U.S. DEPARTMENT OF ENERGY

2022 & 2023 Microgrid and Integrated Systems Program

Report to Congress
May 2024

United States Department of Energy
Washington, D.C. 20585

Message from the Secretary

Pursuant to a legislative request, this report is being provided to the following Members of Congress:

- **The Honorable Cathy McMorris Rodgers**
  Chair, House Committee on Energy and Commerce

- **The Honorable Frank Pallone, Jr.**
  Ranking Member, House Committee on Energy and Commerce

- **The Honorable Tom Cole**
  Chairman, House Committee on Appropriations

- **The Honorable Rosa DeLauro**
  Ranking Member, House Committee on Appropriations

- **The Honorable Chuck Fleischmann**
  Chairman, Subcommittee on Energy and Water Development, and Related Agencies
  House Committee on Appropriations

- **The Honorable Marcy Kaptur**
  Ranking Member, Subcommittee on Energy and Water Development, and Related Agencies
  House Committee on Appropriations

- **The Honorable Joe Manchin**
  Chairman, Senate Committee on Energy and Natural Resources

- **The Honorable John Barrasso**
  Ranking Member, Senate Committee on Energy and Natural Resources

- **The Honorable Patty Murray**
  Chair, Senate Committee on Appropriations

- **The Honorable Susan Collins**
  Vice Chairman, Committee on Appropriations

- **The Honorable Patty Murray**
  Chair, Subcommittee on Energy and Water Development
  Senate Committee on Appropriations

- **The Honorable John Kennedy**
  Ranking Member, Subcommittee on Energy and Water Development
  Senate Committee on Appropriations

If you have any questions or need additional information, please contact me or Ms. Megan Roessing, Deputy Director for External Coordination, Office of Budget, Office of the Chief Financial Officer, at (202) 586-3128, or Mr. Brian Eiler, Deputy Assistant Secretary for Senate Affairs or Mr. Eric Delaney, Deputy Assistant Secretary for House Affairs, Office of Congressional and Intergovernmental Affairs, at (202) 586-5450.

Sincerely,

Jennifer Granholm

List of Acronyms

ACEP	Alaska Center for Energy and Power
APEC	Asia-Pacific Economic Cooperation
ARIES	Advanced Research on Integrated Energy Systems
AURORA	AUtonomous and Resilient Operation of energy systems with RenewAbles
C2C	Clean Energy to Communities
DER-CAM	Distributed Energy Resources Customer Adoption Model
DOE	U.S. Department of Energy
EPRI	Electric Power Research Institute
ERA	Energy Improvement in Rural or Remote Areas
ERC	Energizing Rural Communities
ETIPP	Energy Transitions Initiative Partnership Project
FOA	Funding Opportunity Announcement
F3	Form Follows Function
FY	fiscal year
GMLC	Grid Modernization Laboratory Consortium
HNEI	Hawai’i Natural Energy Institute
LEAP	Local Energy Action Program
MDT	Microgrid Design Toolkit
MIRACL	Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad
NARUC	National Association of Regulatory Utility Commissioners
NASEO	National Association of State Energy Officials
NRECA	National Rural Electric Cooperative Association
NREL	National Renewable Energy Laboratory
NZM	Net-Zero Microgrid
OCED	Office of Clean Energy Demonstrations
OE	Office of Electricity
POET	Power Outage Economics Tool
PROACTIVE	Predictive Community Outage Preparedness and Active Last Mile Visibility Feedback Autonomous Restoration
RACER	Renewables Advancing Community Energy Resilience
RADIANCE	Resilient Alaskan Distribution System Improvements using Automation, Network Analysis, Control, and Energy Storage
R&D	research and development
RD&D	research, development, and demonstration
ReNCAT	Resilient Node Cluster Analysis Tool
REORG	Resilience and Stability Oriented Cellular Grid Formation and Optimizations for Communities with Solar PVs and Mobile Energy Storage
RONM	Resilience of Networked Microgrids
SETO	Solar Energy Technologies Office
Solar-HERO	Solar-Assisted, Stakeholder-Engaged Autonomous Restoration with Data Orchestration
UNIFI	Universal Interoperability for Grid-Forming Inverters

Executive Summary

Localized energy resilience is a high priority for citizens across the United States. Tens of millions of Americans live in remote locations at the fringe of electrical distribution networks—sometimes separated entirely from the main power grid. Many of these rural and Tribal communities are energy-burdened by the high cost of imported fuel and simultaneously vulnerable to supply disruptions, outages, natural disasters, and delayed recovery.[1] More broadly, all Americans are vulnerable to interruptions of critical infrastructure like water treatment plants, transit hubs, and data centers, each requiring a degree of resilient power. A microgrid is a network of distributed energy resources and interconnected loads that can operate as a controllable single entity in connected or disconnected modes relative to the larger electric utility grid—thus allowing the connected loads to continue to be served during electric service interruptions. Microgrids are a proven solution to the challenges facing critical infrastructure and remote communities, as shown by a growing number of deployments facilitated by the U.S. Department of Energy (DOE). For example, modern microgrid sensors and controls recently allowed the remote city of Cordova, Alaska, to prioritize electrical service to essential loads. And in New Orleans, where residents and city officials are exploring energy resilience options together, microgrid design software and support from DOE National Laboratories are revealing how the city can maximize its resilience, cost-savings, and residents' security with microgrids.

