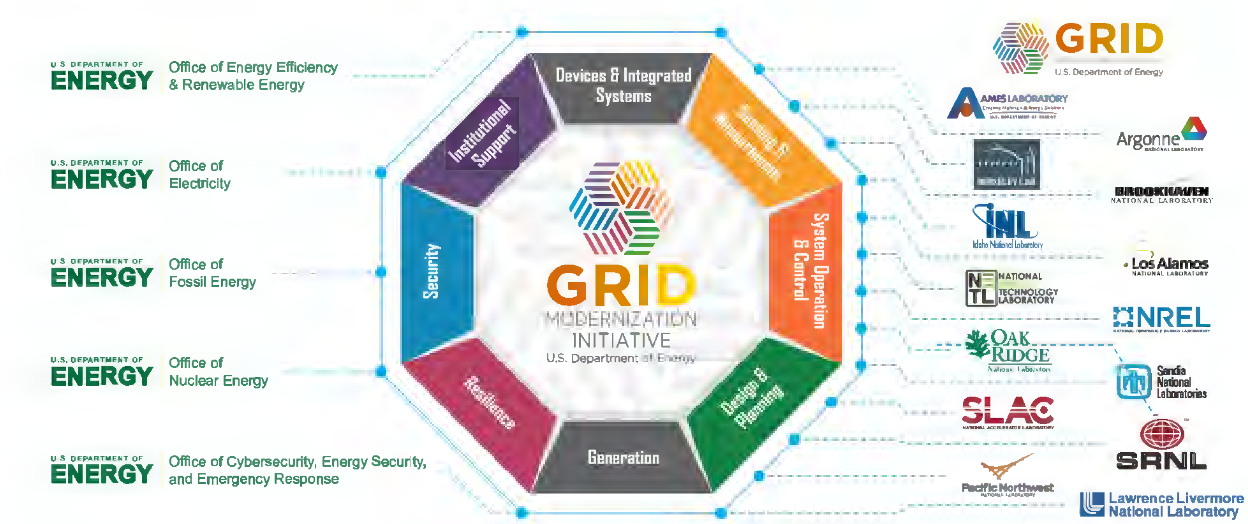

Figure 3. DOE and GMLC Consortium

In 2017, DOE announced up to $32M over three years for seven projects to develop and validate innovative approaches to enhancing the resilience of electricity distribution systems, focusing on the integration of distributed energy resources (DERs), advanced controls, grid architecture, and emerging grid technologies at a regional scale. In 2019, DOE executed a second Grid Modernization Lab Call of $80M over three years for 25 projects. Additionally, several Offices within DOE have successfully conducted lab calls on Office-specific grid modernization topics.

The activities undertaken are intended to facilitate modernization of the grid and ensure the United States is prepared for a variety of potential energy futures while considering evolving national and regional priorities. These activities will also help to ensure that investments are taken at the appropriate scale.

DOE leads the federal R&D investment across an extensive range of energy technologies. A key element of DOE's mission is to direct national efforts in developing technologies to modernize the electric grid; enhance the security, reliability, and resilience of energy infrastructure; improve all energy production and use; and expedite restoration from energy supply disruptions.

Through the GMI, DOE leadership will catalyze private-sector innovation, work with collaborative partnerships to ensure a regional breadth of issues and activities, and bring together stakeholders from government, industry, states and consumers to find common visions and identify activities that benefit all parties.

An important aspect to this update is a more thorough approach to security, an acknowledgment that security is a responsibility of every research endeavor as well as a separate domain for innovative research. To that end, the GMI adopts a Security "T" strategy, addressing security horizontally across every technical area consistently and measurably, and vertically as a technical area in and of itself. CESER, with an explicit mission of grid cybersecurity, will be responsible for establishing a security services and advisory resource, and working as an innovation partner for all technical areas under the GMI. CESER will be responsible for providing subject matter expertise and resources to each technical area for the horizontal security strategy and for its funding.

The GMI program will partner with key stakeholders in the electric power sector, including utilities, independent power producers, transmission organizations, technology developers and vendors, the environmental community, consumer and technology advocacy groups, and the broader research community and standards organizations. DOE will also work with other federal, regional, and state agencies that have critical and evolving roles in grid modernization, including Power Marketing Administrations, the National Institute of Standards and Technology, the Federal Energy Regulatory Commission and state regulatory commissions, and the Departments of Defense, Interior, Agriculture, and Homeland Security.

This report is an update to the 2015 GMI MYPP. It focuses at the level of program strategy and vision, and therefore is not a voluminous, detailed compilation of projects but a readable highlight of strategic and focused actions. This MYPP explains the current set of goals and expected technical achievements while providing examples of projects that will help achieve those goals. Moreover, it provides an *organizing framework* so that projects and partnerships, in the future as new needs and goals evolve, are aligned and focused toward the GMI vision of a modernized grid.

The following sections of this report provide specific challenges, activities, and benefits of the GMI's activities in eight specific technical areas:

1. Generation

2. Devices and Integrated Systems
3. Systems Operations, Power Flow, and Control
4. Sensing and Measurement
5. Planning and Design Tools
6. Resilience
7. Security
8. Institutional Support

2.0 Generation Area

2.1 Generation Area Challenges

The generation technical area assesses the cost and reliability implications of ongoing changes in the generation mix feeding the nation's grid. Understanding these implications should foster R&D activities that support planning, deployment, and operation of a modernized power fleet, part of a grid that delivers electricity that is economically and environmentally efficient while being safe, secure, reliable, and resilient. In addition, this area highlights both existing and new opportunities to ensure seamless integration such that the resulting generation fleet mix remains a platform for greater prosperity, growth, and innovation.

Technologies considered in this area include power plants connected at various levels of the transmission and distribution system that encompass behind-the-meter generation resources, integrated energy storage, and microgrids aggregated to utility-scale levels. The generation area acts as a conduit between several other areas, such as requiring advances in hardware from the devices area, benefiting from the implementation of advanced controls, and transferring advances in flexibility to planning and design tools, so that generating assets help the modern grid meets its objectives.

Challenges in the generation area are listed below:

1. Changing mix of types and characteristics of electric generation, including the retirement of coal and nuclear power plants and increasing deployment of variable renewable energy (VRE) and NG units: Due to policy and market drivers, wind, solar, and NG plants are the main technologies currently being deployed and expected to be deployed in the next decade with consequent grid stability, essential reliability services, and fuel availability impacts yet to be fully understood.
2. Growing demands for more resilient and reliable generation: More frequent and severe weather events, potential cyber-physical threats, and other global events are calling for more robust power systems.
3. Growing supply-side opportunities for customers to participate in electricity markets: As DERs increase and cities and industries are counting on larger volumes of behind-the-meter generation, the bulk system is impacted by changes in net load, the variability of net load, and the uncertainty associated with forecasting net load on multiple timescales. The generation technical area has the challenge of harmonizing the operation of the bulk system in response to these trends, relating to specific regional conditions and needs.
4. The emergence of interconnected electricity information and control systems: It is a challenge to develop and deploy cost-effective advanced communication and control systems that can aid in optimizing planning and operation of generation portfolios that meet all six attributes mentioned above.
5. An aging infrastructure: As the bulk power system continues to age, it is a challenge to allocate timely and cost-effective upgrades to the existing power generation infrastructure. It is also a challenge to correctly estimate and develop methods and technologies to mitigate the shortening lifetime of existing assets—power plants and grid components that are constantly cycling and

operating outside their designed range. Finally, it is a challenge to plan for future power systems based on components with less operational history and experience than conventional generators.

6. Evolving market conditions: It is a challenge for market designs to send appropriate signals to power generators to guarantee the system delivers electricity that meets desired system attributes. Given the interplay between market forces and policy decisions, it is important to evaluate the system needs and investigate how market signals can appropriately value all electricity attributes. This challenge overlaps with the institutional area.
7. Multilevel interdependencies: Challenges include the higher reliance on information technology systems for operating the generation power fleet, the growing complexity of planning for new generation assets to meet new load from electric vehicles (EVs), and power-to-gas technologies that require large amounts of power and storage to be strategically located. Linkages to water availability should be evaluated to determine constraints and vulnerabilities. These are a few areas that present unique and complex challenges for R&D in the generation area. Another challenging interdependency would be the development of a national manufacturing supply chain that meets the needs of the bulk power system.[4]

2.2 Ongoing and Proposed Future Activities

The generation technical area is new to GMI. As such, there are few ongoing projects and multiple gaps to be addressed. The following list describes future activities for this area and highlights ongoing efforts.

a. Assess various risks that the power generation system can face.

    i. Assess cyber-physical threats of standalone and combined power generation units, including electromagnetic threats (ongoing).
    ii. Assess the energy security[5] risk of various alternative power generation portfolios.
    iii. Quantify environmental impacts and critical functions under water, land, and fuel risks (ongoing).
    iv. Respond under an all-hazards approach.

b. Investigate individual generation technologies.

    i. Investigate grid services provision of various generators, including inertia provision limitations of inverter-based technologies, and its impact in the operation of the system.
    ii. Compare lifecycle costs of existing and new generation technologies, with emphasis on the lifetime of critical components or other resources needed to maintain their operation.
    iii. Study the value of next-generation power plants and supportive technologies in terms of their contribution to each of the six attributes of delivered electricity and their direct applicability to other sectors (e.g., industrial, transport).

[4] The recent "Executive Order on Securing the United States Bulk-Power System," published on 1 May 2020 is calling for U.S. based manufacturing. [Online]. Available: https://www.whitehouse.gov/presidential-actions/executive-order-securing-united-states-bulk-power-system/

[5] Energy security is both protecting the energy sector from natural and man-made events (national security) and the availability of natural resources for energy consumption.

- iv. Develop new or improved existing standards and grid codes that are comprehensive, adaptable, and consider the differences between generation technologies.
- v. Improve representation of power generation technologies through validation of existing models or development of new models. Require emphasis in the representation of sub-hourly operation and ancillary services, and in the use of these representations in grid-scale models.

c. Assess generation interdependencies.

- i. Assess the growing interdependency of the gas transportation infrastructure and gas generation power units, and how this impacts the system's reliability and resilience.
- ii. Study innovative technologies that can enhance the coordination of power, gas, and transportation systems.
- iii. Investigate the interdependency of the power generation system and the communication infrastructure. Establish new or improved metrics to value the interdependencies between the power generation fleet and the communication infrastructure.

d. Investigate the deployment and operation of hybrid generation portfolios that include all power generation technologies, including advanced thermal technologies, advanced large-scale and distributed renewable technologies, storage technologies, especially integrated with generating assets and applications of combined heat and power.

- i. Compare various combinations of power technologies meeting desired system attributes.
- ii. Study the value of hybridization of power generation clusters (ongoing), including the design and optimization of infrastructure for tightly coupled hybrid systems (ongoing).
- iii. Estimate the cost and value of additional flexibility, reliability, balancing and frequency control, resilience, and environmental footprint gained with hybridization of generation portfolios.
- iv. Advance technologies that enhance the coordination of operating large-scale thermal VRE units to increase the overall efficiency of the power fleet operation.

e. Asses the cost and value of various generation mixes and supply-side technology innovations that consider state laws and how they impact regional reliability and national-level grid operations.

- i. Study the value and cost of large scale and distributed VRE deployment scenarios, inclusive of power to gas, including the use of fossil/biomass, carbon capture and storage,direct air capture, and advanced nuclear units.

- ii. Study strategic allocation of advanced power plants and cost-effective deployment of storage capacity that enhances cleaner delivered electricity.

- iii. Investigate innovative heat-power operation approaches that can support energy efficiency and other state laws.

iv. Study technology innovations in the continued electrification of other sectors, including the industrial and transportation sectors.

f. Investigate the physical infrastructure and resource needs of a power system with higher VRE and NG power generation units

i. Assess security of generation, fuel supply, and water supply.
ii. Estimate the risks of insufficient resource adequacy under normal conditions and low-frequency events.
iii. Investigate how additional capacity, if needed, can be provided in a way that addresses the six attributes of the power system.
iv. Study how higher penetration of large-scale VRE is impacting the transmission and distribution grids, and the needed supportive communication infrastructure and control technologies that can mitigate some of these impacts.

g. Investigate how to reduce the cost of electricity delivered to ratepayers in accordance with DOE's statutory mandate.[6]

i. Compare electricity rates across states and regions, along with generation and transmission resources, to understand why rates have not fallen for ratepayers even with falling wholesale power prices. Develop a multidisciplinary research and modeling approach to assess large-scale deployment of distributed energy resources and their interaction with the transmission grid, in particular the need for important reliability services as required by NERC.
ii. Compare various combinations of power technologies that in coordination with the transmission and distribution grid can simultaneously deliver economically efficient, safe, reliable, secure, flexible, sustainable, and resilient electricity, highlighting the differences across the U.S. transmission ISO/RTO regions.

In the consideration of any future activities and subsequent projects within the generation technical area, cyber and physical security will be documented and addressed at the level(s) appropriate to the research topic (e.g., policy, conceptual, design, protocol, standard, system, component), aided by embedded security resources established by GMI's Security "T" strategy outlined in the Introduction section.

These activities overlap with the following areas within GMI: planning and design tools; devices and integrated systems; security; resilience; and system operations, power flow, and control. Coordination with these areas will be necessary. Table 1 details ongoing activities and the challenges they address.

[6] *See* 42 USC 16191(a)(1)(C).

