U.S. DEPARTMENT of ENERGY

DRAFT REPORT

Microgrids R&D Strategic Plans

Topic 1 – Overall Program and Introduction

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Disclaimer

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List of Acronyms

AI	Artificial Intelligence
ANL	Argonne National Laboratory
CHP	Combined Heat and Power
DOE	U.S. Department of Energy
EMS	Energy Management System
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LEL	Large Electric Loads
ML	Machine Learning
NLR	National Laboratory of the Rockies
OE	(U.S. DOE) Office of Electricity
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
R&D	Research and Development
RD&D	Research, Development, and Deployment
SMR	Small Modular (Nuclear) Reactor
SNL	Sandia National Laboratories
T&D	Transmission and Distribution
VPP	Virtual Power Plant

Executive Summary

This strategic plan series describes the program vision, objectives, and five-year research and development (R&D) targets for the U.S. Department of Energy (DOE) Office of Electricity (OE) Microgrid R&D Program. This is the first in a series of nine strategy documents in support of the Microgrid R&D Program, and accordingly summarizes the findings of the documents as they concern the overall program objectives.

The vision of the Microgrids R&D Program is that microgrids will become essential building blocks of the future electric grid, leveraging all sources of affordable, reliable, and secure energy. In that context, the Microgrid R&D program seeks to accomplish these three goals to enable that vision:

> Goal 1: Promote microgrids as a core solution for **enhancing resilience** of the electricity delivery system, supporting faster recovery of critical infrastructure during and after blue and black sky events
>
> Goal 2: Ensure that microgrids serve as a driver to maintain a **reliable and secure** electricity delivery system by allowing important infrastructure to have consistently available alternative sources of power that can support the operations through both natural and man-made events.
>
> Goal 3: Use microgrids to **enhance energy abundance** by providing additional capacity through distributed energy supply and demand assets, as well as by providing necessary services and capabilities back to the bulk power system to help maintain consistent operations.

This overview document has eight companion documents that provide the strategic plan for specific program focus areas:

- *Transmission and Distribution (T&D) Co-simulation of Microgrid Impacts and Benefits*, which outlines RD&D targets for T&D co-simulation and co-optimization technologies to valuate microgrid benefits, with significantly enhanced speed and fidelity.
- *Building Blocks for Microgrids*, which describes the roadmap to enhance microgrid system design with modularity and flexibility by systemizing control architectures that can serve diverse edge technologies.
- *Microgrids as a Building Block for Future Grids,* which describes how microgrids can serve as modular components toward serving the needs of the larger power system, providing benefit both during emergency and normal conditions.
- *Advanced Microgrid Control and Protection,* which outlines the complexities in controlling islanded and grid-connected microgrids, as well as how protecting the equipment and general public becomes more complex with advanced microgrid deployments.

- *Integrated Models and Tools for Microgrid Planning and Designs with Operations,* which explores the nuances of siting, designing, and operating a microgrid to deliver maximum benefit to reliability, security, and operational flexibility.
- *Small Nuclear Reactors in Future Microgrids,* which outlines an R&D pathway to enable small reactor deployments so they are ready to serve as standardized, interoperable components in future microgrid platforms.
- *Artificial Intelligence and Machine Learning for Microgrid Applications,* which examines where AI/ML technologies can solve critical grid challenges in and using microgrids, including maintaining reliable power, reasonable costs, and safeguarding against cybersecurity threats.
- *Enabling Regulatory and Business Models for Broad Microgrid Deployment,* which describes how microgrids are being used now, the challenges in both regulations and business justifications, and how microgrids can provide unique capabilities and business opportunities to the larger power system.

