# Fiscal Year 2024 Micro-grid Grid and Integrated Micro-Grid Systems Program

Report to Congress
January 2025

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 Brett Guthrie**
  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 Mike Lee**
  Chairman, Senate Committee on Energy and Natural Resources

- **The Honorable Martin Heinrich**
  Ranking Member, Senate Committee on Energy and Natural Resources

- **The Honorable Susan Collins**
  Chair, Senate Committee on Appropriations

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

- **Chairman**
  Subcommittee on Energy and Water Development
  Senate Committee on Appropriations

- **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 Ms. Jazmin Sorgho, Director of Management and Operations, Office of Congressional and Intergovernmental Affairs, at (202) 586-5450

Sincerely,

Jennifer Granholm

# List of Acronyms

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|---|---|
| AI | Artificial Intelligence |
| ARIES | Advanced Research on Integrated Energy Systems |
| C-LEAP | Communities Local Energy Action Program |
| C2C | Clean Energy to Communities |
| DC | Direct Current |
| DER | Distributed Energy Resources |
| DOE | Department of Energy |
| EERE | Office of Energy Efficiency and Renewable Energy |
| ERA | Energy Improvements in Rural or Remote Areas |
| ETIPP | Energy Transitions Initiative Partnership Project |
| FOA | Funding Opportunity Announcement |
| FY | Fiscal Year |
| GRIP | Grid Resilience and Innovation Partnerships |
| IEEE | Institute of Electrical and Electronics Engineers |
| IIJA | Infrastructure Investment and Jobs Act |
| MG-RAVENS | Microgrid Research Application Verbal Normalization Scheme |
| MVDC | Medium-Voltage DC Converter |
| NREL | National Renewable Energy Laboratory |
| OCED | Office of Clean Energy Demonstrations |
| OE | Office of Electricity |
| PV | Photovoltaic |
| RACER | Renewables Advancing Community Energy Resilience |
| REopt | Renewable Energy Optimization platform |
| R&D | Research and Development |
| SETO | Solar Energy Technologies Office |
| TFP | Transmission Facilitation Program |
| UNIFI | Universal Interoperability for Grid-Forming Inverters |

# Executive Summary

The Energy Act of 2020 directed the Secretary of Energy to promote the development of microgrid systems to support electrically isolated communities and to increase critical infrastructure resilience. It also authorizes support for microgrid demonstrations in isolated communities, rural electric cooperatives, and municipalities. Legislation over subsequent years multiplied the resources available to realize these goals.

The U.S. Department of Energy (DOE) has a deep history of engaging in this area and was able to rapidly mount a strategic approach for microgrid research, development, and demonstration that is playing out in laboratories, utilities, local energy offices, Tribal Nations, and communities in nearly every state.

Microgrids provide a solution to electrical grid threats, such as severe weather events and physical or cyberattacks, via localized grids that can operate autonomously whether interconnected to the traditional grid or “islanded,” as in the case of many remote and Indigenous communities.

When electricity is generated from a microgrid, often drawing on locally available and inexhaustible sources of renewable energy, it does not need to travel a long distance to reach the end user or rely on precarious fuel supply chains. In addition, the National Laboratories have demonstrated resilience enhancements including self-healing microgrids, the ability to “black start” without outside power following an outage, and capacity to autonomously network together to share resources for best service. The strength of microgrids in supplying reliable, locally sourced, and flexible power led DOE to define microgrids as *building blocks* for future power distribution, which is envisioned as power electronics-based systems that support bidirectional transactive power flows and enable large-scale grid-edge device integration and orchestration.

Under the concept of “microgrids as building blocks” microgrids are not merely one-off solutions to deploy in emergencies; they are foundational to a system of systems design for a grid that is rapidly growing in complexity. Customers are installing distributed energy resources in such large numbers that grid operators cannot monitor and control these individual devices using traditional practices. Rather than sourcing energy from a central power plant, power is generated from renewable energy resources located across a larger geographic area. By consolidating these resources into microgrids with internal controls, their power is aggregated to provide services to the various levels of the grid—distribution or transmission—while advancing national priorities of decarbonization and grid modernization.

DOE leads technical assistance partnerships with goals to modernize electric generation facilities, address disproportionately high electricity costs, and support new economic opportunities in historically underserved communities. Selected examples are summarized in Section III of this report. Energy-burdened communities can be hesitant to pursue microgrid systems due to the up-front investment and lack of experience with microgrid operations. This

reluctance is changing as more community microgrids come online and new tools remove the barriers to using them. The microgrid systems designed under DOE partnerships are tailored to local conditions and goals, yet each one presents validated, replicable solutions and valuable lessons for the market at large. DOE has also developed streamlined microgrid planning and operation tools to address common knowledge gaps.

Results from community partnerships and national laboratory research inform DOE program managers of current technology gaps and barriers to maximizing microgrid systems for critical infrastructure resilience. Section V recommends future research needs and next steps including advanced research and development for microgrid controllers and grid-forming controls, continued investment in autonomous operations, and seamless integration of a hybrid mix of distributed energy resources (DERs). DERs refer to technologies connected to the distribution system close to the load (i.e., the user), and may include rooftop solar photovoltaics, wind turbines, combined heat and power, battery energy storage, and diesel generators. Most of these assets use an inverter to interconnect with the grid, and ongoing advancements in grid-forming inverter controls enable DERs to provide valuable grid stability and resilience.

As more commercial microgrid technology comes to market, deployment remains hindered by several factors. The regulatory environment—especially unsure definitions that place microgrids in competition with utilities—presents barriers to interconnecting microgrids. Operators and planners would benefit from resources on microgrid planning and implementation resources to help navigate the complexities of these systems. Technical assistance offerings need to be well-resourced to execute effective outreach, capacity building, and consulting for the full life cycle of microgrid development, particularly in disadvantaged communities where long-term system sustainability is at risk. Deployment times and financing opportunities will also be improved through standardization of key microgrid components, an area of DOE investment that is starting to produce a positive impact.

The 2024 report features project spotlights, such as:

- A black start demonstration of a microgrid in the California desert.
- A resilience initiative led by the Choctaw Nation of Oklahoma, located in the heart of America’s Tornado Alley.
- An outage prediction tool to be field tested in Connecticut.
- A hydroelectric cooperative exploring what would be the first intermunicipal microgrid in Puerto Rico.
- A microgrid use case model applied in a wildfire scenario in which power lines must be shut off while maintaining power to the maximum numbers of customers with special consideration for particularly vulnerable social groups.
- A standardized microgrid modeling and analysis tool that will be free to use in open-source software.

The report also highlights many other notable achievements advancing microgrids as the building blocks of a resilient, affordable, and equitable energy system.