Table 1. Ongoing Activities in the Generation Area

Activities	Challenges Addressed	Technical Achievements by 2025
Investigate deployment and operation of hybrid systems that include one or more power generation technologies, including micro- and small-scale generation technologies, advanced coal, advanced wind and solar, energy storage, and applications of combined heat and power	1, 2, 4	• Study Clusters of Flexible PV-Wind-Storage Hybrid Generation • Design and Optimization Infrastructure for Tightly Coupled Hybrid Systems
Assess a targeted set of risks to the power generation system. In particular, security risks such as cybersecurity, supply chain vulnerabilities and EMP/GMD vulnerabilities.	2, 7	• Vulnerability Assessment of Power Generation Critical Systems Against Electromagnetic Threats • Assess Water, Land, and Fuel Availability Risks for the Power System

2.3 Generation Area Benefits

Studying the deployment and operation of hybrid generation portfolios that include diverse power generation technologies will highlight the additional flexibility and reliability gains of hybrid generation systems. Designing and optimizing infrastructure for tightly coupled hybrid systems will show the importance of considering infrastructure requirements to support hybrid generation power mixes and will describe some innovative hybrid case studies that can increase the appetite for other synergies.

Assessing some of the vulnerabilities power generation assets face—such as electromagnetic threats and water, land, and fuel availability—provide examples of the diversity and severity of different risks associated with the planning and operation of the power fleet.

This generation technical area seeks research that is integrative and holistic, thereby presenting the nation with the critical framework to ensure the generation power fleet provides the reliable and competitive electricity essential to economic productivity. It is looking to advance multidisciplinary research that supports deployment and operation of a modernized generation mix as well as improving methods and tools of analysis to assess how different generation mixes with various technologies can meet their objectives.

This area considers tradeoffs between limited resources, presenting diverse system alternatives that can satisfy the system's core objective of providing economically efficient, safe, clean, and reliable power. Special attention should be given to how smart technologies can support generation portfolios and how different generation technologies and portfolios require more supportive technologies or resources than others.

Table 2 provides a list of projects that have been awarded in the generation area.

Table 2. Awarded Projects in the 2019 GMLC

Project Number	Project Title	Project Description
6.1.1	Clusters of Flexible PV-Wind-Storage Hybrid Generation (FlexPower)	This project demonstrates how technology hybridization can increase the value of utility-scale wind and PV generation from being simple variable-energy resources to ones that provide ability to dispatch and a full range of reliability services to the bulk power system.
6.1.2	Design and Optimization Infrastructure for Tightly Coupled Hybrid Systems	This project models the operation of three hybrid systems: (1) Optimal sizing and operation of a nuclear power plant, a hydrogen production facility, and a gas turbine. The hydrogen facility supplies external customers and, at the same time, hydrogen can be locally stored during low electricity demand periods. The stored hydrogen can be burned in the gas turbine to provide clean power to respond to electricity peak demand. (2) Coupling existing coal or new Coal FIRST technology with energy storage, carbon capture/use, and renewables. (3) Renewable-hybrid topology that combines wind, solar PV, and battery storage systems to take advantage of the complementary nature of wind and solar resources coupled with battery storage.
6.3.2	Vulnerability of Power Generation Critical Systems Against Electromagnetic Threats	This project experimentally evaluates physical security of electric generation infrastructure against electromagnetic threats and attacks, both large-scale and localized.
6.4.1	Water Risk for the Bulk Power System: Asset to Grid Impacts	This project enables utilities to evaluate the impacts and risks associated with water resources. It consists of developing an analysis platform that can provide environmental and economic benefit estimates and aid in making operational decisions in the short term and investment decisions in the long term.

3.0 Devices and Integrated Systems

The electrical grid is fundamentally composed of device technologies physically connected together and linked by control systems, which form integrated systems. Device technologies in this technical area interconnect to the grid at distribution-level voltages (less than 69 kV) and include individual distributed generation systems, storage systems, power delivery technologies, fuel systems, and loads. Distributed generation includes small modular coal, small modular reactors and nuclear microreactors, NG turbines and microturbines, combined heat and power, PV, concentrating solar power, wind power, engine-generator sets, fuel cells, hydropower, marine-kinetic power, geothermal, and biopower technologies. Generation and storage include the power-electronic interfaces (inverters and converters) that connect them to the grid. Some examples of storage technologies include battery storage systems, ultracapacitor systems, pumped storage hydropower, compressed-air energy storage, flywheels, and other mechanical, chemical, and thermal storage technologies such as hydrogen and reversible fuel cells. Once bidirectional EVs are enabled they could act as a moveable storage technology. Loads include EVs and charging stations, building loads, appliances, heating, ventilation, and cooling systems, lighting, motors, industrial and agricultural loads, and electrolyzers. This technical area also covers other grid device technologies such as conductors, cables, switches, overcurrent protection devices, and transformers. A focus of this technical area is on developing better device technologies and grid interfaces that can provide a full range of essential grid services while safely interconnecting and becoming interoperable with the power system. Bulk-system-connected generation and storage (connecting to transmission voltage $\geq$ 69 kV) are covered in the generation technical area (Section 2.0).

Integrated systems combine multiple device technologies together with communication and control systems. Some examples of integrated systems covered in this technical area are distributed solar and wind power integrated into distribution systems; building and industrial facility loads and management systems; aggregations of buildings into facilities and campuses that respond to grid signals; aggregated fleets of EVs; and behind-the-meter charging systems and energy storage. Integrated systems can include microgrids that include multiple technologies, microreactor end-user applications focused on electricity/process heat production for microgrids, and remote community systems. Integrated systems also include grid management applications such as the evaluation of distribution voltage management schemes that accommodate high penetrations of distributed generation and using autonomous fault location, isolation, sectionalization, and restoration systems for distribution reliability and resilience. Bulk hybrid systems and integrated systems that are aggregated to impact the bulk system are covered in the generation technical area (Section 2.0).

The focus of the devices and integrated systems technical area includes improving the performance and security of individual device technologies and validating them in integrated systems as it relates to improving grid flexibility and operational efficiency at the distribution level. To maximize benefits as part of integrated systems, the individual devices should support a range of operational goals considering both critical end-use loads at the distribution system and how they may impact bulk power system operations. Achieving the goals within this plan will require foundational research, applied uses, performance validation, field demonstrations, and development of standards to support industry. This technical area addresses several key challenges to transforming the electric grid to help reach GMI's outcomes. The challenges identified in this technical area include the following.

1. Some device technologies (including distributed generation, storage, power electric interfaces, and grid-interactive efficient building loads or demand flexibility) are not yet capable of securely communicating, coordinating, and transacting with the electrical grid to provide a wide range of grid services (e.g., energy, capacity, voltage and frequency regulation, inertial response, and black start) that benefit both the device owner and the grid.
2. Harmonized standards are necessary to provide requirements for functionality, interoperability, and interconnection to the grid that streamline integration across all device technologies and minimize information exchange to reduce communications bandwidth requirements. These standards need to coordinate appropriately with all relevant regulatory bodies.
3. Integrated energy systems (from microgrids to distributions systems) have not been demonstrated and validated at a size and scale that demonstrate proper operation and verify that new device technologies are able to provide a range of grid services when integrated into systems.

This technical area will develop devices and integrated systems that securely interoperate and interconnect to maintain stable grid operations while providing quantifiable benefits for grid and local energy services. It also covers the embedded controls and decision-making components of technologies that need to be designed with cybersecurity as one of the main objectives.

In the consideration of any future activities and subsequent projects within the devices and integrated systems technical area, cyber and physical security will be documented and addressed at the level(s) appropriate to the research topic (e.g., policy, conceptual, design, protocol, standard, system, component), aided by embedded security resources established by GMI's Security "T" strategy outlined in the Introduction section.

This area works closely with other technical areas to evaluate integrated systems. Grid sensors, measurements, and communications technologies are developed in the sensing and measurements technical area (Section 5.0) and power electronics-based power flow controllers and various control systems are developed in the system operations, control, and power flow technical area (Section 4.0). This area will also coordinate with the security (Section 8.0) and resilience (7.0) technical areas for ensuring cybersecurity of individual devices and integrated systems. Development and integration of bulk power fossil and nuclear plants and the hybridization of these plants are covered in the generation technical area (Section 2.0). The generation technical area and the devices and integrated systems technical area will closely coordinate since both have some level of commonality in making best use of available resources and ensuring safe, reliable, and affordable operations.

To address these key challenges, several teams of national laboratory researchers working in collaboration with industry and academia will focus on three technical activities as shown in Table 3.

Table 3. Activities and Technical Achievements for the Devices and Integrated Systems Area

Activity	Challenges	Technical Achievements by 2025
1. Integrate Advanced Storage Systems, Power Electronics Interfaces, Controllable Loads, and other Grid Devices	1	• Increase the value of deployed grid-scale energy storage systems by improving performance, lowering costs, and enabling new capability. An energy storage system consists of the energy storage technology and balance of plant. • Develop power electronics-based interfaces for a variety of generation (e.g., turbines, engines, fuel cells, renewable, distributed energy), energy storage (battery, thermal, hydrogen, and others), and loads (EVs, electrolyzers, and building loads) that can provide grid services and self-optimize around market and energy environment. • Enable loads (buildings, electrolyzers, EV charging systems) to have embedded control and decision-making tools to provide capacity, energy, and ancillary services to the electrical grid and other valuable services to system owners. • Develop innovative grid infrastructure technologies (advanced transformers and grid materials) that reduce cost and improve device efficiency. • Ensure that devices make best use of distributed decision making and control to reduce communications burdens. • Ensure that embedded controls or decision-making systems within device technologies are designed with cybersecurity as one of the main objectives (security by design).
2. Harmonize Standards and Grid Codes for Providing Interoperability, Interconnection, and Grid Services	2	• Update standards and grid codes that characterize the ability of device technologies (generation, storage, and loads) to provide a full range of grid services and accelerate the uptake of these technologies in the market and integrated into distribution systems. • Develop standards and test procedures for microgrids, storage, and other energy management systems that reduce customer outages and improve resilience. • Update smart grid interoperability reference models and standards. • Update interconnection standards at distribution levels including effects on transmission systems.
3. Conduct Validation of Individual Devices and Integrated Systems at Multiple Scales	3	• Characterize the ability of individual device technologies (distributed generation, storage, loads) to provide a range of grid services at the distribution system. • Validate multiscale (microgrids and distribution systems), integrated energy systems that improve grid reliability, resilience, and affordability through integrated sensing and advanced control constructs that coordinate generation, storage, and controllable loads.

3.1 Activities and Prior GMLC Devices and Integrated Systems Projects

The devices and integrated systems technical area focuses on adding grid service functionality to existing devices, developing new technologies and materials, and innovating other core areas for devices to increase their functionality while decreasing their cost. Selected prior activities are described in Table 4. The device development in energy storage and power electronics delivered enhanced device performance in cost, controllability, and digital functionality that support new grid operation and control requirements. The standards development activities supported establishing common interconnection and interoperability approaches. Integrated system evaluations have also been conducted to validate performance to improve grid reliability, resilience, and affordability.

Table 4. Devices and Integrated Systems Projects

GMLC Project No.	Project Title	Description
1.2.2	Interoperability	Develop Strategic Roadmap for Interoperability
1.2.3	GMLC – Testing Network	Develop list of national lab capabilities and library of models for devices and grid components
1.3.29	Frequency Support in Hawaii	Evaluate use of DER for frequency support
1.4.1	Interconnection and Interoperability Standards	Identify gaps in interoperability standard harmonization
1.4.2	Grid Services from DER	Develop methodology for characterizing DER grid services
SI-1695	Accelerating Codes and Standards	Update IEEE-1547, the interconnection standard for DER
GM0008	Energy Storage Demonstrations	Demonstrate energy storage use and value
GM0237	Advanced Distribution Management System (ADMS) Testbed	Develop ADMS testbed capability
1.5.3	Increasing Distribution Resiliency using Flexible DER and Microgrid Assets Enabled by Open Field Messaging Bus (OpenFMB)	Demonstrate use of OpenFMB for controlling DER and microgrids
1.5.4	Integration of Responsive Residential Loads into Distribution Management Systems	Demonstrate use of residential loads for grid flexibility
2.1.1	Federated Architecture for Secure and Transactive Distributed Energy Resource Management Solutions (FAST-DERMS)	Develop improvements in distribution management systems
2.4.2	Multi-Port Power Electronics Energy Hub	Develop multipower electronics
2.5.2	Energy Services	Develop energy service interface

3.2 Devices and Integrated Systems Benefits

New and improved device technologies such as energy storage, distributed generation, grid-responsive buildings, EVs, fuel cells, and renewable energy technologies are expected to play increasingly critical roles in the future electrical grid and complement the fleet of bulk power generators. These technologies will help improve the overall affordability, resilience, and reliability of the energy grid. Power-electronic interfaces can be designed to provide a range of grid services including voltage and reactive power control, frequency control, and fault ride-though provisions. These services can help the grid by improving stability when programmed correctly. Energy storage devices provide a unique capability to grid operations and already perform a variety of services; but cost, industrial acceptance, safety, and equitable regulatory treatment remain limiting factors to widespread use. Buildings, EVs, and other end-use technologies can also provide grid services by regulating energy use. Improvements to grid infrastructure technologies (advanced switches, wires, cables, transformers, etc.) can help the overall operations in terms of both efficiency and reliability.

It is critical to validate device ability to provide a range of grid services building on the successful prior GMLC project. Validation will be used to ensure that devices meet the operational needs of a future electrical grid to preserve its key functional requirements while maintaining a high level of safety and reliability and support interoperability of new and emergent devices and systems.

Harmonized standards, evaluation metrics, methodologies, and other criteria for evaluating grid interaction of devices and integrated systems are essential to ensure optimal and safe integration into a modern grid. As new devices and systems continue to be integrated at multiple scales from both sides of the utility meter, these criteria will form the basis for a collective understanding and evaluation of performance expectations.

