U.S. DEPARTMENT of ENERGY

DRAFT REPORT

Microgrids R&D Strategic Plan

Topic 6 – Integrated Models and Tools for Microgrid Planning and Designs with Operations

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Disclaimer

Original Authors

The authors of the original 2021 document that formed the basis for this iteration are:

Russell Bent, Los Alamos National Laboratory (LANL)

Wei Du, Pacific Northwest National Laboratory (PNNL)

Miguel Heleno, Lawrence Berkeley National Laboratory (LBNL)

Robert Jeffers, National Laboratory of the Rockies (NLR)

Mert Korkali, Lawrence Livermore National Laboratory (LLNL)

Guodong Liu, Oak Ridge National Laboratory (ORNL)

Dan Olis, NLR

Parth Pradhan, Argonne National Laboratory (ANL)

Ravindra Singh, ANL

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Jim Reilly (Reilly Associates), Adib Nasle (Xendee), David Pinney (NRECA), Amin Salmani (SDG&E), and Muhidin Lelic (ComEd).

Revision Authors

The authors of the 2025 revision to the strategy document are:

Russell Bent, LANL

Christabella Annalicia, LLNL

Kumar Jhala, ANL

Guodong Liu, ORNL

Alyona Teyber, LLNL

Adam Mate, LANL

David Fobes, LANL

List of Acronyms

ADMS	Advanced Distribution Management System
AI	Artificial Intelligence
ANL	Argonne National Laboratory
API	Application Programming Interface
BTM	Behind-the-Meter (customer-owned)
CHP	Combined Heat and Power
CIM	Common Information Model
C-MAP	Community Microgrid Assistance Partnership
DERMS	Distributed Energy Resource Management System
DMS	Distribution Management System
DOE	U.S. Department of Energy
FERC	Federal Energy Regulatory Commission
FTM	Front-of-The-Meter (utility-owned)
GMLC	Grid Modernization Laboratory Consortium
HIL	Hardware In the Loop
IEEE	Institute of Electrical and Electronics Engineers
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LEL	Large Electric Loads
LLNL	Lawrence Livermore National Laboratory
C-MIX	Community Microgrid Innovation Exchange
ML	Machine Learning
NLR	National Laboratory of the Rockies
NRECA	National Rural Electric Cooperative Association

NPV	Net Present Value
OE	(U.S. DOE) Office of Electricity
OMS	Outage Management System
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
R&D	Research and Development
RD&D	Research, Development, and Deployment
SDG&E	San Diego Gas and Electric (utility)
SDN	Software-Defined Networking
SMR	Small Modular (Nuclear) Reactor
T&D	Transmission and Distribution
TA	Technical Assistance
VPP	Virtual Power Plant

Executive Summary

The United States' electric power system is always adapting, both to new conditions and to handle new loads and devices. As industries like artificial intelligence/machine learning data centers and more advanced critical mineral extraction techniques emerge, or as domestic manufacturing ramps up production, many solutions are examined to meet the rising electricity demand. Microgrids are one tool to utilize generation and assets located at the grid edge and near the new industries. To properly deploy and utilize the assets, models and tools to design and operate these components are needed. The U.S. Department of Energy's Microgrids Research and Development program continues to develop tools and techniques to meet these evolving needs.

This strategy document outlines a strategic vision for *Integrated Models and Tools for Microgrid Planning and Designs with Operations:* enhancing the DOE's support for microgrid deployment through improved planning and design tools. These tools are critical in determining microgrid configurations that deliver high performance in resilience, reliability and security, and ensuring energy abundance. Specifically, the Microgrid R&D program seeks to accomplish these three goals:

> Goal 1: Promote microgrids as a core solution for enhancing **resilience** of the electricity delivery system while supporting faster recovery of critical infrastructure during and after black sky events
>
> Goal 2: Ensure that microgrids serve as a driver to maintain a **reliable and secure** electricity delivery system by allowing important infrastructure to have consistently available alternative sources of power that can support the operations through both natural and man-made events.
>
> Goal 3: Use microgrids to enhance **energy abundance** by providing additional capacity through distributed energy supply and demand assets, as well as by providing necessary services and capabilities back to the bulk power system to help maintain consistent operations.

The document reviews current practices, highlighting the main technical approaches and capabilities of modern tools and their gaps. In particular, while the tools developed by the DOE Microgrid program already address design, integration, economic assessment, and resilience evaluation, they often lack capabilities to seamlessly interoperate with one another, which hampers comprehensive planning.

The DOE's Microgrid Program is advancing next-generation capabilities to address this gap through three guiding pillars: *Tool Interoperability*, *Software Architecture Flexibility*, and *Model Integration*. These priorities aim to create a unified ecosystem of planning tools that can evolve, communicate, and span a full range of design and operational requirements. Key initiatives, such as the MG-RAVENS project, demonstrate this vision by promoting standardized data models and Application Programming Interfaced (APIs) to facilitate interoperability and adaptability. Integrated workflows are also being developed to bring together disparate tools, enabling analysis across economic design, operations, cybersecurity, and beyond. Together, these efforts aim to empower microgrid planners with agile, holistic tools that can meet future national energy

challenges, ultimately advancing U.S. grid resilience, energy independence, and security.

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1 Introduction

Advanced aging of energy infrastructures and increasing frequency of threats (including extreme weather and cyberattacks) underscore the importance of investment in integrated models and tools for microgrid planning, deployment, and operations. The mandate for reliable, secure, and affordable domestic energy supply (often termed energy dominance) requires a shift in grid planning: expanding focus to solutions that efficiently meet the growing energy demand, especially in sectors like defense and information technology (e.g., data centers and advanced domestic manufacturing), through dispatchable and flexible distributed energy supply and demand assets that enhance energy independence and national security. Microgrids are a key technology to deliver on this vision by providing localized, reliable energy solutions that bolster the broader grid while helping avoid costly bulk transmission and sub-transmission upgrades that could otherwise increase costs for ratepayers.

The mission of the U.S. Department of Energy (DOE) Office of Electricity (OE) Microgrid Research and Development Program is to facilitate the evolution of the nation's electricity delivery infrastructure to achieve a more reliable and secure future in the most economical and efficient way through advancing microgrid innovations. The Program has invested in developing commercially viable single and networked microgrids, offering benefits such as increased grid reliability by providing power during outages, cost savings through optimized energy usage, integration of distributed energy supply and demand assets, improved power quality, and the ability to reduce peak demand on the main grid by using local generation and demand assets closer to the point of consumption. Technical and economic feasibility under controlled conditions is being verified and validated in the field through collaboration with industry partners and end users. In addition, the Program is contributing to microgrid standards development to support wider technology adoption and ensure U.S. technological leadership. Recent initiatives underscore this commitment: for example, in 2025 DOE, supported by the program, launched the Community Microgrid Assistance Partnership (C-MAP), funding microgrid projects in remote communities to bring the reality of America's energy abundance to rural homes and businesses (DOE OE. 2025). Such projects not only improve reliability and affordability in high energy cost, weak-grid areas, but also strengthen domestic energy and address critical energy security gaps.

