U.S. DEPARTMENT OF ENERGY

Microgrid and Integrated Systems Program

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Executive Summary

Microgrids serve as an effective platform for integrating distributed energy resources (DERs) and achieving optimal performance in reduced costs and emissions while bolstering the resilience of the nation's electricity system. The value of microgrids is further enhanced with issuance of FERC Order 2222, under which the DERs that are aggregated and optimized in microgrids not only can participate in wholesale energy markets but are able to realize more of their maximum potential benefits. As climate-related natural disasters become more frequent and severe, along with greater electrification, microgrids will serve as increasingly valuable resources in support of power system resilience.

A driving force behind DOE's microgrid efforts is the Office of Electricity (OE), which collaborates with other DOE offices, the national laboratory complex, state energy offices, utility regulators, and a broad network of public-private microgrid stakeholders. **DOE's remote microgrid research** has primarily targeted applications in Alaska, where multiple deployments have made significant progress in demonstrating technical solutions for resilient operations and have provided reference systems to plan resilient microgrids elsewhere. **DOE's microgrids for critical infrastructure research** has centered on microgrid design and analysis tools. These design resources provide reliable cost and resilience estimates of microgrid investments, and are being continually improved through diverse applications, such as disaster recovery in Puerto Rico and Texas, and microgrid resilience at critical transit hubs. While DOE has made significant progress in supporting microgrid deployments, there remain research gaps for both remote microgrid, and microgrids for critical infrastructure, which are being addressed in current DOE collaborations and are discussed in this report.

Microgrid and Integrated Microgrid Systems Program

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I. Introduction

DOE's work in microgrid systems for isolated communities and for critical infrastructure draws on significant collaboration, and ranges from microgrid research and development (R&D) to technical assistance in applying emerging microgrid tools. The R&D focuses on improving resilience, reliability, and sustainability of electricity delivery system through advanced microgrid development, including developing and testing use cases to promote energy equity and justice, whereas microgrid demonstrations and technical assistance aim to support equitable energy transition through prioritized provision of at least 40 percent of microgrid benefits going to disadvantaged communities.

A driving force behind DOE's microgrid efforts is the Office of Electricity (OE), which collaborates with other DOE offices including the Arctic Energy Office, the Office of Energy Efficiency and Renewable Energy, and the Office of Indian Energy Policy and Programs to work together and support a range of efforts in research and technology demonstration and technical support for communities. OE also works closely with the national laboratory complex, the National Association of State Energy Offices (NASEO), utility regulators through the National Association of Regulatory Utility Commissioners (NARUC), and specific state energy offices such as the Alaska Energy Authority. Through participation in many other partnerships, DOE is connected to a far-reaching network of public-private microgrid stakeholders.

DOE's remote microgrid research has primarily targeted applications in Alaska, where multiple deployments have made significant progress in demonstrating technical solutions for resilient operations and have provided reference systems to plan resilient microgrids elsewhere. The United States Agency for International Development has also taken advantage of DOE-developed expertise in their remote microgrid work in Africa[1], Haiti[2], and other rural and remote communities, which has provided valuable insight on technical, regulatory, and procedural rollout of microgrids in the United States. Recently, DOE announced the Energy Transitions Initiative Partnership Project, which provides technical assistance to communities looking for support in planning and developing remote microgrids.

Outcomes from DOE projects around remote microgrids have indicated a greater need for:

- Institutional support programs that facilitate knowledge and data exchange, data-sharing resources, supportive policy and regulatory models, development strategies, and wider-scale coordination.
- Microgrid designs that consider heating, cooling, transportation, resilience, interconnected systems, and high contributions from renewable energy.

DOE's microgrids for critical infrastructure research has centered on microgrid design and analysis tools. These design resources provide reliable cost and resilience estimates of

[1] https://www.usaid.gov/powerafrica
[2] https://www.nrel.gov/usaid-partnership/mini-grids-haiti.html

microgrid investments, and have been developed through numerous DoD and military partnerships. DOE's design tools are being continually improved through diverse applications, such as disaster recovery in Puerto Rico and Texas, and microgrid resilience at critical transit hubs.

Across DOE microgrid projects for critical infrastructure, the following research needs have been recommended, and are the subject of current and forward-looking efforts.

