GRID
MODERNIZATION INITIATIVE
U.S. Department of Energy

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Grid Modernization Strategy 2024

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1 Introduction

The U.S. Department of Energy's (DOE) Grid Modernization Initiative (GMI)[1] encompasses activities across the Department focused on research, development, demonstration, and deployment (RDD&D) to ensure a resilient, reliable, secure, affordable, flexible, environmentally sustainable, and equitable grid. The portfolio of grid modernization work helps integrate all sources of electricity, improve the security of our Nation's grid, solve challenges of energy storage and distributed generation, and provide a critical platform for U.S. competitiveness and innovation in a global energy economy. These efforts directly support this Administration's goals to achieve a 50-52 percent reduction from 2005 levels in economy-wide greenhouse gas (GHG) emissions by 2030, a carbon pollution-free power sector by 2035, and a net-zero GHG emissions economy by no later than 2050.

The GMI has established a core partnership of DOE offices for grid modernization by co-funding crosscutting grid RDD&D through competitive opportunities and by coordinating individual office's grid activities for a common future grid. The Grid Modernization Laboratory Consortium (GMLC) was established as a strategic partnership across the National Laboratories to bring together leading experts, technologies, and resources to collaborate on the goal of modernizing the Nation's grid. To accomplish its goals, the GMI regularly engages with the GMLC, academia, industry, Tribal Nations, disadvantaged communities, and the power sector.

The GMI works to set the Nation on an affordable path to a clean energy[2] future. The GMI focuses on developing new tools and technologies to measure, analyze, predict, protect, and control the grid of the future. The GMI envisions a fully integrated electric system from generation to transmission to load consumption, including interdependent infrastructures, with an emphasis on maintaining the reliability and resilience of the grid. The results of this work will inform regulatory authorities and other oversight bodies, policymakers, industry, and broad stakeholders to facilitate widespread adoption of new technologies in generation, transmission, and distribution.

The future modernized grid will need to balance a variety of key priorities that are not all in perfect alignment with one another. These priorities, or system attributes, are all important and system designers should seek solutions that provide multiple benefits. Policymakers, regulatory authorities, grid planners, and operators should ensure that all are given appropriate consideration. These attributes include the following:

- Resilient – Recovers in a timely manner from any situation or power outages;
- Reliable – Delivers power at an acceptable level of quality with an acceptable level of disruptions;
- Secure – Ensures that critical facilities maintain a secure posture against threats;
- Affordable – Delivers power at an acceptable rate for consumers;
- Flexible – Responds efficiently and effectively to the variability and uncertainty of conditions across a range of timescales;

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[1] Department of Energy, "Grid Modernization Initiative", https://www.energy.gov/gmi/grid-modernization-initiative.

[2] For this effort, the term "clean energy" includes electricity generating technologies using wind, solar, geothermal, hydropower, biopower, nuclear, and fossil energy with carbon capture, utilization, and storage (CCUS). In addition to generating technologies, the term sometimes includes hydrogen, energy storage, and Carbon Dioxide Removal (CDR) technologies such as direct air capture and biopower CCUS. CDR technologies are assumed to be suitable tools to offset any residual power-sector emissions, either from fossil CCUS or from any remaining emitting fossil generators. As such, 100% clean energy or clean power in this effort more precisely means net-zero power sector carbon emissions.

- Environmentally Sustainable – Minimizes the environmental footprint of power delivery to a societally acceptable level; and
- Equitable – Centers the concerns of marginalized communities and aims to make energy more accessible, affordable, clean, and democratically managed for all communities through social participation in the energy system. Equity considerations also seek to remediate social, economic, and health burdens on those frontline communities historically harmed by the energy system.

The GMI derives its statutory authority for carrying out electricity delivery activities from multiple public law authorizations including:

- DOE Organization Act of 1977 (42 U.S.C. 7101 et seq.)[3];
- Public Law 109-58, Energy Policy Act of 2005[4];
- Public Law 110-140, Energy Independence and Security Act, 2007[5];
- Public Law 114-94, Fixing America's Surface Transportation Act, 2015[6]; and
- Energy Policy Act of 2020[7].

In addition to regular congressional appropriations, several recent laws such as the Bipartisan Infrastructure Law (BIL)[8], the Inflation Reduction Act (IRA)[9], and the CHIPS and Science Act[10] provide significant opportunities to accelerate grid modernization across the Nation. It is more important than ever to coordinate all DOE grid activities across the RDD&D spectrum to spend tax dollars wisely in support of our nation's clean energy transition. Additionally, the House and Senate Energy and Water Development Appropriations Committees in their 2022 Appropriations Bill Reports specifically requested an update to the grid modernization strategy[11,12].

This document summarizes an overarching grid modernization strategy, which serves as the foundation for future investments and coordination for grid modernization RDD&D at DOE.

2 Drivers for a Better Grid and an Updated Grid Modernization Strategy

Our national power grid has reached a pivotal point – not only does the grid need to provide reliable, resilient, and affordable electricity for societal prosperity and economic development, but the grid also

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[3] DOE Organization Act. United States Code, 2014 Edition, Title 42 - The Public Health and Welfare Chapter 84 - Department of Energy, https://www.energy.gov/sites/prod/files/2017/10/f38/DOE%20Organization%20Act%20in%20U.S.C..pdf.
[4] Public Law 109-58, Energy Policy Act of 2005. https://www.energy.gov/lpo/articles/energy-policy-act-2005.
[5] Public Law 110-140, Energy Independence and Security Act, 2007, https://www.congress.gov/110/plaws/publ140/PLAW-110publ140.pdf.
[6] Public Law 114-94, Fixing America's Surface Transportation Act, 2015, https://www.congress.gov/114/plaws/publ94/PLAW-114publ94.pdf.
[7] Energy Act of 2020 Section-by-Section. https://www.energy.senate.gov/services/files/32B4E9F4-F13A-44F6-A0CA-E10B3392D47A.
[8] The US White House, "Fact Sheet: The Bipartisan Infrastructure Law", 2021. https://www.whitehouse.gov/briefing-room/statements-releases/2021/11/06/fact-sheet-the-bipartisan-infrastructure-deal/.
[9] The US White House, "The Inflation Reduction Act (IRA) Guide Book", 2022. https://www.whitehouse.gov/cleanenergy/inflation-reduction-act-guidebook/.
[10] The US White House, "FACT SHEET: CHIPS and Science Act", 2022, https://www.whitehouse.gov/briefing-room/statements-releases/2022/08/09/fact-sheet-chips-and-science-act-will-lower-costs-create-jobs-strengthen-supply-chains-and-counter-china/.
[11] The House's 2022 Energy and Water Development and Related Agencies Appropriations Bill (H. Rpt. 117-98, page 101), https://www.congress.gov/117/crpt/hrpt98/CRPT-117hrpt98.pdf.
[12] The Senate's 2022 Energy and Water Development Appropriations Bill (S. Rpt. 117-36, page 72), https://www.congress.gov/117/crpt/srpt36/CRPT-117srpt36.pdf.

needs to support a sustainable and equitable energy future, aligning with the Administration's goals to achieve a *carbon pollution-free power sector by 2035 and a net-zero emission economy by no later than 2050 while maintaining the reliability, affordability, security, and resilience of the energy system*[13]. The Administration's goals are:

- Decarbonization: The Administration goals are to remove carbon dioxide and other GHG emissions from our energy ecosystem, and as part of the energy ecosystem, the grid needs to be carbon-free and support electrification and a clean energy transition.
- Infrastructure Modernization: To meet the Administration goals, the Nation must transition to a decarbonized grid and modernize operations of our aging electric infrastructure to accommodate the expected significant increase of electricity demand, optimize the interaction with interdependent infrastructures, and integrate diverse, non-conventional resources.
- Equity and Energy Justice: The clean energy transition must lift up Communities of Interest[14] that have historically been left behind. It takes conscious efforts to ensure equity and energy justice are reflected in grid technology development and implementation[15].
- Climate Adaptation and Mitigation: The Nation must reduce emissions of heat-trapping GHG in the atmosphere ("mitigation") and adapt to changes of the climate that are already happening ("adaptation")[16]. This requires updating grid technologies and policies at all levels from generation, transmission, and distribution through to end use.
- Workforce Development: The electric power system of the future will require the workforce to be prepared for the new technologies necessary to implement this transition.

This Administration's goals require us to establish a concerted vision for the future power grid and pursue a grid modernization strategy that will support the clean energy transition.

2.1 The Grid of the Future

The United States needs a grid that will be able to deploy the technology and infrastructure necessary to implement a decarbonized economy. The necessary shift towards clean energy technology will require the energy grid to have a diverse portfolio of energy options. The scale of new clean energy capacity needed for full decarbonization could be more than 1000 gigawatts (GW)[17,18]. Modern grid infrastructure will allow for reliable and energy efficient delivery of electricity across the vast networks of transmission lines and distribution stations that span the United States. Some studies, such as the one performed by the Electric Power Research Institute (EPRI) for Seattle City Light[19] and DOE's

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[13] *See* Executive Order 14008 of Jan. 27, 2021, Tackling the Climate Crisis at Home and Abroad, 86 FR 7619 (Feb. 1, 2021), https://www.federalregister.gov/documents/2021/02/01/2021-02177/tackling-the-climate-crisis-at-home-and-abroad; Fact Sheet: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies (Apr. 22, 2021), https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/.

[14] Communities of interest means the following communities that could be affected by significant energy infrastructure: disadvantaged communities; rural communities; Tribal communities; indigenous communities; geographically proximate communities; communities with environmental justice concerns; and energy communities.

[15] Department of Energy, "Promoting Energy Justice", https://www.energy.gov/promoting-energy-justice.

[16] NASA, "Responding to Climate Change: Mitigation and Adaptation", https://climate.nasa.gov/solutions/adaptation-mitigation/.

[17] DOE Office of Energy Efficiency and Renewable Energy, "Solar Futures Study", 2021, https://www.energy.gov/eere/solar/solar-futures-study.

[18] The US White House, "The Long-Term Strategy of the United States, Pathways to Net-Zero Greenhouse Gas Emissions by 2050", 2021, Page 27. Available at: https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf.

[19] Seattle City Light Electrification Assessment, 2022, Page 1-7. Available at: https://powerlines.seattle.gov/wp-content/uploads/sites/17/2022/01/Seattle-City-Light-Electrification-Assessment.pdf.

Electrification Futures Study[20], indicate that electric load could at least double in the next two decades as broad sectors of the economy, ranging from transportation to industrial heat, increasingly transition away from fossil fuels. As the national demand for electricity increases, the grid should particularly serve historically marginalized and disproportionally affected groups of people, ensuring dependable power delivery and economic opportunity for them. Further, the grid needs to be exceptionally adept at adapting to extreme weather events made more frequent by climate change while also mitigating its direct causes. All of this is possible through the RDD&D of new technologies and infrastructure, supported by a workforce that is equipped with the skills needed to expand and maintain a more effective and efficient future power grid.

Traditionally, electricity generation is highly centralized and predominantly dependent on fossil fuels. Today, electricity resources are rapidly diversifying to include wind; solar; geothermal; hydropower; nuclear; biomass with and without carbon capture, utilization, and storage; and fossil energy with carbon capture, utilization, and storage[21]. Simultaneously, there is also an increase in smart electric loads on the demand side of the grid from electric vehicles (EVs), grid interactive buildings, industrial heat, and other technologies. These advances increase the complexity of the grid. The grid of the future, that adheres to this vision of distributed assets delivering carbon-free energy and manages the increased complexity, will be achieved by advancing the following fundamental power system objectives:

- <u>Clean Energy Integration</u>: The United States is a resource-rich country with abundant clean energy resources that will require connection to the electric transmission and distribution systems, either in front of or behind the meter[22].
- <u>Grid Infrastructure Expansion</u>: There is broad agreement, supported by the work of DOE and many others, on the need for massive amounts of new transmission capacity[23]. A variety of studies have shown that many tens of GW of additional long-distance transmission capacity would facilitate the export of zero-carbon electricity from resource-rich regions to load centers. Increased transmission interconnection between regions will provide additional benefits, including improved system reliability, resilience to extremes of weather and physical disasters, and operating flexibility.
- <u>Managing Electrification</u>: Massive electrification of transportation, industrial, and building loads will require considerable additional capacity and infrastructure for the power system. This presents a huge opportunity to help meet our grid modernization objectives. By appropriately managing load, newly electrified sectors can provide demand shifting and leveling, supply firming, and essential reliability services.
- <u>Reliability, Resilience, and Security</u>: Operational reliability in the design and engineering of energy delivery along with the functional preservation of the electric grid operations in the face of natural and man-made threats and hazards is a foundational aspect of the grid that needs to be maintained and improved.
- <u>Affordability</u>: A household's energy burden—the percentage of household income spent on energy bills—provides an indication of energy affordability. Researchers define households with

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[20] DOE Office of Energy Efficiency and Renewable Energy, "Electrification Futures Study: Scenarios of Power System Evolution and Infrastructure Development for the United States", 2021, https://www.energy.gov/eere/analysis/articles/electrification-futures-study-scenarios-power-system-evolution-and.

