Integrated Models and Tools for Microgrid Planning and Designs with Operations

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Abstract

Resilience, efficiency, sustainability, flexibility, security, and reliability are key drivers for microgrid developments. These factors motivate the need for integrated models and tools for microgrid planning, design, and operations at higher and higher levels of complexity. This complexity ranges from the inclusion of grid forming inverters, to integration with interdependent systems like thermal, natural gas, buildings, etc.; microgrids supporting local loads, to providing grid services and participating in markets. This white paper focuses on tools that support design, planning and operation of microgrids (or aggregations of microgrids) for multiple needs and stakeholders (e.g., utilities, developers, aggregators, and campuses/installations). This paper covers tools and approaches that support design up to and including the conceptual design phase, operational planning like restoration and recovery, and system integration tools for microgrids to interact with utility management systems to provide flexibility and grid services while ensuring system reliability and resilience. Of particular interest are combinations of tools which span these dimensions and present an integrated view of these activities. A taxonomy of national laboratory tools that support different components of analysis for planning, design and operations are presented. A vision for improved integration and incorporation of complexity is proposed for tool development that enables component-based analysis across the design, planning, and operational landscapes, with a particular on future motivators for microgrid deployment such as de-carbonization and social equity of access to energy.

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1 Executive Summary

This white paper describes the program vision, objectives, and research and development (R&D) targets in 5 to 10 years for the Department of Energy (DOE) Office of Electricity (OE) Microgrid R&D Program. This is the sixth in a series of seven white papers in support of the Microgrid R&D Program, and accordingly summarizes the findings of the papers as they concern the overall program objectives.

The program vision is to facilitate the nation's transition to (1) a more resilient and reliable, (2) more decarbonized electricity infrastructure, in which (3) microgrids have a reduced cost and implementation times, while ensuring that microgrids support an equitable energy transition through prioritized provision of at least 40% of microgrid benefits going to disadvantaged communities in a secure manner. These three enumerated strategic goals are developed in the context that the United States' electricity system is becoming more distributed in nature, and that disruptions to the electricity delivery system (EDS) are occurring more frequently and with greater severity. The vision statement follows.

> *By 2035, microgrids are envisioned to be essential building blocks of the future electricity delivery system to support resilience, decarbonization, and affordability. Microgrids will be increasingly important for integration and aggregation of high penetration distributed energy resources. Microgrids will accelerate the transformation toward a more distributed and flexible architecture in a socially equitable and secure manner.*

The vision assumes a significant increase of DER penetration during the next decade, reaching 30-50% of the total generation capacity. In that context, the Microgrid R&D program seeks to accomplish these three goals:

> Goal 1: Promote microgrids as a core solution for increasing the **resilience and reliability** of the EDS, supporting critical infrastructure and reducing social burdens during blue and black sky events
>
> Goal 2: Ensure that microgrids serve as a driver of **decarbonization** for the US EDS by acting as a point of aggregation for larger number of DERs, with 50% of new installed DER capacity within microgrids coming from carbon-free energy sources by 2030.
>
> Goal 3: **Decrease microgrid capital costs** by 15% by 2031, while reducing **project development, construction and commissioning** times by 20%.

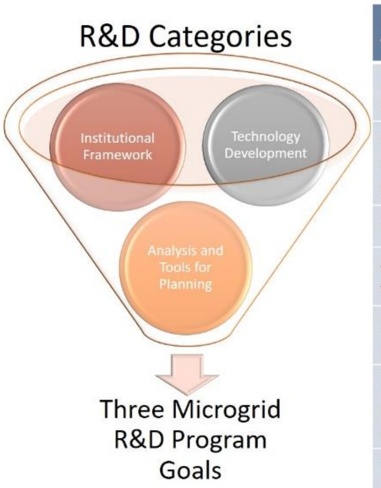
To achieve the three primary goals, the Microgrid R&D Program works in three categories (Figure 1):

Category 1: Technology development,
Category 2: Analysis and tools for planning, and
Category 3: Institutional framework.

This white paper details the activities and goals in the topic of integrated models and tools for microgrid planning, designs, and operations for the DOE Microgrid R&D Program, and is one of seven white papers being prepared addressing various aspects of the strategic vision and program goals through six research and development topical areas. This white paper covers topic area 6. The seven white papers in this series focus on the following areas and fit into one or more of the three R&D categories. The relationship among white papers and R&D categories is also shown in the table of Figure 1.

1. Program vision, objectives, and R&D targets in 5 and 10 years
2. Transmission and distribution co-simulation of microgrid impacts and benefits

3. Building blocks for microgrids
4. Microgrids as building blocks for the future grid
5. Advanced microgrid control and protection
6. Integrated models and tools for microgrid planning, designs, and operations
7. Enabling regulatory and business models for broad microgrid deployment



Microgrid R&D Program Strategy Topical Paper	Technology Development	Analysis and Tools for Planning	Institutional Framework
1: Program vision, objectives, and R&D targets in 5 and 10 years	x	x	x
2: Transmission and distribution co-simulation of microgrid impacts and benefits		x	
3: Building blocks for microgrids	x	x	
4: Microgrids as building blocks for the future grid	x		
5: Advanced microgrid control and protection	x		
6: Integrated models and tools for microgrid planning, designs, and operations		x	x
7: Enabling regulatory and business models for broad microgrid deployment			x

Figure 1: A depiction of how the DOE OE Microgrid R&D Program white papers address the three R&D categories in order to achieve the program goals.

Taken together, this set of white papers envision a future grid with a high penetration of DER’s and of networked microgrids to promote the reliability, resiliency and affordability of the EDS. Within these papers, the current state of technology developments, analysis and tools for planning, and institutional frameworks for microgrids are assessed, gaps are identified, and research needs over the next ten years are described. In the near term of 0-5 years, the successfully executed Microgrid R&D Program will primarily focus on individual microgrids. In the longer term of 5-10 years, the focus will transition more heavily to adoption and operation of networked microgrids and their role in the EDS.