- Detailed, site-specific microgrid feasibility studies
- Quantifiable, standardized, multi-criteria assessments of microgrid performance for critical infrastructure
- Supportive ownership and regulatory conditions of microgrid deployments

The Outcomes and Opportunities sections below explains DOE progress in addressing the research progress and R&D needs of both microgrid categories requested of this report. While DOE has made significant progress in supporting microgrid deployments, there remain research gaps for both remote microgrids, and microgrids for critical infrastructure. The Conclusion section then summarizes the findings and future efforts at the end of this report.

II. Outcomes and Opportunities for Integrated Microgrid Systems for Isolated Communities

More than 1,500 remote communities within the circumpolar Arctic, including many locations in Alaska, are served by microgrids. These communities are mostly dependent on imported fossil energy for electricity, transportation, heating, and other critical services such as potable water, and are therefore important locations to develop clean, resilient, and affordable microgrid solutions that apply modern controls and utilize cleaner energy generation sources.

Microgrids have been deployed in rural and indigenous communities in Alaska since the 1960s. That six-decade history of innovation in bringing power to remote and underserved communities provides significant experience that can be leveraged around the world to meet electrification and resilience goals with microgrids.

Lessons from Alaska and remote or island communities are applicable throughout the energy sector, as microgrids become recognized for improved resilience and efficiency. A recent study by the World Bank Energy Sector Management Assistance Program group suggests that minigrid/microgrid power systems could provide services to almost half a billion people by 2030[3]—a large growth area that could draw directly on experience built in the United States.

[3] https://openknowledge.worldbank.org/handle/10986/31926

DOE has undertaken extensive work to address energy issues in isolated communities. Efforts have largely focused on communities in Alaska but include work in smaller islanded communities in the Northeast with a focus on Maine, the Pacific with a focus in Hawaii and the U.S. Pacific Territories, the Caribbean with a focus on U.S. Territories, and Tribal lands that do not have grid connection. This work has been implemented across Federal agencies, state governments, academic institutions, and community non-government organizations in close collaboration with local energy-serving organizations, typically municipal service providers and energy cooperatives. DOE has provided most of the research investment in these efforts.

Central among these efforts is the Arctic Lab Partnership, which serves to organize research outcomes and direction across a coalition of remote microgrid offices and organizations. The Arctic Lab Partnership recently summarized the following research needs for Arctic microgrids, with relevance for other remote microgrid systems:

- *Higher detail information on community energy needs and local resources*. This could build on existing resources such as the Alaska Energy Data Gateway, Alaska Affordable Energy Strategy Model, and the Alaska Renewable Energy Atlas to provide higher quality assessments of resources and community loads.
- *Better standardization around energy system designs and development*, including documentation of development pathways, performance standards, and technology options.
- *Supportive policy, funding, and collaborative development models*. Energy systems are capital intensive, so policy is needed to articulate the investments using public and private partnerships, to implement an energy transformation in rural Alaska.
- *Global knowledge exchange with islanded and isolated communities around the world*. Initial investments in this type of collaboration include the Island Grid Resource Center and the Arctic Remote Energy Networks Academy, but greater collaboration could be useful to more rapidly advance the science of microgrids in remote places.
- *Expanded research coordination*, including standard forums to support microgrid collaboration with a focus on isolated, islanded, and remote communities.
- *Microgrid design that supports heating, cooling, and transportation, and with relatively high contributions from renewable energy*. The communities of Kodiak and Kongiganak Alaska are working to address heating on a community scale using renewable energy technologies—these and similar projects were implemented through Alaska Renewable Energy Funds, which although largely successful, have not included funding to support wider learning, project documentation, and support for project innovation and improvement.

These research needs can be categorized broadly as institutional support and microgrid design. Institutional support refers to information exchange, supportive policy frameworks, data sharing and standardization. The following DOE Alaska projects are helping to **advance institutional support for remote microgrids**.