[21] Department of Energy, "On the Path to 100% Clean Electricity", 2023, Page 3, Footnote 1. Available at: https://www.energy.gov/policy/articles/path-100-clean-electricity.

[22] Department of Energy, "Renewable Energy Resource Assessment Information for the United States". https://www.energy.gov/eere/analysis/renewable-energy-resource-assessment-information-united-states.

[23] Department of Energy. "National Transmission Needs Study - Draft for Public Comment" (February 2023), https://www.energy.gov/sites/default/files/2023-02/022423-DRAFTNeedsStudyforPublicComment.pdf.

a 6% energy burden or higher to experience a high burden[24]. According to DOE's Low-Income Energy Affordability Data (LEAD) Tool[25], the national average energy burden for low-income households is 8.6%, three times higher than for average households, which is estimated at 3%. In some areas, depending on location and income, energy burden can be as high as 30%. Of all U.S. households, 44% or about 50 million, are defined as low-income[26].

2.2 DOE's New Strategy for Grid Modernization

In order to align DOE's grid modernization efforts with the current national decarbonization goals, we are herein updating DOE's grid modernization strategy. While the decarbonization goals are critical, the electric power system also must be reliable, resilient, flexible, affordable, and equitable. Electricity is thus a cornerstone of our Nation's economy and security. Various offices across DOE work to ensure that the electric grid is reliable, resilient, and secure as part or all of their mission space. In order to tackle the significant challenges of a clean energy transition, significant investments are being made by both the public and private sector. Federal Government investments include BIL[27], IRA[28], and annual appropriations[29]. Significant federal funds pertinent to grid modernization are managed through various DOE offices. This new grid modernization strategy aims to outline a common approach to advancing the clean energy transition across the Department with support from the GMLC. DOE must work closely with all the important partners critical to the development of the grid of the future including Tribal Nations, states, local governments, industry, utilities, vendors, universities, and others. As a result, this strategy will guide the coordination and collaboration across all the relevant stakeholders and consultation with Tribal Nations.

2.3 Six Technical Pillars for Grid Modernization

Deriving from the Administration's goals and power system objectives identified above, the GMI has defined a strategy with six key pillars that will help achieve the grid of the future. The following pillars, their challenges, current activities, plans, and key topics are introduced in this strategy. The topics within each respective pillar are tackled through multiple program types that include RDD&D, testing and validation, simulation, demonstration, technical assistance, and analysis. The pillars are: Devices and Integrated Systems; Operations; Planning; Markets, Policies, and Regulations; Resilient and Secure Systems; and Flexible Generation and Load. It is worthwhile to note that many of these topics are interrelated; in particular, cybersecurity and energy justice are interwoven throughout all pillars. The six pillars are further defined below.

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[24] American Council for an Energy Efficient Economy, "Understanding Energy Affordability", https://www.aceee.org/sites/default/files/energy-affordability.pdf.

[25] Department of Energy, "Low-Income Energy Affordability Data (LEAD) Tool", https://www.energy.gov/eere/slsc/low-income-energy-affordability-data-lead-tool.

[26] Department of Energy, "Low-Income Community Energy Solutions", https://www.energy.gov/eere/slsc/low-income-community-energy-solutions.

[27] The US White House, "Fact Sheet: The Bipartisan Infrastructure Law", 2021, https://www.whitehouse.gov/briefing-room/statements-releases/2021/11/06/fact-sheet-the-bipartisan-infrastructure-deal/.

[28] The US White House, "The Inflation Reduction Act (IRA) Guide Book", 2022, https://www.whitehouse.gov/cleanenergy/inflation-reduction-act-guidebook/.

[29] Fiscal Year 2023 Omnibus Appropriations Bill, 2022, https://www.appropriations.senate.gov/news/majority/chairman-patrick-leahy-d-vt-releases-fiscal-year-2023-omnibus-appropriations-bill.

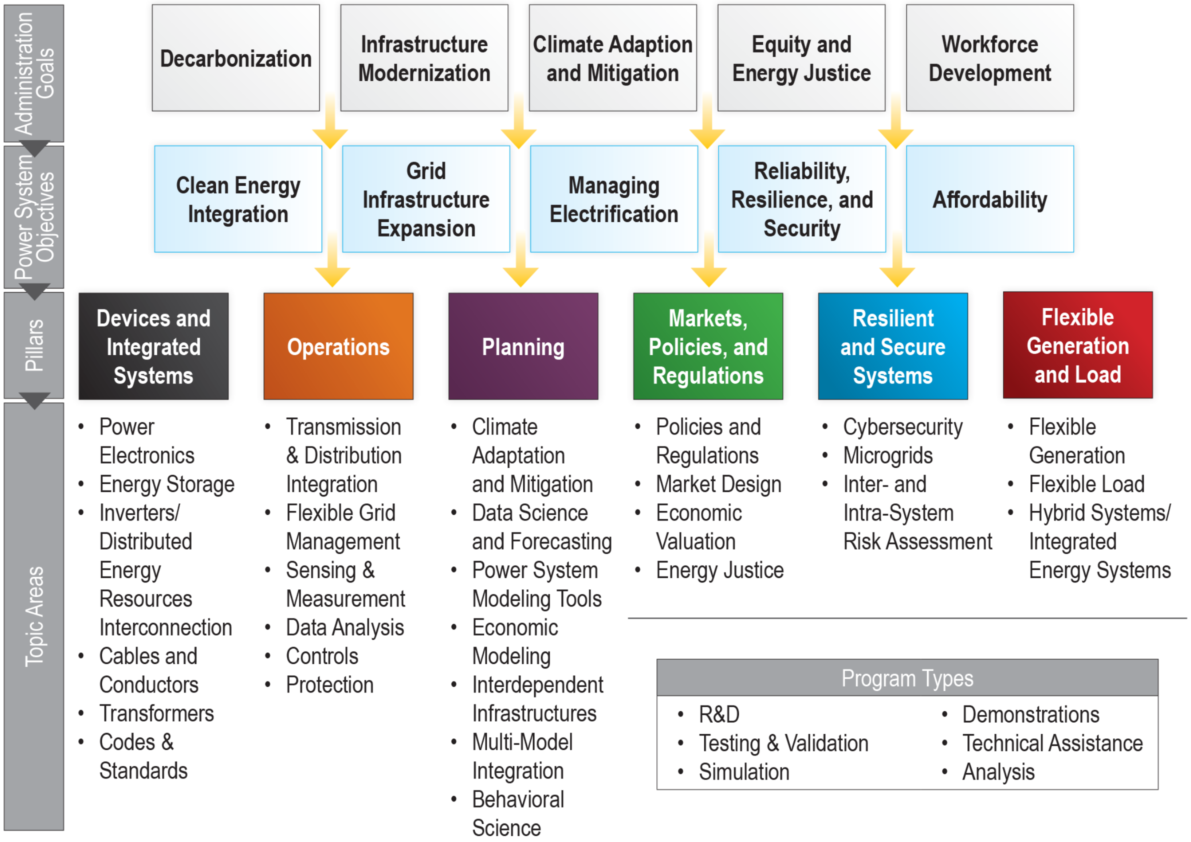

Figure 1. GMI's six technical pillars align with high-level Administration goals and supporting power system objectives and are made up of a number of complex topic areas, all explored and advanced through a number of different program types.

- <u>Devices and Integrated Systems</u>: This pillar aims to create the needed devices with proper controls, establish understanding of the interactions among the devices at the system level, and develop methods for the integration of such devices to ensure the electrical system can operate effectively as a whole.
- <u>Operations</u>: This pillar aims to develop procedures and technologies needed to run the future grid reliably during normal or steady-state conditions, as well as extreme situations.
- <u>Planning</u>: This pillar aims to provide the grid community with next-generation planning tools for policy analysis, grid expansion planning, and day-ahead planning and to support policy development, economic assessments, engineering design, and risk and vulnerability analysis impacting billions of dollars of capital investments and operational costs.
- <u>Markets, Policies, and Regulations</u>: This pillar includes research on the current market, policy, and regulatory environment aimed at developing strategies for a grid which is efficient and capable of ensuring a reliable energy supply, while achieving the Administration's deep decarbonization targets in an equitable and just manner.
- <u>Resilient and Secure Systems</u>: This pillar aims to improve the resilience and security of the electric sector by developing physical and cybersecurity solutions; characterize risk, assess impacts, and develop mitigation approaches; and provide situational awareness/incident support during energy-related emergencies. It also includes supply chain considerations.
- <u>Flexible Generation and Load</u>: This pillar aims to enable and maximize flexibility in energy generation or load that responds to the variability and uncertainty of conditions at one or more temporal and spatial scales, including a range of energy futures.

3 Grid Modernization Initiative

As aforementioned, the GMI works across DOE to advance the modern grid of the future – an essential enabler of a just transition to a carbon pollution-free power sector by 2035 and a net-zero emission economy by 2050 while maintaining the reliability, affordability, security, and resilience of the energy system. Our extensive power grid has fueled the Nation's growth since the early 1900s; however, the grid we have today does not have the attributes necessary to meet the demands of the 21st century and beyond. Since 2015, the GMI has leveraged the expertise of DOE Offices, National Laboratories, and partners to coordinate activities and conduct over $300 million in cutting-edge R&D through the GMLC lab calls[30]. The GMI is also expanding beyond R&D to supporting demonstration and deployment as the industry evolves. R&D is still very important, but DOE's mandate has expanded, notably with the passage of BIL and IRA, to address the full RDD&D continuum.

3.1 GMI Objective and Scope

The GMI focuses on developing new tools and technologies to measure, analyze, predict, protect, and control the grid of the future. The GMI serves two important functions, it serves as 1) a mechanism to enable research, development, demonstration, and deployment for grid modernization through joint funding opportunities by multiple offices; and 2) a platform to consistently share information on each office's individual grid modernization efforts to facilitate coordination. Both functions are essential because many challenges and complementary aspects to the grid are outside of the purview of a single office and require coordination.

3.2 GMI Governance Structure

The GMI governance structure, defined by the 2023 GMI Charter, is shown in Figure 2 and is comprised of four main components:

- The DOE Executive Committee, consisting of two undersecretaries (Under Secretary for Science and Innovation and Under Secretary of Infrastructure) and Assistant Secretaries or Directors of GMI member offices, provides guidance and oversight of all GMI activities;
- The DOE GMI Leadership Team, consisting of a GMI Director out of the Office of the Under Secretary for Science and Innovation and representatives from GMI member offices, develops and implements the entire range of the GMI's activities according to the GMI's strategy and roadmap;
- The DOE GMI Pillar Teams, consisting of members from relevant GMI offices, support the entire range of GMI activities; and
- The Grid Modernization Laboratory Consortium, consisting of a Chair, Vice-Chair, Pillar Lead, and team members, all from National Laboratories, serves as the platform for integrating relevant capabilities across National Laboratories and for collaborating across the National Laboratories.

