U.S. DEPARTMENT of ENERGY

DRAFT REPORT

Microgrids R&DS Strategic Plans

Topic 4 – Microgrids as Building Blocks for Future Grids

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Disclaimer

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List of Acronyms

ADMS	Advanced Distribution Management System
AI	Artificial Intelligence
ARPA-E	Advanced Research Projects Agency-Energy
BMS	Building Management System
CHP	Combined Heat and Power
CODAS	Control and Optimization using Distributed Agent-based System
COMMANDER	COordinated Management of Microgrids and Networked Distributed Energy Resources
DOE	U.S. Department of Energy
EC	Electric Cooperative
EMS	Energy Management System
EPSS	Enhanced Power Line Safety
EV	Electric Vehicle
GMLC	Grid Modernization Laboratory Consortium
HEMS	Home Energy Management System
HIL	Hardware-In-the-Loop
KAFB	Kirtland Air Force Base
LANL	Los Alamos National Laboratory
LDRD	Laboratory Directed Research and Development
LEL	Large Electric Loads
LLNL	Lawrence Livermore National Laboratory
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
PSPS	Public Safety Power Shutoff
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
TA	Technical Assistance
TAMU	Texas A&M University
TCF	Technology Commercialization Fund
VPP	Virtual Power Plant

Executive Summary

The future electricity infrastructure of the United States is projected to have a proliferation of Large Electric Loads (LEL), such as data centers, advanced manufacturing, and mining operations as well as distributed energy supply and demand resources based on natural gas-fueled combined heat and power (CHP) systems, small modular reactors (SMRs), and geothermal. In this future, microgrids will be a fundamental building block in addressing the challenges of interoperability, reliability, and scalability. They will operate in various control architectures to support bulk power system operations, achieve local economic and operational objectives, and support the critical end-use loads where the bulk power system is not available.

To this end, the DOE Microgrid R&D Program vision is to facilitate the microgrids to enable the nation to have (1) a more resilient and (2) more reliable and secure electricity infrastructure, which unlocks an (3) energy abundance to help modern industry and advanced applications flourish. These three enumerated strategic goals are developed in the context that the United States' electricity system is becoming more distributed in nature, and that disruptions to the electricity delivery system (EDS) are occurring more frequently and with greater severity.

The vision assumes an increasing need to provide reliable power to advanced applications like data centers running artificial intelligence algorithms and advanced mineral extraction operations. In that context, the Microgrid R&D program seeks to accomplish these three goals:

> Goal 1: Promote microgrids as a core solution for **enhancing resilience** of the EDS, supporting faster recovery of critical infrastructure after black sky events
>
> Goal 2: Ensure that microgrids serve as a driver to maintain a **reliable and secure** EDS 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 strategy document is one of nine prepared for the DOE Microgrid R&D program as part of the strategic plan for specific program focus areas. The nine strategy documents focus on the following areas:

1. Overall program and introduction
2. T&D co-simulation of microgrid impacts and benefits
3. Building blocks for microgrids
4. **Microgrids as a building block for the future grid**
5. Advanced microgrid control and protection
6. Integrated models and tools for microgrid planning, designs, and operations
7. Small nuclear reactors in future microgrids
8. Artificial intelligence and machine learning for microgrid applications
9. Enabling regulatory and business models for broad microgrid deployment

This strategy document covers Topic Area # 4 and outlines a vision where microgrids will become a fundamental building block of future grids. This will be enabled by emerging concepts such as networked and dynamic boundary microgrids to aggregate a wide variety of local energy supply and demand assets at scale and provide essential grid services at both distribution and transmission levels. Through DOE OE's leadership, diverse microgrid configurations are being demonstrated and deployed currently, setting the stage for more structured, and hierarchical, grid architectures. Ultimately, microgrids are positioned to enhance grid resilience, provide grid reliability and security, and elevate energy abundance, while serving as a practical mechanism for both everyday operations and emergency response.

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1 Introduction

Microgrids have traditionally been recognized as vital resources for delivering resilient power to facilities during emergencies and outages. In many widely-publicized power disruptions, remediation strategies have included the deployment of microgrids and the coordination of local energy supply and demand resources (NRECA 2021). However, the conventional view of microgrids as isolated, statically controlled, and one-off solutions is rapidly evolving. New concepts such as networked microgrids, dynamic boundary microgrids, and hierarchical frameworks are emerging, while positioning microgrids as foundational building blocks in system-of-systems solutions for future grids. The flexibility of these building blocks enables microgrids to help the evolving needs of the power grid; for example to meet the increasing energy requirements of large data centers and domestic critical mineral extraction.

This document presents a broad vision for future grids where microgrids serve as a building block. While the precise trajectory from today's grid to the grid of the future remains uncertain, it is widely anticipated that the integration of distributed local supply and demand assets will continue to accelerate. As this transition unfolds, grid architecture must evolve to enable effective monitoring and control of an increasing number of local distributed energy supply and demand assets drawn from a variety of resources. These assets must operate in concert to provide essential services across all levels of the grid—distribution and transmission—while maintaining or enhancing resilience, reliability, security, affordability, and elevating energy abundance.

Microgrids offer a practical mechanism for aggregating distributed energy supply and demand assets. Through leadership from the Department of Energy's Office of Electricity (DOE OE) and collaborations with stakeholders including industry and academia, a variety of microgrid configurations have already been deployed. In the near term, a mix of individual, segregated, and networked microgrids is likely to coexist, while more structured grid architectures may emerge over time. Multiple architectural pathways are possible, but all will require ongoing technology development, with microgrids serving as the common building blocks.

In summary, this document envisions various possibilities in which microgrids can become building blocks of the future grid. It highlights a hierarchical architecture in which microgrids serve as foundational elements, leveraging local energy supply and demand resources, and advanced control technologies to enhance system resilience, reliability, security, and operational flexibility—both during normal operations and in response to emergencies.