Category 1: Technology development R&D into new controls and protections, cybersecurity, software and hardware are critical areas with a focus on their application to microgrids. Forward looking challenges in these areas to implementing microgrids as building blocks for a networked and highly distributed EDS should be addressed by the DOE OE Microgrid R&D Program. Technology development currently is helping to address institutional barriers to microgrid development by addressing common safety-, consumer protection-, and equity-related concerns and will continue to do so.

Category 2: Analysis and tools for planning are numerous both within the national laboratories and without, and a sizable set of these have been supported by the Microgrid R&D Program. Existing capabilities in analysis and tools are proposed to be expanded and further supported. The next steps are to refine, combine, simplify or otherwise make accessible existing tools to best contribute meaningfully to demonstrations supported by the Microgrid R&D Program, as well as other microgrid projects more broadly that may benefit from utilization of these analysis capabilities and tools.

Category 3: Institutional frameworks have been significantly influential to energy sector investments over the previous decades across various technologies, including for microgrid adoption. The institutional framework includes regulatory paradigms governing microgrid ownership and investment models, consumer protections, safety, and equity, as well as technical codes and standards governing interconnection, and local siting and permitting processes. An institutional framework that enables microgrid investment while balancing the public interest requires a well-informed community of stakeholders and targeted R&D activities to inform evolutions in regulatory approaches, as well as various codes and standards that must be modernized to include novel technologies and approaches. Such a framework could enable private industry to thrive, and through economies of scale and a growing body of deployments, address some of the fundamental goals of the Microgrid R&D Program.

The topic of this white paper directly supports category 2 and category 3 with an outline for R&D requirements for microgrid planning and design tools that account for current and emerging institutional frameworks that regulate and standardize the deployment of microgrids.

Technology Validation Via Partnered Demonstrations

Technology validation via partnered demonstrations is a key element of the Microgrid R&D Program to ensure technology transfer is most effective, and so that the program's activities are grounded in the real world of microgrid deployments, providing near-term value to stakeholders. Program activity impacts must be quantified, along with successful technology transfer to industry, to improve the EDS in the United States. Therefore, continued and new benchmarking studies are necessary to quantify the current state and needs in industry, as well as to measure the program impacts.

Demonstration projects and stakeholder engagement avenues must continue to be carried out to ensure that activities funded to investigate the R&D barriers in the above three categories will provide solutions that are (a) not currently available, (b) valuable to key stakeholders, and (c) measurably impactful to industry and institutional partners. Demonstrations must also leverage past projects and explore new technical and institutional issues to maximize value of investments, while also attempting an approach which could be more broadly replicable by industry upon success. These demonstrations must push the frontiers of microgrids into multi-property and networked microgrid applications in to have a meaningful impact. Stakeholder engagement must become a larger, more diverse, more coordinated effort, formalized through consortia or other venues, in addition to ongoing efforts. Stakeholders must concentrate on local communities and institutions pursuing equity objectives in microgrid deployment, and bring together stakeholders with resilience, decarbonization and affordability mindsets to the future grid to ensure R&D impacts communities in the areas of the program goals.

Next Steps

To achieve the Microgrid R&D Program goals, coordination is critical across relevant DOE programs, with DOD and with other entities including states and collective organizations such as American Public Power Association, National Rural Electric Cooperative Association, National Association of Regulatory Utility Commissions, National Association of State Energy Offices and Edison Electric Institute. These organizations can be leveraged to achieve technology validation, especially in the area of demonstrations in coordination with other DOE efforts, as well as state initiatives. The DOE OE Microgrid R&D Program will leverage the advancements made within DOE’s complementary programs in Office of Energy Efficiency and Renewable Energy (EERE), Office of Electricity (OE), Advanced Manufacturing Office (AMO), and the Grid Modernization Laboratory Consortium (GMLC). The current strategies and roadmaps from these programs are important elements to advance the future EDS with high penetrations of DER many of which are renewables. This strategy further complements the specific roadmaps and strategies put forward on grid forming inverters [1], grid interactive buildings [2], and photovoltaic cyber security [3].

Following this set of white papers being written, and in conjunction with a workshop of stakeholders, a roadmap will be developed. This roadmap will address how to meet the goals and objectives identified in this strategy document. DOE’s OE is well-positioned to lead this strategic effort and to coordinate core R&D activities to meet these objectives following the strategy and forthcoming roadmap. These objectives support the wider DOE OE objectives to achieve megawatt-scale grid storage, revolutionize sensing technology utilization, and address transmission [4].

2 Introduction

Over the next decade, it is expected that the needs of planners charged with ensuring affordable, reliable, and increasingly sustainable power to customers will evolve. Largely in response to the climate challenge, the importance of decarbonization, social equity, and resilience will drive some of this evolution. Planners are expected to consider solutions that are increasingly distributed and decarbonized, with a major dependence on digital and networked devices, combined with electrification of several demand sectors. Some estimates suggest that up to 50% of generation in the United States will come from distributed sources, and that these sources will largely trend away from fossil fuels. Furthermore, planners will need to design systems that equitably serve the most vulnerable and disadvantaged communities, both during normal days as well as during disruptions. However these significant shifts are accomplished, the U.S. public will expect continued or improved energy reliability and affordability, while adding expectations about resilience, security, flexibility, and sustainability.

Fortunately, microgrids are a technology with significant potential to help deliver on this future. As per the Department of Energy (DOE) Office of Electricity (OE) Microgrid R&D Program vision statement

> *By 2035, microgrids are envisioned to be essential building blocks of the future electricity delivery system to support resilience, decarbonization, and affordability. Microgrids will be increasingly important for integration and aggregation of high penetration distributed energy resources. Microgrids will accelerate the transformation toward a more distributed and flexible architecture in a socially equitable and secure manner.*

This is because microgrids offer greatly heightened redundancy for the loads they serve, while also enabling operators enhanced visibility and control over distributed resources.