At the request of Congress, this report details activity in resilient microgrid research and development undertaken by DOE and provides recommendations to direct future efforts. The DOE microgrid effort is expansive, widely collaborative, and entwined with many of DOE's other applied research, development, and demonstration (RD&D) activities. While capturing a full inventory of relevant microgrid efforts is challenging, this report attempts to capture recent progress. Some highlighted recent activities include:

- Completion of a widely informed and circulated Microgrid Program Strategy by the Office of Electricity (OE). The strategy includes 7 white papers that guide research efforts and introduce the vision of microgrids as building blocks for the power system.

- Directed microgrid technical assistance for diverse energy-burdened communities, accomplished through multiple DOE programs such as Communities LEAP and C2C and through DOE tools such as REopt® and ReNCAT.

[1] Brown, Marilyn, et al. "High energy burden and low-income energy affordability: Conclusions from a literature review." *Progress in Energy*, vol. 2, no. 4, 2020, p. 042003, https://doi.org/10.1088/2516-1083/abb954.

- Demonstrations of advanced microgrid deployments and research capabilities. National Lab infrastructure like ARIES and ESnet data connections enable advanced research through the creation of digital twins of partners organizations' microgrid system developments. These capabilities allow for more rigorous validation of system designs and deployment scenarios.

- DOE's Office of Clean Energy Demonstrations (OCED) released a new suite of programs under Energy Improvement in Rural or Remote Areas (ERA) including technical assistance, prizes, and grants for integrated microgrid systems for isolated, underserved, and Indigenous communities and microgrid systems for increasing the resilience of critical infrastructure. Additionally, a Distributed Energy Systems Funding Opportunity Announcement (FOA) was released in September 2023 to enable support demonstrations of connected energy systems including microgrids.

Progress toward resilient microgrids is accelerating, but certain gaps still present roadblocks to realizing affordable and reliable systems at the scale needed. This report highlights those gaps, which include the need for technological and regulatory standardization, deeper community engagement and empowerment, demonstration of advanced power electronics, and others. These issues can be incrementally addressed by projects and partnerships that apply the ideas of OE's Microgrid Program Strategy to build microgrids that are accessible and affordable for residents, compatible with the bulk U.S. grid.

2022 & 2023
Microgrid and Integrated Systems Program

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I. Legislative Language

This report responds to legislative language set forth in the Energy Act of 2020 in Division Z,[2] Sec. 8011 Micro-Grid and Integrated Micro-Grid Systems Program, wherein it is stated:

> *… "Not later than 180 days after the date of enactment of this Act, and annually thereafter until calendar year 2029, the Secretary shall submit to the Committee on Energy and Natural Resources of the Senate and the Committee on Energy and Commerce of the House of Representatives a report on the efforts to implement the program established under subsection (b)(1) and the status of the strategy developed under subsection (b)(2)(B)."*

This report is intended to respond to this request for fiscal years (FYs) 2022 and 2023 by describing the progress on the assessment, implementation, and deployment of: (1) integrated microgrid systems for isolated, underserved, and Indigenous communities—including those that are particularly exposed to extreme weather conditions and high energy costs, including electricity, space heating and cooling, and transportation—and (2) microgrid systems for increasing the resilience of critical infrastructure.

II. Report Summary: Progress and Recommendations

Microgrids are an essential element of the United States' transition to clean and reliable energy. The U.S. Department of Energy (DOE) envisions microgrids to be building blocks for future power distribution.[3] They have the advantage of being able to orchestrate energy resources at a more local scale, while also acting as a nodal point of control for bulk power system operators. In this sense, they can act as the electric grid in stand-alone blocks, which has inherent flexibility and is valuable economically and operationally. Moreover, the technologies that enable microgrids—like sensors, distributed energy resources, data systems, power electronics—are becoming more cost-effective and accessible, making deployment more feasible in more locations. To ensure that microgrids can be coordinated with wider grid operations, and that communities have the access, resources, and technologies to deploy microgrid solutions, DOE leads research, development, and demonstration (RD&D) of microgrids throughout the United States.

In FYs 2022 and 2023, DOE and its laboratories made momentous progress in defining and executing its strategy for microgrid RD&D, which touches all aspects of microgrids and provides clear direction for microgrid development in isolated communities and critical infrastructure.

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[2] *Energy Act of 2020*, Sec. 8011 ed. *Division Z*.

[3] "Microgrid Program Strategy." *Energy.Gov*, www.energy.gov/oe/microgrid-program-strategy. Accessed 4 Oct. 2023.