Finally, it is important to ensure that integrated systems (devices, fuels, sensors, communications, and control systems brought together) are capable of effectively and securely connecting, communicating, and operating in a coordinated fashion that maintains the desired results from each of the key stakeholders' perspectives across a range of physical scales (buildings, campus, microgrids, and distribution). Multiscale, integrated system validation occurs in both controlled laboratory settings and field demonstration locations. Evaluation and characterization of integrated system hardware, software, and controls provide clarity to research efforts and the various stakeholder groups so they can effectively address the technology gaps and adopt new innovations as they become available.

For certain types of integrated systems, such as those with energy storage devices, the relationship between system design, use of protocols, and lifetime economic value can be complex; in these cases it may be necessary to create a path to ensure there is sufficient data to provide the necessary information to achieve the most economically optimized design. Access to this data through sensing and measurements can provide a path toward flexible deployments that can enhance grid resiliency to occasional disruptions.

4.0 System Operations, Power Flow, and Control

As millions of new intelligent devices are being installed on the power system and new business models for the power system are considered, fundamental transformations in controlling the energy infrastructure are vital to achieving an electrical grid that is safe, resilient, reliable, secure, affordable, flexible, and sustainable. The system is becoming more complex with the integration of a range of new generation technologies, new and more flexible transmission and distribution equipment, and a myriad of new opportunities to manage demand. Under this new paradigm, potentially millions of intelligent devices will need to be coordinated with legacy control systems to support the power system across the electricity supply, delivery, and end-use ecosystem. New approaches for improving system operation for enhancing reliability and resilience will be employed. Research is necessary to investigate new technologies and approaches for improving system operations, power flow, and control in response to these changes.

Several key challenges must be addressed as these fundamental transformations affect our ability to control the power system.

1. There needs to be better understanding of how the various structures of industry organization and interaction impact system operations and control. These evolving structures that include markets and incentives are strongly linked to control design and implementations in the power system. This is particularly true as more links are established between distributed controllable grid assets and traditional market and dispatch structures. Real-time valuation and control of various ancillary services that are critical to the operation of the grid require greater coordination and management. It will be necessary to evaluate both the structure and design of markets and market interaction with the impacts on control design.
2. Coordination of transmission and distribution protection and control schemes, especially in relation to adaptive and robust real-time distributed control, has been challenging. Integrating coordinated automation requires unprecedented interoperability between devices at multiple levels (generation, transmission, distribution, end-use) while maintaining stability under a variety of operational conditions. A systematic framework for evaluating and prioritizing these issues is needed.
3. Interdependencies between infrastructures (e.g., fuel supply, communications) can compromise power grid resilience during extreme events. There is a need for enhanced robustness and/or graceful degradation of key interdependent infrastructure systems, and for modular and scalable operations-ready communications and controls that will survive during emergency conditions.
4. There needs to be a better integration of human operators into an increasingly complex automation environment, especially during off-normal conditions. During time-critical and potentially unique situations, human thinking is necessary to comprehend and take appropriate action. Better understanding of the cognitive limitations of operators and an effective means to enhance their interaction with various levels of automation are key challenges. The progression of human-machine interface and predictive systems is required, including robust trust and verification metrics.
5. Increased renewable integration into the power system has increased ramping and flexible operational requirements for dispatchable assets. Maintaining grid reliability and stability in systems with growing inverter-based resources demands innovative solutions to overcome diminishing

system inertia and lack of short-circuit current. New technologies in dispatchable power, including hybrid generation systems and carbon capture and storage, could potentially contribute to increased flexibility, but their control is not fully developed at system or grid integration levels.

In consideration of any future activities and subsequent projects within the system operations, power flow, and control technical area, cyber and physical security will be documented and addressed at the level(s) appropriate to the research topic (e.g., policy, conceptual, design, protocol, standard, system, component), aided by embedded security resources established by GMI's Security "T" strategy outlined in the Introduction section.

To address these key challenges, DOE and several teams of national laboratory researchers, working in collaboration with industry and academia, will focus on six areas of technical activities in coordination with the other grid modernization initiative elements. These six areas of technical activity will provide structure and guidance to current and future projects, as shown in Table 5.

Table 5. Activities and Technical Achievements for System Operations, Power Flow, and Control

Activity	Challenges	Technical Achievements by 2025
1. Architecture and Control Theory	1,2,3,4,5	• Encourage broader industry and regulatory adoption of the previously developed Grid Reference Architecture set via field implementations with external partners, providing tools and training, and by collaboration with other strategic MYPP activities, including advanced controls, sensing and measurement, markets and coordination, and the communications cross-cut areas. • Develop scalable control theory and algorithms to improve the cyber-physical resilience of energy infrastructures using a diverse portfolio of generation and DERs. As the power grid evolves from centralized to distributed generation, the control system transformation is necessary to optimize system operations and handle resilience issues spanning from localized to system-wide consistent with available regulatory mechanisms to enable broad implementation.
2. Coordinated System Controls	1,2,3,4,5	• Coordinate control system designs to build on the essential features of distributed agents and include human decision making directly into the autonomous operation. Because of their distributed nature, these systems will allow self-healing and time-sensitive responses to maintain resilience and include features such as graceful degradation of the control system if compromised. • These systems must provide interoperability and autonomous coordination between bulk generation (including fuel delivery infrastructure and/or carbon capture controls as applicable), transmission, distribution, and DERs including generation, storage, and demand response.
3. Advanced Analytics and Computation for Control	2,3,4	• Research, develop, and demonstrate future real-time operating environments that leverage high-performance computing and advanced algorithms for automating and coordinating protection and control with predictive, proactive, and preventive capabilities, non-linear (convex and non-convex) optimization, highly stochastic processes, and opportunities to deploy advanced trustworthy machine-learning algorithms.

Activity	Challenges	Technical Achievements by 2025
		• Enable development and deployment of next-generation energy management systems, ADMS, DER management systems, and MGC enterprise software solutions with rigorous system architecture and agile development approaches. • Advance decision support for operational systems through situational awareness including predictive analytics and visualization technologies.
4. Enhanced Power Flow Control Device Hardware	1,2,3,4	• Develop low-cost, efficient, and reliable power flow control devices, including power-electronic-based converters and controllable reactance, as actuators to enable improved controllability and flexibility of the grid. • Reduce risk of deployment by characterization in simulation and testing with communication and power flow control device hardware. • Develop interoperability and diversity in communication protocols for controlling power electronics devices, including low-latency communication to provide more robust control. • Focus on implementation issues associated with emerging technologies, including tracking development of advanced and flexible grid-forming inverters associated with generation (wind/solar/battery resources) and transmission and distribution equipment, including high voltage direct current (HVDC) and flexible alternating current transmission systems.
5. Enabling Flexible Generation	1,2,3,4,5	• Develop and deploy control schemes to enable the portfolio of generators (and hybrid generation schemes) to operate in a comprehensive manner enabling overall system objectives associated with resilience and flexible operations while maximizing efficiency and maintaining security for bulk generation, autonomous individual generating facilities, storage, and DER assets (coordinate with the generation and the device and integrated systems technical areas).
6. Cross-cut Initiatives	1,2,3,4,5	• Coordinate R&D for inherently secure and robust systems from a cybersecurity perspective, with an emphasis on new control systems, embedded control, and decision-making tools. Effectively connecting, communicating, and operating in a coordinated fashion with security by design (coordinate with the security technical area). • Leverage advanced modeling capabilities that are pertinent for real-time operations and control applications (coordinate with the planning and design tools technical area). • Deploy low-cost and reliable communications that can be leveraged to enable the system operations and control objectives, including deployment of testing capability of communication for high-speed protection and control applications (coordinate with the sensors and measurement technical area).

4.1 Prior System Operations and Control Projects

As development and application of system operation and control technology are embedded in many of the projects in GMI's other technical areas, the program will engage related projects in the GMI portfolio for coordinated development. Listed in Table 6 are prior related system operations, power flow, and control projects.

Table 6. Projects in the System Operations, Power Flow, and Control Technical Area

GMLC Project No.	Project Title	Description
FY20 2.2.1	Citadels	Enable the operation of networks of microgrids to support bulk-system operations, ensure continuous operation of critical end-use loads when the bulk system fails, and support bulk-system restoration. The operation of networked microgrids will coordinate centralized operations with distributed edge operations enabled using the OpenFMB reference architecture.
FY20 2.3.1	Validation, Restoration, and Black Start Testing of Sensing, Controls, and DER Technologies at Plum Island	Transform black start with DER and storage, from foundational research-based demonstrations to a viable method for restarting and restoring the bulk power system after critical outages. Will provide significant validation data for scale up simulation of utility partners use cases exercised at the facility and procedural documentation for future implementation across the nation.
Crosscutting Projects GMLC 1.2.1	Grid Architecture	Provide a set of architectural depictions, tools, and skills to the utility industry and its extended stakeholders to develop a national consensus on grid modernization and a common basis for roadmaps, investments, technology and platform developments, and new capabilities, products, and services for the modernized grid.
Demonstration Projects GMLC 1.3.01	Southeast Regional Consortium	Oak Ridge and Savannah River National Laboratories formed a Southeast Regional Consortium, with regional stakeholders including utilities, academia, regulatory agencies, and industry that focused on improving distribution system resiliency while increasing the concentration of DERs.
GMLC 1.3.09	Smart Reconfiguration of Idaho Falls Power Distribution Network for Enhanced Quality of Service	Demonstrate use of smart reconfiguration and protection system methods for enhancing the quality of power service for the Idaho Falls Power distribution network.
GMLC 1.3.10	Vermont Regional Partnership Enabling the use of DER	Develop a replicable approach for leveraging energy storage technologies to address these disruptive impacts and allow high penetration of renewable energy generation. Develop a technical approach for resilient distribution feeders with high percentages of low-carbon DERs.
GMLC 1.3.99	Transactive Campus Demonstration	Demonstrate significant energy cost savings in commercial buildings and integration of renewables at a regional scale by using the transactive control technology to coordinate number of energy assets.

GMLC Project No.	Project Title	Description
Foundational Projects GMLC 1.4.10	Control Theory	Achieve transferable, resilient, and deployable control solutions to develop control approaches and theory along with communications and information system architectures.
GMLC 1.4.11	Multi-Scale Integration of Control Systems	Develop an open framework to coordinate energy management system, distribution management system, and building management system operations.
Resilient Distribution System Projects GMLC 1.5.02	Resilient Alaskan Distribution System Improvements Using Automation, Network Analysis, Control, and Energy Storage (RADIANCE)	Deploy advanced technologies and methods for resiliency-enhanced operation of the regional distribution grid in the City of Cordova, Alaska, under harsh weather, cyberthreats, and dynamic grid conditions. The deployment will use multiple networked microgrids, energy storage, and early-stage grid technologies. This project introduces the concept of resilience by design, i.e., incorporating a cybersecure resilience framework with real-time sensing and controls at the design stage.
GMLC 1.5.05	CleanStart – Distributed Energy Resource Management System	Validate and demonstrate at scale a DER-driven mitigation, black start, and restoration strategy for distribution feeders. Includes integration of applied robust control, communications, analytics layers, and a coordinated hierarchical solution.
GMLC Program Specific Projects (a.k.a. “Category 2”) GM0061	Virtual Battery-based Characterization and Control of Flexible Building Loads using VOLTTRON	Enable utilities to use flexible building loads as virtual storage resources to provide grid services, integrate more renewable generation such as wind and PV, and improve building operational efficiency.
GM0062	Vehicle to Building Integration Pathway	Develop and demonstrate pre-normative methods for a standardized and interoperable communication pathway and control system architecture between plug-in EVs, EV support equipment, and building/campus energy management systems.
GM0063	Development of an Open-Source Platform for Advanced Distribution Management Systems	Create an open-source platform (GridAPPS-D) to enable power distribution software applications to be developed for any compliant system instead of just one. This project will reduce costs to develop, integrate, and maintain future applications; improve distribution system reliability; and simplify and accelerate system planning and operations R&D within the DOE labs and industry.
GM0076	Emergency Monitoring and Controls through New Technologies and Analytics	Develop a new generation of emergency control systems for the U.S. power grid based on a combination of new technologies and new analytic capabilities related to recent progress in the power system reliability assessment translated into new real-time algorithms for voltage stability and transient stability.

GMLC Project No.	Project Title	Description
GM0085	Systems Research Supporting Standards and Interoperability	Address the considerable uncertainty regarding the degree to which plug-in EVs can provide grid services and mutually benefit electric utilities, EV owners, and auto manufacturers.
GM0086	Modeling and Control Software Tools to Support V2G Integration	Determine the feasibility of vehicle-grid integration by quantifying the potential value, cost, complexity, and risks in different implementations. Allocate available value among stakeholders and determine pathways for electrification of transportation to enable beneficial grid services such as mitigating renewables intermittency.
GM0091	Unified Control of Connected Loads to Provide Grid Services, Novel Energy Management, and Improved Energy Efficiency	Retrofit control technology that increases the operational flexibility of loads in commercial buildings to improve energy efficiency, reduce peak demand, and reduce energy losses.
GM0140	VOLTTRON Controller for Integrated Energy Systems to Enable Economic Dispatch, Improve Energy Efficiency and Grid Reliability	Field test and commercialize a multipurpose controller and associated open-source algorithms that will ensure real-time optimal operation, increase electric grid reliability, and lead to clean, efficient, reliable, and affordable next-generation integrated energy system.
GM0172	VOLTTRON Message Bus Protocol Adapter	Extend the VOLTTRON platform with a common data model and include support for SEP2, DNP3, and OCPP, which are the most commonly used protocols for grid transactions and EV charging management.
GM0187	Community Control of Distributed Resources for Wide-Area Reserve Provision	Develop and demonstrate an ADMS that allows DERs to improve distribution system operations and simultaneously contribute to transmission-level services.
GM0252	Optimal Stationary Fuel Cell Integration and Control (DG-BEAT)	Implement an open-source dispatch and load control tool for building management that can communicate and transact with a fuel-cell integrated building system and the grid for optimized dispatch of building components, and develop a planning tool for optimal component selection and sizing.
GM0253 (Wind 0253)	Operational and Strategic Implementation of Dynamic Line Rating for Optimized Wind Energy Generation Integration	Develop the essential Dynamic Line Rating system to enable electric utilities to integrate current and future expansion of wind energy into the delivered energy portfolio. Includes necessary software and hardware components as well as assisting vanguard utilities in adoption of the system.
SI-1673 (31081)	Dynamic Building Load Control to Facilitate High Penetration of Solar PV Generation	Develop, demonstrate, and validate a sensing and control mechanism for using loads to mitigate variable PV generation to reduce two-way power flow and lessen voltage instability on distribution-level circuits.