The DOE vision assumes a significant increase of distributed energy resource (DER) penetration during the next decade, reaching 30-50% of the total generation capacity. In that context, the Microgrid R&D program seeks to accomplish these three goals:

> Goal 1: Promote microgrids as a core solution for increasing the **resilience and reliability** of the EDS, supporting critical infrastructure and reducing social burdens during blue and black sky events

Goal 2: Ensure that microgrids serve as a driver of **decarbonization** for the US EDS by acting as a point of aggregation for larger number of DERs, with 50% of new installed DER capacity within microgrids coming from carbon-free energy sources by 2030.

Goal 3: **Decrease microgrid capital costs** by 15% by 2031, while reducing **project development, construction and commissioning** times by 20%.

This report considers how the DOE can continue to support microgrid technologies in meeting these goals through improvement in microgrid planning and design tools (MPDT). These tools are used to determine how and where to deploy microgrids and, once installed, how to most effectively use them. This report focuses on the research and development (R&D) that is needed over the next decade to expand and generalize MPDT capabilities and we expect the future of MPDT to follow three broad themes:

- Interoperability – The seamless ability of MPDT to interact with one another and achieve capabilities and applications that are beyond the scope of an individual tool.
- Software Architecture Flexibility – Native software designs that support ease of repurposing tools to meet evolving needs and requirements.
- Model Integration – Combinations of new and existing capabilities that span and support coupling across the multiple time, spatial, and domain scales of planning and design for different performance metrics, requirements, and environments of microgrids.

Before turning to a detailed discussion of this vision for the evolution of MPDT, it is important to review how microgrids are planned today, and the state-of-the-art for tools used to support such planning. The DOE defines a microgrid as a group of interconnected loads and distributed energy resources (DERs) within clearly defined electrical boundaries that acts as a single controllable entity with respect to the power grid. Traditionally, microgrids have often been used as a mechanism to support islanding from the bulk electric system (BES) and improving the resilience of service to critical loads, but increasingly microgrids are becoming an integrated part of the general power delivery system.

Metrics are used by planners to compare the extent to which alternative designs and plans meet various objectives for use of the microgrid. MDPT calculate these metrics under alternative design considerations, helping planners to improve or optimize their designs while considering tradeoffs between different objectives. While these objectives may vary, most fall within six broad categories: sustainability, efficiency, resilience, flexibility, reliability, and security. For the purposes of this report, these dimensions are defined as follows:

- **Sustainability:** Sustainability is typically a metric that covers performance over long periods of time and is tightly coupled to decarbonization objectives. Usually, sustainability-relevant performance is defined by measuring the performance of Earth systems, as opposed to performance of the power system itself. The most common sustainability performance metrics are *net greenhouse gas emissions* over a planning horizon. This is a generally accepted surrogate of Earth system performance because of science-based correlations between near-term emissions and long-term consequences to Earth systems [5]. Tools may also use attribute-based metrics such as total capacity of installed renewable generation, but this is typically a less direct sustainability metric. Sustainability metrics continue to evolve as scientific understanding supports additional relationships between energy system operation and the long-term performance of the Earth's systems.

- **Efficiency:** Efficiency is also a metric that quantifies performance over extended planning horizons. Often, efficiency is defined in terms of useful work performed with the least possible energy requirements. Because energy markets tend to adequately capture efficiency goals, the most common efficiency metric for distribution system planning is the *net present value of nominal-condition cash flows* over a planning horizon. Other, more energy-specific efficiency metrics may be tracked, such as total energy delivered divided by total energy input.

- **Reliability:** Reliability is a metric that quantifies performance during off-nominal system operating conditions for a defined planning horizon. Reliability is typically restricted to high frequency, low impact conditions, such as N-1 contingencies. Commonly used performance metrics include loss-of-load expectation (LOLE) and system average interruption duration index (SAIDI).

- **Resilience:** Resilience is also a metric that quantifies performance during off-nominal system operating conditions during a defined planning horizon. Per this definition, many of the commonly used reliability metrics are a subset of resilience metrics. However, LOLE, SAIDI, and other reliability metrics ignore major events and other low-frequency/high-impact events which are the focus of resilience. Resilience metrics that include the impact of low-frequency/high-impact events have evolved along with tools to calculate them. A useful distribution system resilience metric is the *fraction of kWh served* that would otherwise be demanded during partial or full grid outage conditions. This metric is sometimes referred to as *energy availability*. Efforts have been developed by DOE and others to extend resilience metrics to capture societal consequence of outages.

- **Security:** Security is a metric that quantifies specific types of reliability metrics related to capabilities to limit outages during contingency events. It is often lumped in with reliability and resilience. Security has also come to be used for performance metrics associated with the cybersecurity of an energy system.

- **Flexibility**: Flexibility is a metric that quantifies the extent to which performance is desirable in meeting service requests to maintain normal grid conditions over planning horizons that include local and regional operations. Flexibility refers to an ability to quickly respond to deviations in demand-supply balance of the grid system microgrids are connected to. Minimum uncertainty, fast response, timely delivery, and availability on-demand are flexibility-based metrics that are often used by system planners. Greater autonomy over flexible generation and load mix offered by the microgrid also helps achieve short-term and long-term system security objectives. Through recent regulation changes, the encouragement received by aggregated DERs to compete in the market will likely shift the way microgrids engage with system planners. The economic benefit of staying flexible to remain competitive in the market will be a guiding factor in the microgrid decision-making process.