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1 Introduction

As the electric grid ages, demand for electricity rises, and natural and human-made threats proliferate, microgrid-based solutions emerge as key to enabling reliable, secure and affordable grid operation. A microgrid is *a localized energy system that can operate independently or in conjunction with the traditional grid*. Microgrid systems will play an increasingly important role in supplying reliable power to systems that are critical to our nation's security and prosperity, such as data centers, military bases, and advanced manufacturing. By optimally aggregating, integrating, and leveraging a wide portfolio of local generation and energy resources (e.g., local distributed generation assets,[1] such as natural gas-fueled combined heat and power (CHP) systems, small modular reactors (SMRs), geothermal, fuel cells, energy storage, and dynamic loads), microgrid systems will support local resilience while also efficiently and securely orchestrating energy additions at the grid edge and supporting overall grid reliability and energy affordability.

Current trends show increasing adoption of microgrid technologies for specialized use cases, such as reducing peak load at commercial facilities and meeting mission-critical needs at military installations. Furthermore, the proliferation of large electric loads (LELs), such as datacenter and advanced manufacturing facilities, motivates utilities and industry to leverage microgrids to efficiently solve LEL integration challenges. According to current market forecasts, the global microgrid market is expected to experience significant growth between 2025 and 2030, with estimates suggesting a market size between $45.39 billion and $59.74 billion by 2030 (Allied Market Research 2022). Growing concerns about grid instability and outages are pushing businesses and communities to adopt microgrids to improve energy resilience. Microgrids can also provide a viable, cost-effective solution for powering electrically remote areas with limited grid access (O'Neil 2023).

To facilitate microgrids' contributions to the overall power system stability and to enable new, innovative loads and industries to be served, this document serves as the overview document for a series of strategy documents describes the vision and objectives of the U.S. Department of Energy (DOE) Office of Electricity (OE) Microgrid Program. The program vision is that *microgrids will become essential building blocks of the future electric grid, leveraging all sources of affordable, reliable, and secure energy*. Specifically,

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[1] Local distributed energy assets generally refer to a wide range of behind-the-meter technologies and assets that generate, store, distribute, or consume electrical energy; thus, local and distributed generation, storage, and dynamic load assets are covered by this term. They are generally designed to be (1) decentralized or distributed and located closer to the point of energy consumption, unlike traditional power plants that are often located far from population centers; (2) smaller in capacity compared to large-scale power plants, allowing for more flexibility and adaptability in energy system design; and (3) inclusive of various technologies, such as CHP, geothermal, energy storage (e.g., batteries, pumped hydro storage), fuel cells, and other local energy technologies.

through catalyzing American innovation in next-generation microgrid systems and architectures, the program envisions to support:

- ***Enhanced Resilience***: Microgrids that enable faster recovery of communities and critical facilities from outages.
- ***Reliable and Secure Operations***: Advanced controls and cybersecurity to handle threats and changing grid conditions and maintain power delivery.
- ***Enhanced Energy Abundance***: Adding local, flexible energy sources to meet rising electricity demand.

To achieve these goals, the program includes research, development, and demonstration (RD&D) targets for the 2025–2030 horizon, with near-term deliverables in three broad RD&D domains:

- ***Infrastructure, Operations, and Control***: Contains RD&D goals associated with the operational aspects of microgrid technologies, including microgrid monitoring, control, optimization, communication, and protection.
- ***Multi-Domain Analysis and Decision-Making Tools***: Contains RD&D goals associated with the design, planning, and analysis aspects of microgrid technologies, including tools, computational methods and models, and corresponding simulation approaches.
- ***Engagement and Institutional Frameworks***: Contains goals associated with market, regulatory, and institutional barriers to microgrid system adoption.

Meeting the overall program goals and applying the broad targets to microgrids can encompass all components of a microgrid system. Fundamentally, microgrid systems are composed of several key components (in addition to typical distribution systems, Figure 1) that enable the flexibility to operate either as part of the bulk electrical system or independently: load assets, generation assets, control and sensing systems, communication system, and ancillary hardware infrastructure.