GMLC Project No.	Project Title	Description
SI-1714 (DE-EE0000-1714)	Enabling High Penetration of Distributed PVs through the Optimization of Sub-Transmission Voltage Regulation	Develop a Coordinated Real-time Sub-Transmission Volt-Var Control Tool (CReST-VCT) to optimize use of reactive power control devices to stabilize voltage fluctuations caused by intermittent PV outputs. To capture the full value of the Volt-Var optimization, the project will aim to couple this tool to an Optimal Future Sub-Transmission Volt-Var Planning Tool (OFuST-VPT) for short- and long-term planning.
SI-1748 (DE-EE0001748)	ToolSuite for Increasing Performance and Reliability of Combined Transmission-Distribution under High Solar Penetration	Develop a suite of software tools that creates a holistic understanding of the steady-state and transient behavior of transmission-distribution networks' interaction under high PV penetration levels, along with the capability of real-time monitoring of the distribution systems and integration of system protection. The outcome will be to develop software tools to help improve grid reliability and performance of combined transmission-distribution systems with high solar penetration.
WGRID-04 (1.3.1.0.412)	Providing Ramping Service with Wind to Enhance Power System Operational Flexibility	Develop a probabilistic wind power ramp forecasting method to characterize and forecast ramps from a utility-scale perspective; design flexible ramping products that can be implemented in a new market model to co-optimize energy, reserve, and ramping; develop a "GridLAB-ISO" tool and integrate the proposed ramping product model into it; and use "GridLAB-ISO" to simulate an actual ISO system.

These system operation and control activities will continue to support broader DOE programs and initiatives, including offices and programs beyond the GMI portfolio of activities.

4.2 System Operation and Controls Benefits

Building a safe, resilient, reliable, secure, affordable, flexible, and sustainable power system requires increased use of distributed control coordinated across the electricity system ecosystem (generation, delivery, and end-use). Technologies that effectively, and currently or foreseeably, address uncertainty while maintaining resilient control under a wide range of operating conditions will be imperative. This will rely on fundamental advances in control theory, efficient mathematical algorithms for improved computational speed, data analytics, and power flow control devices. Implementation of these technologies requires harmonization of grid architectures and integration across various control system platforms. Achieving this vision represents an ambitious change to the existing power system and will require sustained research, development, and demonstration over multiple decades with close coordination among all stakeholders including industry (system operational entities and their vendors) and regulators as well as close coordination among other researchers including academia and industry-focused activities. The activities described in this section present a plan to achieve short-term objectives consistent with this longer term vision. Specifically, the architecture and control theory activities will build the foundation upon which coordinated system controls and advanced analytics and computation for control can be developed and deployed. These control system approaches and technologies will harness enhanced power flow control device hardware and enable flexible generation to provide for a safer, resilient, reliable, secure, affordable, flexible, and sustainable power grid.

5.0 Sensing and Measurement

Limited observability and control latency contributed to historic large-scale power disruptions and outages.[7] The transformation of the nation's energy infrastructure, continuous integration of new systems and devices, more complex device behaviors, faster dynamics, and more complicated system operation underlines the need for enhanced visibility and integrated state awareness throughout the system, across multiple spatial scales (national, regional, local, and device), and at multiple timescales (from microseconds to hours and days).[8,9] This is essential for timely assessment of grid health and operation performance, predictions of potential disruptions and their impacts, controlling the system with distributed intelligence, and fast response to destabilizing events and potential threats. In this context, protection and other control challenges must be addressed by continuous adjustments that require higher resolution sensing, new measurement methods, installations of additional sensing devices, and faster communication.

To develop enhanced visibility, several key challenges need to be addressed.

1. Value/cost of sensor implementation: It is imperative to evaluate cost and performance tradeoffs associated with development and installation of a number of new sensors and communication systems to enable reliable and secure operation of the energy system from generation to end uses relative to the context-dependent performance and value added to diverse stakeholders.
2. Measurement accuracy through disturbances: Sensors and measurement systems must provide accurate and timely data especially when events transpire. Other challenges under measurement accuracy include uncertainty and error. Measurement and data analytics systems must account for the increasing penetration of DERs and the effect this has on system operation, protection, and stability.
3. Communication constraints and data framework: Data transfer characteristics and data storage must match current and anticipated application requirements to enable both analytics and power grid operation in centralized, distributed, and fragmented modes. To reduce data transfer exchanges, analyses can be executed locally to quantify measurement uncertainty during transient and abnormal conditions. Distributed sensing and data architectures that support application decoupling can help improve system resiliency.
4. Lack of actionable intelligence: Data management, analytics, visualization, and cross-sector observability are needed to derive actionable information from large volumes of heterogeneous data (or limited amounts of data) and inform diverse decision and control systems as well as the electricity markets.
5. Security: Although sensing and communication systems can help detect and mitigate disruptive events, they are vulnerable to cyber/cyber-physical hybrid attacks. Hardware security, data quality and integrity, and cyber-physical resilience must be ensured throughout the processing chain.

[7] NERC: 1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report https://www.nerc.com/pa/rrm/ea/1200_MW_Fault_Induced_Solar_Photovoltaic_Resource_/1200_MW_Fault_Induced_Solar_Photovoltaic_Resource_Interruption_Final.pdf

[8] Future of Electric Grid Report. https://mitei.mit.edu/system/files/Electric_Grid_Full_Report.pdf

[9] EPRI Concept Paper, *The Integrated Grid, Realizing the Full Value of Central and Distributed Energy Resources*.

6. System interdependency: Due to the interconnected nature of electrical infrastructure to other critical infrastructures (e.g., oil/gas, communications, water, transportation, defense), any power disturbance has the potential to disrupt critical facilities with debilitating impact on national security, economic security, and public health and safety. Sensing and measurement requirements are not clearly defined across different sectors.

In the consideration of any future activities and subsequent projects within the sensing and measurement technical area, cyber and physical security will be documented and addressed at the level(s) appropriate to the research topic (e.g., conceptual, design, protocol, standard, system, component), aided by embedded security resources established by GMI's Security "T" strategy outlined in the Introduction section.

To address these key challenges, DOE and several teams of national laboratory researchers, working in collaboration with industry and academia, will bring their multidisciplinary knowledge to focus on key activities. This extensive expertise will integrate sensing technologies (getting information), analytics (including advances in machine learning and artificial intelligence), and decision making (use analytics results to inform resource management, etc.) across five priority technical areas as shown in Table 7.

Table 7. Activities and Technical Achievements for Sensing and Measurements

Activity	Challenges	Technical Achievements by 2025
Detecting Incipient Failure/Faults	1,2,3,4	• *Sensing:* New sensors to improve efficacy of traditional measurement systems to reliably capture fault signatures in real time. • *Analytics:* Robust detection of fault events and prediction of equipment degradation, combined with network-scale data analytics to assess fault impact on the grid and address changes to grid assets. Integration of embedded analytics within the sensing systems that can quantify measurement accuracy and uncertainty during transient conditions and predict probability of failure. • *Decision-making:* Tools to evaluate information gain from sensors to inform (1) cost-effectiveness of sensor installation and (2) persistent sensing strategies, e.g., to improve damage assessment.
Detecting and Predicting DER System Behaviors	2,4	• *Sensing:* Novel sensors and measurement systems, including embedded sensors within DERs and the Internet of Things, that can provide dynamic measurements of inverter-based DER systems, weather-dependent VRE systems, flexible loads, and their impacts on the grid. • *Analytics:* A suite of analytics tools, including embedded analytics (to reduce communication bandwidth requirements), utilizing highly granular spatial-temporal, multimodal data to characterize and forecast DER behavior (including inverters and power-electronic devices and autonomous flexible loads) and to quantify impacts on distribution and transmission systems. • *Decision-making:* Real-time visualization and recommendation systems to facilitate stable control of distribution systems with high penetration of DERs.
Supporting Emerging Generation **Technologies**	1,4	• *Sensing:* Low-cost high-performance sensors to monitor generator health in order to handle variable and extreme operating conditions. • *Analytics:* Prediction tools to improve fault response and maintenance of generators and hybrid energy systems to mitigate the risks of forced outages.

Activity	Challenges	Technical Achievements by 2025
		• *Decision-making:* Tools to evaluate information gain from sensors to inform stakeholders on asset health.
Enhancing Sensing System Resiliency	3,4,5	• *Sensing:* A scalable and secure sensing and communication system that is resilient and robust to extreme cyber and physical events and capable to predict and distinguish between man-made outages and naturally occurring failures. • *Analytics:* Robust data analytics and network modeling and reconstruction techniques to provide accurate damage assessment results when the data quality is largely impacted by natural disasters and malicious attacks.
Monitoring Critical Infrastructure	3,4,5,6	• *Sensing:* Novel sensors and measurement systems that can provide dynamic temporally granular measurements. Develop a suite of multi-parameter sensors for extended-grid-state monitoring, while providing situational awareness of network communication information of a utility's (information and operation technologies) system. • *Analytics:* Integrated analytics framework for real-time monitoring of critical infrastructure and interdependencies, with focus on (1) early warning of deteriorating system conditions for operators to take corrective action, (2) holistic data management of interdependent infrastructures, and (3) improvement of wide-area system situation awareness and reliability of coupled systems. • *Decision-making:* Optimal control of decentralized and agile communication networks informed by data analytics needs and visualization tools to enable timely diagnostics, prognostics, and decision making.
Secure, Resilient Communication System	3,5,6	• *Analytics:* System requirements for data transfer to ensure the appropriate level of information is securely and selectively transferred to appropriate stakeholders. Defined computing requirements will enable actionable intelligence on the edge and reduce communication constraints. • Resilient, secure, and affordable communication architecture demonstrated across multiple regional and industrial (e.g., gas, electric) boundaries. Prioritize secure data transport in degraded conditions and ensure reliable communications under extreme conditions. Integration of low-cost, robust, low-latency, and secure communication capabilities (satellite, radio frequency, cellular, Wi-Fi, etc.).

The aim is to advance these concepts from sensor design to analytics development to testing and validation. Benchmarked testing protocols and data sharing across systems will enable faster deployment in the field.

5.1 Activities and Prior Sensing Projects

As development and application of sensing and measurement technology are embedded in many of the projects in GMI's other technical areas, the program will engage related projects in the GMI portfolio for coordinated development. The GMLC effort identified current state-of-the-art technologies.[10] Building

[10] https://gmlc.doe.gov/projects/1.2.5; GMLC Sensing & Measurement Strategy Technology Review Assessment Final Report.

off these systems as well as prior GMLC activities is important to achieve the vision and mission of the GMI. Listed below are GMLC projects that address sensing and measurement challenges.

Table 8. Sensing Projects and Activities

GMLC Project No.	Project Title	Description
GMLC 3.4.2	GridSweep: Frequency Response of Low-Inertia Bulk Grids	Create a new class of measuring instrument to detect and analyze oscillations of bulk grids that potentially threaten the stability of the grid.
GMLC 3.3.3	Incipient Failure Identification for Common Grid Asset Classes	Operationalize a multitiered approach for advanced analytics and sensing integration, to deliver incipient fault identification at multiple granularities (from short-term local failures to longer term predictive diagnostics and prognostics) for common distribution assets, enabling a proactive approach toward improving reliability and resiliency of the energy delivery system.
GMLC 1.2.5	Sensing and Measurement Strategy	Specify measurement requirements, data management, and communication systems to support MYPP goals. This includes 1) definition of grid state, 2) roadmap development, and 3) optimization framework for sensor placement.
GMLC 1.4.4	Advanced Sensor Development	Develop low-cost, more accurate sensors to help increase visibility throughout the energy system including transmission, distribution, and end-use. Thirteen different technologies have been developed including asset monitoring devices to help determine grid component state prior to failure.
GMLC 1.4.9	Integrated Multi-Scale Data Analytics and Machine Learning for the Grid	Develop a data platform to synchronize disparate data sources for distribution grid and buildings analysis and control to enable future distributed applications.
GM0072	Suite of Open-Source Applications and Models for Advanced Synchrophasor Analysis	Develop a suite of software and phasor measurement units and synchrophasor datasets for power system planning, modeling, and analysis. All applications are based on the common open platform concept, have a common data format structure, and have been released under an open-source license.
GM0077	Advanced Machine Learning for Synchrophasor Technology	Developed a suite of machine-learning-based tools to detect and localize frequency events within seconds of occurrence.