Microgrids play a role in supporting the satisfaction of each of these metrics. Given that microgrids are distributed and local, microgrids can improve resilience, security, and reliability via redundancy of energy resources when the service provided by the bulk transmission system is interrupted. Microgrids can improve efficiency and flexibility by providing an alternate source of (cheaper) energy when the bulk transmission price for power is high. Microgrids also contribute to sustainability by reducing greenhouse emissions and larger particulates with the installation of solar, wind and supporting technologies like energy storage. While each of these factors plays a role in driving the adoption of microgrid technologies, it is often the tradeoff between each that is analyzed by MDPT's to support determination of courses of action. For example, when a planner is determining whether to install a microgrid, today's MDPT are used to provide answers to questions inclusive of the following:

- *[Efficiency] How can a microgrid or a system of multiple microgrids operate during blue sky conditions to maximize value, e.g., on a wholesale market or as a generation resource within a vertically integrated utility environment?*
- *[Resilience, Reliability] Where can microgrids be sited to provide resilience that best supports society, the economy, and national security?*
- *[Flexibility] Are there opportunities to coordinate and collaborate with neighboring microgrids to reduce resourcing needs or maximize the value of a new microgrid?*
- *[Sustainability] Can microgrid(s) be used to better coordinate distributed energy resources and improve processes for integrating renewable energy resources such as wind and solar?*
- *[Flexibility] How can microgrids act as flexible resources to provide grid services and enable market participation of DERs?*
- *[Flexibility]* How can microgrids integrate with utility control systems and aggregated DERs?

Once a decision is made to install a microgrid, a planner can use today's MDPT to help answer how to design the microgrid and plan its use, inclusive of:

- *[Resilience, Efficiency, Sustainability] How can microgrid(s) be co-optimized to maximize benefits or consider tradeoffs among resilience, affordability, and sustainability?*
- *[Flexibility] What are the cost-benefit tradeoffs when considering flexible/dynamic microgrids (e.g. microgrids that can dynamically adjust the footprint of load they serve)?*
- *[Efficiency, Resilience, Reliability] How does operation of other microgrids (e.g. in a networked microgrid environment) impact operations and economic value of this microgrid? Resilience? Reliability?*

Today's MDPT primarily rely on two computational technologies: simulation and optimization. *Simulation* relies on a formal definition of a microgrid (i.e., a mathematical formulation of electrical physics, policy responses of controllers, etc.) to predict the evolution and behavior of an electric power system with microgrids given initial conditions (load profiles, dispatch schedule, disruption scenarios, etc.). *Optimization* also relies on a formal definition of a microgrid; however, it focuses on a search of design and operational parameters to identify those choices that best meet a target performance (or other) objective. Simulation is typically computationally efficient, but requires the user to manually explore different outcomes and options. Optimization is suited to automate this search for solutions. There is computational effort inherent to search, but replicating optimization-based search though simulation is typically much slower. Finally, there is some overlap between the two technologies, where optimization can be embedded within a simulation to model a response to changing conditions or a simulation is used to validate a solution produced by an optimization (optimization will sometimes use reduced formal definitions to improve computational time). A representative (non-exhaustive) list of national laboratory MDPT developed by or leveraged by DOE's microgrid R&D program includes:

- DER-CAM – Technically mature and extensively peer-reviewed, DER-CAM has been developed by Lawrence Berkeley National Laboratory (Berkeley Lab) since 2000, and can be used to find the optimal portfolio, sizing, placement, and dispatch of a wide range of DER, while co-optimizing multiple stacked value streams that include load shifting, peak shaving, power export agreements, or participation in ancillary service markets. Its application use cases include using microgrids as part of the portfolio of choices [6][7]. Differently from other microgrid design tools in the space, DER-CAM captures the internal microgrid power flow and heat transfer constraints and offers advanced functionalities for multi-objective planning (including resilience and environmental targets).

- REopt – Developed by the National Renewable Energy Laboratory (NREL), REopt is an open-source techno-economic decision support model used to optimize energy systems for buildings, campuses, communities, and microgrids [8]. The primary application of the model is for optimizing the integration and operation of behind-the-meter energy assets. Formulating the problem as a mixed-integer linear program, REopt solves a deterministic optimization problem to identify the optimal selection, sizing, and dispatch strategy of technologies chosen from a candidate pool such that electrical, thermal, and water loads are met at every time step at minimum life cycle cost. The tool allows detailed economic inputs including complex utility rate tariffs, value streams from grid services and incentives, regulatory constraints, and technology cost data.

- MADRA – Microgrid Assisted Design for Remote Areas (MADRA) is an open-source microgrid design tool developed (in Python 2.7) by Oak Ridge National Laboratory (ORNL) under DOE/NETL Project #M615000481. MADRA is capable of providing professional analysis for designers to make design decisions that satisfy user-defined objectives and constraints for costs and reliability. With typically available resources and load profiles of various remote communities, MADRA evaluates the financial feasibility and provides the optimal microgrid design, which includes the siting and sizing of each technology, the installation and operation cost of these technologies and/or the present values of future energy cost. MADRA provides a novel, user-friendly interface with convenient network drawing on a map and a dynamic component library.

- LPNORM – LPNORM is a capability developed by Los Alamos National Laboratory, Pacific Northwest National Laboratory, and the National Rural Electric Coop Association (NRECA) to assess the ability of distribution feeders with microgrids to respond to extreme events and recommend upgrades, network design, and hardening to improve the response of distribution systems during such events using microgrids [9] [10]. At the time of its development, LPNORM was one of the first capabilities to include the availability of communication pathways when considering the response of a microgrid to extreme events.

- RONM – RONM (Resilient Operations of Networked Microgrid) is a capability developed by Los Alamos National Laboratory (LANL), Sandia National Laboratories, the National Renewable Energy Laboratory, and the National Rural Electric Coop Association (NRECA) to plan operating and restoration activities for electric power systems with microgrids that have capabilities to network together and provide services outside the boundaries of a microgrid. This application was built using a LANL developed open source software library entitled, PowerModelsDistribution.jl, which is designed to support the modeling of generic distribution system optimization problems such as those related to microgrid planning, design, and operations. One of the unique capabilities of RONM is its direct modeling of important constraints related to protection, stability, and regulation directly into the resilient operations and planning model [11] [12].