- Alaska Microgrid Partnership (AMP)—An effort within DOE's Grid Modernization Laboratory Consortium to develop more systemized, modular, and scalable development and deployment concepts that could be widely implemented across communities with different energy needs and community readiness. Work has focused on developing a holistic, all-energy approach with technical and financial replicability as a key component.
- The Energy Transitions Initiative (ETI)—Implemented by DOE in 2020, ETI builds on decades of earlier DOE efforts such as the Islands Energy Playbook and the DOE-funded Island Grid Resource Center to further advance self-reliant island and remote communities through the development of resilient energy systems. Microgrid planning and deployment are programmatic focus areas executed between communities and national lab technical experts, under the recently established Energy Transitions Initiative Partnership Project (ETIPP). Other opportunities to expand technical assistance and increase local capacity in remote communities are being explored within ETIPP and ETIPP-like expansions.
- Alaska Regional Collaboration for Technology Innovation & Commercialization (ARCTIC)—A collaborative project to build local capacity and support a thriving economy through resilience research, technology development and deployment, and education centered on energy and related industries such as water, food, manufacturing, and transportation. The overarching objectives are to demonstrate that 50 percent penetration of variable renewable energy on microgrids is technically and economically feasible, to enhance local sustainability by extending and leveraging local know-how, and support the diversification of Alaska's ecosystem.

Microgrid design research refers to technical innovations, design strategies, renewable-integration solutions, development pathways, and the sharing of these approaches. DOE projects that are contributing to **improved remote microgrid designs** include the following.

- Resilient Alaskan Distribution system Improvements using Automation, Network analysis, Control, and Energy storage (RADIANCE)—A project within the DOE Grid Modernization Laboratory Consortium, RADIANCE involves regional field validations of resilience methods for distribution grids under harsh weather, cyber-threats, and dynamic grid conditions. These resilience methods use multiple networked microgrids, energy storage, and early-stage grid technologies such as micro-phasor measurement units (PMUs). This will cultivate a better fundamental understanding of microgrid resilience by using a resilience-by-design approach.
- Development and Validation of Models to Assess the Dynamic Response of Converter-Dominated Power Systems Across Multiple Spatiotemporal Scales—With funding from DOE EPSCoR (Established Program to Stimulate Competitive Research) to support early-stage research, this project is performing dynamic modeling of converter-dominated power systems, including at the microgrid scale.
- Connecting Alaska Remote Villages using Energy Storage Ready Medium Voltage DC Interties—This project explores the economics, topologies, and control strategies for

using cable-based medium voltage direct current (MVDC) interties as an energy storage-based alternative to traditional overhead medium voltage alternating current distribution.
- The Assessment of marine hydrOkinetic-based reliable and Resilient eleCtrification in Alaska (ORCA)—ORCA utilizes MVDC connectivity among remote microgrids in Alaska. The objective of ORCA is to resiliently operate regional and remote microgrids in coastal Alaska under harsh weather, cyber-threats, and dynamic grid conditions. The project also aims to develop a cost-effective solution to enhance the resilience of connected microgrids. This project will support equity and economic development for remote and tribal communities.
- The MIRACL (Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad) project implemented by the Wind Energy Technology Office, along with other DOE offices, supports innovative work in microgrid systems with a focus on grid and microgrid integration of wind energy technology with other DERs. The project will develop controls, cybersecurity, and valuation of multi-technology, high renewable energy power systems, and will define system design requirements to enable wind to deliver on-site power in grid-connected and both islanded and isolated microgrid settings.
- The Grid Resiliency with a 100% Renewable Microgrid project, funded by the Solar Energy Technologies Office, in collaboration with other DOE offices, will research and validate microgrid technologies that enable the use of solar and other distributed energy resources (DER) with grid-forming inverters. These devices can improve grid stability and resilience. The project will develop new controls and software for smart inverters and DER management systems that may allow more flexibility for small-scale PV and other DER systems.

Additionally, OE leads efforts to research, develop, and demonstrate microgrids as interconnected building blocks of a future power grid to enhance grid resilience and efficiency. These interconnected microgrid building blocks can improve power system resilience through reconfiguration and seamless dis- and re-connection. While real-system demonstrations are needed to advance the concept of these dynamic microgrids, or “dynagrids,” the following DOE efforts have made progress in **developing dynamic microgrid controls and operations.**

- OE’s Networked Microgrids research is taking the first step towards microgrids as building blocks by developing an optimization-based microgrid design tool[4] and a system restoration tool[5] for distribution systems that contain multiple microgrids that can be networked. It also includes an effort to demonstrate operation of networked

[4] K.P. Schneider, H. Nagarajan, A. Pratt, et al., “Preliminary Design Process for Networked Microgrids,” Technical Report PNNL-30066, June 2020.
[5] https://www.osti.gov/biblio/1638627

microgrids in a distributed manner using collaborative autonomy concepts implemented in an OpenFMB architecture[6].