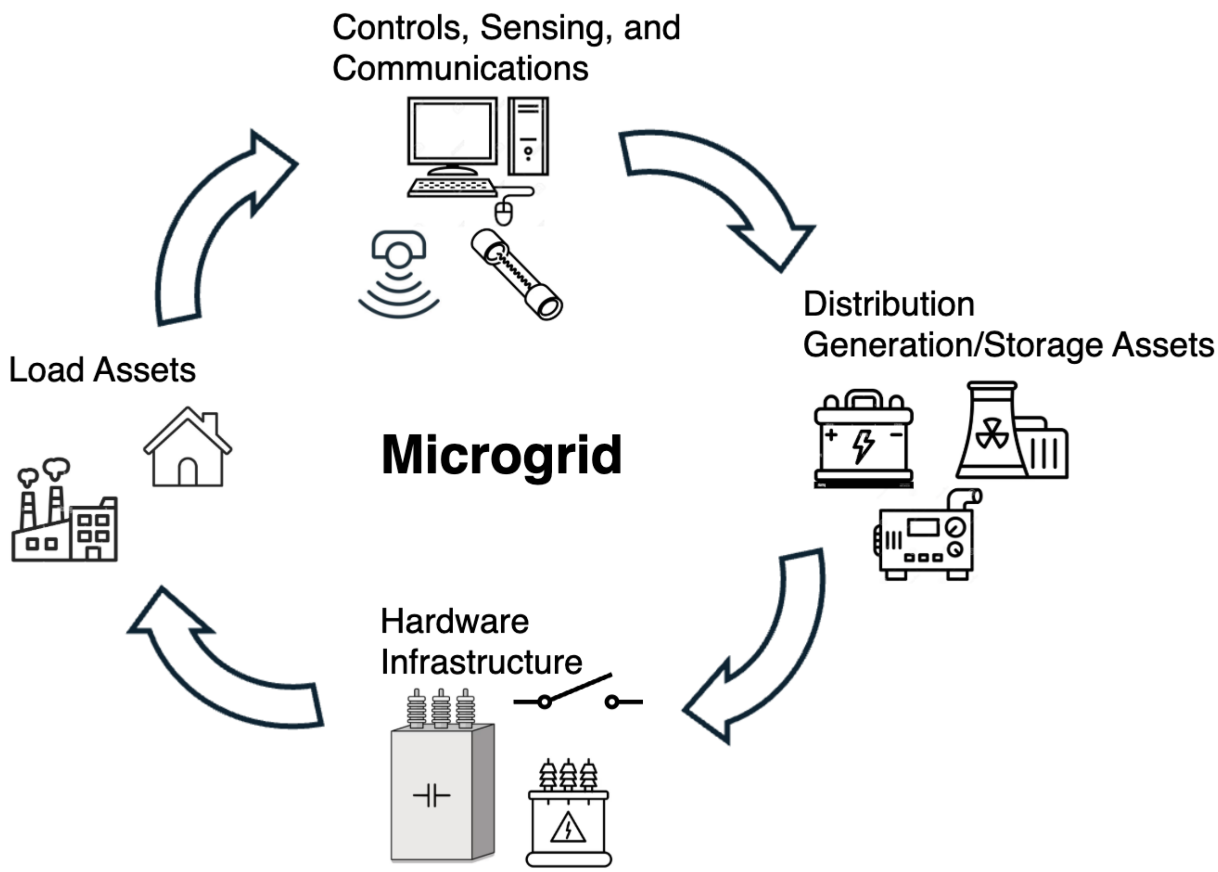

Figure 1. Fundamental components of a microgrid: Load assets, distribution generation and storage assets, hardware infrastructure, and controls, sensing, and communications.

- Microgrids utilize local generation (e.g., natural gas-fueled CHP systems, SMRs, geothermal, fuel cells), energy storage, and dynamic loads. These resources must be controlled and managed to balance energy production with consumption to maintain microgrid stability. Generation within the microgrid must be sized larger than the load to ensure operation of the microgrid under all load levels.