This strategic document explores how the DOE/OE can further support microgrid technologies through improved microgrid planning and design tools to achieve the energy goals outlined above. These tools are essential for determining the best location, design, and operation of microgrids, ensuring that installed systems deliver maximum benefit in terms of reliability, security, affordability, and operational flexibility for both utilities and large electric load customers. This paper highlights the research and development (R&D) priorities through 2030 and beyond, focusing on expanding tool capabilities in line with three core themes: *Tool Interoperability, Software Architecture Flexibility, and Model Integration,* with an emphasis on driving integrated toolchains toward mid-range technology readiness levels in the near term and enabling faster deployment and industry uptake over the subsequent decade.

1.1 Current Planning Practices and Tools

Before delving into the technical vision for advancing microgrid planning and design tools, it is essential to first understand current practices and the capabilities of today's tools. These tools are widely used by microgrid planners to evaluate designs against key performance metrics that capture the core values of reliability, resilience, security, energy abundance, and affordability. These metrics align with ensuring continuous power delivery (reliability), withstanding and recovering from disruptions (resilience), protecting the system against threats (security, including cyber and physical threats), ensuring ample energy supply for demand (energy abundance), and keeping costs reasonable (affordability). Microgrids inherently contribute to many of these metrics: by providing local generation and backup capacity, they improve reliability and resilience through redundancy, enhance security by isolating critical customers from broader grid disturbances, and lower costs by reducing peak power purchases and avoiding or deferring some bulk transmission and sub-transmission upgrades. Achieving the right balance among these factors is a complex task – planners must evaluate tradeoffs between these competing goals to meet the specific needs of each community or installation, particularly where large electric loads such as data centers, advanced manufacturing, or defense installations are involved.

To analyze these trade-offs, today's microgrid planning and design tools primarily rely on two computational approaches: **simulation** and **optimization**. Simulation involves modeling the microgrid to predict how it will perform under various scenarios. It allows planners to examine behavior over time for a given design or operations strategy. Optimization automates the search for the best design or operating strategy by systematically exploring choices that meet defined metrics or planner criteria. Many tools use a combination of both approaches – for example, utilizing optimization to identify candidate designs and then simulating those designs in detail and higher granularity. Using these techniques, planners can consider various scenarios and identify solutions that best meet the metrics (reliability, cost, etc.) for their microgrid project, while respecting technical requirements. Although metrics vary by project, they typically map to the five categories noted earlier, and modern tools are built to quantify each of these metrics to inform decision-making and to demonstrate how proposed solutions can enhance grid reliability and resilience while managing cost impacts on ratepayers.

Several advanced tools have been developed (largely through the DOE Microgrid Program's R&D at national laboratories) to assist in microgrid planning and design. Table 1 (below) summarizes capabilities of prominent tools including whether they use optimization, simulation, or both, and which aspects of microgrid planning they cover – focusing on common use cases and analysis including 1) capability to model the integration of microgrids into energy delivery systems, 2) design of microgrids, 3) assessment of economic benefits, and 4) reliability and resilience assessment, particularly restoration and recovery after extreme events. Each tool is summarized in more detail in a glossary at the end of this document, and together they provide a foundation for the next generation of interoperable, flexible, and integrated toolchains described in subsequent sections.

Table 1. Summary of national laboratory developed microgrid planning tools. X is used to denote the capabilities a tool supports.

Tool	Optimization	Simulation	Microgrid Integration	System Design	Economic Planning	Reliability and Resilience Modeling
DER-CAM	X		X	X	X	
CleanStart DERMS	X	X				X
REopt	X		X	X	X	
MADRA	X		X	X	X	
LPNORM	X		X	X		
RONM	X		X	X		X
MDT	X	X		X	X	
ReNCAT	X	X	X		X	
ESM	X			X		X
COSTAD-MG	X	X	X			

In addition to DOE's suite of tools, the private sector has developed numerous microgrid planning software platforms. While a full survey of commercial tools is beyond the scope of this report it is important for DOE's Microgrid R&D Program to monitor and leverage industry developments. In many cases, federally funded research has been transferred to industry, leading to widely used products. The DOE and the Microgrid R&D Program should continue their successful history of commercializing R&D when such opportunities present themselves. Homer (a microgrid planning and design tools for pre-feasibility analysis and conceptual design) and XENDEE (a web-based microgrid optimization and decision support platform) are very good examples of successful transfer of the Microgrid Program's capability to industry. HOMER began as a NLR tool for microgrid feasibility analysis, and XENDEE evolved from LBNL's DER-CAM research.

1.2 Future Vision for Advanced Microgrid Tools Goals

Even with these tools, microgrid planning is complex, driven by the need to diversify energy resources, enhance integration with the larger electric grid, and bolster cybersecurity and physical security to protect critical infrastructure. Planners must strategically site microgrids to maximize regional resilience and meet the growing, concentrated demands of energy-intensive sectors, such as AI data centers and transportation hubs and other large electric loads critical to national security and economic competitiveness. These challenges underscore the necessity for advanced microgrid planning tools capable of navigating the intersection of technical, economic, and national security priorities. One of the biggest challenges for planners is that most microgrid design and planning tools address only parts of the overall complexity, making it hard to conduct comprehensive analyses. Additionally, these tools often lack interoperability in data, inputs, outputs, and solutions, hindering the ability to create holistic solutions by combining the analysis provided by multiple tools.

To address this challenge, the DOE's Microgrid R&D Program emphasizes advancements in interoperability, software architecture flexibility, and model integration for planning tools. These themes define a vision where different tools and models seamlessly work together, adapt quickly to new requirements, and encompass the full spectrum of microgrid and grid behavior. Each theme is described below in the context of supporting reliability, resilience, affordability, and energy security goals and in enabling faster movement from early-stage research tools to field validated, industry-adopted platforms over a 10-year horizon:

- **Interoperability** – The ability of microgrid planning and design tools to interact with one another and achieve capabilities and applications that are beyond the scope of an individual tool. **Developments support the greatest reuse of existing tools for uses of microgrid planning and design tools that lie at the intersection of current technologies.**

  In response to this recommendation, DOE's Microgrid R&D Program initiated the MG-RAVENS project to establish a unified data model based on the Common Information Model (CIM) and guide its implementation and use for applications related to modeling the grid for multiple purposes, including economic design, grid operations, asset management, and statistical analysis. Many of the capabilities listed in Table 1 have adopted the data model, including DER-CAM, REopt, and RONM, as well as some other capabilities not listed, such as QuEST, with several additional tools already in progress of adoption.