- The Autonomous Energy Grids portfolio of research[7] is one example of a DOE-developed innovation that, though relatively early-stage, could support microgrids operating as power system building blocks. Autonomous Energy Grids facilitate integration of renewables and distributed energy resources (DERs) using distributed and hierarchical controls. In this way, multiple communities can join together to benefit one another during normal operation or become islanded microgrids that autonomously operate during emergencies and disruptions. This direction is currently further explored in the OE-funded project on Dynamic Microgrids for Real-Time Resilience (DynaGrid), where a flexible definition of microgrids is considered with boundaries adapting to changing operational conditions and disruptions.

In remote communities of Alaska, dynamic interconnection with nearby power systems could increase energy supply, including from nearby renewable resources like near-shore wind, solar, and tidal marine hydrokinetics. The added power supply could be used to develop commercial industries within communities such as aquaculture and provide redundant power for community resilience.

From its many projects in remote communities, DOE in collaboration with local partners has developed insight into multiple angles of remote microgrid operation, including its technical, economic, institutional, and social aspects. Looking ahead, to realize the greatest benefits in cost, resilience, and equality for isolated communities and communities everywhere, emphasis will be placed on sharing these insights to streamline resilient, reliable, and clean microgrid deployments.

III. Outcomes and Opportunities for Microgrid Systems to Increase the Resilience of Critical Infrastructure

A variety of existing, growing, and emerging hazards challenge the ability of the bulk power system to maintain uninterrupted service to critical electricity loads. As a result, microgrids are often considered to be a key strategy for improving energy resilience for critical infrastructures and services, including those that are required for continuity of national security and community functions.

For over a decade, DOE has supported analysis to understand the resilience benefits of microgrids serving defense, energy, and other critical infrastructures. DOE has been particularly

[6] https://gmlc.doe.gov/projects/2.2.1
[7] https://spectrum.ieee.org/energy/the-smarter-grid/tomorrows-power-grid-will-be-autonomous

active in developing microgrid design tools, which have been implemented extensively to determine the potential benefits, appropriate sizing, security, and functionality of microgrid solutions for critical infrastructure. This effort fulfills the need to provide **detailed, reliable, site-specific microgrid analysis.**

- The DOE-supported Renewable Energy Optimization (REopt) tool developed at the National Renewable Energy Laboratory is often applied to understand both the specific bill savings and resilience benefits that can be achieved with microgrid solutions for critical infrastructure:
  - REopt was used to evaluate how long existing and proposed backup energy systems could sustain the critical load during an outage at an Army National Guard base. This analysis helped the Army quantify the resilience benefits and trade-offs of a PV-plus-storage system.
  - REopt has been used to perform an integrated microgrid feasibility analysis for three U.S. military installations to support U.S. Army energy resilience requirements, resulting in a successful request for proposal for an optimized microgrid design.
  - REopt analysis informed microgrid design for two Texas Army National Guard sites: Camp Mabry, selected for 2019 DoD funding; and Camp Swift, selected for 2021 DoD funding.
- The OE-supported Microgrid Design Toolkit (MDT) and Resilience Node Cluster Analysis Tool (ReNCAT) developed at Sandia National Laboratories helps design and evaluate microgrids as resilience investments.
  - Both the MDT and ReNCAT tools are used within the Critical Infrastructure Resilience Technical Assistance project, which delivers direct technical assistance in support of microgrid planning and design for energy resilience at defense critical infrastructure facilities.
  - MDT and ReNCAT have been applied to the Puerto Rico system in the aftermath of Hurricane Maria to estimate the social burden caused by a lack of infrastructure services due to long-duration power outages. In particular, they helped to identify and design microgrid solutions for clusters of critical services, with an emphasis on those which could help to minimize the effort that a population must expend to attain all lifeline service.
  - MDT is currently being used—with REopt and other microgrid evaluation tools—to explore microgrid designs that can provide energy assurance for critical infrastructures. Modeling is currently underway to evaluate the resilience and techno-economic benefits of microgrid solutions that are designed to serve critical loads at Kirtland Air Force Base.