# 2024
# Microgrid and Integrated Systems Program

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# I. Legislative Language

This report responds to legislative language set forth in Section 8011 of the Energy Act of 2020, Micro-grid and integrated micro-grid systems program, codified at 42 U.S.C. §17392(d) wherein it states:

> *… "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 Year (FY) 2024 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 ideal solution for sites that are underserved by the bulk power system—whether because the site is remote, economically burdened, or requires enhanced resilience. These sites benefit principally from microgrids' local deployment, which often reduces energy costs and provides an emergency energy supply, while also taking advantage of microgrid features such as operational flexibility and opportunity to generate renewable energy. Indeed, the strength of microgrids in supplying reliable, lower-cost, and flexible power led the U.S. Department of Energy (DOE) to define microgrids as *building blocks* for future power distribution in the DOE Microgrid Strategy.[1]

DOE programs in the past year have continued to make progress on microgrids for remote, underserved, and resilient applications. DOE's assistance has led to system reliability and resilience enhancements across the United States and its territories, spanning Tribal lands, abandoned mines, medical centers, and more. These microgrid projects have embraced a large portfolio of assets, such as fuel cells, biogas, geothermal, and floating solar, and have resulted in tools that make microgrids more accessible and easily managed. These projects resulted from the strategic investment in microgrid R&D that DOE has supported in the last several decades, improving critical system components such as inverters, microgrid controllers, and advancing standards for interconnecting distributed generation to the transmission system.

[1] "Microgrid Program Strategy," Energy.Gov, www.energy.gov/oe/microgrid-program-strategy.

Modernizing the national energy system for the 21st century requires transformative change to meet the goal of delivering energy that is secure, affordable, equitable, reliable, and resilient. Energy security means the uninterrupted availability of energy sources at an affordable price, while minimizing negative consequences from energy use. Participants in DOE's community-based technical assistance programs often identify energy security as a top priority in their energy transition goals. The Federal Government regulates energy reliability, reviewing standards that ensure the grid has adequate capacity to meet customer needs and remains functional during unanticipated but common system disturbances.

Along with energy security and reliability, DOE identified a key priority in energy resilience, which has various definitions but focuses on the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruption. Resilience events are defined as low-frequency but high-consequence disruptions (e.g., extreme weather or cyberattacks). These events pose a particular challenge for energy system operators and stakeholders weighing the trade-offs of different resilience investments.

Renewable generation is integral to the success of all these goals, since the clean energy economy enhances energy independence, economic growth, and the health and well-being of the American people. Recognition of the historically disadvantaged communities that are marginalized by energy system underinvestment and overburdened by pollution, noise, health impacts, and financial pressures, as well as the remediation of these impacts, is implemented in all DOE's work through energy justice practices, in adherence to the Biden-Harris Administration's Justice40 Initiative.[2]

In accordance with DOE's vision of microgrids as building blocks, the networking and intercommunication of microgrids is a sustained research interest for academia and industry. Networked microgrids will facilitate an even more flexible and resilient power system, but to get there will require investments in emerging solutions, such as autonomous operations, advanced sensing and prediction of grid conditions and demand, and advanced grid controls. These topics often surface in technical assistance efforts for microgrids.

Another recommended area of research is novel microgrid deployment strategies. Some strategies that have been gaining traction through public interest or research projects include mobile microgrids, microgrids in brownfield sites that otherwise sit undeveloped, and communal ownership of microgrid assets. To achieve these innovative microgrid developments, and to expand solutions that are commercially available today, stakeholder engagement and institutional frameworks are especially important. These ideas are discussed below in the report in the context of early projects.

[2] "Justice 40," The White House, https://www.whitehouse.gov/environmentaljustice/justice40/.

In FY 2024, several DOE offices committed to large investments for enhancing resilience of critical infrastructure and support for isolated communities, with many selected projects concerning microgrid solutions. These funding opportunities include, but are not limited to, the following examples:

- The Office of Clean Energy Demonstrations' (OCED) Energy Improvements in Rural or Remote Areas (ERA) program was appropriated $1 billion from the Infrastructure Investment and Jobs Act (IIJA) to provide financial investment, technical assistance, and other resources to advance clean energy demonstrations and energy solutions that benefit rural and remote communities. In 2024, ERA selected projects for award negotiations in two different funding announcements: $366 million for 17 projects selected for cooperative agreement funding in DE-FOA-0002970[3]; $78 million for 19 small, community-driven projects with fixed grants under DE-FOA-0003045[4]. Of the 36 projects selected from those two funding announcements, 42 percent of these projects will utilize microgrids that communities can operate autonomously to strengthen grid resilience and help mitigate disturbances. OCED also awarded prizes to the 67 finalists of the $15 million Energizing Rural Communities Prize. With technical assistance from energy system integration experts, the communities are pursuing many different types of renewable energy technologies, including more than 20 projects incorporating replicable microgrid solutions.
- In the last few years, DOE has introduced several technical assistance programs that bring expertise directly to forward-looking yet hard-to-reach communities across the United States. These programs have proven their value with success stories in clean energy plans that reflect the goals, priorities, and resources of participants while applying best practices for reaching underserved populations. As of 2024, DOE awarded $34 million to the Communities Local Energy Action Program (C-LEAP), $50 million to Clean Energy to Communities (C2C), and more than $20 million to the Energy Transitions Initiative Partnership Project (ETIPP). From the hundreds of communities that have participated in these opportunities, DOE has observed a growing trend of interest in microgrids that alleviate dependence on fossil fuels and enhance energy resilience.
- In May 2024, the DOE Office of Electricity (OE) announced selectees that will benefit from $10.5 million in funding[5] from DE-FOA-0002934 to bring replicable microgrid solutions to underserved and Indigenous communities in remote, rural, and islanded regions throughout the United States. Historically, microgrid deployments have often been limited to single demonstration projects with minimal replicability. Standardizing

[3] "Energy Improvements in Rural or Remote Areas Selections for Award Negotiations," OCED, https://www.energy.gov/oced/energy-improvements-rural-or-remote-areas-selections-award-negotiations.
[4] OCED, https://www.energy.gov/oced/energy-improvements-rural-or-remote-areas-grant-selections-award-negotiations.
[5] "Energy Department Announces $10.5M for Microgrid Solution Projects in Underserved and Indigenous Communities," OE, https://www.energy.gov/oe/articles/energy-department-announces-105m-microgrid-solution-projects-underserved-and-indigenous.

microgrid technology will improve scalability and affordability while allowing for unique configurations that adapt to local needs and preferences. Programs like this aim to ensure low-cost, clean energy is available to support and improve the lives of every American.