Figure 1. Illustrative example of the concepts behind interoperability. Thinking abstractly, given a software toolbox with capabilities (a hammer and a wrench) and another software toolbox with capabilities (a screwdriver), interoperability allows the creation of a new software toolbox with capabilities hammer, a

wrench, and a screwdriver. In the context of microgrid planning and design tools, a tool like a hammer equates to an implementation of a grid forming inverter, a storage model, etc. These Photos by Unknown Author are licensed under CC BY-SA and BY-SA-NC.

- **Software Architecture Flexibility** – Native software designs that support ease of repurposing tools to meet evolving needs and requirements. **Developments support agile software that can quickly be modified to meet new needs that are unanticipated over the next 5, 10, or more years.**

  To support this effort, under MG-RAVENS, a group representing the key performers of the Microgrid R&D Program was convened to steer the development of a standard Application Programming Interface (API) for software flexibilities. This led to the establishment of a Working Group, consisting of experts from academia, national laboratories, and industry, to provide feedback on the proposed software and data standards as enhancements to the CIM (MG-RAVENS 2025).

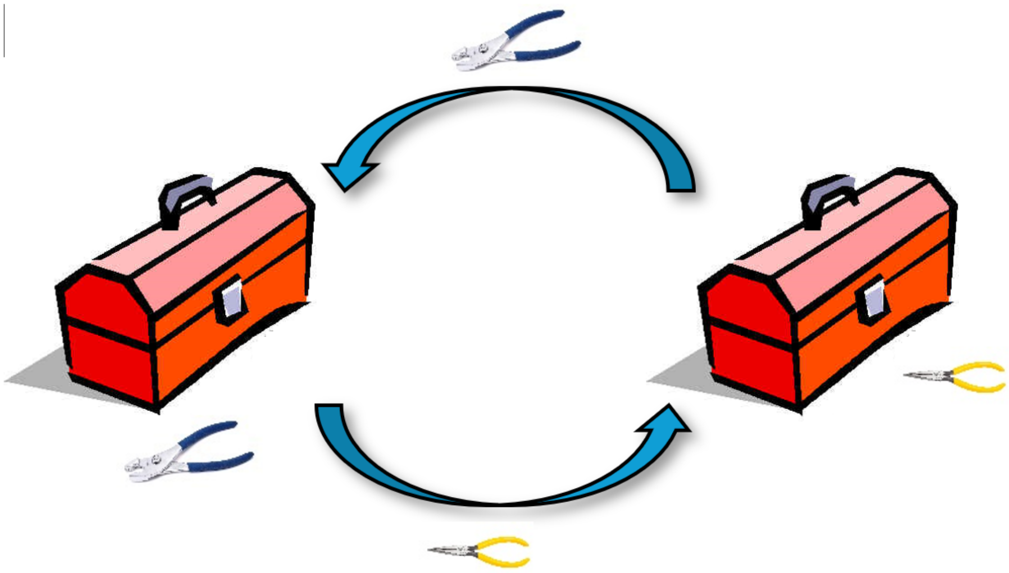


Figure 2. Illustrative example of the concepts behind software architecture. Thinking abstractly, given a desired application or problem (tighten a bolt) there are different ways to implement the capability (basic pliers, needle nose pliers, etc.). Software architecture allows for the creation of a toolbox with an implementation of the capability that is necessary for a specific job. An example of different microgrid planning and design tool implementations of a capability might be a three-phase unbalanced power flow model or a balanced single-phase approximation. These Photos by Unknown Author are licensed under CC BY-SA and BY-SA-NC.

- **Model Integration** – Combinations of new and existing capabilities that span and support coupling across the multiple time, spatial, and domain scales of planning, design, and operations for different performance metrics, requirements, and environments of microgrids. **A collection of new and existing capabilities to enhance microgrid planning and design tools, implemented under the principals in interoperability and software flexibility, including:** modeling the microgrid or sets of microgrids and the associated distribution systems, small modular reactors, AI data centers and storage modeling, microgrid integration with utility control systems, cyber security requirements, interdependency modeling, protection coordination and adaption, and system stability, microgrid market participation, and technoeconomic tradeoff analysis.

To demonstrate the integration of disparate microgrid tools, MG-RAVENS developed a prototype two-step workflow built on a common data model, using tools that were never designed to directly interface. This initial workflow combines economic design with optimal operations and illustrates the interoperability standards developed for microgrid tools. Future milestones expand the workflow by incorporating capabilities like protection optimization, advanced statistical analysis, and enhanced visualization.

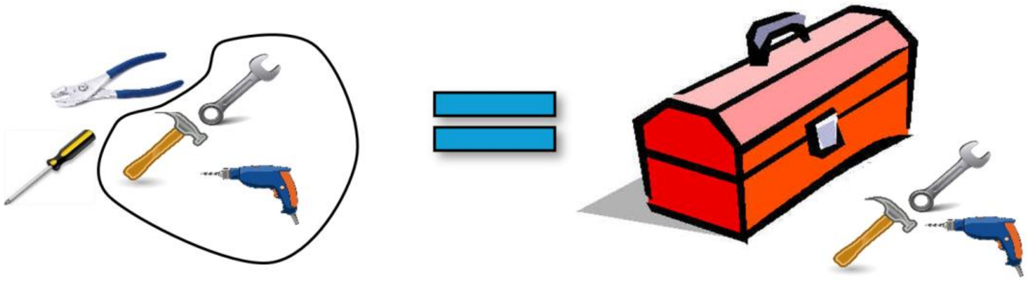


Figure 3. Illustrative example of the concepts behind modeling integration. Thinking abstractly, given a set of capabilities (pliers, screwdriver, hammer, wrench, drill), different combinations will allow various application problems to be solved. Model integration supports the creation of a toolbox with the set of capabilities best suited for an application. These Photos by Unknown Author are licensed under CC BY-SA and BY-SA-NC.

These three pillars – interoperability, flexibility, and integration – guide the DOE’s development of next-generation Microgrid Planning and Design Tools. They are mutually reinforcing: interoperability and modular architectures enable integration, and integrated models highlight further needs for interoperability and flexibility. By focusing tool R&D around these themes, the DOE provides planners with comprehensive and policy-aligned capabilities, that can be matured from research prototypes in the near term to widely deployed toolchains within the next decade. The goal is to ensure that as microgrids become essential building blocks of the future grid, the planning tools are ready to optimize their deployment for maximum reliability, security, and national benefit. This approach is consistent with broader U.S. energy policy objectives that prioritize grid resilience, domestic energy supply security, and the efficient expansion of energy infrastructure. In advancing microgrid tools under this framework, DOE’s Microgrid R&D Program is helping to secure an energy-abundant future where communities and critical facilities across the nation benefit from uninterrupted, affordable power, even in the face of disruption, thereby reinforcing U.S. energy resilience and security.