2 Vision for the Future

The future power systems may experience a significant increase in the adoption of distributed energy supply and demand assets. As increasing levels of resources—including large electric loads such as data centers, advanced manufacturing, and mining operations, and distributed energy supply such as natural gas generators small modular reactors, and other distributed assets—are integrated into the grid, the number of active control points could become too numerous for current control approaches to manage effectively. Consider, for example, the distribution system of the San Francisco Bay Area with more than four million customers. If each customer has at least one local general resource installed, this could lead to millions of control points. Today's control systems are designed for a limited number of centralized power plants, typically in the thousands. To effectively manage the integration of a wide range of energy technologies in a scalable fashion, the current approach to power grid planning and operations must evolve to accommodate large-scale integration of all types of local energy supply and demand assets. A modernized framework will need to monitor, control, and optimize large-scale grids with high levels of distributed energy supply and demand assets integration, process vast amounts of data from pervasive metering, and implement new market mechanisms, including multilevel ancillary services. At high penetration levels, local assets connected at the distribution grid—regardless of energy source—must support bulk system operations by providing essential grid services to ensure system reliability, resilience, security and stability. Therefore, a future grid framework should be capable of supporting large-scale aggregation of local energy supply and demand assets at the distribution grid level for the provision of grid services.

Today's power grid relies largely on centralized control architecture. The growing number of distributed assets cannot be easily integrated into existing centralized operational systems due to limitations on its scalability. Several alternative control frameworks have been proposed in recent years, including decentralized, meshed, distributed and hierarchical control architectures. While each architecture has its own benefits and drawbacks, there is broad consensus (Bidram and Davoudi 2012)(Kroposki 2017)(Molzahn, et al. 2017)(Bernstein and Dall'Anese 2019) that a more distributed framework (GMLC Architecture n.d.) with hierarchical control and communication structure offers greater scalability for monitoring, control and communications, and computational needs. This approach is also advocated in the grid architectures developed under the DOE's Grid Modernization Laboratory Consortium (GMLC) (GMLC Control n.d.).

A hierarchical architecture as shown in Figure 1 effectively integrates the increasing number of distributed assets. At the lowest level are individual energy supply and demand resources as well as loads d such as data centers, each with local controllers. Industrial, commercial, and residential buildings may use building management systems (BMS) or home energy management systems (HEMS) to coordinate their combination of loads and generation. These assets, located within a section of a distribution feeder, are collectively managed as a "cell." Each cell represents a unique combination of local generation, storage, and loads. Multiple cells are managed at the substation level, and so on, creating a hierarchy. This structure provides a scalable framework for managing millions of local energy assets and controllable loads, with decentralized or distributed control and optimization as key tools.

Through hierarchical control, each cell participates in optimal grid operation under normal conditions. In emergency situations, increased presence of local energy supply and demand assets can help set voltage and frequency for loads in addition to providing them the needed power backup when grid power is lost. These assets, deployed by consumers or utilities, can provide resilience for individual sites during extreme events. Aggregated with other local assets and loads, these sources would allow cells to form microgrids. The ability to aggregate distributed assets into microgrids depends on technical capabilities and available resources. According to the DOE definition, a microgrid must be able to island, requiring sufficient generation to supply all (or critical) loads within its boundaries, a voltage and frequency master, and switches to enable islanding. Not all hierarchical cells can operate as microgrids during resilience events, but as more assets capable of grid-forming are deployed, more cells can transition to microgrids. During major disruptions, the hierarchical cell structure provides a foundation for adaptive microgrid formation, or large scale self-assembly, making microgrids a fundamental building block for system planning and operations, and increasing reliability and resilience.

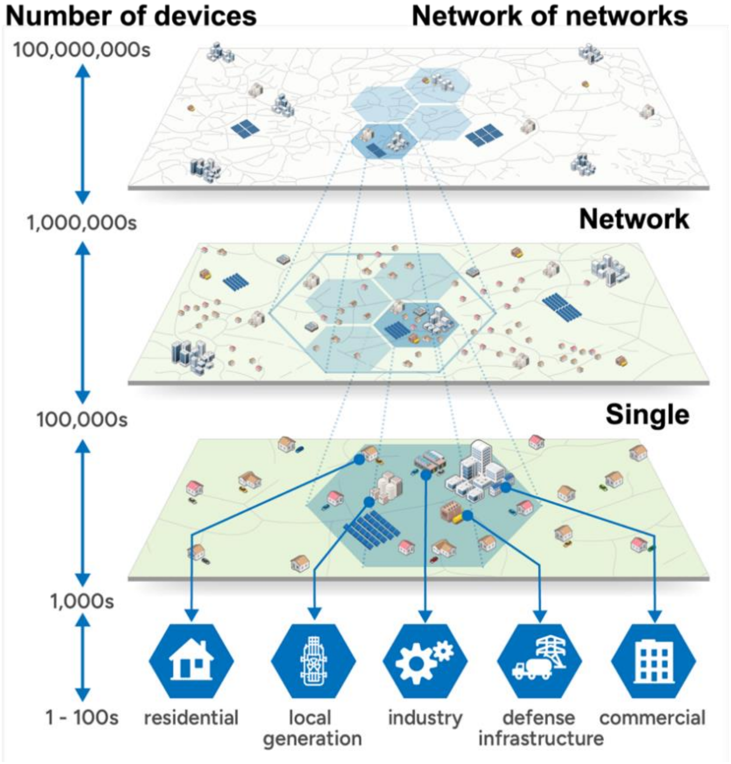


Figure 1. A future grid vision with a hierarchical cell structure and distributed hierarchical control system that integrates individual technologies hierarchically into the bulk power system as the control points increase in number

To illustrate, Figure 2 shows a hypothetical feeder with cells having various types of energy resources. For the sake of simplicity, loads are not shown. This shows some cells that do not have adequate energy supply and demand resources to form a microgrid, indicated by green hexagons, as well as cells that can form microgrids, shown as blue hexagons. Sectionalizing switches that enable microgrids to island are shown as black dots. In this example, we also illustrate the potential for individual microgrids to network in the top right, where two microgrids (blue hexagons) are shown within a larger microgrid, and that only portions of a cell may be able to operate as a microgrid, in the center, top and bottom, where a microgrid (blue hexagon) is shown within a cell (green hexagon). Some microgrids can network together, and boundaries can be dynamic, allowing for flexible operation. As more local energy assets—of all types—are deployed, the boundaries and capabilities of microgrids can expand, further realizing the vision of microgrids as foundational building blocks of the future grid.