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[30] Grid Modernization Lab Call 2023. https://www.energy.gov/sites/default/files/2023-05/2023-gmi-lab-call_0523.pdf

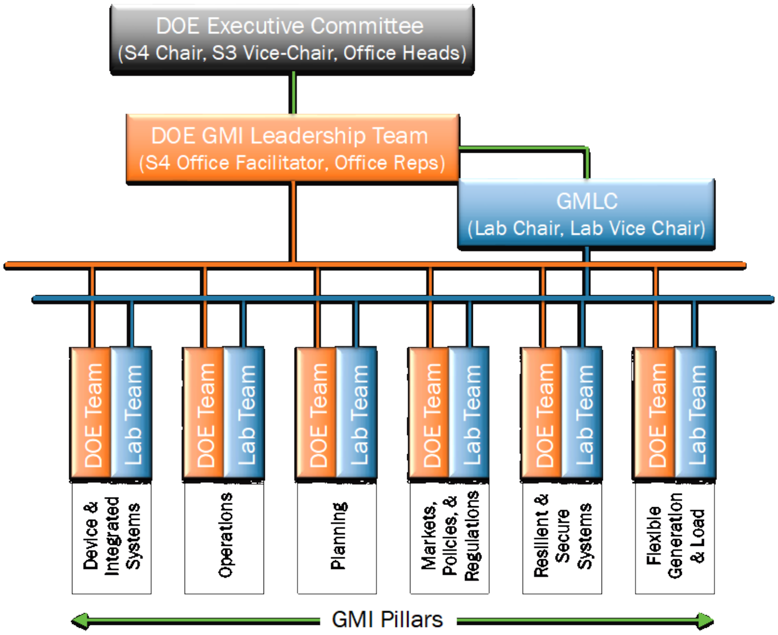

Figure 2. GMI governance structure consisting of interested federal offices directed by the Executive Committee and led by the GMI Leadership Team with participating National Laboratories organized through the GMLC.

GMI activities are supported by 14 National Laboratories under the GMLC, a structure established to enhance laboratory coordination and impact for grid modernization activities. In addition, national and regional organizations and private-industry participants have been and will continue to be partners in implementing GMI activities.

The GMI aims to be a strong partnership of DOE offices, National Laboratories, state and local governments, academia, community groups, and private industry stakeholders, for advancing the grid of the future.

4 Grid Modernization Pillar 1: Devices and Integrated Systems

This pillar area will develop devices and integrated systems that securely interconnect and interoperate 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.

The electrical power grid is fundamentally composed of millions of devices physically connected and linked by control systems, which form integrated systems. These devices and integrated systems serve the functions of generating, transferring, storing, and consuming electricity across large geographical regions. With the clean energy transition, all these functions are fundamentally changing, and so are the devices. This requires significant advancements of device technologies and their integration for system performance.

The power grid needs to be expanded significantly to accommodate the new generation capacity anticipated in the next two decades due to deeper electrification and increased renewable energy development. New technologies for direct current (DC) transmission and circuit breakers; transformers;

and cables and conductors need to be developed through foundational research, applied uses, performance validation, and field demonstrations. Development of new ***Codes and Standards*** is necessary to support equipment interoperability and accelerate industry adoption. ***High Voltage DC (HVDC) and Power Electronics*** can efficiently move electricity over long distances, while medium voltage DC (MVDC) transmission has important applications for integrating offshore wind generation. HVDC and MVDC transmission are being actively evaluated in the ongoing National Transmission Planning Study[31] and offshore wind transmission studies for both coasts[32]. In likely scenarios, HVDC and MVDC transmission need to go beyond point-to-point connections and support multi-terminal DC systems. DC circuit breakers are essential devices in such multi-terminal DC systems, but they are not yet cost-effective. ***Cables and Conductors*** and ***Transformers*** are important to support HVDC and MVDC development as well as the development of other system components such as enabling grid enhancing technologies (GETs)[33] that can increase grid capacity through reconductoring the rights of ways. Supply chain issues associated with all this equipment as identified in previous DOE reports also need to be addressed[34].

Devices and Integrated Systems

- HVDC/Power Electronics
- Energy Storage
- Inverters/ Distributed Energy Resources Interconnection
- Cables and Conductors
- Transformers
- Codes & Standards

Inverters are another category of devices that are essential for integrating wind and solar renewables, discharging battery storage, enabling EV-to-grid use, and many other applications. The number of these applications are projected to increase. For example, the past decade has seen significant growth of wind and solar generation. According to the U.S. Energy Information Administration (EIA) Annual Energy Outlook 2023[35], U.S. wind power capacity has more than tripled, from 39.6 GW in 2010 to 145.0 GW in 2022, and U.S. solar generation has increased 46 times from 2.7 GW in 2010 to 125.1 GW in 2022. The EIA and many other organizations have projected continued rapid growth of wind and solar energy in the next two decades. As a result, the penetration of power electronics inverters is significantly increasing. Inverters cannot just be devices that convert DC to alternating current (AC); they also need to engage in the provision of grid services to enable the regulation of power system frequency and voltage. Inverters need to achieve performance that ensures stable operation of the future power system and mitigates issues related to mechanical inertia being displaced by new energy resources. This requires basic and applied R&D to realize more flexible, modular, and efficient power electronics materials, devices, and controls. "Grid-forming" inverters[36] are an example of such expanded capabilities.

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[31] DOE National Transmission Planning Study, https://www.energy.gov/gdo/national-transmission-planning-study.

[32] Offshore Wind Transmission Federal Planning & Support, https://www.energy.gov/gdo/offshore-wind-transmission-federal-planning-support.

[33] DOE Office of Electricity, "Grid-Enhancing Technologies: A Case Study on Ratepayer Impact", 2022, https://www.energy.gov/sites/default/files/2022-04/Grid%20Enhancing%20Technologies%20-%20A%20Case%20Study%20on%20Ratepayer%20Impact%20-%20February%202022%20CLEAN%20as%20of%20032322.pdf.

[34] 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://trumpwhitehouse.archives.gov/presidential-actions/executive-order-securing-united-states-bulk-power-system/.

[35] U.S. Energy Information Administration (EIA), "Annual Energy Outlook 2023", March 2023. Available at: https://www.eia.gov/outlooks/aeo/ppt/AEO2023_Release_Presentation.pptx.

[36] UNIFI Grid Forming Consortium, 2021, https://www.nrel.gov/news/program/2021/nrel-to-lead-grid-forming-inverter-consortium.html.

Variable renewable energy resources such as wind and solar energy challenge the ability to reliably match electricity generation with consumer demand. ***Energy Storage*** can help solve this challenge. Energy storage refers to a broad range of diverse technologies in several categories: electrochemical, electromechanical, and thermal storage; these technologies offer opportunities to increase grid reliability, resilience, and demand management. Examples of storage technologies include battery storage, ultracapacitors, pumped hydropower, compressed-air storage, flywheels, hydrogen, thermal energy storage, and reversible fuel cells. Emerging bidirectional EVs could act as moveable or portable energy storage. Energy storage technology is a vital component for modernizing and decarbonizing the electrical grid. The future power grid will need energy storage deployed at many generation sites and at many locations across transmission and distribution networks. Energy storage can interact with these integrated systems. This interaction needs to be studied further to understand how it can ensure grid reliability and resilience across these integrated systems. DOE has a crosscutting initiative called the Energy Storage Grand Challenge (ESGC)[37] that leads the development of a diverse portfolio of new energy storage technologies. The GMI coordinates closely with ESGC on how best to integrate energy storage technologies to cost-effectively enhance grid performance.

Besides the development of wind and solar generation, other generation technologies are also evolving to be cleaner and/or modular, and as such, their integration with the grid poses new research needs. Active development is ongoing in fossil energy combined with carbon capture, advanced nuclear technologies (e.g., small modular reactors, advanced reactors, and microreactors), and combined heat and power generation. In the future, these technologies may be integrated into distribution systems like behind-the-meter photovoltaic (PV) generation. Distributed energy systems include generation technologies, loads, energy storage, and physical system components. ***Distributed Energy Resources Integration*** is essential to maximize the benefits of distributed energy systems to support a range of operational goals considering both critical end-use loads in the distribution system and how they may impact bulk power system operations. For more on generation topics, see Section 9 on the Flexible Generation and Load pillar.

4.1 Connection to Power System Objectives and Administration Goals

The efforts in the Devices and Integrated System pillar will contribute to the goals of the other pillars, the GMI power system objectives, and the Administration's goals.

- Connections with other pillars: Device development efforts in mobile and stationary energy storage, distribution system inverters and controls, and other technologies depend upon the **Operations** pillar for advancements in emerging requirements in grid architecture and control paradigms that account for new system-level interdependencies that need to be considered in standards and testing. The **Resilient and Secure Systems** pillar addresses security validation within evolving testing and interoperability standards, as well as ensuring supply chains for those systems.
- Power System Objectives: Technologies such as mobile and stationary energy storage and power electronics are critical to many of the Power System Objectives including **Managing Electrification** and **Clean Energy Integration**. GETs will help support our investments in new and existing transmission and will support cost effective **Grid Infrastructure Expansion**.
- Administration Goals: Power electronics, energy storage technologies, and electricity delivery equipment are necessary for the successful interconnection and integration of clean energy. As

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[37] DOE Energy Storage Grand Challenge (ESGC), https://www.energy.gov/energy-storage-grand-challenge/energy-storage-grand-challenge.

a result, power electronics and energy storage technologies are critical for the Nation to meet its goals for **Decarbonization** and **Infrastructure Modernization.**

5 Grid Modernization Pillar 2: Operations

This pillar area aims to develop procedures and technologies needed to run the future grid reliably with millions of active devices beyond the scale and nature of conventional power systems during normal or steady-state conditions, as well as in extreme situations. The scope of this pillar area includes both transmission and distribution systems (or the holistic grid as the division line between transmission and distribution are blurring) and associated sensing, communication, control, and protection.

Operations

- Transmission and Distribution Integration
- Flexible Grid Management
- Sensing and Measurement
- Data Analysis
- Controls
- Protection

As millions of new intelligent devices are installed and new business models are considered, the power grid is expanding and transforming to be more distributed with faster dynamics and more complex interactions. Power grid dynamics are fundamentally changing as inverter-based resources (IBRs) displace conventional generation. Conventional generation resources contribute to maintaining stability through their mechanical inertia, which slows down power system dynamics in response to disturbances (i.e., the frequency of the power system does not change quickly because of the large inertia in the system). The slowing down of frequency changes allows an important time window for the rest of the system to respond, which is also slow due to large inertia. Recent studies performed by the North American Electricity Reliability Corporation (NERC) clearly indicate that frequency response capability is declining in the U.S. Eastern Interconnection power system[38]. Similarly, a declining trend in minimum system inertia has been observed in the Electric Reliability Council of Texas (ERCOT) system in recent years, particularly since 2015[39]. On May 8, 2022, California's solar and wind generation exceeded its load, and the state exported the excess generation to the rest of Western Interconnection[40]. Ireland, the UK, and South Australia have also experienced high penetration of inverter-based generation[41]. This trend can result in reduced mechanical inertia and fundamentally alter dynamics in future power systems and thus pose significant reliability challenges for power system operation. ***Controls*** need to be fundamentally and systematically assessed and developed to keep up with the increased speed of intrinsic system dynamics. This presents a significant opportunity to use high-speed control capabilities of inverters to achieve better power system performance than its conventional large-inertia counterpart. On the other hand, IBRs present a major challenge to

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[38] North American Electricity Reliability Corporation (NERC), "Frequency Response Initiative, Industry Advisory – Generator Governor Frequency response", April 7, 2015. Available at: https://www.nerc.com/pa/rrm/Webinars%20DL/Generator_Governor_Frequency_Response_Webinar_April_2015.pdf.

[39] Julia Matevosyan, "Inertia Trends in ERCOT", February 25, 2020. Available at: https://www.esig.energy/inertia-trends-in-ercot/.

[40] National Public Radio, "California just ran on 100% renewable energy, but fossil fuels aren't fading away yet", May 13, 2022, https://www.npr.org/2022/05/07/1097376890/for-a-brief-moment-calif-fully-powered-itself-with-renewable-energy.