- The DOE Office of Indian Energy is soliciting proposals for Clean Energy Technology Deployment on Tribal lands in the 2024 DE-FOA-0003298 of $50 million.[6] DOE anticipates selecting 10 to 20 projects focused on installing clean energy generation or energy storage, and integrating autonomous operation solutions that advance Tribal community resilience. Similarly, the DOE Office of State and Community Energy Programs announced DE-FOA-0003229 distributing $18 million for municipality- or Tribal-led high-impact clean energy projects in disadvantaged communities, energy communities, small- and medium-sized jurisdictions, and Tribal communities. The funding opportunity invited proposals for a broad range of projects that illustrate technologies, approaches, and models tailored to local community contexts, which may include building efficiency and/or electrification, energy infrastructure upgrades, and microgrid development and deployment.
- The Grid Deployment Office (GDO) is funding deployment of operational microgrids through several mechanisms. In early FY 2024 GDO announced the first round of Grid Resilience and Innovation Partnerships (GRIP) Program investments to strengthen electric grid resilience and modernize power systems across the country.[7] The selected projects will deploy utility-scale microgrids across eight states to enhance resilience against natural disasters or grid failures, including several in the often storm-ravaged Southern region of the country. The $457 million in federal funds support $911 million in transformational projects that will deploy microgrids to enhance power system resilience to natural disasters, improve electric grid reliability, and expand utility use of modern energy technologies and resources.
- In addition, GDO provides $2.3 billion in Grid Resilience Formula Grants to states, Tribes, and territories over five years, which may be used to invest in projects that reduce the likelihood and consequence of grid outages due to extreme weather, wildfire, and other natural disasters.[8] Many grant recipients are planning to utilize their grant funds to develop microgrids, including in Colorado, Maine, and Puerto Rico. GDO also provides technical assistance to support grant recipients with grid resilience planning, investment decision-making, and access to National Laboratory expertise in microgrid design and implementation.

[6] "FOA Update: DOE Doubles Funding to $50 Million for Tribal Clean Energy Projects," Energy.Gov, March 22, 2024, https://www.energy.gov/indianenergy/articles/foa-update-doe-doubles-funding-50-million-tribal-clean-energy-projects.

[7] The full set of GDO selected GRIP round-1 projects is found here: https://www.energy.gov/gdo/grid-resilience-and-innovation-partnerships-grip-program-projects

[8] The Grid Resilience State and Tribal Formula Grant program is authorized by Section 40101(d) of the Bipartisan Infrastructure Law: https://www.energy.gov/gdo/grid-resilience-statetribal-formula-grants-program

- In the second quarter of FY 2024, GDO announced a request for proposals (RFP) for up to $200 million through the Transmission Facilitation Program's (TFP's) Public Private Partnership funding mechanism for transmission projects to connect remote and isolated microgrids to existing infrastructure corridors (such as a road, railway, or telecommunication line) in Alaska, Hawaii, and the U.S. Territories. This mechanism was designed to address the unique electric grid configurations and challenges faced by residents in these remote and often isolated communities. Strategic interconnection of existing microgrids to each other and to a larger operating transmission system will enhance grid reliability and resilience and expand access to clean, diverse, and more affordable energy in these areas. The RFP produced two applications which are currently under review. Selections and announcements are anticipated in the fourth quarter of FY 2024 and will leverage the same selection and announcement cycle of TFP Capacity Contracts Round 2 effort.

DOE's resilient microgrid projects have featured collaboration from not only utilities, co-ops, and cities but also from a variety of organizations such as the Alaska Center for Energy and Power, the Hawai'i Natural Energy Institute, the Guam Power Authority, the Standing Rock Renewable Energy Power Authority, Iowa State University, Purdue University, the Coastal Studies Institute, the Island Institute, Renewable Energy Alaska Project, Spark Northwest, and others that contribute data, scale findings, or provide wraparound services for under-resourced communities participating in DOE programs. Industry collaborators include Electrical Grid Monitoring, NEC Laboratories American, Intelligent Energy Systems, Survalent, Copper Labs, Camus Energy, CMBlu Energy, and DataCapable. Additionally, microgrid work crosscuts Federal entities, including the DOE Arctic Energy Office, DOE Office of Indian Energy, Grid Modernization Laboratory Consortium, Department of Defense, Federal Emergency Management Agency, 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

Microgrids can provide local power generation to remote and rural customers that pay a disproportionately high percentage of their monthly income on electricity bills. Microgrids designed to be islanded from a centralized bulk electrical grid present a verified solution for communities that are already off-grid. However, historically disadvantaged communities face challenges in accessing advanced technology, despite standing to gain the most from its deployment.

The declining price for renewable energy generation and increasing cost for fossil fuels is leading more communities to explore diversifying their energy resources. For example, Alaska is projecting a substantial increase in fuel prices due to the declining supply of natural gas from the Cook Inlet. With more than 200 communities disconnected from a centralized electrical grid, Alaska provides more than 200 opportunities to substantiate the benefits of energy efficiency, demand-side management, and other methods of managing load and generating electricity with more local control. DOE is supporting dozens of microgrid projects in Alaska managed through different technical assistance programs and research demonstrations.

The effectiveness of these programs continues to improve as DOE incorporates important lessons learned on working with populations challenged by a shortage of technical knowledge and strained resources. One such lesson is initiating outreach before issuing a funding opportunity announcement, so interested communities can develop their applications in collaboration with a support system. This wraparound support is best delivered by a regional partner organization with established relationships, trusted connections to the area, and cultural fluency. The partner could be a university, technical college, nonprofit, or other community organization equipped to deliver flexible wraparound services and sustained support from the initial resource assessments to design and financing and through to maintenance and system longevity. The partnership model also facilitates knowledge sharing as communities with similar goals and conditions become models for replicable solutions.

The impact of the IIJA and the injection of funding for energy system improvements cannot be overstated. The ERA program has provided several pathways for soliciting creative proposals from communities with fewer than 10,000 residents, and the fixed-amount grants waive a recipient cost-share requirement to help ensure an equitable transition to a clean energy future. The proposals often set goals to decrease the frequency of power outages and lower rates, but they also benefit communities by strengthening resilience hubs and helping preserve traditional ways of life. With 93 projects selected in FY 2024, the program effects will be felt from coast to coast.

As OCED invests in rural communities to develop energy systems that meet their needs, OE studies whether the grid is ready to support new generation and develops solutions to ensure it can. The middle ground between these offices exists an opportunity to expand the impact of OE technical solutions. OE projects offer operational breakthroughs, and often involve a deployment partner, but the solutions sometimes lack uptake beyond the partner following the end of a project.

The research, development, and demonstration projects awarded by OE focus on microgrid-enabling technologies that can make these systems feasible for implementation, including renewable generation and storage systems; multimodal, small-scale high-voltage direct current (DC); advanced demand-side management strategies, and microgrid control systems. Feasibility analyses that evaluate technical feasibility and economic benefits of integrated microgrid systems have been the focus, but more testing and validation studies are needed to verify the real value of the integrated systems.

Remote, coastal, and Indigenous communities are key partners in DOE's microgrid strategy. Collaborations this year include everything from responsive peer-to-peer cohorts and technology innovation prizes to long-term engagement where researchers replicate a partner's energy system within a National Laboratory test bed to simulate a microgrid's resilience response in various extreme scenarios or a gradual transition from fossil fuel dependence. Projects are selected based on innovative applications of microgrid technology, potential for replicability, and commitment to disseminating the lessons learned.