2 Research and Development Recommendations

This section considers the vision articulated in Section 1, identifies key requirements, suggests research and development direction, and discusses a timeline of enabling technologies to achieve this vision. While the modeling integration section contains the largest number of recommendations, these denote specific advances in microgrid planning and design capabilities whose full value are realized through software interoperability and flexible software architectures that ensure such capabilities are leveraged in multiple ways and applications. Thus, each model integration recommendation is accomplished through an interoperable software implementation that adopts best-practice software architectures. It is useful to note that the dates in the table were baselined/referenced as part of the original 2021 document, so any references to follow on years reflect that definition. As such, 2021/2022 goals were explored starting with the original white paper, 2026 goals reflect current work/accomplishments, and 2031 goals reflect a 5-year outlook from the time of the revised strategy document.

2.1 Interoperability

The last several decades have seen considerable developments in new capabilities that support microgrid investments and deployments. What began as efforts to target specific microgrid tool solutions has now evolved to where capabilities are needed that combine two or more of these solutions. This observation suggests a recommendation to develop interoperable modeling environments that support direct or indirect integration of microgrid tools and their underlying capabilities. Specifically, these modeling environments need to:

Support Needed	Description	Key Requirements
Provide tradeoff analysis between metrics	Assess and balance multiple performance goals	Interoperable tools that capture all key metrics and facilitate comprehensive benefit and tradeoff analysis
Improve modeling of uncertainty	Manage and propagate uncertainty across coupled modeling tools	Ability to specify sources and manifestations of uncertainty in each tool and across interfaces between tools
Model interdependence and interoperability	Integrate microgrid modeling tools with other critical infrastructure system modeling tools (Portante 2007) (Bent 2020) (Palmintier 2017) (InfrastructureModels 2025)	Interfaces to connect with non-electrical system models to holistically assess the benefits of microgrid deployment

To achieve these requirements, the following research and development activities are recommended:

Focus Area	Description	Key Recommendations
Standardization of tool inputs/outputs	Enables plug-and-play development, rapid deployment, and commercialization by standardizing data and interfaces (Wang 2025) (Curtiss 2025) (Sharma 2025)	Adopt/retrofit tools to industry standards (e.g. IEEE, CIM) and the standards developed by the microgrid program (e.g. MG-RAVENS), develop conversion tools, encourage new capability development, unify data
Interdependent system assessment	Integrated modeling of microgrids with other critical infrastructures (gas, water, telecom, etc.) for economic and resilience analysis (Portante 2007) (Bent 2020) (Palmintier 2017) (Gleason 2025)	Leverage existing models, enable co-simulation/co-optimization, automate nodal/interdiction/capacity expansion analysis
Open source and open access	Facilitates collaboration and interoperability through open release or accessible licensing of tools	Encourage open source/access, develop straightforward licensing, support via C-MIX and C-MAP partnership.

Based on these research and development recommendations, the following interoperability targets are suggested:

Support Needed	Description	Key Targets
API standardization	Develop program-wide API standards for microgrid tools to ease interoperability and collaboration	**[2022]** Expand MG-RAVEN API standards working group to support the larger Microgrid R&D Program **[2026]** Establish and deploy versioned API standards by all major Microgrid R&D tools **[2031]** Maintain continuous API governance and automated compliance validation
Interdependence interoperability prototyping	Enable automated interoperability between microgrid planning and design tools and third-party interdependent infrastructure tools	**[2022]** Select tools for prototyping **[2026]** Build/verify automated interoperability, leverage interdependent tools developed across DOE **[2031]** Expand workflow steps (e.g., protection)

Support Needed	Description	Key Targets
Interoperability with threat models	Integrate hazard models (e.g., wildfire, hurricane) with microgrid planning tools to assess and mitigate risk	**[2022]** Identify a hazard of interest and associated hazard simulation **[2026]** Integrate hazard simulation with microgrid planning tools **[2031]** Integrate uncertainty propagation from hazard-to-grid for risk mitigation assessment

2.2 Architecture

Flexible software architectures are tightly coupled with interoperable modeling and simulation environments. While microgrid planning and design tools achieve their project goals and requirements, repurposing them to meet new or evolving requirements is often a time consuming and a difficult proposition. Therefore, this observation recommends native software architectures that are designed for agility and flexibility to meet changing needs. Specifically, software architectures need to accomplish:

Support Needed	Description	Key Requirements
Software modularity	Microgrid planning tools should support modeling at various levels of granularity and fidelity via modules	Use modular software architectures (e.g., GridAPPS-D, PowerModelsDistribution.jl (Fobes 2020), CleanStartDERMS, MG-RAVENS (MG-RAVENS 2025) for flexibility and standardization

To achieve these requirements, the following research and development activities are recommended and go hand-in-hand with supporting the interoperability recommendations:

Focus Area	Recommendation	Key Recommendations
Flexible component modeling	Support a range of modeling approaches for microgrid components to address varying fidelity and application needs	Adopt flexible software architectures (Fobes 2020) (Gan 2014) (Vanin 2020) (Molzahn 2019) (Biswajit 2022) and allow users to select/validate appropriate models. Microgrid R&D examples include REAP (top-down retrofitting), DynaGrid (multiresolution/networked microgrids)

Based on these research and development recommendations, the following architecture targets are suggested:

Support Needed	Description	Targets
Flexible reliability metrics	Traditional metrics (e.g., IEEE 1366) are insufficient for distributed energy supply/demand resource and/or microgrid reliability and resilience evaluation	**[2022]** Develop/benchmark new resilience metrics **[2026]** Integrate validated resilience metrics into all program planning and operation tools **[2031]** Achieve regulatory recognition and widespread adoption
Flexible component modeling	Implement multiple peer-reviewed modeling methods for key microgrid components and enable flexible use in planning tools	**[2022]** Identify at least two modeling methods in year one; implement flexibility in existing tools (e.g. MG-RAVENS) **[2026]** Expand modeling library to cover all critical microgrid components **[2031]** Establish adaptive data-driven component modeling in all tools

2.3 Integration

The environment of a microgrid is increasingly complex with benefits and requirements that span multiple time scales (minutes or hours for operations, years or more for design), that span multiple spatial scales (the microgrid boundary, the distribution feeder connected to the microgrid and neighboring microgrids, and the main electric grid), and that span multiple infrastructure domains (thermal, natural gas, buildings, communications, etc.). The recommendations do not develop a single tool that captures all benefits and requirements, but rather they leverage the interoperability and architecture recommendations to develop modeling enhancements that can be combined depending on the specifics of needs of a microgrid planner.