These sensing and measurement activities support other DOE programs and initiatives. For example, GMI is working with the North American Energy Resilience Modeling (NAERM)[11] team to address communications and data processing needs for this DOE/Office of Electricity priority initiative. GMI also coordinates with DOE/CESER on collaborative R&D for next-generation tools and technologies to improve the cybersecurity and resilience of the nation's critical energy infrastructure. GMI activities will

[11] North American Energy Resilience Model, Department of Energy, July 2019; https://www.energy.gov/sites/prod/files/2019/07/f65/NAERM_Report_public_version_072219_508.pdf.

be coordinated with and build on projects funded by DOE ARPA-E, Fossil Energy, Nuclear Energy, CESER, Electricity, and EERE programs.

5.2 Sensing and Measurement Benefits

Fast, high-fidelity, affordable, and high-resolution measurements increase grid visibility and allow timely and precise grid event detection, protection, and control. Utilities will be able to assess the grid operational state more comprehensively in real time, predict behavior and potential disruptions, quickly respond to events (both natural and man-made), and better address future challenges. Enhanced situational awareness of the entire power system allows more efficient, effective, flexible, and secure 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 predictive maintenance programs ubiquitously throughout electric transmission and distribution systems will provide utilities and other stakeholders with sufficient warning time and specificity to enable predictive and prescriptive actions that prevent disruptive and costly failures before they occur. Integration with decision and control advances will result in more effective asset utilization and defer or mitigate 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 infrastructures and services under all predictable circumstances.

6.0 Planning and Design Tools

Planning and design tools are used widely within the grid community to support policy development, economic assessments, engineering design, and risk and vulnerability analysis that drive operations and capital investments. These tools are embedded in the numerous modeling, simulation, and analysis software packages used in planning and design, performing such technical functions as capacity expansion planning, production cost modeling, contingency analysis, modeling dynamic response, and transient stability analysis. Unfortunately, existing tools are not keeping pace with the increasing system complexity and computational requirements of a rapidly changing electric grid. Examples of research gaps in system complexity include understanding the impacts of external sectors such as communications, NG, and transportation on grid performance; improving models for new technologies such as inverter-based resources and new fossil fuel generator concepts (e.g., CO_2 capture and use); and addressing new threats such as cybersecurity. An example of research gaps in computing include performing highly detailed scenario analysis using economic models that can consume millions of hours of computer time.

To manage this complexity and overcome these gaps, R&D is needed to address a wide range of algorithmic, methodological, and software challenges. These can be arranged from very large-scale considerations to key underlying challenges as follows:

1. Capturing interdependencies: While recent advances such as the Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS) have enhanced our ability to simulate the coupled nature of multiple critical infrastructures (e.g., NG and power grid), there remain challenges. These include effectively incorporating grid models with increased electrification (e.g., transportation and buildings); simulating the interactions of power flow, controls, and communication; and bridging multiple spatial (bulk power system to buildings) and temporal (years to microseconds) scales for the grid alone and for multi-energy systems.
2. Modeling human dynamics: Technology is not the only contributor to system complexity. Human interactions with the power system and connected infrastructure—operator management of extreme events, customer adoption of EVs, etc.—are critical to actual grid planning and operations. Human behavior is seldom captured in modern modeling tools. Non-physical factors that "bound rationality" such as non-economic preferences, peer influence, and risk aversion can lead to very different decisions. Thus, validating such models can be very challenging.
3. Modeling emerging and future components: Even within the power grid, the rapid increase of new technologies—such as advanced inverters, distributed control schemes, small modular nuclear reactors, DERs, changing loads, and fossil-hybrid generation—demand advances in both realistic new models and support for higher space and time fidelity compared to similar analysis for traditional grid systems. There is an urgency to developing these models so as to impact timelines for development and deployment.
4. Integrating risk and uncertainty: Multisector coupling, human interactions, and massive increases in the number of new technologies all introduce unprecedented avenues for uncertainty across timescales from operational (e.g., weather impacts on load and renewables, intentional threats) to long term (e.g., fuel price, technology development, and policy). Yet existing planning tools and

operational paradigms use simplified deterministic approaches that cannot adequately evaluate corresponding risks or efficient strategies for managing them, especially at realistically large grid scales.

5. Improved simulation of inertia: Existing model structures and solution methods can break down outside of the narrow range of operating conditions seen on today's grids, yet both expanded use of power-electronic interfaces for generation (e.g., inverters, HVDC) and demand (e.g., variable speed drives), and operations of traditional generation during wide excursions of resilience events may fall far outside these ranges and capabilities.
6. Ensuring result integrity: New models, simulation approaches, and tool interconnections may introduce error sources in analysis. This is further complicated by gaps and errors in data and their availability. R&D are needed to ensure that novel simulations for grid modernization accurately capture reality.
7. Leveraging modern computing advances: Recent advances in computing architectures (e.g., cloud, graphic processing units, custom chips) and algorithms (e.g., machine learning) have caused revolutions in other fields, but fundamental research is required to unlock potential advances for the next generation of power system planning tools.

In the consideration of any future activities and subsequent projects within the planning and design tools technical area, cyber and physical security will be documented and addressed at the level(s) appropriate to the research topic (e.g., policy, conceptual, design, simulation, software, system, component), aided by embedded security resources established by GMI's Security "T" strategy outlined in the Introduction section.

To address these key challenges, DOE and several teams of national laboratory researchers, working in collaboration with industry and academia, will focus on seven areas of technical activities that will provide structure and guidance to current and future projects, as shown in Table 9. While other MYPP technical areas such as generation includes modeling research, the planning and design tools technical area represents a broader set of challenges associated with grid modeling including computer science, applied mathematics, probabilistic methods, scalable algorithms, and data science. Finally, research in this technology area will be coordinated with the other seven areas of the MYPP to develop new research concepts and conduct crosscutting projects.

Table 9. Activities and Technical Achievements for Planning and Design Tools

Activity	Mapping to Challenges	Technical Achievements by 2025
1. Multiple Domains and Technologies	1, 2, 3, 5, 7	• Develop and validate computational methods and tools for modeling dynamic interactions across transmission, distribution, different energy technologies (e.g., new solar technologies, carbon capture devices), and critical infrastructure (e.g., communications, oil and gas pipelines). • Improve and validate models for individual grid technologies to improve fidelity and accuracy for multi-domain/technology simulations. Work could range from models of transformer failure based on geomagnetic disturbances to human operator actions subject to blue-sky to black-sky events.

Activity	Mapping to Challenges	Technical Achievements by 2025
		• Develop an integrated modeling environment to simulate grid management compute systems, information technology, and communications to effectively evaluate new control approaches and incorporate into multi-domain planning and design tools.
2. Techno-economics	1, 4, 5, 6, 7	• Enhance capacity expansion approaches for generation, transmission, and distribution to support investment planning for modern grid systems with high penetration of emerging technologies while improving cost-effectiveness, reliability, and resilience. • Develop, calibrate, validate, and deploy models for pricing different levels of resilience and other risks to justify levels of investment considering economy-wide impacts of extreme events under a range of system conditions and customer behaviors.
3. Fast Grid Phenomena	3,5,6,7	• Develop and validate scalable simulation capabilities for fast grid phenomena from hundreds of nodes/devices to interconnect scale approaching millions of devices, while solving in minutes. • Adapt fast grid phenomena simulators and component models to accurately capture system behavior under both widespread non-synchronous resource deployment and other weak grid conditions.
4. Extreme Events	1,2,3,4,5, 6,7	• Develop fully autonomous tools for multi-contingency analysis, reducing turnaround time from hours to seconds at interconnect scale, while capturing uncertainty and high-impact low-probability events across multiple infrastructures to provide rapid screening capability for high-impact contingencies for subsequent in-the-loop analysis by human operators. • Develop and validate simulation approaches for mitigation (pre- and post-event), restoration and recovery, and corrective actions. Reduce solve times from hours to minutes to support advanced look-ahead and situational awareness applications for enhancing resilience and reliability.
5. Model Accuracy and Sufficiency	2,5,6,7	• Develop data repositories for analysis and validation of planning and design tools, including open-access synthetic datasets and sensitive real-world datasets available in a DOE-hosted secure platform to ensure relevance and fidelity of planning and design tools for industry. • Develop approaches to characterize and analyze uncertainty for single-domain, multi-domain, and multi-infrastructure models to rigorously assess propagation of errors across disparate infrastructures and increase trust in coupled infrastructure models that is necessary for eventual operations.
6. Computational Approaches	3,6,7	• Develop machine-learning methods for planning and design applications that are resilient to low-quality and adversarial data. Deploy machine-learning approaches to reduce model solve times by up to 50%, leveraging significant available historical input and solution data. These activities will mitigate potential impacts of low-quality data and adversarial injections to operations computational models. • Develop computational models and solvers to address uncertainty associated with spatial and temporal correlations in load and renewables production, considering systems with 10K buses under

Activity	Mapping to Challenges	Technical Achievements by 2025
		significant renewables penetration; scale performance of interconnect-scale transmissions electromagnetic transient solvers.
7. Cross-Cut Activities	1,2,3,4,5,6,7	• Coordinate planning and design tool development efforts to ensure integration of and relevance to operations, controls, and communications applications, including advanced grid management systems. • Support transition of advanced planning tools to provide institutional support for public utility commission (PUC), state, local, and tribal energy analyses. Coordinate with industry to drive requirements on planning and design tools, focusing efforts on highest-impact model fidelity enhancements. • Working with the generation technical area team, develop planning tools to understand the system benefits and impacts of new hybrid generation concepts (e.g., coordinated nuclear and megawatt-scale storage), improve the accuracy of generation models, and assess the value of generation fleet flexibility to affordability, resilience, etc.

6.1 Prior and Current Planning and Design Tool Projects

Listed in Table 10 are a selected subset of prior and current GMLC-funded planning and design tool projects.

Table 10. GMLC Planning and Design Tool Projects

GMLC Project No.	Project Title	Description
1.3.2 (Current)	HELICS+: From Facilitator to Hub	Expand the capabilities of HELICS to natively support domains beyond transmission, distribution, and communication; to greatly enhance the ease of use for modelers; enable enhanced performance particularly in multi-domain convergence and support for extremely large numbers of simulations such as distributed control/Internet of Things; and address unique challenges around hardware-in-the-loop and near real-time simulation.
1.1.3 (Current)	Development and Calculation of Performance-Based Resilience Metrics for Defense Critical Infrastructure	Develop resilience metrics relevant to defense critical infrastructure owners and operators. It develops and tests a dynamic model consisting of complex behaviors that calculates resilience metrics subject to large-extent, long-duration power outage scenarios on the bulk power system.
1.4.15	Development of Integrated Transmission, Distribution and Communication Models	Develop a next-generation co-simulation tool (HELICS) to model the connections between transmission, distribution, and communication systems. It successfully enabled interactions between leading commercial and lab developed simulators for computing environments ranging from high-performance computing to laptops.

GMLC Project No.	Project Title	Description
1.4.17	Extreme Event Modeling	Develop a suite of computational tools for modeling cascading outages at high fidelity and enable new approaches for n-k contingency analysis.
1.4.18	Computational Science for Grid Management	Transition new DOE innovations in computational science to GMLC and support development of a unified electric grid math library optimization, dynamics, and uncertainty.
1.4.26	Development and Deployment of Multi-Scale Production Cost Models	Develop scalable algorithms and a deployable tool for modeling deterministic and stochastic production costs at interconnection-wide scales.
1.3.33	Interconnections Seam Study	Develop a wide-area analysis of the reliability and efficiency of four transmission futures for the United States. Each future explored a proposed modernization of the facilities that connect the western and eastern power systems.
WGRID-38	North American Renewable Integration Study	Develop an analysis for how the power systems of Canada, the United States, and Mexico could be planned to work together. The analysis sought to understand the impacts of infrastructure investment and changing operational practices on costs of providing electricity in the modern electricity grid in North America.
1.3.21	Alaska Microgrid Partnership	Develop and implement a technical and economic assessment of remote-island Alaskan community microgrids focused on reducing imported energy by 50%.
GM0057	LPNORM: A LANL, PNNL, and NRECA Optimal Resiliency Model	Build a network design tool to support decision makers in upgrading distribution systems for resilience to extreme events.
GM0074	Models and Methods for Assessing the value of HVDC and Medium-Voltage Direct Current Technologies in Modern Power Grids	Develop models and methods for assessing and amplifying the value of direct current technologies. The multi-objective control and system models developed in this project targeted solutions to current and future issues of regional transmission organizations, independent system operators, and utilities by HVDC systems.

6.2 Planning and Design Tools Benefits

Research in planning and design tools will be critical in enabling a wide range of stakeholders—from engineers to policymakers—to achieve the GMI goals. Research in multiple domains and technologies will enable understanding of impacts of NG and other sectors to electric grid operations and improve understand of new generation technologies in the context of the existing and future generation fleet. New techno-economic tools will provide pathways to performing tradeoffs between cost and other important factors associated with resilience, reliability, etc. Research in tools for fast grid phenomena will produce more accurate modeling approaches to new inverter-based and solid-state devices that are critical to new grid control and protections. Research in extreme events modeling will provide quantitative tools to assess impacts of natural and man-made threats and hazards to short operations, restoration, and recovery. Data repositories and uncertainty quantification methods developed under model accuracy and sufficiency will be critical to validate new complex modeling software and provide a means of quantifying the errors in simulations and analyses. Finally, computational approaches provide both algorithms, new computer hardware, and math libraries required to scale calculations to timeframes useful for decision making.