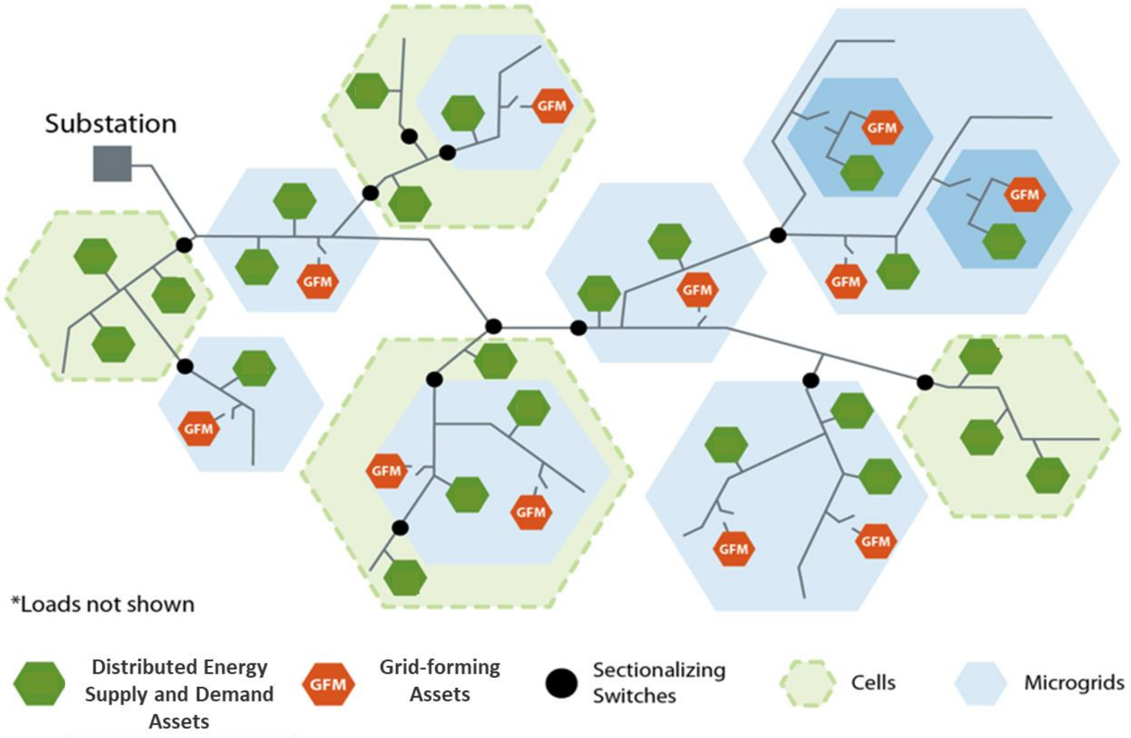


Figure 2. Hypothetical distribution feeder with co-located cells (hexagons), microgrids (blue hexagons), and sectionalizing switches (black dots).

While a hierarchical framework supports the vision of microgrids as building blocks for future grids, other pathways will also emerge as the integration of distribution system level local energy supply and demand assets continues. They will provide services to both local distribution and bulk systems, individually or in aggregate. Microgrids offer a mechanism to aggregate local assets for reliability, resilience and security, forming units that can connect or disconnect from the grid as needed. Across the US, many microgrids already operate alongside the main grid. In the future, microgrids may link with each other to form networked microgrids, dynamically change boundaries, or merge into larger multi-customer microgrids (Schneider et al. 2020)(US DOE 2020). These architectures are not mutually exclusive and may combine features such as networked microgrids and dynamic boundaries. The common thread is the central role of microgrids. These different futures may converge on the hierarchical framework, or, in its most advanced form, create a fractal grid—a system-of-systems. The ultimate vision of a hierarchical structure brings benefits such as ease of control, scalability, and efficient data exchange.

3 Technology Developments

The vision of a future grid leveraging microgrids as fundamental building blocks will require several technologies. These include:

Control and Protection

- Distributed control and optimization capabilities for optimal operation of individual and networked microgrids, having local generation sources and loads.
- Controls that leverage the latest advancements in data analytics, ML and AI, with a focus on monitoring and maintaining power quality.
- Integrated approaches for the codesign of control, protection, and communication systems, explicitly considering the interdependencies among these elements.
- Cell-level controllers, compliant with IEEE 2030.7 microgrid controller requirements, capable of managing islanding and reconnection transitions, as well as dispatch and steady-state voltage and frequency regulation.
- Innovations in inverter controls, particularly for grid-forming inverters (Lin et al. 2021), to address stability and oscillation challenges in low-inertia systems.
- Capabilities to distinguish, prioritize, and selectively serve critical and large electrical loads, such as data centers and military installations.
- Enhanced protection coordination strategies for networks with microgrids operating in various combinations of grid-connected and islanded modes.

Analytics and Algorithms

- Scalable monitoring and state estimation tools leveraging distributed algorithms while utilizing advanced data analytics and ML/AI for networked microgrids.
- Optimization methods that facilitate greater customer participation in demand side management by coordinating the dispatch of building loads and local generation.
- Planning tools for optimal placement of devices, such as local generation and switches, to support network reconfiguration and microgrid formation.
- Distribution network reconfiguration algorithms designed to respond to faults and outages, enabling dynamic microgrid formation.
- Upgrades to utility management systems, such as Advanced Distribution Management Systems (ADMS), with capabilities to support distributed and hierarchical controls.

Communications and Sensors

- Distributed communications capabilities for networked microgrids
- Advanced technologies such as passive and active sensing by GridSweep sensors (Top and Shehada 2025), combined with AI/ML methods. Data interoperability across various technologies. Cybersecurity aspects including data privacy preservation and command verification.

Hardware

- Substation switch upgrades to accommodate feeder-level cells combining into a substation-level cell. Grid forming inverters to support blackstart services.
- Leverage advanced hardware, such as solid-state transformers and supercapacitor, in Hardware-in-the-Loop (HIL) simulations to help technology transition to field pilots.

4 Enabling Technologies

Design and implementation of a future grid architecture that uses microgrids as a building block would require technological innovations, deployments and adoptions addressing:

- Standardized Architectures for Interoperability and Distributed Assets Integration
- Modeling, Simulation, and Analysis for Microgrid System Planning and Design
- Monitoring, Control, Protection, and Communications for Secure Microgrid Operations
- Support Accelerated Technology Adoption

These research and development (R&D) activities require close coordination with the other eight topic area strategy documents and leveraging of enabling technologies discussed therein, for example, co-simulation (Topic 2), control and protection (Topic 5), tools for planning and operation (Topic 6), role of SMR (Topic 7), leveraging AL/ML (Topic 8), and the regulatory and business models for broad microgrid deployment (Topic 9). Enabling technologies would be drawn from the DOE funded prior and current work, including:

Control and Protection

- Hierarchical optimization for coordinated dispatch of building loads and local generation with network reconfiguration during faults and outages (Liu and Ding 2020a)(Liu and Ding 2020b) (NREL).
- Resilient system dispatch tools for dynamic microgrid clustering and operation to enhance distribution system resilience developed under DynaGrid (NREL)
- Networked microgrid tools and algorithms from the Citadels project (PNNL).
- “Microgrid protection in a box” solution (SNL).
- Control, protection, and distributed dispatch methods for resilient networked community microgrids (ORNL).