Each community partnership, shaped by their unique priorities and conditions, is a step forward in microgrid planning, design, and operations. Communities connect through their DOE programs and through broader forums for knowledge sharing on workforce development, access to funding streams, renewable energy potential, and other common concerns. The movement toward siting advanced microgrids in remote and islanded communities is being led by municipalities, Tribes, community organizations, electric cooperatives, and other local decision-makers who look to DOE for critical technical support in their transition to reliable, affordable, and equitable energy.

**Exemplary outcomes from DOE microgrid work for rural, remote, and isolated communities in FY 2024 include the following:**

**Clean energy demonstrations aim to benefit rural areas.** The OCED ERA program elevates solutions that will improve the resilience, reliability, and affordability of energy systems for remote communities facing high stakes. The selected projects in 2024 often target key support infrastructure such as a solar plus storage microgrids project that will benefit up to 175 rural community health centers across eight states in the Southeast. A microgrid effort in Fort Lupton, Colorado, proposes to increase reliability of the municipal water treatment plant by replacing the aging diesel generator with an 850-killowatt floating solar photovoltaic (PV) array with a battery storage system.

The Choctaw Nation of Oklahoma is in the heart of the infamous Tornado Alley. In fact, the Choctaw's Poteau campus has averaged three power outages a year since 2018 with as many as five annual outages. In 2024, they were selected to negotiate an award with the ERA program to develop a microgrid that will provide backup power during outages for a health clinic, child development center, and food distribution center, allowing Tribal members to receive these vital services regardless of the weather. The microgrid is also projected to save the Tribe $140,000 annually in electricity costs.

**Researchers target barriers to microgrid standardization and scalability.** In May 2024, OE announced support for eight multiyear research, development, and demonstration projects that will all take place in underserved and/or Indigenous communities to show real-world load applications, strategies to address stability and control questions, and plug-and-play integration of varied clean energy resources. Several projects are developing controls for modular microgrid configurations that enhance operational flexibility and resilience, in some cases leveraging artificial intelligence (AI). Others target barriers to microgrid system deployment by easing issues around integration and operability between multiple vendor products and standardizing key software components for controllers and communication systems.

**Rural innovation stimulated with prizes.** Through workshops and community input, OCED's ERA program found that two of the biggest barriers to improving energy systems in rural or remote areas are developing the necessary partnerships and securing financing models that advance clean energy projects. In response, OCED released the Energizing Rural Communities Prize,[9] which provides technical assistance focused on building local capacity and accessing capital.

The 67 finalists that won $100,000 in the first phase of the prize are competing for additional awards of $200,000; winners were be announced in August 2024. Many projects focus on microgrids, such as a submission from Midi Enterprises, LLC, a Native-owned company that will work with Bloom Energy Corporation to explore obtaining grants, loans, and contracts to finance a solid oxide fuel cell microgrid. This collaboration will benefit from the U.S. Small Business Administration's Mentor-Protégé Program. On the frontier of the Wallowa Mountains in Oregon, a county of approximately 7,700 residents is planning two interconnected resilient microgrids that will harness renewable resources including solar, hydropower, and a biogas generation station fed by residuals from a local National Forest restoration project.

**Microgrids adopted in local energy action plans.** Upon the conclusion of the DOE Communities Local Energy Action Program (LEAP) pilot in 2022, DOE announced the second cohort in March 2024. Community resilience microgrids are a feature in 15 of the 30 projects in Cohort 2, from Oil City, Pennsylvania to Utah's coal country to Native villages in Alaska. This opportunity is specifically open to low-income, energy-burdened communities that are also disadvantaged and/or are experiencing direct economic impacts from a shift away from historical reliance on fossil fuels. Under Communities LEAP, DOE matches selected communities with technical assistance providers who assist them with bringing their clean energy planning and economic development vision to life.

The outcomes of the previous Communities LEAP cohort are bearing fruit. Techno-economic analysis and engineering support to the Iowa Tribe of Kansas and Nebraska was instrumental in the Tribe receiving an implementation grant to execute microgrid projects on the Reservation. A project in Louisiana helped inform policies in New Orleans, where legislation disallowed "intentional islands," effectively blocking microgrid development. Regulatory changes are currently underway to remedy this barrier, and National Laboratory experts supported the municipal government's objectives for improving energy resilience through building-level microgrids.

[9] "American Made: Energizing Rural Communities Prize," Herox, https://www.herox.com/rural-energy.

**Hawaii microgrid validates national standards and technology performance requirements.** Technical assistance bridges gaps between goals and implementation for communities in an energy transition, but they also offer opportunities to field test R&D sponsored by DOE. The In-Depth Energyshed Partnerships of C2C are selected competitively and provide years of assistance and direct funding to the community partner. One Energyshed microgrid project is in Molokai, Hawaii, where the project team will help validate a portfolio of renewable generation that supports the community's goal of 100% clean and resilient electricity. The energy system will be heavily permeated with DERs and inverter-based resources. DOE was, and continues to be, instrumental in the development and testing of standards related to inverter performance capabilities (i.e., IEEE Std 1547 and IEEE Std 2800), both at the DER and transmission levels. These capabilities and the experience with these performance capabilities are being evaluated, tested, and validated at the Molokai microgrid.

C2C partners are eligible to use next-generation modeling and analysis tools from the National Laboratories, such as the National Renewable Energy Laboratory's (NREL) Advanced Research on Integrated Energy Systems (ARIES) platform,[10] on which local leaders can see how a virtual model of their community interacts with actual and emulated clean energy infrastructure and devices, such as wind turbines, controllers, and electric charging stations. Decision-makers can visualize their systems with current—and future—microgrid deployments, helping de-risk future investments.

**Coastal communities assess their microgrid potential.** The DOE Office of Energy Efficiency and Renewable Energy's (EERE) Energy Transitions Initiative Partnership Project (ETIPP) program provides in-depth technical assistance and financial assistance awards to help U.S. coastal, remote, and island communities become more energy resilient. The majority of the 32 projects to date have involved techno-economic analysis of potential microgrid projects to provide power during outage events and enhance self-sufficiency. The microgrid projects address needs at the community-scale, resilience hubs, and specific critical infrastructure. As of the end of FY 2023, ETIPP supported the distribution of upwards of $1 million in grants to communities for implementation of their projects.

Assessing the resilience of an energy system requires all-hazards analysis and an understanding of infrastructure costs and tradeoffs in the context of local conditions, risks, and priorities, both in the present and through changing conditions in the future. The National Renewable Energy Laboratory has incorporated the principles of resilience science into the popular decision-making tool called the Renewable Energy Optimization platform (REopt®) to make these complex assessments more accessible. Through the ETIPP program, NREL engineers used REopt to evaluate solar photovoltaics and battery storage microgrids for community resilience in Nags Head, North Carolina—a town in the Outer Banks prone to extreme weather events that disrupt town operations and safety. NREL worked with Sandia National Laboratories to identify clusters of facilities that support a wide range of community needs, including grocery stores, fire

[10] https://www.nrel.gov/aries/

stations, hospitals, gas stations, and more. The team identified opportunities for cost-effective solar plus storage to provide 2-3 days of resilience via microgrids at several prioritized critical facilities and reported out to Nags Head leaders and community members about potential system sizing, engineering considerations, project economics, and emissions reduction potential.