This work is intended to benefit three groups of stakeholders: (1) engineering and planning staff at utilities, PUCs, regulators, etc.; (2) industry vendors who provide tools for industry and regulatory customers; and (3) academic and other research organizations developing and applying next-generation modeling tools. The research described in this section will be transitioned for external use via collaborations with tools developers and users with relevant and challenging problems. Such collaborations will provide a pathway to deployment into industry, academia, and government programs such as NAERM.

7.0 Resilience

Our nation's power grid must be more resilient to an evolving spectrum of threats and hazards. DOE's resilience research develops grid architectures that are inherently resilient to all hazards, at low cost and while preserving other key operational criteria such as stability, reliability, etc. As the engine of our industrial and economic growth, the electric grid has grown and evolved over the past century with emphasis on providing reliable power at all times and has become a critical element of our national security and defense infrastructure. Today, the grid faces ever-increasing and complex threats, including intensifying cyber and physical attacks, severe weather, wildfires, and fuel delivery failures. Coupled with factors such as managing some legacy infrastructure while increasing reliance on digital and communications technologies, these threats can cause devastating large-area, long-duration outages.[12] Our standard measures of reliability and today's accepted planning and operational practices do not sufficiently address these threats.

The technological transformation of the grid, including renewables, DERs, and smart grid, presents both new vulnerabilities as well as opportunities for resilience. The President's National Infrastructure Advisory Council defines resilience as the ability to prepare for and adapt to changing conditions and reduce the magnitude and/or duration of disruptive events.[13] This is differentiated from the NERC definition of reliable operation, which focuses strictly avoiding instability, uncontrolled separation, or cascading failures of the bulk power grid.[14] DOE is leading the transition to a resilient power system that minimizes the impacts of such events. NAERM will be informed by such developments, which will be applied to Defense Critical Energy Infrastructures as well as civilian applications. Specific challenges to be addressed with regard to resilience include:

1. Ensuring secure energy supply chains and delivery systems.
2. Mitigating vulnerabilities associated with interdependencies between the electric grid and other infrastructures.
3. Achieving sustained system availability with current technologies, architectures, and computing tools while the grid continues to evolve with the addition of new technologies.
4. Understanding human-machine interfaces and effects of human behavior, including societal, physical, and economic impacts.
5. Developing new analytical methods that provide readily usable decision and visualization tools for disaster mitigation and recovery.

In the consideration of any future activities and subsequent projects within the resilience technical area, cyber and physical security will be documented and addressed at the level(s) appropriate to the

[12] National Academies of Sciences, Engineering, and Medicine 2017. Enhancing the Resilience of the Nation's Electricity System. Washington, DC: The National Academies Press. https://doi.org/10.17226/24836

[13] NIAC Surviving a Catastrophic Power Outage: How to strengthen the Capabilities of the Nation, 2018, https://www.cisa.gov/sites/default/files/publications/NIAC%20Catastrophic%20Power%20Outage%20Study_FINAL.pdf

[14] Glossary of Terms Used in NERC Reliability Standards, June 2, 2020. https://www.nerc.com/files/glossary_of_terms.pdf

research topic (e.g., policy, conceptual, design, procedure, system, component), aided by embedded security resources established by GMI's Security "T" strategy outlined in the Introduction section.

Resilience comprehensively reaches across all areas of grid research; coordinating activities across the GMI will ensure appropriate integration of resilience concepts. Specifically, this research will guide and incorporate valuation and metric outputs from the institutional support technical area (Section 9.0); inform designs for graceful degradation with the system operations, power flow, and control area (Section 4.0); leverage advancements in energy storage and power electronics from the devices and integrated systems area (Section 3.0); build on software advances from planning and design tools (Section 6.0); take advantage of the vast data generated in the sensing and measurement area (Section 5.0), and leverage cybersecurity resilience research from the security area (Section 8.0).

To address these challenges, DOE and national laboratory researchers, working in collaboration with industry and academia, will focus on the key thrust areas and target technical achievements shown in Table 11. It is anticipated that individual research projects may focus on one or more than one activity area, depending on the application or specific technology.

Table 11. Activities and Technical Achievements for Resilience

Activity	Challenges	Technical Achievements by 2025
1. Prepare	1,2,3,4,5	*Approach*: All-hazards planning to characterize and implement system resilience—considering infrastructure interdependences, diversity in generation sources, and supply chains—against emerging multifaceted threats (including physical, cyber, extreme weather, pandemic, wildfire, geomagnetic disturbance, and earthquake). Develop resilience-based criteria for performance of the power system. *Outcomes*: A full threat-to-consequence characterization of various resilience tradeoffs; a value-based approach to resilience decision making that serves the U.S. government, private sector, and other stakeholders. Software tools that identify and quantify the costs and benefits of proposed resilience investments.
2. Adapt	2,3,4	*Approach*: Multiscale, self-healing grid control methodologies and processes that implement graceful degradation over wide areas. Advancements to improve resilience to disruptive events including coordination of grid components that add protective grid services to all hazards (e.g., component hardening, parts inventory, energy storage, and adaptable transmission and distribution architectures), fuel switching capabilities, and emergency preparedness measures. *Outcomes*: Conditions, requirements, and integrated technology demonstrations for a highly adaptive grid infrastructure on multiple physical and timescales.
3. Withstand	2,3,5	*Approach*: Widely distributed, dynamic power system elements organized and selectively hardened to prevent destabilization of controlled systems. Advanced data analytics and cognitive learning, spanning timescales and data sources across the system lifecycle, to enable understanding of the state of threats and real-time resilience. More comprehensive analysis of compounding hazards and cascading impacts to understand the potential

Activity	Challenges	Technical Achievements by 2025
		series of events and interdependencies that may trigger additional impacts or hazards. *Outcome*: Resilient materials, components, and systems that address the need for power to critical loads at all times.
4. Recover	1,4,5	*Approach*: Field-deployable tools and technologies to improve grid decision making, planning, and prioritization during restoration and recovery from disaster events. Assessment of critical system loads to maintain lifeline infrastructures and critical functions. Achieve optimal recovery in coordination with other infrastructures and leverage all resources considering supply chains to gradually recover system service to critical priority loads and finally to non-critical loads. *Outcomes*: Technologies and tools to minimize societal costs of power outages across end-use sectors.
5. Integrate and Communicate	1,2,4,5	*Approach*: Data collection from events to improve and validate threat, vulnerability, and system behavior models. Dissemination of resilience technologies and tools to other GMI program areas for rapid utilization. *Outcomes*: A broad-based and fully integrated approach to resilience across GMI and in continuing coordination with DOE initiatives such as NAERM.

These technical thrust areas will provide structure and guidance to current and future projects.

7.1 Activities and Prior Resilience Projects

GMI has invested in a number of resilience-related projects, including a funding call in 2017 focused specifically on resilient distribution systems. Several of these projects are listed in Table 12. The last two projects in this table are investments associated with the 2019 GMLC call. HELICS and many other products from these projects are being leveraged for development of NAERM.

Table 12. Prior and Current Resilience Projects

GMLC Project	Project Title	Description
GMLC 1.3.04	Industrial Microgrid Analysis and Design for Energy Security and Resiliency	Develop methodology of designing industrial-scale microgrids and determine their effects on facility risk and ancillary grid services with a large private sector partner.
GMLC 1.3.11	Grid Analysis and Design for Energy and Infrastructure Resiliency for New Orleans	Propose key electrical distribution system upgrades and advanced microgrid pilot projects that can help bolster community-level storm resilience for New Orleans and other coastal U.S. cities.
GM0119 GM0217	Improved Forecasts of Electric Outages from Tropical Cyclones	Improve forecasts of distribution-level electric outages for tropical cyclone events affecting U.S. territory in the Caribbean, Atlantic seaboard, and Gulf of Mexico regions.
GM0131	A Closed-Loop Distribution System Restoration Tool for Natural Disaster Recovery	Develop a decision support tool that will assist utilities in performing distribution restoration after extreme weather events in an optimal and efficient manner.

GMLC Project	Project Title	Description
GM0180	Recommendations for Population, Location, and Operation of a Strategic Transformer Reserve	Provide inventory, logistic, and procedural assessments of a transformer reserve to respond to incidents that result in the loss of large power transformers and improve recovery time.
GMLC 1.5.01	Grid Resilience and Intelligence Platform (GRIP)	Develop a suite of novel software tools to anticipate, absorb, and recover from extreme events.
GMLC FY20.1.1.3	Energy Resilience for Mission Assurance	Incorporate national security objectives into power system planning by theorizing, demonstrating, and vetting approaches to explicitly represent mission performance during long-duration power system disruptions.

7.2 Resilience Benefits

The nation's electric system must be positioned to operate through current threats while adapting to mitigate threats and hazards yet unknown. Thus, this research will lead to resilient power sector architectures from devices to systems to systems-of-systems and more resilient system lifecycles covering a spectrum of legacy and emerging technologies. The outcomes of resilience research will directly support DOE's continued development of NAERM and its application to Defense Critical Energy Infrastructures and the civilian infrastructure.

8.0 Security

Malicious threats pose a significant challenge to the power grid given its sheer physical vastness, interconnectivity, and enormous operational complexity with new and legacy components involving architectural and supply chain issues. Over the past five years, the cyberthreat to the power grid has evolved significantly and continues to advance. The disruption of the Ukrainian power grid in December 2015 marked the first time a cyberattack was used to interrupt the delivery of electricity to customers. One year later, the December 2016 Ukrainian power grid attack introduced Crashoverride/Industroyer, the first malware specifically designed to attack the power grid. Additionally, physical threats from kinetic and directed energy weapons persist as well as attacks using emerging technologies like unmanned aerial vehicles and consumer-owned drones. National-level exercises[15] provide an opportunity for electric utilities to demonstrate their response and recovery actions to a hypothetical coordinated cyber and physical attack. Traditionally, these types of exercises use blue-sky backdrops, but it is essential they expand to include settings during pandemic, storm, or other natural disaster event contexts.

It is also important to recognize that the electric grid faces threats from a wide variety of adversaries. These threats range in capability and motivation from the disgruntled novice to highly sophisticated adversaries who can leverage the full resources of a nation-state to create and insert vulnerabilities into a system and exploit them to meet their goals on long-term horizons.[16] Not all utilities are equipped with the resources and knowledge to address the threat from higher tier adversaries, so partnership with government entities is essential to thwart the full spectrum of attacks. This approach aligns with the national security strategy[17] and current DOE security plans.[18]

Key challenges considered under the GMI that must be addressed to keep the grid secure in light of growing and evolving threats and infrastructure interdependencies include:

1. Understanding and securing the physical-cyber nexus where digitally initiated attacks result in physical consequences in the power grid. One area of interest is evolution of the grid attack surface due to infrastructure interdependencies and the addition of new technologies at the grid edge, including DERs, energy storage, small modular reactors, EVs, and other technologies.
2. Detecting and mitigating insider threats and vulnerabilities imposed through manipulating human behavior. Areas of interest include increased threats from social media, increased availability of commercial and consumer data, misinformation threats, privacy invasion, and mobile device threats.

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[15] GridEx, https://www.nerc.com/pa/CI/CIPOutreach/Pages/GridEx.aspx

[16] Executive Order on Securing the United States Bulk Power System, May 1, 2020 https://www.whitehouse.gov/presidential-actions/executive-order-securing-united-states-bulk-power-system/

[17] National Security Strategy, December 2017 https://www.whitehouse.gov/wp-content/uploads/2017/12/NSS-Final-12-18-2017-0905.pdf

[18] DOE Multiyear Plan for Energy Sector Cybersecurity, 2018 https://www.energy.gov/sites/prod/files/2018/05/f51/DOE%20Multiyear%20Plan%20for%20Energy%20Sector%20Cybersecurity%20_0.pdf

3. Securing the operational technology supply chain. Research will explore securing the supply chain for legacy systems, novel technology, and technology entering the industrial space as a result of information and operational technology convergence.
4. Advancing capabilities to move rapidly from discovery of a threat or attack to executable action. Research will explore the application of artificial intelligence, machine learning, and other techniques to shorten the time between discovery and recovery.
5. Grid-focused education and training tools and capabilities to prepare the utility sector to rapidly address cyber threats and to incorporate advances in technologies and techniques to secure the grid from the spectrum of cyber and physical threats. This research area will take into account the potential of a cyber or physical-cyber coordinated attack with other adverse events.
6. The security technical area has an ongoing obligation to provide support to every other technical area. CESER, with an explicit mission of grid cyber and physical security, will be responsible for establishing a security services and advisory resource within this technical area. This service will work as an *innovation partner* for all technical areas as well as providing guidance and advising new GMLC projects initiated under the GMI. CESER will be responsible for providing subject matter expertise and resources to each technical area for the horizontal security strategy and for its funding.

The security component of this MYPP defines key activities for DOE grid modernization based on the National Institute of Standards and Technology cybersecurity framework[19] but expanded to secure against both cyber and physical threats, account for the diverse sophistication of adversary levels, and capture the need for enduring security. Education, training, and information sharing for electricity sector stakeholders will also be key to implementing the outcomes under each activity. Proposed technical achievements by activity area are shown in Table 13.