In FY 2022, with substantial input from partners throughout the energy industry, DOE published 7 white papers[4] framing its Microgrid Program Strategy. These white papers set research and development (R&D) priorities for the next 5 and 10 years, concerning the topics of:

- Overall Program Vision and Objectives
- T&D Co-simulation of Microgrid Impacts and Benefits
- Building Blocks for Microgrids
- Microgrids as a Building Block for Future Grids
- Advanced Microgrid Control and Protection
- Integrated Models and Tools for Microgrid Planning and Designs with Operations
- Enabling Regulatory and Business Models for Broad Microgrid Deployment

These strategic R&D areas are structured around supporting isolated communities and critical infrastructure. The white papers ensure that DOE microgrid work follows unified goals of improved reliability, resilience, decarbonization, and equitable electricity access. The program seeks to decrease microgrid capital costs by 15% by 2031, while reducing project development, construction, and commissioning times by 20%.

In FYs 2022 and 2023, at least $471 million was obligated specifically to programs based around resilience for critical infrastructure and support for isolated communities, with many selected projects concerning microgrid solutions. This included:

- The Office of Clean Energy Demonstration's (OCED) Energy Improvements in Rural or Remote Areas Program (ERA) released $365 million in 2023 in technical assistance, Prizes, and grants to support resilient energy infrastructure for areas with less than 10,000 residents.[5] This funding is focused on clean energy deployments supported by community and Tribal leaders that includes integrated microgrid deployments. Recipients will be announced in 2024.

- In 2022, the Solar Energy Technologies Office (SETO) Renewables Advancing Community Energy Resilience (RACER) program announced $33 million in project awards to communities using solar and storage technologies to prevent power disruptions and facilitate rapid recoveries.[6] Several of the solutions in this program are specifically developing microgrid technologies.

[4] "Microgrid Program Strategy." *Energy.Gov,* https://www.energy.gov/oe/microgrid-program-strategy.
[5] "Energy Improvements in Rural or Remote Areas." *Energy.Gov*, www.energy.gov/oced/energy-improvements-rural-or-remote-areas-0. Accessed 4 Oct. 2023.
[6] "Renewables Advancing Community Energy Resilience (Racer) Funding Program." *Energy.Gov*, www.energy.gov/eere/solar/renewables-advancing-community-energy-resilience-racer-funding-program. Accessed 4 Oct. 2023.

- The DOE Communities Local Energy Action Program (LEAP) selected 24 communities in 2022 for a first round of technical assistance for $16 million.[7] It issued an opportunity announcement for a second round of technical assistance for another $18 million in 2023,[8] which provides targeted support for underserved community energy transitions. Many of the applicants and selected communities are seeking direct or indirect support with resilient and critical microgrid systems.

- The DOE Clean Energy to Communities (C2C) program provided $25 million to help 6 community teams develop tailored decarbonization plans, with several using microgrid solutions.[9] These and other ongoing C2C projects provide impactful solutions for clean and affordable electricity in communities spanning rural to urban, and Tribal to metropolitan.

- In 2023, OE announced a $14.7 million funding opportunity for microgrid RD&D in underserved and Indigenous communities.[10] These funds aim to transform the energy future of sites that need solutions to address increasingly extreme weather events and high-priced fuel.

In the United States, Alaska is a major innovator of microgrid solutions. It is warming faster than any other state,[11] has more than 150 small isolated electrical systems that are largely dependent on fossil fuels and is home to many distinct Tribal Nations. Because of Alaska's unique geography, weather, and economy, microgrid innovation in the state considers multi-energy designs, emergency shelter backups, and networked microgrid concepts, which DOE supports through various programs. Outside of Alaska, DOE projects across the United States reveal that microgrid resilience is needed in remote and critical sites everywhere—from tropical islands to New England neighborhoods to rural villages.

DOE's resilient microgrid projects have featured collaboration from not only utilities, cooperatives (co-ops), and cities, but also various organizations like the National Rural Electric Cooperative Association (NRECA), the Alaska Center for Energy and Power (ACEP), the Hawai'i

[7] "Leap Communities." *Energy.Gov*, www.energy.gov/communitiesLEAP/leap-communities. Accessed 4 Oct. 2023.
[8] "DOE Invests More than $18 Million to Continue Empowering Low-Income, Energy-Burdened Communities to Support Clean Energy-Related Economic Development." *Energy.Gov*, https://www.energy.gov/communitiesLEAP/articles/doe-invests-more-18-million-continue-empowering-low-income-energy-burdened.
[9] "DOE Announces $25 Million to Help Communities Expand Affordable and Reliable Clean Energy across America." *Energy.Gov*, www.energy.gov/articles/doe-announces-25-million-help-communities-expand-affordable-and-reliable-clean-energy. Accessed 4 Oct. 2023.
[10] "U.S. Department of Energy Announces $14.7 Million for Microgrid Technologies for Underserved and Indigenous Communities." *Energy.Gov*, www.energy.gov/oe/articles/us-department-energy-announces-147-million-microgrid-technologies-underserved-and. Accessed 4 Oct. 2023.
[11] Thoman, R. & J. E. Walsh. (2019). Alaska's changing environment: documenting Alaska's physical and biological changes through observations. H. R. McFarland, Ed. International Arctic Research Center, University of Alaska Fairbanks.

