SOAR

STATE-OF-THE-ART REPORT (SOAR)
APRIL 2023

HDIAC-BCO-2022-258

RESILIENCE BY DESIGN: MICROGRID SOLUTIONS FOR INSTALLATION ENERGY

By Joel Hewett
Contract Number: FA8075-21-D-0001
Published By: HDIAC

This Page Intentionally Left Blank

SOAR

STATE-OF-THE-ART REPORT (SOAR)
APRIL 2023

RESILIENCE BY DESIGN: MICROGRID SOLUTIONS FOR INSTALLATION ENERGY

JOEL HEWETT

ABOUT HDIAC

The Homeland Defense & Security Information Analysis Center (HDIAC) is a U.S. Department of Defense (DoD) IAC sponsored by the Defense Technical Information Center (DTIC). HDIAC is operated by SURVICE Engineering Company under contract FA8075-21-D-0001 and is one of the three next-generation IACs transforming the DoD IAC program: HDIAC, Defense Systems Information Analysis Center (DSIAC), and Cybersecurity and Information Systems Information Analysis Center (CSIAC).

HDIAC serves as the U.S. national clearinghouse for worldwide scientific and technical information in eight technical focus areas: alternative energy; biometrics; chemical, biological, radiological, and nuclear (CBRN) defense; critical infrastructure protection; cultural studies; homeland defense and security; medical; and weapons of mass destruction. As such, HDIAC collects, analyzes, synthesizes, and disseminates related technical information and data for each of these focus areas. These efforts facilitate a collaboration between scientists and engineers in the homeland defense and security information community while promoting improved productivity by fully leveraging this same community's respective knowledge base. HDIAC also uses information obtained to generate scientific and technical products, including databases, technology assessments, training materials, and various technical reports.

State-of-the-art reports (SOARs)—one of HDIAC's information products—provide in-depth analysis of current technologies, evaluate and synthesize the latest technical information available, and provide a comprehensive assessment of technologies related to HDIAC's technical focus areas. Specific topic areas are established from collaboration with the greater homeland defense and security information community and vetted with DTIC to ensure the value-added contributions to Warfighter needs.

HDIAC's mailing address:

HDIAC
4695 Millennium Drive
Belcamp, MD 21017-1505
Telephone: (443) 360-4600

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE April 2023	**2. REPORT TYPE** State-of-the-Art Report	**3. DATES COVERED**

4. TITLE AND SUBTITLE Resilience by Design: Microgrid Solutions for Installation Energy	**5a. CONTRACT NUMBER** FA8075-21-D-0001
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Joel Hewett	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Homeland Defense & Security Information Analysis Center (HDIAC) SURVICE Engineering Company 4695 Millennium Drive Belcamp, MD 21017-1505	**8. PERFORMING ORGANIZATION REPORT NUMBER** HDIAC-BCO-2022-258
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Defense Technical Information Center (DTIC) 8725 John J. Kingman Road Fort Belvoir, VA 22060	**10. SPONSOR/MONITOR'S ACRONYM(S)** DTIC
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES
Energy and Power Technologies: Energy Storage, Power Distribution and Control, Power Generation/Energy Conversion; Alternative Energy; Critical Infrastructure Protection

14. ABSTRACT
Microgrids are an increasingly promising solution for providing the U.S. Department of Defense (DoD) with energy resilience, or the ability to provide uninterrupted electricity supply to—and recover from disruptions in power at—fixed military installations. This state-of-the-art report combines an assessment of the voluminous research literature on grid-tied microgrids with critical insights gathered from engineers, scientists, government research and development program officials, and several energy and utility managers currently overseeing microgrid operations on DoD installations in the homeland. This report surveys the utility grid's vulnerabilities; the benefits of a microgrid to the DoD energy assurance mission; advancements in microgrid design, planning, and simulation tools; theories and emerging systems for microgrid control; and several critical organizational considerations that can have an outsized effect on how a cutting-edge DoD microgrid is designed, funded, operated, and sustained over the long run.

15. SUBJECT TERMS
microgrid, energy assurance, energy resilience, power grid

16. SECURITY CLASSIFICATION OF: U			**17. LIMITATION OF ABSTRACT** UU	**18. NUMBER OF PAGES** 92	**19a. NAME OF RESPONSIBLE PERSON** Vincent "Ted" Welsh
a. REPORT UNCLASSIFIED	**b. ABSTRACT** UNCLASSIFIED	**c. THIS PAGE** UNCLASSIFIED			**19b. TELEPHONE NUMBER** *(include area code)* 443-360-4600

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

ON THE COVER:
(Source: Shutterstock)

THE AUTHOR

JOEL HEWETT

Joel Hewett is an energy policy and national defense researcher, writer, and analyst for KeyLogic Associates, where he applies more than 15 years of experience in assessing the utility of advancements in science and technology for furthering national aims. In his role, he supports the Homeland Defense & Security Information Analysis Center (HDIAC), a component of the U.S. Department of Defense, with a focus on energy systems and critical infrastructure protection. He holds an M.S. from the Georgia Institute of Technology in the history and sociology of technology and science, where he was the inaugural Melvin Kranzberg graduate fellow; he also holds an A.B. in literature from Davidson College, where he was a John Montgomery Belk scholar.

ABSTRACT

Microgrids are an increasingly promising solution for providing the U.S. Department of Defense (DoD) with *energy resilience*, or the ability to provide uninterrupted electricity supply to—and recover from disruptions in power at—fixed military installations. This state-of-the-art report combines an assessment of the voluminous research literature on grid-tied microgrids with critical insights gathered from engineers, scientists, government research and development program officials, and several energy and utility managers currently overseeing microgrid operations on DoD installations in the homeland. This report surveys the utility grid's vulnerabilities; the benefits of a microgrid to the DoD energy assurance mission; advancements in microgrid design, planning, and simulation tools; theories and emerging systems for microgrid control; and several critical organizational considerations that can have an outsized effect on how a cutting-edge DoD microgrid is designed, funded, operated, and sustained over the long run.

ACKNOWLEDGMENTS

The author would like to thank the following individuals for their contributions to the report:

- Dr. Kate Anderson—Power Systems Engineering Center, National Renewable Energy Laboratory (NREL)
- Peter Asmus—Senior Advisor, Microgrid Strategy
- Jackie Baum—Technical Leader, Electric Power Research Institute
- Thomas Bozada—Universal Battlefield Power Portfolio Manager, U.S. Army Corps of Engineers, Engineer Research and Development Center
- Joseph Cole—Senior Operations Manager/Program Manager, KeyLogic Associates
- Jerry Davis—Laboratory Program Manager, Advanced Research on Integrated Energy Systems, Energy Systems Integration Facility, NREL
- Dr. Regis P. Dowd, Jr.—Power and Systems Engineer, Emerging Technologies Innovation Center, MITRE
- Daniel Herring—Associate Staff, Massachusetts Institute of Technology (MIT) Lincoln Laboratory
- Steve Hoffman—President and Chief Executive Officer, Hoffman Power Consulting
- David J. Irwin—Program Director, Project Development, Office of Energy Initiatives, Office of the Deputy Assistant Secretary of the Army (Energy & Sustainability)
- Dr. Nathan Johnson—Associate Professor, The Polytechnic School, and Director, Laboratory for Energy and Power Solutions, Arizona State University
- Dr. Nicholas Judson—Associate Leader, Energy Systems Group, MIT Lincoln Laboratory
- Dr. Amin Khodaei—Professor, Department of Electrical and Computer Engineering, University of Denver
- Dr. Jan Kleissl—Professor, Department of Mechanical and Aerospace Engineering, and Director, Center for Energy Research, University of California, San Diego
- Michael Lambert—Emergency Preparedness/Homeland Security, Houston-Galveston Area Council of Governments
- Erik Limpaecher—Senior Technical Staff, Energy Systems Group, MIT Lincoln Laboratory
- Dr. Chen-Ching Liu—American Electric Power Professor, and Director, Power and Energy Center, Virginia Tech
- Dr. Jeffrey Marqusee—Senior Research Advisor, NREL
- Mark Maxwell—Executive Vice President, Defense Programs, Aura Technologies
- Gregory Nichols—Corporate Quality Manager/Public Health Expert, KeyLogic Associates

ACKNOWLEDGMENTS, *continued*

- Ben Ollis—Research and Development Staff, Grid Components and Controls Group, Oak Ridge National Laboratory
- Audrey D. Oxendine—Chief, Energy and Utilities Branch, Operations and Maintenance Division, U.S. Army Garrison Fort Bragg, NC
- Dr. Annabelle Pratt—Chief of Staff, Energy Systems Integration, NREL
- Jarrod Ross—Resource Efficiency Manager, U.S. Army Garrison Fort Hunter Liggett, CA
- Dr. Kevin Schneider—Laboratory Fellow/ Subsector Manager, Pacific Northwest National Laboratory
- Dr. Michael Stadler—Cofounder and Chief Technology Officer, XENDEE Corporation
- Dr. Jason Stamp—Special Initiatives, Sandia National Laboratories
- Tim Tetreault—Program Manager, Energy and Water, Department of Defense Strategic Environmental Research and Development Program and Environmental Security Technology Certification Program
- Dan Ton—Program Manager, Smart Grid Research and Development, Department of Energy Office of Electricity
- Mick Wasco—Utilities and Energy Management Director, S-4 Public Works Division, Marine Corps Air Station Miramar, CA
- Dr. Annie Weathers—Technical Staff, MIT Lincoln Laboratory
- Ryan Wiechens—Technical Staff, MIT Lincoln Laboratory
- Dr. Mark C. Williams—Principal Engineer, KeyLogic Systems

EXECUTIVE SUMMARY

The idea of connecting local electrical loads to a series of distributed energy resources (DERs) to form a microgrid "islandable" from the utility has a long history. It is only in the past few years, however, that three key trends have coincided to make conditions immensely favorable for the expanded deployment of grid-tied microgrids on U.S. Department of Defense (DoD) installations:

1. The levelized installed costs of new solar photovoltaic modules and large-scale lithium-ion battery energy storage systems have plummeted, with the former sagging 15% year over year between 2010 and 2020.
2. The array of microgrid-focused equipment manufacturers and energy systems integrators has expanded dramatically, all while vendors have also delivered critical improvements in the novel "power electronics" devices needed for the widespread adoption of renewable generation.
3. DoD and U.S. Department of Energy research and development (R&D) efforts have pivoted away from the pursuit of demonstration microgrid pilot projects and toward addressing the challenges of microgrid deployment as ones of systems integration.

As a result, microgrids are an increasingly promising solution for the DoD to achieve *energy resilience* on its fixed bases. Equipped with ample DERs and an advanced microgrid control system, an installation can remain powered during a contingency event and recover quickly if the utility grid goes down for an extended period. Moreover, advanced microgrid systems can provide an installation with a host of ancillary benefits, including the optimization of energy cost savings, electricity consumption reductions, price arbitrage opportunities, emissions reductions, and the capacity to assist local utilities in keeping the lights on across the host communities that surround many DoD installations.

For its part, the U.S. Army has certainly taken notice. In early 2022, the service announced its intent to install a microgrid on every Army installation by 2035—a number no less than 130, well above the approximately 15+ grid-tied systems currently operational across the DoD. With this impending expansion in mind, this report assesses the state of the art in U.S.-based microgrid R&D projects, technologies, in situ deployments, and management practices to (1) identify those most relevant for DoD use and to (2) highlight salient points that may pose barriers to—or present opportunities for—the continued DoD adoption of installation microgrids. This report combines a thorough assessment of the voluminous literature on microgrid technology and practice with critical insights gathered from engineers, scientists, industry consultants, government R&D program officials, and DoD energy and utility managers who currently oversee microgrid operations on bases in the homeland.

At a section-by-section level, this report surveys the vulnerabilities of the national power grid and explores the benefits that a microgrid can bring to the DoD energy assurance mission and other defense objectives. Recent technical advancements in microgrid design, forecasting, modeling, and simulation tools are then detailed, before the functionality of existing commercial microgrid controllers—and various rival theories

EXECUTIVE SUMMARY, *continued*

of control—are assessed for DoD use in the near term. Finally, the report discusses several critical organizational and structural considerations that can have an outsized effect on a microgrid's design, operations, and long-term sustainment.

To ground its discussion of cutting-edge R&D in real-world DoD scenarios and mission requirements, woven throughout the text of this report is the story of how the microgrid at Marine Corps Air Station Miramar was conceived, funded, developed, tested, and commissioned to ultimately become one of the most energy-forward defense installations in the nation. To make this state-of-the-art report most accessible to the reader, a set of 17 findings is presented directly following the introduction. When read together, these findings provide the reader with a far-reaching understanding of how the DoD is likely to expand its use of novel microgrid solutions to deliver energy resilience to its constellation of installations in the homeland and across the globe.

This Page Intentionally Left Blank

CONTENTS

CONTENTS, *continued*

FIGURES

CONTENTS, *continued*

TABLES

This Page Intentionally Left Blank

SECTION 01

INTRODUCTION: "MCAS MIRAMAR TO THE RESCUE"

In the late summer of 2022, the usually temperate weather around San Diego, CA, was running hot. For several days in a row, above-average temperatures had increased electricity demand, as millions of air conditioning units strained to keep cool. Persistently high humidity levels did not help much, either. By Wednesday, August 17, high power draws and the additional off-lining of some generation sources threatened to overwhelm the resources of the local utility, San Diego Gas & Electric (SDG&E). Looking to avoid any loss of service to its customers—and prevent a possible power emergency—SDG&E picked up the phone and called one of the area's most reliable and resilient sources of electrical power: the microgrid at Marine Corps Air Station (MCAS) Miramar, located just 14 miles north of downtown San Diego [1, 2].

Over at MCAS Miramar, the installation's utilities and energy management staff were amply prepared for just such a contingency. They fired up the microgrid's backup power plant, which is rated to produce 7 megawatts (MW) of electricity: 3 MW from two natural gas generators and an additional 4 MW from twin diesel engines [3]. (Although they are representative of more traditional energy sources, both systems are carefully engineered to meet precise emission standards—with the knock-on benefit of also making them highly efficient [4, 5].) From the base's Energy and Water Operations Center (EWOC), staff technicians and managers monitored the microgrid's power-generation sources, loads, health of its distribution lines, and connection to the larger grid. With the backup power plant spun up, they then directed the microgrid controller (a combination of software, communication networks, servers, and smart actuators) to reduce the amount of power drawn from SDG&E, increasing the utility's overall electricity supply [2].

In the end, the power plant at Miramar ran for 5 hours that day, boosting local generation sources enough to help prevent approximately 3,000 nearby homes from going dark [1]. The power plant finally kicked off at 9:00 p.m., about 90 minutes after sunset [2]. A few weeks later, Miramar reprised its assistance to the utility multiple times, at one point reducing its draw from SDG&E 7 out of 8 days in a row [2, 6]. One online news source focused on the microgrid industry aptly remarked, "MCAS Miramar to the rescue" [7].

Across the approximately 15+ U.S. Department of Defense (DoD) installation-grade microgrids currently in operation in the homeland [8], the system at MCAS Miramar is one of its largest, most technically complex, and complete microgrids built and operated to date [8–10]. The Office of the Secretary of the Navy has repeatedly recognized it through its Energy Excellence Awards Program, and the Miramar project has stood for years as one of the "most-watched" microgrids within the DoD [9, 10]. In addition to its backup power plant, the microgrid boasts 3.2 MW of landfill gas power generated by methane captured from the nearby West Miramar Landfill, 1.3 MW from distributed solar photovoltaic (PV) panels (see Figure 1-1), and 2 MW of storage provided by an advanced "EnergyPod" zinc bromide flow battery manufactured by Primus Power [11]. The United States Marine Corps (USMC) rightfully regards MCAS Miramar as "one of the most energy-forward defense installations in the nation" [12].

Figure 1-1. A 250-kW Section of Solar PV Modules Serves Double Duty at MCAS Miramar, Contributing to the Microgrid's 1.3 MW of Solar PV Capacity and Providing Sun Protection for Parked Cars *(Source: NREL [13])*.

The engineering effort at Miramar has benefitted from close collaboration with key technical leaders from industry, cooperation from the public utility commission, funding from multiple sources, and a fruitful partnership with the National Renewable Energy Laboratory (NREL). Even so, developing the microgrid was no swift or easy process. USMC leaders began discussing a microgrid effort in 2007, and support from NREL to model the Miramar system's parameters first arrived in 2011. Initial funding from the DoD Energy Conservation Investment Program (ECIP) was approved in 2012, and a follow-on grant from the California Energy Commission funded the addition of energy storage and a base-wide heating, ventilation, and air conditioning (HVAC)-based demand response program, allowing for up to 1.6 MW of controllable building load [3]. In 2016, Black & Veatch and Schneider Electric were selected to design and build the microgrid at Miramar, which was commissioned in full 4 years later [3].

Over 2020–2021, a series of "full-islanding" and "black start" tests proved that when all on-site generation sources are available, the microgrid can sustain mission-critical loads at MCAS Miramar without external fuel resupply for days or potentially even weeks [2, 3]. A successful Energy Resilience Readiness Exercise (ERRE) further verified the microgrid's ability to function separately from the utility grid under real-world conditions and during high-tempo base operations [14]. With the microgrid in place, MCAS Miramar more than meets what both statute (10 U.S.C. § 101(e)(6)) and the DoD define in broad language as *energy resilience*:

> *"…the ability to avoid, prepare for, minimize, adapt to, and recover from anticipated and unanticipated energy disruptions in order to ensure energy availability and reliability sufficient to provide for mission assurance and readiness, including mission essential operations related to readiness, and to execute or rapidly reestablish mission essential requirements" [15].*

Notwithstanding the microgrid's sophisticated design and its advanced generation sources, the fact that SDG&E could even call upon the resources of its nearby military base stands as a particularly notable innovation all its own—albeit one more organizational than technical in nature. Central to the microgrid's ability to aid the utility was a novel agreement that MCAS Miramar, SDG&E, the California Public Utility Commission, and Naval Facilities Engineering Systems Command (NAVFAC) Southwest had signed just months earlier. The Miramar Summer Generation Availability Incentive set a specific electricity export tariff for the base and made it significantly easier for SDG&E to call upon its resources to preclude a power emergency [2]. "This is a first-of-a-kind [event]," said public works officer Cdr. John Angle. "[It is] one of the most innovative things we have done" [1].

For its part, MCAS Miramar earned energy credits (or direct revenue) for its help, and its staff gained valuable experience liaising with the utility. It also earned a visit in September 2022 from Secretary of Defense Lloyd J. Austin III, who toured the facility and received a briefing from Mick Wasco, the utilities and energy director at Miramar who has doggedly championed the project to fruition over many years of effort [6]. Moreover, the microgrid at Miramar delivered benefits that, while not explicit in the definition of energy resilience, are increasingly part of the vision for the future of DoD installation microgrids [8]. Its renewable power helps reduce greenhouse gas (GHG) emissions [16]; its novel arrangement with the utility can earn additional revenue [17]; and its power assistance builds shared resilience among local populations, especially within those host communities adjacent to a military base [18].

1.1 EVERY BASE A MICROGRID

As the Miramar example makes clear, the ability of a microgrid to island, or power its critical loads when independent of the main utility grid (or "macrogrid"), is both its defining characteristic and the primary source of its energy resilience benefits. Even though most microgrids remain grid-connected well over 99% of the time [19], the ability to island is at the core of what defines a microgrid, as the U.S. Department of Energy (DOE) notes [20].

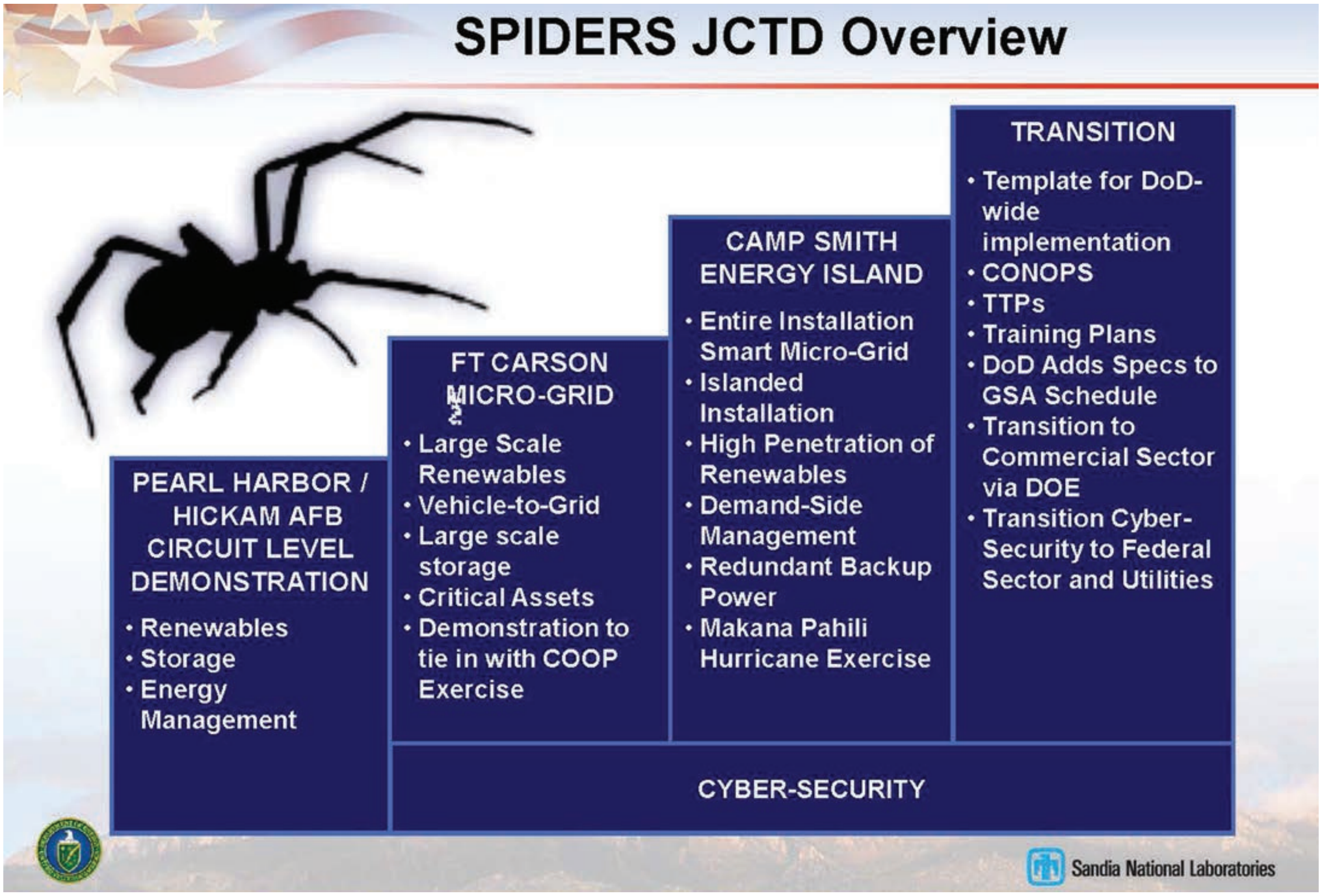
While the Secretary of Defense's tour of the Miramar system was the result of a decade-plus of dedicated work, the timing of its commissioning in 2020 is also reflective of several currents that have made microgrids increasingly attractive to the DoD over the past few years. As Section 3 explores in depth, the national grid system in the United States has grown increasingly fragile and prone to outages, besieged by extreme temperatures and destructive weather events; physical and cyberattacks from domestic terrorists and other adversaries; and even the failure of mundane pieces of electrical equipment. In 2018, a simple metal C-hook—an unremarkable piece of equipment no larger than a hockey puck—broke on a high-voltage transmission line in the Feather River Canyon, starting the most destructive wildfire in California's history. The named "Camp Fire" burned 150,000 acres, resulted in 85 deaths, and caused billions of dollars in damage, requiring a substantial response from both the California Army and Air National Guard [21].

Moreover, the era of "strategic competition" with adversarial nation-states such as China, Russia, Iran, and North Korea, is paired with urgent calls for strengthening critical infrastructure and the national defense establishment in the homeland [22]. A fundamental tenet of the DoD's strategic shift away from counterterrorism and toward preparation for large-scale combat operations (LSCO) with peer threats is to bolster the armed forces' capability to project power from the strategic support area (SSA) while protecting defense-critical infrastructure in the homeland. Those efforts, in turn, also start from the assumption that homeland installations will be contested in all domains during periods of strategic competition, not just after the start of armed conflict [23]. Already, military risk-assessment experts and garrison commanders alike routinely cite disruption to the wider power grid as one of the top vulnerabilities to military readiness at home [24].

While the idea of connecting local electrical loads to a series of distributed energy resources (DERs) to form a microgrid islandable from the utility has a long history, for the DoD it is only in the past decade or so that the concept has matured from existing at the pilot or demonstration level to where it stands today: as a still-evolving but mostly commercialized set of industrial practices, systems, and products [8, 25–27]. While various groups within the DOE have engineered and tested microgrid concepts for more than 20 years, until recently these systems remained prohibitively complex and expensive to merit early DoD adoption. As a result, most military installations still rely on large quantities of standalone backup diesel generators to provide emergency power [8, 28, 29], apart from a handful of facilities dependent on narrow power quality conditions (such as the signal corps at Fort Detrick, MD) that rely on specialized uninterruptible power supply (UPS) systems [30].

The department began to engage seriously with microgrid research and development (R&D) through two complementary approaches: upping its investment in the DoD Environmental Security Technology Certification Program (ESTCP) and launching its landmark Smart Power Infrastructure Demonstration for Energy, Reliability, and Security (SPIDERS) program, a Joint Capability Technology Demonstration (JCTD) cosponsored by DoD, DOE, and the U.S. Department of Homeland Security. In a phased-project approach that lasted from 2011 to 2015, SPIDERS built and demonstrated three pilot microgrids—each designed with increasingly advanced capabilities—at Joint Base Pearl Harbor-Hickam, HI; Fort Carson, CO; and Camp H. M. Smith, HI (see Figure 1-2) [31].

In many ways, SPIDERS was a pioneer well ahead of its time, and its contributions to the state of the art are laudable [8, 32]. However, it fell short of its goal to deliver "permanent energy systems" to its test locations, a point rarely noted in surveys of recent progress in the development of microgrid technologies [31]. (In all fairness, some of the commercial technologies relied upon by SPIDERS, such as battery storage systems, underperformed.) For one, the SPIDERS systems transferred their loads to backup diesel generators in the event



SPIDERS JCTD Overview

PEARL HARBOR / HICKAM AFB CIRCUIT LEVEL DEMONSTRATION
- Renewables
- Storage
- Energy Management

FT CARSON MICRO-GRID
- Large Scale Renewables
- Vehicle-to-Grid
- Large scale storage
- Critical Assets
- Demonstration to tie in with COOP Exercise

CAMP SMITH ENERGY ISLAND
- Entire Installation Smart Micro-Grid
- Islanded Installation
- High Penetration of Renewables
- Demand-Side Management
- Redundant Backup Power
- Makana Pahili Hurricane Exercise

TRANSITION
- Template for DoD-wide implementation
- CONOPS
- TTPs
- Training Plans
- DoD Adds Specs to GSA Schedule
- Transition to Commercial Sector via DOE
- Transition Cyber-Security to Federal Sector and Utilities

CYBER-SECURITY

Sandia National Laboratories

Note: AFB (Air Force Base), COOP (Continuity of Operations Program), CONOPS (concept of operations), TTPs (tactics, techniques, and procedures), GSA (General Services Administration)

Figure 1-2. SPIDERS JCTD's Ambitious Technology Demonstration and Transfer Goals for Installation Microgrids, May 2012
(Source: Stamp [31]).

of an outage—not to their renewable or other fixed DER assets—which to some indicated an organizational reluctance to move away from the familiar emergency diesel systems [33]. Moreover, each SPIDERS microgrid lay dormant by 2018, casualties of unexpectedly high operations and maintenance (O&M) costs, bureaucratic confusion over operational responsibilities and ownership, and even an expired system password that proved too costly to recover [29, 33, 34]. To leaders at NAVFAC Pacific, the more challenging issue was an absence of the type of training curricula and tools needed to instruct DoD energy management personnel in how to operate the highly innovative systems [33].

Since the SPIDERS program ended in 2015, three key trends have converged over the last 1–3 years to make DoD installation microgrids increasingly feasible for achieving base resilience. One, the underlying economics behind DER adoption has improved nearly exponentially. Two, the array of microgrid-focused equipment manufacturers, consultants, and systems integrators has expanded dramatically—perhaps two- to three-fold—while also delivering much-needed advances in power electronics devices. Three, federal and national laboratory-managed R&D efforts shifted their emphasis away from advancing SPIDERS-like demonstrations and toward fostering research that conceives of the challenges of a microgrid deployment as ones of systems integration [35]. Each of these changes is reviewed in the next three sections.

1.1.1 DER Economics

The cost of installing new solar PV modules has plummeted since 2010, falling an average of 15% annually through 2020 (as measured by the observed global average levelized cost of electricity, or LCOE), more than double the decline projected by expert groups like the International Energy Agency [36]. The installed cost of large-scale lithium-ion battery energy storage systems (as measured per kilowatt-hour or kWh) declined at an even quicker rate between 2015 and 2019, sagging an average of 27% year over year [37]. Reflecting their newly competitive market pricing, new solar PV and wind projects accounted for an impressive 75% of all global capacity additions made in 2021 [38]. In the United States, the continued (relative) low price of utility-grade piped natural gas has also helped to promote growth in microgrid adoption, as DERs (of any source) comprise the single largest capital cost for most customers, typically upward of 50% [8].

1.1.2 Manufacturers and Systems Integrators

Industry observers consider 2014 to be something of a "launch party" for the microgrid concept, as several landmark projects were sanctioned, and firms began to form a handful of affinity groups and joint ventures [39]. The consulting group Guidehouse routinely calculates the capacity of installed microgrids worldwide (both grid-connected and standalone), and in 2015, the firm identified roughly 12 GW of total capacity [40]. By late 2022, that figure had jumped to 26 GW, with the United States home to more than any other nation (10+ GW) [41]. Engineering firms have also dramatically improved the functionality of power electronic devices, especially grid-forming inverters, which dampen frequency fluctuations caused by sources like solar PV that provide no inertia [42]. To construct a DoD microgrid, acquisition personnel and installation commanders now have a wide variety of design, engineering, and energy systems integration firms to partner with [43–45]. Improved microgrid processes and technologies are significantly decreasing the cost of design and the time to deploy a new system [32].