[41] ERCOT, "Inertia: Basic Concepts and Impacts on the ERCOT Grid", 2018, https://www.ercot.com/files/docs/2018/04/04/Inertia_Basic_Concepts_Impacts_On_ERCOT_v0.pdf.

maintaining ***Protection*** of the system because inverters, by design, provide lower –sometimes much lower – fault currents, and these faults might not be detected by conventional protection systems[42].

These control and protection issues are compounded by the fact that conventional large-scale generation facilities are being or can be replaced by a large number of smaller generation assets, such as wind, solar, small modular nuclear reactors, and microreactors, energy storage, buildings, and EVs. These diverse assets make the requisite sensing and control systems much more complex and challenging. Wide area control and operation for seamless ***Transmission and Distribution Integration*** are an important research area. Some of the key operation and control technologies include wide-area control for voltage and frequency stability, optimal dispatch for resource adequacy, advanced remedial action schemes, adaptive islanding, and self-organizing microgrids. The faster dynamics and wider-area control needs pose additional challenges for ***Sensing and Measurement*** as well as real-time ***Data Analysis***. Real-time phasor measurements and emerging waveform measurements as well as customer behaviors and operational human factors are important considerations for meeting these future operation and control needs. See Section 6 on the Planning pillar for more on data analytics and human behavior modeling.

Fundamental transformations in controlling and protecting the electric infrastructure are vital to achieving an electrical grid that is safe, resilient, reliable, secure, affordable, flexible, sustainable, and equitable. The system is becoming more complex with the integration of a range of new generation technologies, new and more ***Flexible Grid Management***, 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 ecosystem of electricity supply, delivery, and end-use. New approaches for improving system operation for enhancing reliability and resilience will need to be employed. Research is necessary to investigate new technologies and approaches for improving system operations, power flow, control, and protection in response to these changes. 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 is requiring the 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 RD&D over multiple decades with close coordination among all stakeholders including industry (system operation entities and their vendors), regulators, and other researchers including from academia.

5.1 Connection to Power System Objectives and Administration Goals

The efforts in the Operations pillar will contribute to the goals of the other pillars, the GMI power system objectives, and the Administration's goals.

- Connections with other pillars: Development of next generation communication protocols requires an understanding of any new demands driven by new architecture and control concepts from the **Operations** pillar. These communication specifications must be informed by cybersecurity and disaster recovery needs and further studied by the **Resilience and Secure System** pillar. Communication protocols also relate to the **Markets, Polices, and Regulations**

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[42] Yashen Lin, Joseph H. Eto, Brian B. Johnson, Jack D. Flicker, Robert H. Lasseter, Hugo N. Villegas Pico, Gab-Su Seo, Brian J. Pierre, and Abraham Ellis. 2020. Research Roadmap on Grid-Forming Inverters. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5D00-73476. Available at: https://www.nrel.gov/docs/fy21osti/73476.pdf.

pillar in examining future market and regulatory options that entail broad consumer engagement with grid services that will dictate communications requirements.

- Power System Objectives: Technologies such as energy management systems and advanced distribution management systems are critical to many of the power system objectives such as **Managing Electrification** and **Clean Energy Integration**. Better system operations will also support **Grid Infrastructure Expansion** and **Reliability, Resilience, and Security**.
- Administration Goals: New system operations and controls paradigms are necessary for integrating the large number of variable renewables and distributed energy resources into the grid. As a result, these new paradigms are critical for the Nation to meet its **Decarbonization** and **Infrastructure Modernization** goals**.**

6 Grid Modernization Pillar 3: Planning

This pillar area aims to develop next-generation tools for policy analysis, grid expansion planning, and day-ahead planning and to support policy development, economic assessments, engineering design, and risk and vulnerability analyses. The results of these tools can impact billions of dollars of capital investments and operational costs. The scope of this pillar area includes power system modeling, economic modeling, interdependencies with other critical infrastructures, simulation techniques for large-scale modeling analysis, climate impact assessment, and human behavioral modeling.

Power system planning must go beyond the traditional focus on the electricity network, as the power system is not a closed system but a part of an energy ecosystem. Regarding the clean energy transition, the power system is both a major contributor to climate change and is more dependent on weather and climate than ever before. Weather and climate can impact variable energy resources, such as wind and solar generation, and weather- and climate-dependent loads, such as air conditioning. ***Climate Adaptation and Mitigation*** is an important research area for future power system planning. Two recent examples – the California rolling blackouts in 2020[43] and the Texas cold storms in 2021[44] – clearly show the impact of weather conditions on how electricity is generated, delivered, and consumed. Furthermore, the power system is increasingly intertwined with critical ***Interdependent Infrastructures***. Gas pipeline systems provide natural gas for power generation; transportation systems are increasingly relying on the power grid for EV charging and in turn potentially providing battery storage for the grid; and communication systems are essential for monitoring and controlling power system devices. Failures in these other infrastructures can have major impacts on the safety, reliability, and resilience of the power grid and thus should be understood and mitigated.

Planning

- Climate Adaptation and Mitigation
- Data Science and Forecasting
- Power System Modeling Tools
- Economic Modeling
- Interdependent Infrastructures
- Multi-Model Integration
- Behavioral Science

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[43] California Independent System Operator. “Final Root Cause Analysis: Mid-August 2020 Extreme Heat Wave”, 2021, http://www.caiso.com/Documents/Final-Root-Cause-Analysis-Mid-August-2020-Extreme-Heat-Wave.pdf.

[44] ERCOT, “Update to April 6, 2021 Preliminary Report on Causes of Generator Outages and Derates During the February 2021 Extreme Cold Weather Event”, 2021, https://www.ercot.com/files/docs/2021/04/28/ERCOT_Winter_Storm_Generator_Outages_By_Cause_Updated_Report_4.27.21.pdf.

Within the grid, ***Power System Modeling Tools*** need advancement to keep up with the increasing scale and complexity of the grid. Power system planning and design tools are embedded in numerous modeling, simulation, and analysis software packages, performing such technical functions as power flow analysis, capacity expansion planning, production cost modeling, contingency analysis, modeling dynamic response, and transient stability analysis. Grid models need to reflect the collective behaviors of nodes growing from ten thousand to millions through appropriate and novel abstractions. This increase in complexity will require ***Multi-Model Integration*** that considers electromagnetic phenomena to capture faster dynamics introduced by IBRs and DC transmission, beyond the steady-state and electromechanical phenomena; new fossil fuel generation concepts (e.g., carbon dioxide capture and use); flexible modular nuclear; and cybersecurity threats. Plus, the grid needs to be optimized for many more scenarios and conditions to account for the increasing variable nature of a number of generation resources. Multi-Model Integration will also be needed to cross-link long term ***Economic Models*** like capacity expansion and production cost models with short term models like network reliability models. Development of this cross-linking capability will enable the dynamic recalibration of security constraints within Economic Models.

As grid models grow in size and complexity, solution methods and computing techniques need to advance accordingly. An example of a research gap in computing is the ability to perform highly detailed scenario analysis using economic models; currently, such calculations can consume millions of hours of computer time. Fundamental computing techniques, including artificial intelligence and machine learning, and high-performance computing resources, including exascale computing and quantum computing, that are being advanced in DOE's Office of Science programs should continue to be leveraged and/or explored for grid tools. Application of innovative sensor technologies, including existing quantum sensors and evolving high speed communication approaches (e.g., quantum information technologies) should also be explored.

To understand the complexity of the future grid, we need data. One category of data comes from the grid (i.e., measurements of electrical metrics such as voltage, current, and frequency). We have accumulated significant volumes of historical grid data but need novel methods to parse out useful trends and patterns from that data to better understand grid behaviors for planning purposes. For decades, DOE has used Supervisory Control and Data Acquisition (SCADA) measurements at a speed of one sample every few seconds to support grid planning and operation. Since the early 2000s, DOE has sponsored the development of phasor measurements at a speed of 30-120 samples per second through its North American SynchroPhasor Initiative (NASPI)[45]. More recently, waveform measurements[46,47] at a speed of thousands of samples per second are emerging in the context of capturing faster dynamics of IBRs. Another category is data external to the grid, including weather conditions, wildfire information, market conditions, and cybersecurity situations. These external data support load and generation forecasting, Public Safety Power Shutoff (PSPS) planning, and cybersecurity assessments. To truly benefit from the increased volume and diversity of data, we need improved ***Data Science and Forecasting*** techniques in the areas of statistics-based models, data reduction techniques, artificial intelligence and machine learning approaches, and data-model convergence to support robust operational planning to ensure resource adequacy and mitigate power system disruptions.

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[45] North American SynchroPhasor Initiative (NASPI), at https://naspi.org/.

[46] J. Follum, H. Kirkham, A. Riepnieks, P. Etingov, L. Miller, X. Fan, AND E. Ellwein, NASPI Report: Roadmap for Advanced Power System Measurements. United States: 2021. doi:10.2172/1871292. https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-31214.pdf。

[47] W. Xu, Z. Huang, X. Xie and C. Li, "Synchronized Waveforms – A Frontier of Data-Based Power System and Apparatus Monitoring, Protection, and Control," Visionary Paper in IEEE Transactions on Power Delivery, vol. 37, no. 1, pp. 3-17, Feb. 2022, doi: 10.1109/TPWRD.2021.3072889. https://ieeexplore.ieee.org/document/9403991。

In addition to addressing the physical system, power system planning must include a human element. Related to the Operations pillar (see Section 5), human operators are still essential in an increasingly automated operating environment. How they respond to grid situations in a short timeframe should inform the design of future control room functions. Another important human element is electric consumers. As load and edge devices become more interactive, consumers can become active participants that influence grid performance. It is important to incorporate human behavior models and ***Behavioral Science*** into planning analyses for designing and assessing grid control and operation approaches.

6.1 Connection to Power System Objectives and Administration Goals

The Planning pillar will contribute to the goals of the other pillars, the GMI power system objectives, and the Administration's goals.

- Connections with other pillars: The development of high-performance, high-resolution production cost planning and optimization tools will relate closely to the **Operations** pillar in the development of advanced solvers and algorithms that underlay tool platforms developed by both teams. The design and planning tools targeted to support the future distribution system will have significant linkage to the **Markets, Policies, and Regulations** and **Devices and Integrated Systems** pillars in their development of distributed energy resources (DER) valuation analytics and metrics; model attributes necessary to enable analysis of new grid attributes; and business/market models for both transmission and distribution grid assets (i.e., grid edge).
- Power System Objectives: Future power system planning needs to consider new demand from deeper electrification, new generation from clean energy sources, and infrastructure expansion to maintain system reliability, resilience, and security. Therefore, planning has clear ties with many of the power system objectives including **Managing Electrification**, **Clean Energy Integration**, **Grid Infrastructure Expansion,** and **Reliability, Resilience, and Security**.
- Administration Goals: Enhancing the available power system modeling tools with improved data science, forecasting, and multi-model integration to account for **Climate Adaptation and Mitigation** will inform the necessary **Clean Energy Integration** and **Grid Infrastructure Expansion** to achieve power sector-wide and economy-wide **Decarbonization.**

7 Grid Modernization Pillar 4: Markets, Policies, and Regulations

This pillar area aims to develop next-generation methods and tools for markets, policies, and regulations for a grid that is efficient and capable of ensuring a reliable energy supply while achieving the Administration's deep decarbonization targets. The scope of this pillar area includes policies and regulations at the Federal, Tribal, regional, state, and municipal levels; market designs to enable just and equitable integration of all clean energy resources; and economic valuation that incorporates and prioritizes energy justice.

Grid modernization presents a complex bundle of technological, economic, institutional, and regulatory challenges. This pillar area primarily addresses the latter three challenges. New ***Market Design*** as well as updated ***Policies and Regulations*** will be needed to incorporate decarbonization goals into the electric grid while maintaining high levels of grid reliability in a cost-effective manner. The clean energy transition and energy justice are two relatively new dimensions for the current market, policy, and regulatory environment. Organized wholesale electricity markets are embedded within generation and transmission control segments, intermixing financial, regulatory, and operational issues that are not always fully congruent with system goals for the electric sector, especially clean energy goals set anywhere from the local to the national level. Some retail markets offer opportunities for grid services, but more needs to be done to increase flexibility for consumer participation, to enable further adoption of grid-edge resources (e.g., rooftop PV and energy storage) at consumer sites, and/or to increase utilization of distributed resources to support grid performance (e.g., vehicle-to-grid technology).