Natural Energy Institute (HNEI), the Electric Power Research Institute (EPRI), the National Association of State Energy Officials (NAESO), the National Association of Regulatory Utility Commissioners (NARUC), the University of Alaska Fairbanks, Asia-Pacific Economic Cooperation (APEC), the Great Plains Institute, and others that can help circulate results and represent constituents. Additionally, microgrid work crosses U.S. government departments and programs, including the U.S. Department of Interior Bureau of Indian Affairs, DOE's Grid Modernization Laboratory Consortium (GMLC)[12], Department of Defense, and others.

The following sections report on the outcomes and opportunities for resilient microgrids in remote communities and critical infrastructure and summarize where further work is needed.

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

Principally because of climate vulnerability and electricity costs, remote and isolated communities stand to gain the most from microgrid deployments. These communities tend to pay a premium for electricity, since it is either supplied from distant generation or dependent on imported fuel. In addition to high costs, remote communities face higher stakes during outages, as their remoteness may delay repairs or acquisition of backup fuel. Such risks have been evident in Puerto Rico, where hurricanes and earthquakes have wrecked the country's infrastructure and cut off power to millions of residents. Residents there, and in many other isolated communities throughout the United States, are at the mercy of their local infrastructure and costly electrical systems.

DOE microgrid programs include a growing and diverse catalogue of successful pilots and collaborations aimed at delivering microgrid solutions to remote U.S. sites. This work includes everything from technology demonstrations to system modeling and planning and has led to integrated microgrid transformations with insights for other remote systems. Some exemplary outcomes from DOE microgrid work for isolated communities in FY 2022 and 2023 include:

- **Expanded capabilities for microgrid RD&D.** Through partnerships and DOE investments, the National Laboratories have expanded their research capabilities for microgrid validation. One such project, Advanced Research on Integrated Energy Systems (ARIES) platform[13] at the National Renewable Energy Laboratory (NREL), has added megawatt-sized grid assets and customization abilities to the platform, allowing researchers and project developers to emulate diverse microgrid systems based on hydropower, wave energy, battery storage, and more. The same platform has been used for digital twin

[12] "Grid Modernization Lab Consortium." *Energy.Gov*, www.energy.gov/gmi/grid-modernization-lab-consortium. Accessed 16 Apr. 2024.

[13] "Aries: Advanced Research on Integrated Energy Systems." *National Renewable Energy Laboratory (NREL) Home Page*, www.nrel.gov/aries/.

modeling of community microgrids that uses live data from the microgrid to provide replica system modeling. This can be used to stress-test technologies and validate them for implementation and has already proven its importance in a major remote microgrid application: The city of Cordova, Alaska's microgrid modernization through OE's Resilient Alaskan Distribution System Improvements using Automation, Network Analysis, Control, and Energy Storage (RADIANCE) project.[14] The digital twin modeling allowed Cordova to assess and deploy advanced sensing and control technologies. Additionally, several National Laboratories have synchronized research assets over high-speed data networks to emulate partner microgrids. As part of current microgrid projects, the ARIES platform is building out a controller hardware-in-the-loop environment with 600+ internet-of-things controllers for users to test various microgrid assets and distributed energy resources in the loop.

- **Provided strategic technical assistance.** DOE's Energy Transitions Initiative Partnership Project (ETIPP) connects remote and island communities to energy resilience experts, including from National Laboratories, to analyze their energy options. Since 2021, 23 remote and island communities in the United States have engaged in ETIPP projects. These projects have clarified the value of investments in resilience and renewable energy for diverse communities, including a large proportion of Native American Tribes. The city of Eastport, Maine, is composed entirely of islands. ETIPP is performing a techno-economic analysis to help plan, site, and optimally size a community-scale microgrid for Eastport that draws baseload support from a marine hydrokinetic device and leverages its huge tidal energy potential. A related initiative at DOE is Communities LEAP,[15] which supports low-income and energy-burdened communities with energy transitions. Twenty-four communities are receiving direct support from DOE National Laboratory specialists and benefitting from knowledge sharing with other participating groups, facilitated by DOE. The strength of both the ETIPP and Communities LEAP programs is that the community leads its own transition, so the solutions respond to real community needs. For example, the rural Iowa Tribe of Kansas and Nebraska is participating in Communities LEAP to determine how microgrid deployments could reduce the high costs of its electricity. Another such program is Clean Energy to Communities (C2C),[16] led by NREL, which uses hardware emulation and software modeling as well as expert support and peer-learning cohorts to close the gap between community-set goals and implementation. Principally, the In-Depth Energyshed Partnerships of C2C provide years of assistance and direct funding. One project in Molokai, Hawai'i, leverages ARIES research capabilities to support Molokai's Community Energy Resilience Action Plan, which includes goals for deploying microgrids for