Under another ETIPP project in rural Alaska, NREL has been working with the village council of Igiugig to integrate their energy system with a grid-forming battery energy storage system and a device that generates power from the river current. The ARIES platform, designed to validate future integrated energy systems, plays a critical role in running the simulations and experiments to support the field deployment of these assets.

**A 100% renewable energy microgrid proves to be resilient in remote desert community.** In the EERE Solar Energy Technologies Office's (SETO) Grid Resiliency with a 100% Renewable Microgrid project, the San Diego Gas & Electric Company and NREL are demonstrating that renewable, inverter-based battery energy storage can black start and island the Borrego Springs Microgrid, reducing the need for fossil fuel generators. The achievement of operating a microgrid with high intermittent solar energy generation is enabling decarbonized resilience in an isolated desert community of 2,800 that faces extreme weather events and higher risk of outages. Field implementation is de-risked through NREL's hardware-in-the-loop platform, which can simulate renewable microgrid scenarios in advance of field operations.

**Clean energy projects target transformation of mine lands.** The OCED Clean Energy Demonstration Program on Current and Former Mine Land was appropriated $500 million from the IIJA for demonstrations of the technical and economic feasibility of deploying clean energy projects on current (operating) and former (abandoned or inactive) mine land across the country. One of the five selected projects will demonstrate installation of a geothermal clean heat, microgrid, and battery energy storage system on an active mine in the rural counties of Graham and Greenlee, Arizona, two of the least-populated counties in the state.

**Tribes launch leading-edge microgrid demonstrations**. The OCED also awarded up to $26.07 million of Federal cost share to the Tanana Chiefs Conference that unites Nulato, Huslia, Minto, Kaltag, Grayling, Anvik, Shageluk, and Holy Cross to improve microgrids serving eight Alaskan communities inaccessible by road, by deploying extensive solar PV and battery storage systems. These systems can help mitigate power quality and reliability issues, as well as help reduce the high cost of relying on imported diesel fuel for generators. In North Dakota, the Standing Rock Sioux Tribe aims to transform the energy landscape by developing, prototyping, and demonstrating modular microgrid systems with standardized functionalities and advanced black-start control. These are only two examples of microgrid development and improvements on Native lands.

**Microgrids offer new options for islands.** The island of Islesboro, Maine, is served by one line that connects the island grid with the mainland. The community and utility requested technical assistance from grid researchers at NREL to support their goals for developing a microgrid, building out electric vehicle charging infrastructure, and integrating more distributed renewable energy generation. This will be a valuable demonstration of how islands may benefit from increasing their share of renewable energy and reducing their dependence on mainland support.

**Puerto Rico builds back better.** The Puerto Rico Community Development Block Grant Program for Disaster Recovery was announced in 2018 to ensure decent and affordable housing opportunities, provision of services, assistance to the most vulnerable populations, and the expansion and preservation of jobs. NREL and Sandia National Laboratories have been providing in-depth, responsive technical assistance to the Puerto Rico Department of Housing, which aims to deploy microgrids as a means to improve the reliability and resilience of Puerto Rico's energy system. As part of this support, the laboratories developed a framework to identify strategic microgrid locations across the territory and have supported the department in the technical review of the various projects to date, including the Centro Medico Microgrid, which is part of the Block Grant–Disaster Recovery Action Plan. This work was partly led by the Puerto Rico Grid Recovery and Modernization Team, which received the Secretary of Energy's 2024 Achievement Award.

The newest ETIPP Puerto Rico cohort is providing support to the communities of Vieques and Culebra in assessing how residential rooftop programs can complement planned microgrid deployments in the two remote island communities. Cooperativa Hidroelectrica de la Montaña, a hydroelectric cooperative in Puerto Rico, is working with DOE to determine specifications and designs for batteries and distribution, as well as pricing for implementing what would be the first intermunicipal microgrid created in Puerto Rico.

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

Investment in critical infrastructure minimizes the occurrence of energy system disruptions and their impacts on services, missions, and people. Hazards that cause disruptions include natural disasters that are increasing in severity and frequency, cyberattacks, and vulnerabilities in system stability. We can mitigate these risks through grid modernization solutions such as advanced microgrids. Microgrids sited strategically can assure continuity of services during a power outage at critical infrastructure such as ports, evacuation routes, water treatment plants, defense facilities, medical centers, and telecommunication nodes.

Many of the remote communities discussed in Section III are interested in developing off-grid, stand-alone microgrid systems, but this is not their only configuration. Multiple adjacent microgrids connected through communications or controls can share power across their boundaries during normal operating conditions and then isolate into islanded mode in a gray-sky or black-sky event. These networked microgrids offer flexibility and more opportunities to integrate DERs that support the bulk power system. A critical technology that enables microgrid networking and load sharing for optimized performance is the multiport medium-voltage DC converter, commonly called the MVDC converter. Projects focused on the development of MVDC converters are specifically prioritized under Topic Area 2 of the FOA-0002934 for supporting underserved and Indigenous community microgrids. Many DERs generate DC power, and many advanced loads such as electric vehicles consume power in DC form. Standard, modular MVDC design configurations and topologies can enable DC interconnections to solar PV, small wind, hydropower, marine hydrokinetic power, and energy storage located within a few tens of miles from communities in a cost-effective manner.

Researchers supported by DOE have made significant progress in detecting faults and automating an optimal response across a system of networked microgrids. Self-healing microgrids rely on automated controls that can isolate the affected area with greater precision and make rapid decisions to allocate resources to emergency facilities or account for social burden. These leading-edge solutions are validated in realistic simulations in the National Laboratories before field demonstrations with partner electric utilities and cooperatives.

**The activities highlighted below applied microgrid systems to enhance the resilience of critical infrastructure in FY 2024:**

**Self-healing microgrids reconfigure to maximize resilience.** A cross-lab team is embedding energy-justice-informed principles into networked microgrid operation in the project named DynaGrid. It specifically addresses the OE microgrid topic of "Microgrids as Building Blocks for Future Grids" by designing algorithms that can autonomously reconfigure microgrids into optimally resilient and reliable networks by sharing local energy resources. DynaGrid will enable electrification and DER integration while improving transmission and distribution-level reliability and resilience. For example, in one case study, the DynaGrid model is applied in a wildfire scenario in which power lines must be shut off while maintaining power to the maximum numbers of customers with special consideration for particularly vulnerable social groups. DynaGrid technology will be demonstrated in Detroit with the utility partner DTE Energy. DTE is leading a project under the IIJA's Grid Resilience and Innovation Partnerships program called Adaptive Networked Microgrids that will apply the DynaGrid reconfiguration algorithms to improve DTE system reliability and resilience.