- CleanStartDERMS – is a capability developed by Lawrence Livermore National Laboratory, Los Alamos National Laboratory, and Pacific Northwest National Laboratory to model how to restore distribution feeders when power has been lost utilizing resources like DERs. The simulation capabilities are based upon PNNL's open source GridLAB-D distribution simulation software and the optimization capabilities are based on PowerModelsDistribution.jl [13]. It is primarily a tool for restoration and recovery of distribution feeders [14]; however, it will leverage microgrids when available and the project's underlying capabilities are being leveraged in more direct microgrid tools such as RONM.

- MDT – Microgrid Design Toolkit (MDT) is a decision support tool developed by Sandia National Laboratories for microgrid designers to conduct microgrid design feasibility studies. The MDT allows designers to model, analyze, and optimize the size and composition of new microgrids or modifications to existing systems. Technology management, cost, performance, reliability, and resilience metrics are all offered by the tool. The MDT has been used to design microgrids supporting critical loads on military installations and civilian systems providing backup power for urban centers. MDT is unique among MDPT's in that it includes more complex detail within the design optimization about the operations of microgrids while they are operating in islanded mode during grid outage conditions [15].

- ESM – Energy Surety Microgrid is a tool developed by Sandia National Laboratories for managing energy risks through DER-integrated microgrids. The ESM framework allows a microgrid to be grid-tied or islanded, enables demand response, selection of DERs within microgrid, net-metering to cater to the community energy needs. The tool has been used to design the microgrid to support critical loads independently such as military installations and to provide backup power for urban centers [16].

- ReNCAT – The Resilience Node Cluster Analysis Tool (ReNCAT), developed at Sandia National Laboratories, enables users to site and size microgrids across a large distribution system – up to a medium-sized city. One of ReNCAT's unique operating modes allows system planners to site microgrids to optimally decrease a community-focused resilience metric called social burden, which measures how hard people have to work in order to achieve their basic human needs. This allows planners to consider how microgrids may best be deployed to improve equitable infrastructure service during black sky conditions [17].

Some of the capabilities of these tools are summarized in Table 1. The first two columns refer the tools' underlying technology (simulation, optimization, or both). The last four columns highlight some of the key capabilities of MDPT.

Table 1: Summary of national laboratory developed MDPT. X is used to denote a capability a tool supports

Tool	Optimization	Simulation	Microgrid Integration with	Microgrid Capacity Design	Techno-Economic Planning	Restoration and

			Distribution Systems			Recovery 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

It is important to note that in addition to the national laboratory suite of MDPT, there are MDPT developed by industry and software vendors. *It is outside the scope of this report to provide a comprehensive overview of industry state-of-the-practice, however, industry is making considerable strides in many areas of MDPT where there are business cases for software products*. Thus, industry developments should continue to be monitored, leveraged, and used by the Microgrid R&D program. Moreover, DOE and the Microgrid R&D program should continue its successful history of commercializing R&D when such opportunities present themselves. Homer (a MPDT 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 capability to industry: Homer from NREL and XENDEE from LBNL (DER-CAM).

These examples illustrate how MDPT have made considerable strides in advancing the state-of-practice. However, as the needs, uses, and requirements of microgrids continue to evolve, the MDPT must also evolve. Some of the needs of and questions to be answered by MDPT over the next five to ten years can be anticipated (in addition to continuing to support the types of questions discussed earlier):

- How can existing microgrids transition from diesel and natural gas based DERs?
- How can microgrids best use new storage and other types of fuel, such as hydrogen?
- What technologies, in particular controller combinations, need to be adopted by a microgrid to improve its participation with the broader electricity delivery system?
- How can the microgrid and its connected distribution system be protected, especially during reconfiguration and networking of microgrids?
- What cybersecurity measures need to be included when deploying a microgrid?
- How should microgrids be sited throughout a system to improve metrics of social equity?
- To achieve decarbonization goals, recognizing that many demand sectors may be electrified, how do microgrids as a solution category compare to centralized renewables and storage coupled with traditional grid hardening measures?

There will also inevitably be other unanticipated questions that MDPT should be prepared to answer, which leads to the vision outlined at the beginning of this report:

- Interoperability – The seamless ability of MPDT 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, in particular, for uses of MDPT that lie at the intersection of current technologies.**

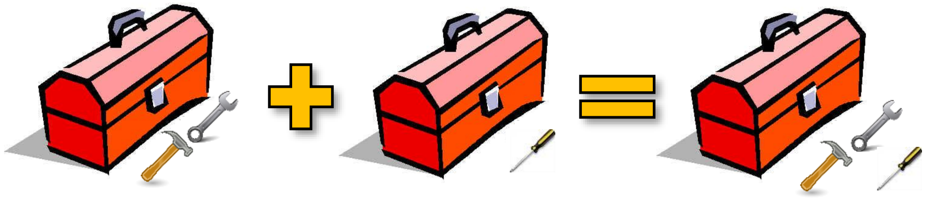


Figure 2: Illustrative example of the concepts behind interoperability. Thinking abstractly, given a software toolbox with capabilities (a hammer and a wrench) and another software toolbox with capabilities (a screwdriver), interoperability allows the creation of a new software toolbox with capabilities hammer, a wrench, and a screwdriver. In MPDT, a tool like a hammer equates to an implementation of a grid forming inverter, a storage model, etc. [These Photo](#)s 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 be quickly be modified to meet new needs that are unanticipated over the next 5, 10, or more years.**