[14] Aug. 10, 2023, Connor O'Neil "City of Cordova and U.S. Department of Energy Push Envelope of Microgrid Design." NREL, www.nrel.gov/news/program/2023/city-of-cordova-and-us-department-of-energy-push-envelope-of-microgrid-design.html.
[15] "Communities Leap." *Energy.Gov*, www.energy.gov/communitiesLEAP/communities-leap.
[16] "Clean Energy to Communities Program." *NREL*, www.nrel.gov/state-local-tribal/clean-energy-to-communities.html.

resilience and transitioning to 100% renewable generation. Research capabilities to support the C2C program won an R&D 100 award in 2023. Similarly, through the PR100 Study,[17] the National Laboratories have been evaluating Puerto Rico's microgrid options, given projected capacity expansion on the island. The project Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL),[18] which finished in 2023, has delivered targeted technological guidance around distributed wind energy installations. MIRACL analyzed how remote communities from rural Alaska to northern Iowa could benefit from the cost savings and reliability of small-scale wind plants.

- **Assessed hydropower technologies of wave, hydrokinetic, pumped storage, and tidal power for remote Alaska.** More than 150 distinct electrical systems power remote communities throughout Alaska. Many of these communities are islanded but may have the opportunity to power their systems reliably with local hydropower resources. DOE and the National Laboratories have several concurrent efforts to determine the feasibility of hydropower resources. A study under DOE's HydroWIRES[19] program looked at the potential for pumped storage hydropower for remote communities throughout the state,[20] identifying 1,800 suitable sites. Related projects have directly led to remote Alaskan cities integrating marine renewable energy devices, including a unique river-based hydrokinetic system that has been fully adopted in Tribal Igiugig, and a run-of-river hydroelectric system in remote Dillingham that received technical assistance in the ETIPP program.

- **Supported microgrid technology deployment in remote communities.** Deploying remote microgrids requires a mix of technical integration and operational training. DOE microgrid projects have emphasized both angles; for example, the GMLC project Resilient Alaskan Distribution System Improvements Using Automation (RADIANCE) assisted the isolated city of Cordova, Alaska, in deploying new resilient microgrid technology such as advanced metering infrastructure, distribution system sensors, and a battery energy storage system. Using a digital twin environment, researchers successfully transferred a new microgrid management approach to Cordova's electrical co-op. The DOE-supported microgrid in Borrego Springs, southern California is an example of a state-of-the art remote microgrid installation at utility scale. The microgrid has been a model system for ongoing DOE analysis and technology validation and has

[17] "Puerto Rico Grid Resilience and Transitions to 100% Renewable Energy Study (PR100)." *Energy.Gov*, www.energy.gov/gdo/puerto-rico-grid-resilience-and-transitions-100-renewable-energy-study-pr100. Accessed 4 January 2024.
[18] "MIRACL: Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad." *NREL*, www.nrel.gov/wind/miracl.html.
[19] "Hydrowires Initiative." *Energy.Gov*, www.energy.gov/eere/water/hydrowires-initiative. Accessed 4 January 2024.
[20] https://www.energy.gov/arctic/articles/harnessing-power-water-argonne-and-nrel-study-shows-potential-pumped-storage.

begun a pilot project with DOE around hydrogen energy storage.

- **Promoted financial opportunities for remote communities to develop microgrids.** In July 2023, OCED announced 67 ($100,000 each) winners from 31 states and 1 territory in the first phase of the $15 million Energizing Rural Communities (ERC) Prize. [21] The prize challenges organizations to develop partnership and financing strategies that advance rural or remote communities toward clean energy projects. Over the next year, DOE and National Laboratories will work with the teams to build local capacity and connect financing to rural areas, enabling their transition to clean energy. This prize is part of DOE's $1 billion Energy Improvements in Rural or Remote Areas (ERA) Program and the 67 prize winners will compete for an additional award of $200,000 in July 2024.

- **Deployed critical resilient microgrids for remote Tribal territories.** The San Pasqual Band of Mission Indians commissioned a microgrid system following multiple years of strategizing and support from the DOE Office of Indian Energy.[22] The solar-storage-liquid propane microgrid will protect the Tribe's power supply in remote California, where past wildfires have severely damaged property and critical services.

- **Conducted cross-cutting research toward making microgrids zero carbon.** DOE has invested in the Net-Zero Microgrid (NZM) program to perform cross-cutting research with other agencies to provide tools that consider all clean energy sources, including nuclear energy, for an economically sustainable transition of microgrids from the current approximate amount of 80% fossil fuels to zero-carbon solutions. The program's modeling and analysis capabilities have been demonstrated in a rural corridor of northeast Oregon and an urban corridor in Pennsylvania. Additionally, the underserved municipalities in the mountainous areas of Puerto Rico that initially received support from the NZM program have obtained additional technical support through the ETIPP program.