At Sandia National Laboratories, researchers developed a library of algorithms[11] for self-healing microgrids that are coded into grid relays and based on all local measurements. By excluding the communication network from decision-making, this solution helps communities avoid the expense of advanced communication systems and is less vulnerable to digital failures or cyberattacks. The team used computer-aided-design software to model a small system of three interconnected microgrids and showed how, even without communications, their algorithms allowed the system to balance power production and consumption, isolate certain issues such

[11] "Creating the self-healing grid of the future," Sandia Labs News Releases, Sandia National Laboratories, January 23, 2024, https://newsreleases.sandia.gov/healing_grid.

as tree-downed lines or a damaged power plant, and work around the issue to restore power to high-priority facilities, such as hospitals and water treatment plants.

**AI-optimized controls boost resilience of community microgrids.** As control rooms face a deluge of data, AI offers an invaluable tool for quick, accurate decision-making in complex systems with many DERs. Multiple projects awarded by OE in 2024 build on this potential, including an AI-informed microgrid controller and an AI-enhanced strategy for standardized and scalable microgrids. NREL is innovating a solution that optimally partitions the distribution system into resilient community microgrids and dynamically reconfigures these community microgrids for improved resilience. The method uses machine learning and AI to optimally cluster DERs for a variety of operating scenarios. The technology has been fully validated at NREL facilities, and now it is being piloted in the headquarters of a local Colorado cooperative, Holy Cross Energy.

**Solar energy assists with grid reliability and restoration.** In 2022, SETO introduced the Renewables Advancing Community Energy Resilience (RACER) program to fund $33 million in projects that enable communities to use solar and solar-plus-storage to prevent power disruptions, and to rapidly restore electricity if it goes down. In one project, the University of Connecticut will field test an autonomous grid restoration solution on a microgrid in Hartford. The university's outage prediction tool can forecast how infrastructure may be damaged before the storm hits, allowing grid managers to position restoration crews in advance.

Solar-HERO, another project funded by SETO under the RACER program, is leveraging renewable energy and advanced data tools to stop power outages. All utility partners in the project are rural cooperatives that serve areas subject to extreme weather: forest fires and blizzards for United Power in Colorado, and extreme cold, snow, and wind for Connexus Energy in Minnesota. These co-ops serve communities that are economically vulnerable to outages, so they are all investing in solutions that use distributed energy and sensing for embedded resilience. Connexus Energy, the Midwest's largest cooperative and among the top 5% nationwide for reliability, was selected to host the field pilot and prove its reliability and resilience with the use of solar and storage. Industry partners are bringing their most advanced sensing technologies to the project, giving the researchers every recourse to detect a power outage. The enhanced grid visibility brings together technologies provided by Electrical Grid Monitoring, NEC Laboratories American, Survalent, Copper Labs, Camus Energy, and DataCapable. Meanwhile, Iowa State University will design an optimized black-start and service restoration scheme that maintains stability while shifting between microgrid configurations.

**Battery technology validated for microgrid services.** Argonne and Idaho National Laboratories have been selected by OCED to validate an innovative long-duration energy storage system developed by battery manufacturer CMBlu Energy.[12] The collaborative project aims to improve microgrids in cold climates and make fast charging of electric vehicles more affordable in underserved communities. The materials used in the construction of these batteries are nonmetallic and abundant, with a goal to build resilient domestic supply chains.

**Accessible tools illuminate microgrid design trade-offs.** Flaws in the early microgrid design process can create problems around maintenance, safety, stability, and central dispatch control. With the Microgrid Design Toolkit,[13] users can see many candidate microgrid designs to determine which options best meet user-defined objectives, such as cost, performance, and reliability. The toolkit was instrumental in Sandia National Laboratories' finding that microgrids are a win-win for resilience and clean energy in San Juan, Puerto Rico, where fuel costs are high, the grid is unreliable, and hurricanes and storms are frequent.[14] This analysis was supported by the DOE Grid Modernization Initiative.

Throughout the past year, NREL's REopt team has been hard at work expanding the capabilities and underlying code of this techno-economic decision support web platform, which is a crucial tool for optimizing energy systems in diverse settings, including buildings, campuses, and microgrids.[15] REopt's resilience model now considers how technology reliability—along with a site's critical load, dispatch strategy, and outage timing—impact the probability a site can sustain critical operations during a grid outage. It also incorporates all tax incentives, including those covered by the Inflation Reduction Act. REopt was recently used to evaluate the techno-economic potential of deploying DERs in a microgrid in Highland Park, Michigan, a low-income, energy-burdened community participating in C-LEAP.[16]

**Integrated design tool helps standardize and validate microgrid deployment.** Microgrid planning is a detailed and complex problem. The OE project Microgrid Research Application Verbal Normalization Scheme (MG-RAVENS) will provide an open-source model for reliable microgrid designs that will be available to academia and industry at no cost. MG-RAVENS combines microgrid planning capabilities across five domains:  Design, operations, dispatch, protection, and finance.

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[12] Briggs, Jonathan, "Argonne and Idaho National Laboratories partner with CMBlu Energy for innovative long-duration energy storage project," Argonne National Laboratory, December 4, 2023, https://www.anl.gov/article/argonne-and-idaho-national-laboratories-partner-with-cmblu-energy-for-innovative-longduration-energy.
[13] Microgrid Design Toolkit, Sandia National Laboratories, https://www.sandia.gov/csr/center-for-systems-reliability/tools/mdt/.
[14] Villa, Daniel et al., "Microgrid Tiered Circuits Effects for a Planned Housing Community in Puerto Rico," Sandia National Laboratories, October 2022, https://www.osti.gov/servlets/purl/2005690.
[15] Hausler, Courtney, "Leap Into New Capabilities: REopt Offers Enhanced Energy Solutions," NREL, February 24, 2024, https://www.nrel.gov/news/program/2024/reopt-web-tool-offers-enhanced-energy-solutions.html.
[16] Oddleifson, Tucker et al., "Prefeasibility Analysis of Behind-the-Meter Distributed Energy Resources in Highland Park, MI," NREL, March 2024, https://www.nrel.gov/docs/fy24osti/87988.pdf.

The research team set out to standardize application programming interfaces (APIs) and create workflows that integrate capabilities that are challenging to combine. The common exchange medium brings together design tools developed at the National Laboratories. By introducing this API standardization, creating new integrated workflows that will be demonstrated and validated on real use cases with utility partners Holy Cross Energy in Colorado and Delaware Electric Cooperative, and building extensive supporting tools and documentation, MG-RAVENS is enabling fair and equitable access to advanced modeling and analysis tools. These tools are critical to planning and evaluating microgrid installations, which are especially relevant to rural and Indigenous communities, whose access to reliable energy resources has been challenging historically.

The microgrid designs produced by the tool for the use cases will be validated through hardware-in-the-loop testing in the laboratory. The team developed a grid-forming DER model for the microgrid simulations that complies with the specifications developed under the DOE SETO Universal Interoperability for Grid-Forming Inverters (UNIFI) Consortium[17] that will be made publicly available.