Specifically, these modeling enhancements capture the complex realities of modern energy systems. These include integrating operational considerations into the design models, as tools that decouple design from operations can lead to suboptimal operating conditions or vice versa. Incorporating engineering constraints, including protection systems and black start capabilities (building on (PowerModelsONM 2025)), are also necessary (DER-Dispatch-app 2025). Expanded modeling of non-conventional storage (Heleno 2020), such as thermal systems and natural gas will enhance the valuation of diverse resources across both normal and islanded operations. High-fidelity restoration and recovery simulations, especially those coupled with extreme event scenarios, are critical for evaluating resilience. Additionally, advanced modeling of communication systems, controller and protection configurations, and evolving market participation—including aggregator roles—is crucial for aligning microgrid capabilities with performance goals, operational coordination, and economic incentives. These improvements underscore the need for flexible, extensible tool architectures that adapt to emerging needs and stakeholder priorities:

Focus Area	Description	Key Requirements
Enhanced modeling capabilities	Integrate operational considerations, engineering constraints, and diverse resources into microgrid modeling tools	Couple design and operations; include protection/black start; expand to non-conventional storage (e.g. thermal, gas); high-fidelity restoration simulations
Advanced system modeling	Model communication, control, energy management, and market participation to align with evolving performance and economic goals	Simulate communication/control systems; support aggregator roles; coordinate operations and market incentives
Flexible, extensible architectures	Develop tool architectures that can adapt to new technical requirements and stakeholder needs	Ensure modeling tools are modular and flexible to support future scenarios and priorities

To achieve this goal, the following research and development activities are recommended:

Focus Area	Description	Key Recommendations
Controller-aware planning	Integrate microgrid controllers with distribution feeder controllers (centralized via distributed management systems (DMS) or decentralized via DERMS); ensure planning tools are controller-aware and flexible for emerging technology	Develop evaluation capabilities for controller integration; support compatibility and flexible operations.
Combined microgrid and distribution feeder planning	Integrate microgrid planning tools with detailed distribution system models, including virtual power plants (VPPs) and aggregators	Use co-simulation (PowerModelsITD (Ospina 2024), TDcoSim (TDcoSim 2025), BARMEN (Bernstein 2022)); evaluate costs, resilience, and operational constraints.
Reliability modeling in design and operations	Advance tools for optimal microgrid placement/operation to improve system reliability (e.g. adapting IEEE 1366 metrics)	Model microgrid/network reliability; address regulatory barriers; develop business models for reliability value (e.g. the AVISTA project (McDermott 2022)).

Focus Area	Description	Key Recommendations
Advanced techno-economic analysis (TEA)	Develop cost-optimal architectures considering resilience, affordability, efficiency; enable robust trade-space analysis	Incorporate grid-islanded nonlinearities, grid-responsive loads; use unified frameworks (e.g., the AVISTA project (McDermott 2022)).
Imposing stability requirements	Move beyond bulk power stability models; develop microgrid-specific dynamic simulation tools	Model unbalanced loads, distributed energy supply/demand resources, complex control/protection; integrate stability checks into design tools (e.g. the RONM project (Bent 2020) (Barnes 2021)).
Protection-aware planning and design	Ensure planning/design tools account for modern protection systems and requirements	Address load variability, responsive distributed energy supply/demand resources, advanced breakers; integrate protection modeling (DynaGrid (Bernstein 2022), RONM (Bent 2020) (Barnes 2021)).
Resilience modeling in design and operations	Standardize resilience metrics and integrate into optimization/simulation tools for pre/during/post-event analysis	Use accepted metrics (e.g. RONM (Bent 2020), LPNORM (Barnes 2021), BRICK-MG enable resilience-focused recommendations (REPAIR, BRICK-MG).
Cybersecurity planning and design	Develop modeling enhancements for assessing and mitigating microgrid cybersecurity risks	Recommend software-defined networking (SDN), cryptography, vulnerability assessments, and cybersecurity valuation studies.
Planning for microgrid grid services	Develop modeling enhancements for assessing and enhancing microgrid flexibility for providing grid services and market integration	Link microgrid operations to bulk power system and market participation.

Based on these research and development recommendations, the following integration targets are suggested:

Focus Area	Recommendation	Key Targets
Integrated microgrid design	Develop tools to define microgrid boundaries and design structures to maximize feeder reliability/resilience under constraints	**[2022]** Develop capability, building on the DynaGrid project, determine boundaries of microgrid to ensure resilience of the distribution feeder it is connected to. **[2026]** Enable integration as standalone, networked, or VPP; leverage/extract portfolio

Focus Area	Recommendation	Key Targets
		tool features (e.g., DynaGrid (Bernstein 2022)). **[2031]** Achieve real-time, adaptive microgrid boundary optimization across multiple feeders and networked microgrids.
Dynamic models of microgrids	Create a simulation library for dynamic, three-phase unbalanced systems with diverse distributed energy supply/demand resources and loads	**[2022]** Deliver general purpose simulation library for dynamic three-phase simulation. **[2026]** Integrate library with Microgrid R&D program planning tools. **[2031]** Enable real-time, high-fidelity dynamic simulation for operational decision support and automated system modifications.
Aggregated microgrids and distributed energy supply/demand resources	Support integration and dynamic reconfiguration of microgrids, distributed energy supply/demand resources, and VPPs for grid services and network constraints	**[2022]** Demonstrate integration and dynamic reconfiguration of aggregated distributed energy supply/demand resources and microgrids in a testbed environment. **[2026]** Demonstrate integration and dynamic reconfiguration of aggregated distributed energy supply/demand resources and microgrids in a testbed environment; develop flexible optimization tools beyond traditional power flow models (e.g., PowerModelsDistribution.jl); deploy flexible optimization and reconfiguration tools for real-world pilot projects; support VPP/grid services. **[2031]** Achieve fully automated, scalable aggregation and reconfiguration for microgrids and distributed energy supply/demand resources, supporting grid-wide services.
End-to-end planning, design, operations, recovery	Combine capabilities for optimal microgrid siting/design to improve normal and extreme event operations and recovery	**[2022]** Develop initial framework for integrated planning, design, and recovery; coordinate with outage management system (OMS); develop cyber-physical hardening frameworks. **[2026]** Deploy end-to-end platform integrating planning, design, operations, and recovery; balance efficiency, resilience, security, and flexibility. **[2031]** Achieve continuous, adaptive, and automated end-to-end microgrid management for both routine and extreme events.