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

The resilience of critical infrastructure is a mounting concern that blends consideration of cyberattacks, extreme weather, and system stability. Microgrids are one solution for supporting critical infrastructure, as they can allow important assets to survive broader outages and they

[21] "Energizing Rural Communities Prize." *American*, americanmadechallenges.org/challenges/rural-energy.
[22] "Microgrid Boosts San Pasqual Band's Energy Sovereignty and Security." *Energy.Gov*, www.energy.gov/indianenergy/articles/microgrid-boosts-san-pasqual-bands-energy-sovereignty-and-security.

can prioritize critical loads with precise and local controls. DOE microgrid projects support critical infrastructure resilience through autonomous controls, well-validated technological solutions, trusted design tools, and system emulation research.

The criticality of infrastructure depends on its site and purpose. Military bases are deemed critical as nodes of national security, while a community's school buildings might be critical because they double as emergency shelters. Protecting such varied sites has led to innovative solutions from DOE and the National Laboratory complex, with much work converging on the sensing and controls necessary to make autonomous decisions about how a grid should be partitioned to guarantee critical system resilience. Common partners in this work have been military offices and bases, Alaskan energy and power organizations and the communities they represent, underrepresented groups that are vulnerable to outages, and more. The following projects indicate some of the work that has been completed in this area in the past couple years.

- **Developed and deployed data-enhanced microgrid systems.** Through extensive data collection and advanced metering, microgrid operators can better manage assets on their systems. In a groundbreaking deployment of the RADIANCE project in Cordova, Alaska, National Laboratories and the local co-op installed a "surgical load management" scheme that uses expanded data monitoring and control points to prioritize critical loads during normal and resilient operations. In another effort as part of the Solar Energy Technologies Office (SETO) RACER Program, the project Solar-Assisted, Stakeholder-Engaged Autonomous Restoration with Data Orchestration (Solar-HERO)[23] is working with a rural community to deploy extensive sensors and data monitoring to design a robust and automated microgrid restoration method for essential community services. Other SETO RACER projects are also using microgrid technologies to strengthen the resilience of critical assets: the Form Follows Function (F3) project in Duluth, Minnesota, is designing a resilience-planning process that will support emergency community needs during disruptions and will be applicable to other cold climate communities; the Demonstration of a VOLTTRON-based platform to Enable Rapid Energy Restoration at Castañer in Puerto Rico project is designing, testing, and deploying sensing and control systems for community-owned microgrid restoration; and the Predictive Community Outage Preparedness and Active Last Mile Visibility Feedback Autonomous Restoration (PROACTIVE) project, which is developing a community outage preparation tool that will integrate with the microgrid of Hartford, Connecticut.

- **Integrated microgrid modeling for resilience.** DOE supplies many trusted first-stop and whole-project tools for modeling, designing, and selecting microgrid systems. The popular Microgrid Design Toolkit (MDT)[24] led by Sandia National Laboratory provides

[23] April 20, 2023 Connor O'Neil "NREL and Partners Build All-Data Approach for Automated Grid Recovery." *NREL*, www.nrel.gov/news/program/2023/nrel-and-partners-build-all-data-approach-for-automated-grid-recovery.html.
[24] "Microgrid Design Toolkit." *Energy.Gov*, www.energy.gov/indianenergy/microgrid-design-toolkit.

users with decision support around optimal microgrid designs. It has recently been used to analyze critical loads in coastal Puerto Rico, among many other applications. The MDT has added another useful and often used microgrid tool, REopt,[25] which determines cost- and resilience-optimized mixes of renewable energy resources. The Resilient Node Cluster Analysis Tool (ReNCAT), a publicly available software application, analyzes geographical areas for optimal placement of microgrids and other grid resilience investments, ensuring critical services remain available and are equitably distributed during grid outages. The tool uses distribution system topology, critical infrastructure locations, demographic information, and anticipated threat impacts to prioritize the areas that can maximize access to critical services while benefitting the greatest number of impacted people. ReNCAT recently launched a pilot project with a California utility to analyze the social burden of outages. Another DOE tool, Distributed Energy Resources Customer Adoption Model (DER-CAM)[26] uses mathematical modeling to quickly answer customer questions, including questions related to the optimal portfolio of distributed energy resources that meet the specific needs of a microgrid on their site. Other DOE tools allow policymakers and system planners to calculate resilience variables for estimating the direct costs to customers from short-term power interruptions, such as the ICE Calculator[27], and for long-term interruptions, such as the in-development Power Outage Economics Tool (POET).

- **Designed resilient microgrid systems for military bases.** U.S. military bases adopt microgrid technologies to increase site resilience and reduce exposure to fuel unavailability. DOE's design tools described above are frequently used by military facilities. One example is Kirtland Air Force Base, which received an analysis of economic and resilience trade-offs as part of the GMLC Energy Assurance for Critical Infrastructure program.