Analytics and Algorithms

- Restoration and networking algorithms and tools from the RONM project (LANL).
- Black start optimization and restoration algorithms and tools from the GMLC CleanStart Distributed Energy Resource Management System project and pathway to commercialization via a Technology Commercialization Fund (TCF) project (LLNL).
- Decision support tool for early-stage, resilience-based microgrid design (SNL).
- System design and operation of hierarchical, power electronics microgrid (SNL)
- Networked microgrid controller for orchestration of Networked Microgrids, under commercialization via TCF project (ORNL).
- Synchro-waveform measurements for data analytics and control (LLNL)(Mohsenian et al. 2024)

Communications and Sensors

- Control and Optimization using Distributed Agent-based System (CODAS): a multilayered and distributed platform that provides secure and reliable peer-to-peer communication between the upper-level controllers and the field devices (ORNL).
- GridSweep sensors for passive and active sensing of power grids (Top and Shehada 2025)

Hardware

- COordinated Management of Microgrids and Networked Distributed Energy Resources (COMMANDER) Hardware Testbed (ORNL)

5 Use-case / Scenario Examples

These use cases highlight how the concept of microgrid as a building block for the future grid can be used in the next 5-10 years as part of a larger strategy to enhance the utility of microgrid technologies. The vision would enable the grid to evolve from individual microgrids to networked microgrids, microgrids with varying boundaries, to a heterogeneous collection of individual and networked microgrids, to ultimately a grid of the future where the concept of grid-of-the-grids is realized—where microgrids serve as a building block for the future grid.

5.1 Use Case 1: Real-time operations under normal conditions

As a first use case, we consider real-time operations of a large-scale power system with various local energy sources (such as natural gas-fueled combined heat and power systems, small modular reactors, geothermal sources, and fuel cells) added at the distribution level. This will demonstrate the effectiveness of the proposed hierarchical control structure under normal operating conditions, and how it addresses the challenges of applying advanced controls and optimization approaches to a large-scale power system to improve system reliability.

5.1.1 Large-scale simulation study

This use case is proposed to demonstrate the different approaches presented in this paper to realize the vision of a grid with microgrids as foundational building blocks using large-scale simulations of the distribution system of the San Francisco Bay Area illustrated in Figure 3. The overall system has more than 10 million electric nodes, with more than 4 million customers. Different scenarios of various amounts of local generation source and large electric loads will be considered. At the extreme situation, with each customer having several controllable devices, this leads to millions of control points.

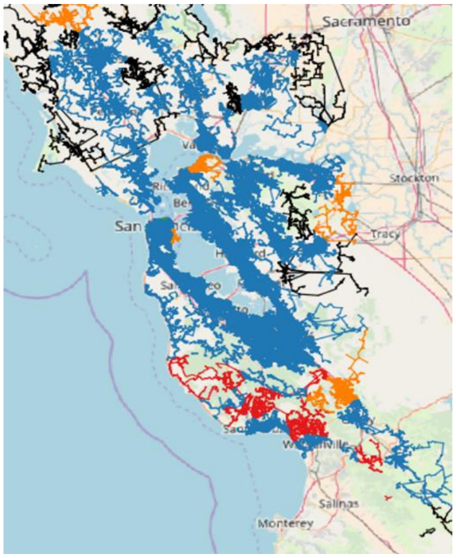


Figure 3. San-Francisco Bay Area Distribution Network

A large-scale distribution system scenario previously developed at NLR for the Autonomous Energy Systems study will be leveraged, which also includes a demonstration of an advanced hierarchical control framework (Kroposki et al. 2020)(Zhou et al. 2019). To model the distribution network, the synthetic models developed by the Advanced Research Projects Agency-Energy (ARPA-E) SmartDS project (Krishnan et al. 2017) will be used. These models have more than a million nodes across 264 feeders. These feeders can be partitioned into cells and microgrids as described earlier. Using the concept of microgrids as building blocks for the overall grid, this large-scale simulation will demonstrate scalability of computations and control under normal grid conditions. This use case can also be extended to abnormal operations, implementing extreme disruption scenarios such as hurricanes, wildfire, and earthquakes.

5.1.2 Pilot Deployment

This use case is a pilot demonstration site for the proposed vision of microgrids as building blocks. As part of a Cooperative Research and Development Agreement, Sandia National Laboratories and Emera Technologies developed a 10-node, 250 kW (nameplate) power electronics-based, hierarchical, modular, dc microgrid. This load-serving dc microgrid was commissioned in December 2019 on Kirtland Air Force Base (KAFB) in Albuquerque, New Mexico and served as a long-term experiment to evaluate the ability of hierarchical, power electronics-based dc microgrids to meet load with high system reliability through a mixture of autonomous operation and cooperative power sharing between individual nodes.

The KAFB microgrid is enabled through the use of modular, power electronic-based blocks at each node known as a nanoblock, as shown in Figure 4 (left). Each nanoblock contains storage, control, protection, communications, and power conversion to connect to a variety of different ac/dc loads, ac/dc generation, and an intertie. As each node contains co-located generation, load, and storage, they can operate independently (as a nanogrid) or cooperatively (to form a coupled microgrid with other nodes). Additionally, the coupling of aggregations of nodes in their own microgrid can form a meso-grid. In this way, the hierarchical base of the dc microgrid starts with a nanogrid, which serves a single node (e.g., a house). A collection of nanogrids comprises a microgrid, which can serve multiple nodes (e.g., an entire community). This can continue to even higher levels of aggregation in a hierarchical structure shown in Figure 4 (right). The building block concept allows for hierarchical microgrids where nanogrids can be combined to work in a cooperative fashion and form a microgrid. Similarly, individual microgrids can be joined to form mesogrids.