Markets, Policies, and Regulations

- Policies and Regulations
- Market Design
- Economic Valuation
- Energy Justice

Grid-related incentives and requirements will evolve significantly when driven by markets, policies, and regulations. As a result, power system economics will change. It will be necessary to develop ***Economic Valuation*** approaches for both the structure and implementation of markets, policies, and regulation. There needs to be a better understanding of how various grid industry organizations and structures impact the economics of system planning, operations, and control. The evolving market and incentive structures are strongly linked to control design and how electricity is delivered in the power system. This connection will increase as more links are established between distributed controllable grid assets and traditional market and dispatch structures. Furthermore, real-time valuation and control of various critical ancillary services will require greater coordination and management.

We anticipate rapid changes in potentially disruptive technologies (e.g., distributed generation, energy storage, grid-interactive efficient buildings, EVs, small modular generation units, and offshore wind). We also anticipate rapid growth in electricity demand, aging infrastructure, customer desires for more choices and innovative services, and cyber and physical threats. These rapid technological changes and growth highlight issues around the roles and functions of consumers, electric utilities, and other service providers. In some cases, utilities' integrated resource planning processes face challenges when they attempt to incorporate those disruptive technologies. A key challenge is the alignment of existing regulatory/utility planning and operational models with state and Federal goals while addressing longer-term issues.

Workforce Development is another policy area that is key to promoting sustainable and robust grid development in the long term. The rapid transformation of the grid demands a new skill set that combines traditional engineering expertise with capabilities in data science, behavioral science, and human dimension considerations, as well as risk and decision analytics. There is a need to cultivate and attract a diverse range of talent to the sector, develop educational pathways that align with the evolving demands of the industry, and establish mentorship programs to facilitate knowledge transfer from seasoned professionals to the next generation of grid experts. Expanding upon existing programs and opportunities that foster partnerships between academia, Federal agencies, and industry is essential.

Energy Justice is “the goal of achieving equity in both the social and economic participation in the energy system, while also remediating social, economic, and health burdens on those disproportionately harmed by the energy system.”[48] Advancing this concept in the power sector requires research into how the decision-making processes for grid operation, planning, and investments can consider and address the sector’s impact on historically disadvantaged communities. Much of grid and energy development, such as wind and solar farms and long-distance transmission, impact local communities but may not deliver equitable benefits to those same local communities. Emergency decisions such as controlled outages may affect disadvantaged communities more than other communities. Grid investments that increase reliability and resilience are lacking in some disadvantaged communities, while other disadvantaged communities may face high environmental impacts of compounding infrastructure investments located in their geographic areas. DOE research in this space will aim to develop metrics, methods, and procedures to internalize energy justice into grid market design and policies.

It is important to note that the ownership structures and regulatory landscapes in the electric power sector are diverse, complex, and evolving, particularly as consumers become more active participants; thus “one size fits all” approaches and solutions may be problematic.

This pillar area will have a special emphasis on community engagement as Tribal groups, state-level decision makers, regulatory commissioners, and regional planning organizations play critical roles in working with utilities to shape both the direction and pace of grid modernization.

7.1 Connection to Power System Objectives and Administration Goals

The Markets, Policies, and Regulations pillar will contribute to the goals of the other pillars, the GMI power system objectives, and the Administration’s goals.

- Connections with other pillars: This pillar will work with policymakers and key partners to obtain input on design requirements and use cases, which will be shared with the **Planning** pillar. The pillar will also involve working with partners to incorporate the latest information from the **Resilient and Secure Systems** and **Planning** pillars as well as working with sensing and measurements devices in the **Devices and Integrated Systems** pillar to support valuation of grid assets and services at the distribution and transmission levels.
- Power System Objectives: Future innovations in this pillar will be necessary to achieve both **Clean Energy Integration** and **Affordability**. In addition, new market signals may be required for the power system to maintain **Reliability, Resilience, and Security** throughout the energy transition.
- Administration Goals: As the power system transitions to a clean energy future, this pillar will work to ensure that **Workforce Development** and **Energy Justice** are focuses when setting parameters around both social and economic participation in the energy system and its supporting industries, while also remediating social, economic, and health burdens on those disproportionately harmed by the energy system.

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[48] Department of Energy, “How Energy Justice, Presidential Initiatives, and Executive Orders Shape Equity at DOE”, https://www.energy.gov/diversity/articles/how-energy-justice-presidential-initiatives-and-executive-orders-shape-equity.

8 Grid Modernization Pillar 5: Resilient and Secure Systems

This pillar area aims to develop physical and cyber solutions for improving the resilience and security of the electric sector. The scope of this pillar area includes characterization of all-hazard risks and energy-related emergencies internal and external to the grid; assessment of impact and consequences of such risks and emergencies; and development of mitigation approaches including situational awareness, incident support, and secure control design. Mitigation approaches should include robustness of critical grid systems prior to the event, resourcefulness during the event, rapid recovery following an event, and adaptability to future adverse events and threats.

Our Nation's power grid must be more resilient to an evolving spectrum of threats and hazards. DOE's resilience research aims to develop grid architectures for operation, planning, and regulatory layers that are inherently resilient to all threats and hazards, low cost, and preserve other key operational criteria such as reliability and stability. 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 societal prosperity, national security, and economic wellbeing. As we transition to a decarbonized economy, it is expected that the grid will become more interdependent with national economic activity. As such, there is a renewed need to address our Nation's long-term ***Energy Security*** which can be enabled by grid modernization. Maintaining affordable access to energy by deeply understanding technology life cycle and supply chain risks, while concurrently incorporating the risks of acute shocks, requires new integrated analytical capabilities and technologies. Examples include updated architectures, standards, and guidelines focused on ensuring that electricity infrastructure provides resilient, consistently accessible and affordable energy while transitioning to and operating an increasingly decarbonized grid.

Today, the grid faces ever-increasing and complex threats, including intensifying cyber and physical attacks, severe weather, wildfires, fuel delivery issues, and even supply chain challenges[49]. Combined with factors such as managing legacy infrastructure and increasing reliance on digital and communications technologies deployed at a massive number of active locations, these threats can cause devastating large-area, long-duration outages[50]. Our current standard measures of reliability and accepted planning and operational practices do not sufficiently address these threats. To properly address the full spectrum of risks resulting from these threats, ***Inter- and Intra-System Risk Assessment*** should be a research focus. Intra-system risk assessment allows deep and precise analysis of risks, while inter-system risk assessment captures feedback and interdependencies at a more holistic level. These complementary risk assessment methods focus on the probability versus consequences of major outages and other failures that involve the grid. Together, they acknowledge the deep interdependencies between the grid, communication systems, natural gas, and other infrastructures, as well as social, economic, and national defense systems.

Resilient and Secure Systems

- Cybersecurity
- Energy Security
- Microgrids
- Inter- and Intra-System Risk Assessment

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[49] DOE Office of Electricity, 2022, "Securing America's Clean Energy Supply Chain", https://www.energy.gov/policy/securing-americas-clean-energy-supply-chain.

[50] 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.

Malicious cyber threats pose a significant challenge to the power grid given its physical immensity, interconnectivity, and enormous operational complexity (e.g., new and legacy components introducing architectural and supply chain issues). It is imperative that we take new and holistic approaches to the ***Cybersecurity*** of electric infrastructure. Over the past five years, cyber threats to the power grid have evolved significantly and continue to increase in frequency and severity. Additionally, while directed energy weapons remain a possibility, physical threats from ballistic weapons have increased in frequency, impact, and diversity to include attacks using emerging technologies like unmanned aerial vehicles and consumer-grade drones. Physical threats have also included accidental manned flight collisions with energy infrastructure. National-level exercises[51] 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 are conducted under scenarios that reflect typical operating conditions (blue-sky backdrops), but it is essential they expand to include settings such as pandemics, storms, or other natural disasters.

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 disgruntled novices to highly sophisticated adversaries who can leverage the full resources of a nation-state to create and exploit vulnerabilities in a system and exploit them to meet their long-term goals [52]. Not all utilities are equipped with the resources and knowledge to address threats from higher tier adversaries, so partnerships with government entities is essential to thwart the full spectrum of attacks. This approach aligns with this Administration's *National Security Strategy*[53] and current DOE security plans[54].

As part of this mitigation strategy, ***Microgrids*** can function autonomously as independent systems for normal and emergency operations. Microgrids for emergency operations can be a particularly crucial in maintaining electric supply to critical loads while the main grid is under attack or down due to other threats. Previous GMI efforts have demonstrated such microgrid operations in industrial contexts. Future efforts will focus on incorporating more diverse technologies and scenarios, scaling up for broader applications as well as value stacking considerations.

8.1 Connection to Power System Objectives and Administration Goals

The Resilience and Secure Systems pillar will contribute to the goals of the other pillars, the GMI power system objectives, and the Administration's goals.

- Connections with other pillars: The development of new threat detection and prediction modeling tools can benefit from advanced algorithm solvers (e.g., high performance computers) being developed in the **Planning** and **Operation** pillars. Novel technologies studied in these pillars (e.g., quantum sensors, quantum secure communications) and the need for high volume, high velocity data stream management in real-time for enhanced security, precise timing, situational awareness, and threat detection and prediction can leverage sensing and measurements efforts as well as advanced data analytics and communications. Resilience and

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[51] NERC, GridEx, https://www.nerc.com/pa/CI/ESISAC/Pages/GridEx.aspx.

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

[53] National Security Strategy, October 2022, https://www.whitehouse.gov/wp-content/uploads/2022/10/Biden-Harris-Administrations-National-Security-Strategy-10.2022.pdf.

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

security against higher-consequence and lower-frequency events require new considerations in the **Markets, Policies, and Regulations** pillar for proper incentives to invest in resilience and security measures.

- Power System Objectives: As the number and complexity of security threats and operational hazards increases, we face new challenges in maintaining the resilience and reliability of our power grid. Therefore, the Nation must continue research in this pillar to meet our goals for **Reliability, Resilience, and Security**.
- Administration Goals: As the climate changes and our electric power system transitions to incorporate more clean energy, the Nation must continue research in this pillar to meet our goals for **Climate Adaption and Mitigation** and will require careful attention to appropriately secure **Workforce Development**.

9 Grid Modernization Pillar 6: Flexible Generation and Load

This pillar area aims to enable and maximize flexibility in energy generation and load that can respond to the variability and uncertainty of conditions at multiple temporal and spatial scales for a range of energy futures. The scope of this pillar area includes generation, load, and hybrid energy systems.

Flexible Generation and Load

- **Flexible Generation**
- **Flexible Load**
- **Hybrid Energy Systems/Integrated Energy Systems**

The power system needs more flexibility for several reasons: wind and solar generation introduce more variability and uncertainty; new loads and DERs impact the bulk system by increasing load variation and uncertainty in forecasting net load on multiple timescales; hazards such as weather events, potential cyber and physical threats, and other global events increase in frequency and severity; and the aging electric infrastructure poses high probability of failures and interruptions in electricity delivery.

The future grid needs ***Flexible Generation.*** The generation mix feeding the Nation's grid is changing and the different pathways forward have varying cost and reliability implications. Understanding these implications should foster R&D activities that support planning, deployment, and operation of a modernized generation fleet. Generation technologies considered in this area include power plants connected at various levels of the transmission and distribution system. They can encompass solar generation, distributed wind, integrated energy storage, and microgrids aggregated to utility-scale levels. They also encompass technologies that revolutionize conventional nuclear and fossil energy resources such as advanced nuclear technologies (e.g., small modular reactors, advanced reactors, and microreactors) and advanced fossil technologies (e.g., carbon capture and clean hydrogen production). These generation technologies can potentially provide increased flexibility.

On the consumption side, there are opportunities to utilize more ***Flexible Load*** to support grid operation and planning. Traditionally-passive consumption devices are evolving to smartly respond to grid conditions. Air conditioners, gas furnaces, and water heaters can adjust their thermostat settings to decrease consumption when the grid is under stress. Refrigerators and lights are also incorporating smart settings. EVs can charge or not charge depending on electricity price or other incentive signals.