- **Developed and deployed algorithms for resilient operations of networked microgrids.** The project Resilience of Networked Microgrids (RONM) released a set of core algorithms that manage grid reconfiguration and restoration. The RONM algorithms were awarded an R&D 100 award in 2023[28] and are currently being incorporated into NRECA's open modeling framework, where co-ops and utilities can freely use the algorithms to develop resilient operations. The algorithms are also being used to validate utility microgrid operations in the Resilience and Stability Oriented Cellular Grid Formation and Optimizations for Communities with Solar PVs and Mobile Energy Storage (REORG) and MG-RAVENS projects, which are pioneering models and methods for utilities and companies to adapt in support of critical and clean energy microgrid systems. REORG applies networked microgrid resilience concepts to a rural Colorado co-

[25] "REOPT Energy Integration & Optimization Home." *NREL*, reopt.nrel.gov/.
[26] Mashayekh, et al. "Der-Cam." *DER-CAM | Grid Integration Group*, gridintegration.lbl.gov/der-cam.
[27] *Ice Calculator*, icecalculator.com/home.
[28] "Microgrid Software Program at Los Alamos Lab Honored." *Energy.Gov*, www.energy.gov/oe/articles/microgrid-software-program-los-alamos-lab-honored.

op's goal of using clean energy to maintain critical loads at a mountain town's airport, transportation authority center, and wastewater treatment facility. Another OE project, DynaGrid, is creating open-source algorithms that equitably partition networked microgrids. Their project deployment will take place in Detroit, where extensive community engagement is underway to determine how to incorporate energy justice into the algorithms. Other microgrid efforts, especially in Puerto Rico, are leading the way in incorporating residents' well-being and equitable access into microgrid planning, which will ultimately influence the design and operation of networked microgrid infrastructure throughout Puerto Rico. Two community-owned microgrids, which will soon provide solar power to Adjuntas, Puerto Rico, were validated in an OE microgrid testbed at Oak Ridge National Laboratory. These systems feature a novel microgrid orchestrator—software designed to manage the exchange of power between multiple microgrids within a network. When Hurricane Fiona hit Puerto Rico in September 2022, a smaller, previously installed Adjuntas microgrid kept the power on for nine days when other parts of the island went dark.

V. Research Needs and Next Steps

As microgrid pilots proceed, early results are generating enthusiasm and interest. When natural disasters result in power disruptions, communities take note of the self-sufficiency benefits of microgrids and small-scale distribution systems that provide rapid restoration of electrical service. The Federal Energy Regulatory Commission introduced an important regulatory change with FERC Order 2222, which allows aggregated resources to sell electricity into the bulk market and thereby encourages microgrid development. The microgrid market—which stood at around 10 gigawatts in United States in 2022—could double by 2028.[29]

Current microgrid projects have also revealed where to focus RD&D for anticipated growth in the industry. Research gaps in key areas act as roadblocks to sustained microgrid deployments and should be addressed to keep momentum where microgrids are identified as a valuable solution. The following is a list of research needs and next steps, including topics that are actively being developed.

- **Protection scheme R&D.** Updating grid protection—the infrastructure for maintaining safe power flow—is a challenge throughout modern power systems, but the issue stands out for microgrids because of their range of architectures and designs. This point is emphasized in the DynaGrid project, which specializes in reconfiguring the grid into resilient cells. To operate such a system with dynamic configuration, protection schemes must be equally adaptive. Relatedly, microgrid white paper 5 covers the topic of "Advanced Microgrid Control and Protection." Improved protection schemes will require modeling of faults in renewable energy systems, enhanced coordination of inverter devices, more sensitive schemes for high-impedance fault currents, controlling

[29] https://www.woodmac.com/reports/power-markets-us-microgrid-outlook-2022-150083554/.

system grounding, and more.

- **Grid-forming inverter development**. Microgrids comprise increasing numbers of inverter-based resources, like solar and wind power and energy storage devices. To sustain an inverter-dominated infrastructure, RD&D is needed for emerging inverter control approaches, known as "grid-forming inverters," which can actively control voltage output and frequency. This provides stability and allows inverter-based resources to recover during a grid disturbance or outage. Grid-forming inverters are critical for power systems with a large proportion of renewable energy devices. Ongoing efforts in this area include: AUtonomous and Resilient Operation of energy systems with RenewAbles (AURORA), which demonstrated benefits of grid-forming inverters for microgrid resilience, and the Universal Interoperability for Grid-Forming Inverters (UNIFI) consortium, which is preparing a demonstration for megawatts of renewable energy in providing resilience. This area is developing rapidly, but will require larger-scale demonstrations, continued technology validation, and collective standardization efforts to expand the application of grid-forming inverters.

- **Autonomous operation for remote microgrids.** Microgrid solutions for remote and critical applications use increasingly complex and interdependent data systems that can only be managed with autonomous controls. RD&D is needed for autonomous controls in remote microgrids, where there may be a lack of experienced workers or hardware controllers to manage complex operations. Simple, reliable controls could make the difference for system resilience in such cases. Work here is being developed through projects like Autonomous Energy Grids, REORG, DynaGrid, and Solar-HERO, all of which are designing and demonstrating autonomous power flow algorithms for resilience. The next step is more commercial demonstrations through public-private partnerships, improving algorithms through community engagement and field testing, and demonstration of larger-scale composites of networked microgrids. Additionally, state-of-the-art controls will require ongoing data, sensing, and artificial intelligence RD&D to improve resilience and efficiency benchmarks.