Table 13. Activities and Technical Achievements for Security

Activity	Challenges	Technical Achievements by 2025
1. Identify	1,2,3,5	Intelligence and threat-informed proactive technologies and solutions for consequence prioritization, quantitative risk assessment, asset inventory and management, and critical failure/component analysis to improve understanding of systems and emerging threats, including the spectrum of cyber and physical threats, while taking into account the possibility of concurrent multifaceted hazards (storm, pandemic, wildfire, other) and vulnerabilities in the bulk grid and grid edge.
2. Protect	1,2,3,	Technologies and standards that significantly increase the difficulty for attackers to achieve their desired outcomes and maintain resilience and enduring security, including capabilities to secure the supply chain. Repeatable or automated approaches to verify software, firmware, and hardware that control devices in the electric grid, and secure and assure communications and commands over operational technology networks. Technologies that leverage component diversity and engineered functions to create secure systems from insecure components. Leveraging the increasingly distributed nature of the grid

[19] https://nvlpubs.nist.gov/nistpubs/CSWP/NIST.CSWP.04162018.pdf

Activity	Challenges	Technical Achievements by 2025
		to enable decentralized control and operation, allowing for continued function through a compromise.
3. Detect	2,3,4	Advanced cyber-physical data analytics and cognitive learning, spanning timescales and data sources across the system lifecycle, to enable proactive and real-time detection of compromise. Methodologies, architectural frameworks, and security metrics that assess system degradation to all hazards and provide diverse attack recognition. Capabilities for sector-wide situational awareness combined with time-sensitive analysis, visualization, and dissemination of near-real-time actionable cyberthreat and vulnerability information.
4. Respond	2,4	Increasingly automated responses to cyber and other hazards so infrastructure can respond to attacks at the speed those attacks are generated. This includes developing a wide range of responses from low-regret actions that can easily be executed to high-regret options.
5. Recover	2,4,5	Technologies, education, training, and information sharing to speed up recovery time, reconstitute system operations in compromised environments, improve forensics analysis, and advance overall learnings from malicious attacks.

These activities provide structure and guidance to current and future projects and strongly link to other technical areas in this strategy. Specifically, this research will be closely coordinated with the sensing and measurement area (Section 5.0) because of the emphasis on communication systems; the institutional support area (Section 9.0) for security training, metrics, and valuation; the devices and integrated systems area (Section 3.0) for supply chain and device level security; the system operations and control area (Section 4.0) to provide tools that improve security awareness and real-time grid response during a security event; the generation area (Section 2.0) for bulk grid generation security; and the resilience area (Section 7.0) to assure resilience of security systems is considered.

Other government agencies, including the Department of Defense and Department of Homeland Security, are also investing significant resources in the security area. Coordination across current DOE investments with these other efforts is necessary to maximize effectiveness.

8.1 Activities and Prior Security Projects

The GMI has invested in several security-related projects, with an emphasis on cybersecurity, as summarized in Table 14. The last five projects are newly funded under the 2019 Grid Modernization Laboratory call.

Table 14. Prior and Current Security Projects

GMLC Project No.	Project Title	Description
GMLC Project 1.4.23	Threat Detection and Response with Data Analytics	This project was the first effort looking at various data sources on the distribution system that could potentially be used for identifying and detecting cyberattacks and differentiating them from physically induced events.
GM0068	MultiSpeak® - Secure Protocol Enterprise Access Kit (MS-SPEAK)	Develop ESB+ (enterprise service bus) to support increased interoperability and security of the MultiSpeak standard and reduce costs for its use.
GM0100	Cybersecurity for Renewables, DERs, and Smart Inverters	Develop a cybersecurity framework that can be used for analysis of DERs at the device, network, and utility levels.
GM0163	Diagnostic Security Modules for EV-to-Building Integration	Advance cybersecurity of EV-to-building integration through development and demonstration of diagnostic security modules.
SI-1541	Secure, Scalable, Stable Control and Communications for Distributed PV	Evaluate the tradeoffs between power system performance and cybersecurity metrics for several grid services.
GMLC FY20.5.1.1	Firmware Command and Control	Integrate firmware machine learning and structured threat for response across the diverse architectures supporting the grid.
GMLC FY20.5.1.4	Byzantine Security	Develop a Byzantine fault-tolerant cybersecurity solution for protective relays on bulk power system components, extensible to substations, control centers, and balance of plant control systems.
GMLC FY20.5.2.2	Digital Twin Reinforcement Learning	Use artificial intelligence deep-reinforcement learning approaches to detect sophisticated, previously unknown threats and deploy appropriate response actions.
GMLC FY20.5.2.3	Blockchain for Optimized Security and Energy Management (BLOSEM)	Create a multi-laboratory/DOE consortium to develop cross-sector guidance, standardized metrics, and testing environments for technology maturation of novel blockchain-based concepts for device security, secure communications, and grid resilience.
GMLC FY20.5.3.2	Deep Learning Malware	Apply machine-learning techniques to understand the potential of malware threats to firmware used in power grid operational technology.

8.2 Security Benefits

Expected outcomes from security research include more holistic grid security, not security as an afterthought. Research will improve security from devices to systems to systems-of-systems, while taking into account infrastructure interdependencies and security across the grid's lifecycle. Continual research in security and monitoring of the threat space will be necessary to meet today's and tomorrow's challenges given the nature of evolving threats and advancements in technology.

Potentially disruptive technologies that could impact or enhance grid security must be considered. These include 5G communications, quantum information and encryption, artificial intelligence/machine learning, unmanned aerial vehicles, and many others. Additionally, the migration to more distributed energy systems and increasing interdependencies between the power grid and other infrastructures are potential points of strength as well as security vulnerability.

Close coordination with NAERM development will be essential to provide security perspectives to overall grid resilience management, especially given initial NAERM focus on Defense Critical Electrical Infrastructure. While technology alone will not create perfect security, this strategy provides a forward-looking systems approach to advance the state of grid security.

9.0 Institutional Support

Grid modernization presents a complex bundle of technological, institutional, and regulatory challenges. The institutional support area informs key stakeholders involved in the electric power system so they can make the best decision possible in a rapidly changing energy landscape. State decision makers, regulatory commissions, and regional planning organizations play critical roles in working with utilities to shape both the direction and pace of grid modernization. Examples of institutional and regulatory challenges include:

1. The ownership structure and regulatory landscape in the electric power sector are diverse, complex, and evolving; thus "one size fits all" approaches and solutions may be problematic.
2. Organized wholesale electricity markets are embedded within the generation and transmission control segments, intermixing financial, regulatory, and operational issues that are not always fully congruent with state laws and regulations impacting the electric sector.
3. Rapid changes in the power system including the growth in potentially disruptive technologies (e.g., distributed generation, storage, smart grid, grid-interactive efficient buildings, small modular generation units under development, offshore wind) in conjunction with slowing growth in energy demand, aging infrastructure, customer desires for more choice and innovative services, and increasing cyber and physical threats highlight issues regarding the roles and functions of electric utilities and other service providers. In some cases, utility integrated resource planning processes are challenged in their attempts to incorporate new, emerging technologies (e.g., carbon capture, utilization, and storage; small modular nuclear reactors).

Many decision makers experience difficulties in addressing the complex technological, regulatory, institutional, and market issues related to grid modernization.

To address these key challenges, DOE and teams of national laboratory researchers, working in collaboration with stakeholders, academia, and subject matter experts, will facilitate and conduct targeted engagements on high-priority topic areas in the electric power sector that address the current and expected needs of decision makers, including state PUCs, energy offices, reliability organizations and market operators, electric utilities, communities, consumer advocates, and federal agencies (see Figure 4).

In providing institutional support on grid modernization issues, it is important to recognize that DOE's role is not a policymaker nor regulator, nor intervenor in state regulatory proceedings. DOE is not engaged in the development or access of state legislative or regulatory proposals.

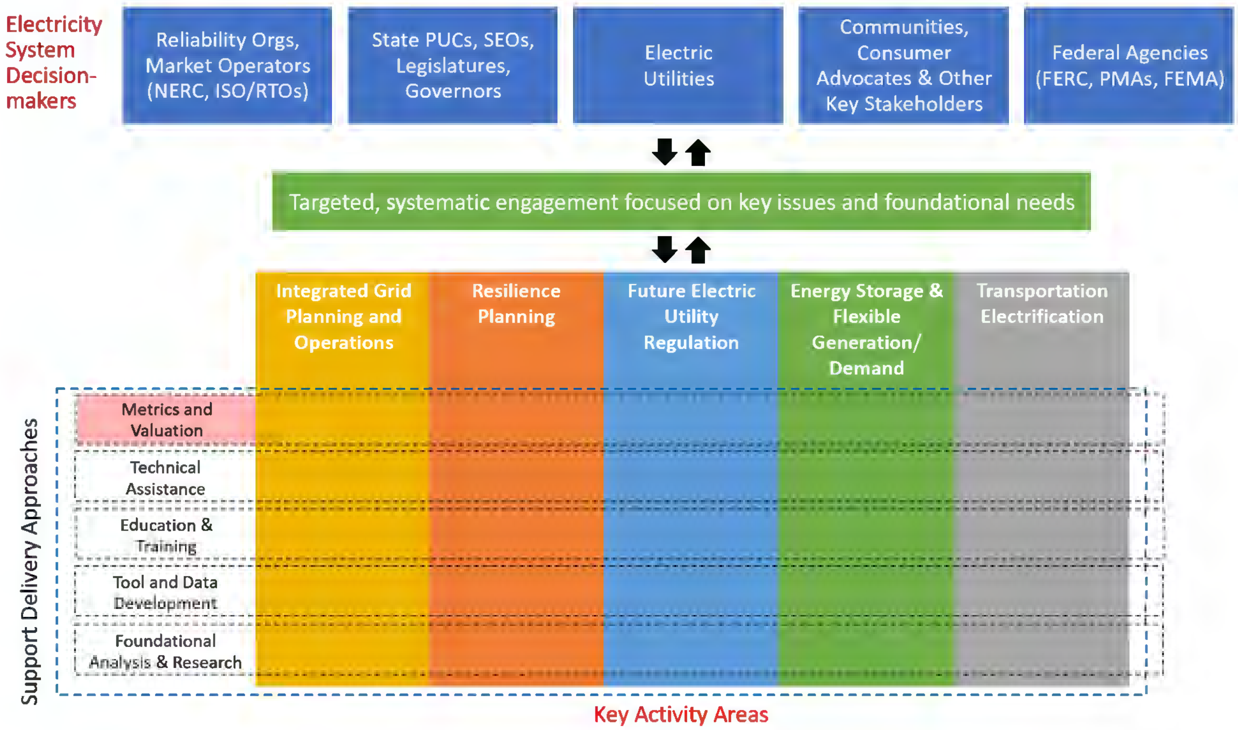

Figure 4. Institutional Support: Decision Makers, Key Activity Areas, and Support Approaches

The institutional support activity areas (and support delivery approaches) require coordinated efforts and can provide structure and guidance to current and future GMI projects; institutional support activities are intended to inform decision makers and provide information, data, and tools to help them make informed decisions (see Table 15).

Table 15. Activities and Technical Achievements for Institutional Support

Activity	Challenges	Technical Achievements by 2025
Metrics and Valuation	3, 4	• New and enhanced performance and impact metrics for high-priority system attributes (e.g., resilience, affordability) and supporting data collection methods are used by state and regional planning and reliability organizations to inform decisions, evaluate potential investments, and track grid modernization progress. • Broad acceptance and utilization by regulators, electric power industry, and stakeholder groups of GMLC valuation framework that allows electricity sector stakeholders to conduct, interpret, and compare valuation studies of existing and emerging grid services and technologies with high levels of consistency, transparency, repeatability, and extensibility.
Integrated Grid Planning and Operations	1, 2, 3, 4	• Decision makers adopt integrated grid planning approach with improved or customized tools and training that advance reliability, resilience, and affordability; facilitate the efficient integration of innovative and emerging technologies; and assess the risks and opportunities associated with the needs of interdependent infrastructures and economic sectors (e.g., convergence between modern electricity grids and other essential services).

Activity	Challenges	Technical Achievements by 2025
		• Analytical approaches and supporting data requirements for coordinating planning, operations, and market design strategies across the bulk power, distribution, and customer/third-party domains are established and implemented across leading jurisdictions.
Resilience Planning	2, 3, 4	• Federal, state, and local decision makers have the necessary tools and training to characterize, value, optimize, and consider tradeoffs related to resilience. • State and local decision makers have improved alignment with electric utilities and state regulatory commissions regarding the benefits of a more resilient grid to communities. Technical assistance has been provided to decision makers demonstrating coordinated planning for resilience of energy systems and communities. • Stakeholders have the necessary understanding, tools, and training on threat-based risk assessment to align utility and independent power producer planning/investment processes with national security objectives, such as the goals of the defense mission assurance community.
Future Electric Utility Regulation	1, 2, 3	• States initiate proceedings that determine new roles, responsibilities, and investment opportunities for utilities. • Access to datasets, tools, and scenario analysis increases stakeholder participation in regulatory proceedings on novel regulatory approaches, utility business models, and retail rate design. • Analysis and technical support sufficiently inform state regulators and decision makers to enable utility innovation through new product and value-added service offerings to consumers.
Energy Storage and Flexible Generation and Demand	3, 4	• Valuation of grid services provision, non-monetized benefits, and compensation mechanisms for emerging technology solutions (e.g., including energy storage, flexible generation, buildings that provide demand flexibility, and hybrid energy systems) for specific use cases; systems and electricity market designs inform planning and operations in leading jurisdictions. • Analytical approaches to characterize the current and potential future cost and performance characteristics of storage and other flexible generation and demand technologies are established and implemented.
Transportation Electrification	3, 4	• Car manufacturers are introducing more models of EVs. This support activity area will help decision makers understand the implications of EVs on the electric grid such as managed EV charging and analytical support for grid planning with higher EV penetrations. This will include a variety of approaches – including artificial intelligence=based tools – to manage the impact of charging loads to prevent potential distribution congestion and/or transformer overload.