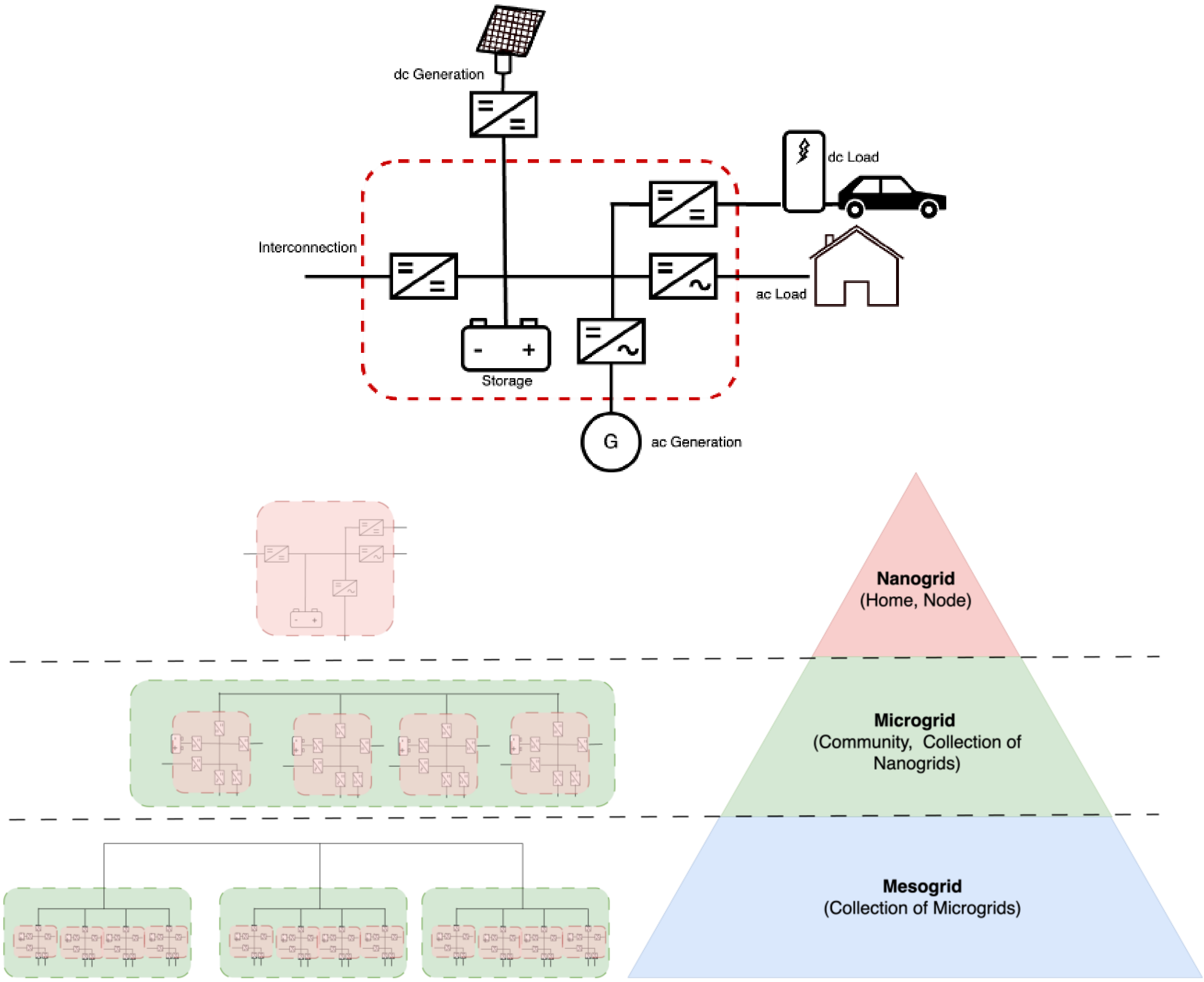


Figure 4. (left) Line diagram for a power electronic building block in the Kirtland AFB., (right) Hierarchical Nature of Kirtland AFB microgrid.

The hierarchical nature of the microgrid is enabled through a modular power electronics interface at each node known as a nanoblock. The Kirtland dc microgrid in Figure 5 is made up of nine nanoblocks interconnected via a main ~1 km long, bipolar ±375 V_{dc} bus. Nanoblocks 1-6 (denoted n1, etc.) serve KAFB temporary base housing loads. Nanoblock 7 serves a purpose-built community center with an electric vehicle (EV) dc fast-charging station (7.2 kW). Nanoblock 8 serves the Kirtland Family Camp (RV Park) and laundry units, and Nanoblock 9 serves a controllable load bank at Sandia's Distributed Energy Technology Laboratory. The microgrid's central box (orange block marked c1 in Figure 5) regulates voltage for the main dc bus.

The microgrid has been operated in a number of different scenarios including: black start, bipolar power transfer, load/generation balancing, seamless islanding and reconnection, fault ridethrough, and ring-bus operation. Results from this demonstration system indicate that a modular, hierarchical, power electronics-based, dc microgrid can reliably provide power to load in a variety of conditions and are a viable and scalable option for microgrid implementation.

Figure 5. Layout of the Kirtland AFB microgrid. It is composed of load-serving nodes with nanoblocks (blue), a 750 V interconnection dc bus (yellow), and a central energy storage system (orange) with grid and backup NG generation.

5.2 Use Case 2: Real-time operations under emergency conditions

As a second use case, we consider the impact of a shift to the vision of a grid with microgrids as building blocks on grid operations under planned and unplanned outages due to weather and/or fire events.

5.2.1 Planned outage use case for wildfires

California has experienced unprecedented wildfire activity levels in the past several years. These include the well-publicized “Camp Fire” that destroyed the town of Paradise and the Santa Rosa fire which destroyed major parts of the city of Santa Rosa. A root cause of these events is a confluence of ignition point or the spark that the utility equipment would provide to start the fires, vegetation management challenges, state versus federal zoning, aging equipment, extreme weather events (both heat, wind, and storms), and maintenance delays. In response to these deadly fires, PG&E created a program called the Public Safety Power Shutoff (PSPS) and EPSS (Enhanced Power Line Safety), where the utility identifies high risk areas, specifically during high temperatures and red flag wind events, using overlays of vegetation and wind projections with existing power infrastructure. Several other utilities have mirrored this program.

When a PSPS is invoked, a utility proactively de-energize any power lines at risk. *Resilience Hubs* program (PG&E n.d.) has been underway at PG&E where funded projects to help communities build a network of local transient microgrids. Many methods are proposed for this, from the most basic level (diesel generators) up to collaborative aggregation techniques for using local generation, and all combinations in-between.