1.1.3 R&D Efforts

As privately-owned commercial microgrids began to debut at a faster clip in the mid-2010s, the DOE's Office of Electricity began to deemphasize pilot projects in favor of addressing systems integration issues by prioritizing real-world deployments [35]. This pivot included the development of tools for the design and operation of microgrids and means of evaluating microgrid controllers, including improved "hardware-in-the-loop" (HIL) practices for testing and verifying power and control systems [35, 46, 47]. Microgrid R&D efforts within the DoD followed a mostly parallel course, moving away from the JCTD model and toward joint projects with industry—of which the MCAS Miramar microgrid is a good example [2, 8]. As mentioned in Section 1.1, the DoD also increased its support of the ESTCP Energy & Water program, which demonstrates available commercial technologies and reduces the implementation risks of emerging systems. In 2016, ECIP tellingly added the word "resilience" to its charter, with the name of the new Energy Resilience and Conservation Investment Program (ERCIP) signaling its prioritization of resilient energy-secure systems over merely efficient ones [8]. By 2021, the Office of the Deputy Assistant Secretary of Defense (ODASD) (Energy) was retitled as the ODASD (Environment & Energy Resilience), further solidifying the department's shift toward resilience.

As a result, the current environment is more favorable for the adoption of DoD installation microgrids than ever before. A major federal electricity regulatory change in 2020 set the foundation for microgrid-hosted DERs to increase their participation in grid support services [48], and throughout 2021–2022, numerous microgrids have repeatedly proven their ability to successfully island. Policymakers have also found cause to significantly increase appropriations for ERCIP's energy resilience projects [8, 49]. For its part, the U.S. Army has certainly taken notice, instructing in early 2020 that Army installations would be required to withstand a long-duration utility outage for a minimum of 14 days [50]. By early 2022, with discrete microgrid solutions more clearly in view, the U.S. Army's new climate strategy announced the service's intent to "install a microgrid on every installation by 2035"—a number no less than 130 [51].

Accordingly, this report assesses the state of the art in recent U.S.-based microgrid R&D efforts, technologies, in situ deployments, and management practices with an eye toward (1) identifying those most relevant to DoD use and (2) highlighting salient points that may pose barriers—or opportunities—to the continued military adoption of grid-connected microgrids. The report presents 17 findings that together provide the reader with a thorough understanding of the department's current and likely near-term use of microgrid solutions for energy resilience. Each section expands substantially on the findings it covers and adds important context to each.

1.2 STUDY METHODS AND SCOPE

To produce this report, the Homeland Defense & Security Information Analysis Center (HDIAC) reviewed academic research, industry white papers, conference recordings and webinars, government research reports and project summaries, DOE databases, and sources of relevant gray literature such as industry publications. HDIAC also conducted expert-elicitation interviews with subject matter experts (SMEs) from commercial entities, academic institutes, and various divisions within the DOE, DoD, and the individual service branches. HDIAC identified SMEs using a snowball sampling method, in which early interview participants were asked to identify other leaders in the field—a process that aids the delineation of a distinct research community [52]. HDIAC interviewed a total of 24 SMEs via telephone or video, with discussions lasting from 30 minutes up to 2 hours. An additional 6 SMEs provided written comments via email in place of an interview. Where possible, SMEs provided peer review of segments of this report.

Interviewees included engineers and research directors at NREL, Oak Ridge National Laboratory, Sandia National Laboratories (SNL), Massachusetts Institute of Technology (MIT) Lincoln Laboratory, the Electric Power Research Institute (EPRI), program managers at DOE headquarters, academic scholars, microgrid design and planning firms, and independent electric power consultants. HDIAC also interviewed DoD civilian and contractor personnel from ESTCP; the Office of the Assistant Secretary of the Army for Installations, Energy & Environment (ASA IE&E); the U.S. Army Corps of Engineers, Engineer Research & Development Center; and energy managers from MCAS Miramar, Fort Bragg, and U.S. Army Garrison Fort Hunter Liggett. HDIAC sought this wide range of SME input to gather insight from practitioners familiar with each aspect of a military microgrid—from those engaged in highly technical R&D, to those on the ground at active installations.

Particularly valuable has been insight offered by Tim Tetreault of ESTCP and Jeffrey Marqusee of NREL (both involved in ESTCP's programmatic DoD microgrid efforts); Dan Ton, program manager for DOE's smart grid and microgrid R&D programs; Ben Ollis in the power and energy systems at Oak Ridge National Laboratory; Annie Weathers in the technical staff at MIT Lincoln Laboratory; and MCAS Miramar's Mick Wasco. (Please note that the assistance of any SME with this study does not necessarily reflect any agreement with or endorsement of this report's findings or statements either in whole or in part.)

In assessing the state of a field of practice, gathering input from experts and experienced hands via elicitation interviews is always helpful. However, this report has benefited significantly from SME input. Their experience provided insights that are not readily available in print sources, contributing valuable knowledge that helped offset three challenging research barriers that would otherwise frustrate any assessment of the state of the art in microgrids:

1. As the rapid increase in microgrid capacity evinces, the popularity of microgrids as an engineering, computing, business, and energy policy topic is booming. To wit, recent publication activity on microgrids is both global in scope and overwhelming in volume. Indeed, one scholarly survey of the "state of the art in research" on microgrids published in 2015—and styled as a comprehensive but concisely written literature review—runs nearly 25,000 words in length, with references to 392 sources, almost all of them highly technical [53]. A similar study conducted today would be proportionately longer and simply unusable by most audiences [32, 54].
2. A microgrid does not represent a single coherent technology, art, or field of practice but is instead a "system of systems" [55, 56] enabled by experts working cooperatively across a multitude of disciplines [8, 26]. These include electrical engineering, heat transfer physics, computer science, systems engineering, modeling and simulation, regulatory affairs, and financial management, to name but a few. Not only is there no Platonic microgrid that exists in isolation from the specifics of its physical and organizational environment; to indeed be a microgrid at all, it must be built and then *put into use*, operated, and monitored by personnel working within its control loop (see Figure 1-3). A microgrid is a learned behavior or group practice as much as it is a technology or field of knowledge [2, 8].

Figure 1-3. Leaders From Fort Hunter Liggett and Its Partners Ceremonially Break Ground on the Base's Microgrid Project in May 2021 *(Source: Croft [57]).*

3. The scope of what microgrid innovations or breakthroughs may be relevant to a DoD installation is much narrower than the field at large. The state of the art of a university campus microgrid (some of the earliest examples of operational microgrids), for example, is important here only insofar as it is translatable to DoD energy resilience metrics, requirements, and goals [2, 8, 29]. While the ample commercialization of microgrid equipment and energy system professional services makes the full scope of industry solutions available for DoD use, a base's expenditures for the constituent components of a microgrid are driven by its pursuit of guaranteeing energy mission assurance—achievement of which will be unique to each installation [26, 58, 59].

A few caveats bear mentioning. First, cybersecurity (including communications security) and economics are deemed outside the scope of this report (except where the optimization of a microgrid's operation may yield revenue benefits). Similarly, issues related to the selection, sizing, or siting of generation assets are not directly addressed. For any microgrid proposal, local utility regulatory practices, environmental conditions, project budgets, and site specifics will collectively influence those choices (e.g., not many bases can tap into landfill-generated natural gas as at MCAS Miramar). The appendix briefly considers recent developments in the design and production of small modular reactors (SMRs) and nuclear microreactors for potential DoD use. It summarizes the findings of two recent Idaho National Laboratory studies on the technical benefits and limitations that come with building a microgrid around a small nuclear generation source used for reliable baseload power.

Finally, this report focuses on grid-tied alternating current (AC) and hybrid alternating current/direct current (AC/DC) microgrids, and does not address what are known as standalone, tactical, or expeditionary microgrids. This approach follows the common understanding within the DoD R&D community that the latter three system types are properly considered offshoots or subcategories of a grid-connected microgrid [8, 60, 61].

SECTION 02

REPORT STRUCTURE AND FINDINGS

To make this report easily accessible, it first presents two sets of overarching findings that are applicable to the entire study. In Section 2.1, three general findings provide an assessment of the current state of the art of microgrids in the United States writ large, with limited commentary on their implications for DoD concerns. An additional two findings in Section 2.2 describe a mostly consensus vision held by government R&D groups on how future microgrid technologies and configurations may evolve in the next 5–10 years. Sections 2.3–2.6 provide specific and detailed findings drawn from each of the core content sections. The body text of each section elaborates on each finding and provides additional context.

2.1 CURRENT STATE OF THE ART

At the broadest level, HDIAC's review of the literature and discussions with industry, government, and academic SMEs found a high level of consensus on three descriptive characterizations of the current state of practice and engineering of microgrids in the United States.

Finding 1: The microgrid concept has been proven and is mostly commercialized—although its constituent technologies will continue to evolve and mature. Market assessments and experts generally agree that microgrid systems are a somewhat mature but not-yet-stabilized suite of technologies and industry practices [8, 25, 62–65]. One SME pointed out that in some circumstances, microgrid systems can be offered as full-service "turnkey" solutions, purchased (nearly) ready to operate [66]. However, unlike as it is within many technology markets, the DoD is not a prime mover in the microgrid space and enters it as a customer—albeit a distinctive one with potentially immense demand [32, 34, 67]. Competition in the microgrid equipment manufacturing and professional services spaces is strong, and energy systems integrators have developed and operated enough DoD installation microgrids to have attained ample experience navigating the idiosyncrasies of military energy contracts and of meeting precise DoD requirements [8].

Finding 2: Almost all grid-tied microgrid deployments are unique—and costly because of it. Outside of a few private fleets based on a common plan (such as H-E-B Grocery Company's ~45 systems near Houston), very few microgrids now in operation have repeatable designs, standardized control protocols, or modular components, the absence of which necessitates bespoke design, engineering, and integration services—at great cost [34, 58, 67, 68]. While a newly developed microgrid can achieve a high level of interoperability if it relies on systems drawn from a single manufacturer or integrator [33, 66], many microgrids (especially those within the DoD) use a "hodgepodge" of devices sporting dissimilar protocols [66]. Most new developments are retrofits rather than greenfield projects, further stifling any attempt at standardization [34, 67–69]. A standing joke within the R&D community is, "When you've seen one microgrid...you've seen *one* microgrid" [8, 26]. Each DoD installation microgrid also varies widely in its energy resources and viable technical paths for meeting energy resilience requirements [26, 58, 59].

Finding 3: Renewable generation sources (especially solar PV paired with battery storage) will continue to see rapid adoption rates—and are robust enough for DoD installation use. Between 2015 and 2020, fossil generation accounted for 75% of newly installed microgrid capacity in the United States, with the share of solar + storage less than 20% [70]. However, microgrid solar + storage penetration is expected to double in the near term [70], as large-scale solar projects grow increasingly co-located with lithium-ion battery storage systems [71] and as long-duration battery technology approaches an eventual market breakout point [67, 72]. Similar growth rates in solar and lithium-ion battery use are expected for DoD microgrids [8, 73], especially as more government and commercial microgrid operators gain valuable experience with the use of battery storage to help regulate microgrid voltage and frequency [53]. Moreover, inverter-based systems are more than durable and robust enough for DoD applications: while some solar PV modules have proved susceptible to environmental damage in harsh environments [58], they have also already found use in heavy industry [66].

2.2 VISIONS FOR FUTURE MICROGRIDS

HDIAC also found a general sense of agreement (particularly within but not exclusive to the DOE microgrid R&D program community) regarding how future microgrids might take shape in the medium term, between 5 and 10 years away. While some SMEs expressed varying levels of confidence in whether (or how) these R&D goals will be achieved, they shared a general notional vision for how microgrids will evolve.

Finding 4: Future microgrids will become increasingly standardized, interoperable, and flexible in their design, control architecture, and operation. To counter the high cost and labor intensiveness of current deployments, future microgrids are likely to adopt standardized communications and control protocols and vendor-agnostic software, as well as utilize interoperable design and planning tools to minimize capital costs and easily optimize for efficient operations [67–69, 73, 74]. Doing so will reduce the phenomenon of "vendor lock," facilitating the addition of generation assets to a DoD microgrid (or the expansion of its areal reach) after its construction, without a costly design reassessment [32, 67–69, 75]. Multiple efforts are seeking to, at minimum, streamline design techniques to allow for easier DoD reiteration of the planning process, or to standardize microgrids at the systems level into a series of modular "building blocks" [73, 75–77]. Due to organizational and economic reasons like vendor fragmentation—and the natural market incentive to resist the building-in of interoperability at present—true standardization will likely be slow in coming [26, 65, 77]. However, as the market grows, customers will increasingly demand commodity-like standardization and grow more sensitive to costs; a similar trend is already noticeable in industry applications like data centers [32].

Finding 5: The relationship of future microgrids to the macrogrid (and to each other) will trend toward closer connection. As renewable penetration expands and more systems connect to the utility, microgrids of all types—whether community, industrial, or government in nature—may cluster together to form "networked microgrids" [26, 73, 74, 78]. Their ability to sectionalize after a network fault could boost overall resilience and enable a cluster of networked microgrids to nimbly adapt or "self-heal" via advanced reconfiguration and restoration algorithms [26, 79, 80]. The microgrid-to-utility interface will also evolve: more microgrids will provide power services to the main grid (e.g., voltage stability, black start restoration assistance), and microgrid controllers will respond increasingly dynamically to changing utility power conditions, optimizing among cost savings, resilience, revenue arbitrage, emissions reduction, and reliability goals [73, 79, 81]. For example, one effort funded by the U.S. Navy is developing interoperable and technology-agnostic machine learning (ML)-enabled strategies for microgrid self-regulation against changing market tariffs during normal operations, and to maximize operational time when islanded [65].

2.3 VULNERABILITIES AND BENEFITS

Section 3 provides additional details regarding the vulnerabilities of the national grid system and the benefits installation microgrids bring to military operations in the homeland (see Figure 2-1). It also reviews how the DoD measures its requirements for military installations to achieve energy resilience and security, and how those metrics may affect microgrid design and operations.

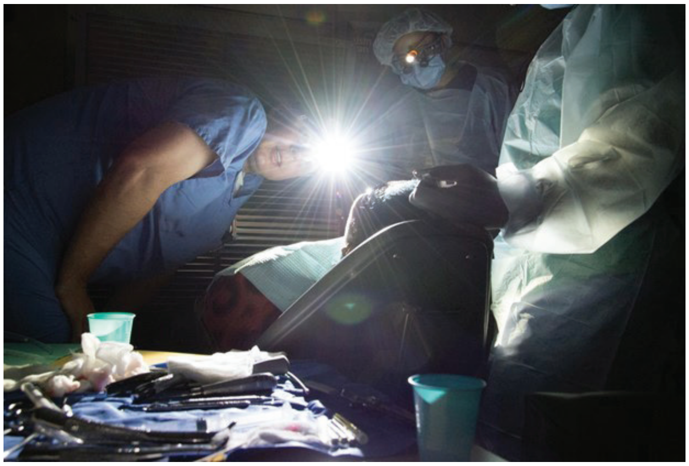


Figure 2-1. National Guard Troops and Reservists Continue With a Dental Procedure During a 2019 Power Outage in Illinois *(Source: Schulze [82])*.

Finding 6: Diesel generator systems used for emergency backup power are difficult to maintain, often unreliable, and not designed for use in extended outages. Most homeland DoD installations rely on emergency diesel generators (EDGs) for backup power, whether tied to individual buildings, linked together, or networked as part of a microgrid [8, 28]. While similar generators are successfully used in expeditionary microgrids, most vintages of existing EDGs are suboptimal for the installation use case to provide long-duration power: they match their emergency loads inefficiently and are labor intensive to service [28]; can pose a safety hazard to the Warfighter when tested properly [28, 29]; and in some studies display unacceptably low reliability rates after just 12 hours of operation [83, 84]. Moreover, the minimum value proposition of a military microgrid is the fact that a system of networked EDGs is both more resilient and cost effective than their use as standalone assets. Additionally, recent modeling from NREL shows that hybrid microgrids (containing solar PV, storage, and networked EDGs) are more resilient and cost effective than diesel-only systems, even when islanded [85]. Upgrading EDGs for dual-fuel and continuous operations would slake fuel availability concerns, yield a greater return on investment from utility market participation, and deliver more reliable runs due to more frequent use [32].

Finding 7: While it is evident that microgrids can sustain critical loads while islanded, the DoD could benefit from more nuanced quantitative measures of installation energy resilience. The concept of resilience is notoriously difficult to quantify, perhaps doubly so for a microgrid system. Even so, multiple SMEs told HDIAC that DoD investments would benefit from the establishment of more contextual and detailed quantitative resilience metrics in addition to the "electricity availability" calculations currently in use [2, 8, 67, 69, 86]. Availability measurements lack the nuance needed to guide a thorough assessment of an installation's energy vulnerabilities (including via its peripheral systems), prioritize protection against short-lived or "nuisance" outages, and rule out the core of resilience, being the ability to recover from a disruption [8, 53]. Furthermore, central to command interest in microgrids is the flexibility that its power options allow during a contingency event [29, 59, 66]. Resilience indices such as the Naval Postgraduate School's (NPS) "expected electrical disruption mission impact" (EEDMI), which is based on a systems-engineering approach, may be useful for supplementary analysis [87]. Finally, as the duration of an outage grows longer, the corpus of which loads are deemed critical tends to grow, eventually encompassing the host community around an installation [32].

2.4 MICROGRID DESIGN, FORECASTING, MODELING, AND SIMULATION

Section 4 reviews methodological approaches to scoping, designing, engineering, and modeling an installation microgrid before its deployment. It also assesses existing microgrid design tools like the NREL-developed REopt software and the decision support platform marketed by XENDEE, both of which have supported previous DoD microgrid builds. Section 4 also reviews ongoing DoD ESTCP projects aimed at making the microgrid design framework and process more automated and repeatable.

Finding 8: The planning, design, and modeling of a microgrid is in many respects the most important step in its deployment. Because a DoD installation microgrid will operate for decades—and at present, cannot be easily expanded—it is critical that every facet of its architecture, control scheme, and operational objectives be examined closely at the start. Complex systems like microgrids, once built, fall into a high level of "lock-in," or technological path dependency [8, 32]. One key goal of the DOE microgrid R&D program is the standardization of microgrid design and planning tool (MDPT) software, source codes, and tool inputs and outputs. Doing so would allow for both the maximal use of available datasets, and for multiple tools to "close couple" their analyses to yield results superior to those produced by any single approach [55, 67, 68, 88]. As one SME put it, the "cutting edge" of microgrid R&D rests in using multiple MDPTs in the design workflow to accurately size needed resources and pre-gauge a system's performance [69]. Future MDPTs may improve on combined simulation and optimization approaches [88], better assess a microgrid's dependence on other sectors [68, 88], model multiyear climate-change-induced weather forecasts [89], and conduct real-time systems emulation [55, 90].

Finding 9: While no single tool is regarded as best for designing a microgrid, this is indicative of a healthy field rather than a lagging R&D sector. A plethora of viable, field-tested MDPTs have emerged from DOE efforts, including DER-CAM, the Microgrid Design Toolkit (MDT), and REopt [55, 88]. Indeed, the two leading commercial offerings, marketed by XENDEE and Homer Energy, are spin-offs from Lawrence Berkeley National Laboratory and NREL work, respectively [8, 3, 88]. While these products are more advanced in some respects, most follow similar means of linear optimization; much of their commercial value-add derives from enhanced user interfaces, faster processing times, integration with electric power flow tools, and around-the-clock customer technical support [8, 89]. There are ample high-quality MDPTs at the disposal of the DoD and its contractors to meet the department's energy resilience requirements and any financial outlay constraints. Moreover, the selection of an MDPT for a given locale is likely to depend mostly on the specifics of the installation site [8, 66, 67]. Ongoing R&D efforts such as MicrogridUP (where UP refers to utility privatization) are working to build tools specific to unique DoD installation use cases, modeling how a rural utility cooperative's grid may best integrate with a high-renewables DoD microgrid, to lower both technical and "soft" costs [8, 91].

Finding 10: Future approaches will seek to standardize or streamline the design process, better plan for changing operations, and anticipate extreme outage events. Research is ongoing to bring microgrid design, planning, simulation, and other analytical approaches "under a single entity," or to integrate methodologies as much as possible [88, 92]. Doing so may both reduce costs and allow for easier HIL testing [90], although some question the purported benefits of a unified tool [67]. Future MDPTs should also incorporate a wider range of potential mission scenarios when assessing an installation for a microgrid deployment, actively assuming dramatic shifts in its demand profile (and distribution) that might result from unexpected contingency operations [93]. Microgrid design and planning tools must incorporate projections of future temperature ranges, weather patterns, and extreme-event environments at a resolution usable at the installation level [88, 89, 93]. (Such refinements are common as technologies mature and begin to reach into a wider market [32].) MDPTs must also presume that a system will experience extreme—but realistic—long-duration outage events, records for which are mostly absent from the historical climatological and electrical datasets currently used to bound the scope of a microgrid's resilience capabilities [94]. Failing to do so undermines a microgrid's resilience benefits and generates reliability on paper that may prove unreliable in real world scenarios [94].

2.5 MICROGRID CONTROL AND ARCHITECTURE

Section 5 addresses recent R&D in microgrid control theory, controller systems, and ways for a microgrid to manage both DERs and loads while optimizing its interaction with the bulk power market. It briefly surveys the microgrid building blocks concept mentioned in Finding 4 and discusses efforts to replace centralized microgrid architectures with a distributed or peer-to-peer control scheme.

Finding 11: While microgrid controllers (MGCs) and control systems currently receive the lion's share of R&D interest, commercially available MGCs meet DoD needs in the near term. Because a controller serves as the microgrid's "brain" [20], forward-looking R&D places great emphasis on proving out new control techniques and architectures [26, 68, 95]. In tandem with the recent acceleration in microgrid build-outs, such research has grown incredibly complex and narrowly detailed; as one SME remarked, "There is no literature more opaque than the control literature" [8]. However, high-quality commercial MGCs vary minimally in efficiency and are available from top-tier manufacturers like Schneider Electric, Siemens, and Schweitzer Engineering Laboratories (SEL) [8, 32, 43]. Commercial controllers have already served DoD installations well (e.g., the microgrid at MCAS Miramar uses a system from Schneider Electric). Ameresco—a leading integrator that has overseen multiple DoD energy projects, including at Joint Base San Antonio and Marine Corps Recruit Depot (MCRD) Parris Island—has chosen at least three different MGC vendors for military microgrids, based on minor differences among the sites [8]. While a commercial MGC can range in cost from $50,000 to $500,000 [96], that figure is likely closer to $100,000 for DoD bases—inexpensive given its central role in delivering energy mission assurance [8].

Finding 12: Algorithms and control schemes for microgrids will continue to grow in sophistication, likely allowing automatic optimization during "blue sky" and islanded operations, and seamless control of subordinate systems. As extant microgrids accrue more and more operating years, research in multi-objective optimization algorithms (including robust, fuzzy, and other approaches) has risen in prominence, surpassing more foundational topics like stability and forecasting [97, 98]. In the near term, control systems will grow more complex and flexible, implementing advanced algorithms that can support dynamic (or automatic) multi-objective optimization—potentially via ML-enabled predictive qualities [8, 65, 95, 97, 98]. Future advancements are likely to (1) simplify the addition or integration of new assets/devices into an existing microgrid; (2) expand black start capabilities in low-inertia microgrids; (3) improve monitoring and diagnostic capabilities, such as non-intrusive metering or high-fidelity sensing; (4) simplify the "self-assembly" of clustered or networked microgrids; and (5) increasingly adopt modular or open-source components [66, 68]. When linked to a program like a building energy management system (BEMS) that provides highly specific metering data, the MGC can precisely trim away or reschedule the load, as well as better predict upcoming building load profiles to counter demand uncertainty (known as a longer control horizon) [66].

Finding 13: Distributed control concepts hold promise for boosting overall system resilience but remain unproven—and are hindered by cybersecurity concerns. Centralized control comes with one significant downside: the controller's station as a single point of failure [26, 81]. For at least a decade, the concept of "distributed control"—in which DERs and devices directly connect, as in a peer-to-peer network, has gained traction [99, 100]. For larger systems with numerous devices spread over a large area (as future DoD microgrids are likely to be), centralized control requires lengthy linkages and can suffer from latency issues [100]. Distributed control may offer a near-instant response to power-condition changes—possibly autonomously, where aided by ML [101]. Ongoing efforts like the Resilient Information Architecture Platform for the Smart Grid (RIAPS) project seek to manage control tasks via a combination of embedded computing and powerful cloud-based user platforms [102–104]. While the core argument of centralization's vulnerability is valid, the cost effectiveness of distributed control remains unproven [8]. It also may present threat actors with a wider range of attack vectors to exploit [26, 100, 105]. One recent Pentagon-sponsored hacking challenge revealed that more traditional microgrid control architectures are already extremely vulnerable to cyberattack [105]. However, market and ownership models can strongly influence which control options are deemed most feasible; solutions may converge on a hybrid approach, distributing control to localized power networks while centralizing control within them [32].

2.6 ORGANIZATIONAL CONSIDERATIONS

The report's conclusion (Section 6) discusses several critical organizational and structural considerations that can assist or hinder a DoD microgrid's deployment, including the need for more sophisticated operator training tools (see Figure 2-2). Because the cheapest energy available is that saved via energy efficiency measures, Section 6 first briefly reviews a suite of cost-saving innovations that reduce facility energy consumption, including passive cooling materials, smart occupancy sensors for buildings, and neural-network-enabled HVAC control systems.

Figure 2-2. Inside the EWOC at MCAS Miramar, February 2021 *(Source: Hess [107]).*

Finding 14: The success of a DoD microgrid depends more on organizational actions and the "tacit knowledge" accumulated by project leaders than any cutting-edge equipment or system. Studies of engineering communities show that R&D-generated knowledge is less a collection of facts than a series of informed practices, oftentimes left "tacit" or unwritten [106]. This is especially true for a DoD microgrid, which one SME described as more a "form of a sophisticated construction project" than an advanced technology [8]. For microgrids, there is perhaps no better example of the centrality of tacit knowledge than the execution of regular islanding tests and ERREs, which have proven powerful in uncovering flaws in microgrid systems and procedures, allowing for their mitigation after the fact [2, 3, 8, 32]. As MCAS Miramar's Mick Wasco has explained, the most valuable technical knowledge about a microgrid is gained through such exercises: "You don't even know what you need to be worried about, until you start poking and prodding" [3]. After Miramar's 2021 ERRE outage exercise, one participant noted that it brought to the fore critical questions around what it means to achieve real resilience, remarking, "This has caused a 20-year conversation to happen in one 1-hour meeting" [3]. As the DoD continues to gain experience in building new microgrids, it will likely adapt existing processes (e.g., its ongoing microgrid work under the auspices of the Unified Facilities Criteria program) to better acquire and manage them [32].

Finding 15: A microgrid's funding—and the contracts it lets to industry—can greatly affect its design, operations, and long-term sustainment. HDIAC heard from multiple SMEs that differences in funding and contract types (especially their fractionation across multiple sources and years) can hamper resilience planning, lead to variations in the thoroughness of islanding tests, and make O&M funds for sustainment costs difficult to access—costs that have already proven higher than expected for many DoD microgrids [2, 8, 65]. Similar influences exist in the private sector. As one key study noted in 2020, a "disconnect between real-world financing and technical modeling remains one of the largest barriers" to microgrid adoption [108]. A central issue is whether O&M funds are dedicated or relegated to service base operations; in other words, the microgrid can be viewed by the command as either a value generator or a cost center [2, 8, 65]. Direct monies focused on energy savings may not allow cost reductions to flow into sustainment [2, 8, 58], leaving a microgrid less self-sufficient than it appears [2]. On the other hand, while many third-party-financed contracts now include dedicated O&M accounts, attendant to them is a partial loss of autonomy [58, 109]—non-DoD operators may not truly stress test their energy systems under real-world conditions, as the microgrid at Miramar has done [2].

Finding 16: Shifts in DoD's approach to deploying installation microgrids will influence what technologies and R&D are most useful to the department. Recently, some leading thinkers in the DoD microgrid community, previously bullish on the concept of networked microgrids, shifted their views on the concept's usefulness due to market growth and the advent of increased ERCIP funding [8]. These trends caused the justification behind a strategy of building multiple small microgrids, and then clustering them, to dim somewhat. Successful projects like Ameresco's overhaul of the power and distribution system at MCRD Parris Island (done concurrent with the addition of a microgrid) also bolstered arguments for a "one and done" approach [8, 110]. As a result, it might make sense for the DoD to defer any investment decisions in cluster-focused R&D for the time being [8, 66]. Moreover, organizational approaches to a microgrid's operation can be highly determinative of its success; the SPIDERS pilot program fell short in part due to a lack of integration of bureaucratic operational and ownership responsibilities. Finally, the DoD's approach to maintenance will also play an outsized role in sustaining microgrid uptime; Fort Belvoir, VA, undertook a dedicated tree-trimming, maintenance, and line-undergrounding campaign several years ago and drove the number of power outages due to on-base causes down nearly to zero.

Finding 17: Providing the DoD energy management workforce with accessible training, professional networking opportunities, and highly immersive microgrid training simulators is of paramount importance to the long-term sustainment of military microgrids. The value of collaboration among DoD energy communities cannot be overstated.

Each of the base utility managers that HDIAC interviewed cited attendance at a professional conference as the origin of (or a major turning point in) their command pursuing a microgrid or other energy-resilience project [2, 3, 58]. Acquiring and retaining this talented workforce is likely to prove a continuing challenge, as demand for skilled energy-sector labor already far outstrips supply in the United States [32, 111] and few have direct experience with microgrid operations [2, 68]. Even a landmark project like Miramar's struggles to fully staff its energy operations group [2, 112]. Moreover, most microgrid-specific training is expensive, outdated, or remains difficult to access [65, 113]. Most pressingly, it is critical for microgrid operators to practice their data management and control skillsets in a realistic training environment, one similar to a flight simulator [2, 25, 56, 65, 69]. As one DOE report contends, simulators greatly improve an operator's ability to take appropriate action in an "off-normal" or emergency event, like an unplanned power outage. When, to successfully run a microgrid, operators must navigate a bevy of digital alarms and databanks presented on an array of monitors, there is no substitute for the "learning-by-doing" that training within a flight simulator environment provides [114].