2.4 Enabling Technologies and Concepts

Section 2.3 has largely identified recommendations for the Microgrids R&D Program on the topic of integrated microgrid planning and design tool advancement. However, there are enabling technologies and concepts whose continued adoption and advancement will help support the goals and outcomes of these recommendations, in particular, those connected with companion strategic documents:

Enabling Technology or Concept	Motivation	Recommendations
Advanced smart grid devices and control	Expect increased integration of smart devices (e.g., software-defined switches, controllers) in microgrids	Need detailed device models/APIs for interoperability; incentivize vendors via case studies
Artificial intelligence and machine learning (AI/ML)	AI/ML will play a growing role in microgrid control and management	Monitor and leverage new AI/ML developments for microgrid planning and design (e.g. distribution system state estimation, anomaly detection). (See Strategy Document #8 in this series on AI and ML in Microgrids) .
Advanced smart devices and control systems	More complex control systems (e.g., dynamic islanding, edge-intelligent inverters) are anticipated	Require documentation for assessment; focus on flexible, interoperable software architectures
Education, technology transfer, and adoption	Emphasize education, usability, and industry engagement to bridge research-to-practice gaps	Continue collaboration, training, and peer review; showcase research in industry projects (e.g. The C-MIX). The DOE OTT TCF program has funded projects enabling technology transfer from laboratory to industry (e.g. (Gleason 2025)).
Hardware-in-the-loop (HIL) simulation	Use HIL simulation to validate and verify planning/design tools and cyber-physical system approximations	Continue leveraging scalable HIL platforms as intermediaries before field deployment
Customer impact models	Develop and use economic models to assess affordability and consumer impacts of microgrid deployment	Integrate with techno-economic tools; inform planning and design decisions.

3 Use Case and Scenario Examples

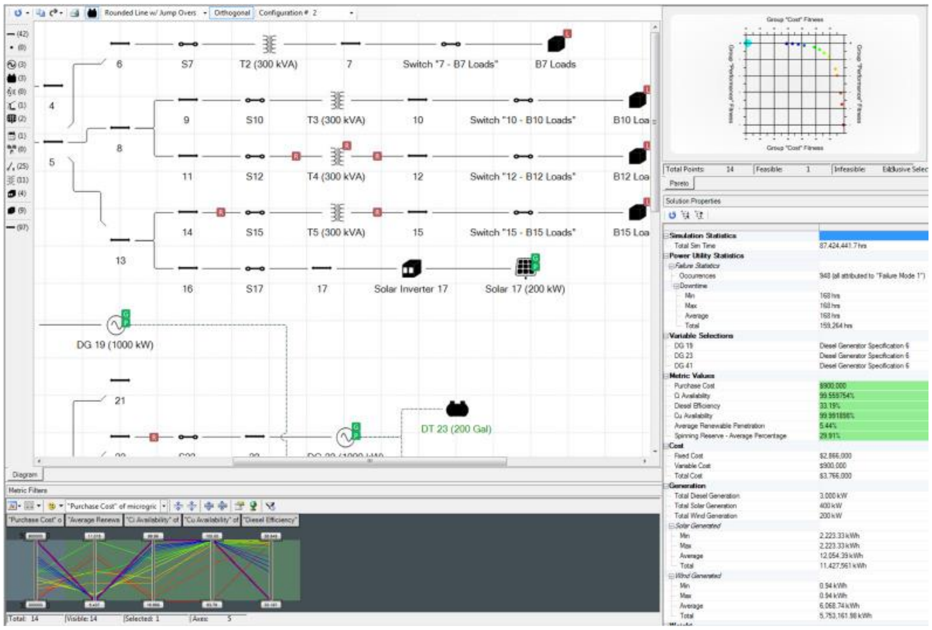
Use cases and scenarios are important drivers of efforts in microgrid planning and design tools. They are used to demonstrate tool usage, provide concrete examples of a tool's value, and provide immediate support and recommendations on microgrid planning. This section describes a few microgrid use cases and scenarios and how they can be used to support the development of microgrid planning and design tools.

3.1 Grid-isolated microgrids

Power systems in remote or rural locations often face a unique combination of challenges that can increase the cost of energy and lower resilience and reliability. It is often impossible or not beneficial to connect these systems to the main electric grid. Grid-isolated microgrids can also model grid-connected microgrids that disconnect from the main electric grid. The primary recommendation for the Microgrid R&D Program is to test the most advanced features of new developments on grid-isolated microgrid case studies because of the relatively straightforward design needs of these systems. One need for advancement is in resilience-inclusive optimal design with demand growth and resource availability uncertainty embedded in these projections. Remote communities are often especially vulnerable to such uncertainties and therefore would benefit greatly from such an approach.

In this case study, the goal is to upgrade the isolated microgrid in the most cost-effective manner, perhaps leveraging new energy storage solutions with local energy resources, to meet existing and new reliability and resilience metrics developed in this program. Moreover, this case study provides an opportunity to exercise flexible software architecture to determine the appropriate level of modeling of the components in the case study.

This document recommends revisiting past grid-isolated case studies as they are already configured to leverage existing microgrid planning and design tools and can be naturally used to demonstrate new enhancements. For example, as part of DOE's Grid Modernization Laboratory Consortium (GMLC) in 2017, NLR and Sandia along with several additional partners executed the Alaska Microgrid Partnership project which focused on the remote village of Shungnak, Alaska. In Shungnak, diesel and heating fuel are either shipped in by barge or flown in by aircraft. Reducing fuel usage saves money and makes the village more resilient to disruptions in fuel supply. One of the main outcomes of the project was demonstrating conceptual designs for Shungnak to reduce dependence on imported energy by 50% or more while maintaining or improving resilience and achieving a positive net present value (NPV) on investments. A useful follow-on to a case study such as this includes incorporating metrics for resilience, such as mission assurance focused metrics for critical operations. Additionally, adding interdependency modeling between potable water, wastewater, and heating systems should be included in this case study.



Simulation Statistics	
Total Sim Time	87,424,441.7 hrs
Power Utility Statistics	
Failure Statistics	
Occurences	948 (all attributed to "Failure Mode 1")
Downtime	
Min	168 hrs
Max	168 hrs
Average	168 hrs
Total	159,264 hrs
Variable Selections	
DG 19	Diesel Generator Specification 6
DG 23	Diesel Generator Specification 6
DG 41	Diesel Generator Specification 6
Metric Values	
Purchase Cost	$900,000
Ci Availability	99.559754%
Diesel Efficiency	33.19%
Cu Availability	99.991898%
Average Renewable Penetration	5.44%
Spinning Reserve - Average Percentage	29.91%
Cost	
Fixed Cost	$2,866,000
Variable Cost	$900,000
Total Cost	$3,766,000
Generation	
Total Diesel Generation	3,000 kW
Total Solar Generation	400 kW
Total Wind Generation	200 kW
Solar Generated	
Min	2,223.33 kWh
Max	2,223.33 kWh
Average	12,054.39 kWh
Total	11,427,561 kWh
Wind Generated	
Min	0.94 kWh
Max	0.94 kWh
Average	6,068.74 kWh
Total	5,753,161.98 kWh

Figure 4. Microgrid Design Toolkit model highlights the use of visualization to explore tradeoffs relating design parameters to multiple performance dimensions.