**DER modeling to support industry with system simulation and in-loop testing.** A new generation of DERs is emerging on power systems, and models of these devices will help industry test and simulate microgrid deployment. The DOE labs have united behind this effort, with the primary development happening under the UNIFI Consortium. The UNIFI Consortium has published grid-forming model specifications that labs and industry reference in their own experiments. As mentioned above, these have been applied in the MG-RAVENS project, among others. Other DER model development has come from the Resilient Operation of Networked Microgrids project, which configured a grid-forming DER model for hardware-in-the-loop testing and networked microgrid validation.

# V. Research Needs and Next Steps

Across DOE's technical assistance programs there is a growing demand for information and access to microgrids and technical support for microgrid controls. Microgrid controllers operate the system's components (e.g., energy storage, renewable energy generation, and demand-management tools), and grid-forming controls are key for black-start and recovery capabilities. The National Laboratories have made significant progress in self-healing microgrids, but there is still opportunity to improve autonomous controls and derive maximum resilience value from networked microgrids. Mobile microgrids may offer value in scenarios where temporary distribution resilience is needed, although more modeling and simulation of mobile microgrid use cases are needed to build this area of knowledge.

[17] "UNIFI Consortium," Solar Energy Technologies Office, https://www.energy.gov/eere/solar/unifi-consortium.

While more commercial microgrid technology comes to market, deployment remains hindered by several factors. Some challenges come from coordination among entities with different jurisdictions and objectives, traditional ownership models, and a regulatory environment that equates a microgrid with an electric utility. Deployment times and financing opportunities will also be improved through standardization of key microgrid components, an area of DOE investment that is starting to produce a positive impact thanks to collaboration with the Institute of Electrical and Electronics Engineers (IEEE).

Decision-makers weighing microgrids as a potential option for meeting their energy goals would also benefit from resources tailored to the interests of microgrid operators and planners. This could include a handbook for states, and a roadmap for a microgrid rollout that features the many planning and analysis tools DOE has already developed with stakeholder input. Disadvantaged communities, often in remote or under-resourced areas, face additional challenges in accessing microgrid technology and Federal support for critical infrastructure resilience. DOE needs to shape technical assistance offerings around effective outreach, capacity building, and technical support for the full life cycle of microgrid development in underserved communities, and there are initiatives on the horizon to address this insufficiency while advancing replicable solutions.

**This section highlights several existing gaps and research needs:**

**Reduce barriers to microgrid interconnection.** Microgrid interconnection is integral to the vision of microgrids as building blocks, but the most suitable configurations and controls to enable grid and networked connections vary by site and require coordination among multiple entities that can have conflicting objectives. DOE can support this area by identifying best-fit modes of interconnection and deploying easy-to-use controls and system configurations that apply to common interconnection scenarios. Regulatory challenges also present barriers to networked microgrids. Microgrids are often mischaracterized and regulated as electric utilities. This can make microgrids—and especially resilient networked microgrids—financially unsustainable or put them in competition with the incumbent utility. Since microgrids often serve a smaller, voluntary customer base, microgrid-specific regulation needs to be scoped differently than utility regulation to deliver on the promise of resilience benefits. Communities, cooperatives, utilities, and state/local energy system planners need regulations that match the scale of a microgrid of 20 to 100 megawatts.

**Use performance studies to de-risk technology before deployment.** Performance studies are a useful tool for energy system planners and investors seeking to seamlessly integrate distributed energy resources onto the grid while balancing that generation with traditional utility generation. Researchers have developed free and accessible tools for techno-economic analysis such as the popular REopt platform. Analysts in this area are developing frameworks to answer the difficult questions such as how system controls may need to adapt to maintain resilience under changing conditions, or how to calculate cost-benefits not just for customers on average, but also the distribution of benefits for customers with different characteristics, such as vulnerable populations. The National Laboratories have also developed advanced platforms for co-simulating interdependent infrastructure in software and hardware-in-the-loop lab setups. Inviting more utilities and cooperatives to use these platforms to validate novel technologies prior to using them with customers is an effective way to increase confidence in high-renewable energy systems and understand their value before transferring to the real-world operating environment. Many utilities have already used these resources as a bridge to deployment and while the results are customized, all lessons learned support a growing microgrid community of practice.

**Improve regulation and standardization to streamline technical compatibility.** DOE supports extensive work in microgrid standardization, such as IEEE 2030.7-2017 and IEEE 2020.8-2018 for the specification and testing of microgrid controllers, and more is needed.[18] Especially given DOE's considerable effort in mapping out standardization and regulation needs, future programs should execute in these directions by mobilizing and supporting industry-academic-government alliances. Swift progress in this area will reduce deployment times and assist in financing.

**Develop microgrid roadmaps and handbooks for deployment and operations.** The DOE Microgrid Program Strategy provides a roadmap for research, but more relevant to microgrid operators and planners would be a roadmap for deployment. Such a resource would cover everything from siting and permitting to controls and security configurations. It would be a comprehensive guide to navigating microgrid rollout from start to finish. A roadmap would also orient users to the wealth of DOE design tools for microgrids, which are well-validated and accessible, but users may not know when and how to engage these tools.

**Provide resources and targeted assistance for states.** Like the roadmap suggestion above, and possibly contained within it, clear guidance could help states understand Federal rules and policies related to microgrids. Some states have drafted their own microgrid strategies, whereas others have ambiguous or impeding policies. In either case, states will benefit from direct assistance for designing regulations and incentivizing microgrid development.

**Support initiatives for microgrid deployments in underserved and Indigenous communities.** As discussed earlier in this report, rural and electrically islanded communities have much to gain from cost-effective solutions to energy security through microgrids powered by local generation of renewable energy. Numerous projects have been developed, but most are single demonstrations with limited direct replicability or monitoring and may not have the desired cost-stabilization effect due to insufficient resourcing for long-term maintenance and operation. Through FOA-0002934, OE encouraged regional pilot initiatives that enhance human and technical capacity together, and OE is developing a Community Microgrid Assistance Partnership that will commence supporting underserved and Indigenous community partners in

[18] "Standardization and Standards," OE, Energy.gov, https://www.energy.gov/oe/standardization-and-standards.

early FY 2025. The partnership is built on a community of practice that will improve the participants' ability to apply for and effectively implement development projects, improve the operation of existing microgrid systems, and communicate effective solutions to others with similar conditions and goals.

**Power up microgrids for industrial and commercial sectors.** Microgrids are emerging as a viable option for ship ports and airports, with recent projects underway in Port of Oakland, Port of Long Beach, and John F. Kennedy International Airport, among others. These projects follow from investments in on-site generation and storage, and they are enticing given their potential to enhance resilience during bulk system outages and reduce energy costs and emissions. Funding for ports to scope microgrid investments, as well as for knowledge transfer from early projects, is needed to continue progress in this exciting application.