- A control system and associated sensing/protection is essential for managing the operation of a microgrid. These control systems typically utilize an Energy Management System (EMS), a software platform that integrates all the components of a microgrid, analyzes data from various sources, forecasts energy demand, communicates with the main grid, and optimizes the operation of resources to ensure a reliable energy supply. To enable the EMS, additional data collection, via smart meters and sensors, is required to monitor load and generation levels

- Some communication infrastructure is typically utilized for operation of microgrids. Advanced communication technologies enable real-time data exchange between different components of the microgrid, allowing for better decision-making and coordination, enhancing the overall efficiency, controllability, and reliability of the system.

- The above systems require additional ancillary hardware above what is typically utilized for other grid connected systems. Fundamentally, a method of disconnecting from the main grid when needed is required via a relay or switch.

Microgrids represent a significant advancement in the way electricity is generated and distributed. By providing a more reliable, resilient, and secure energy solution, they have the potential to transform the U.S. energy landscape. While there are challenges to overcome, microgrids can maximize the utilization of domestic energy resources and supply chains to orchestrate energy abundance through energy additions, lower electricity costs, and improve energy choices for U.S. consumers. As microgrid technology evolves, it is crucial for the Microgrid R&D program to help unlock strategic opportunities to identify and address the various requirements of single customers to grid system operators, owners, suppliers, technology developers, and regulators.

2 State of Microgrids Now/Challenges

While modern microgrids have the capability to operate connected to the main grid or islanded, most of the advanced controls are only utilized during islanded or stand-alone operations. When grid connected, the generation assets of the microgrid are often under-utilized, either via very simple controls or not at all. The capabilities of the microgrid, especially with diverse generation sources, can often provide significantly more benefit to the main power grid. However, providing that functionality is not straightforward. Interacting with the main power system raises a number of challenges:

- **Multi-ownership**: Microgrids, especially their generation sources and load devices, are often owned by private individuals or associations/companies, not the local utility. This creates complexities in not only building and connecting the microgrid, but also operationally. Even if coordinated with a local utility, what level of control do they have over a microgrid compared to the individual asset owner/operator, and what are the responsibilities for each entity? If something abnormal happens, which party is responsible? Contracts or agreements on how money is distributed also create complexities in the microgrid interactions.

- **Value of Resilience**: Microgrids can either provide support to the main power system to help stabilize the system, or operate in an islanded form to provide power to critical assets during a grid outage. In both situations, the value of that resilience capability is not always easy to estimate. The cost of an avoided outage helps quantify the value during islanded operation, but an obvious metric does not exist for demonstrating the value when grid connected. This can make justifying the cost to deploy a microgrid difficult.

- **Cybersecurity**: Microgrids can require not only coordination with the local utility, but also the individual generators and controllable devices within the microgrid. Different security stances, as well as varying versions of the firmware and control, can mean any one of these devices may be a point of attack on the microgrid. Cybersecure communications and controls are often an after-thought or late addition to the microgrid, which do not always properly protect the system from malicious actions. If the microgrid is compromised, there is potential for the microgrid to "infect" the main power system.

- **Interoperability**: Microgrids can contain generator and load controls from a variety of vendors and with equally varying capabilities. The operational requirements and dynamics vary significantly between on-grid and islanded operations. Microgrids and their component devices must function properly and coordinate through this complex landscape, which often includes vendor-specific solutions and/or requires unique analysis and design for each microgrid. Modularity (the ability to substitute or add a similar component quickly) is not typically a priority in modern microgrid, as specific vendor solutions often meet the needs of a specific deployment. However, this forces vendor-lock-in and may prevent future upgrades or repairs to the system. The lack of modularity, as well as unique design for every microgrid, increases the cost to deploy a microgrid, as well as challenges to maintain equipment and operations if original vendors change solutions. Interoperability is especially critical to ensure the microgrid can continue to function safely and properly, even after equipment failures or system/software upgrades. Specific interoperability challenges for controls and protection to maintain this operation are:

- **Controls**: On aspect of interoperability in microgrids is how devices are controlled. Microgrids have device-level controls on the individual generators and loads, and may also have a microgrid or site controller. This may be further augmented by some form of controlling multiple microgrids, possible as a virtual power plant (VPP) provider. Modern microgrids may only have device-level controls or a microgrid controller that manages a small collection of devices; VPP and multiple site coordination are not typical implementations in microgrids today.