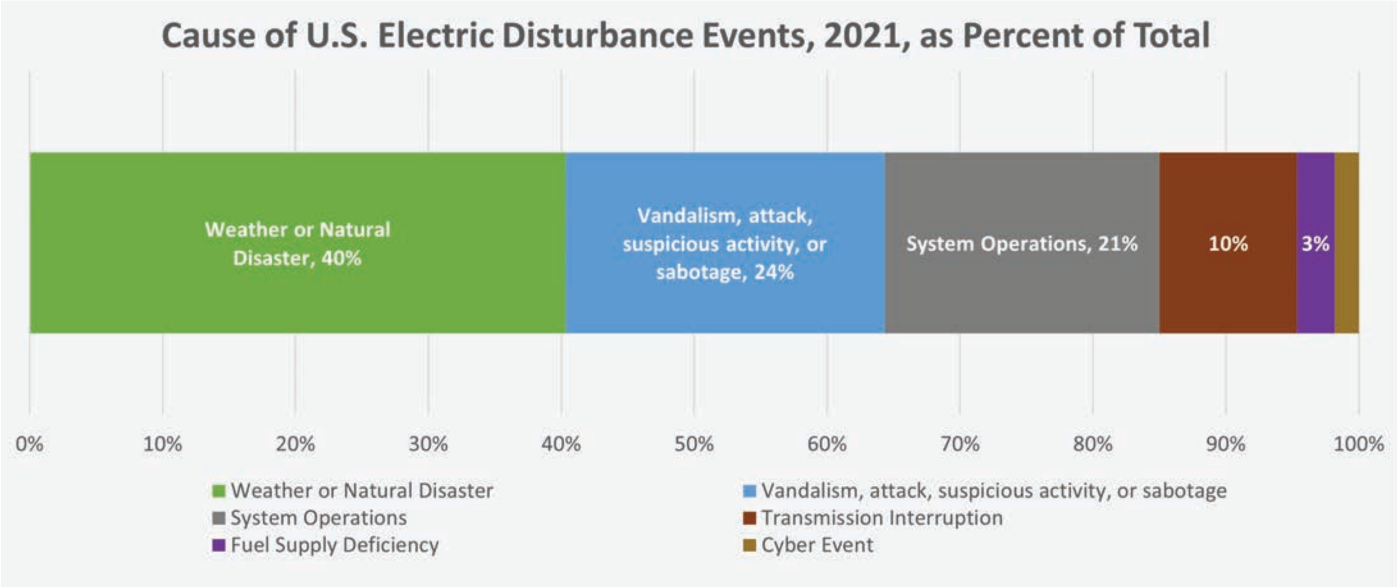
SECTION 03

WHY MICROGRIDS?

3.1 MACROGRID VULNERABILITIES

Although the occasional downed tree branch or insulation-chewing squirrel causes its share of routine power outages, the electric grid in the United States currently faces a host of threats more systemic and serious in nature (and worse, increasingly reinforcing ones) that are already taking their toll on the system's stability and reliability. The grid's vulnerability is amply reflected in official outage statistics: the DOE tracked 387 electric disturbance events (a good index of overall reliability) across the national grid system in 2021 (see Figure 3-1). This was up from 220 such events recorded 3 years earlier, and more than double the 143 recorded in 2015. The extent of electric disturbance events has increased as well, with the estimated 20.8 million customers affected in 2021 far outpacing the mere 7.2 million affected 6 years earlier [115].

Chief among these threats is a rise in extreme-weather events exacerbated by global climate change, which the Government Accountability Office expects to have "far-reaching effects on the electricity grid that could…affect every aspect of the grid from generation, transmission, and distribution to demand for electricity" [116]. While severe wildfires in the American West—and powerful hurricanes along the Gulf Coast and Atlantic Seaboard—are particularly demonstrable instances of the threats posed by powerful weather



Note: Several categories have been combined for simplicity.

Figure 3-1. Reported Electric Disturbance Events (OE-417) in 2021 as Compiled by the DOE *(Source: U.S. DOE [115])*.

systems, temperature extremes alone can have a dramatic effect on system reliability. As MCAS Miramar witnessed in 2022, hot temperatures increase consumer demand, putting a high strain on generation resources. Moreover, while demand is peaking, excessive heat can constrain transmission line capacity, damage distribution networks, and in some areas limit or take offline much needed hydroelectric power (especially when mated to chronic drought conditions) [116]. Even power plants that combust natural gas—at around 2,000 °F—suffer efficiency losses in high heat and can unexpectedly trip off [117].

Grid vulnerabilities catalyzed by extreme cold are no less serious. In February 2021, a winter storm blanketed much of the central and southern plains and the State of Texas in snow and ice, as the area settled into a prolonged deep freeze. At its coldest point in the 2-week affair, large swaths of Texas witnessed temperatures 30–40 °F lower than the average daily minimum temperature for that period [118]. As electric power plants of all generation types began to operate below expected levels (or fail outright), the decrease in power was met by a concomitant record high in electricity demand across the Lone Star State (backcasted to 76,819 MW, absent load shed). This necessitated the imposition of rolling blackouts by grid operators—service losses that only added to the affliction of other storm-caused outages [118, 119]. By one estimate, 10 million people lost power, sometimes for days on end, and even more likely lost residential water flow [120].

Critically, a precipitous frequency drop in the Electric Reliability Council of Texas (ERCOT) system in the early hours of February 15, 2021, nearly triggered an automatic (and potentially total) blackout of the Texas grid—a collapse that could have required months to restore [120, 121]. ERCOT was a mere 4.5 minutes [120] from darkening the grid and ushering in a period of grave social disruption.

The persistently frigid temperatures froze natural gas in distribution lines and at the wellhead, dropping production of dry gas by 85% [119]—a bottleneck that contributed to processing outages and derates of natural-gas-fired power plants. Natural gas generation units accounted for the bulk of event area outages by nameplate capacity, at 55% of the total—a very high outage rate, but one roughly commensurate with its share of installed generation [118]. Solar and wind resources suffered from freezing, mechanical/electrical issues, and transmission problems as well, but also posted an important datum for energy resilience: they are not subject to the "fuel issues" that contributed to the outages of coal and natural gas plants and do not require the same degree of costly winterization modifications to remain operable [118]. At DoD installations in the storm zone, several bases turned to their backup EDGs when the utility went dark, while others remained powered but lost municipal water supply when the host community lost power [122]. Near Killeen, U.S. Army Fort Hood, TX, remained online, but due to the quirks of ERCOT's deregulated scarcity pricing system, its electric bill for February 2021 reached $30 million—roughly as much as it paid for electricity over the entirety of fiscal year 2020 [123].

The national grid system in the United States also faces real and present threats from bad actors, ranging from destructive but relatively benign copper thieves ("plinkers") to violent radicals, transnational criminal organizations, terrorists, and proxy actors for adversarial nation-states [124]. As utilities have increasingly leashed their electric industrial control systems to cyber-based capabilities that allow for remote access and control, both transmission and distribution systems have risen in prominence as prime targets for cyberattacks. Malicious hackers have repeatedly penetrated electric system devices and networks via malware, spearfishing, and the manipulation of products in the supply chain [125].

Even so, direct physical attack appears to be the most pressing threat to grid reliability at present. Over 2021, actions categorized by the DOE as either vandalism, suspicious activity, sabotage, or an actual/potential physical attack made up 24% of disturbance events reported that year—a classification second only to weather (see Figure 3-1). Energy infrastructure (and the electric grid in particular) is the preferred target of many domestic extremist groups, as its centrality to day-to-day life all but guarantees "general chaos" were it to massively fail [126, 127]. It should be noted that one of the core concepts underpinning the resilience value of DERs is the spreading out of generation sources, which itself discourages attempts at the widescale sabotage of an electrical grid.

Several attempted (or rehearsed) attacks have demonstrated the ease with which system-wide failure can be induced. In 2013, at least one assailant severed telephone wires to a substation south of the San Francisco Bay area and fired 100 rounds from a high-powered rifle into high-voltage transformers, damaging 17 out of 21 [128, 129]. As the then-chairman of the Federal Energy Regulatory Commission (FERC) later recalled, the operation had all the hallmarks of a special forces attack. Had it been successful, he warned, it could have "brought down all of Silicon Valley" [129]. While many substations have since been physically hardened, key grid assets remain easily accessible and vulnerable to sabotage [130].

More prosaically, however, the grid is old—very old. The average power plant in the United States was commissioned more than 30 years ago, while the average power transformer has an additional decade of vintage to its age [131]. Nearly three-fourths of all transmission and distribution (T&D) lines are "well into the second half" of their 50-year life expectancies, yet still receive insufficient maintenance attention [132]. The U.S. electricity delivery system routinely receives poor marks from the American Society of Civil Engineers' annual national infrastructure report card; the "C– grade" it bestowed upon the grid in 2021 reflects a recent high-water mark for the system [133, 134]. Other measures similarly show a decline in grid reliability, if not merely stagnation: the average duration of a customer-experienced power outage has barely budged between 2013 and 2020, even when major event causes are excluded from the calculation [135].

As mentioned in Section 1.1, it was the failure of a metal C-hook on a 115,000-volt line in northern California that kicked off the destructive Camp Fire that raged for 2 weeks in 2018 [136]. With the line in service for more than 100 years, the hook's interjoining metal piece had worn a deep channel into it, finally severing the hook in two. While it is unverified whether the hook was an original component from the line's construction, one study determined that its channel was "consistent with approximately 97 years of rotational body on body wear" [137] (see Figure 3-2).

Figure 3-2. A C-Hook From Pacific Gas and Electric Company Tower 27/222 Shows Metal Channeling Due to Decades of Wear
(Source: Long [137]).

Finally, the national grid system is on the cusp of a massive reformation, one "systemic" in scope and no less than the "largest transformation in its history," as energy journalist and author Katherine Blunt has put it [132, 138]. To oversimplify, its watchword is *electrification*. Consumers are turning to the grid for more energy services, as they adopt more electric vehicles in lieu of new gasoline-powered cars, replace indoor natural-gas cooking ranges with electric ones (due to indoor air quality concerns), and reap the cost savings of grid-powered heat pumps. On the generation side, rapid increases in the volume of non-dispatchable power, coupled with gradual declines in nuclear and coal-fired fleets (due to retirements as well as a lack of new facility starts) have shrunk operator reserve margins in many regions [132].

The influx of intermittent assets like solar PV and wind farms poses additional difficulties to this already uneasy balance of generation and load. While power inverters that link non-dispatchable assets to the grid in the United States are required to be programmed with a "ride through" capability to remain online during minor grid disturbances, they often trip off, removing dangerously high amounts of power from the grid [139]. As the director of reliability assessment for the North American Electric Reliability Corporation (NERC) recently commented to *EnergyWire*, while this issue is no reason to slow down on the adoption of renewable power, the "pace of our grid transformation is a little out of synch" with efforts to meet its technical requirements for operation [139]. The application of ML-enabled tools may improve the control of new generation types in years to come; the DOE is funding research projects to optimize energy storage systems to bolster stability in the future macrogrid [140].

Although the DoD has made great progress over the past 15 years in reducing its consumption of fossil-based primary energy sources, most homeland installations (more than 98%) remain dependent on power systems located outside the wire [28, 141]. The Defense Science Board warned as early as 2008 that DoD installations face an "almost complete dependence…on a fragile and vulnerable commercial power grid," one that places "critical military and Homeland defense missions at an unacceptably high risk of extended disruption" [142]. Moreover, as the Deputy Assistant Secretary of the Army for Energy & Sustainability noted in 2018, the disruption of even just non-critical loads on homeland bases could hinder the services' ability to deploy or project power abroad when needed [143].

Compounding this vulnerability is the department's massive installation footprint and fixed-source energy demands. The DoD is the largest single institutional user of electricity in the United States, routinely accounting for just over half of the entire federal government's consumption, spread across the 284,000 buildings it owns or occupies worldwide [144, 145]. Beginning in earnest around 2005, new statutes and departmental policies have set a series of energy resilience goals for military installations, requiring increases in DoD's sourcing of renewable power, updates to its energy-use monitoring systems, reductions in facility energy intensity (consumption per gross square foot) and driving an overall push toward "net-zero" installation operations (producing as much energy, typically from renewable sources, as a base consumes) [146].

The DoD has made significant progress in meeting these goals. Over the past decade, the department has reduced its greenhouse gas emissions noticeably (scope 1 and 2), and in fiscal year 2021, the DoD directly generated 13,735 billion British thermal units (BBtus) in renewable power, mostly (46%) from solar PV modules—a not-insignificant amount, but a figure representing no more than 6.5% of total DoD-facility electricity consumption [145, 147]. As previously discussed, even renewable power in the absence of an islandable microgrid may not be sufficiently reliable to meet critical mission needs. In fact, DoD installations reported 3,018 unplanned utility outages in fiscal year 2020, 649 of which lasted for 8 hours or longer [145].

3.2 MICROGRID BENEFITS

Grid-tied microgrids currently in operation in the United States vary widely in their composition, size, and technical architecture. Their variability is a key source of their versatility, allowing a microgrid to power a single customer, serve a full or partial feeder, or plug into the macrogrid at the distribution or substation level [148]. Apart from their ability to guarantee installation energy resilience in a short or prolonged utility outage, microgrids can significantly reduce emissions and may limit some costs, whether through the optimal use of renewable generation or by maximizing the use of a fuel type when its market price is at its nadir [148]. Whether a given microgrid can reduce energy outlays on a per-kilowatt basis depends on its DER mixture, scope of work, and the customer's regulatory market; even so, at present, microgrid-produced power remains generally more expensive than utility power [148]. However, overall costs may decline in the medium term as vendors gain more experience building and operating microgrid systems—a phenomenon known in the economic and business history literature as learning-by-doing [36, 148, 149].

The local nature of a microgrid's operation also brings additional resilience benefits and efficiencies. A microgrid's shorter T&D lines may reduce the risk of weather- or debris-caused line outages [53] and are known to minimize electricity losses during transportation. The U.S. Energy Information Administration estimates that T&D losses in the United States equal about 5% of generated power, while other authorities see T&D losses averaging 8% globally, although that figure has marginally improved over the past 20 years [150, 151]. Whether at the transmission or distribution level, line outages have become an ever more frequent (and expensive) occurrence over recent decades.

At minimum, a grid-tied microgrid must possess a handful of characteristics. It requires (1) a clearly defined electrical boundary, (2) a control system that operates DERs and electrical loads together as a single controllable entity, and (3) sufficient DER capacity to meet the system's peak critical load when islanded [53]. In practice, this typically translates into the inclusion of dispatchable or "spinning" generation assets alongside variable sources like solar PV, as well as battery energy storage; safety-assurance or "protection" equipment, such as fault interrupters and control-based protection schemes; loads designated as critical and those that can be adjusted/curtailed when necessary; and a point of common coupling (PCC), a technical design that connects the microgrid to the bulk power system and provides both protection and isolation from the utility in the event of a fault [53, 148, 152]. As seen at MCAS Miramar's microgrid, the PCC is best understood as a technical instantiation of any contracts and agreements reached between the microgrid operator and the connected utility [148]. Indeed, a microgrid can cause electrical damage—and is certain to face exorbitant fine—if it exceeds its negotiated power export limit [32]. A microgrid's primary control challenges relate to its low system inertia, a lack of devices that can provide fast regulation, and the uncertainties that currently surround inverter-based renewable generation [81].

Finally, a microgrid must deliver key power services typically provided by the macrogrid, including voltage and frequency regulation, surge capability (being able to handle the large spikes in demand that accompany the start-up of some high-powered loads), protection system coordination, and the ability to black start or energize the microgrid from zero when power stops flowing from the utility [152]. While advanced microgrids often integrate components of the "smart grid" concept (e.g., digital controls for better measurement and sensing, or dynamic line rating systems for transmission monitoring), the two concepts are distinct [153].

An advanced microgrid can also deliver a host of ancillary benefits. As previously discussed, a microgrid—especially one with energy storage—can provide frequency control and power quality services to the macrogrid, while granting the customer the ability to peak shave, engage in energy price arbitrage, and have flexibility in selectively energizing loads during operations [148, 152]. Battery storage does more than just pair well with variable sources like solar PV; it also improves a microgrid's economic operation and helps to maintain power quality while regulating voltage and frequency [53, 148]. A smart microgrid employs a substantial amount of digital monitoring, control, and diagnostic tools at both the communications and applications layers [148]. Software and sensors in the latter draw upon the smart microgrid's system awareness to intelligently—and increasingly, automatically—optimize its economic operation, repair faults and disturbances, alert operators to conditions-based maintenance needs, and even optimize the use of assets like battery storage systems to increase their lifespan [148, 154]. In September 2022, the landfall of Hurricane Ian in southwest Florida put thousands of operational microgrids (whether "smart" or not) through their paces, and they emerged to rave reviews. Amidst Ian's devastation, one industry news outlet opined that microgrids created "electric sanctuaries" [155].

Most pressingly for the DoD, even a minimally capable microgrid represents a step-change beyond the reliability and efficiency of backup or emergency diesel generators (EDGs). Almost all DoD homeland installations rely on standalone EDGs, hard-wired directly into a building, to provide backup power to supply both critical and non-priority loads (whether fueled by natural gas, propane, or jet fuel) [8, 28]. While simpler to operate and requiring lower up-front capital costs than other DERs, EDGs on a standard military installation vary widely in size, manufacturer, and vintage, complicating their maintenance and sustainment and contributing to markedly high failure rates [28, 83]. Their dispersal also makes them more labor intensive to service, as compared to a lower number of higher-powered DERs. Unlike the prime-rated diesel generators at MCAS Miramar's backup power plant, typical EDGs also produce emissions with unhealthily high levels of certain particulate matter. Even without the incorporation of more reliable DERs, the minimum value proposition of a military microgrid is the fact that networking existing EDGs into a microgrid is both more resilient and cost effective than their use as standalone assets [29, 85].

To guarantee that EDGs can meet a building's peak load, they are often grossly oversized, typically around 400% larger than required [28]. This practice, while resilient in one sense, imposes significant costs: for one, it raises the capital needed to acquire a new EDG. It also encourages superfluous fuel use, which decreases an EDG's lifespan (due to its inefficient operation at mid-load rates) [28, 29], and further exacerbates the difficult process of testing and maintaining each generator unit. To properly test an EDG, it must be run at full (or high) load while connected to a set of heating wires, which poses a safety threat to the Warfighter. Most EDGs are poorly maintained as a result [28, 29].

As an NREL study completed in 2020 found, a poorly maintained EDG is unlikely to remain online beyond a few days' time and may have an average reliability rate of 80% after just 12 hours of operation [84]. Even well-maintained EDGs cannot guarantee energy resilience during a long-duration outage, as their reliability similarly falls to an estimated 80% after 2 weeks of use [84] (see Figure 3-3). Some experts have questioned the validity of how the NREL study assessed generator reliability, but DoD's interest in renewable DERs for both installation and expeditionary microgrids evinces a recognition that, at minimum, EDGs are a sub-optimal approach for providing long-duration power.

3.3 MEASURING MICROGRID RESILIENCE

The DoD promulgates its installation energy resilience requirements and assessment procedures across several documents, key among them DoD Directive (DoDD) 4170.11, "Installation Energy

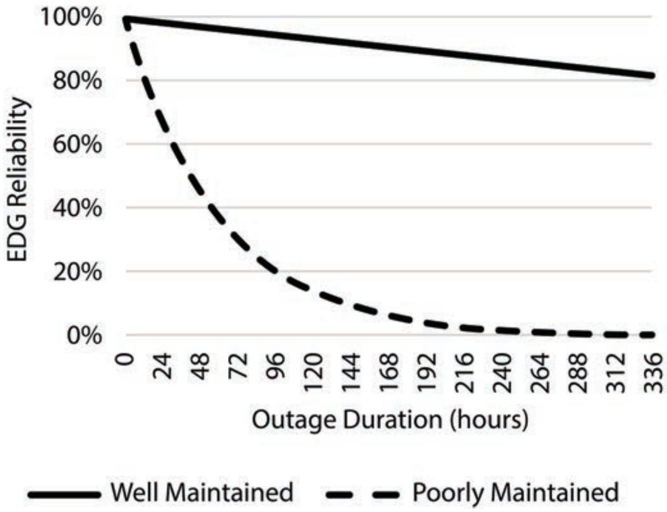


Figure 3-3. Reliability of a Single EDG Over 2 Weeks *(Source: Marqusee et al. [84])*.

Management" (last amended in August 2018) [156], and a May 2021 implementing memorandum, "Metrics and Standards for Energy Resilience at Military Installations," which calls for a minimum of 14 days' resilience against energy disruptions in the absence of other guidance [86]. Furthermore, 10 U.S.C. § 2911(h)(1) places a preference (when feasible) for the DoD to develop on-site energy production infrastructure and incorporate "energy resilience features, such as microgrids" into its installation plans [157].

Since DoDD 4170.11 was first released in 2009, military energy managers and officials within the Office of the Secretary of Defense (typically from the recently restructured ODASD/E&ER) alike have engaged in public discussions around how the DoD can best (1) understand each installation's mission requirements, including how to best identify which loads qualify as critical, and (2) enumerate a series of metrics that aid the selection of solutions to satisfy the statutory definition of *energy resilience* (see Section 1) [158, 159]. Officials from ODASD/E&ER have noted a long-term goal of aligning mission requirements with mission-performance resilience metrics (i.e., energy availability, reliability, and/or quality) [158]. Third-party studies sponsored by the office similarly call attention to the difficulty of making criticality designations (especially among multiple-tenant joint bases) and the need to understand "the integrative nature of multiple variables" in assessing and quantifying energy resilience solutions and their alternatives [160].

While the May 2021 implementing memorandum lays out several metrics and standards for achieving energy resilience—and although multiple assessment tools are available—they are all subordinate to a statutory requirement that, by the end of fiscal year 2030, a full 100% of the energy needed for each DoD installation to maintain its critical missions have an annual availability of no less than 99.9% and no more than 99.9999% [86]. When translated to cumulative outage times, 99.9% availability represents no more than 8 hours and 45 minutes of downtime per year, while 99.9999% availability allows for a maximum of 31 seconds of downtime. Electricity availability is currently used because no technical or policy consensus exists within the DoD or DOE (or elsewhere) on how to measure facility energy resilience [67, 88, 94, 161].

While specific, such a directive lacks the nuance needed to guide a thorough assessment of an installation's energy vulnerabilities or inform the complexities of designing and investing in the multiyear construction of a microgrid [8, 109, 162]. For one, defining resilience as maximal *availability* insufficiently considers the overwhelming need to protect against low-probability, high-consequence events, instead prioritizing the avoidance of short-lived or nuisance outages. The availability metric also insufficiently captures the risks posed to a microgrid's uptime by its interdependent systems, including the cybersecurity of communications networks. While ensuring resilience for a 14-day period is certainly a desirable quality, that figure, too, strikes many in the community as arbitrary. Most of all, the electricity availability metric rules out the one concept central to the design of a resilient system—its ability to withstand, endure, and *recover* from a disruptive event [8, 88, 162].

The work of quantifying the measure (and economic value) of energy system resilience has become something of a cottage industry over the past decade [163–166], and the enterprise extends to the specifics of the military context as well [167]. While many of these efforts do account for some extreme events, their application is mostly limited to specific scenarios, matting their universality and usability [164]. Means of quantifying the resilience of microgrids, specifically, remain largely unexplored [162, 165]. One promising approach posits a straightforward metric of a microgrid's resilience as the probability of its "survivability," defined as meeting its critical loads while islanded; the metric uses Markov chains to assess probabilities while incorporating asset-level reliability data (e.g., downtime, failures to start) [168].

A series of recent papers from authors at the NPS are of particular note [87, 93, 167, 169], as they address the resilience of military installation microgrids, building upon the EEDMI index first proposed in September 2021 (see Finding 7) [87]. EEDMI is partially derived from the commonly used Mission Dependency Index but improves significantly upon it, integrating nuanced inputs such as "mission impact," measured as "the base commander's preference for completion of a particular mission." EEDMI further incorporates a full assessment of system-failure scenarios, the recovery time of each microgrid component (likely a scenario-constrained probabilistic estimate) and uses Monte Carlo simulation techniques to quantify the expected mission impact for each scenario [87].

EEDMI yields an ordinal ranking of possible microgrid architectures, a valuable input for assessing multiple design choices. EEDMI's attention to commander's intent is a keen one; several SMEs informed HDIAC that the flexibility of a microgrid's power options is central to command interest in them [29, 59, 66, 93]. In a contingency operation, a base's gymnasium (typically a sheddable load and not a critical one) may need to be powered up for casualty triage or other operations. An ideal approach may be to develop four or five "base power conditions" for a commander to select from during a disruption or unexpected change of mission—predetermined based on a careful study of the effect of changing operational requirements to a base, including the consideration of extreme or contested combat conditions [66, 93].

SECTION 04

MICROGRID DESIGN, FORECASTING, MODELING, AND SIMULATION

Conceptualizing, setting goals and objectives for, scoping out, and designing a microgrid's structure and architecture are incredibly complex—and perhaps nowhere more so than for a DoD installation. It is not only that each base is unique [58], but that many lack detailed documentation of their electric systems, including for any follow-on upgrades. This is especially true for homeland bases built during the second world war [32]. Some installations even run at different voltages [59]. Furthermore, each new DoD microgrid project is likely to face a unique assemblage of state and local standards and requirements; must conform to an installation's master plan (if applicable); and may have to juggle among fragmented command authorities, base tenants, and the differing terms and conditions of dissimilar funding sources [112].

Moreover, planning for a microgrid is in many respects the most important step in its build-out and commissioning. Most microgrids in the United States are bespoke, one-off designs, lacking easily interoperable components or modular software architectures [67, 74, 88], although that has changed recently somewhat due to vendor efforts [34, 66]. As a result, once a design and architecture are set, it will be difficult to alter the microgrid's scope during a project's development and implementation phases—prohibitively so after its commissioning [8]. Thus, after consultation with stakeholders, the enumeration of system risks, identification of loads as critical (or adjustable/sheddable), and the setting of the microgrid's high-level goals is complete [109], comprehensive data acquisition is perhaps the most critical step in the process [112]. Engineers will require ample data on base-wide electrical load histories, granular metering data (ideally <20 ms), system single line diagrams, utility control systems, load-flow calculations, existing communication networks, and much more [109]. High-quality inputs enable the rightsizing of generation, optimal distribution line layouts, the maximization of electric system stability, and a reduction in (or the more efficient redirection of) capital costs.

The DOE and the national laboratories identified early on that microgrid adoption would stagnate without better tools for designing systems to operate resiliently and deliver economic benefits to a customer [170]. The SPIDERS JCTD used the Energy Surety Microgrid tool developed by SNL, an early effort aimed at integrating multiple data sources to generate a conceptual microgrid plan alongside a preliminary electric-grid design output [31, 170, 171]. For MCAS Miramar, NREL conducted a conceptual assessment of its microgrid plan in 2012 using its Continuously Optimized Reliable Energy (CORE) process, which helped scope the project and secure DoD ECIP funds (see Figure 4-1) [109]. As discussed at the start of Section 1, two contractors were awarded the Miramar design-build contract in 2016, outsourcing the system's design and engineering steps—an approach that almost all recently completed or currently in-progress DoD microgrids have also followed [8, 112]. As one of the final steps before its commissioning, the Miramar microgrid controller

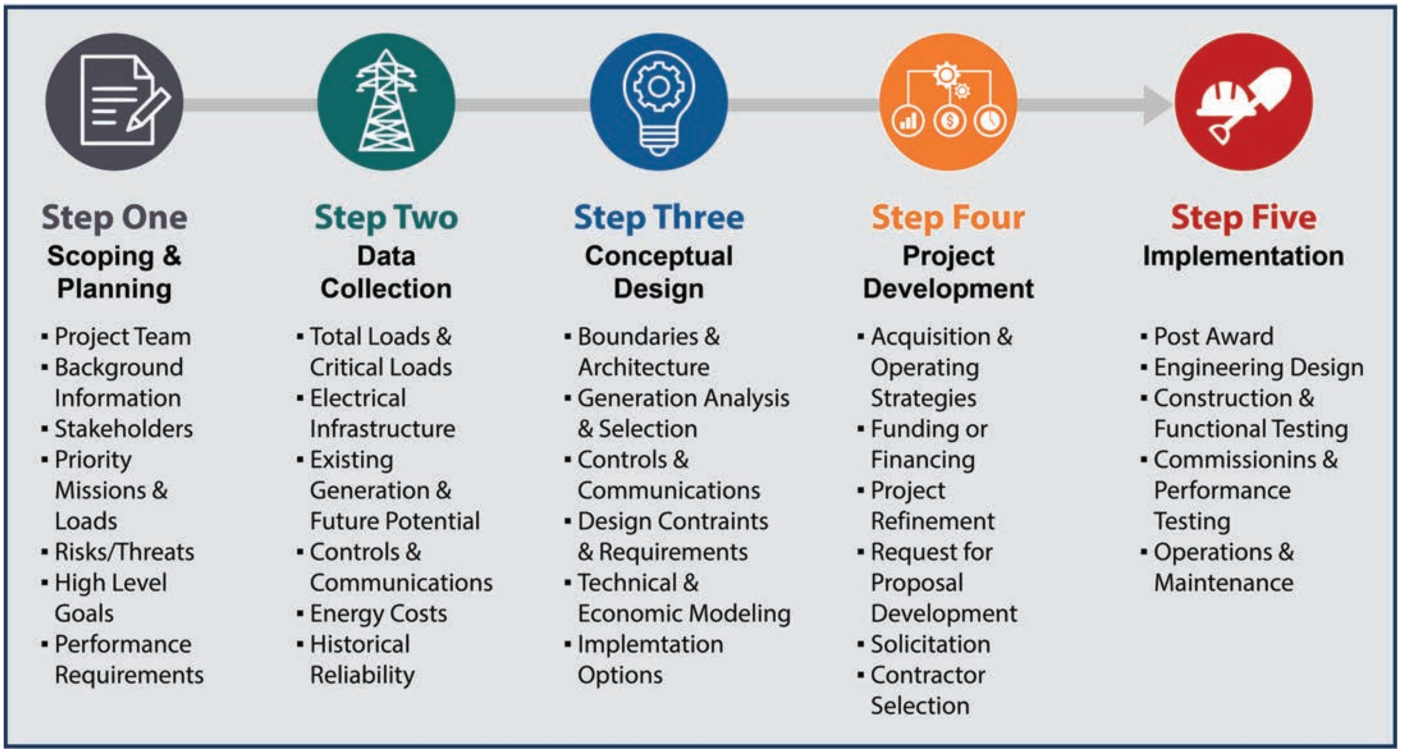


Figure 4-1. NREL's CORE Microgrid Design Process as Revised *(Source: Booth et al. [109])*.

was also subjected to HIL testing to verify its functionality and allow for any needed system refinements [109].

That MCAS Miramar had both national laboratory-provided and commercial design and engineering solutions available to it nearly a decade ago is indicative of a key finding of this report: while "no single tool" is regarded as best for designing a microgrid, this suggests a healthy field rather than a lagging R&D sector [55, 66, 89]. There are ample high-quality microgrid design and planning tools (MDPTs) at the disposal of DoD and its contractors to meet the department's energy resilience requirements and any financial outlay constraints. Different tools furnish different advantages and drawbacks in different contexts, and an MDPT's selection will most likely depend on the specifics of each installation site [8, 66, 67]. Most of all, it must be acknowledged that existing MDPTs do not exactly "spit out a solution" that encompasses every factor from conceptual design to dynamic power analysis [8, 66, 67]. They instead inform the ongoing workflow within the sophisticated capital and construction project that is a microgrid deployment.