- **Power electronics interface development.** Microgrids can use a range of power electronic hardware like switches and transformers. These technologies enable applications like two-way power flow and all-DC architectures, which are useful for renewable energy-based microgrid operations. These technologies are relatively modern and are undergoing innovation from the component level up through deployment. They are essential technologies for unlocking all the advantages of microgrids, but further research is needed to log hours of live operations before they can expand commercially. Power hardware-in-the-loop research is useful for logging these hours.

- **Community engagement.** Microgrids can serve local needs more acutely than imported supplies and are sometimes the only power option available. Therefore, it is highly important to bring public engagement to the forefront of projects. For example, the

DynaGrid project relies on feedback that comes from customers at an individual home level to design equitable system controls. Additionally, many microgrids feature entirely new and unfamiliar technologies that communities likely need training to operate. Projects should empower communities to own and operate microgrids, and to provide input and learn about microgrid options.

- **Integration with multi-energy systems.** As seen in the Borrego Springs microgrid and in numerous Alaskan villages, technologies like hydrogen and hydropower are finding a place in microgrid systems. These technologies diversify the flow and management of energy throughout a system. Multi-energy microgrids provide unique options for energy storage, dispatch scheduling, decarbonization, and more, but designing such systems can be technically challenging and usually proceeds case-by-case. More field demonstrations, laboratory validations, commercial demonstrations, and results-sharing will help realize multi-energy microgrids.

- **Regulatory barriers.** Microgrids continue to face regulatory barriers, especially from discordant regulation across U.S. states, delays and complexities in grid interconnection, and disincentivizing policies from utilities. Another of the DOE microgrid white papers focuses specifically on "Enabling Regulatory and Business Models for Microgrids," and recommends direct technical assistance to regulatory commissions around microgrids, support for regulatory sandbox pilots, and training series for microgrid developers. These will allow microgrids to overcome common challenges and develop a supportive regulatory ecosystem.

- **Integrated planning and design tools.** Much progress has been made in connecting DOE's microgrid design tools together, granting wider functionality to users and standardizing the planning ecosystem. Next steps should focus on adding climate modeling to reflect future conditions and address resilience impacts on load and renewable resources deployment.

- **Standardization of microgrid components and subsystems**. Standardization plays into the Microgrids as Building Blocks concept, which is the cornerstone of OE's microgrid strategy. As explained thoroughly in the topic 3 white paper, Building Blocks for Microgrids, standardization of microgrid interfaces, designs, components, communications, and controls are key to achieving modular, lower-cost, and widely compatible microgrids. For example, microgrid connections to the bulk grid use power electronic interfaces that should be standardized to support mass manufacturing and reduce balance of system costs. As another example, controls for microgrids follow largely relatable schemes, such that a standardized universal controller could overcome some of the skill barriers to deploying microgrids and support interoperability. Achieving standardization will depend on more projects that intentionally include this work as a requirement, such as Topic 1 of DOE's 2023 $14.7 million Funding Opportunity Announcement No. DE-FOA-0002934 Underserved and Indigenous

Community Microgrids.[30] Field tests and participation with commercial entities will help standardization, especially projects that target least-cost, most-universal, and most-fundamental microgrid designs.

VI. Conclusion

DOE support of remote and critical microgrids is making progress on all fronts for the development of resilient, equitable, reliable, and clean energy microgrids. With guidance from the Office of Electricity's microgrid white papers, current projects are confronting all topics of controls, community engagement, regulation, business environments, research capabilities, and networked architectures.

RD&D projects often pair DOE National Laboratories with communities facing representative problems of remoteness and critical resilience. These cities, villages, military bases, and neighborhoods have taken large steps toward developing their future energy systems thanks to projects that provide technical assistance, system modeling, and deployment support. They are also the microgrid systems that can be used to inform future applications.

Through microgrid RD&D projects, DOE National Laboratories have added and adapted capabilities to model, simulate, and control power systems. These microgrid research environments—like digital twins, superlabs, and megawatt hardware-in-the-loop—are major RD&D achievements that will enable continually larger and more complex demonstrations. Equally, DOE microgrid decision-support tools continue to gain users and broaden their use cases.

As interest in microgrids remains high, and regulatory and technological trends continue in their favor, DOE's RD&D support for resilient microgrids should evolve and expand to take on the challenges identified in this report. The most useful steps forward include:

- Deeper integration of DOE capabilities across the lab complex
- More pilots and commercial demonstrations with diverse and engaged communities
- Projects that standardize microgrids from planning to operations.

With this support, microgrids can flourish where they are most needed—in remote communities and for critical infrastructure—and continue to emerge as a building block for grid resilience and clean energy across the United States.

[30] "Opportunity Summary." *FedConnect*, www.fedconnect.net/FedConnect/default.aspx?ReturnUrl=%2Ffedconnect%2F%3Fdoc%3DDE-FOA-0002934%26agency%3DDOE&doc=DE-FOA-0002934&agency=DOE.