The integrated grid planning and resilience planning activity areas focus on sharing and disseminating information on enhancements to planning processes, tools, and analytic methods that enable utilities, grid operators, and regulatory/oversight agencies to address emerging issues that span multiple technologies, challenges, and threats to the electric power system. The energy storage and flexible generation/demand and transportation electrification activities will provide technical support on institutional, regulatory, and market issues that arise with increased penetration of emerging technologies and new end uses of electricity. The future electric utility regulation activity focuses on supporting state decision makers, PUCs, and utilities that are exploring changes to regulatory approaches, utility business models, innovative rate designs, and/or product and service offerings.

These activity areas are aligned with GMI research, design, and development (RD&D) activities conducted by other technical teams. For example, the integrated grid planning and resilience planning activities in institutional support can inform use cases, modeling needs/gaps, and tools development in the planning and design tools technical area and can inform valuation and metrics development in the resilience technical area.

Many of these activity areas are intertwined and need ongoing, consistent, and transparent technical support. DOE approaches to the delivery of support (e.g., metrics and valuation methods, technical assistance, education and training, tools and data development, and foundational analysis) will be guided by several principles: transparency, equality of opportunity, inclusiveness, accountability, and performance. Institutional support needs are defined and selected by consumers not DOE. [20] DOE will work with established groups such as the National Association of Regulatory Utility Commissioners (NARUC) and the National Association of State Energy Officials (NASEO) to ensure that training and education for government officials is inclusive and tailored to provide value to stakeholders across jurisdictions and regions.[21] Education and training activities will also address specific needs in each technical activity area and thus cover all grid-related technologies (e.g., EVs, storage, advanced metering infrastructure), or region since many issues are shared regionally based on common resources or challenges.

A key goal of institutional support is to build capabilities that facilitate sharing best practices and innovative concepts among stakeholders through education and training. Certainly one of the challenges of GMI successfully providing institutional support is efficiently aligning the needs of stakeholders with the abilities and resources of DOE and national labs, and coordinating technical assistance activities of various DOE program offices that target the same stakeholders.

In consideration of any future activities and subsequent projects within the institutional support technical area, cyber and physical security will be addressed at the level(s) appropriate to the research topic (e.g., conceptual, design, procedure, implementation), aided by embedded security resources established by GMI's Security "T" strategy outlined in the Introduction section.

9.1 Prior and Current Institutional Support Projects and Activities

Table 16 provides descriptions for current GMLC projects and accomplishments for completed institutional support projects.

[20] In assessing needs for education and training and technical assistance, DOE will rely on periodic and regularly scheduled Requests for Information (RFIs) to ensure that technical support needs are addressed as they evolve and change.
[21] Large-scale technical assistance activities that are offered to individual entities (e.g., state PUC, energy office, ISO/RTO, utility) will utilize open solicitation and/or competitive solicitation processes.

Table 16. GMLC Projects and Activities

GMLC Project No.	Project Title	Description
Current Projects		
4.2.1	Foundational Analysis for Regional Transmission Organizations and Independent System Operators	Leverage the advanced methods, tools, datasets, and resources of the national labs and partners to provide robust analytical support to address identified challenges for regional transmission organizations, and independent system operators, including maintaining the reliability, resiliency, and affordability of an evolving power system.
4.2.2	Technical Assistance to State PUCs	Provide technical assistance to 10-20 state PUCs on topics that substantively support grid modernization or energy infrastructure initiatives based on a proactive, annual solicitation process.
4.2.3	Future Electric Utility Regulation	Support state decision makers and regulators exploring changes to regulatory approaches, utility business models, and rate design that balance the interests of customers and utilities with grid modernization goals.
4.2.4	Integrated Distribution System Training	Provide training and education for state PUCs, energy offices, utility consumer representatives, governor energy advisors, and state legislators—in partnership with their national organizations (NARUC, NASEO, NASUCA, NGA and NCSL)—on best practices in integrated grid planning with a focus on grid modernization strategies to achieve state goals for improving electric grid reliability, resilience, flexibility, and affordability.
4.2.5	Grid-Interactive Efficient Buildings	Provide technical assistance directly to state energy offices and PUCs to educate on buildings capabilities to provide grid services through demand flexibility by using DERs to reduce, shed, shift, modulate, and generate electricity.
5.7.1	Lab Valuation Analysis Team	Develop methodologies for estimating the value of projects intended to improve the resilience of distribution systems and assess the value of six DOE-funded Resilient Distribution Systems demonstration projects. Engage with state decision makers, regulators, and key stakeholders to communicate lessons learned.
Completed Projects		**Accomplishments**
1.1	Foundational Metrics Analysis for GMLC	Produced a comprehensive reference document on metrics for different grid attributes and worked directly with strategic stakeholders to confirm the usefulness of new and enhanced existing metrics that can guide grid modernization efforts to maintain and improve system reliability, resilience, flexibility, sustainability, affordability, and physical security.
1.2.4	Grid Services and Technology Valuation Framework	Developed a high-level valuation framework that enables electricity sector stakeholders to conduct, interpret, and compare valuation studies of existing and emerging grid services and technologies with high levels of consistency, transparency, repeatability, and extensibility.

GMLC Project No.	Project Title	Description
1.3.22	Technical Support to the NY Reforming Energy Vision (REV) Initiative	Provided technical assistance to support New York's REV initiative, focusing on high-priority issues identified by the Public Service Commission: design of innovative, time-based rates and performance-based regulation, advanced metering infrastructure rollout, distribution system planning, and grid architecture.
1.4.25	Distribution System Decision Support Tool Development and Application	Provided training for 34 states (PUCs and state energy offices) and utility consumer representatives in 38 states on electric distribution systems and advanced planning methods and tools with a focus on incorporating grid modernization technologies and potential significant deployment of DERs. Completed four technical reports and provided technical assistance to several states to supplement training.
1.4.29	Future Electric Utility Regulation	Provided technical assistance directly to 13 state PUCs and indirectly to 20 states through regional workshops; analyzed the financial impacts of DERs on ratepayers and utilities; and wrote six multi-perspective reports on evolving issues in utility regulation and ratemaking, utility business models, and electricity markets.

These projects support other programs and initiatives conducted by DOE's applied energy offices. For example, GMI will coordinate with Energy Storage Grand Challenge activities, particularly in the valuation area.

9.2 Institutional Support Benefits

The GMI's institutional support technical area will provide a valuable and transparent platform for collaborative dialog and engagement with key electricity system stakeholders as they seek to address their specific grid modernization challenges. The platform will also strengthen and inform the R&D areas and can facilitate and accelerate industry adoption of key R&D results. DOE will strive through the GMI to provide greater coordination, transparency, and a stakeholder-service orientation across the various DOE applied energy offices and national labs to both be responsive to stakeholder requests for technical assistance and to communicate useful information that results from DOE's many grid-related efforts.

Development and widespread utilization of unifying metrics, a valuation framework, and a shared understanding of the maturity of the sector's cybersecurity capabilities will support cost-effectiveness analysis of proposed investments, enable decision makers to track progress in achieving grid modernization objectives, manage the large-scale integration of emerging technologies, and consider impacts of investments and operational practices on a variety of system attributes (including demand and generation flexibility, and cyber and physical security).

Development of an analytical framework for integrated planning and operations can consider grid modernization strategies and technologies from a broader perspective than current, more siloed planning approaches (e.g., integrated resource planning, distribution system planning, and transmission system planning in isolation) and operational practices. This framework can also facilitate consideration of resilience objectives and a long-term trend toward convergence between modern electricity grids and other essential services.

At present, there is a critical lack of alignment between resilience planning for the electric grid and for communities and critical infrastructure (including defense): the latter focuses on reducing societal consequence of major disruptions while the former focuses on maintaining standard reliability metrics and cost recovery strategies. Resilience planning analytic methods and tools can provide multiple stakeholders with information on how investments support grid and community resilience and assess the impact of regulatory guidelines and practices in achieving resilience objectives.

Through regularly scheduled Requests for Information (RFIs), technical support provided through future projects can support key decisionmakers in their legislative and regulatory responsibilities.

Various DOE offices, coordinating through the Energy Storage Grand Challenge, are also supporting initiatives on energy storage and flexible generation and demand, including technology RD&D and institutional support activities. For example, energy storage can invigorate both the grid and the U.S. economy more broadly by increasing system- and facility-level resilience against various threats, improving the operation and value of existing grid assets, reducing the cost of integrating new assets, catalyzing technology innovation and commercialization, and decreasing the overall cost of energy for consumers and the United States as a whole. It is also necessary to understand how other sectors (e.g., transportation and industry) and the performance and cost of flexible demand will impact the role of storage in the power sector. However, these impacts may only be realized if legislation, regulations, and market rules are designed to appropriately value the benefits these various technologies can provide to the grid and its end users.

Electrification of transportation will have profound impacts on power sector planning and operations (e.g., maximizing benefits of EV integration, managed charging, synergies with build-out of DER). The pace of change will be influenced by the ability to provide sound, objective technical support that informs the adoption of electrified transportation technologies while maintaining (or improving) reliability, resilience, and affordability.

10.0 Conclusion—Benefits of Continued GMI Efforts

The technical achievements both within and across the GMI's eight technical areas will provide the tools and technologies necessary to achieve the vision of a modernized grid that is resilient, reliable, secure, affordable, flexible, and sustainable as well as providing a platform for innovation and economic growth. By demonstrating the value of new grid modernization technologies and applications, DOE will provide the technical foundation to aid decision-makers on infrastructure investments and grid requirements in order to meet state laws. The GMI provides an organizing framework under which projects and partnerships, including future ones as needs and goals evolve, are aligned and focused. The GMI envisions a fully integrated energy system from fuel to generation to load, including interdependent infrastructures, and an emphasis on maintaining the reliability and resilience of a secure grid.

Equally important, the GMI is a collaborative effort of five DOE applied offices working with a consortium of national laboratories and other organizations and partners to produce results beyond the capacity of individual offices working independently.

While the work to be performed under the GMI has been categorized in eight technical areas, implementation will necessarily require coordinating results across multiple areas to provide real solutions for the future. Solutions must address these key challenges identified by DOE:

- Changing mix of types and characteristics of electric generation
- Growing demands for a more resilient and reliable grid, especially due to weather impacts
- Growing threat of cyber and physical attacks
- Opportunities for customers to provide grid services and participate in electricity markets
- Increased use of digital and communication technology in the control of power systems
- Address the growing need for investment in electricity delivery systems that supports adoption of renewable generation and load electrification
- Ensuring the affordability of electricity to rater payers, and especially low-income consumers.

10.1 Foundation for Programmatic Efforts

Many GMI projects are jointly funded and managed by several of the five DOE applied offices. These projects are designed to leverage the capabilities and expertise of multiple offices because the challenges being addressed overlap multiple technical domains. Jointly managed and funded projects decrease the likelihood or working at cross-purposes in these overlap areas. Similarly, as most GMI projects involve the combined effort of several national laboratories and external partners, the work ensures the nation's best resources are focused on specific challenges and builds a foundation for future collaboration within the national laboratory complex.

10.2 Technology Transfer

Technology transfer is an important element of the GMI effort because actual modernization of the nation's infrastructure will be done through investments by the utility industry (public and private) as well as through consumer investments via commercial offerings. Technology transfer, in concert with the Office of Technology Transitions, will occur primarily through GMI functions designed explicitly for collaboration with industry (utilities, vendors, and service providers) and demonstration partners and traditional federal RD&D mechanisms.

Traditional technology transfer mechanisms are associated with existing contracting approaches used with universities, industry, and the national laboratories. Intellectual property developed using federal funds is made available for licensing and commercialization consistent with the RD&D contracts used by DOE. In addition, industry can access knowledge through joint contracts to accelerate industry benefit from R&D advances.

Additional pathways to encourage rapid transfer of GMI innovations include:

- Development of open-source tools platforms (e.g., software) that aggregate advances from the participating national laboratories and work with vendors to enable them to leverage these tool sets into their proprietary tool offerings.
- Development of open testing and computational test beds that enable vendors and researchers to use specialized federal scientific and engineering capabilities customized to support grid modernization efforts.

10.3 Increased Partnerships

DOE has an established Electricity Advisory Committee to provide direct feedback to DOE's R&D Grid Modernization agenda through the Federal Advisory Committee Act. It includes members representing industry, academia, and regulators with experience in all facets of power system planning, operation, regulation, and policy. The Electricity Advisory Committee will engage and advise the GMI effort with an emphasis on the adequacy, rate of progress, and quality of results for the overall process.

In addition to receiving feedback on its mission, DOE also reaches out to provide technical assistance to states, regions, and tribes in support of stakeholder electric system policy analysis, planning, and regulatory developments. Historically, this work included grants to stakeholders, support from national laboratories and experts on multiparty efforts (typically DOE-funded or directly funded by stakeholders), and development of tools and datasets to facilitate effective stakeholder analysis and other activities. The GMI has a technical team focused on institutional support that builds on past work to develop new tools and analytic frameworks that better inform state, regional, and tribal grid analysis, and planning efforts.

The GMI engages stakeholders from the outset, and stakeholders have opportunities to provide input and participate in initiative forums, solicitations, and technology transfer efforts. Five pathways for stakeholder engagement are:

- Competitive research funding opportunities issued by DOE
- Technology transfer from DOE programmatic advances
- Periodic peer reviews and insights from DOE's security and resilience programs
- Regional dialogs to gather a broad perspective of grid modernization needs and priorities

- Technical assistance to states, regions, and tribes.

DOE's research and development investments envisioned in the GMI can help make the trillions of dollars in expected private investments more effective by spurring technology innovation, sharing best practices across the sector, and fostering a common vision among diverse stakeholders. This will lead to a grid that will support our 21st century economy and expectations.