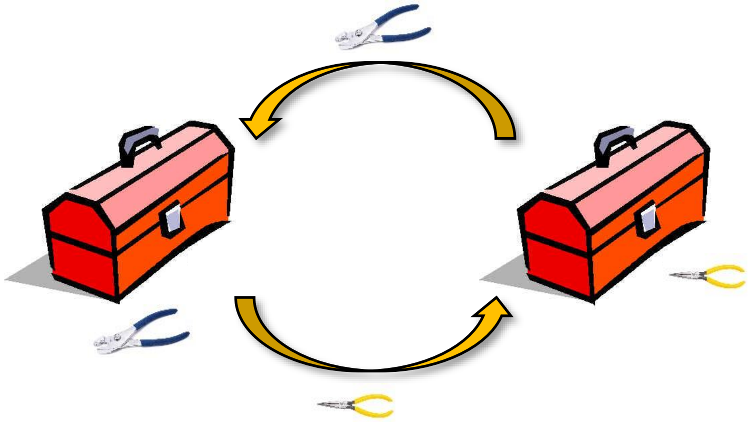


Figure 3: Illustrative example of the concepts behind software architecture. Thinking abstractly, given a desired application or problem (tighten a bolt) there are different ways to implement the capability (basic pliers, needle nose pliers, etc.). Software architecture allows for the creation of a toolbox with an implementation of the capability that is necessary for a specific job. An MPDT example of different implementations of a capability might be a three phase unbalanced power flow model or a balanced single phase approximation. [These Photo](#)s 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 the MPDT, implemented under the principals in interoperability and software flexibility, including**: modeling the microgrid or sets of microgrids and the associated distribution systems, alternative fuels (other than NG and diesel) and storage modeling, microgrid integration with utility control systems, cyber security requirements, interdependency modeling, protection coordination and adaption, and system stability, microgrid contributions to grid services and market participation, and technoeconomic tradeoff analysis.

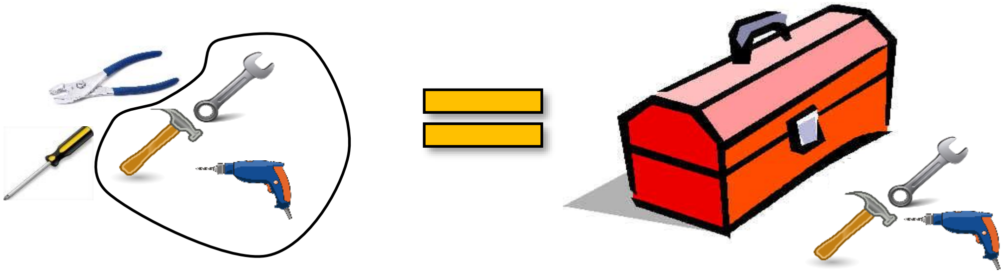


Figure 4: Illustrative example of the concepts behind modeling integration. Thinking abstractly, given a set of capabilities (pliers, screw driver, hammer, wrench, drill), different combinations will allow various application problems to be solved. Model integration supports the creation of a toolbox 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

Each of the elements of this vision are discussed in detail in the next section and directly support the achievement of this vision in microgrid software tools by enabling a suite of capabilities to model specific aspects of a microgrid and its environment. The capabilities are designed to interact with one another (interoperability), define solutions to future needs of microgrid tools (architecture requirements), and identify features future microgrid planning and design tools will require (integration).

3 Research and Development Recommendations

This section considers the vision articulated in the Introduction, identifies key goals, suggests potential solutions, and discusses enabling technologies to achieve this vision. While the modeling integration section contains the largest number of recommendations, these recommendations denote specific advances in microgrid planning and design capabilities whose full value are only 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.

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 there is a need for capabilities 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 tradeoff analysis between performance objectives. The existing computational tools described in the Introduction were designed to generate a cost-optimal architecture, design more resilient distribution systems, model operations and restoration, and generate resilience metrics, all towards the goals of sustainability, resilience, reliability, flexibility, efficiency, and security. But, each individual tool may neglect or diminish one or more these objectives to the benefit of the others. An interoperable modeling environment that fully captures each of these objectives will facilitate a full assessment of the benefits of a microgrid, potential tradeoffs between each criteria, and maximize the utility of existing tools.

Support for uncertainty propagation. Each microgrid tool handles uncertainty according to the requirements inherent to the tool itself. This presents a challenge when coupling the capabilities of tools together as the approaches for propagating uncertainty across coupling points are often ill-defined. An interoperable modeling environment requires the capability to specify the sources of uncertainty in each tool and how the uncertainty manifests in its output.

Support for interdependence interoperability. Microgrids do not operate in isolation and exist in a broader environment that includes relationships with water, natural gas, communication, thermal, and other critical infrastructure. Microgrid tools typically focus on the electrical system and the control interfaces between the microgrid and its feeder. Given the extensive development of tools for modeling non-electrical systems like natural gas (see [18][19], co-simulation (See HELICS [20]), and co-optimization (see InfrastructureModels.jl [21]), a microgrid interoperable modeling environment should fully capture the interfaces to connect with these software ecosystems and leverage ongoing interoperability efforts.

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

Standardization of microgrid tool inputs and outputs. This standardization will allow current and future microgrid tools to close couple with one another and support "plug-and-play" development of new capabilities at the intersection of two or more tools. Emphasis is placed on retrofitting existing tools to support these standards through development of conversion tools (such as DiTTo [22]) or direct refactoring of these tools to support standardization. New capability development efforts, such as those outlined in Section 2.3, should be encouraged during their implementation. Coordinated standardization facilitates workflow and iterations between tools and yields efficient planning and design processes that approach optimality.

Microgrid interdependent system assessment. Microgrids are often installed to provide reliable and resilient power to critical loads, such as military facilities, and support the continuity of service to other critical infrastructure such as natural gas, thermal, water, wastewater, and telecommunications and future infrastructure such as hydrogen. Microgrids, in turn, are then dependent on these infrastructures, such as natural gas, to provide fuel for DERs. A technology development that leverages interdependence modeling interoperability will accomplish a recommended integrated modeling of different infrastructure systems, their impact on microgrids, and how microgrids can benefit an integrated energy system. This will enable stakeholders to better understand the dependencies a microgrid has on other sectors. Rather than developing new interdependency solutions from scratch, it is recommended that existing capabilities be leveraged. This includes (but is not limited to) natural gas modeling (i.e., *NGfast* [18], *GasModels*, [19] etc.), thermal modeling (i.e., DER-CAM, REopt, etc.), telecommunications, etc., for models of individual infrastructures and integration technologies. Integration technologies are inclusive of co-simulation of interdependent infrastructures (see, e.g., HELICS [20]) and co-optimization to support joint choices of design, planning, and operations across microgrids and their co-dependent infrastructures.