In general, *techno-economic models* inform the microgrid scoping, planning, and conceptual design phases, while *power system and transient analysis models* ensure system stability and reliability during the design phase [53, 172]. Existing MDPTs typically follow a computational model based on either optimization or simulation—the former searches through design and operationally-defined parameters to find an answer that best meets a target objective, while the latter predicts (but does not exactly solve for) the behavior of a given microgrid design given its inputs [88, 89]. As a result, while simulation can provide finer time granularity and faster calculation rates, it does not deliver truly optimal results. While simulation is computationally more efficient, it can also require extensive user sorting of options and alternative outcomes; some optimization strategies boost their processing speeds by setting simplified or "reduced formal definitions" of input parameters [88]. Future MDPTs may also improve upon existing combined simulation–optimization approaches, including the embedment of optimization algorithms within a simulation to "model a response to changing conditions," or by validating an optimization solution via simulation [88].

4.1 SELECTED DESIGN AND PLANNING TOOLS

MDPTs in both the public and private sector are not in short supply. One recent study—billed as a "non-exhaustive" review of MDPTs developed by the national laboratories—counted no less than nine major tools active in the public realm, albeit with varying combinations of features [88]. Firms like Schneider Electric and PowerSecure provide comprehensive front-end engineering and design (FEED) services for microgrid customers, whether via proprietary solutions or by augmenting the use of government-developed MDPTs. Some firms that specialize in microgrid design and modeling, including recognized industry leaders XENDEE and Homer Energy, have licensed MDPTs first developed by DOE laboratories before substantially expanding their capabilities, ease of use, and customer-support features [8, 3, 88]. Several leading MDPTs are briefly discussed below, while excluding tools that are relevant but not commonly used for microgrid design (such as NREL's System Advisor Model, which simulates technical and financial performance of renewable generation projects).

4.1.1 DER-CAM

The Distributed Energy Resources Customer Adoption Model (DER-CAM) was first developed at Lawrence Berkeley National Laboratory (LBNL) in 2000 and has been extensively modified since. It is a mixed-integer linear-programming (MILP) decision-support optimization tool for investments in DERs that are intended to power a series of buildings or a microgrid [173]. Freely accessible to the public, DER-CAM is actively used by industry to design microgrid deployments [174], and government and academic scholars use it to assess DER use as well as ancillary topics like electric vehicle charging [175, 176]. Researchers also routinely modify DER-CAM's parameters to incorporate additional variables into its analysis [173, 177]. For a microgrid, DER-CAM calculates the "least cost combination and dispatch" of power drawn from the utility and on-site DERs, optimizing their balance over the period of a year based on different "design day types" (e.g., an average weekday, an outlier day) [172]. DER-CAM achieves this through a "peak-preserving day-type approach" that finds the optimal solution to reduce overall run-times [174]. By doing so, DER-CAM solves for an economic optimization in the sizing, placement, type, and dispatch of DERs to a microgrid, while also quantifying the design's economic value based on the financial performance of the proposed microgrid versus the avoided cost of the system's conventional utility and fuel purchases [172, 178].

DER-CAM is technically mature, and newer versions co-optimize "stacked value streams" like load shifting, peak shaving, utility exports, and participation in macrogrid service markets at time intervals as granular as 1 hour [88, 172, 179, 180]. The software can also incorporate thermal modeling, integrate requirements for compliance with state and local regulations, and model both grid-tied and islanded operations [88, 172, 179]. DER-CAM can be tooled for multi-objective optimization—such as the need to reduce both costs and emissions in balance—and, importantly, produces usable insights into how operational considerations can affect design choices [88, 180]. While DER-CAM is a linear model, segmented linearization means have also been embedded into it to integrate non-linear effects into its analysis [35]. DER-CAM has been used to support several DoD installations; Fort Hunter Liggett developed its microgrid in part by using the operations version of DER-CAM, which generated day-ahead battery storage charge/discharge schedules to inform cost minimization [181, 182].

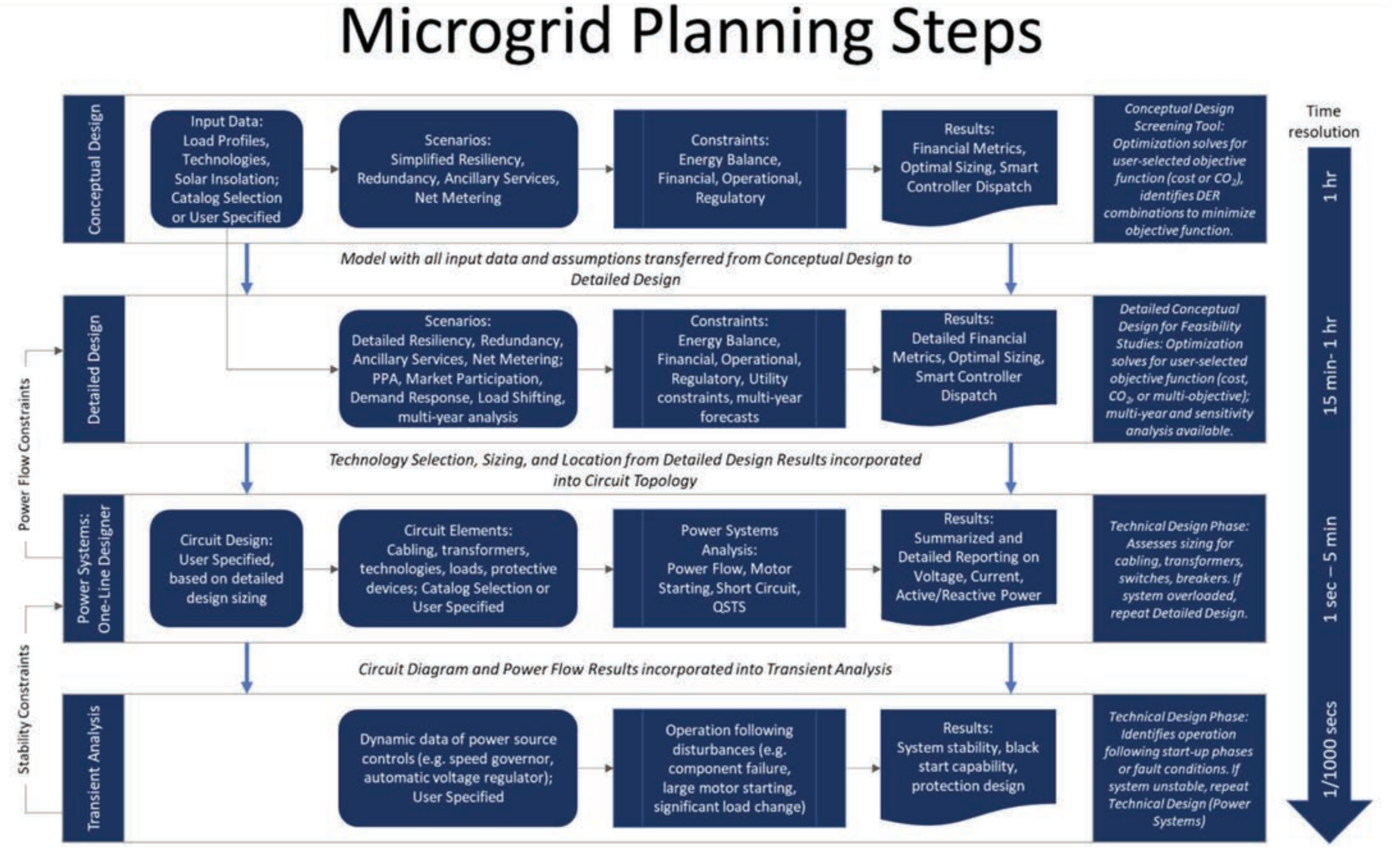
4.1.2 XENDEE

LBNL began the process of commercializing DER-CAM in 2016, in the wake of its many years of iterative improvements through use by industry and academia. It released DER-CAM$^+$ for licensing, after first adding electrical power flow models for active and reactive power, and a more complete revenue model [183]. In 2018, XENDEE (a La Jolla, California-based firm) acquired the license, with DER-CAM's lead developer at LBNL also signing on as the firm's Chief Technology Officer (CTO). XENDEE's microgrid modeling platform is a cloud-based program built around a holistic mixed-integer linear optimization model that—like DER-CAM—combines planning variables with operational parameters, an approach that reduces system latency and maximizes continuity over a project's lengthy development stages [184]. XENDEE also plans to adapt its design platform for use in microgrid control services, slated for likely release in early 2023 [184]. Among the SMEs who discussed MDPTs with HDIAC, XENDEE repeatedly came up as a "very good" or "great" tool, one regarded as the leading offering from industry—including for use in the DoD installation market [8, 73, 89]. Indeed, XENDEE's platform won the 2021 gold medal in the prestigious Edison Awards for automated infrastructure design.

The source of XENDEE's competitive advantage is twofold. For one, it is easy to use: the platform's graphical interface is intuitive, adaptive, and guides a user (who is more likely to be a group of several representatives from multiple stakeholders) through the design process [185]. Its processing algorithms are also substantially fast, allowing for the rapid consideration of alternative microgrid architectures "on the fly" [89]. Second, unique to XENDEE at present is its ability to model changes over time in a multiyear setup, even decades into the future [89, 184]. The platform also minimizes requirements for customer-supplied data inputs. Equipment-cost catalog data, tariff prices, weather conditions, siting-based geographical information system (GIS) data, and financial conditions—including a set of generic economic assumptions to use before specific financing structures are agreed to—are largely pre-populated into the platform, to a level of specificity that includes technical specifications of some vendor-specific equipment [172, 184]. Of all existing MDPTs available on the market, XENDEE comes closest to fully integrating all phases of the microgrid scoping, design, and engineering process into a single tool—from economic optimization to short-circuit, dynamic, and harmonic power flow modeling (see Figure 4-2) [92].

4.1.3 REopt

The REopt tool, in development by NREL since 2007, is an open-source decision-support optimization model that also follows a MILP approach. Generally tailored toward more novice users (or purposefully more to inform integrated feasibility conceptual studies), REopt has seen very wide application within industry, including at multiple DoD homeland installations [186]. Recent uses of REopt for the DoD resulted in the funding of at least two Texas Army National Guard energy resilience projects [179, 186]. As its name suggests, REopt is a techno-economic model, which follows a time series approach to solve a deterministic optimization problem where energy balances (i.e., size and dispatch of generation and storage assets) are maintained, and operational constraints (e.g., critical-load sustainment) are upheld, while full-cycle energy costs are minimized (see Figure 4-3) [172]. Similar to DER-CAM and XENDEE, REopt can model a microgrid design in both grid-connected and islanded mode, and its data inputs are extensive, allowing for consideration of complex utility-rate tariffs and incentives, ancillary value streams, technology costs, geospatial site data, and tax/discount rates [88, 187]. One leading scholar in renewable power modeling told HDIAC that REopt provided the best value among the public-sector MDPTs, sporting a well-designed user interface with a nearly "daunting" array of potential variables for input—a nice combination of complexity and simplicity [89].



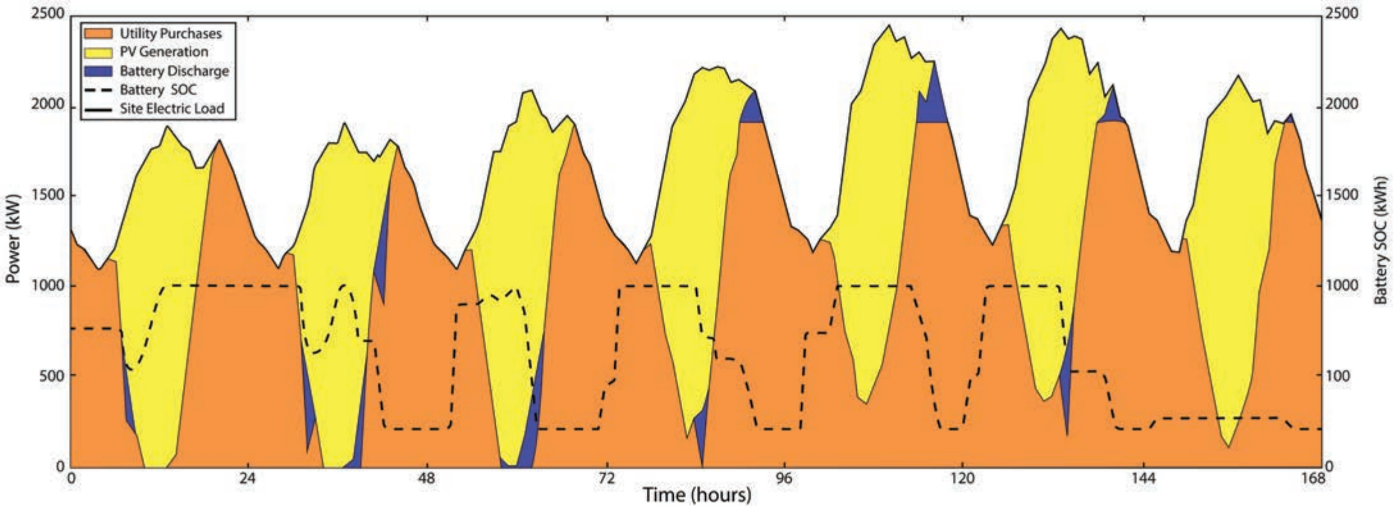
Note: PPA (power purchasing agreement), QSTS (quasi static time series)

Figure 4-2. Microgrid Planning Steps Captured in the XENDEE Corporation's Holistic Planning and Operations Platform *(Source: Stadler and Pecenak [184], Reprinted With Permission From XENDEE)*.

REopt's outputs are customizable and provide actionable insights for a microgrid scoping and planning team. REopt can identify the types and sizes of DERs (both conventional and renewable) that meet site goals at the lowest lifecycle cost, and it can determine the net present value of discrete energy systems under consideration. Most useful to DoD purposes, REopt can also quantify the survivability of a microgrid during an extended outage as a function of time [187]. Previously available only as a loadable tool, NREL released a simplified version of REopt onto the web in 2017, dubbing it "REopt Lite." The laboratory has since dropped the "Lite" moniker, reflecting REopt online's growing capabilities and reputation in 2022 as a mature and "heavy-hitting" optimization tool [188]. Since its debut, REopt has supported the installation of more than 260 MW of renewable capacity across thousands of locations, including at U.S. Army Fort Huachuca, AZ, and USMC Base Camp Lejeune [188].

4.1.4 HOMER Pro

Just as XENDEE derives in part from DER-CAM, HOMER Energy's design software—named after the Hybrid Optimization Model for Multiple Energy Resources—emerged from work at NREL, dating back to 1990s-era research on what was then called micropower DERs [189]. HOMER Energy was founded in 2009 (and acquired in 2019 by UL), and as with XENDEE, its leadership drew upon the original talent that developed the HOMER tool at NREL (and may have drawn some inspiration from REopt) [8, 189]. Of the MDPTs previously surveyed, the commercial HOMER Pro tool represents the greatest departure from the mainstream use of mixed-integer linear programming for microgrid optimization. HOMER does not use a mathematical method to solve for an answer but follows a more enumerated trial-and-error (or "exhaustive search") simulation and optimization approach, via proprietary algorithms that deliver a design



Note: SOC (state of change)

Figure 4-3. REopt-Generated Cost-Optimal Economic Dispatch Strategy for a Combined PV and Battery System *(Source: NREL [190])*.

result based on minimizing long-term capital and O&M costs [89, 172, 178]. However, that difference may not necessarily detract from its usefulness, given its powerful sensitivity analysis features that allow careful comparison of system configurations [35, 172, 191]. HOMER Pro is also often preferred for the planning and design of off-grid or remote microgrids.

4.1.5 Models Under Development

The short list of MDPTs surveyed previously is not intended to be a restrictive one; however, several other tools merit mention. SNL presents a qualitative methodology in its *Microgrid Conceptual Design Guidebook*, written to guide users toward a 20%-complete solution that yields a preliminary configuration assessment and range of lifecycle costs [192]. The MDT—also developed by SNL—is one of the earliest and most complex MDPTs, and it has been routinely used to design systems to support critical loads, including at DoD facilities [88, 186]. It is a powerful tool, using both Monte Carlo simulation and multi-objective evolutionary optimization algorithms; it also gives a user more granularity than some MDPTs in setting load or demand-side management strategies for islanding operations, allowing for the definition of loads as "priority," "non-priority," "critical, uninterruptible," or "critical, interruptible" [88, 172, 178]. However, the MDT can be difficult to access and tedious to operate and appears to have been very lightly used by the DoD installation microgrid community in recent years [8, 186].

Two forthcoming tools are also of note. A multidisciplinary team at the Naval Postgraduate School (NPS), working under the Navy Shore Energy Technology Transition and Integration (NSETTI) program, is several years into the development of a microgrid design tool focused on efficiently "rightsizing" the size, location, and distribution of DERs (especially solar + storage) for critical loads at naval facilities [8, 193, 194]. While an early version of the tool is available online (and includes an API, or application programming interface), the NPS team is actively programming more flexibility for the user into the tool [194]. Moreover, NPS is working to add the EEDMI military mission-specific resilience index discussed in Section 3.3 into its function [194].

Elsewhere, the National Rural Electric Cooperative Association (NRECA)—which represents the constellation of electric cooperatives that serve just 12% of the U.S. population but cover more than 55% of its landmass—has tapped DOE and DoD ESTCP funds to develop MicrogridUP, an in-development microgrid planning framework that seeks to simplify "the process of planning for the integration of assets with legacy infrastructure" [91]. Using an open-source solution, NRCEA plans to leverage its member utilities that hold UP contracts with DoD installations to acquire comprehensive electrical distribution data for them. NRECA will then extend its utility-facing power system analytical tools to the modeling of its integration with a future DoD microgrid's high level of renewable power generation [91, 195]. This will lower both the technical and soft costs of connecting a rural utility to a DoD microgrid system, help optimize the microgrid's design itself, and purportedly deliver a "scalable microgrid planning framework" to the department that can reduce the software and planning difficulties that currently limit the widespread adoption of microgrids within the DoD [195].

4.2 STANDARDIZATION AND ANOMALIES

In recent years, MDPTs have evolved toward the exploitation of increasingly wider ranges of data and engineering requirements, tightened the coupling of design and operational considerations within their architectures, and improved their treatment of unconventional energy storage assets (e.g., thermal loads) in their models [88]. Future MDPTs are likely to incorporate at least a minimal analysis of a microgrid's interfaces with peripheral infrastructures like natural gas distribution mains and water utilities. Current design tools focus on a microgrid's electrical systems to the detriment of a holistic assessment of its dependence on supporting services [68, 88, 162]. While cybersecurity is outside the scope of this report, it should be noted that MDPTs will need to better assess system vulnerabilities as designs grow in complexity, as even traditional microgrid architectures have recently proven extremely susceptible to cyberattack. At an August 2022 Pentagon-sponsored hacking challenge, the most successful white-hat attempt exploited a microgrid's use of National Oceanic and Atmospheric Administration weather data to inject killer code into its controller. Another hacker—a teenager—exploited the system's use of the non-negative Kelvin temperature scale to crash the controller [105].

Dynamic modeling or simulation of a microgrid is also likely soon to be within the reach of laboratory bench-grade MDPT systems [55, 88]. Elsewhere, research efforts, including one notable ESTCP-funded effort led by the firm Typhoon HIL, hope to deliver integrated "model-based" design approaches that use flexible, modular, and interoperable processes and software [90]. Model-based modularity, in turn, supports easy application of physical control-HIL testbeds to conduct systems-wide validation at ultrahigh fidelity prior to deployment [88, 90].

As the Typhoon HIL and MicrogridUP efforts make clear, there remains an especially strong interest within the DoD (and elsewhere) to standardize, or at least streamline, the microgrid design, planning, and engineering process—to both improve system functionality and reduce deployment and lifecycle O&M costs. This should entail, at a minimum, the normalization of existing MDPT data formats (so-called plug-and-play functionality), which would allow tools to freely input and export reports, permitting their analyses to "close couple" and yield results superior to those of any one tool used in isolation [67, 68, 88]. At its maximum, standardization might entail a single tool that captures all needed MDPT requirements from tooth to tail, although opinion is divided as to the feasibility or desirability of such an arrangement [67, 88].

Still, there is a wide gap between increased interoperability and a one-size-fits-all footing. Although current microgrid projects are generally well served by existing MDPTs and design-build contractors [8], even minimal streamlining of microgrid planning approaches could bring immense benefits to the DoD. ESTCP investment in an R&D effort by XENDEE engineers (in collaboration with multiple partners, including Pacific Northwest National Laboratory and Arizona State University [196]) is seeking to standardize and adapt the firm's platform for DoD use, in part by integrating data on military-specific configurations, interfaces, and equipment catalogues [92]. While many deem the XENDEE platform as already quite proximate to a standardized (or at least streamlined) approach, this study would render those benefits directly for repeated DoD use, reducing reliance on external energy vendors/consultants and potentially knocking down microgrid FEED costs from around 25% of total project implementation costs to "less than 5%" [92].

XENDEE demonstrated its preliminary work product in 2022 across a set of three disparate DoD installations, including the strategic Naval Submarine Base Kings Bay in the State of Georgia and at U.S. Army Garrison Bavaria in Germany, well outside the homeland [196]. Critically, XENDEE's DoD-facing product has already tailored its platform training resources to the nuances of the DoD utilities and energy resilience community [92]. As two XENDEE leaders explained in September 2022 after the pilot demonstrations concluded, "it was clear that the people in charge of getting microgrids built were not equipped with the tools or network to do so"—because they lacked the time and institutional experience with microgrid design. Such organizational barriers further contribute to the services' already heavy reliance on third-party design-and-build energy firms [196].

Finally, while a military microgrid is protected from many of the threats facing the macrogrid detailed in Section 3.1, it will not remain invulnerable to all. Future MDPTs—as well as organizational actions taken at the conceptual scoping phase of a DoD microgrid—should plan for long-term changes in the climate, based on reliable projections of future temperature, weather, and extreme-event environments [162]. ESTCP has already funded several projects to produce improved defense climate information at a resolution usable at the installation level [197, 198]. Efforts to predict how future climate and weather trends will affect the grid at the macro-level are also under way, involving research universities, regional utilities, DOE laboratories, and the Electric Power Research Institute [199], while other groups are applying ML to forecast future wildfire risks to grid infrastructure sites [200].

While HDIAC understands that no existing MDPT currently integrates a forecast of future climate-change-accelerated environmental extremes [88, 89], a landmark 2022 paper in *iScience* by the University of California San Diego's Ryan Hanna and Jeffrey Marqusee of NREL [94] details how microgrid modeling tools can and should incorporate extreme or outlier events. Namely, the incorporation of exceedingly long-duration outage assumptions will result in a more resilient system and better capture the broad range of a microgrid's economic resilience benefits. They note that while some recent MDPT research has expanded from a focus on system considerations toward a broader focus on modeling microgrid resilience (including a 2021 NREL simulation-assisted optimization approach that probabilistically estimates system resilience using REopt Lite [201]), microgrid model developers at large have "not tackled long-duration outages generally, their fat-tailed distributions, or the effects they have on optimal DER selection in microgrids and on system reliability and resilience" [94]. Failing to do so undermines a microgrid's resilience benefits and generates reliability on paper that may prove unreliable in real world scenarios.

Moreover, planning for extreme, anomalous scenarios is unlikely to entail an outsized increase in cost. As Hanna and Marqusee write, "including long-duration outages can lead to moderate shifts in investment but large increases in resilience value. In some circumstances, resilience benefits can grow faster than the costs of protecting against long-duration outages" [94]. Furthermore, where existing MDPTs have considered the restoration/recovery operation of a microgrid, they have generally used simulation tools to do so; as one DOE report noted in 2021, these simulation tools have not been "directly coupled to models of extreme events (wildfire, cold weather, etc.) that create situations that require restoration and recovery" [88].

This Page Intentionally Left Blank

SECTION 05

MICROGRID CONTROL AND ARCHITECTURE

More than simply the brain of a microgrid, its controller is the "defining and enabling technology" underlying the concept [148, 202]. There are several fundamental functions that a microgrid controller (MGC) must deliver. It must represent the microgrid to the utility as a single controllable entity (so as to receive frequency control); dispatch power from DERs to balance generation and load; avoid routing power flows that exceed line or device ratings; smoothly disconnect from the macrogrid when needed, while maintaining frequency and voltage regulation and damping any transients; and safely reconnect and resynchronize [53, 62, 202]. Low system inertia and relatively short distribution lines can make maintaining frequency and voltage stability during islanding a primary control challenge of an MGC [203].

Some would add to this list—and appropriately so for a DoD installation—the requirement that a microgrid be able to perform a black start independently of external assistance [8, 81, 204]. Furthermore, with R&D in controllers and control theory receiving more academic and commercial attention with each passing year, expectations of an MGC's minimum functions have progressed in kind. Many would now include functions like demand response, load shedding, remote monitoring and control of assets, and proactive cost-reduction optimization (via minimized LCOE) as no less than mandatory tasks for a modern controller system [205, 206].

Control schemes for larger grid-tied microgrids mirror the approach adopted by the bulk power system in the United States, which uses a hierarchical control system that subdivides control actions into a multilayer structure to keep the system stable and running efficiently [95, 203]. *Primary control* ensures system voltage/frequency stability, divides power sharing among DER units, and detects islanding conditions. *Secondary control* mitigates voltage/frequency deviations caused by primary control and may facilitate the utility connection or perform optimization actions. *Tertiary control* regulates active/reactive power exchange and synchronizes the system to achieve multi-objective optimization and respond to changing conditions (e.g., utility rates, weather) [35, 203, 206, 207]. Each layer operates on a different timescale; tertiary actions can take a few or several minutes to execute, while primary control actions come at the scale of tens of milliseconds [95].

There is no generally agreed-upon or standard microgrid control architecture, although approaches are generally classified as *centralized, decentralized*, or *distributed* (the third is briefly addressed in Section 5.2). Seeing value in each, the DOE microgrid R&D program is agnostic on whether one architecture should be preferred [81]. Most extant microgrids follow a centralized approach in which the MGC receives data from DERs and all other components, returning commands based on a complete view of system inputs (note that some primary control actions may remain localized) [207, 208]. Centralized control brings immense benefits. Its use is familiar to the utilities and energy workforce, for one [34], and it delivers high system observability and allows a close grip on a microgrid's operations (see Figure 5-1) [208]. While the centralization of control does bring high communications system requirements, leads to greater low-voltage distribution losses along extended lines, and can pose a single point-of-failure risk, it is relatively easy to implement and enables the "continuously updated optimization" of a microgrid [95, 100, 208].

Figure 5-1. A General Electric (GE) U90^{Plus} Microgrid Generation Optimizer Monitors and Forecasts Solar PV Production at the USMC Air Ground Combat Center, Twentynine Palms, 2014 *(Source: Mudd [209])*.

In decentralized control, each DER acts on signals from its local controller, which does not require communication with other components of the microgrid [208, 210]. This approach can improve system scalability and reliability, making it less susceptible to the loss of a component or its communication link [210]. It also obviates the need for a master controller, which may lower overall costs [210]. However, the relatively low cost of commercial MGCs to DoD (around $100,000 by one estimate [8]) limits the appeal of that rationale. Most of all, decentralized control lacks performance in reaching optimal solutions, which a centralized MGC excels at. Indeed, a major focus of recent R&D in the control space is the encoding of advanced power management or optimization algorithms aimed mostly at centralized secondary and tertiary control; these include hybrid optimization techniques such as genetic harmony search, reinforcement learning, multi-agent systems, long short-term memory, and deep recurrent neural networks [206, 208]. Some observers see a recognizable trend in controller theory and R&D as moving away from the perennial topics of stability and prediction and toward system optimization [97, 98].

5.1 CONTROLLER DEVELOPMENT AND RESEARCH

In general, the complexity of an MGC and its communication system increases with a rise in the number and type diversity of its DERs, the areal extent of its network, and the number and sophistication of its connected loads [207]. In tandem with the recent acceleration of real-world microgrid build-outs and project sanctions, research in the microgrid control space has grown incredibly complex and narrowly detailed [81, 95, 208]. As one SME remarked to HDIAC, "There is no literature more opaque than the control literature" [8].

What is evident is that existing, commercially available MGCs more than meet the DoD's needs in the near term. Multiple manufacturers produce top-tier controllers and ancillary equipment, including GE, Schneider Electric, Siemens, PowerSecure, and SEL [8, 32, 43, 66]—and have done so for many years. For example, the U90^{Plus} Microgrid Generation Optimizer pictured in Figure 5-1 was first marketed in 2012. For the most part, vendors differ only marginally in efficiency or capability and their provision of professional services is likely to be more determinative in their selection. One SME described the innovation-speak-heavy marketing language that vendors use to differentiate their controllers as just their "secret sauce"; in practice, their MGCs and ancillary services are fairly equivalent [32, 66]. The control-related market at large is both strong and broad. SEL has built improved relays that limit inverter power "twitchiness" [211]; Toshiba has released grid-forming inverters that improve the stabilizing effects of algorithmically created synthetic "pseudo-inertia" [212]; and Schneider Electric's building-level, load-management equipment features local digital twin capabilities and automated diagnostic tools [213]. Through an ongoing ESTCP grant, SEL is also currently investigating more intelligent distribution-fault-location devices designed to communicate with a centralized controller [214].

Commercial controllers have already served DoD installations well. The control system delivered to MCAS Miramar by Schneider Electric uses the firm's proprietary and real-time OASyS SCADA (supervisory control and data acquisition) software and a certified network linked to the centralized controller. Even leading systems integrators like Ameresco find commercial MGCs to be largely substitutable, if particular to specific installation missions—the firm has used at least three different MGC vendors for three different DoD microgrid contracts [8].

Moreover, commercial investment in improving MGC technology over the past decade has less in common with traditional R&D than what scholars of innovation have termed its "less often noticed inverse, development and research" [215]. Whereas R&D begins with the search for foundational knowledge, the most common form of corporate innovation might be termed development and research, or *D&R*, which pursues specific developmental goals—like a new product—in a situation of inadequate but not wholly uncertain knowledge [215].

While the work done by the DOE and the national laboratories on microgrids can more properly be considered R&D, the DOE routinely uses commercial technology as a starting point in anticipating the needs of microgrid systems years into the future [68, 81]. In 2018, NREL held a microgrid controller challenge, a two-stage competitive procurement that evaluated five different MGC products across a series of 100-minute-long simulation sequences [216]. In the end, NREL selected—and purchased—a controller from SEL, which it then installed in its Energy Systems Integration Facility, a permanent hardware-based microgrid research testbed facility located in Golden, CO [216].

Future advancements in microgrid control are likely to (1) simplify the addition or integration of new assets/devices into an existing microgrid; (2) expand black start capabilities in inverter-based microgrids, in part to support the macrogrid; (3) improve microgrid monitoring and diagnostic capabilities, like non-intrusive metering or high-fidelity sensing; (4) simplify the self-assembly of clustered or networked microgrids; and (5) increasingly adopt modular or open-source components [66, 68]. In the near term, control systems will grow more complex and flexible, implementing advanced control algorithms and tools that can support dynamic (or automatic) optimization of multiple objectives—potentially with ML-enabled predictive qualities [8, 65, 95, 97, 98]. Ongoing research at Arizona State University for the U.S. Navy is developing ML strategies for microgrid self-regulation against changing market tariffs, and the maximization of operational time when islanded [65]. At present, many of these operations are not automated, the latter of which limits an installation's ability to efficiently balance loads and generation during an extended islanded period [8, 65].