  The different types of controls interact, both through control commands issued and through the physics of the power system. Connecting and coordinating these controls can differ by fundamental design approaches, firmware versions of the devices, and even capabilities a specific vendor supports on the device. Coordinating the different controls is necessary to ensure consistent, reliable operation of the microgrid during all conditions. Currently, these interactions often require costly, site-specific evaluations and designs to ensure overall stability of the power system.

- **Protection**: Interoperability of a microgrid also includes how to minimize damage and danger to devices, users (the public), and the system during abnormal conditions. This can be as simple as a standard fuse to coordinated schemes using multiple measurements and communication. Providing that protection in a microgrid can be complicated – the system can have vastly different requirements when operating grid-connected compared to islanded operations. Furthermore, microgrids may have a mix of traditional rotating machinery and power-electronics-based devices, which can drastically influence how protection on the system is implemented. Devices and methods to standardize and modularize the protection have shown success, but they are not widely deployed. Most microgrids still require detailed site-specific analysis, often for many operating conditions to ensure public and equipment safety.

- **Market Interactions**: Distributed generation in the microgrid, and the microgrid itself, may participate in different energy service markets to help produce additional revenue. This can be a simple rate for generating or consuming power, but may include more complex interactions for grid services through an aggregator or VPP. Microgrid participation in larger energy markets is limited and not fully utilizing existing microgrid capabilities, but also focuses on traditional energy distribution structures. Microgrids are often capable of providing benefits and services to the local distribution grid, but few of those markets exist. Standardized methods to setup and participate in distribution/local markets, as well as transmission/large-scale markets are needed to maximize the capabilities of microgrids to the larger power system, as well as provide another mechanism to improving the affordability of deploying and operating the system.

3 Vision and Goals

The overall vision of the DOE OE Microgrid program is that *microgrids will become essential building blocks of the future electric grid, leveraging all sources of affordable, reliable, and secure energy*. To implement this vision and address the challenges described in Section 2, the program strategy includes objectives in the following RD&D domains:

- **Infrastructure, Operations, and Control:** Contains RD&D goals associated with the operational aspects of microgrid technologies, including microgrid monitoring, control, optimization, communication, and protection.
- **Multi-Domain Analysis and Decision-Making Tools:** Contains RD&D goals associated with the design, planning, and analysis aspects of microgrid technologies, including tools, computational methods and models, and corresponding simulation approaches.
- **Engagement and Institutional Frameworks:** Contains goals associated with market, regulatory, and institutional barriers to microgrid system adoption.

These domains serve as the foundation for the program RD&D activities, targeting the three goals from Section 1:

- **Enhancing Resilience**
- **Reliability and Security**
- **Enhanced Energy Abundance**

Specifically, the main outcomes and expected benefits of the program RD&D activities include:

- Significant enhancement of interoperability within and across microgrids, and seamless coordination of a wide portfolio of distributed energy assets in the grid through microgrid-based architectures
- Reduction of microgrid capital costs by 15% by 2031, while shrinking project development, construction, and commissioning times by 20%, by leveraging standardized building block architectures
- Improvement in survivability of local grids during extreme events by leveraging local resources in a distributed manner
- Enablement of continuous operation of critical infrastructure and large electric loads, such as data center and military installations, with significant improvement in power quality and reliability

- Up to an order of magnitude acceleration in microgrid design and benefit evaluation processes
- Systematic identification and mitigation of market, regulatory, and institutional barriers to microgrid system adoption.