3.2 Grid-connected microgrids

When planning for and designing microgrids that will operate connected to the main power grid at least part time, tools must be able to reflect how microgrid design parameters can generate revenue for the microgrid owner subject to rules and market design of the utility and/or the wholesale market operator. Tools must also reflect how microgrid design parameters can enable the microgrid to provide resilience to critical loads when islanded from the utility, especially since the microgrid will do so during a disruptive event.

Within DOE, case studies have been performed on grid-connected use cases using microgrid planning and design tools. For example, a recent analysis performed by the Microgrid R&D Program created several conceptual designs for microgrids that could provide a wide array of community services to the residents of New Orleans, LA. In this project, two microgrid use cases were explored. The first – intended for utilization by the city's emergency management office – provided resilient and low-cost energy to a large emergency shelter, a grocery store, bank, pharmacy, and maintenance facility for machines which repair dikes and levees throughout New Orleans. The second – intended for utilization by the Sewerage and Water Board of New Orleans – provided resilient and low-cost energy for the city's drainage pumps and potable water system, which is critical for the entire city especially during flood and hurricane conditions. These conceptual designs were developed by running a design optimization for least-cost operations separately from a grid-islanded design optimization for maximum resilience operation. By running these tools iteratively, a near-optimal design which balanced economic value, affordability and resilience for critical loads was obtained. The lessons learned from this case study provide the foundation for future grid-connected microgrid use cases that will make the case studies more effective as well as to demonstrate the latest developments in the Microgrid R&D Program.

One of the biggest lessons learned from conducting grid-connected microgrids case studies was the process of transitioning research tools to case study can be inefficient and prone to error, especially by modelers not trained in the intricacies of modeling tools. So, it is recommended that case studies based on this (and the other) use cases plan for education and training. In future case studies, we expect the following features to be covered in collaboration with microgrid owners. It is not expected that each case study will include all these features, rather, a collection of case studies should cover these themes thereby exercising the goals of interoperable capabilities:

- Co-optimize resilience, efficiency, reliability, security, and flexibility leveraging both existing tools that support this co-optimization and capabilities outlined in Section 2.3 to improve the accuracy of the co-optimization.
- Ensure that grid-tied microgrids be considered within the overall distribution planning processes.
- Identify how rate design evolutions change the planning processes, for both developers of behind-the-meter microgrids, as well as those regulators and utilities considering the rate designs. Identify the optimal protection system that keeps the microgrid and its distribution feeder protected in both grid-connected and grid-islanded modes.
- Identify the most cost-optimal cybersecurity features to include in microgrid to demonstrate the value of the targets of cybersecurity planning and design.
- For a defense critical infrastructure facility, apply advanced contingency analysis to identify failures that disrupt service to this facility and recommend designs to a microgrid that will make this facility robust to service loss when grid-interrupted and demonstrating resilience modeling in coupled design and operations.

3.3 Networked microgrids

An emerging use case scenario for demonstrating the value of new technological developments in microgrid planning and design tools is networked microgrids. While, as discussed in the previous sections, an individual microgrid has potential capabilities to satisfy many stakeholder needs, interconnecting multiple islanded microgrids can further increase system resiliency, better accommodate uncertainties, and increase market share—often more than the aggregate of what the microgrids can accomplish individually. Therefore, it is recommended that new tool developments be assessed using case studies based on networked microgrid use cases.

Recent GMLC and Microgrid R&D Program projects provide a template for networked microgrid uses that could be expanded to meet the needs of the next 5-10 years. For example, the GMLC project, Citadels (GMLC 2.2.1), has developed networked microgrid case studies based on four operation modes:

1) Normal Operations: operating networked microgrids to support normal operating goals such as maximizing economic benefit.
2) Abnormal Operations: networks of microgrids collaboratively operating to support the main power grid and to prevent bulk power system collapse.
3) Extreme Events: networks of microgrids operate to support critical end-use loads and self-assembly to provide increased resilience when service from the main electric grid is interrupted.
4) Restoration: networks of microgrids coordinating with centralized efforts to provide services to increase the speed of restoration.

Networked microgrid use case development is a natural opportunity to coordinate and collaborate with industry on how to transition DOE-funded R&D into practice. In considering the research targets of the previous section, it is recommended that future case studies for the networked microgrid use case consider the following features:

- Determine the optimal load that can be picked up outside the microgrid boundaries using a networked configuration, showcasing integrated microgrid design.
- Model and optimize the control system to support the networking of microgrids and supporting controller-aware optimization.
- Optimize the system necessary to protect the networked configurations. A case study with this feature will support protection-aware microgrid planning and design.

3.4 Integrated Advanced Distribution Management System (ADMS) - Microgrid and Utility Interaction for Flexibility (Grid Services) and Resilience

ADMS interactions with the microgrid controller is a critical technology requirement for the future development of a grid with greatly increased bidirectional power flows and demands for enhanced levels of flexibility, reliability, and resiliency. Thus, it is recommended that case studies centered around a use case for these interactions be developed. Such case studies should consider specific ADMS/DERMS (for example, Schneider Electric’s EcoStruxure) and specific microgrid controllers (such as, Schweitzer Engineering Laboratories’ controller), utilize the results of the controller-aware optimization R&D recommendations to determine the best microgrid and distribution feeder design to implement. Case studies like this will establish the operational relationship between the microgrid and the distribution network and how these relationships define design. This use case is also an important component of demonstrating potential future roles of microgrids, such as:

- Demonstrating how a utility operated ADMS with embedded DERMS functionality can flexibly manage a variety of microgrids and other aggregated distributed energy supply/demand resources in concert with the wider distribution grid.

- Demonstrating how a utility's ADMS/DERMS can effectively manage microgrids to provide visibility and control functionalities, thereby using the microgrid as a dispatchable resource to support the utility grid.
- Demonstrating how to meet a key challenge of integrating multi-vendor systems, i.e., given two technologies, one on the grid side, the other on the utility side, supplied by different vendors, one operated by the microgrid and the other by the utility, how can integration be planned to yield a successful result.

Future extension of this research requires aggregation of multiple microgrids, Behind-the-Meter (BTM)/Front-of-the-Meter (FTM) distributed energy supply/demand resources, VPPs and demand response enabled loads that are integrated with control center to support various grid services in varying time horizon (Figure 5). ANL-led "Beyond DERMS" demonstrates a holistic platform that bridges across time scales (historical, real-time and future planning) to enable electric utilities to better evaluate the impact of future distributed energy supply/demand resources deployments, load growth, electrification initiatives and distribution network changes using the same tools that they use for real-time operations.