Across the board, loads are evolving to be active participants and provide flexibility to support grid performance.

Hybrid Energy Systems include multi-fuel inputs and outputs and can further provide flexibility for the grid. A recent multi-National Laboratories report defines hybrid energy systems as "systems involving multiple energy generation, storage, and/or conversion technologies that are integrated—through an overarching control framework or physically—to achieve cost savings and enhanced capabilities, value, efficiency, or environmental performance compared to the independent alternatives."[55] Hybrid energy systems can play a major role in decarbonizing the U.S. economy[56]. ***Integrated Energy Systems*** address a multi-system energy challenge holistically rather than looking at each of the systems in isolation. For example, if the goal is to provide heat and electricity to a group of buildings while reducing natural gas use, an integrated energy system would co-optimize several energy generation sources to achieve this goal more effectively and efficiently than any single system alone[57]. Integrated energy systems are generally larger than or can encompass hybrid energy systems. Both can manage uncertainties and offer flexibility to the rest of the system. Studying the deployment and operation of hybrid generation systems that include diverse power generation technologies will identify additional flexibility and reliability gains. Designing and optimizing infrastructure for tightly coupled hybrid energy systems will be important to support deployment of these hybrid generation mixes.

9.1 Connection to Power System Objectives and Administration Goals

The Flexible Generation and Load pillar will contribute to the goals of the other pillars, the GMI power system objectives, and the Administration's goals.

- Connections with other pillars: The R&D executed in this pillar will contribute closely to the **Planning** and **Operations** pillars to understand what new grid services will be available from future generation and load. As virtual power plants become more common, interoperability standards developed through the **Devices and Integrated System**s pillar will be critical to success.
- Power System Objectives: As variable renewable energy sources become more prolific on the grid, the power system needs additional flexibility to balance the variability. Thus, flexible generation and load is increasingly important to **Clean Energy Integration**.
- Administration Goals: Similarly, flexible generation and load are necessary to meet the Administration's **Decarbonization** goals. This pillar area becomes especially necessary to handle periods of low power generation.

10 GMI Execution Plan

The GMI plans to execute comprehensively on the strategy described herein through multiple program types described below:

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[55] U.S. Department of Energy (DOE). 2021. Hybrid Energy Systems: Opportunities for Coordinated Research. Golden, CO: National Renewable Energy Laboratory. DOE/GO-102021-5447. https://www.nrel.gov/docs/fy21osti/77503.pdf.

[56] Energy Department Unlocks Innovative Opportunities for Coordinated Research on Hybrid Energy Systems, https://www.energy.gov/eere/articles/energy-department-unlocks-innovative-opportunities-coordinated-research-hybrid-energy#:~:text=The%20report%20is%20a%20collaborative%20effort%20among%20DOE,a%20major%20role%20in%20decarbonizing%20the%20U.S.%20economy.

[57] National Renewable Energy Laboratory (NREL). Integrated Energy System Simulation. https://www.nrel.gov/grid/integrated-energy-system-simulation.html

- Research and Development: Both basic and applied science necessary for the innovation and invention of new tools, technologies, and systems that will enable the grid of the future.
- Testing and Validation: Testing and technology validation to confirm that component technologies can be incorporated into a complete system solution and that system performance and operation are met under anticipated operating scenarios.
- Simulation: Tools needed for power system planning that will model emerging needs driven by changing technologies and operational capabilities, larger and more complex infrastructure , more challenging forecasting, and new types and sources of data.
- Demonstrations: Projects to prove the effectiveness of innovative technologies in real-world conditions at scale in order to pave the way for widespread adoption and deployment.
- Technical Assistance: Support for stakeholders such as state regulatory agencies and regional planning organizations on grid modernization topics as evolving grid requirements rapidly gain momentum.
- Analysis: The process of breaking a complex topic or substance into smaller parts in order to gain a better understanding of it, including future power sector scenario development.

The technical achievements both within and across the six grid modernization pillar areas will provide the tools and technologies necessary to achieve the vision of a modernized grid that is resilient, reliable, secure, affordable, flexible, sustainable, and equitable as well as provide a platform for innovation and economic growth. By demonstrating the value of grid modernization technologies and applications, DOE will provide the technical foundation to inform decision-makers about infrastructure investments and policy requirements. The GMI provides an organizing framework under which current and future projects and partnerships are aligned and focused. The GMI envisions a fully integrated energy system from fuel to generation to load and their interdependent infrastructures, with an emphasis on maintaining the reliability and resilience of a secure grid.

To support these efforts, the GMLC works closely with DOE as part of the GMI to produce results beyond the capacity of individual offices and Labs working independently.

10.1 Funding Opportunities

Many GMI projects are jointly funded and managed by several of the DOE member 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 of duplication in these overlapping 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.

The GMI uses multiple funding mechanisms to drive the development and adoption of grid technologies, including lab calls[58], funding opportunity announcements (FOAs), and other office specific activities.

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[58] As a lab call, only DOE national laboratories, plants, and sites are eligible prime applicants, but other entities can be included as partners or advisors.

In 2016, DOE announced the first Grid Modernization Lab Call[59] — a comprehensive, $220 million, three-year effort that funded 88 projects across the National Laboratories complex, bringing together DOE and the National Laboratories with more than 100 companies, utilities, research organizations, state regulators, and regional grid operators 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.

In 2017, DOE announced up to $32 million over three years for seven projects[60] to develop and validate innovative approaches to enhancing the resilience of electricity distribution systems, focusing on the integration of DER, advanced controls, grid architecture, and emerging grid technologies at a regional scale.

In 2019, DOE announced the third Grid Modernization Lab Call[61] with an $80 million investment in six areas: Resilience Modeling; Energy Storage and System Flexibility; Advanced Sensors and Data Analytics; Institutional Support and Analysis; Cyber-Physical Security; and Generation.

In early 2023, DOE announced the fourth Grid Modernization Lab Call[62] with $38 million to support five topics: Power and Control Electronics (PACE); Cybersecurity for Architectures, Standards, and Practices (CASP); Quantum Facilities for Applied Computing, Sensing, and Security (qFACSS); Equitable System Operation and Planning (ESOP); and Climate Impact on Energy Resources (CIER).

Additionally, several offices within DOE have successfully conducted lab calls and FOAs on office-specific grid modernization topics[63].

DOE intends to continue to develop and release joint lab calls and FOAs through the GMI, as well as through individual offices.

10.2 Coordination of DOE Grid Activities

Through the GMI, DOE coordinates grid modernization activities across the Offices of Electricity (OE), Energy Efficiency and Renewable Energy (EERE), Fossil Energy and Carbon Management (FECM), Grid Deployment (GDO), Nuclear Energy (NE), Science (SC), Cybersecurity, Energy Security, and Emergency Response (CESER), Technology Transitions (OTT), Energy Justice and Equity (EJE), Clean Energy Demonstrations (OCED), and Advanced Research Projects Agency-Energy (ARPA-E).

Other offices, such as the Office of Policy and Loan Programs Office, may contribute staff time and coordinate with the RDD&D funding offices to enhance the impact of the Department's investments.

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[59] Department of Energy Announces $220 Million for the Grid Modernization Initiative, January 2016. https://obamawhitehouse.archives.gov/blog/2016/01/13/220-million-for-grid-modernization-initiative.

[60] Resilient Distribution Systems Lab Call Awards, 2017. https://www.energy.gov/resilient-distribution-systems-lab-call-awards.

[61] 2019 Grid Modernization Lab Call Awards, 2019. https://www.energy.gov/2019-grid-modernization-lab-call-awards.

[62] 2023 Grid Modernization Lab Call, 2023. https://www.energy.gov/gmi/2023-grid-modernization-lab-call.

[63] Examples of office-specific funding opportunities in the grid modernization area are: Increasing Utilization and Reliability of Electric Infrastructure with Grid-enhancing technologies (GETs) (https://www.fedconnect.net/FedConnect/default.aspx?ReturnUrl=%2fFedConnect%2f%3fdoc%3dDE-FOA-0002948%26agency%3dDOE&doc=DE-FOA-0002948&agency=DOE); Solar Energy Technologies Office Lab Call FY 2022-24 – Systems Integration (https://www.energy.gov/eere/solar/solar-energy-technologies-office-lab-call-fy2022-24-systems-integration); Wind Energy Technologies Office Releases $28 Million Funding Opportunity to Address Key Deployment Challenges for Offshore, Land-Based, and Distributed Wind (https://www.energy.gov/eere/wind/articles/weto-releases-28-million-funding-opportunity-address-key-deployment-challenges).

10.3 Technology Transfer

Technology transfer is an important element of the GMI effort because modernization of the nation's electric infrastructure will require investments by the utility industry as well as through consumer investments via commercial offerings. Technology transfer will occur primarily through GMI functions, in concert with the OTT activities, designed explicitly for collaboration with the electric power industry (utilities, vendors, and service providers) and demonstration partners.

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 benefits from RD&D advances.

Additional pathways to encourage rapid transfer of GMI innovations include:

- Development of open-source tools and platforms (e.g., software) that aggregate advances from the participating National Laboratories and work with vendors to enable them to include these tool sets in their proprietary 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.

10.4 Increased Stakeholder Engagement and Partnership

DOE will partner with key stakeholders in the electric power sector. Regular reviews will occur between experts leading technical areas and industry stakeholders to seek input on the most promising grid modernization research pathways. In tandem with lab-operated projects, DOE will issue competitive research funding opportunities and establish appropriate R&D agreements address challenges identified in the GMI strategy. Centralized information exchange will facilitate best practices and reduce duplicative or unproductive technology pathways. DOE will provide additional focus on translating advances in underlying grid technologies into meaningful knowledge and tools for Tribal Nations, states, regions, and regulatory communities. Finally, DOE will rely on partners to participate in the execution of multi-scale demonstrations, including at a regional level, to prove concepts of the modernized grid.

DOE will work with other Federal, regional, and state agencies that have critical and evolving roles in grid modernization. Key Federal agency partners include the Department of Defense (as a large purchaser and user of clean energy), the Power Marketing Administrations (as a manager of large hydropower resources and operator of major transmission systems), the Departments of the Interior and Agriculture (as managers of siting on Federal lands), the National Institute of Standards and Technology (as a developer of interoperability standards), and the Department of Homeland Security (as a developer of national security policies affecting the energy sector).

DOE will also seek partnerships with those who regulate the grid. Wholesale electricity markets and the reliability of the bulk power system, both interstate in nature, are regulated by the Federal Energy Regulatory Commission (FERC) and the North American Electric Reliability Corporation (NERC), respectively. State public utility commissions (PUCs) regulate investor-owned utilities that serve retail customers and determine the allowed rate of return for utility investment. Consumer- or publicly-owned utilities (e.g., rural cooperatives, public utility districts, and municipal utilities) also serve retail customers, and are overseen by elected boards, commissions, and even city councils. State legislatures, governors, and energy offices set policy; consumer advocates often enter into PUC dockets; and state agencies have specific roles such as siting of transmission, environmental compliance, and monitoring of energy consumption.

DOE will also partner with other major groups of key electric grid participants:

- **Utility companies.** Investor-owned utilities (IOUs), utility cooperatives, power marketers, municipal utilities, and their trade associations (e.g., APPA, NRECA, EEI) produce or acquire electricity and distribute that electricity to consumers. Some are regulated and others are self-regulated (e.g., municipal utilities and cooperatives).
- **Independent power producers.** Developers who bid into both long-term and daily electricity markets to supply generation capacity.
- **Transmission organizations such as regional transmission organizations (RTOs), independent system operators (ISOs) and reliability organizations.** Organizations that carry out system planning, grid operations, and regional reliability activities.
- **Technology developers and vendors.** Companies with products that sell into the electricity system, ranging from transformers to software control systems.
- **Environmental community.** Advocates and non-governmental organizations that support cleaner energy sources and minimal environmental impacts from new generation, transmission, distribution, and end use.
- **Disadvantaged and Communities with Environmental Justice Concerns.** Community-based groups that represent the needs and priorities of communities most impacted by our energy system.
- **Consumer and technology advocacy groups.** Advocates for major consumers of electricity, individual power generation technology, and electrical system devices.
- **Research community and standards organizations.** This community is vast and makes vital intellectual contributions to grid modernization in all areas. It includes research divisions of utility trade associations, universities, standards bodies, the Electric Power Research Institute, and others. Many companies have their own private research groups, ranging from small businesses to international corporations like General Electric or Siemens. Universities, either individually or groups of universities (such as those under the Consortium for Electric Reliability Technology Solutions (CERTS) and Power Systems Engineering Research Center (PSERC)), are also key players in grid modernization RD&D.