Similar to how the MCAS Miramar microgrid can draw upon an HVAC-based demand response program, more microgrid control systems will incorporate sophisticated load management capabilities (also known as "advanced distribution management systems") to avoid having to shed whole classes of low priority loads when there is insufficient power [93]. These systems can help perform demand response (consumption limitation) and load shifting (moving energy-intensive processes to off-peak hours) [8, 32, 90]. When linked to a system like BEMS that provides highly specific metering data, the MGC can precisely trim away (or reschedule) the load, as well as better predict upcoming building load profiles to counter demand uncertainty (known as a longer control horizon) [66, 217]. A critical question will be whether these subsystems should be integrated into the master controller, or just coordinate with it—and how closely [8, 66].

5.2 DISTRIBUTED CONTROL

The concept of distributed control is a variation or improvement upon a decentralized approach. Sometimes called multi-agent system control, distributed systems also do not rely upon a centralized controller, and further dispense with physical links between local or DER-connected controllers [99]. By attaching a local controller (an agent) to each asset or load, distributed control can perform primary control actions cooperatively and rely on more centralized—but less "authoritative" or controlling—elements to array secondary and tertiary control responses [100]. Actively considered since the mid-2000s, agent or distributed control relies on direct, peer-to-peer communication between devices, which may improve a microgrid's reliability and flexibility [99]. Moreover, it removes a central vulnerability inherent in a centralized MGC, its single point of failure [26, 100]. Distributed systems also make more efficient use of available computational systems [95].

To date, distributed microgrid control systems have rarely, if ever, emerged beyond the simulation or lab bench-evaluation stage [100]. With DOE Advanced Research Project Agency–Energy and ESTCP funding, a team led by researchers from Vanderbilt University recently debuted a distributed control system that runs on an open-source network (using OpenFMB and other interfaces) based on a series of inexpensive embedded computing nodes (here, Kunbus devices) [218]. The cloud computing platform developed by the Resilient Information Architecture Platform for the Smart Grid (RIAPS) project manages the control algorithms and provides users with a complete operating system while also conducting fault management, maintaining logs, and allowing remote access. The project team has also successfully tested its approach in an HIL testbed and an expanded Banshee distribution network across multiple operating modes (e.g., grid connected, islanded, during transitions) [218]. The group is building out a reference set for future site-specific designs and hopes to test its approach in a small but real-world laboratory test microgrid by early 2023 [218]. Ongoing work even more advanced seeks to use breakthroughs in quantum science to devise quantum communication schemes for future distributed microgrid controllers to improve system synchronization [219].

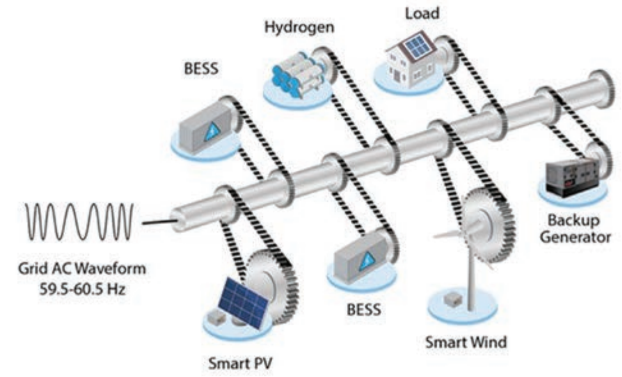
If successfully field-demonstrated, distributed control could bring immense benefits to a DoD installation microgrid. It can allow precise power flow control at the PCC, optimize power sharing among base DERs, and further guarantee the seamless and safe transition between operating states [218]. Many researchers also see it as a key enabler of the clustered or networked microgrids concept [220]. Another ESTCP-funded effort from LBNL is using a multilayered, distributed controller based on the DER-CAM design tool, to boost microgrid scalability and reduce DoD costs. It would enable an installation microgrid to incorporate critical loads into its coverage first, before expanding its reach over a period of several years in a truly modular fashion [104]. Major utilities like Duke Energy also remain interested in similar grid-edge distributed-control methods [221]. For a DoD microgrid, distributed control, if successfully implemented, may significantly reduce costs and could grant a commander more flexibility in selecting among DER and/or utility usage.

Nevertheless, distributed microgrid control has yet to make its case both for its technical superiority to centralization or its potential to reduce costs [8]. Many commercial relays only support standard point-to-point supervisory control protocols [100], and serious cybersecurity concerns remain prominent, only compounding existing worries about the cyber-vulnerability of solar PV and battery storage DERs. Even though efforts like Vanderbilt's comply with DoD's risk management framework and National Institute of Standards and Technology guidelines on security and privacy controls for interconnected networks [102], distributed control appears to provide malicious actors with a wider range of attack vectors to exploit, with little additional upside as of yet.

In 2020, a power outage hit the National Renewable Energy Laboratory itself, catching the microgrid R&D hub at its Flatirons Campus a bit off guard. "We didn't have a microgrid controller capable to black start and manage all the microgrid assets," said Przemyslaw Koralewicz, an electrical engineer at NREL, "and building a controller from scratch was impractical with such short notice" [222]. Instead, the team built a decentralized—but "communication-less"—control system, programming each DER independently to coordinate without data exchange (see Figure 5-2). While perhaps not exactly a distributed control system, its approach follows a similar philosophy. NREL's system relies on individual DER generation sources to detect the microgrid's frequency and self-stabilize it, by increasing or reducing power accordingly [223]. The system could one day "become the standard for fail-safe microgrids," Koralewicz concluded [222].

5.3 BUILDING BLOCKS AND LINCOLN LOGS

Even more than the streamlining of microgrid planning and design tools discussed in Section 4.2, proposals for the standardization of MGCs (and even a microgrid's fundamental architecture) are fraught with technical challenges and organizational hurdles. While a handful of microgrid standards exist, they are closer to guidelines in practice—very generic ones at that [74, 100]. One SME explained to HDIAC that while you can take ten M16 rifles, disassemble and mix their components in a box, and easily build them back at random, that interchangeability is impossible with microgrid components [32]. The mishmash of devices and systems caused by vendor lock, proprietary protocols/networks, and customized centralized controllers raises costs and increases the labor intensiveness of current microgrid deployments [32]. Although tailoring a microgrid to specific mission needs is possible, to do so entails great cost and a lifespan of system complexity. Moreover, because of this market fragmentation—and the microgrid market's continued rapid evolution—powerful incentives oppositional to standardization are likely to win out in the near and even midterm [26, 65, 77].



Note: BESS (battery energy storage system)

Figure 5-2. Conceptual Schematic of NREL's Communication-less Microgrid Control Design *(Source: Koralewicz et al. [223])*.

Even so, the eventual success of a push toward standardized communications and control protocols, vendor-agnostic software, and interoperable components seems almost self-evident [67, 68, 73]. Perhaps more so than any other technical hurdle, the constellation of systems and processes frustrates both microgrid R&D engineers and on-the-ground practitioners [26, 32, 69, 73, 74]. The vision of modularity and flexibility in microgrid control architectures is central to the

DOE microgrid R&D program's research strategy, and prime within it is the concept of inventing building blocks for microgrids [68].

As its name clearly telegraphs, the Microgrid Building Blocks (MBB) project seeks simplicity and ease for the microgrid developer and customer alike. A collaboration among eight DOE national laboratories, two universities, and industry advisors, the MBB effort dates back to 2019. Its core goal is to design modularity into the basic functions of a microgrid—power conversion, control and communications, protection, islanding and reconnection, and storage [75]. Standardizing power-conversion communication and control interfaces is particularly central to achieving this vision [73]. While the vision behind MBB is an original one for microgrids, the building block concept has found success elsewhere before, namely in power electronics and in solid-state transformers and power substations [75].

Once developed, the MBB concept could bring immense benefits both to the DoD and the broader microgrid market. A modular, MBB-built microgrid would display enhanced transient stability; have communication delays well below the system's critical latency; run on three-phase, unbalanced power flow optimized in light of higher non-dispatchable (or variable) DER use; and reliably deliver restoration or black-start capabilities, including at the bulk power level [224]. As Chen-Ching Liu, project co-lead and American Electric Power Professor at Virginia Tech told HDIAC, although the MBB concept remains in its early stages, it is no longer a basic research challenge but "a technology issue" [225].

While developments in "foundational technologies" are still required to facilitate its adoption [68]—and some SMEs expect the MBB concept to remain in development for a lengthy period—Liu sees the timeline ahead as mostly uncomplicated (see Figure 5-3). The project team hopes to have a virtual prototype developed soon, and to start validating the physical design at a national laboratory one year afterward [225]. However, the next step is an organizational challenge that may prove to be an even larger hurdle—seeking collaboration and eventual buy-in from additional industry members in the manufacturer space [225].

Another vision for microgrid standardization—one perhaps more ambitious than MBB—is an offshoot of the tactical microgrid standard (TMS), developed by a consortium consisting of the U.S. Army Corps of Engineers Construction Engineering Research Laboratory (USACE CERL); MIT Lincoln Laboratory; the U.S. Army Combat Capabilities Development Command (CCDC) C5ISR Center; Parsons; Humber-Garick Consulting Engineers; SEL; U.S. Army Project Manager Expeditionary Energy and Sustainment Systems (PM E2S2); and hundreds of other government and industry participants. In various stages of conceptualization, development, and prototyping since 2013, TMS was first developed for use in truly remote microgrids with military forward operating bases (FOBs) and even combat outposts in mind [226] and stands as a proven concept [32].

TMS is designed to network multiple traditional diesel-fired battlefield generators as well as renewable sources in a fashion that simplifies system communication, control, and cybersecurity while also delivering superior Warfighter safety protection. It was designed with an understanding of the realities of a combat-focused mindset: it is Warfighter-friendly and sports true plug-and-play operation [227]. Indeed, one of its core benefits is that any new load or generation device can be seamlessly plugged into it, literally: the standardized interface definition language of the TMS network causes it to reform its entire topology once a new device connects [77]. TMS has the potential to transform how bases plan and deploy microgrid technology, making the rapid assembly of modular components pain-free and affordable, allowing incremental expansion without costly engineering assessments, and enabling rapid system reconfiguration to meet changing mission

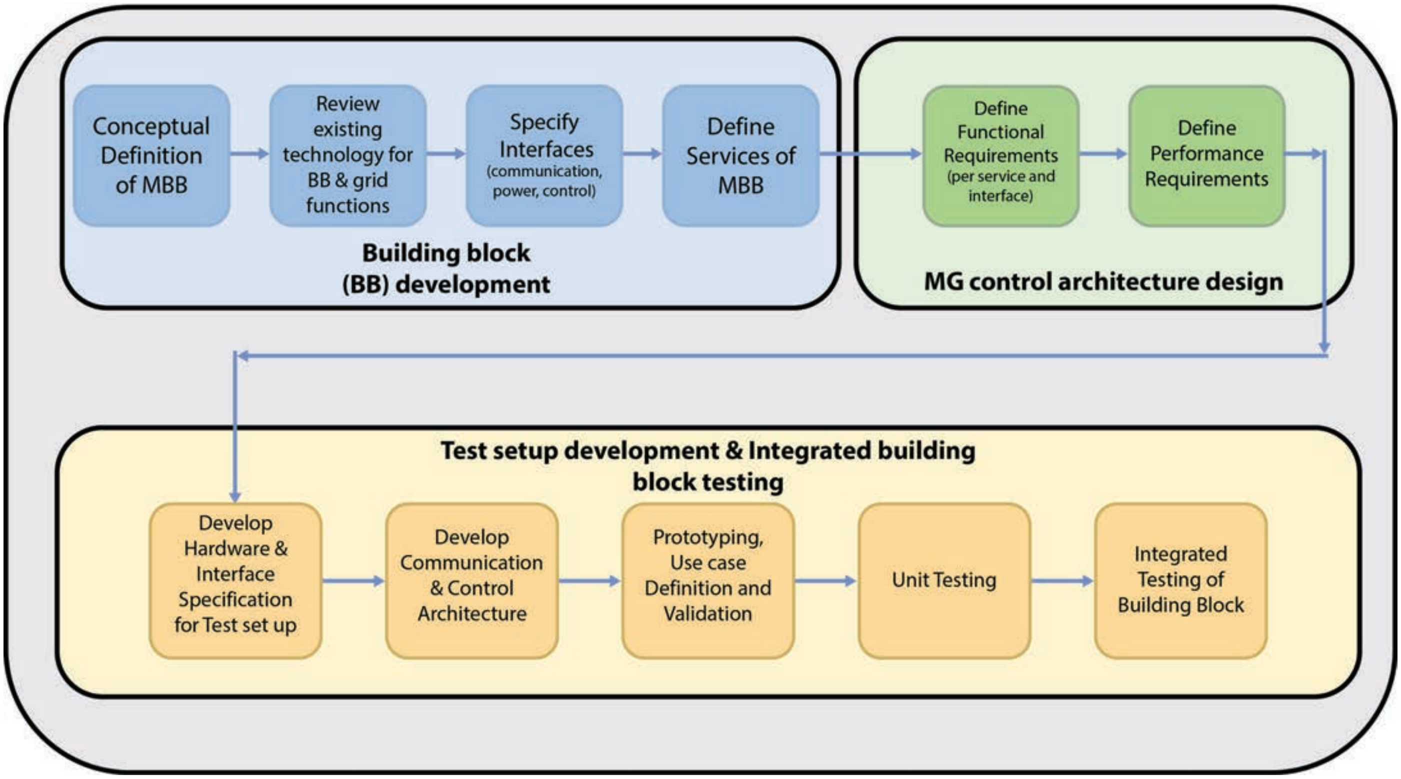


Figure 5-3. MBB Design, Development, and Testing Roadmap *(Source: Liu et al. [75])*.

requirements [32]. In one sense, TMS is a type of distributed control system, if an exceptionally advanced one. TMS has gone through multiple validations, HIL tests, and field demonstrations. It is central to the Secure Tactical Advanced Mobile Power (STAMP) JCTD, which is recognized as a high-priority U.S. Army initiative [228]. Actual TMS standards documents are now in review, and the project has transferred to the U.S. Army PM E2S2 [32].

Since its development, TMS's designers and proponents have also sought to apply it to the DoD installation use case. Doing so could dramatically reduce the design and engineering burden of deploying an installation microgrid, as well as allow for easy phased development of smaller-scale clustered microgrids across a large installation [76, 77]. Under current practice, to combine two closely sited microgrids into single operation, at least one must be decommissioned to allow for various configurations and safety checks. A universal TMS system for grid-tied microgrids would make such requirements obsolete [77]. Future work includes refining its integration with the utility PCC and supporting features specific to the power dynamics of a larger installation [32].

While there are still technical issues to be ironed out for fixed TMS use, the hurdles to its adoption are likely to be organizational and commercial in nature. For one, the phenomenon of vendor lock is a powerful force, and it remains to be seen what value manufacturers, system integrators, and microgrid customers will place on the TMS standard [26, 77, 202]. While DoD adoption of the installation TMS could prove a boon for its incorporation into vendor equipment, there is also a strong argument that the DoD should follow commercial microgrid trends, not diverge from them [8]. Some also question whether the clear interoperability that TMS provides is suited to the installation environment—an overly one-size-fits-all standard may not allow for *enough* control and optimization of operations [66]. However, TMS is seeking to implement microgrid functionality as a general-purpose technology that could flex according to mission needs while remaining backward-compatible with older versions [32]. Industry interest in TMS for an installation waned somewhat when a funding shift limited its further iteration; however, the release of further standards documents may revitalize that interest, especially in light of the U.S. Army's intention to widely adopt base microgrids by 2035 [32].

SECTION 06

CONCLUSION: "A SILVER BULLET SOLUTION"

6.1 SPECIALIST REFINEMENTS

Perhaps the most important and cost-effective energy technology that a DoD microgrid can install is any that reduces electricity consumption. Far from being a "green" preoccupation, the insight that "the average cost of saving electricity is less than the cost of producing it" has been a key tenet of energy policy and economics in the United States since the late 1970s [229, 230]. LBNL reconfirmed this adage yet again in 2021, finding that the cost of saving energy remains at about 3 cents per kWh, while the LCOE of new resources averages between 3 and 12 cents per kWh. Moreover, some of the lowest-cost efficiency interventions include building upgrades and improvements that are relatively easy to implement [229].

As an installation microgrid is planned and designed, DoD energy and utilities managers should consider the reduction in new DER costs (typically the single largest capital cost for most customers) that a synchronized program of base-wide energy efficiency measures can deliver. Some of the most forward-leaning DoD microgrids have pursued a similar approach; both MCAS Miramar and MCRD Parris Island included HVAC, building energy management controls, and lighting upgrades and controls in their energy resilience programs [3, 13, 110]. The opportunity to do so may be limited, however. For example, a major improvement of the energy system at Portsmouth Naval Shipyard—which also added a microgrid—was done in part because the base was already due for an overhaul [8].

The use of BEMS systems alone can substantially reduce nonresidential building consumption. One national laboratory study found that optimal (shortened) HVAC scheduling can reduce energy use by 7.1% [231]. More innovative and automated systems like multimodal occupancy detection and neural-network-enabled HVAC control may deliver even greater savings [148, 232, 233]. In addition to traditional thermal measures like installing double-glazed windows, passive cooling materials and devices can appreciably reduce energy consumption as well as reduce strain and lifetime maintenance costs for HVAC and other physical plant systems [234–236]. Moreover, efficiency need not be limited to consumption—the energy technology press routinely reports on minor inventions that improve DER performance or increase their lifespans. One exceptionally low-tech device (essentially a plastic clip) improves water drainage off low-slope PV modules, with generation gains of 3.5% or more [237].

Even so, initiatives for the incremental reduction of base-wide energy demand should not receive higher billing than a holistic assessment of future weather and climate threats [162]. During the 10 years it took to develop the microgrid at MCAS Miramar, it was a running question whether the system could economically justify its own cost (apart from its clear mission-assurance benefits). Then, just months after its commissioning, California started seeing rolling blackouts for the first time in two decades. Since MCAS Miramar could withstand the demand spikes, it was able to participate in the state's Emergency Load

Reduction Program, routinely earning $25,000 and as much as $50,000 in a single day [2, 238].

6.2 MAJOR PROPONENTS

Three-fourths of the way through the 1970 cinematic classic *Patton*, the M4 Sherman tanks commanded by Lt. Gen. George S. Patton run out of gasoline just short of the Moselle River as they push into Germany—part of Maj. Gen. Omar Bradley's Twelfth Army Group's sprint toward Berlin. With an enemy column crossing in enfilade ahead in the dark, one tanker unit chooses to fight, taking substantial casualties. Surveying the battlefield the next day, George C. Scott's Patton takes in the sight expressionless. Turning to his aide-de-camp, Patton reflects that only several hundred miles stood between him and the Reich capital. "Now I have precisely the right instrument," he says, "at precisely the right moment of history, and exactly the right place." The three-star spreads out a map against a disabled tank, then says, "All I need is a few miserable gallons of gasoline" [239].

The provision of reliable and resilient installation energy in the homeland is hardly cinematic, and the power of a kilowatt-hour is not as legible to the layman as the importance of a jerrycan of M4 diesel. However, as discussed in Section 3.1, experts have warned since the mid-2000s that their defense value may already be close to equivalent. When the Defense Science Board sounded the klaxon in 2008 about the vulnerability of the commercial grid in the United States, it titled its report "More Fight—Less Fuel" [142]. Most of the board's study addressed operational energy, but it might have titled its section on installation power the obverse, "Less Fuel—Less Fight." The U.S. Army is already pushing to fully electrify its non-tactical fleet, and General Motors is experimenting with electrifying tactical platforms like the Infantry Squad Vehicle [240]. Even the revered armor of Patton's Third Army may eventually run on jerrycans of kilowatts. To lessen their heat and noise signatures—and increase range and lethality—the U.S. Army is investigating how to adapt the Bradley Fighting Vehicle, variants of the Stryker, and even the venerable M1A2 Abrams Main Battle Tank to electric propulsion systems driven by hybrid powerplants [240, 241].

While drawing power from a socket to brew a pot of coffee no longer inspires visions of technological progress, the image of a microgrid invulnerable to outside threats certainly does. The scope of R&D into microgrids that this report surveys is impressive and foresighted, and the technical tools needed to make every base a microgrid already exist. However, one must be careful not to conflate the advent of new technologies with the genesis of useful innovation. As retired USMC Gen. Anthony Zinni, Mie Augier, and USMC Maj. Sean Barrett write in the August 2022 edition of the *Proceedings* of the U.S. Naval Institute, "New technology is important, but it is not a silver bullet solution that can be added at random" [242]. They continue, almost as if the increasingly quick adoption of microgrids by institutions hoping for resilience was at the front of their minds:

> *"New technology…must be built into an organization's capabilities, resources, and processes by collaborative, charismatic leaders who can think strategically, critically, and creatively but also encourage, lead, and manage teams to adopt, integrate, and maintain technologies over time…the road to progress is often messy, lengthy, meandering, and unpredictable" [242].*

As the SPIDERS program showed, even those technologies most useful to a command's energy security mission may fall into disrepair unless the teams who adopt and operate them are fully socialized to how they are operated [29, 33, 66]. Zinni et al.'s point on the importance of integration is also salient. The ownership and operation of the SPIDERS pilot microgrids were not adequately integrated; those tasked with system control were not fully briefed on the dimensions of the resilience benefits they could achieve or on how to fully implement them [66]. So too are the drudging tasks of maintenance central to capitalizing on the promises of new technology (see Figure 6-1). One of the most cutting-edge guarantors of microgrid uptime is routinely trimming the trees around its distribution lines [243]. It is no lighthearted pun; Fort Belvoir undertook a dedicated trimming, maintenance, and line-undergrounding campaign several years ago and drove the number of power outages due to on-base causes down "to near zero" [243].

Figure 6-1. Staff Sgt. Gabriel Carias, 624th Civil Engineer Squadron, Conducts a Routine Maintenance Check on the Battery of an Electrical Generator at Bellows Air Force Station, HI, January 2020 *(Source: Kurka [244])*.

In their *Proceedings* article, Zinni et al. further argue that innovation more closely resembles an organizational practice than a piece of new equipment or laboratory breakthrough. Quoting from a scholarly study in business history and management published in 1994, they write, "Organizations must create new knowledge through a 'continual dialogue between explicit and tacit knowledge,'" the latter formed "through socialization and bringing together shared experiences" [242]. For microgrids, perhaps no better example of how this continual dialogue creates new knowledge is the frequent execution of islanding tests and Energy Resilience Readiness Exercises, which have proven powerful in uncovering flaws in microgrid systems that then can be mitigated [2, 3, 8, 32]. In the opinion of Mick Wasco, the longtime utilities and energy director at MCAS Miramar, the most valuable technical knowledge about a microgrid possible is that created by the ERREs. "You don't even know what you need to be worried about," Wasco has said, "until you start poking and prodding" [3].

The *Proceedings* article's mention of how shared experiences generate knowledge is also a compelling one. Each of the on-base energy and utility managers that HDIAC interviewed cited attendance at a professional conference as the origin of (or a major turning point in advancing) their base pursuing a microgrid or other advanced energy-resilience system [2, 58, 245]. The more frequently that DoD energy management personnel and the commanders who "own" their energy assurance missions can network and make unexpected professional connections in the energy community, the more likely it is that the installation enterprise at large will alight upon superior microgrid solutions [8]. It is not just that the road to progress is "unpredictable," as Zinni et al. write, but that interpersonal connections and institutional collaborations have been central to the success of existing DoD microgrids. As Wasco has said about the Miramar project, his team knew from the start that no technical solution could come from solely within the fence line. Getting the microgrid built, he explains, "was all about partnerships" [238].

Gen. Zinni, Augier, and Maj. Barrett are at their most blunt when articulating the centrality of the workforce to the successful integration of new technology into the DoD's processes and capabilities. Indeed, their headline is unequivocal, proclaiming in bold type, "People Are More Important Than Technology" [242]. That same profession rings true for the building-out and sustainment of a military microgrid. "Now that we expect resilience" from base microgrids, Wasco often explains, "it's all about the people" [238]. Acquiring and retaining those people, however, is likely to prove a continuing challenge for the department. Even a landmark microgrid project like Miramar's struggles to fully staff its energy operations group [2], as demand for skilled, energy-sector labor already far outstrips supply in the United States [32, 111]. The cadre of professionals with relevant microgrid experience is even smaller and more highly pursued [2, 68]. MCAS Miramar had to create a new billet in 2022 just to be able to hire a dedicated primary microgrid operator, who is now training other associates to share in those responsibilities [238].

At least some of the solutions to these challenges are clear. Curricula and training materials for all facets of grid-tied microgrids should be more accessible and flexible, to better suit the wide variety of educational and professional backgrounds of DoD energy and utility managers [112, 24]. Most microgrid-specific training remains expensive, difficult to access [65], or outdated. The *DoD Energy Manager's Handbook*, available online from the Office of the Assistant Secretary of Defense for Sustainment, was last updated in August 2005—long enough ago that the word "microgrid" is understandably not present in the text [113]. One other DoD energy handbook is more recent, written by experts at the former Advanced Materials and Manufacturing Technology Information Analysis Center, but it still dates to 2011 and only cursorily addresses microgrid technologies [246, 247].

One training requirement stands out as paramount to the successful long-term sustainment of an installation microgrid: the need for a highly immersive training platform or simulator [2, 65]. As Zinni et al. note, training and instructional resources represent "explicit knowledge," which must be "internalized by members of the organization" to be of value. Internalization is achieved by engaging in scenarios, games, and exercises, a process that the *Proceedings* article terms "learning-by-doing." In turn, learning-by-doing is the most effective way to "embody" knowledge and turn it into skilled actions [242].

As discussed in Section 2.6, it is critical for microgrid operators to practice their control and system management skillsets in a realistic training environment, one similar to a flight simulator. Not only does the Office of the Under Secretary of Defense for Research and Engineering rightfully consider highly immersive training systems to be a critical national defense technology; they are widely used in the energy industry to train personnel who operate high-reliability, no-fail systems, such as deepwater oil and gas well control equipment. Training simulators greatly improve an operator's ability to take appropriate action in an off-normal or emergency event, like an unexpected microgrid frequency anomaly. When, to successfully run a microgrid, operators must navigate a bevy of digital alarms and databanks presented on an array of monitors, there is no substitute for the learning-by-doing that training within a flight simulator environment can provide [114].

Finally, Gen. Zinni, Augier, and Maj. Barrett write convincingly about the need for more leaders who display what they call "we-leadership," or the selfless dedication to an organization's long-term goals paired with little regard for rapid career advancement [242]. HDIAC found one especially prominent theme while interviewing SMEs familiar with the many steps needed to launch—and successfully finish—a new DoD installation microgrid. The project would need a "champion," they said, an indefatigable proponent willing to see it through years of technical reviews, accounting reports, and endless coordination tasks [2, 32, 58, 112]. Writing recently in *Microgrid Knowledge*, the CTO and the lead engineer of XENDEE both agree. "It is important that there is a microgrid champion on the installation," they write, "who can work with the third-party consultants or service entity," and bring all stakeholders together to see the mission through (see Table 6-1) [112].

Table 6-1. Some of the Many Stakeholder Groups Likely to Be Involved in a DoD Installation Microgrid Project *(Source: Booth et al. [109])*

Stakeholder Groups	Roles
Installation and Mission Leadership and Staff	Installation leadership
	Mission owners
	Emergency management personnel
	Installation security
	Legal
Public Works Management Staff and Departments	Energy manager
	Electrical engineering and operations staff
	Water program manager
	Wastewater management
	Generator testing and maintenance staff
	Geographic information systems
	Environmental
	Real property
	Conctracting and acquistion
Information Systems	Information technology
	Communications
	Cybersecurity
Outside Utilities	Electric
	Water
	Gas
	Communications
Other Authorities	Environmental quality
	Energy commission
	Utility privatization contractors (if any)
Community	Local emergercy management
	Other critical facilities near the installation

While he is by no means the only one, Miramar's Mick Wasco embodies the dedication needed to bring a microgrid project from concept to commissioning, as he has worked more than a decade in his role to see the project complete. As Wasco granted at a recent conference, "This project, this microgrid, has basically been my entire career," and almost the entirety of his 12 years at the USMC base [2, 3]. One SME familiar with how the Miramar microgrid came to fruition, recognizing like Gen. Zinni the need for a project "champion," remarked to HDIAC in an aside, "If only we could clone Mick Wasco!" Another excellent example of "we-leadership" is Jarrod Ross, who has worked as the Resource Efficiency Manager at Fort Hunter Liggett since 2017. "I have one energy manager," the base's Garrison Commander, Col. Lisa M. Lamb, pointed out at a recent conference. "He is a contractor, and—I mean, *he is it*. So, if we lose Jarrod Ross, then we lose all of the institutional knowledge of energy resiliency on our installation" [238].

6.3 GENERAL CONTRACTING

The DoD does not make its pivot to energy resilience alone but armed with a panoply of qualified contractors and systems integrators, some of which specialize in the federal market [143]. Even at a microgrid that will remain operated by government employees, contractors are almost certain to be involved in some way—and the type of contracts used can have a noticeable effect on the technical scope a DoD microgrid takes, as well as the host's approach to securing its long-term sustainment activities [2, 32, 58, 59]. Whether a microgrid is funded by upfront DoD or appropriated monies, enhanced by federal or state grants, or financed via third parties can also determine how the system is built, operated, tested, implemented, and maintained [109].

Many sources outside of this report provide ample detail on how appropriated funds, grants, and third party financing methods such as the commonly used Energy Savings Performance Contracts (ESPCs) and Utility Energy Service Contracts (UESCs) differ, and under what conditions each may be preferable [109, 248, 249]. For example, DoD regards ERCIP funds as best targeted to those projects that "would not necessarily be candidates for other types of funding" [250]. ESPCs and UESCs are a method preferred by some service branches for resilience projects, as they do not require programmed funds; the service contractors front the capital costs and earn fees drawn from energy cost savings.

The U.S. Army has engaged in more than $3.2 billion of ESPCs and UESCs since 1992, and a policy change in November 2021 sought to further "re-energize" their use [251]. The Army now expects ESPC/UESC contract totals to jump from around $90 million for 2020 to nearly $420 million in 2022 [248]. Both contract types have found great success in energy projects like Ameresco's ESPC contract covering the overhaul at MCRD Parris Island and its UESC-enabled development of a 1.1 MW floating solar PV system at Fort Bragg's Camp Mackall. Some regard ESPCs as facilitating more of a collaborative process, while UESCs often find wider use in more one-off developments [58]. One emerging innovation of interest within DoD mirrors the commercial Energy-as-a-Service (EaaS) model, in which an installation retains ownership of its assets and a single service provider assumes management over "the complicated web of business arrangements" that power the base. The installation then purchases its power (including from its own on-site DERs) in a pay-for-performance model [34, 252].