Open source and open access. Interoperability may be achieved in different ways. One recommended activity is the encouragement, to the extent possible, of open source or open access release of capabilities. Such releases ease collaboration and ease the development of interoperable codes. Alternatives include software licensing; however, efforts should be made to develop licensing procedures that are straightforward and are easily agreed to.

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

API standardization. In the next one-two years, convene a workshop or series of workshops amongst key performers of the Microgrid R&D program and select industry advisors. The goal of the workshop is to identify core input and output specifications that tools and capabilities developed under the program will adhere too. A cohesive, program-specific set of standards helps ease interoperability with external partners by limiting the need to develop a new interface every time an external partner develops a collaboration with the program. The subsequent one-two years should be used to identify and retrofit capabilities to support this standard.

Interdependence interoperability prototype. In the next two-three years, choose a planning and design tool developed under the Microgrid R&D program and develop capability to automatically interoperate with a third party capability that models an interdependent infrastructure. It is important to note that tools like DER-CAM and REopt have native support for interdependent systems such as thermal; however, the goal of this target is to expand interoperability to other infrastructures, build pathways to leveraging existing capabilities and verify that interoperability has been accomplished. One potential point of leverage is the GMLC ERMA project which is developing "by-hand" interoperability between interdependent infrastructures that support microgrids. Synergies with this project could be explored to develop automation.

Interoperability with threat models. National labs, universities, and industry have developed models of hazards (e.g., wildfires and hurricanes) that potentially impact distribution feeders and the microgrids that support them. These models can be coupled with MPDT to identify undiscovered risks of such hazards by simulating the hazard in the same locations as distribution feeders. As the predictions of such hazards are uncertain, the uncertainty in the simulation of these hazards should be propagated into the simulation of the microgrid thereby demonstrating the capability to have interoperable uncertainty propagation. In the first year, a hazard of interest and hazard simulation capability should be identified. In the next two years, the hazard capability should be made interoperable with a microgrid planning tool in the Microgrids R&D portfolio. The subsequent two years should be used to develop the uncertainty propagation approach to identify risk. The next year should be used to promote interoperability with a design tool to recommend microgrid designs to mitigate risks to this hazard.

2.2 Architecture

Tightly coupled with interoperable modeling environments, are flexible software architectures. 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 difficult proposition. This observation recommends native software architectures that are designed for agility and flexibility to meet changing needs. Specifically, software architectures need to accomplish:

> *Software Modularity*. Microgrid planning tools rely on a variety of methods for modeling microgrid components and their capabilities. Often, the required level of granularity needed for a planning application is not clear *a priori*. This suggests the need for software architectures that support modeling of microgrids at different levels of granularity and fidelity implemented as independent modules.

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

> *Flexible component modeling*. Power system and microgrid component modeling is necessary for capturing the complexity of microgrids and their connected systems. The last several years have seen the emergence of a wide variety of approaches for modeling power flows, constraints, components, and physics to support microgrid tools [23][13][24][25]. Each approach introduces relative strengths, weaknesses, and assumptions with respect to fidelity, accuracy, computational requirements, data requirements, and other factors. MDPT R&D should adopt the use of software architectures that support flexibility when it comes to choosing a computational model of these features. This will allow the user of a tool to choose and validate the "right" fidelity model for the application at hand. Modular software architecture is one way to accomplish an implementation with varying degrees of complexity and fidelity, an example being the new PowerModelsDistribution.jl [13] library for supporting modular development of optimization models for distributions feeders and microgrids.

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

> *Flexible reliability metrics*. Widely used reliability metrics, such as SAIDI and SAIFI, are not suited to describe a customer's reliability experience. They do not capture the reliability value that DERs and private islanded capabilities provide for customers and systems. In the first year develop a proposed reliability metric for measuring the value DERs and islanding provided to customers. In the subsequent one-two years, using an existing Microgrids R&D MPDT, implement the metric in a flexible manner so that it or standard reliability metrics can be chosen by the user. This will demonstrate the feasibility of repurposing existing tools that do not currently have software flexibility to have such flexibility.
>
> *Flexible component modeling*. For a key feature of microgrid and distribution feeder modeling, such as power flow, storage capabilities, DER details, etc., identify at least two peer-reviewed methods for modeling these components in the first year. In the subsequent one-two years, using an existing Microgrids R&D MPDT or capability, implement the component in a flexible manner so that both approaches can be utilized. This will demonstrate the feasibility of repurposing existing tools to have such flexibility.

2.3 Integration

Finally, 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 of the microgrid and neighboring microgrids, and the bulk transmission system), and that span multiple infrastructure domains (thermal, hydrogen, buildings, communications, natural gas, etc.). The recommendations here are not to develop a single tool that captures all benefits and requirements, but rather to leverage the interoperability and architecture recommendations to develop the following capabilities that can be combined depending on the specifics of applications at hand.