During power outages, the number of backup generators purchased by utility customers is significant and could be useful to create ad-hoc microgrids to support the resilience zone microgrids. Another example of recent microgrids upgrades motivated by increased resiliency, including wildfire risk, is at Anza Electric Cooperative (EC)(NRECA 2021). Anza EC is a distribution cooperation in Anza, California who receives its wholesale power over a single radial 32.5 kV transmission line. This transmission line crosses U.S. Forest Service land and is responsible for three-quarters of the co-op's outages, including a ten-day outage in 2018 due to a wildfire. Motivated by deferring capacity upgrades to this transmission corridor, and increased resiliency during line-outages, Anza have recently installed a 2MW/4MWh lithium-ion solid state battery, 1.4MW PV system and microgrid controller. This solar-plus-storage microgrid was identified as the most cost-effective solution.

Resilience Hubs could form the building blocks of larger grids—the neighboring resilience hub microgrids can be networked to provide grid services and blackstart support to each other, or they can merge into each other to form larger microgrids. This paradigm will perfectly fit the vision of microgrid as a building block of future grids or grid-of-the-grids during planned outage scenarios. During situations such as these when loss of power and communications is a significant challenge, microgrids will help with resilience of the distribution grids during outages.

5.2.2 Extreme weather event use case

This use case is proposed to demonstrate the performance of a power system with microgrids as building blocks when subjected to a severe weather event, using power system in Texas as an example. The state of Texas is vulnerable to extreme weather events that impact electric grids not only by physically damaging infrastructure, such as hurricanes (e.g., Hurricane Dolly in 2008 and Hurricane Beryl in 2024), but also by creating simultaneous conditions of high electric demand and supply shortages,

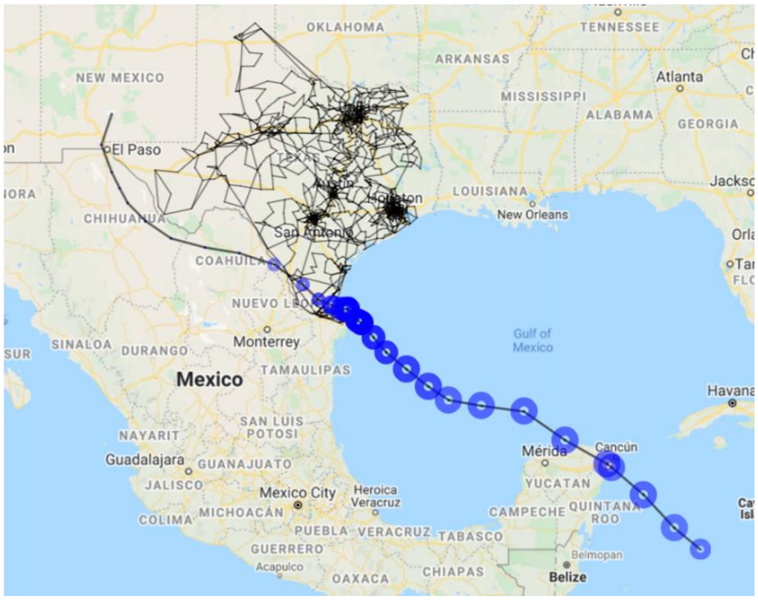


Figure 6. Path of the Hurricane Dolly (July 20 -27, 2008) and synthetic TAMU 2000 bus transmission grid. Size of the blue circles corresponds to hurricane's radii and their color intensity correspond to maximum wind speed.

such as was experienced in February 2021 during an extreme cold spell.

This use case will provide a realistic extreme weather scenario based on the effects of Hurricane Dolly on the Texas electric grid (July 20-27, 2008). Figure 6 shows the path of the hurricane and the Texas transmission grid.

Simulations of the damage to the power systems in Texas, developed through NREL's Laboratory Directed Research and Development (LDRD) funding, under the Resilience Science project (Singh et al. 2021), will be leveraged. The scenario includes modelling the wind damage to electric infrastructure (generators, lines, substations) using fragility curves(Panteli et al. 2017). The transmission grid is modelled using synthetic data from Texas A&M University (TAMU grid). The distribution system will be modelled using either standard IEEE test feeders, or synthetic data from the ARPA-E Smart DS project. The feeders will then be partitioned into cells and microgrids and the control approaches proposed in this paper will be applied. This use case will demonstrate how the architecture and approaches proposed in this paper can improve the resilience of the grid during major natural disasters.

6 Research Targets and Goals for 5 Years

Several new technology developments are required to realize the vision set out in this strategy document, as described in Section 3. This section sets out in more detail the R&D needs for those developments and identifies gaps that need to be addressed between the current state of the art and technologies under development as described in Section 4. A more comprehensive roadmap should be devised by a cross-laboratory team with input from academia and industry—through workshops—within the first 18 months of this effort to further refine the research and development work to be performed.

A key area of research is the development and maturation of distributed control and optimization capabilities to support the proposed vision. These controls should be able to optimally operate a grid—under normal and abnormal conditions—that is comprised of local generation and loads organized into cells and microgrids with dynamic boundaries. For cells to operate as microgrids, cell-level controllers that meet the requirements set out for microgrid controllers in IEEE 2030.7, including managing islanding and reconnection transitions, dispatch and steady-state voltage and frequency regulation, will be required. Many different control approaches may be utilized for cell-level and higher levels of control, but these should incorporate the latest advances in data analytics, AI/ML, where applicable. Research towards such an architecture has been recently carried out in several national labs and universities. Some examples of activities under discussion as part of the Microgrid R&D portfolio include:

- **Advanced microgrid-based architectures for providing reliability and resilience of the distribution grid and supporting energy addition (3 years):** This activity will focus on microgrid-based architectures for aggregating diverse types of distributed energy assets, providing enhanced reliability and resilience for the distribution grid. This includes: (i) implementation of microgrid-based Virtual Power Plants (VPPs) and seamless integration of all types of energy resources, optimizing the use of distributed energy assets and supporting energy addition; and (ii) integration of VPP/microgrid/DERMS/ADMS controllers for single and multiple (networked) microgrids, enabling interoperability of these different technologies. This is described in more detail in the use cases in Section 2.2.
- **Standardized microgrid-based architectures for uninterrupted power supply of critical and defense infrastructure (3 years):** The developed architectures will provide benefits for both civilian and military/space applications, including data centers and the infrastructure they enable, military installations, and space missions.
- **Microgrid-based architectures with heterogenous ownership (5 years):** This activity will develop plug-and-play microgrid-based architectures that can seamlessly

integrate microgrids owned by different entities (utility, community, commercial, and military).