The EaaS model may prove a huge boon in making DoD installation microgrids easier to manage and maintain, or the resilience promises of its structure could fail to materialize during a long-duration outage [34]. Indeed, HDIAC heard from microgrid practitioners that some funding or contract types—and especially their fractionation among multiple sources and across lengthy timelines—can hamper resilience planning and lead to variations in the thoroughness of islanding tests among sites. It can also make it more difficult to access O&M funds for long-term sustainment costs, which have already proven higher than expected for many installation microgrids [2, 8, 65]. Ensuring that ample O&M funds will be available almost certainly brings potent economic and resilience benefits. The DOE estimates that predictive maintenance alone on energy systems can reduce costs by as much as 30%, paying for itself within 10 years [249].

A central issue is whether O&M funds are dedicated, or relegated to service base operations, as they often are with appropriated monies. Furthermore, funds focused on energy savings may not allow achieved cost reductions to flow back into sustainment [2, 8, 58], leaving a microgrid less self-sufficient than it appears to one outside the fence line [2]. While many ESPCs and UESCs now include dedicated O&M accounts, attendant to them can be a partial loss of autonomy [58, 109]—non-DoD operators may not truly stress test their microgrids in real-world conditions, as the government-operated system at MCAS Miramar system has done [2]. As the DoD expands its investments into installation microgrids, the value of a project might be assigned some financial sum that reflects the critical but economically intangible mission energy assurance that its system provides [8]. Moreover, seeing an installation microgrid as a value generator, and not as a cost center, will speed the rate at which future DoD microgrids can deliver resilience by design [2, 8, 65].

This Page Intentionally Left Blank

REFERENCES

1. Close, C. “MCAS Miramar Islands Micro-Grid to Support Community.” Defense Visual Information Distribution Service, https://www.dvidshub.net/news/428062/mcas-miramar-islands-micro-grid-support-community, 25 August 2022.
2. Hewett, J., and M. Wasco. Personal communication, 9 June and 7 September 2022.
3. Wasco, M. “Installation Microgrid Project Overview (P-906).” Presentation at the International Microgrid Symposium, Virtual Seminar 1: The Americas, https://www.youtube.com/watch?v=g8NstCHf0s4, 26 January 2022.
4. California Air Resources Board. “BACT Program: Stationary Source Permitting.” https://ww2.arb.ca.gov/BACT, accessed on 5 September 2022.
5. U.S. Environmental Protection Agency. “Regulations for Emissions From Heavy Equipment With Compression-Ignition (Diesel) Engines.” https://www.epa.gov/regulations-emissions-vehicles-and-engines/regulations-emissions-heavy-equipment-compression, 7 March 2022.
6. Rush, J. “Secretary of Defense Visits MCAS Miramar.” Defense Visual Information Distribution Service, San Diego, CA, https://www.dvidshub.net/news/430720/secretary-defense-visits-mcas-miramar, 4 October 2022.
7. Hitchens, K. “Military Microgrids to the Rescue in California and New Mexico.” Microgrid Knowledge, https://microgridknowledge.com/army-navy-marine-microgrid-commitments/, 29 August 2022.
8. Hewett, J., and J. Marqusee. Personal communication, 27 September 2022.
9. Wood, E. “Miramar, One of Largest Military Microgrid Projects, Readies to Show How It’s Done.” Microgrid Knowledge, https://microgridknowledge.com/military-microgrid-projects/, 8 July 2016.
10. Dorsey, C. “Marine Corps Air Station Miramar and NREL: Allies in Energy Efficiency, Systems Integration, and Resilience.” NREL, https://www.nrel.gov/news/features/2021/marine-corps-air-station-miramar-and-nrel-allies-in-energy-efficiency-systems-integration-and-resilience.html, 6 April 2021.
11. Callaghan, C. A., D. R. Peterson, T. J. Cooke, B. K. Booker, and K. P. Trubac. “Installation Resilience in Cold Regions Using Energy Storage System.” ERDC/CRREL TR-21-13, U.S. Army Corps of Engineers Engineer Research and Development Center Cold Regions Research and Engineering Laboratory, Hanover, NH, https://erdc-library.erdc.dren.mil/jspui/bitstream/11681/42200/1/ERDC-CRREL%20TR-21-13.pdf, September 2021.
12. USMC. “Microgrid at Marine Corps Air Station Miramar.” Marine Corps Installations Command, https://www.marines.mil/News/News-Display/Article/2677033/microgrid-at-marine-corps-air-station-miramar, 30 June 2021.
13. NREL. “NREL Enhances Energy Resiliency at Marine Corps Air Station Miramar.” https://www.nrel.gov/energy-solutions/partner-mcas-miramar.html, accessed on 15 September 2022.
14. Wasco, M. “Why the Electric Grid Is No Longer Enough.” Virtual panel discussion at the Microgrid Knowledge 2021 Conference, https://microgridknowledge.com/video/electric-reliability-why-the-grid-is-no-longer-enough/, 11 May 2021.
15. U.S. DoD and DOE. “Memorandum of Understanding, Concerning a Collaboration to Enhance Energy Resilience.” Washington, DC, https://www.acq.osd.mil/eie/Downloads/IE/DoD%20DOE%20MOU%20for%20Energy%20Resilience.pdf, 28 September 2020.
16. U.S. Department of the Navy. “Climate Action 2030.” Press release, U.S. Navy Office of Information, Washington, DC, https://www.navy.mil/Press-Office/Press-Releases/display-pressreleases/Article/3041221/department-of-the-navy-releases-climate-action-2030, 24 May 2022.
17. U.S. DoD. “Energy Resilience on DoD Installations: ESTCP, Installation Energy and Water Program Area.” ESTCP FY 2023 Solicitation, Strategic Environmental Research and Development Program, Environmental Security Technology Certification Program. https://www.serdp-estcp.org/workingwithus/callforproposal?id=e30a77dd-82e6-4df3-8d31-cb6c649aef94, 6 January 2022.
18. U.S. DoD. “Department of Defense Draft Climate Adaptation Plan.” Report submitted to the National Climate Task Force and Federal Chief Sustainability Officer, Office of the Undersecretary of Defense (Acquisition and Sustainment), Washington, DC, https://www.sustainability.gov/pdfs/dod-2021-cap.pdf, 1 September 2021.
19. Baum, J. “Microgrid Overview.” Presentation before the Sacramento Municipal Utility District Strategic Development Committee, Sacramento, CA, https://www.smud.org/-/media/Documents/Corporate/About-Us/Board-Meetings-and-Agendas/2021/August/EPRI-Presentation.ashx, 3 August 2021.

REFERENCES, *continued*

20. U.S. DOE. NREL, Smart Electric Power Alliance. "Voices of Experience: Microgrids for Resiliency." Advanced Grid Research, Office of Electricity, Washington, DC, https://www.smartgrid.gov/files/documents/NREL_VOE-MicrogridofResiliency_Report_Digital-012821.pdf, November 2020.
21. Pawlyk, O. "California Air National Guard Units Called in to Fight Wildfires." Military.com, https://www.military.com/daily-news/2018/11/16/california-air-national-guard-units-called-fight-wildfires.html, 16 November 2018.
22. The White House. *National Security Strategy*. National Security Council, Washington, DC, https://www.whitehouse.gov/wp-content/uploads/2022/10/Biden-Harris-Administrations-National-Security-Strategy-10.2022.pdf, 12 October 2022.
23. Shapiro, S., T. J. Allison, and J. Jeckell. "Power Projection | Adapting the Strategic Support Area for the Future Operating Environment." Army Sustainment, https://www.army.mil/article/237341/power_projection_adapting_the_strategic_support_area_for_the_future_operating_environment, July–September 2020.
24. Loredo, E. N., K. D. Stanley, R. Consaul, J. R. Reimer, and A. Szafran. "The End of Sanctuary: Protecting the Army's Installations From Emerging Threats." RR-A107-1, RAND Corporation, Santa Monica, CA, https://www.rand.org/pubs/research_reports/RRA107-1.html, 2020.
25. Hewett, J., and S. Hoffman. Personal communication, 18 April 2022.
26. Hewett, J., and B. Ollis. Personal communication, 15 July 2022.
27. Naval Facilities Engineering Command. "Technology Transition Final Public Report: Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS), Joint Capability Technology Demonstration (JCTD), Version 1.0." https://apps.dtic.mil/sti/citations/AD1074742, 31 December 2015.
28. Marqusee, J., C. Schultz, and D. Robyn. "Power Begins at Home: Assured Energy for U.S. Military Bases." Noblis, Reston, VA, https://noblis.org/wp-content/uploads/2017/11/Power-Begins-at-Home-Noblis-Website-Version-15.pdf, 12 January 2017.
29. Hewett, J., and J. Stamp. Personal communication, 21 September 2022.
30. Van Broekhoven, S. B., N. Judson, S. V. T. Nguyen, and W. D. Ross. "Microgrid Study: Energy Security for DoD Installations." Technical Report 1164, Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA, https://apps.dtic.mil/sti/citations/ADA565751, 18 June 2012.
31. Stamp, J. E. "SPIDERS: Smart Power Infrastructure Demonstration for Energy, Reliability, and Security." Presentation at the Military Smart Grids and Microgrids Conference, SAND2012-3088C, Sandia National Laboratories, Albuquerque, NM, https://www.osti.gov/servlets/purl/1117582, 1–2 May 2012.
32. Hewett, J., A. Weathers, D. Herring, R. Wiechens, and N. Judson. Personal communication, 5 May 2022.
33. Asmus, P. "Lessons Learned From U.S. Navy Microgrids in Hawaii." GreenBiz, https://www.greenbiz.com/article/lessons-learned-us-navy-microgrids-hawaii, 22 June 2018.
34. Hewett, J., and P. Asmus. Personal communication, 26 September 2022.
35. Feng, W., M. Jin, X. Liu, Y. Bao, C. Marnay, C. Yao, and J. Yu. "A Review of Microgrid Development in the United States – A Decade of Progress on Policies, Demonstrations, Controls, and Software Tools." *AppliedEnergy*, vol. 228, pp. 1656–1668, https://doi.org/10.1016/j.apenergy.2018.06.096, 15 October 2018.
36. Way, R., M. C. Ives, P. Mealy, and J. D. Farmer. "Empirically Grounded Technology Forecasts and the Energy Transition." *Joule*, vol. 6, pp. 2057–2082, https://doi.org/10.1016/j.joule.2022.08.009, 13 September 2022.
37. U.S. DOE. "Battery Storage in the United States: An Update on Market Trends." U.S. Energy Information Administration, Washington, DC, https://www.eia.gov/analysis/studies/electricity/batterystorage/pdf/battery_storage_2021.pdf, August 2021.
38. Maia, S., and L. Demôro. "Power Transition Trends 2022: Coal Power Spikes, But Progress on Renewables Brings Hope." BloombergNEF, https://assets.bbhub.io/professional/sites/24/BNEF-Power-Transition-Trends-2022_FINAL.pdf, 21 September 2022.
39. Wood, E. "What Does 2015 Hold for Microgrids?" Microgrid Knowledge, https://microgridknowledge.com/2015-hold-microgrids/, 15 January 2015.
40. PR Newswire. "Microgrid Deployment Tracker 2Q15: Commercial/Industrial, Community, Utility Distribution, Institutional/Campus, Military, Remote, and DC Microgrids: Operating, Planned, and Proposed Projects by World Region." Cision, https://www.prnewswire.com/news-releases/microgrid-deployment-tracker-2q15-commercialindustrial-community-utility-distribution-institutionalcampus-military-remote-and-dc-microgrids-operating-planned-and-proposed-projects-by-world-region-300095664.html, 8 June 2015.

REFERENCES, *continued*

41. Guidehouse, Inc. “Microgrid Deployment Tracker 3Q22.” Guidehouse Insights, https://guidehouseinsights.com/reports/microgrid-deployment-tracker-3q22, September 2022.
42. Antilla, S., J. S. Döhler, J. G. Oliveira, and C. Boström. “Grid Forming Inverters: A Review of the State of the Art of Key Elements for Microgrid Operation.” *Energies*, vol. 15, no. 5517, https://doi.org/10.3390/en15155517, July 2022.
43. Guidehouse, Inc. “Guidehouse Insights Leaderboard: Microgrid Controls Vendors Assessment of Strategy and Execution for 16 Providers.” Guidehouse Insights, https://guidehouseinsights.com/reports/guidehouse-insights-leaderboard-microgrid-controls-vendors, 2021.
44. Wood, E. “Microgrids as the Next Duct Tape: The Military’s Latest Projects.” Microgrid Knowledge, https://microgridknowledge.com/us-military-microgrids/, 4 May 2022.
45. Luckenbaugh, J. “Long-Time Defense Contractor Unveils Microgrid Lab.” National Defense, https://www.nationaldefensemagazine.org/articles/2022/9/27/long-time-defense-contractor-unveils-microgrid-lab, 27 September 2022.
46. Cardoso, G. “Microgrids: U.S. DOE Overview.” Lawrence Berkeley Laboratory, Emeryville, CA, http://microgrid-symposiums.org/wp-content/uploads/2018/07/Cardoso-2018-08-30.pdf, 30 August 2018.
47. Limpaecher, E., R. Saleco, E. Corbett, S. Manson, B. Nayak, and W. Allen. “Lessons Learned From Hardware-in-the-Loop Testing of Microgrid Control Systems.” Presented at the Grid of the Future Symposium, Cleveland, OH, https://archive.ll.mit.edu/mission/engineering/Publications/Limpaecher_LessonsLearnedFromHITLTesting-MicrogridControlSystems.pdf, 22–25 October 2017.
48. Schneider, K. P., K. Balasubramaniam, D. Fobes, A. Moreira, V. Donde, B. Palmintier, T. Kuruganti, M. E. Ropp, and C-C. Liu. “Microgrid R&D Program White Papers, Topic Area #2: T&D Co-Simulation of Microgrid Impacts and Benefits.” PNNL-31903, Pacific Northwest National Laboratory, Richland, WA, https://www.nrel.gov/grid/assets/pdfs/2-microgrid-impacts.pdf, March 2021.
49. House Committee on Appropriations. “Appropriations Committee Releases Fiscal Year 2023 Military Construction, Veterans Affairs, and Related Agencies Funding Bill.” Press release, U.S. House of Representatives, Washington, DC, https://appropriations.house.gov/news/press-releases/appropriations-committee-releases-fiscal-year-2023-military-construction, 14 June 2022.
50. U.S. DoD. “Army Directive 2020-03 (Installation Energy and Water Resilience Policy).” Memorandum, Secretary of the Army, Washington, DC, https://armypubs.army.mil/epubs/DR_pubs/DR_a/pdf/web/ARN21689_AD2020_03_FINAL_Revised.pdf, 31 March 2020.
51. U.S. Department of the Army. “United States Army Climate Strategy.” Office of the Assistant Secretary of the Army for Installations, Energy and Environment, Washington, DC, https://www.army.mil/e2/downloads/rv7/about/2022_army_climate_strategy.pdf, February 2022.
52. Oregon State University. “Snowball Sampling.” Human Research Protection Program and Institutional Review Board, Corvallis, OR, https://research.oregonstate.edu/irb/policies-and-guidance-investigators/guidance/snowball-sampling, 14 September 2010.
53. Parhizi, S., H. Lofti, A. Khodaei, and S. Bahramirad. “State of the Art in Research on Microgrids: A Review.” *IEEE Access*, vol. 3, pp. 890–925, https://doi.org/10.1109/ACCESS.2015.2443119, 2015.
54. Hewett, J., and A. Khodaei. Personal communication, 21 April 2022.
55. Schneider, K. “Tools for Microgrid Design (The Need for Dynamic Simulations).” Presentation before the ARPA-E Workshop, Engineering Microgrids With Control Co-Design, https://arpa-e.energy.gov/sites/default/files/EMC2%20Workshop%20Day%201%20-%20KSchneider.pdf, 5 September 2020.
56. Johnson, M. “Installation Power and Energy: Delivering Resilient Electric Power.” Construction Engineering Research Laboratory, Engineer Research and Development Center, U.S. Army Corps of Engineers, Champaign, IL, https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiLhtCtz8D6AhXWmWoFHSBsDekQFnoECBcQAQ&url FnoECBcQAQ&url=https%3A%2F%2Fwww.nationalacademies.org%2Fevent%2F09-162021%2Fdocs%2FD37B642FC39E9D8A20FC41B5A78849B95E3DE862D0B3&usg=AOvVaw04NOcfYXfcij7xKKIpwwhg, 16 September 2021.
57. Croft, J. “Fort Hunter Liggett Breaks Ground on Microgrid Project (Image 5 of 5).” Photo ID 6673925, Defense Visual Information Distribution Service, https://www.dvidshub.net/image/6673925/fort-hunter-liggett-breaks-ground-microgrid-project, 25 May 2021.
58. Hewett, J., and J. Ross. Personal communication, 18 July 2022.

REFERENCES, *continued*

59. Hewett, J., and D. Irwin. Personal communication, 25 July 2022.
60. Castillo, A. "Military Installation Energy Resilience and Microgrid Overview Paper." Office of the Assistant Secretary of Defense for Sustainment, Attachment 1 to N. Judson et al., "Application of a Resilience Framework to Military Installations: A Methodology for Energy Resilience Business Case Decisions," TR-1216, Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA, https://www.acq.osd.mil/eie/Downloads/IE/ER%20and%20Microgrid%20One-Pager.pdf, 4 October 2016.
61. Wilson, B. "Tactical Microgrids: Mobile and Sustainable Power." Naval Postgraduate School, NPS Defense Energy Seminar, Virtual Seminar, https://nps.edu/web/nps-video-portal/-/bwqan4valdcrws-9fj2dnst0x9kzr11, 27 February 2020.
62. Hirsch, A., Y. Parag, and J. Guerrero. "Microgrids: A Review of Technologies, Key Drivers, and Outstanding Issues." *Renewable and Sustainable Energy Reviews*, vol. 90, pp. 402–411, https://doi.org/10.1016/j.rser.2018.03.040, July 2018.
63. Guidehouse, Inc. "Microgrid Controls Mature but Consensus on Ideal Approach Remains Elusive." Guidehouse Insights, https://guidehouseinsights.com/news-and-views/microgrid-controls-mature-but-consensus-on-ideal-approach-remains-elusive, 1 December 2020.
64. Miller, B. "Summary of Microgrid Activities in the USA." Presentation at the International Microgrid Symposium, Virtual Seminar 1: The Americas, https://www.youtube.com/watch?v=g8NstCHf0s4, 26 January 2022.
65. Hewett, J., and N. Johnson. Personal communication, 5 October 2022.
66. Hewett, J., and K. Schneider. Personal communication, 7 October 2022.
67. Hewett, J., and T. Tetreault. Personal communication, 26 September 2022.
68. Ferreira, S., M. Baggu, R. Bent, V. Donde, M. Heleno, T. King, K. Schneider, and R. Singh. "DOE OE 2021 Strategy White Papers on Microgrids: Program Vision, Objectives, and R&D Targets in 5 and 10 Years–Topic Area #1." Sandia National Laboratories, Albuquerque, NM, https://www.nrel.gov/grid/assets/pdfs/1-microgrid-vision-targets.pdf, May 2021.
69. Hewett, J., and J. Davis. Personal communication, 27 July 2022.
70. Maze-Rothstein, I. (moderator). "Drivers of the US Microgrid Market." Wood Mackenzie Focus Grid Edge Virtual Event, https://www.bloomenergy.com/event/drivers-of-the-us-microgrid-market/, 10 June 2021.
71. U.S. DOE. "Solar Futures Study." Office of Energy Efficiency and Renewable Energy, Washington, DC, https://www.energy.gov/sites/default/files/2021-09/Solar%20Futures%20Study.pdf, September 2021.
72. Penrod, E. "Long-Duration Storage at the Cusp of a Breakthrough, but Market Constraints Persist: RE+ Panelists." UtilityDive, https://www.utilitydive.com/news/long-duration-energy-storage-re-lightsource/632300/, 21 September 2022.
73. Hewett, J., and D. Ton. Personal communication, 26 September 2022.
74. Hewett, J., and J. Baum. Personal communication, 6 September 2022.
75. Liu, C.-C., M. Chinthavali, R. Hovsapian, H. Burroughs, S. Gonzales, F. K. Tuffner, M. Heleno, R. Singh, A. Mate, D. Boroyevich, and H. Ginn. "Topic 3: Building Blocks for Microgrids." White Paper, U.S. Department of Energy, Washington, DC, https://www.nrel.gov/grid/assets/pdfs/3-microgrid-building-blocks.pdf, 2021.
76. U.S. DoD. "Open Architecture Microgrid Controller and HIL Validation." EW20-52915, Environmental Security Technology Certification Program, https://serdp-estcp.org/projects/details/ bd8aeb67-c542-4b63-939c-86aef3c231cb, accessed on 30 August 2022.
77. Hewett, J., and T. Bozada. Personal communication, 6 October 2022.
78. Microgrid Knowledge. "Benefits of Sectionalizing the Power Grid: Evolution of Microgrid Clustering." Webinar, https://microgridknowledge.com/video/sectionalizing-the-power-grid-evolution-of-microgrid-clustering/, 16 June 2022.
79. Donde, V., A. Pratt, A. Bernstein, J. Flicker, A. Madduri, B. Ollis, C. Roberts, R. Singh, J. Tabarez, and F. Tuffner. "Microgrids as a Building Block for Future Grids–Topic 4." LLNL-MI-820265, Lawrence Livermore National Laboratory, Livermore, CA, https://www.nrel.gov/grid/assets/pdfs/4-microgrid-future-grid.pdf, 17 May 2021.
80. Bent, R., A. Pratt, M. Reno, D. Pinney, and F. Flores-Espino. "Resilient Operations of Networked Microgrids (RONM)." LA-UR-22-28129, Los Alamos National Laboratory, July 2022 Microgrid R&D Program Meeting, https://www.nrel.gov/grid/assets/pdfs/10-resilient-operations-of-networked-microgrids.pdf, 27 July 2022.

REFERENCES, *continued*

81. Ollis, B., M. Ferrari, T. Smith, M. Reno, M. Ropp, L. Rashkin, W. Du, F. Tuffner, R. Singh, A. Barnes, Y. Lin, K. Prabakar, V. Donde, and C. Roberts. "Topic #5: Advanced Microgrid Control and Protection." Draft, Oak Ridge National Laboratory, Oak Ridge, TN, https://www.nrel.gov/grid/assets/pdfs/5-microgrid-control-protection.pdf, 19 March 2021.
82. Schulze, K. "Military Members Persevere Despite Power Outage (Image 1 of 5)." Photo ID 5493582, Defense Visual Information Distribution Service, https://www.dvidshub.net/image/5493582/military-members-persevere-despite-power-outage, 16 June 2019.
83. Rocky Mountain Institute. "Advancing Military Microreactors: Challenges and Recommendations Based on Insights From a Two-Day Workshop to Support Naval Facilities Engineering Command Southwest's Microgrid Efforts." Electricity Innovation Lab, Boulder, CO, https://rmi.org/wp-content/uploads/2017/04/NavyReport.pdf, April 2017.
84. Marqusee, J., S. Ericson, and D. Jenket. "Emergency Diesel Generator Reliability and Installation Energy Security." NREL/TP-5C00-76553, NREL, Golden, CO, https://www.nrel.gov/docs/fy20osti/76553.pdf, April 2020.
85. Marqusee, J., W. Becker, and S. Ericson. "Resilience and Economics of Microgrids With PV, Battery Storage, and Networked Diesel Generators." *Advances in Applied Energy*, vol. 3, https://doi.org/10.1016/j.adapen.2021.100049, 25 August 2021.
86. U.S. DoD. "Metrics and Standards for Energy Resilience at Military Installations." Memorandum, Office of the Under Secretary of Defense for Acquisition and Sustainment, Washington, DC, https://www.acq.osd.mil/eie/Downloads/IE/Metrics%20and%20Standards%20for%20Energy%20Resilience%2020%20May%202021.pdf, 20 May 2021.
87. Peterson, C. J., D. L. Van Bossuyt, R. E. Giachetti, and G. Oriti. "Analyzing Mission Impact of Military Installations Microgrid for Resilience." *Systems*, vol. 9, no. 3, https://doi.org/10.3390/systems9030069, September 2021.
88. Bent, R., W. Du, M. Heleno, R. Jeffers, M. Korkali, G. Liu, D. Olis, P. Pradhan, and R. Singh. "Integrated Models and Tools for Microgrid Planning and Design With Operations." U.S. DOE, https://www.nrel.gov/grid/assets/pdfs/6-microgrid-models-tools.pdf, 2021.
89. Hewett, J., and J. Kleissl. Personal communication, 3 October 2022.
90. U.S. DoD. "Integrated Model-Based Design Process for Affordable, Scalable, and Resilient DoD Installation Microgrids." EW20-5049, Environmental Security Technology Certification Program, https://www.serdp-estcp.org/projects/details/47826366-5625-4e3d-9a4c-ca6e2e92f216/ew20-5049-project-overview, accessed on 30 August 2022.
91. U.S. DoD. "Microgrid Planning Utilizing an Open Modeling Framework for Resilient Installations Leveraging Their Utility Privatization (MICROGRID UP)." EW20-5055, Environmental Security Technology Certification Program, https://www.serdp-estcp.org/projects/details/cf4dcc73-0a57-4ff3-bd17-4e066bdbecff/ew20-5055-project-overview, accessed on 30 August 2022.
92. U.S. DoD. "DoD Standardized Platform to Guide Rapid and Repeatable Modeling and Design of Secure and Resilient Microgrids (Rapid-Resilient-Microgrid)." EW20-5271, Environmental Security Technology Certification Program, https://www.serdp-estcp.org/projects/details/32fcde60-980f-4ecd-9978-c0cc97c67ead/ew20-5271-project-overview, accessed on 30 August 2022.
93. Mallery, J., D. L. Van Bossuyt, and A. Pollman. "Defense Installation Energy Resilience for Changing Operational Requirements." *Designs*, vol. 6, no. 28, pp. 1–27, https://doi.org/10.3390/designs6020028, 3 March 2022.
94. Hanna, R., and J. Marqusee. "Designing Resilient Decentralized Energy Systems: The Importance of Modeling Extreme Events and Long-Duration Power Outages." *iScience*, vol. 25, no. 1, https://doi.org/10.1016/j.isci.2021.103630, 21 January 2022.
95. Ishaq, S., I. Khan, S. Rahman, T. Hussain, A. Iqbal, and R. M. Elavarasan. "A Review on Recent Developments in Control and Optimization of Microgrids." *Energy Reports*, vol. 8, pp. 4085–4103, https://doi.org/10.1016/j.egyr.2022.01.080, November 2022.
96. Poteet, T. "Microgrid Costs: What Accelerates and What Inhibits a Microgrid Project?" Microgrid Knowledge, https://microgridknowledge.com/microgrid-costs-microgrid-projects-mesa/, 3 August 2021.
97. Gao, K., T. Wang, C. Han, J. Xie, Y. Ma, and R. Peng. "A Review of Optimization of Microgrid Operation." *Energies*, vol. 14, no. 10, https://doi.org/10.3390/en14102842, May 2021.
98. Mathiesen, P., M. Stadler, J. Kleissl, and Z. Pecenak". Techno-Economic Optimization of Islanded Microgrids Considering Intra-Hour Variability." *Applied Energy*, vol. 304, https://doi.org/10.1016/j.apenergy.2021.117777, December 2021.

REFERENCES, *continued*

99. Espina, E., J. Llanos, C. Burgos-Mellado, R. Cárdenas-Dobson, M. Martínez-Gómez, and D. Sáez. "Distributed Control Strategies for Microgrids: An Overview." *IEEE Access*, vol. 8, pp. 193412–193448, https://doi.org/10.1109/ACCESS.2020.3032378, November 2020.

100. Schneider, K. P., S. Laval, J. Hansen, R. B. Melton, L. Ponder, L. Fox, J. Hart, J. Hambrick, M. Buckner, M. Baggu, K. Prabakar, M. Manjrekar, S. Essakiappan, L. M. Tolbert, Y. Liu, J. Dong, L. Zhu, A. Smallwood, A. Jayantilal, C. Irwin, and G. Yuan. "A Distributed Power System Control Architecture for Improved Distribution System Resiliency." *IEEE Access*, vol. 7, pp. 9957–9970, https://doi.org/10.1109/ACCESS.2019.2891368, January 2019.

101. Zhang, P. "AI-Enabled, Programmable, Networked Microgrids." Naval Postgraduate School Defense Energy Seminar, https://nps.edu/web/nps-video-portal/-/ai-enabled-programmable-network-microgrids, 19 April 2022.

102. U.S. DoD. "Integrated Microgrid Control Platform." EW20-5139, Strategic Environmental Research and Development Program, Environmental Security Technology Certification Program, https://www.serdp-estcp.org/projects/details/e5bd7922-ae85-4d9f-8bab-6e0d20cdc5ad, accessed on 30 August 2022.

103. U.S. DoD. "A Resilient Distributed Platform for Microgrid Control." EW20-5040, Strategic Environmental Research and Development Program, Environmental Security Technology Certification Program, https://www.serdp-estcp.org/projects/details/4e2e5507-3504-47f5-b725-a5f47ffdff54/ew20-5040-project-overview, accessed on 30 August 2022.

104. U.S. DoD. "Integrated Resilient Node Hardware and Supervisory Control for Phased Microgrid Installation at Military Facilities." EW20-5223, Strategic Environmental Research and Development Program, Environmental Security Technology Certification Program, https://www.serdp-estcp.org/projects/details/eea6eb6c-c3fc-4fef-b8c1-9ed565dad7ef/ew20-5223-project-overview, accessed on 30 August 2022.

105. Smalley, S. "Pentagon Put Microgrid Technology to the Test at DEF CON, Drawing on Hackers' Ingenuity." Cyberscoop, https://www.cyberscoop.com/pentagon-hackers-secure-the-microgrid/, 16 August 2022.

106. Amsterdamska, O. "Practices, People, and Places." *The Handbook of Science and Technology Studies*, 3rd ed., pp. 205–209, edited by E. J. Hackett, O. Amsterdamska, M. Lynch, and J. Wajcman, Cambridge, MA: The MIT Press, 2008.

107. Hess, D. "Control Room." Video ID 788150 (Screen Grab), Defense Visual Information Distribution Service, https://www.dvidshub.net/video/788150/control-room, 18 February 2021.

108. Pecenak, Z. K., P. Mathiesen, K. Fahy, C. Cannon, E. Ayandele, T. J. Kirk, and M. Stadler. "The Impact of Project Financing in Optimizing Microgrid Design." *Journal of Renewable and Sustainable Energy*, vol. 12, no. 6, https://doi.org/10.1063/5.0026187, November 2020.

109. Booth, S., J. Reilly, R. Butt, M. Wasco, and R. Monohan. "Microgrids for Energy Resilience: A Guide to Conceptual Design and Lessons from Defense Projects." NREL/TP-7A40-72586, NREL, Golden, CO, https://www.nrel.gov/docs/fy19osti/72586.pdf, January 2020.