4 How do we get there?

To support **enhanced resilience**, investments are needed in the development of advanced industry-informed microgrid systems with adaptive controls, automation, and protection. These innovations will enable adaptivity to dynamically changing operating conditions (i.e., both within and external to the microgrid system), such as disruptions in communications and data availability, unpredicted failure of microgrid system elements, and the effects of connected neighboring systems (e.g., main grid connection, networked microgrid, dynamic load systems, etc.). This will improve grid survivability and electricity service continuation during extreme events. To support a **reliable and secure** electric grid, the program will invest in codesign of controls and communication that is inherently robust to adversarial attacks or events. Moreover, the program will focus on how to design self-sufficient microgrid systems that integrate diverse energy sources and prioritize, as well as optimize, local energy use in a secure way. To **enhance energy abundance**, the program will focus not only on the electrical and physical enablement of microgrid systems, but also analysis of regulation, business and market models, and gaps for different implementation and ownership contexts will be conducted. This analysis will help with designing microgrids and microgrid-based architectures to operational specifications that satisfy regulatory, business, and market requirements; furthermore, this analysis will help state and regional regulators, as well as state energy officials, translate grid-related concerns and priorities into actionable objectives and supportive regulation, thus facilitating broader commercial adoption of microgrid solutions.

To achieve these goals, the strategy and roadmap for the program includes objectives in three broad domains, illustrated in Figure 2. As can be seen, the Microgrids R&D program addresses challenges associated with the scale and complexity of the architecture as they apply to the three domains. In terms of scale, the program considers systems at an increasing degree of scale, from single to networked to network of networked systems. In terms of architectural complexity (e.g., relating to control, computing), the challenges are described through the transition from centralized to distributed paradigms. Table 1 summarizes some of the objectives in the individual strategy documents and how they may to the primary objectives of the program.