- The Distributed Energy Resources Customer Adoption Model (DER-CAM) developed by Lawrence Berkeley National Laboratory with support from OE is a tool to determine optimal DER parameters (portfolio, sizing, placement, and dispatch), while co-optimizing multiple value streams for microgrids. DER-CAM applications include resilient design analysis to meet state and local government requirements.
    - The DER-CAM-based platform has also been adapted by a commercial entity to demonstrate a standardized approach to guide rapid and repeatable modeling and design of secure and resilient microgrids under the DoD Environmental Security Technology Certification Program (ESTCP).[8]

In order to safely and effectively streamline microgrid deployments, DOE-funded projects are addressing another research need for critical microgrids. A variety of projects are helping to **standardize and quantify multi-criteria assessments of microgrid performance for critical infrastructure.**

- The DOE national laboratory complex is working with critical infrastructure sites and their serving energy utilities to generate high-level designs that are appropriate for the U.S. Department of Defense's Installation Energy Planning process. This effort is rooted in multi-criteria feasibility analysis that weighs the affordability, resilience, sustainability, and security benefits of various microgrid designs.
- An OE-led microgrid feasibility analysis at the Port of Alaska in Anchorage, one of the busiest air cargo hubs in the United States, is being used to establish buy-in and develop a roadmap toward full microgrid implementation.
- Another such microgrid feasibility analysis is underway at Naval Station Norfolk. The project is leveraging the MDT model to implement a holistic approach to improving resilience through consequence-focused system analysis and design of electric power distribution systems. The work focuses on improving energy resilience of the naval station in collaboration with the power utility Dominion and other infrastructure utilities such as the local water utility.

One result of these feasibility analyses and multi-criteria design efforts is the acknowledgement that utilities have very little monetary incentive to plan for improved resilience at the point of service to military installations. This motivates another research need**: clarity around ownership and regulatory conditions of microgrid deployments**. Future work includes making a value proposition to DOD and to state regulators, exploring whether the cost burden on electric utility investments that benefit national security should be borne by the ratepayer or the taxpayer.

[8] https://www.serdp-estcp.org/Program-Areas/Installation-Energy-and-Water/Energy/Microgrids-and-Storage/EW20-5271

Other important research directions looking ahead will build on current DOE tools to advance the reliability of feasibility analyses. This will include greater consideration of interdependencies with other critical services, more rigorous technical understanding of the reliability of assets, and deeper collaboration with microgrid stakeholders to understand performance metrics.

IV. Conclusions

Seeing the importance of stability and resilience on increasingly distributed and renewable energy systems, DOE is heavily invested in advancing microgrids for remote communities and critical infrastructure applications. Out of DOE's close engagement with partnering organizations and governments, we have identified research needs for each of the two microgrid areas covered under the request.

Generally, regulatory and institutional support is an important research direction to support microgrid deployments. Conflicting regulatory decisions for microgrid projects proposed across the country create regulatory uncertainty associated with resilience investments. In some cases, microgrids may be a good technical solution but they cannot overcome regulatory or utility barriers. Clarifying regulatory and ownership approaches is a significant need moving forward, as well as direct DOE collaboration with institutional microgrid stakeholders including utility commissions, state and local governments, and utilities, to develop balanced and modern microgrid regulations at the state and local level.

Another general area of necessary research lies in developing industry standards and/or best practices for multiple aspects of microgrid design and deployment, such as quantifying the resilience benefits of a given investment, and sharing those best practices to streamline microgrid deployments. Closer knowledge sharing could also result in closer communication between microgrid designers and microgrid stakeholders.

In addition, the following research topics have been discussed in this report, along with DOE projects that target these topics:

- Better understanding of whole-system interdependencies (e.g., microgrid relation to water system, heating, and transportation fuels)
- Deeper understanding of community energy needs and local energy resources—taking a community-wide approach to addressing needs
- New quantitative analysis tools and expansion of current tools for valuing and justifying microgrid investments
- Demonstration and operational research of high-renewable contribution microgrids

More than ever, microgrids are poised to interoperate with an emerging modern grid. With the approval of FERC Order 2222, microgrids are able to participate in energy markets, driving new use cases and value propositions. The recent order places new urgency on microgrid designs that are grid-interactive, stable, replicable, and easily deployed. DOE envisions microgrids as building blocks of the future grid that can realize the full value of microgrids across multiple criteria including grid services. Further research can support microgrid and larger grid designs that are clean, reliable, and resilient.