110. Ameresco. "Project Highlight: U.S. Marine Corps Recruit Depot Parris Island, SC." https://www.ameresco.com/wp-content/uploads/2020/10/us-marine-corps-recruit-depot-parris-island-sc.pdf, October 2020.

111. Ethington, J. "The Energy Industry Wants to Bounce Back—All It Needs Is Workers." *Forbes*, https://www.forbes.com/sites/forbesagencycouncil/2022/01/10/the-energy-industry-wants-to-bounce-back--all-it-needs-is-workers/?sh=65ad73cf343b, 10 January 2022.

112. Stadler, M., and Z. Pecenak. "Major Hurdles to the Fast and Scalable Deployment of Microgrids in the Defense and Government Marketplace." Microgrid Knowledge, https://microgridknowledge.com/xendee-defense-and-government-microgrids/, 23 November 2021.

113. U.S. DoD. *Department of Defense Energy Manager's Handbook*. Office of the Deputy Under Secretary of Defense, Installations and Environment, Intuitive Research and Technology Corporation, Washington, DC, https://www.acq.osd.mil/eie/ie/FEP_Manager_Support.html, accessed on 10 October 2022.

114. U.S. DOE. Grid Modernization Initiative. "Grid Modernization: Updated GMI Strategy 2020." Grid Modernization Initiative, Washington, DC, https://www.energy.gov/sites/prod/files/2021/02/f82/ GMI_Strategy_FINAL%20as%20of%201.20.21.pdf, December 2020.

115. U.S. DOE. "Electric Disturbance Events (OE-417) Annual Summaries." https://www.oe.netl.doe.gov/OE417_annual_summary.aspx, accessed on 26 September 2022.

116. U.S. Government Accountability Office. "Electricity Grid Resilience: Climate Change Is Expected to Have Far-Reaching Effects and DOE and FERC Should Take Actions." GAO-21-423T, statement of Frank

REFERENCES, *continued*

Rusco, Director, Natural Resources and Environment, testimony before the Committee on Environment and Public Works, U.S. Senate, https://www.gao.gov/assets/gao-21-423t.pdf, 10 March 2021.

117. Penn, I. "Dodging Blackouts, California Faces New Questions on Its Power Supply." *The New York Times*, https://www.nytimes.com/2022/09/25/business/energy-environment/california-energy-grid-heat.html, 26 September 2022.

118. Federal Energy Regulatory Commission, North American Electric Reliability Corporation, and Regional Entities (Midwest Reliability Organization, Northeast Power Coordinating Council, Reliability First Corporation, SERC Corporation, Texas Reliability Entity, and Western Electricity Coordinating Council). "The February 2021 Cold Weather Outages in Texas and the South Central United States/FERC, NERC, and Regional Entity Staff Report." https://www.ferc.gov/media/february-2021-cold-weather-outages-texas-and-south-central-united-states-ferc-nerc-and, November 2021.

119. The University of Texas at Austin Energy Institute. "The Timeline and Events of the February 2021 Texas Electric Grid Blackouts." https://energy.utexas.edu/sites/default/files/UTAustin%20%282021%29%20EventsFebruary2021TexasBlackout%2020210714.pdf, July 2021.

120. Lambert, M. "HDIAC Webinar: Preparedness Lessons Learned From the 2021 Texas Power Failure." HDIAC, Belcamp, MD, https://hdiac.org/webinars/preparedness-lessons-learned-from-the-2021-texas-power-failure/, 16 March 2022.

121. Traywick, C., M. Chediak, N. S. Malik, and J. Saul. "The Two Hours That Nearly Destroyed Texas's Electric Grid." Bloomberg, https://www.bloomberg.com/news/features/2021-02-20/texas-blackout-how-the-electrical-grid-failed, 21 February 2021.

122. Bennett, S. "Why the Electric Grid Is No Longer Enough." Panel discussion at the Microgrid Knowledge 2021 Virtual Conference: The World Awakens to Microgrids, https://microgridknowledge.com/video/electric-reliability-why-the-grid-is-no-longer-enough/, 11 May 2021.

123. Cohen, R. S. "Winter Storm Uri Spotlights Gaps in Military Base Preparedness." *AirForceTimes*, https://www.airforcetimes.com/news/pentagon-congress/2021/03/27/winter-storm-uri-spotlights-gaps-in-military-base-preparedness/, 26 March 2021.

124. Torres, J. "An Overview of Threats to the Power Grid." SAND2015-3329PE, Sandia National Laboratories, Albuquerque, NM, https://www.osti.gov/servlets/purl/1250738, April 2015.

125. U.S. Government Accountability Office. "Electricity Grid Cybersecurity: DOE Needs to Ensure Its Plans Fully Address Risks to Distribution Systems." GAO-21-81, report to Congressional Requesters, https://www.gao.gov/assets/gao-21-81.pdf, March 2021.

126. Walton, R. "Extremists Have Developed 'Credible, Specific Plans' to Attack the U.S. Power Grid, DHS Says in New Warning." UtilityDive, https://www.utilitydive.com/news/extremists-have-developed-credible-specific-plans-to-attack-the-us-power/617741/, 26 January 2022.

127. Krill, I., and B. Clifford. "Mayhem, Murder, and Misdirection: Violent Extremist Attack Plots Against Critical. Infrastructure in the United States, 2016–2022." Program on Extremism, the George Washington University, Washington, DC, https://extremism.gwu.edu/sites/g/files/zaxdzs2191/f/CriticalInfrastructureTargeting09072022.pdf, September 2022.

128. Harris, S. "'Military-Style' Raid on California Power Station Spooks U.S." Foreign Policy, https://foreignpolicy.com/2013/12/27/military-style-raid-on-california-power-station-spooks-u-s/, 27 December 2013.

129. Whitaker, B. "Vulnerable U.S. Electric Grid Facing Threats From Russia and Domestic Terrorists." *CBS News, 60 Minutes*, https://www.cbsnews.com/news/america-electric-grid-60-minutes-2022-08-28/, 28 August 2022.

130. National Academies of Sciences, Engineering, and Medicine. *The Future of Electric Power in the United States*. Washington, DC: The National Academies Press, https://nap.nationalacademies.org/catalog/25968/the-future-of-electric-power-in-the-united-states, March 2021.

131. McBride, J., and A. Siripurapu. "How Does the U.S. Power Grid Work?" Council on Foreign Relations, https://www.cfr.org/backgrounder/how-does-us-power-grid-work, 5 July 2022.

132. Blunt, K. "America's Power Grid Is Increasingly Unreliable." *The Wall Street Journal*, https://www.wsj.com/articles/americas-power-grid-is-increasingly-unreliable-11645196772, 18 February 2022.

133. Johnson, S. "Can the Infrastructure Be Fixed? Experts Give a D+ Mark to the U.S. Infrastructure and Grid, Saying It'll Cost Billions to Modernize." NRECA: America's Electric Cooperatives, National Rural Electric Cooperative Association, https://www.electric.coop/

REFERENCES, *continued*

united-states-electric-grid-infrastructure-acse, 17 March 2017.

134. American Society of Civil Engineers. “Energy: C-.” ASCE’s 2021 Infrastructure Report Card, Reston, VA, https://infrastructurereportcard.org/wp-content/uploads/2020/12/Energy-2021.pdf, December 2020.
135. U.S. Energy Information Administration. “U.S. Electricity Customers Experienced Eight Hours of Power Interruptions in 2020.” https://www.eia.gov/todayinenergy/detail.php?id=50316, 10 November 2021.
136. Van Derbeken, J. “Long-Term Wear Found on PG&E Line That Sparked Camp Fire.” *NBC Bay Area*, https://www.nbcbayarea.com/news/local/long-term-wear-found-on-pge-line-that-sparked-camp-fire/2151906/, 11 December 2019.
137. Long, T. J. “Comments of the Utility Reform Network on the Request for Safety Certification by Pacific Gas & Electric Company.” Rulemaking 18-10-007, Before the Public Utilities Commission of the State of California, Order Instituting Rulemaking to Implement Electric Utility Wildfire Mitigation Plans Pursuant to Senate Bill 901 (2018), The Utility Reform Network, San Francisco, CA, https://energysafety.ca.gov/wp-content/uploads/docs/safety-certificates/comments/turn-comments-on-2020-pge-safety-certification-request-20200812.pdf, 12 August 2020.
138. Magill, J. “As It Undergoes Transformation, U.S. Power Grid Embraces AI.” *Forbes*, https://www.forbes.com/sites/jimmagill/2021/03/29/as-it-undergoes-transformation-us-power-grid-embraces-ai/?sh=5381826d7a52, 29 March 2021.
139. Behr, P., and J. Plautz. “Grid Monitor Warns of U.S. Blackouts in ‘Sobering Report’.” *EnergyWire*, https://www.eenews.net/articles/grid-monitor-warns-of-u-s-blackouts-in-sobering-report/, 19 May 2022.
140. University of Wyoming. “UW’s Nguyen Receives Grant to Study Reliability of Clean Power Systems Through Machine Learning.” http://www.uwyo.edu/uw/news/2022/10/uws-nguyen-receives-grant-to-study-reliability-of-clean-power-systems-through-machine-learning.html, 4 October 2022.
141. Douglas, A., A. Pina, and M. Pringle. “Exercise Roadmap for Resilience: Requirements, Results, and Resourcing.” *Combating Terrorism Exchange*, vol. 12, no. 1, https://nps.edu/documents/110773463/135759179/Exercise+Roadmap+for+Resilience-+Requirements%2C+Results%2C+and+Resourcing.pdf/085dab03-053a-9464-c41d-94c392b12228?t=1652135881385, April 2022.
142. U.S. DoD. “Report of the Defense Science Board Task Force on DoD Energy Strategy, ‘More Fight—Less Fuel’.” Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, Washington, DC, https://apps.dtic.mil/sti/pdfs/ADA477619.pdf, 4 February 2008.
143. Surash, J. “Army’s Pivot to Resilience: The Federal Utility Partnership Working Group.” Office of the Acting Deputy Assistant Secretary of the Army for Energy and Sustainability, Washington, DC, https://www.energy.gov/sites/default/files/2018/11/f57/23-fupwg_fall_18_surash.pdf, 8 November 2018.
144. U.S. DOE. “Comprehensive Annual Energy Data and Sustainability Performance: FY 2021.” All Agency Energy Consumption Data by End Use Sector in FY 2021 (Billion Btu), Office of Energy Efficiency and Renewable Energy, https://ctsedwweb.ee.doe.gov/Annual/Report/AgencyMasterDataByYear.aspx, accessed on 28 August 2022.
145. U.S. DoD. “Department of Defense Annual Energy Management and Resilience Report (AEMRR), Fiscal Year 2021.” Office of the Assistant Secretary of Defense for Sustainment, Washington, DC, https://www.acq.osd.mil/eie/Downloads/IE/FY%202021%20AEMRR.pdf, October 2022.
146. Samaras, C., W. J. Nuttall, and M. Bazilian. “Energy and the Military: Convergence of Security, Economic, and Environmental Decision-Making.” *Energy Strategy Reviews*, vol. 26, pp. 1–11, https://doi.org/10.1016/j.esr.2019.100409, 2019.
147. White House Council on Environmental Quality. “Department of Defense Agency Progress.” Office of the Federal Chief Sustainability Officer, Washington, DC, https://www.sustainability.gov/dod.html, October 2022.
148. Roosa, S. A. (editor). *Fundamentals of Microgrids: Development and Integration*. Boca Raton, FL: CRC Press, 2021.
149. Lamoreaux, N. R., D. M. G. Raff, and P. Temin (editors). *Learning by Doing in Markets, Firms, and Countries*. Chicago, IL: University of Chicago Press, 1999.
150. U.S. Energy Information Administration. “How Much Electricity Is Lost in Electricity Transmission and Distribution in the United States?” https://www.eia.gov/tools/faqs/faq.php?id=105&t=3#:~:text=The%20U.S.%20Energy%20Information%20Administration,States%20in%202016%20through%202020, updated 13 July 2022.

REFERENCES, *continued*

151. The World Bank. "Electric Power Transmission and Distribution Losses (% of Output): IEA Statistics From OECD/IEA." https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS, 2018.

152. Atcitty, S., M. Ropp, and V. De Angelis. "An Introduction to Microgrids and Energy Storage." Sandia National Laboratories, Albuquerque, NM, https://www.energy.gov/sites/default/files/2022-08/3_Stan-Atcitty_Microgrids-and-Energy-Storage.pdf, 3 August 2022.

153. U.S. DOE. "2020 Smart Grid System Report." Office of Electricity, Washington, DC, https://www.energy.gov/sites/default/files/2022-05/2020%20Smart%20Grid%20System%20Report_0.pdf, January 2022.

154. Hewett, J., and M. Maxwell. Personal communication, 13 June 2022.

155. Cohn, L. "Microgrids Created Electric Sanctuaries Amidst the Devastation of Hurricane Ian." Microgrid Knowledge, https://microgridknowledge.com/microgrids-hurricane-ian/, 7 October 2022.

156. U.S. DoD. "Installation Energy Management." Directive 4170.11, Under Secretary of Defense for Acquisition and Sustainment, Washington, DC, https://www.esd.whs.mil/Portals/54/Documents/DD/issuances/dodi/417011p.pdf, 31 August 2018.

157. U.S. DoD. "Energy Policy of the Department of Defense," 10 U.S.C. § 2911.

158. Lopez, L. "Department of Defense Installation Energy: Energy Resilience Review." Office of the Assistant Secretary of Defense, Energy, Installations and Environment, Washington, DC, https://www.energy.gov/sites/prod/files/2017/04/f34/fupwg_spring17_lopez.pdf, 13 April 2017.

159. Castillo, A. "Measuring Success in Resilience." Presentation at the Energy Exchange 2019 Conference, Denver, CO, https://oldcc.gov/sites/default/files/news/Measuring-Success-in-Resilience.pdf, 20–22 August 2019.

160. Judson, N., A. L. Pina, E. V. Dydek, S. B. Van Broekhoven, and A. S. Castillo. "Application of a Resilience Framework to Military Installations: A Methodology for Energy Resilience Business Case Decisions." Technical Report 1216, Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA, https://www.acq.osd.mil/eie/Downloads/IE/TR-1216.pdf, 4 October 2016.

161. Zinaman, O., J. Eto, B. Garcia, J.-Y. Joo, R. Jeffers, and K. Schneider. "White Paper: Enabling Regulatory and Business Models for Broad Microgrid Deployment." NREL, Golden, CO, https://www.nrel.gov/grid/assets/pdfs/7-microgrid-regs-bus-models.pdf, March 2021.

162. Mishra, S., T. Kwasnik, and K. Anderson. "Microgrid Resilience: A Holistic and Context-Aware Resilience Metric." Energy Systems, https://doi.org/10.1007/s12667-022-00509-4, 21 March 2022.

163. Anderson, K., N. D. Laws, S. Marr, L. Lisell, T. Jimenez, T. Case, X. Li, D. Lohmann, and D. Cutler. "Quantifying and Monetizing Renewable Energy Resilience." *Sustainability*, vol. 10, no. 4, https://doi.org/10.3390/su10040933, March 2018.

164. Liu, G., T. Jiang, T. B. Ollis, X. Li, F. Li, and K. Tomsovic. "Resilient Distribution System Leveraging Distributed Generation and Microgrids: A Review." *IET Energy Systems Integration*, vol. 2, no. 4, pp. 289–304, https://doi.org/10.1049/iet-esi.2019.0134, April 2020.

165. Rickerson, W., K. Zitelman, and K. Jones. "Valuing Resilience for Microgrids: Challenges, Innovative Approaches, and State Needs." Converge Strategies and National Association of Regulatory Utility Commissioners, Washington, DC, National Association of State Energy Officials, Arlington, VA, https://www.naseo.org/data/sites/1/documents/publications/NARUC_Resilience_for_Microgrids_INTERACTIVE_021122.pdf, February 2022.

166. Macmillan, M., C. A. Murphy, and M. D. Bazilian. "Exploring Acute Weather Resilience: Meeting Resilience and Renewable Goals." *Renewable and Sustainable Energy Reviews*, vol. 168, https://doi.org/10.1016/j.rser.2022.112841, October 2022.

167. Kain, A., D. L. Van Bossuyt, and A. Pollman. "Investigation of Nanogrids for Improved Navy Installation Energy Resilience." *Applied Sciences*, vol. 11, https://doi.org/10.3390/app11094298, May 2021.

168. Nelson, J., N. G. Johnson, K. Fahy, and T. A. Hansen. "Statistical Development of Microgrid Resilience During Islanding Operations." *Applied Energy*, vol. 279, https://doi.org/10.1016/j.apenergy.2020.115724, December 2020.

169. Anuat, E., D. L. Van Bossuyt, and A. Pollman. "Energy Resilience Impact of Supply Chain Network Disruption to Military Microgrids." *Infrastructures*, vol. 7, no. 4, https://doi.org/10.3390/infrastructures7010004, December 2021.

170. Ton, D. T., and M. A. Smith. "The U.S. Department of Energy's Microgrid Initiative." *The Electricity Journal*, vol. 25, no. 8, https://doi.org/10.1016/j.tej.2012.09.013, October 2012.

171. Broderick, R. J., M. A. Cook, M. DeMenno, M. E. Khatib, R. Guttromson, M. Hightower, K. Jones, A. Nanco, B. L. Schenkman, D. A. Schoenwald, and C. Silva Monroy.

REFERENCES, *continued*

"Energy Surety Design Methodology." SAND2019-11463, Sandia National Laboratories, Albuquerque, NM, https://www.osti.gov/servlets/purl/1567837, September 2015.

172. Hossain-McKenzie, S., M. J. Reno, J. Eddy, and K. P. Schneider. "Assessment of Existing Capabilities and Future Needs for Designing Networked Microgrids." SAND2019-2436, Sandia National Laboratories, Albuquerque, NM, https://www.osti.gov/servlets/purl/1761847, February 2019.

173. Morgan, E. R., S. Valentine, C. A. Blomberg, E. R. Limpaecher, and E. V. Dydek. "Boston Community Energy Study–Zonal Analysis for Urban Microgrids." Technical Report 1201, Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA, https://apps.dtic.mil/sti/pdfs/AD1033735.pdf, March 2016.

174. Stadler, M., Z. Pecenak, P. Mathiesen, K. Fahy, and J. Kleissl. "Performance Comparison Between Two Established Microgrid Planning MILP Methodologies Tested on 13 Microgrid Projects." *Energies*, vol. 13, no. 17, https://doi.org/10.3390/en13174460, August 2020.

175. Michalitsakos, P., L. Mihet-Popa, and G. Xydis. "A Hybrid RES Distributed Generation System for Autonomous Islands: A DER-CAM and Storage-Based Economic and Optimal Dispatch Analysis." *Sustainability*, vol. 9, no. 11, https://doi.org/10.3390/su9112010, 2017.

176. Momber, I., T. Gómez, G. Venkataramanan, M. Stadler, S. Beer, J. Lai, C. Marnay, and V. Battaglia. "Plug-in Electric Vehicle Interactions With a Small Office Building: An Economic Analysis Using DER-CAM." Lawrence Berkeley National Laboratory, Berkley, CA, http://escholarship.org/uc/item/8kt8x90t, 1 June 2010.

177. Stadler, M., Groissböck, G. Cardoso, and C. Marnay. "Optimizing Distributed Energy Resources and Building Retrofits With the Strategic DER-CAModel." Lawrence Berkeley National Laboratory, Berkley, CA, https://www.osti.gov/servlets/purl/1163652, July 2014.

178. Mathur, S., S. Haase, and T. Jimenez. "Microgrid Analysis Tools Summary." NREL/PR-5000-70578, NREL, Golden, CO, https://www.nrel.gov/docs/fy18osti/70578.pdf, 27 November 2017.

179. U.S. DOE. "Microgrid and Integrated Systems Program." Office of Electricity, Washington, DC, https://www.energy.gov/sites/default/files/2022-05/Microgrid%20and%20Integrated%20Microgrid%20Systems%20Program%20Report%20050922.pdf, January 2022.

180. Lawrence Berkeley National Laboratory. "The Distributed Energy Resources Customer Adoption Model (DER-CAM)." Grid Integration Group, https://gridintegration.lbl.gov/der-cam, accessed on 4 October 2022.

181. Stadler, M., S. Mashayekh, S. Narayanan, N. DeForest, and T. Brandt. "Supervisory Controller for PV and Storage Microgrids." Lawrence Berkeley National Laboratory, Berkley, CA, https://escholarship.org/content/qt95z5j33p/qt95z5j33p.pdf, October 2015.

182. U.S. DoD. "Modular, Secure, and Replicable Microgrid Control System for Generation and Storage Management at Military Installations." EW-201602, Strategic Environmental Research and Development Program, Environmental Security Technology Certification Program, https://serdp-estcp.org/projects/details/839b2716-37f5-46f9-9359-f45f66cf138f, accessed on 1 October 2022.

183. Lawrence Berkeley National Laboratory. "Distributed Energy Resources Customer Adoption Model Plus (DER-CAM+) 2016-075." Intellectual Property Office, https://ipo.lbl.gov/lbnl2016-075/, accessed on 2 October 2022.

184. Stadler, M., and Z. Pecenak. "Effective Design of Microgrids With State-of-the-Art Planning Methods." Presentation at the Microgrid Knowledge 2022 Conference, https://www.youtube.com/watch?v=pfm4tIDvTCs, 15 June 2022.

185. Mayfield Renewables. "Macro Guide to Microgrids." *Solar Builder*, pp. 46–55, https://www.mydigitalpublication.com/publication/?m=59310&i=756796&p=1&ver=html5, 2022.

186. Hewett, J., and K. Anderson. Personal communication, 5 October 2022.

187. Cutler, D., D. Olis, E. Elgqvist, X. Li, N. Laws, N. DiOrio, and K. Anderson. "REopt: A Platform for Energy System Integration and Optimization." NREL/TP-7A40-70022, NREL, Golden, CO, https://www.nrel.gov/docs/fy17osti/70022.pdf, September 2017.

188. NREL. "REopt Is Not Lite Anymore: REopt Techno-Economic Optimization Tool Brings Enhanced Renewable Energy Optimization Capabilities to Every User." https://www.nrel.gov/news/program/2022/reopt-is-not-lite-anymore.html, 2 February 2022.

189. Lambert, T., P. Gilman, and P. Lilienthal. "Micropower System Modeling With HOMER." *Integration of Alternative Sources of Energy*, F. A. Farret, and M. G. Simões (editors), pp. 379–418, Hoboken, NJ: John Wiley & Sons, 2006.

REFERENCES, *continued*

190. NREL. "Renewable Energy Optimization (REopt)." NREL/FS-7A40-62320, https://www.nrel.gov/docs/fy14osti/62320.pdf, June 2014.

191. Mahmud, D. M., S. M. M. Ahmed, S. Hasan, and M. Zeyad. "Grid-Connected Microgrid: Design and Feasibility Analysis for a Local Community in Bangladesh." *Clean Energy*, vol. 6, no. 3, pp. 447–459, https://doi.org/10.1093/ce/zkac022, June 2022.

192. Broderick, R., B. M. Garcia, S. E. Horn, and M. S. Lave. *Microgrid Conceptual Design Guidebook 2022*. SAND2022-4842 R, Sandia National Laboratories, https://energy.sandia.gov/wp-content/uploads/2022/05/ETI_SNL_Microgrid_Guidebook_2022_SAND2022-4842-R_FINAL.pdf, May 2022.

193. Van Bossuyt, D., and G. Oriti. "Energy Security for Naval Station Rota, Spain: Three-Year NSETTI Funded Project Concludes With Strong Results for the Navy." Naval Postgraduate School, https://nps.edu/web/eag/energy-security-for-naval-station-rota-spain-three-year-nsetti-funded-project-concludes-with-strong-results-for-the-navy, 1 January 2021.

194. Hewett, J., G. Oriti, and D. L. Van Bossuyt. Personal communication, 17 October 2022.

195. National Rural Electric Cooperative Association. "Programs and Services: MicrogridUP." https://www.cooperative.com/programs-services/bts/microgrid-up/Pages/default.aspx, retrieved 1 October 2022.

196. Stadler, M., and Z. Pecenak. "Building the Case for the Standardization of Microgrid Platforms for the DOD." Microgrid Knowledge, https://microgridknowledge.com/the-case-for-the-standardization-of-microgrid-platforms-for-the-military/, 27 September 2022.

197. U.S. DoD. "Development of a Decision Support Aid System Connecting Climate Model Downscaling and DoD Infrastructure." RC22-7335, Strategic Environmental Research and Development Program, Environmental Security Technology Certification Program, https://www.serdp-estcp.org/projects/details/c07b1896-7278-4539-a58f-1313a2e03705/rc22-7335-project-overview, accessed on 30 August 2022.

198. U.S. DoD. "Climate Model Comparative Assessment for DoD Infrastructure Applications." Strategic Environmental Research and Development Program, Environmental Security Technology Certification Program, https://www.serdp-estcp.org/blogs/details/ad0ce384-1ae7-46fb-8035-8637fa449325/climate-model-comparative-assessment-for-dod-infrastructure-applications, 5 May 2022.

199. Behr, P. "Can a DOE Backed Project Help Save the Grid?" *EnergyWire*, https://www.eenews.net/articles/can-a-doe-backed-project-help-save-the-grid/, 16 June 2022.

200. Sickinger, T. "Oregon Utilities Crunch Big Data, Tap Artificial Intelligence to Reduce Wildfire Risks." *The Oregonian*, https://www.oregonlive.com/wildfires/2022/06/oregon-utilities-crunch-big-data-tap-artificial-intelligence-to-reduce-wildfire-risks.html?utm_medium=email, 7 July 2022.

201. Anderson, K., and S. Mishra. "Probabilistic Resilience of DER Systems—A Simulation Assisted Optimization Approach." Paper no. 21ISGT1243, presentation at the IEEE Power & Energy Society Conference, https://www.nrel.gov/docs/fy21osti/78910.pdf, 16–18 February 2021.

202. Reilly, J., A. Hefner, B. Marchionini, and G. Joos. "Microgrid Controller Standardization: Approach, Benefits and Implementation." Paper Session 5B (Distribution Technical Track), presentation to the Grid of the Future Conference, Cleveland, OH, https://cigre-usnc.org/wp-content/uploads/2017/10/1_REILLY_GOTF_Cleveland_Oct-24-2017.pdf, 24 October 2017.

203. Vasilakis, A., I. Zafeiratou, D. T. Lagos, and N. D. Hatziargyriou. "The Evolution of Research in Microgrids Control." *IEEE Open Access Journal of Power and Energy*, vol. 7, pp. 331–343, https://doi.org/10.1109/OAJPE.2020.3030348, October 2020.

204. Cai, N., X. Xu, and J. Mitra. "A Hierarchical Multi-Agent Control Scheme for a Black Start-Capable Microgrid." 2011 IEEE Power and Energy Society General Meeting, Detroit, MI, https://doi.org/10.1109/PES.2011.6039570, 24–28 July 2011.

205. Hamilton-Antonson, J. "Benefits of a Synchronous Generator in a Microgrid." POWER, https://www.powermag.com/benefits-of-a-synchronous-generator-in-a-microgrid/, 1 September 2022.

206. Zahraoui, Y., I. Alhamrouni, S. Mekhilef, M. R. Basir Khan, M. Seyedmahmoudian, A. Stojcevski, and B. Horan. "Energy Management System in Microgrids: A Comprehensive Review." *Sustainability*, vol. 13, no. 19, https://doi.org/10.3390/su131910492, September 2021.

207. Chen, B., J. Wang, X. Lu, C. Chen, and S. Zhao. "Networked Microgrids for Grid Resilience, Robustness, and Efficiency: A Review." *IEEE Transactions on Smart Grid*, vol. 12, no. 1, https://doi.org/10.1109/TSG.2020.3010570, January 2021.

208. Ahmed, K., M. Seyedmahmoudian, S. Mekhilef, N. M. Mubarak, and A. Stojcevski. "A Review on Primary and Secondary Controls of Inverter-interfaced Microgrid."

REFERENCES, *continued*

Journal of Modern Power Systems and Clean Energy, vol. 9, no. 5, https://doi.org/10.35833/MPCE.2020.000068, September 2021.

209. Mudd, T. "Combat Center PWD Works Toward Water, Energy Conservation (Image 1 of 7)." Photo ID 1643452, Defense Visual Information Distribution Service, https://www.dvidshub.net/image/1643452/combat-center-pwd-works-toward-water-energy-conservation, 6 October 2014.

210. Eto, J. H., R. Lasseter, D. Klapp, A. Khalsa, B. Schenkman, M. Illindala, and S. Baktiono. "The CERTS Microgrid Concept, as Demonstrated at the CERTS/AEP Microgrid Test Bed." Energy Analysis and Environmental Impacts Division, Lawrence Berkeley National Laboratory, Berkely, CA, https://eta-publications.lbl.gov/sites/default/files/certs_microgrid_concept_final.pdf, September 2018.

211. Manson, S. "Challenges and Solutions in Microgrid Controls and Protection." Presentation at the ARPA-E Engineering Microgrids With Control Co-Design Workshop, https://arpa-e.energy.gov/sites/default/files/EMC2%20Workshop%20Day%201%20-%20SManson.pdf, 5 October 2020.

212. Bellini, E. "Grid-Forming Inverter to Stabilize Microgrids." *PV Magazine*, https://pv-magazine-usa.com/2022/08/29/grid-forming-inverter-to-stabilize-microgrids/, 19 August 2022.

213. Clarke, S., and D. C. Jeyamohan. "Executive Summary: Schneider Electric Leverages Digital Twin Capabilities to Enhance Facilities Optimization." Verdantix, https://www.verdantix.com/report/schneider-electric-leverages-digital-twin-capabilities-to-enhance-facilities-optimization, 10 May 2021.

214. U.S. DoD. "Energy Disturbance Resiliency Through Automated Fault Isolation and Restoration." EW21-5204, Strategic Environmental Research and Development Program, Environmental Security Technology Certification Program, https://www.serdp-estcp.org/projects/details/5a384388-5592-400a-867d-cc9c8550db49/ew21-5204-project-overview, accessed on 14 October 2022.

215. Scranton, P., and P. Fridenson. *Reimagining Business History*. Baltimore, MD: The Johns Hopkins University Press, 2013.

216. NREL. "Unique Procurement Process Expands Microgrid Research Capabilities at the ESIF." https://www.nrel.gov/news/program/2018/procurement-expands-microgrid-research-capabilities-at-esif.html, 28 February 2018.

217. Masburah, R., R. L. Jana, A. Khan, S. Xu, S. Lan, S. Dey, and Q. Zhu. "Adaptive Learning Based Building Load Prediction for Microgrid Economic Dispatch." 2021 Design, Automation & Test in Europe Conference & Exhibition, Grenoble, France, https://doi.org/10.23919/DATE51398.2021.9474041, July 2021.