- **Value of networking (3 years):** This activity will carry out advanced applied research on feature selection using ML techniques to discover the best metrics—in addition to establishing practical lower and upper bounds for each metric—for different use cases and scenarios

The following questions would need to be addressed to close the major gaps.

- **Distributed microgrids reconfiguration**: How can dynamic reconfiguration solutions be incorporated within the hierarchal control framework to allow microgrids to reconfigure without the need for a centralized controller? What dynamic controllability hardware is required to enable seamless microgrid configuration? What is the appropriate placement of additional hardware to globally optimize cost of implementation with operational benefits?
- **Real-time operation with dynamically reconfigured system**: What is the efficacy of hierarchal control approaches when applied to a dynamically reconfigured system in theoretical studies and simulations? How can AI/ML approaches be used to reliably control dynamic microgrids?
- **Large Electric Loads**: How can microgrids be formed and controlled dynamically to adjust to the time-varying nature of large electric loads and their impact on the larger power system (e.g., advanced data centers and advanced manufacturing)?
- **Interdependent utility networks**: How can microgrids be dynamically formed and controlled while considering gas and water network constraints?
- **Human-in-the-loop**: How can dynamic microgrids incorporate people's preferences and behavior into the control framework to consider demand flexibility/elasticity and human behavior during extreme events?
- **Asynchronous operation**: Most of the distributed methods rely on the fact that controllers act in a synchronous fashion. Achieving synchronization is possible in simulation environments or in small-size networks, but hard, if not impossible, in large-scale systems with heterogeneous controllers with different sensing, communication, and control rates. How can practical implementation of advanced control and monitoring platforms in utilities and aggregators be enabled through asynchronous control and estimation algorithms?
- **Data-driven/model-free methods:** The existing methods typically require accurate model information; however, controllers might not be able to acquire accurate network model and real-time measurements due to communication loss or delay caused by outages or extreme events. How can AI/ML approaches and model-free

control techniques be used to estimate current and future system state with limited information?

- **Behind-the-meter information**: How can behind-the-meter local energy assets information and flexibility be integrated into utility operation systems while protecting customer privacy and considering occupant preferences?

Implementation of a distributed control framework will also require distributed, cyber-secure communications—including peer-to-peer—capabilities and advanced, interoperable sensors that should incorporate data privacy preservation. Research targets related to some of these are discussed in the Topic 5 strategic document.

Systems with very high penetrations of local energy assets will require greater flexibility in loads to offset the need for storage. Therefore, optimization approaches that enable increased involvement of customers in demand side management through dispatching building loads and local generation in a coordinated way will be needed. This will require higher resolution load forecasting that uses artificial intelligence and machine learning approaches. Additionally, distribution network reconfiguration algorithms to adapt to the propagation of faults and outages, and that can dynamically form microgrids, will be needed. These should be able to distinguish, prioritize and selectively serve critical loads. In order to deploy these controls, optimization and network reconfiguration approaches in the field, upgrades to utility management systems, such as advanced Energy Management Systems (EMS) will be needed, especially the ability to host distributed, hierarchical controls. Utility management systems will also need monitoring and state estimation tools that can function effectively in areas of high penetration of local generation with microgrids, and the latest advances in AI/ML should be incorporated into developing these.

In addition to operational tools, planning tools will also need to be updated to account for the operational changes. Research targets for planning tools are described in the Topic 6 strategic document. Specific planning tools need to enable the vision for microgrids as building blocks include the ability to optimally place utility-owned local energy assets and sectionalizing switches to enable dynamic network reconfiguration and the formation of microgrids. Design of incentives from utilities and/or federal agencies to encourage placement of local energy assets at residential and/or commercial building sites that support the formation of microgrids should also be considered.

Advances in protection coordination for networks with microgrids that can be operating in various combinations of grid-connected and islanded modes will be needed. Research targets are laid out in the Topic 5 strategic document for protection. A specific need to realize a grid with microgrids as building blocks is substation switches to accommodate feeder-level cells combining into a substation-level cell. Methods to design and adjust protection devices in coordination with network topology changes caused by network reconfiguration, such as incorporating adaptive protection settings, will also need to be developed.

All of these developments should be combined into development of full architectures for a grid with microgrids as building blocks. These architectures should be proven first through large-scale simulations which can use power system models and damage scenarios previously developed, as described in the use cases. The GridAPPS-D platform could be used to implement and demonstrate the viability of the proposed controls. These large-scale simulations could also be coupled with advanced hardware for realistic HIL simulations to help de-risk field deployment of these new technologies. This should then be followed by a transition to field pilots that incorporate advanced controls, hardware and communications technologies.

Beyond the technology development requirements, there is also a need to ensure that a regulatory framework exists that can support the deployment of the proposed vision. The topic 9 strategic document addresses these aspects, and there should be collaboration to ensure that considerations specific to the proposed vision are included, such as new billing rules to address a local energy asset from one customer serving a different customer, and ensuring customer fairness.

These developments should proceed along the following timeline over the next 5 to 10 years. Over the shorter term, i.e., the first three years, the focus should be on extracting learnings from currently funded projects and developing a road map and grid architecture as well as funding opportunities for future work. In the medium term, over the 3 to 5-year horizon, new projects should be funded to address remaining gaps, and in the long term, 5-10 years, the focus should turn to pilot demonstrations and technology transfer to industry to set the foundation for longer-term changes.

1-3 years:

- Develop a roadmap to enable a move from a centralized to a distributed paradigm by demonstrating current-generation hierarchical controls and dynamic microgrid formation during extreme events through simulation of one, or more, use cases.
- Develop a draft architecture specification for a grid with microgrids as building blocks. Consider interplay between interdependent infrastructure systems, in particular large electric loads, water, and gas networks. This includes: implementation of microgrid-based VPPs, seamless integration of all types of energy resources, optimizing the use of distributed energy assets and supporting energy addition, integration of VPP/microgrid/DERMS/ADMS controllers for single and multiple (networked) microgrids, and developing plug-and-play microgrid-based architectures that can seamlessly integrate microgrids owned by different entities (utility, community, commercial, and military).

- Issue a call for proposals for projects in the 3-5 years phase to address the gaps identified in the roadmap and that are consistent with the architecture specification.
- Provide input to the regulatory roadmap development proposed under Topic 7 that identifies the additional changes required in regulatory and business practices to allow the implementation of the proposed future vision.