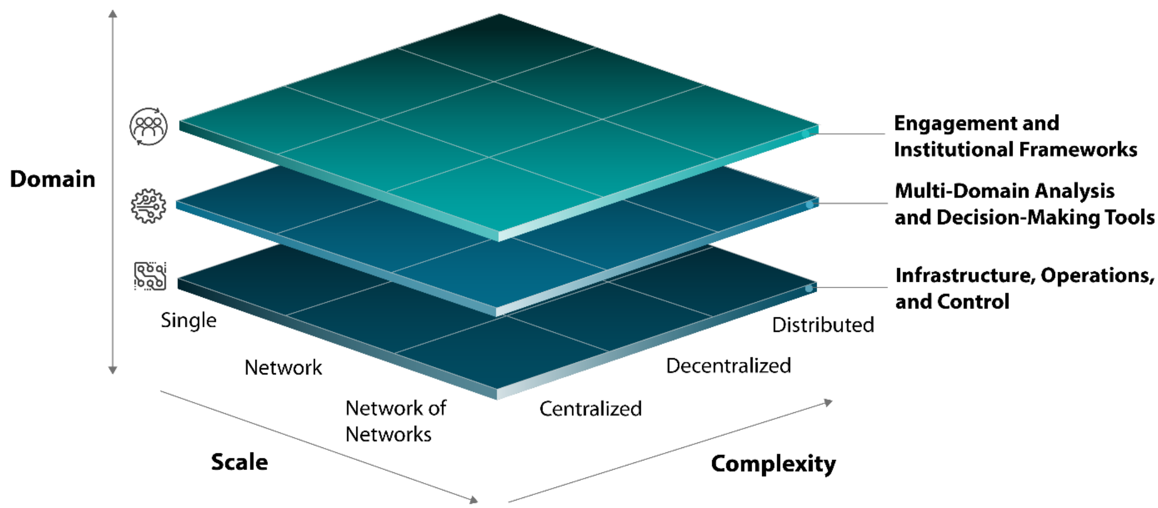

Figure 2. Illustration of program domains and challenges

Table 1: Microgrid R&D Program Goals and Sampled Strategy Document Objectives

Goals	Related Strategy Document Objectives
Enhanced Resilience	<u>Strategy Document 5 – Microgrid Controls and Protection</u> • Develop self-healing protection schemes for fractal grid implementation <u>Strategy Document 6 – Integrated Models and Tools</u> • Develop capability, building on the DynaGrid project, to determine boundaries of microgrids to ensure resilience of the distribution feeder it is connected to.
Reliability and Security	<u>Strategy Document 2 – T&D Cosim</u> • Develop high-level controller models over aggregated resources that can support networked microgrid operations with respect to frequency and voltage control during normal and transient conditions. <u>Strategy Document 3 – Building Blocks for Microgrids</u> • Advancement forward field deployment of a matured microgrid building bloc solution that can cost-effectively enhance performance, reliability, and supply security for critical customers. <u>Strategy Document 4 – Microgrids as Building Blocks</u> • Develop standardized microgrid-based architectures for uninterrupted power supply of critical and defense infrastructure <u>Strategy Document 5 – Microgrid Controls and Protection</u> • Develop fast fault detection schemes for DC microgrids, including arc fault detection and fault location in DC systems.

	Strategy Document 7 – Small Nuclear in Microgrids • Develop standardized thermal interfaces and storage systems through modular designs and validated storage configurations to simplify integration and maintain reactor safety margins. Strategy Document 8 – AI/ML in Microgrids • Develop real-time visibility and state-estimation in microgrids using AI/ML approaches
Enhanced Energy Abundance	Strategy Document 3 – Building Blocks for Microgrids • Development of universal microgrid building block controller with ultra-fast local control to meet evolving grid codes Strategy Document 4 – Microgrids as Building Blocks • Develop market-informed microgrid-based heterogeneous-ownership architectures that encompass merging of several microgrids with dynamic boundaries to integrate fleets of all types of local energy assets. Strategy Document 6 – Integrated Models and Tools • Link microgrid operations to bulk power system planning and market participation. Strategy Document 7 – Small Nuclear in Microgrids • Support formation of the Small Nuclear Reactor Microgrid Consortium to create an industry stakeholder-driven community to define and execute needed R&D at the national laboratories and academia. Strategy Document 8 – AI/ML in Microgrids • Develop forecasting and market scheduling coordination algorithms leveraging AI/ML approaches for improved accuracy and predictability. Strategy Document 9 – Enabling Regulatory and Business Models • Develop innovative concepts and methodologies to help utilities plan and analyze distribution systems under uncertainty and understand the value of local energy supply and demand resources in power grid applications.

5 Why DOE?

The challenges that the program aims to tackle are of utmost importance to American industry and the American public. Given our nation's growing reliance on electricity, maintaining reliable, resilient, secure, and affordable electricity service has become essential to our nation's economic prosperity. Achieving a highly dependable national electrical infrastructure and enabling grid resilience and reliability through microgrid innovations under blue sky, black sky, and gray sky conditions (e.g., supporting the U.S. Department of Defense critical energy infrastructure in line with national security priorities and sustaining national, regional, and local civilian economic subsectors) can present tremendous return on investment for the federal government. Thus, the program RD&D would support the programmatic administration of federal investments in the evolution of the nation's electrical infrastructure—as informed by and working closely with industry—toward a more reliable, resilient, secure and affordable energy future, one that supports U.S. energy independence through energy additions and indigenous supply chain prioritization and advances U.S. energy (market) dominance by leapfrogging global competition in microgrid innovation and domain expertise, enabling the export of homegrown microgrid innovations and domain expertise abroad.

Microgrids affect many stakeholders, from single customers to grid system operators, owners, suppliers, technology developers, and regulators. The DOE OE ability to convene industry and catalyze broad research is the most efficient way to unlock solutions that meet the requirements of these diverse stakeholder groups. The activities in this program are aligned with the DOE OE mission to strengthen and modernize our nation's electrical energy grid to reliably, resiliently, securely, and affordably handle projected energy demands and associated grid stresses. These activities could not be successfully achieved without DOE OE support, due to the multi-stakeholder nature of microgrid research and innovation and the private sector's imperative to consider private corporate interests and priorities over nationwide objectives and priorities.

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