218. Li, F., and G. Karsai. "Results From Testing Advanced Microgrid Control Algorithms." Webinar, Strategic Environmental Research and Development Program, Environmental Security Technology Certification Program, https://www.serdp-estcp.org/toolsandtraining/details/b6da8c13-42b9-4bc2-83b6-74eb59cb2b19/results-from-testing-advanced-microgrid-control-algorithms, 15 July 2022.

219. Babahajiani, P., P. Zhang, T.-C. Wei, J. Liu, and X. Lu. "Employing Interacting Qubits for Distributed Microgrid Control." *IEEE Transactions on Power Systems*, https://ieeexplore.ieee.org/document/9850415/, 4 August 2022.

220. Zhu, L., C. Zhang, H. Yin, D. Li, Y. Su, I. Ray, J. Dong, F. Wang, L. M. Tolbert, Y. Liu, Y. Ma, B. Rogers, J. Glass, L. Bruce, S. Delay, P. Gregory, M. Garcia-Sanz, and M. Marden. "A Smart and Flexible Microgrid With a Low-Cost Scalable Open-Source Controller." *IEEE Access*, vol. 9, pp. 162214–162230, https://doi.org/10.1109/ACCESS.2021.3131995, December 2021.

221. Laval, S. "Enabling Grid-Edge Interoperability to Accelerate DER Adoption and Integration." Presentation Before the ARPA-E Workshop, Engineering Microgrids With Control Co-Design, https://arpa-e.energy.gov/sites/default/files/EMC2%20Workshop%20Day%202%20-%20SLaval.pdf, 9 October 2020.

222. O'Neil, C. "Microgrids for Anyone: Communication-Less Scheme Streamlines Microgrid Setup, Simplifies Recovery." NREL, https://www.nrel.gov/news/features/2022/microgrids-for-anyone.html, 29 September 2022.

223. Koralewicz, P., E. Mendiola, R. Wallen, V. Gevorgian, and D. Laird. "Unleashing the Frequency: Multi-Megawatt Demonstration of 100% Renewable Power Systems With Decentralized Communication-Less Control Scheme." NREL/TP-5000-80742, NREL, Golden, CO, https://www.nrel.gov/docs/fy22osti/80742.pdf, September 2022.

224. Liu, C.-C., K. Schneider, M. Chinthavali, and R. Hovsapian. "Enabling a Decarbonized, Equitable Grid With Microgrid Building Blocks." U.S. Department of Energy 2022 Microgrid Program R&D Peer Review, https://www.nrel.gov/grid/assets/pdfs/02_enabling-a-decarbonized-equitable-grid-with-microgrid-building-blocks.pdf, 26–27 July 2022.

REFERENCES, *continued*

225. Hewett, J., and C.-C. Liu. Personal communication, 10 October 2022.

226. U.S. DoD. "An Assessment of Operational Energy Capability Improvement Fund (OECIF) Programs." Office of the Deputy Assistant Secretary of Defense for Operational Energy, Washington, DC, https://apps.dtic.mil/sti/pdfs/AD1047768.pdf, 2017.

227. Manson, S. "Tactical Microgrid Systems for the U.S. Military." Schweitzer Engineering Laboratories, presentation at the 2018 Microgrid Knowledge Conference, Chicago, IL, https://www.districtenergy.org/viewdocument/1b-tactical-microgrid-systems-for, 7 May 2018.

228. The National Academies of Sciences, Engineering, and Medicine. *Powering the U.S. Army of the Future*. Washington, DC: The National Academies Press, https://doi.org/10.17226/26052, 2021.

229. Lawrence Berkeley National Laboratory. "Still the One: New Study Finds Efficiency Remains a Cost-Effective Electricity Resource." https://emp.lbl.gov/news/still-one-new-study-finds-efficiency-remains, 22 July 2021.

230. Hakes, J. *A Declaration of Energy Independence: How Freedom From Foreign Oil Can Improve National Security, Our Economy, and the Environment*. Hoboken, NJ: John Wiley & Sons, 2008.

231. Fernandez, N., Y. Xie, S. Katipamula, M. Zhao, W. Wang, and C. Corbin. "Impacts of Commercial Building Controls on Energy Savings and Peak Load Reduction." PNNL-25985, Pacific Northwest National Laboratory, Richland, VA, https://buildingretuning.pnnl.gov/publications/PNNL-25985.pdf, May 2017.

232. Advanced Research Projects Agency–Energy. "Multi-Modal Sensor Platform for Occupancy Detection." ARPA-E project, 15 May 2018—31 May 2022, Syracuse University, Syracuse, NY, https://arpa-e.energy.gov/technologies/projects/multi-modal-sensor-platform-occupancy-detection, 16 November 2017.

233. Advanced Research Projects Agency–Energy. "Accelerating Coupled HVAC/Building Simulation With a Neural Component Architecture." ARPA-E project, 12 May 2020—31 July 2022, https://arpa-e.energy.gov/technologies/projects/accelerating-coupled-hvacbuilding-simulation-neural-component-architecture, 5 April 2019.

234. Chandler, D. L. "Passive Cooling System Could Benefit Off-Grid Locations." *MIT News*, https://news.mit.edu/2022/passive-cooling-off-grid-0920, 20 September 2022.

235. Advanced Research Projects Agency–Energy. "ARPA-E—Enhancing Energy Security Through Defense Partnerships." https://arpa-e.energy.gov/news-and-media/blog-posts/arpa-e-enhancing-energy-security-through-defense-partnerships, 17 March 2020.

236. Advanced Research Projects Agency–Energy. "Passive Radiative Cooling Film." ARPA-E Project, 26 August 2019—25 November 2022, St. Paul, MN, https://arpa-e.energy.gov/technologies/projects/passive-radiative-cooling-film, 15 November 2018.

237. Santos, B. "PV Water-Draining Device With New Anti-Clogging Design." *PV Magazine*, https://www.pv-magazine.com/2022/10/12/pv-water-draining-device-with-new-anti-clogging-design/, 12 October 2022.

238. Association of the U.S. Army. "Army Installation Partnerships for Mission Assurance." Professional Development Forum, Arlington, VA, https://www.youtube.com/watch?v=N4XjxKXyrTM, 13 April 2022.

239. Schaffner, F. J. (director). *Patton*. United States, 20th Century Fox, 1970.

240. Harper, J. "U.S. Military Wants Its Vehicles to Go Electric—With Detroit's Help." *National Defense*, https://www.nationaldefensemagazine.org/articles/2022/2/4/military-wants-its--vehicles-to-go-electricwith-detroits-help, 4 February 2022.

241. General Dynamics. "General Dynamics Business Units to Participate in AUSA 2022." https://www.gd.com/Articles/2022/10/04/general-dynamics-business-units-to-participate-in-ausa-2022, 4 October 2022.

242. Zinni, A., M. Augier, and S. F. X. Barrett. "Innovation: People Are More Important Than Technology." U.S. Naval Institute, *Proceedings*, vol. 148/8/1,434, https://www.usni.org/magazines/proceedings/2022/august/innovation-people-are-more-important-technology, August 2022.

243. Marqusee, J. "Huntoon Microgrid Critique 'Seriously Flawed'." *RTO Insider*, vol. 2017, no. 24, https://www.rtoinsider.com/articles/26840-soapbox-huntoon-microgrid-critique-seriously-flawed-, 20 June 2017.

244. Kurka, A. "624th CES Airmen Keep the Electricity Flowing at Bellows AFS (Image 2 of 4)." Photo ID 6045375, Defense Visual Information Distribution Service, https://www.dvidshub.net/image/6045375/624th-ces-airmen-keep-electricity-flowing-bellows-afs, 25 January 2020.

245. Hewett, J., and A. Oxendine. Personal communication, 13 July 2022.

REFERENCES, *continued*

246. Craig, B. D., R. A. Lane, S. L. Knoeller, O. R. Conniff, C. W. Fink, and B. J. Ingold. *Department of Defense Energy Handbook: Alternative and Renewable Energy Options for DoD Facilities and Bases (Spiral 2)*. Defense Technical Information Center, Advanced Materials, Manufacturing, and Testing Information Analysis Center, Washington, DC, https://www.asaie.army.mil/public/es/netzero/docs/ammtiac_energy_handbook.pdf, March 2011.

247. Zhou, J. "Slipstream Researchers Take on Three New Projects for the U.S. Department of Defense ESTCP in 2022." Slipstream, https://slipstreaminc.org/news/estcp-dod-new-projects-2022-gebs, 27 January 2022.

248. Surash, J. E. "Federal Utility Partnership Working Group." Deputy Assistant Secretary of the Army for Energy and Sustainability, presentation at the Federal Utility Partnership Working Group, slides 82–89, https://www.energy.gov/sites/default/files/2022-05/2022-fupwg-uesc-overview-day2.pdf, 4 May 2022.

249. Vaughn, K., and P. Barton. "Beyond Appropriated Funding: An Innovative Financial Equation for Building Energy Resilience." White Paper, Schneider Electric, https://www.se.com/us/en/download/document/0100AC1801/, 30 July 2018.

250. U.S. DoD. "Fiscal Year (FY) 2023 Budget Estimates: Military Construction, Family Housing, Defense-Wide." Justification data submitted to Congress, Washington, DC, https://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2023/budget_justification/pdfs/07_Military_Construction/Military_Construction_Defense-Wide_Consolidated.pdf, March 2022.

251. Farnan, P. "Update on U.S. Army Use of ESPCs and UESCs." Office of the Acting Assistant Secretary of the Army (Installations, Energy & Environment), https://www.army.mil/article/252164/update_on_u_s_army_use_of_espcs_and_uescs, 19 November 2021.

252. Correll, M., and S. Bennett. "Piloting Energy-as-a-Service." *The Military Engineer*, vol. 112, no. 726, pp. 54–56, March–April 2020.

APPENDIX

NUCLEAR MICROEATERS FOR MICROGRID POWER

Once hailed as the cleanest, most reliable, and most promising source of electrical power generation, nuclear power has long since fallen out of favor in the United States and much of the world. The share of global gross electricity production from nuclear power fell below 10% in 2021, the lowest level in nearly 40 years [A1]. Realistic hopes for a nuclear renaissance in the late 2000s were overrun by the Fukushima Daiichi nuclear disaster in 2011 and then soon met by the rapidly dropping cost of new renewable power installations [A1, A2]. However, "financial momentum" has been building behind the industry since the invasion of Ukraine in early 2022 elevated concerns over energy security, and the negligible emissions offered by nuclear power has also increasingly found favor among environmental protection analysts and interest groups [A3, A4].

The largest contributor to this momentum, however, is the emerging series of Generation III+ and IV designs for small modular reactors (SMRs), which typically have a planned capacity between 20 and 300 MW_e (megawatts electric), and a series of still-emerging, highly innovative nuclear microreactors—which, with capacities ranging from 1 to perhaps 20 MW_e, would truly live up to their name [A4]. Research and development efforts into SMRs are much further along than for microreactors. Roughly fifty SMR designs are in various stages of design worldwide, and in the United States, the Nuclear Regulatory Commission (NRC) has already telegraphed its intent to certify the SMR design from the Oregon-based firm NuScale Power, which is all but slated to be the first to receive the critical NRC safety approval, although approval is unlikely to come swiftly [A5]. NuScale's base commercial design would include twelve of its modular 77-MW_e power modules, linked in sequence into a 924-MW_e plant [A6]. Central to its appeal is a design that is orders of magnitude simpler (and cheaper) than nuclear plants now in operation, as well as a smaller footprint that largely eliminates many of the siting challenges that have beleaguered the nuclear industry in the United States and caused new plant cost overruns to run into the many billions of dollars [A2]. Instead of performing laborious and costly on-site construction and assembly of reactor components, as is required for the current domestic reactor fleet, the modular approach front-ends most of that assembly process within the factory.

Despite their head start, SMRs are unlikely to emerge on the commercial market anytime soon. At best, the NuScale design could go online at a test site on the Idaho National Laboratory (INL) campus as early as 2029 [A5], but by the estimation of Michael Liebreich, founder of BloombergNEF and a widely respected energy expert, "not a single SMR will be operating much before 2030" [A7]. While some military analysts have argued that the U.S. Department of Defense (DoD) should pursue the use of SMRs on domestic installations to the exclusion of microreactors—which may hit the commercial market a decade after SMRs [A8]—the DoD remains bullish on microreactors. It supported a major microreactor technology roadmap drawn up by the Nuclear Energy Institute in 2018, and in 2021, the U.S. Air Force nominated Eielson Air Force Base in Alaska to host the service's first next-generation microreactor [A4]. As of late 2022, the Air Force expects construction of this "nuclear microreactor energy production facility" to begin in 2025, with commercial operation to follow 2 years later, producing electricity and steam to meet a baseload demand of 5 MW_e [A9]. The Eielson microreactor will remain permanently sited on the Alaskan installation until it is eventually decommissioned.

Of course, the installation near Fairbanks will not host DoD's truly first microreactor. In the 1950s, the U.S. Army Nuclear Power Program (ANPP) produced multiple small-scale reactor prototypes for military use, and, for example, the PM-2A reactor was used to power Camp Century in Greenland until 1964 [A10, A11]. The Army dubbed it "portable," as even at 330 tons, its constituent pieces could fit in a C-130's cargo hold [A11].

A.1 PROJECT PELE

The dozen or so microreactor concepts currently under development far exceed in sophistication and safety what the ANPP engineers could have imagined 70 years ago. Advanced microreactor designs are expected to have a longer core life, allowing up to 10 years between refuelings, and like SMRs, will use simpler designs and processes and sport passive safety systems that are designed to eliminate the potential of overheating or a meltdown event [A12].

Many of the designs garnering interest from the service branches and DoD leadership are also intended to be truly portable in a way the PM-2A reactor did not quite achieve. In the wake of a 2016 Defense Science Board (DSB) report on energy systems for forward operating bases and remote bases, the DoD's Strategic Capabilities Office (SCO) launched Project PELE to demonstrate a prototype portable microreactor within 5 years—just as the DSB had recommended [A13]. In March 2020, the SCO awarded $39.7 million across three firms to perform engineering and evaluative design work sufficient for the department to fully assess them [A14]. The DoD laid out five technical objectives:

1. Life: generate threshold power of 1–10 MW_e for more than 3 years without refueling.
2. Wrap-up: take less than 7 days for a planned shutdown, cooldown, disconnect, prepared transport, and safe transport.
3. Startup: take less than 72 hours from arrival of a unit at its destination to full electric power operations.
4. Size: fit all components in an International Organization for Standardization 688-certified 20-ft or 40-ft CONEX containers (20 ft preferred, no count specified).
5. Operation: operate semi-autonomously, requiring minimal monitoring of system health with minimal routine preventative maintenance and repair required [A15, A16].

The SCO, partnering with the U.S. Department of Energy (DOE), the NRC, the National Aeronautics and Space Administration, and the U.S. Army Corps of Engineers, selected BWX Technologies' (BWXT) design in June 2022, garnering it a cost-type contract of approximately $300 million to develop an operable prototype [A15].

BWXT's concept is a high-temperature gas-cooled reactor that will operate between 1 and 5 MW_e, powered by a novel fuel fabrication approach. Tristructural Isotropic (TRISO) fuel is pelletized, made from a fuel kernel of uranium oxycarbide (a mixture of uranium dioxide and uranium carbide) encapsulated within three layers of highly engineered protection materials [A16]. As the SCO program manager for Project PELE recently explained, TRISO fuel is a "commercial reactor game changer"; its particles have already been extensively tested by the DOE, and its high melting point allows for "a passively safe reactor which can significantly reduce capital investment and O&M [operations and maintenance] cost" [A17].

A.2 OTHER EFFORTS

The DOE is also working to advance microreactor technology, with the Microreactor Applications Research Validation and Evaluation (MARVEL) project its flagship effort. Led by INL, it will come into being as a very small test reactor, or "more of a nuclear battery," as the project's technical lead describes it [A18]. Design and modeling work began in 2020, and one of its two primary objectives is to yield an operational reactor that produces combined heat and power "to a functional microgrid" [A19]. The DOE expects to begin work on the "MARVEL Microgrid" in calendar year 2023 [A19].

The DOE Microreactor Program estimates that roughly 12 microreactor concepts are under various stages of development, presenting a potential DoD customer with a wide variety of refueling intervals (3+ to 20 years), coolants (sodium, helium, liquid metal), and fuel types, with roughly half employing TRISO [A19]. Manufacturers include Westinghouse (who competed in the PELE selection), NuScale Power (with a design to accompany its SMR), and Oklo, which has submitted the first of any microreactor design to the NRC for licensing project plan review. It was denied in January 2022, but Oklo resubmitted its application in September [A20].

A.3 MICROGRID INTEGRATION

To power a microgrid (for the purposes of this appendix, both grid-tied and remote or standalone microgrids are considered) an SMR or nuclear microreactor can provide power that is both "excellent" for baseload generation and complements the non-dispatchability of variable sources like solar photovoltaic (PV) and wind [A21, A22]. Nuclear generation in a microgrid is most likely to displace fossil-fuel-based assets, namely natural-gas- and diesel-fired generators (either utility-grade plants or networked emergency diesel generators), presenting a major benefit to DoD installation microgrids that would otherwise remain reliant on continual external fuel resupply for power. This includes piped natural gas, which is vulnerable to off-site interruptions.

Most research to date on the potential use of an SMR or microreactor (hereafter called small reactors, or SRs) in a microgrid has indeed presumed that an SR would typically be paired with a combination of solar PV, wind, and battery energy storage systems (see Figure A-1). An SR's ability to generate combined heat and power (CHP) also appears as a major technical and economic selling point; not only does it enhance the appeal of an SR's promised emissions reductions, it also increases a microgrid's "flexible operation capabilities" [A22].

Powering a microgrid solely by an SR, while potentially desirable for an extremely remote operation (or for a limited amount of time), presents extreme reliability and resilience vulnerabilities, as it would function as a sole and highly visible single point of failure. Although large-scale nuclear power plants display incredibly high uptime ratios over their long lifecycles, maintenance is still occasionally required, and the refueling process can be a lengthy one. Moreover, it requires the importation of off-site fuel; multiple-module SRs could alleviate these concerns, but only somewhat. As discussed next, attendant to the use of an SR to provide both baseload and peak-following load are several severe technical limitations regarding component fatigue and potential system failure.

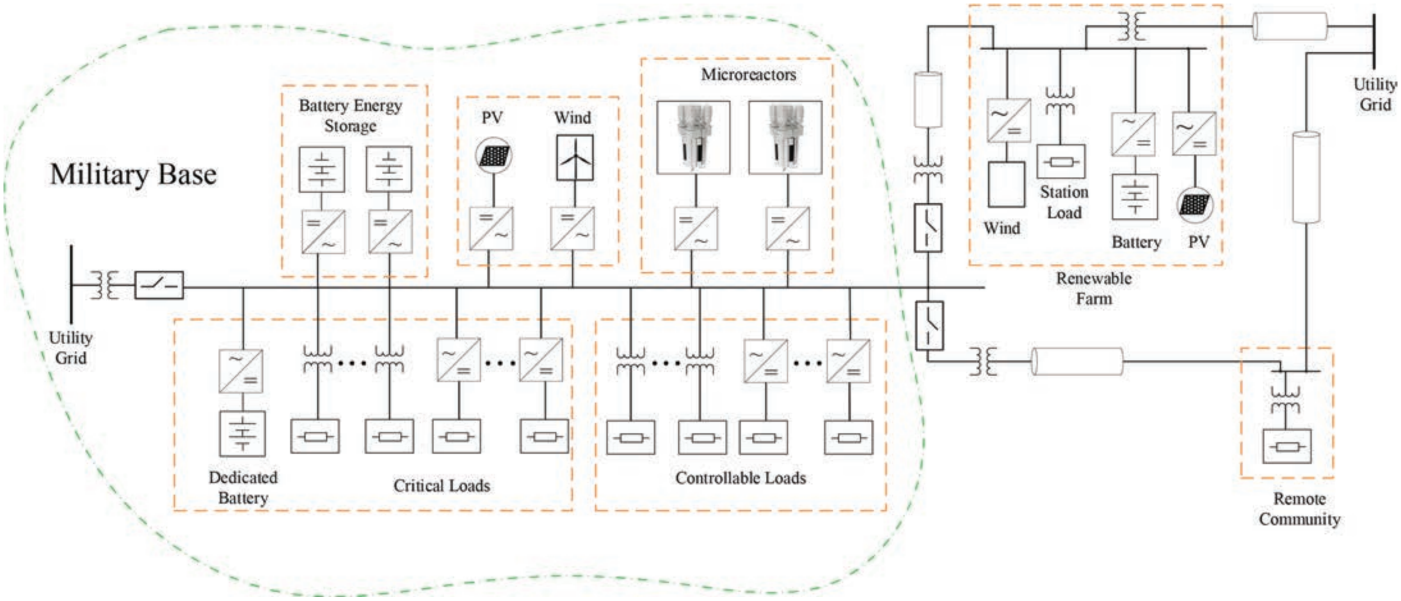


Figure A-1. Design of a Hybrid Military Microgrid Based on an SMR/Microreactor and Other Distributed Energy Resources (DERs) *(Source: Poudel et al. [A23])*.

SMRs and microreactors, while significant enablers of flexible operation in a microgrid, "still face technical limitations" in how they provide power. Over-reliance on an SR to power an installation's entire demand profile requires frequent operation of the reactor's control rods, which causes thermal fatigue, speeds up the aging of multiple reactor and thermal components, exacerbates the corrosion and erosion of key hydraulic components, and can cause fission poisoning of the core itself [A22]. As a result, the design limits of an SR used for a microgrid will include "the rate of change, the total change, and the total number of large power cycles" [A22]. Fixed, standard generation schedules and daily power-cycling will be all but mandated to ensure safety, as well as to fully capture the SR's economic potential to deliver long-term efficient operation. During normal operational conditions, battery energy storage is especially well positioned to handle short-term power imbalances when paired with an SR [A22].

Since 2021, researchers at INL's Net-zero Microgrid Program, in collaboration with outside consultants, have conducted a series of in-depth reviews of the potential use of SRs in microgrids, producing two recent major studies: a technical guidance report (published October 2021) [A23] and a technoeconomic analysis (published August 2022) [A24]. The technical guidance report notes that an SR-powered microgrid could operate either via an alternating-current or a direct-current distribution system and could be configured to exploit thermal energy storage systems. The technical guidance study also notes that a larger SR (i.e., likely a small SMR) could stand in for multiple smaller microreactors in a given microgrid configuration without the need for significant changes to its system design or control parameters [A23].

Again, while an SR must be appropriately sized to meet an installation's baseload demand, battery storage will play a significant role in providing power flexibility to the microgrid. Noting that most microreactor concepts will not require access to water sources to serve as a reactor coolant, the siting constraints of an SR microgrid are significantly reduced. With regard to specific siting, an SR would likely be collocated within (at the center of) the microgrid boundary. Future technical study needs include (1) the dynamic modeling and simulation of microreactors within a microgrid, (2) the alignment of microreactor manufacturing specifications to allow testing by the MARVEL system, and (3) continuation of data collection on SR generator controls [A23].

INL's technoeconomic analysis uses XENDEE's mixed-integer linear programming optimization design tool to assess an SR-powered microgrid, evaluating the scope of DER sizing, placement, and type, to best meet system demand given multiple objectives [A24]. The study used the XENDEE tool to consider an SR under two policy and economic scenarios: (1) presuming the presence/absence of a carbon tax and then (2) assuming either a "flat cost" model, or one in which reactor capacity can benefit from its economies of scale (a larger SR will reduce the specific unit cost of electricity).

The report concludes that SRs "can be as cost competitive" as traditional natural-gas generators when larger SR reactors are used. However, as the report notes, a microreactor-powered microgrid with especially critical loads would benefit immensely if set free from its reliance on external fuel supplies. When paired with on-site-generating DERs, an SR could sustain a microgrid during an extreme outage, due to its long-lasting fuel (a minimum of 2 years between refuelings for most concepts) [A24].

This Page Intentionally Left Blank

APPENDIX REFERENCES

A1. Chestney, N. "Nuclear Share in Energy Generation Falls to Lowest in Four Decades-Report." Reuters, https://www.reuters.com/business/energy/nuclear-share-energy-generation-falls-lowest-four-decades-report-2022-10-05/, 5 October 2022.

A2. Portuondo, N. "Is Nuclear Energy Poised for an ESG-Fueled Comeback?" *EnergyWire*, https://www.eenews.net/articles/is-nuclear-energy-poised-for-an-esg-fueled-comeback/?utm_medium=email, 4 October 2022.

A3. Tuhus-Dubrow, R. "The Activists Who Embrace Nuclear Power." *The New Yorker*, https://www.newyorker.com/tech/annals-of-technology/the-activists-who-embrace-nuclear-power, 19 February 2021.

A4. Conca, J. "U.S. Air Force Base to Be First to Deploy New Nuclear 'Microreactor' - Soon Every Town Could Have One." *Forbes*, https://www.forbes.com/sites/jamesconca/2021/11/01/us-picks-eielson-air-force-base-for-the-air-forces-first-nuclear-microreactor/?sh=1dbf07433983, 1 November 2021.

A5. Pearl, L. "NRC to Certify NuScale Small Modular Reactor Design for Use in the U.S." UtilityDive, https://www.utilitydive.com/news/nrc-certifies-nuscale-small-modular-reactor-design-SMR-nuclear-us/628519/, 1 August 2022.

A6. Gordon, O. "Small Modular Reactors: What Is Taking So Long?" Power Technology, https://www.power-technology.com/uncategorized/small-modular-reactors-smrs-what-is-taking-so-long/, August 2022.

A7. Liebreich, M. "After Ukraine–The Great Clean Energy Acceleration." BloombergNEF, https://about.bnef.com/blog/after-ukraine-the-great-clean-energy-acceleration/, 30 September 2022.

A8. Renahan, T. "Realizing Energy Independence on U.S. Military Bases." *Joint Force Quarterly*, vol. 103, https://ndupress.ndu.edu/Media/News/News-Article-View/Article/2808076/realizing-energy-independence-on-us-military-bases/, 14 October 2021.

A9. World Nuclear News. "U.S. Air Force Issues RFP for Microreactor Project." https://www.world-nuclear-news.org/Articles/US-Air-Force-issues-RFP-for-microreactor-project, 28 September 2022.

A10. U.S. Army Corps of Engineers. "Army Nuclear Power Program, 1954-1976." https://www.usace.army.mil/About/History/Exhibits/Nuclear-Power-Program, accessed on 21 June 2022.

A11. Bierman, P. "The U.S. Army Tried Portable Nuclear Power at Remote Bases 60 Years Ago–It Didn't Go Well." *The Conversation*, https://theconversation.com/the-us-army-tried-portable-nuclear-power-at-remote-bases-60-years-ago-it-didnt-go-well-164138, 20 July 2021.

A12. U.S. DOE. "What Is a Nuclear Microreactor?" Office of Nuclear Energy, Washington, DC, https://www.energy.gov/ne/articles/what-nuclear-microreactor, 26 February 2021.

A13. U.S. DoD. "PROJECT PELE: Mobile Nuclear Reactor." Office of the Under Secretary of Defense, Research and Engineering - Office of the Secretary of Defense, Strategic Capabilities Office, Washington, DC, https://www.cto.mil/pele_eis/, accessed on 16 October 2022.

A14. Nuclear News. "Defense Department Invests in Three Microreactor Designs." *Nuclear Newswire*, https://www.ans.org/news/article-6/defense-department-invests-in-three-microreactor-designs/, 16 March 2020.

A15. BWX Technologies, Inc. "BWXT to Build First Advanced Microreactor in United States." https://www.bwxt.com/news/2022/06/09/BWXT-to-Build-First-Advanced-Microreactor-in-United-States, 9 June 2022.

A16. U.S. DoD. "Construction and Demonstration of a Prototype Mobile Microreactor: Final Environmental Impact Statement, Volume 1: EIS and Appendices." Strategic Capabilities Office, Washington, DC, https://www.cto.mil/wp-content/uploads/2022/05/Final-EIS-Vol-1-Distro-A.pdf, February 2022.

A17. Waksman, J. "Project PELE Overview: Mobile Nuclear Power for Future DoD Needs." Strategic Capabilities Office, Office of the Secretary of Defense, Strategic Capabilities Office, Washington, DC, https://www.nrc.gov/docs/ML2212/ML22126A059.pdf, May 2022.

A18. Clifford, C. "Inside the U.S. Government Project to Create Tiny Nuclear Reactors Like Batteries." *CNBC*, https://www.cnbc.com/amp/2022/06/15/inside-the-marvel-micronuclear-reactor-project-at-idaho-national-lab.html, 15 June 2022.

A19. Jackson, J. "Microreactor Program FY2022: Winter Program Review." U.S. DOE, Microreactor Program, https://gain.inl.gov/SiteAssets/MicroreactorProgram/2022MicroreactorProgramWinterReview/02-MRP_FY22%20Winter%20Program%20Review-Jackson.pdf, 3–4 March 2022.

A20. Patel, S. "Oklo Relaunches NRC Licensing Process for Nuclear Microreactor." POWER, https://www.powermag.com/oklo-relaunches-nrc-licensing-process-for-nuclear-microreactor, 20 September 2022.

APPENDIX REFERENCES, *continued*

A21. Schneider, K. P., S. Laval, J. Hansen, R. B. Melton, L. Ponder, L. Fox, J. Hart, J. Hambrick, M. Buckner, M. Baggu, K. Prabakar, M. Manjrekar, S. Essakiappan, L. M. Tolbert, Y. Liu, J. Dong, L. Zhu, A. Smallwood, A. Jayantilal, C. Irwin, and G. Yuan. "A Distributed Power System Control Architecture for Improved Distribution System Resiliency." *IEEE Access*, vol. 7, pp. 9957–9970, https://doi.org/10.1109/ACCESS.2019.2891368, January 2019.

A22. Poudel, B., V. Agarwal, T. R. McJunkin, L. Lin, and T. B. Phillips. "Operational Resilience of Nuclear-Renewable Integrated-Energy Microgrids." INL/JOU-21-65397-Revision-0, Idaho National Laboratory, Idaho Falls, ID, https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_54846.pdf, January 2022.

A23. Poudel, B., T. McJunkin, N. Kang, and J. T. Reilly. "Net-Zero Microgrid Program Project Report: Small Reactors in Microgrids, Technical Studies Guidance." INL/EXT-21-64616, Idaho National Laboratory, Idaho Falls, ID, https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_53291.pdf, October 2021.

A24. Poudel, B., T. McJunkin, N. Kang, J. T. Reilly, and M. Stadler. "Net-Zero Microgrid Program Project Report: Small Reactors in Microgrids, Technoeconomic Analysis." INL/RPT-22-67704 (Revision 0), Idaho National Laboratory, Idaho Falls, ID, https://inldigitallibrary.inl.gov/sites/STI/STI/Sort_62790.pdf, August 2022.

This Page Intentionally Left Blank

This Page Intentionally Left Blank

This Page Intentionally Left Blank

RESILIENCE BY DESIGN: MICROGRID SOLUTIONS FOR INSTALLATION ENERGY

By Joel Hewett

HDIAC-BCO-2022-258