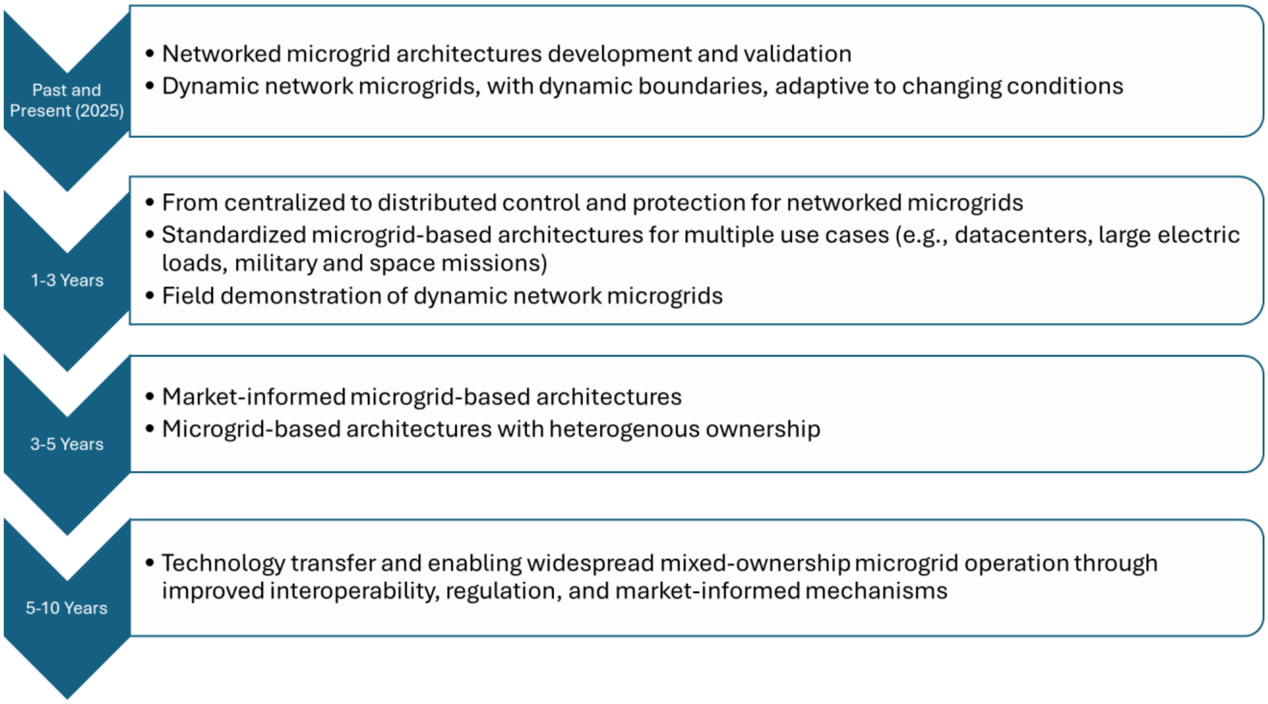
3-5 years:

- Mature the technology and tool developments from the networked microgrid projects, including protection, control, and communication technologies through additional pilot demonstrations and simulations.
- Implement the roadmap to move from networked microgrids to advanced market-informed microgrid-based heterogeneous-ownership architectures that encompass merging of neighboring microgrids, dynamic boundaries for microgrids that integrate fleets of all types of local energy assets providing services to the bulk power system.
- Design advanced protection, next-generation control algorithms and communications and demonstrate through large-scale co-simulation. Decrease control reaction times to, at most, a one-second level for system-level real-time control, and to at most a 100-millisecond level for device-level controls. Adapt networked microgrid system protection settings for the new system configuration within one minute for accurate protection coordination, aiming to reduce fault clearing time to no more than 0.5 seconds.
- Develop final architecture specification for a grid with microgrids as building blocks.
- Engage regulatory entities to lay groundwork for pilot deployments of grids with microgrids as building blocks.

5 years:

- Move toward the implementation of distributed control and communication, where multiple cells interact with each other in a distributed fashion through pilot implementations of distribution grids with microgrids as building blocks.
- Work on technology transfer to ensure this work does not only end in pilot projects but in actual products and solutions from the private sector, e.g., through start-ups or collaboration with existing vendors.
- Lead technology transfer efforts and enable widespread mixed-ownership microgrid operation through improved interoperability, regulation, and market-informed mechanisms

The roadmap is summarized in Figure 7 below.



Past and Present (2025)

- Networked microgrid architectures development and validation
- Dynamic network microgrids, with dynamic boundaries, adaptive to changing conditions

1-3 Years

- From centralized to distributed control and protection for networked microgrids
- Standardized microgrid-based architectures for multiple use cases (e.g., datacenters, large electric loads, military and space missions)
- Field demonstration of dynamic network microgrids

3-5 Years

- Market-informed microgrid-based architectures
- Microgrid-based architectures with heterogenous ownership

5-10 Years

- Technology transfer and enabling widespread mixed-ownership microgrid operation through improved interoperability, regulation, and market-informed mechanisms

Figure 7. Research Targets

7 Why Should DOE be Funding these Goals and Visions

The topic of *microgrids as a building block for future grids* is ideally suited for DOE funding, as it establishes the architectural basis for a secure and resilient US grid capable of integrating diverse energy generation sources at scale. Ensuring that critical energy infrastructure can quickly recover from disruptions is vital for both national and economic security. Realizing this vision will require the development of new technologies, and DOE is well-positioned to accelerate these advancements while mitigating the risks associated with their adoption.

To date, the power industry has focused on developing key microgrid components, including local energy generation assets, responsive loads, management systems, and the control and communication technologies that enable microgrid functionality. Networked microgrids—an essential step toward utilizing microgrids as grid building blocks—remain in the early stages of research and development, with several DOE-funded pilot projects expected to launch in the coming years. Given that different microgrid installations will likely utilize a variety of technologies and vendors, ensuring interoperability is a significant challenge. DOE can play a pivotal role in bringing stakeholders together and supporting research to address this issue.

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 addressed in this strategic document 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.

Clearly articulating the value of microgrids as foundational elements of the grid is essential to realizing the full potential of a “grid-of-grids” vision. This provides DOE with a unique opportunity to lead in defining and promoting the benefits of microgrid-based architectures. By continuing to invest in this vision, DOE can ensure that microgrids become a core component of future grid operations at both the distribution and bulk levels, enhancing the security and resilience of the nation’s electrical infrastructure while maximizing the benefits of integrating all forms of local distributed generation.

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