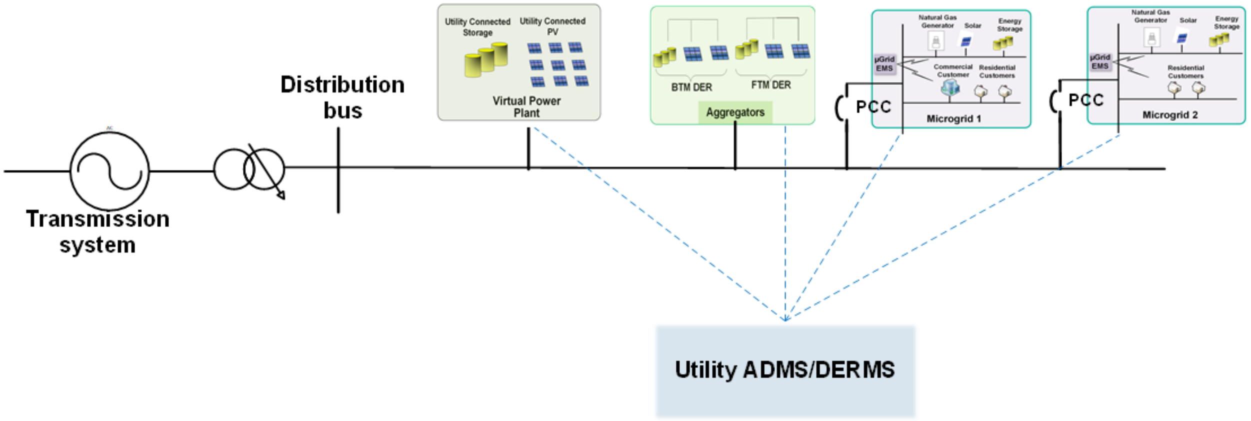


Figure 5. Flexible integration of grid service resources.

3.5 Virtual Microgrids and Virtual Power Plants

Both microgrids and VPPs involve aggregation and optimization of distributed energy supply/demand resources. Aggregation is particularly useful in managing large numbers of these distributed resources and enable them to provide grid services, complying with Federal Energy Regulatory Commission (FERC) Order 2222. This use case defines case studies that establish how microgrids and virtual power plants could be networked in distribution systems and how the utility ADMS/DERMS could be used to manage multiple microgrids and virtual power plants as aggregations.

In this use case, the owner of a microgrid provides grid services in any number of different ways to meet the operational objectives set by the utility. The manner of aggregation (microgrid or virtual power plant) should not be important to the utility as long as the grid services from the aggregated distributed energy supply/demand resources are available.

Meanwhile, the microgrid owner is free to innovate solutions for their specific operation and customers.

4 Justification of DOE Investment

The challenges, gaps, and tasks identified in this document outline a research and development path for the future of microgrid planning and design tools. Investments in these areas will support the DOE’s goals for microgrid investment and deployment in the United States. A DOE program in this area will produce the tools and capabilities that are critically needed for microgrid stakeholders—these tools, built in collaboration and consultation with industry, will allow diverse stakeholders to fully assess the potential benefits of a microgrid or a network of microgrids in their system. This type of DOE, academia, national laboratory, and industry partnership to further the state of practice has long provided success through the DOE’s Microgrid Research and Development Program.

It is not the DOE’s role to dictate the future of microgrids in the United States; however, the DOE has an important role in making strategic investments in enabling technologies and capabilities that will support industry in its efforts to make a final determination on how microgrid investments will be made. The DOE can play a role in looking forward at the challenges the industry will face in the next 5-10 years so that microgrid deployment and investments are not stunted by a lack of capabilities and support.

Glossary – Microgrid Planning Tools

Microgrid Planning Tools Developed by DOE’s National Laboratories

The following is a representative (non-exhaustive) list of key microgrid planning/design tools and their unique value:

DER-CAM (LBNL) – The Distributed Energy Resources Customer Adoption Model (DER-CAM) is a decision-support tool that optimizes the portfolio, sizing, placement, and dispatch of distributed energy supply/demand resources while co-optimizing multiple value streams such as load shifting and participation in energy markets. It models internal power and heat flows and supports multi-objective planning, including resilience and affordability goals (Cardoso 2015) (Cardoso 2014).

REopt (NLR) – REopt is an open-source, techno-economic optimization model for designing energy systems in buildings, campuses, and microgrids. It uses mixed-integer linear programming to select, size, and dispatch behind-the-meter technologies that meet electrical, thermal, and water loads at the lowest life cycle cost. The model incorporates detailed economic factors such as utility tariffs, incentives, grid services, regulatory limits, and technology costs (Anderson 2017).

MADRA (ORNL) – MADRA is an open-source tool for designing microgrids in remote communities. It helps users evaluate cost and reliability trade-offs to create optimal designs based on available resources and load profiles. MADRA outputs siting, sizing, and cost details for each technology, and includes a user-friendly interface with map-based network drawing and a dynamic component library.

LPNORM (LANL/PNNL/NRECA) – LPNORM is a tool that evaluates how distribution feeders with microgrids respond to extreme events and recommends upgrades to improve resilience. It was one of the first tools to consider communication pathway availability in microgrid response analysis (Barnes 2019) (Byeon 2020).

RONM (LANL/Sandia/NLR/NRECA) – Resilient Operation of Networked Microgrids (RONM) is an optimization tool for planning operations and restoration in systems with interconnected microgrids. Built on LANL’s PowerModelsDistribution.jl, it integrates protection, stability, and regulation constraints into resilient planning and operations (Bent 2020) (Barnes 2021).

CleanStartDERMS (LLNL/LANL/PNNL) – CleanStart is a distributed energy resource (DER) management tool for restoring distribution feeders, leveraging microgrids when available. It combines GridLAB-D for simulation and PowerModelsDistribution.jl for optimization, and its core capabilities support tools like RONM (Fobes 2020) (Rhodes 2021).

MDT (Sandia) – MDT supports feasibility studies by modeling, analyzing, and optimizing microgrid design. It considers cost, performance, reliability, and resilience, with a focus on islanded operation during outages. MDT has been used for critical military and civilian microgrid projects (Eddy 2020).

ESM (Sandia) – ESM) is a risk management tool for microgrid-integrated distributed energy supply/demand resources, supporting grid-tied or islanded modes, demand response, distributed energy supply/demand resource selection, and net-metering. It has been used to design microgrids for critical loads on military bases and urban backup power (Broderick 2019).

ReNCAT (Sandia) – ReNCAT helps site and size microgrids across large distribution systems. It optimizes microgrid placement to reduce customer burden—a measure of effort needed to meet basic needs—enhancing resilience for all customers during extreme events (Jeffers 2018).

CoSTAD-MG (LANL/ANL/LBNL) is a recently initiated tool aimed at combining co-simulation and co-optimization for transmission system, distribution systems and microgrid; it is still under development.

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