GMI plans to conduct an annual Grid Modernization Summit and regional technical workshops to engage stakeholders and foster partnerships.

DOE's research and development investments informed by the GMI can help make 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 support the Nation's grid as it transitions to meet the needs of our 21st century economy.

11 Appendix I: Current GMI Member DOE Offices

As of August 2023, the GMI member offices are categorized in the following in two categories[64]:

Category 1:

- Office of Electricity (OE)
- Office of Energy Efficiency and Renewable Energy (EERE)
- Grid Deployment Office (GDO)
- Office Fossil Energy and Carbon Management (FECM)
- Office of Energy Justice and Equity (EJE)
- Office of Cybersecurity, Energy Security, and Emergency Response (CESER)

Category 2:

- Office of Science (SC)
- Office of Nuclear Energy (NE)
- Office of Technology Transitions (OTT)

12 Appendix II: GMLC Member National Laboratories

The 14 National Laboratories that support the GMI activities are as follows:

1. Ames National Laboratory
2. Argonne National Laboratory
3. Brookhaven National Laboratory
4. Idaho National Laboratory
5. Lawrence Berkeley National Laboratory
6. Lawrence Livermore National Laboratory
7. Los Alamos National Laboratory
8. National Energy Technology Laboratory
9. National Renewable Energy Laboratory
10. Oak Ridge National Laboratory
11. Pacific Northwest National Laboratory
12. Sandia National Laboratories
13. Savannah River National Laboratory
14. SLAC National Accelerator Laboratory

13 Appendix III: Overview of DOE Grid Activities

Multiple DOE offices have activities pertinent to the national power grid. These activities cover a diverse spectrum of grid relevance: some directly contribute to the technologies that drive better operation, planning, and performance of the grid; some improve the policy and market environments for the grid;

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[64] Any DOE office, if desired, can become a GMI member in one of two categories: Category 1 members commit annual funding to support joint RDD&D and GMI operation, and they lead strategic directions of the GMI; and Category 2 members support GMI activities and can fund RDD&D on an *ad hoc* basis.

and some ensure equitable benefits of grid development to all communities. These DOE offices work together to meet the demands for implementing the grid of the future.

13.1 Office of Electricity (OE)

Grid modernization is a critical aspect of all OE programs and all OE program funding except OE Program Direction is included in the Grid Modernization crosscut. In FY 2024, OE plans to continue pursuing research of technologies that improve grid reliability, resilience, efficiency, flexibility, and functionality. These activities include developing technologies, from inception to demonstration, that automatically detect, reject, and withstand cyber incidents. OE will also continue to develop core analytic, assessment, and engineering capabilities that can evolve as technology and policy needs mature to support decision making involving complex interdependencies among energy infrastructure systems, such as between electricity and natural gas systems. OE plans to continue supporting private sector innovation investment in data platforms and advanced communications/control designs as well as regional and national deployment through cooperative agreements.

13.2 Office of Energy Efficiency and Renewable Energy (EERE)

Historically, EERE has focused on driving down the costs and improving the performance of clean energy technologies. These long-term efforts have helped an array of clean energy technologies become more cost competitive, resulting in a dramatic increase in the number of these technologies being integrated into the electrical power system. Success integrating these technologies at scale will be critical to delivering on the Nation's climate and energy goals. This integration introduces new challenges for the operation of the U.S. power system that will require the development and deployment of new tools and technologies to ensure the electrical power system continues to operate in a safe, reliable, and cost-effective manner. However, it also provides new opportunities to transform our grid into a platform for greater prosperity, growth, and innovation.

EERE's grid integration activities focus on ensuring the seamless integration of energy efficiency, renewable power, and sustainable transportation technologies into the electrical power system. Clean energy technologies connect through the grid and form power systems at a variety of physical scales, from individual buildings to distribution systems to regional systems that can stretch across continents. Interactions and interdependencies are increasing within and among power system infrastructures and other interrelated systems such as communications networks. These interactions can have profound implications for the reliability and security of the energy system.

The suite of technologies and techniques required for successful grid Integration includes improved approaches to renewable power forecasting; application of energy storage technologies; advanced power electronics; "grid responsive" building technologies; vehicle-to-grid technologies; and new approaches to grid sensing, control, and operations. Furthermore, close engagement and collaboration with and among industry, regulators, and other stakeholders are needed to develop and deploy the necessary standardized communication and control protocols that enable these devices to successfully interface and interact, enabling grid operations at the lowest cost possible while maintaining or improving grid reliability.

In FY 2024, grid modernization activities across the EERE technology offices include the following:

1. Advanced Materials and Manufacturing Technologies Office (AMMTO): Building off the success of the Conductivity-enhanced materials for Affordable, Breakthrough Leapfrog Electric and thermal applications (CABLE) Conductor Manufacturing Prize, AMMTO will continue to invest in the development and demonstration of highly conductive materials that can provide significant efficiency improvements to the grid and grid-connected applications.
2. Building Technologies Office (BTO): Through its RDD&D on advanced and grid-interactive technologies, such as controls, interoperability, and energy storage, BTO will partner with industry stakeholders to develop and deploy grid-interactive efficient buildings related systems capable of connecting with the power grid in new and increasingly adaptive manners to help with overall energy system efficiency, reliability, resilience, environmental performance, and affordability. These capabilities are an integral and necessary part of a decarbonized power system that maximizes use of renewable resources and can significantly reduce energy use at times when it provides a valuable option for utilities and their customers.
3. Hydrogen and Fuel Cell Technologies Office (HFTO): HFTO funds RD&D in energy storage and grid integration including the National Renewable Energy Laboratory's (NREL) Advanced Research on Integrated Energy Systems (ARIES). In addition, HFTO's portfolio includes systems development and integration, including hybrid energy systems such as wind/offshore-wind to hydrogen, microgrids for underserved communities, along with their supporting analysis.
4. Vehicle Technologies Office (VTO): VTO will continue laboratory and industry-led projects to develop secure vehicle-to-grid connection and communication technologies, as well as high power grid-tied charging systems. VTO is also involved (along with OE and the Joint Office of Energy and Transportation) on EVGrid Assist[65], an effort to provide technical assistance supporting vehicle to grid integration.
5. Wind Energy Technologies Office (WETO): WETO will prioritize RD&D in offshore transmission analysis and technology advancement, grid reliability and resilience, wind control and cybersecurity research, and crosscutting demonstrations in grid-enhancing technologies and hybrid energy systems. This body of work will align with the *Renewable Energy Grid Integration Action Plan*, developed to align grid activities across EERE and OE to enable an equitable transition to a grid that supports a decarbonized power system by 2035 and a zero-emission economy by 2050, all while maintaining the reliability, affordability, security, and resilience of the energy system.
6. Solar Energy Technologies Office (SETO): SETO will support analysis and RDD&D of grid integration technologies at the bulk power and distribution system levels to allow reliable, resilient, and secure grid planning and operation with increasing amounts of solar, energy storage, hybrid energy systems, and other inverter-based assets.
7. Renewable Energy Grid Integration (REGI)[66]: REGI will expand power system planning and operations support to communities looking to deploy larger amounts of renewable energy, provide analysis-based technical assistance to power system operators and regulators, provide technical assistance for siting and permitting of renewable energy projects, and support investments in power electronics and clean energy modeling.
8. Water Power Technologies Office (WPTO): WPTO, through the HydroWIRES Initiative, will provide funding for hydropower hybrid demonstrations through a comprehensive Hydropower Futures Study[67] to quantify emission and cost reductions enabled by increased hydropower flexibility and

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[65] EVGrid Assist: Accelerating the Transition. https://www.energy.gov/eere/evgrid-assist-accelerating-transition.

[66] "FY2023 Energy Efficiency and Renewable Energy Proposed Appropriation Language", Page 7. Available at: https://www.energy.gov/sites/default/files/2022-04/doe-fy2023-budget-volume-4-eere-v2.pdf.

[67] "Hydropower Value Study: Current Status and Future Opportunities", January 2021. Available at: https://www.energy.gov/eere/water/articles/hydropower-value-study-current-status-and-future-opportunities.

new pumped storage hydropower (PSH) development, and expansion of the *PSH Valuation Guidebook* to include non-power values.

13.3 Office of Cybersecurity, Energy Security, and Emergency Response (CESER)

CESER supports and coordinates R&D efforts across the GMI pillars and DOE to develop tools and technology that effectively monitor, detect, and protect critical energy infrastructure and networks from threats; and enable automated assessments, situational awareness, and response to threats to the sector. CESER leverages DOE's National Laboratories to advance the goal of securely modernizing the Nation's electric grid. The dynamic threat landscape, climate crisis, advances in energy system technologies, increasing supply chain cybersecurity risks, and the use of legacy devices in an aging infrastructure are all continuous challenges to the resilience of the energy sector. CESER advances efforts to design and build new architectures (e.g., virtual power plants, cloud resources, artificial intelligence) and systems (e.g., grid management systems, automated management systems), with integral resilience to the growing climate, cybersecurity, and physical risks. In FY 2024, such efforts include developing cyber situational awareness and analytics; cradle to grave supply chain cybersecurity, including programs like Energy Cyber Sense; digital subcomponent enumeration and mitigation efforts; developing tools, guidance, and practices that help energy organizations' understanding and management of cybersecurity risk; cyber resilience through cyber engineering by way of programs such as the Consequence-driven Cyber-informed Engineering (CCE); and collaborations with universities to support workforce development and to stimulate innovation by students to address cyber risks to energy infrastructure.

13.4 Office of Fossil Energy and Carbon Management (FECM)

FECM minimizes environmental and climate impacts of fossil fuels and industrial processes while working to achieve net-zero emissions across our economy. Priority areas of technology work include carbon capture, carbon conversion, carbon dioxide removal, carbon dioxide transport and storage, hydrogen production with carbon management, methane emissions reduction, and critical minerals production.

FECM participation in GMI has historically been from the perspective of assuring grid stability through fossil generation and fuel security. In addition to this traditional role, FECM's mission within GMI has now also expanded to address decarbonization in the power sector and the economy to enable the achievement of the Administration's climate goals. FECM has an extensive portfolio of research, development, and demonstration (RD&D) activities that also contribute to the Department's GMI efforts.

In FY 2024, FECM will seek to directly fund FECM projects involving several GMI topic areas: 1) climate change impacts; 2) post-quantum cybersecurity; 3) energy justice; and 4) deep decarbonization grid planning analyses. Execution of these projects is expected to be done through GMI's GMLC and joint funding opportunity announcements mechanisms in coordination with other program offices.

13.5 Office of Nuclear Energy (NE)

NE supports targeted research across all six pillar areas (Figure 1) with industry, universities, and National Laboratories through competitive FOAs and directed research to enhance nuclear energy's contribution to a clean, reliable, resilient, and equitable electrical grid.

a. Integrated Energy Systems (IES) Program: The IES Program conducts RD&D activities to expand the role of nuclear energy beyond direct electricity grid support, to include industrial and transportation applications. In FY 2024, the IES Program is performing a study to understand how variation in electricity market structure, policy, and competition affects how nuclear plants operate and engage with the grid.
b. Light Water Reactor Sustainability (LWRS) Program: The LWRS Program conducts R&D to develop the technical basis and economic justification for commercial light water reactors (LWR) to operate more flexibly, including the use of nuclear power to produce products other than electricity and optimize participation in electricity markets. In FY 2024, the Program will continue to advance the technical, economic, and regulatory evaluations for utilizing commercial LWR to produce hydrogen. The resulting hydrogen can be stored to support the grid during periods of high demand or variable seasonal demand.
c. Advanced Small Modular Reactor (SMR) RD&D Program: The SMR RD&D Program works with industry through private-public partnerships (PPP) to conduct RD&D on advanced SMR designs that have the potential to provide safe, clean, and affordable energy generation options. In FY 2024, the program will continue to support industry efforts needed to successfully demonstrate SMR technology.