**Support grid controls for seamless and diverse operations.** Microgrid controls are the most frequently requested support in DOE technical assistance projects. Future controls should focus on automating actions such as black-start, system reconfiguration, and multi-DER operations. They should also support networking with other microgrids and the bulk grid. This involves islanding, communications, protection schemes, and interfacing with new hardware, such as solid-state transformers. Special controls development will be needed for diverse end uses, such as temporary and mobile microgrids, which assist in distribution system resilience. Self-healing and fractal grids are functional control solutions that can dynamically enhance resilience, as demonstrated in the DOE DynaGrid project. Further lab-to-market work is recommended in this area, which includes the proven concept of autonomous energy systems.[19]

**Provide decision support for increasing resilience via mobile microgrids.** Portable microgrids can increase disadvantaged community resilience in rural and remote areas and are flexible to capture the locational benefits of energy storage. Dispersed disadvantaged community pockets within regions lack the resources to establish their own renewable energy microgrids. By deploying mobile microgrids from a nearby local central microgrid during grid outages, these communities and Tribes could gain resilience and reduce dependence on diesel generators. When not deployed during outage, the mobile microgrid can be used as a resource to the central microgrid, increasing the use cases and value of the asset. Modeling and simulation of mobile microgrid use case scenarios will help quantify the value proposition and support replication.

**Implement advanced forecasting and dispatch technologies.** Among the systems upgrades recommended in the Puerto Rico Grid Resilience and Transitions to 100% Renewable Energy Study,[20] researchers stated that advanced forecasting and dispatch technologies will need to be

[19] "Autonomous Energy Systems," NREL, https://www.nrel.gov/grid/autonomous-energy.html.
[20] Baggu, Murali et al., *Puerto Rico Grid Resilience and Transitions to 100% Renewable Energy Study (PR100): Final Report* (Golden, CO: NREL, 2024), https://doi.org/10.2172/2335361.

capable of operating the energy system in the long term. Implementing black-start and recovery capabilities via grid-forming controls can support full-scale combined use of energy storage, renewables, and microgrids to black start the entire Puerto Rico energy system. The analysis for Puerto Rico focused on rooftop PV and storage deployment for individual buildings, but some of the new capacity to be added in the years ahead will likely be connected as microgrids rather than all on individual roofs. This interconnection solution can address the challenge of insufficient rooftop space and may make economic sense even when considering the costs of requiring additional infrastructure.

**Study Brownfield siting options for microgrids to support critical infrastructure.** Redeveloping Brownfields for clean energy projects offers myriad economic and environmental benefits, including local job generation, new revenue streams for municipalities, preservation of natural habitats, and leveraging of existing infrastructure. For example, an ongoing NREL study on the potential for redeveloping brownfields and reservoirs in Puerto Rico for solar PV and floating PV has found many of these sites are near critical infrastructure and last-mile communities.[21] Analysis so far has focused on evaluating the techno-economic potential of utility-scale solar development on these sites, but given their size and location they offer a key opportunity for microgrid deployment that can support this critical infrastructure while addressing long-standing environmental and social neglect in these communities. Further, this analysis would provide an opportunity to identify socially acceptable clean energy siting locations and address land use concerns.

**Conduct supply chain and infrastructure analysis.** The anticipated ramp-up of grid reconstruction activities in Puerto Rico, coupled with significant deployments of rooftop PV and other behind-the-meter solutions, such as microgrids, will depend on a complex and extensive supply chain. Analysis is needed to understand the myriad components that will need to be outsourced, as well as their lead times, risks, and possible bottlenecks.

**Community-centered resilience through microgrids.** Traditional ownership models can pose a barrier to microgrid adoption. By analyzing communal ownership models, researchers can determine the effectiveness of local governance structures in managing and maintaining microgrid systems in the face of natural disasters and economic challenges. Key questions this research would seek to answer include: How does ownership affect the operational efficiency, cost-effectiveness, and community engagement in the maintenance and expansion of microgrids? What are the most effective strategies for communities to achieve energy independence through microgrids? How do microgrids affect local economies, especially in terms of job creation, energy costs, and social cohesion?

[21] Last-miles communities are a census block that (a) has a high percentage of very low-income households, and (b) experiences frequent and prolonged power outages.

# VI. Conclusion

As interest in microgrids is growing for resilient, remote, and critical applications, enough real-world examples and industry buy-in now exist that microgrids are synonymous with stable, local power, and this association has fomented broad attention to microgrids. Such interest is evident in the variety of projects communities request, the energy solutions Tribes select, and the energy technologies companies offer. The overall vision is a secure, resilient, and reliable grid, with adaptive, modular, distributed microgrid architectures. Much of this progress can be traced to Federal research and development (R&D) support for early-stage innovation and industry-research-community collaborations fostered by DOE.

But as the concept becomes more prevalent, it is important that microgrids are supported by high-fidelity testing, modern regulations, and automated operations. These ingredients are especially needed in the under-resourced and energy-burdened areas where microgrids most alleviate costs and outages. Presently, microgrids are at a juncture where, with the right R&D, present momentum can manifest in reliable and clean energy systems that meet users' diverse goals. That success is contingent on the readiness and reliability of technologies and regulations.

Many microgrid projects launched in 2024 provide technical and financial assistance for remote and rural sites—including Tribal and islanded areas—and critical applications, including economically stressed communities facing climate catastrophes. A large proportion of these programs include field demonstrations, which are a double win because they result in direct microgrid deployment while also validating technology and advancing the market. Interest in these programs is high, with microgrids standing out as a popular topic among local stakeholders, who view Federal grants and programs as a pathway for realizing their energy goals.

An important piece of maintaining momentum will be to address the barriers to microgrids' expansion. The most broadly felt barriers include power grid rules and regulations, which are geographically inconsistent and typically unfavorable to microgrid interconnection and financing. Other barriers that deserve attention include device availability and supply chain vulnerability, and, of course, technological readiness.

The national lab complex has an extensive and rich variety of technology-focused projects to help microgrids operate autonomously, safely, and in a standardized way. These efforts have resulted in common models of microgrid devices, popular microgrid design and planning tools, industry-collaborative controls and hardware development, and new technological standards. Progress in AI, predictive forecasting, distributed algorithms, and other directions should remain the focus of lab R&D, to ensure microgrids are accessible and technologically mature for easy and robust deployment.

Among the microgrid projects underway in 2024, several have expanded the scope of microgrid deployments to sites such as abandoned mines. This shows the diverse draws to microgrid applications and has opened the door to other sites, including ports and brownfields, and emerging technologies, such as floating solar and mobile microgrids. Such projects will de-risk microgrids at sites where microgrids might not otherwise be considered, and where other energy options are not viable.

At this important juncture in energy systems transformation, microgrids solve many pressing energy system challenges from decarbonization to resilience and energy security for hard-to-reach corners of the county. There are more collaboration opportunities than ever to advance a microgrid strategy with national impact, and Federal support has led to valuable tools and success stories, but work is far from over. Next steps will need to establish the regulations, technologies, and resources for microgrids to thrive where they have the greatest impact: critical infrastructure resilience for all.