13.6 Office of Science (SC)

SC is the lead Federal agency supporting fundamental scientific research for energy. SC has an important role to play in grid modernization. For the last 50+ years, SC programs funded research and SC National Laboratories and user facilities have laid the basic science groundwork for some of the core technologies that will help us modernize the grid. From batteries to superconducting materials to environmental effects on grid infrastructure, we now can set ambitious targets due to SC's past and continuing investments in fundamental research provides the evidence-based foundation needed for the future grid infrastructure.

These SC investments have been extensive. For example, the Exascale Computing Project (ECP), jointly funded by SC's Office of Advanced Scientific Computing Research (ASCR) and the National Nuclear Security Administration's Advanced Simulation and Computing Program, supports the ExaGraph co-design project, which develops highly efficient graph algorithms and techniques for exascale computers, with application to large power grid problems. The primary focus of ExaGraph is to make combinatorial problems tractable, which otherwise become computationally unwieldy as their size grows. ExaSGD is the application project focused on electrical-grid challenges such as optimizing the grid's response to many potential disruption events under different weather scenarios. The power system modeling framework ExaGO, a part of ExaSGD, was released in February 2023 and is the first grid application to run on Frontier. The Mathematical Multifaceted Integrated Capability Centers (MMICCs) Program funded the Multifaceted Mathematics for Rare, High Impact Events in Complex Energy and Environment Systems (MACSER) center. A primary application for MACSER was the U.S. power grid, and the study of rare events such as blackouts and their impact on optimization, data analyses, stochastic processes, and mathematical representations.

Through its Office of Basic Energy Sciences (BES), SC supports the foundational research in experimental and computational materials science that is required for the discovery and design of new materials with properties that meet the requirements of future grid technology. For example, the Ultra Materials for a Resilient, Smart Electricity Grid (ULTRA)—a BES Energy Frontier Research Center (EFRC)—is advancing the science of ultra-wide band gap semiconductors and dielectric materials to enable more efficient energy conversion and control and reduction in the physical size of components required for the future smart grid. This work within the EFRC program, as well as many core research activities supported by BES, are part of a coordinated effort across SC and across DOE to advance the science and technology of microelectronics. Such efforts are essential to meeting Administration goals for a completely decarbonized electric grid by 2035 that can accommodate the required diversity in energy generation and dramatically increased and variable demands of a highly electrified nation.

Beyond microelectronics, BES is a leader in supporting the foundational science for next generation batteries, including at the grid scale. For example, the Joint Center for Energy Storage Research (JCESR), the DOE's Batteries and Energy Storage Energy Innovation Hub, will complete its 10th year in FY 2023. Over the last decade, JCESR has delivered scientific discoveries that are enabling the more resilient and energy dense batteries required to accommodate increased contributions from variable energy resources. A re-competition of the Batteries and Energy Storage Hub was completed at the end of FY 2023. Through JCESR, multiple EFRCs, and numerous single investigator/small team research awards, BES is delivering the science for energy storage needed to meet the unique demands of the modern grid.

Finally, the basic and applied science supported by DOE that contributes to grid modernization is enabled by the suite of experimental scientific user facilities stewarded by BES. Five X-ray and two neutron scattering facilities, along with five Nanoscale Science Research Centers, provide the unique, world-leading tools required to rapidly discover and synthesize new materials, interrogate their properties, and probe their behavior under real-world operating conditions. Coupled with ASCR-stewarded High Performance Computing capabilities, as well as BES-sponsored tools like The Materials Project, such capabilities contribute to accelerating both the pace of discovery and the pace of transitioning discovery to technology.

13.7 Grid Deployment Office (GDO)

GDO serves as the catalyst for the development of new and upgraded high-capacity electric transmission lines nationwide and the deployment of transmission and distribution technologies to improve the resilience of our Nation's electric infrastructure. GDO utilizes its unique tools and authorities for coordination, planning, financing, and permitting to drive transmission investment. GDO also directs investments in the distribution system that must accompany transmission deployment to modernize, harden, and expand the grid. GDO provides technical assistance to energy sector stakeholders to inform the formulation and implementation of policies, programs, and strategies for electricity system planning, design, and operation for all levels of a decarbonized grid including both transmission and distribution. In line with this mission space, GDO is carrying out the provisions provided from BIL and IRA. All GDO activities fall under the grid modernization crosscut and all GDO program funding except GDO Program Direction is included in the crosscut. In FY 2024, GDO will accelerate the planning and development of transmission through the *National Transmission Planning Study* and interregional transmission plans; provide grid technical assistance to industry and public stakeholders to enable policy and investment decisions; assist regions and states in improving or establishing wholesale electricity markets; conduct siting and permitting activities, such as improving Federal coordination and providing support to states and local communities; and help develop offshore wind transmission infrastructure.

13.8 Office of Technology Transitions (OTT)

OTT's mission is to help commercialize DOE technologies and accelerate adoption of innovative technologies to meet DOE objectives with a thoughtful approach to market strategy and partnerships that maximize the use of federal resources and private investment. Grid modernization is a core DOE objective and often requires innovative technologies that need a path to market acceptance by helping identify use cases and reducing market barriers (e.g., interconnection; market access; size, weight, power, and cost (SWaP-C) analysis). OTT's commercialization executives (CEs) serve as subject matter experts with business and strategy backgrounds to work collaboratively with DOE program offices to facilitate public-private partnerships and assess market opportunities to determine high value technology areas and create pathways to demonstration, deployment, and commercialization. OTT's CEs serve not only as a bridge between Federal government and industry, but also between fundamental science and applied research to shepherd promising technologies across the development continuum and provide feedback loops with industry through collaborative initiatives where gaps exist. These feedback loops and initiatives include collaboration with the Quantum Economic Development Consortium to identify energy applications that can harness near term quantum information science such as quantum sensing, quantum computing, and quantum networking and security. Another key initiative includes the DOE V2X MOU to facilitate partnerships with DOE labs, utilities, virtual power plant providers, electric vehicle manufacturers, electric vehicle supply equipment, state and local governments, and utility regulators to leverage bidirectional electric vehicles and provide power or energy services to the grid as an approach to better integrate electric vehicles and optimize the use of renewable energy while maintaining reliability and resilience on the grid.

OTT also provides funding to the DOE National Laboratories to enable technology transfer and commercialization of technologies and tools developed by or in collaboration with the labs. Technologies and tools developed or furthered by DOE National Laboratories that support the GMI could be eligible for OTT's Technology Commercialization Funding (TCF) as follow-on DOE investment. For example, OTT's TCF could support commercialization of DOE technologies and tools, such as quantum sensing for grid timing and synchronization or anomaly detection and security, and quantum computing algorithms to optimize the grid for resilience or renewable energy utilization.

OTT seeks to optimize public and private sector investments that enable a clean, reliable, resilient, secure, and affordable energy system. OTT develops thoughtful and holistic market approaches and pathways catalyzing DOE technologies in key areas under grid modernization that considers the technology, market, and regulatory landscape from various perspectives.

13.9 Office of Energy Justice and Equity (EJE)

EJE works to research, develop, and evaluate Federal energy policy focused on advancing energy equity and environmental justice for historically disadvantaged communities. EJE also provides technical assistance to programmatic offices across DOE to facilitate the implementation and practice of equity in agency and programmatic office decision-making and action. DOE has identified eight policy priorities that help guide equity work across DOE offices:

1. Decrease energy burden in disadvantaged communities;
2. Decrease environmental exposure and burdens for disadvantaged communities;
3. Increase parity in clean energy technology (e.g., solar, storage) access and adoption in disadvantaged communities;
4. Increase access to low-cost capital in disadvantaged communities;
5. Increase clean energy enterprise creation and contracting in disadvantaged communities;
6. Increase clean energy jobs, job pipeline, and job training for individuals from disadvantaged communities;
7. Increase energy resiliency in disadvantaged communities; and
8. Increase energy democracy in disadvantaged communities.

The goals and pillars guiding the GMI align with these policy priorities. EJE will collaborate with our GMI partners to further these policy priorities as they relate to grid modernization and grid activities. EJE will work with GMI partners to ensure that Federal investments in grid modernization account for and provide direct and measurable benefits to environmental justice and other disadvantaged communities.

13.10 Advanced Research Projects Agency-Energy (ARPA-E)

As defined by its authorization under the America COMPETES Act, ARPA-E catalyzes transformational energy technologies to enhance the economic and energy security of the United States. ARPA-E funds high-potential, high-impact energy projects that are too risky to attract private sector investment but could significantly advance the ways to generate, store, distribute, and use energy. In FY 2022, ARPA-E selected and/or obligated $8 million in grid modernization funding to projects aligned with the GMI through ARPA-E's Supporting Entrepreneurial Energy Discoveries (SEED) Exploratory Topic and Grid Optimization (GO) Competition. In FY 2023, ARPA-E selected $88 million in grid modernization funding to projects aligned with the grid modernization crosscut through ARPA-E's Grid Overhaul with Proactive, High-speed Undergrounding for Reliability, Resilience, and Security (GOPHURRS) and Unlocking Lasting Transformative Resiliency Advances by Faster Actuation of power Semiconductor Technologies (ULTRAFAST) Programs. ARPA-E is developing programs for transformational research across a wide range of energy technologies and applications. The assessment process for new programs is now underway and any potential future investments in grid modernization will be determined in FY 2024

13.11 Office of Clean Energy Demonstrations (OCED)

OCED was established in December 2021, building on DOE's expertise in clean energy research and development and expanding DOE's scope to fill a critical gap on the path to net-zero emissions by 2050. OCED's mission is to deliver clean energy demonstration projects at scale in partnership with the private sector to accelerate deployment, market adoption and the equitable transition to a decarbonized energy system. OCED has several programs funded through the Bipartisan Infrastructure Law (BIL) that align with and support GMI objectives. Note, funding levels reflect BIL totals, not currently released programs through Funding Opportunity Announcements, National Laboratories, Prizes, or other mechanisms.

The Long-Duration Energy Storage (LDES) Demonstrations program ($505 million) will validate new energy storage technologies and enhance the capabilities of customers and communities to integrate grid storage more effectively. This program will help advance LDES systems toward widespread commercial deployment by providing an opportunity for nascent LDES technologies to overcome the technical and institutional barriers that exist for full-scale deployment with a focus on a range of different technology types for a diverse set of regions. This investment is aligned with DOE’s Energy Storage Grand Challenge and the Department-wide Long-Duration Storage Shot goal of reducing the cost of grid-scale energy storage by 90% within the decade. Additionally, the Pathway to Commercial Liftoff report for LDES outlined the challenges and opportunities for market liftoff.

The Energy Improvements in Rural or Remote Areas (ERA) program ($1 billion) will support projects to improve the resilience, reliability, and affordability of energy systems in communities across the country with 10,000 or fewer people. ERA aims to fund community-driven energy projects that demonstrate new energy systems, deliver measurable benefits to customers and build clean energy knowledge and capacity throughout rural America. The ERA program will leverage DOE’s expertise and experience in resilient energy solutions to modernize electric generation facilities, address disproportionately high electricity costs, and support new economic opportunities in rural and remote communities.

The Clean Energy Demonstration Program on Current and Former Mine Land (CEML, $500 million) will demonstrate the technical and economic viability of deploying clean energy on current (operating) and former (abandoned or inactive) mine land. These projects are expected to be replicable, providing knowledge and experience that catalyze the next generation of clean energy on mine land projects.

Other programs such as the Clean Hydrogen Hubs Program and Industrial Demonstrations Program may also support specific projects or efforts that advance GMI goals through electrification, operational flexibility, and additional renewables.

Under FY 2023 base appropriations, OCED supports commercial-scale demonstrations related to the integration of renewable and distributed energy systems. The goal of this new investment area is to support demonstrations that de-risk controlling flexible loads from renewable energy, energy storage, EV charging, and other facilities into the U.S. transmission and distribution grids.