> *Operational considerations within design*. Microgrid planning tools that decouple design and operations hinder the ability to make design choices based on operational requirements. Efforts are needed to continue recent efforts in this area and incorporate increasingly complex operational considerations into design tools. Recently developed tools, such as DER-CAM, LPNORM, REopt, and MDT, as well as industry developed tools, have demonstrated how design and capacity choices are impacted by operational considerations and serve as a technical basis for furthering operation and design integration.
>
> *Engineering limits*. In the past several years, MPDT have evolved to handle wider and wider ranges of engineering requirements (see, e.g., RONM). This integration has informed stakeholders on how microgrid operation (e.g., DER dispatch) solutions cause the system the microgrid is installed on to operate closer or further away from engineering limits. Efforts are needed to engage with stakeholders to incorporate any remaining under-represented engineering requirements. This gap reinforces the recommendation for flexible software architectures to easily accommodate new limitations as they are identified.
>
> *Non-conventional storage modeling*. Tools such as REopt and DER-CAM, as well as industry tools, have developed new models of thermal loads and their capability to provide storage services to microgrids and the feeders they support [26]. When combined with advanced technoeconomic analysis, non-conventional storage modeling can reveal benefit streams for storage not commonly integrated within design optimization. For instance, tradeoffs must be assessed when considering utilization of storage for grid services during blue sky days, yet also reserving energy for the microgrid during grid-islanded conditions. This benefit suggests the need for further extensions unconventional energy storage modeling and the services a microgrid can provide with this type of storage, such as hydrogen.
>
> *High-fidelity restoration and recovery modeling*. To date, MPDT have focused on using simulation to evaluate how a proposed design or plan behaves during restoration and recovery. These tools are not directly coupled to models of extreme events (wildfire, cold weather, etc.) that create situations that require restoration and recovery. Initial efforts to directly incorporate restoration and recovery modeling, such as RONM, MDT, and others, need to be built upon to capture the broad suite of restoration and recovery implications of design.
>
> *Communication modeling.* Many of the potential benefits of a microgrid are realizable through systems that allow microgrids to communicate with one another and the control systems of the feeders they are connected to. Initial work by the LPNORM project [27] and other projects have provided evidence of the importance of communication modeling (i.e., restoration sequences can only be executed if the communication system exists to send messages to DERs, switches, and

other controllable devices) and further work is needed to account for effects like latency. Unlike the more general interdependence modeling described under Section 3.1, there are specifics to the modeling of communications in a microgrid environment that go beyond connecting together existing software capabilities.

Controller and energy management system modeling. Many microgrids receive power from sources both within the microgrid and outside the microgrid. The methods by which these microgrids are controlled vary widely and the visibility of behind-the-meter DER is often limited. This suggests a need for capabilities that model different control arrangements, such as through ADMS, Aggregators or DERMS, and the visibility of control so that stakeholders may assess the degree to which the capabilities of the microgrid can be used to meet stated performance objectives as dictated by the controller arrangement.

Markets and grid service modeling. The involvement of DERs in activities of transmission and distribution grid operators to maintain and improve power flow and power quality is increasingly important. Many tools currently include some treatment of various market participation programs. For example, the role of microgrids that encompass DERs for delivering reliability and resiliency benefits to the grid and bringing economic benefits to the DERs is in early stages of development with the REPAIR tool co-funded by the Microgrids R&D program. Market rules and participation options are constantly evolving. Variation of the treatment of markets across tools and across markets can result in time-intensive customization or uneven valuation. Further development of methods for modeling market participation is required as is flexibility within the models for adapting to different and evolving market rules. Additionally, the ability to model aggregators' impacts on markets, system operation, and DER valuation is important.

Protection modeling. As designs for microgrids consider higher penetration of renewable and inverter-based energy sources, the need to consider the design of protection systems within MDPT becomes pronounced. This is largely due to inverters fundamentally behaving differently during fault conditions than traditional generation sources, as well as the differences in protection design with meshed versus radial systems. Although tools exist to design protection systems once resource selection, placement, and microgrid topology are finalized, this process can be inefficient, resulting in sub-optimal designs or greatly increased effort. Integrating the protection design capabilities within microgrid feasibility analysis tools can enable protection costs and constraints to be internalized within the design optimization stage, potentially saving a great deal of effort for complex inverter-dominated designs.

Black Start Generation. Black start is used to re-energize parts of a power system after a black out. As microgrids are used more and more often for resiliency, islanded during extreme conditions, and restoration, it is important to consider the black start requirements to support the microgrid and size the distributed energy resources appriopriately.

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

Controller-aware optimization. Under this activity, we recommend building on technologies used to model the way microgrid controllers are integrated with the controller of the distribution feeder the microgrid is connected to. Independent of whether the microgrid is owned by the customer, the distribution utility or a third party, the utility is responsible for maintaining grid stability, ensuring reliability, and providing grid services. The utility accomplishes this in one of two ways. First, the microgrid controller can be integrated with the utility's distribution management system (DMS) directly in the form of centralized management. Second, the microgrid controller can be integrated indirectly using decentralized management via a Distributed Energy Resources Management System (DERMS). In both cases, we recommend capabilities be developed that allow microgrid planning and design tools to account for the specifics of controller technologies with flexibility (Section 2.2) to account for emerging technologies. Specifically, a technology development to support the evaluation of different approaches to controller integration will ensure a microgrid design is compatible with the control architecture and facilitate operations between the microgrid and the outside world.

Combined microgrid and distribution feeder planning. This activity recommends extending recent efforts, such as those by DER-CAM, REopt, ReNCAT, LPNORM, RONM, and industry tools, to integrate microgrid planning tools with models of the broader distribution system it is connected to. Suggested enhancements to current and emerging capabilities include:

- The development of accurate representations of virtual power plants and resource aggregator behavior.
- The development of accurate representations of distribution system constraints on microgrid capabilities.
- Methods for evaluating the operational cost of an entire distribution system with and without microgrids. This advancement requires the capability to simulate how distribution system resources – including DERs – are dispatched both within a vertically integrated utility environment and within a wholesale power market.
- The evaluation of resilience benefits of a system of microgrids. This advancement dovetails with *resilience modeling in coupled design and operations*.
- Optimization across a multi-parameter design space for portfolios of microgrids within a distribution system.

The combination of these developments identifies benefits that microgrids can provide within many aspects of distribution planning. Ultimately, this development will enable microgrids to be included within transmission-level resource planning such as integrated resource planning processes. Most critically, portfolios of multiple microgrids will be able to be compared with other distribution technologies to form a system-wide distribution plan that balances performance across multiple dimensions.

Reliability modeling in coupled design and operations. Reliability metrics are a critical component of evaluating the performance benefits of microgrids [28]. Commonly used reliability indices used by utilities include: System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Frequency Index (CAIFI), and Customer Average Interruption Duration Index (CAIDI). These reliability indices measure the performance of a distribution system or microgrid during high-probability, low-impact events. Electrical distribution system reliability is typically evaluated with historical assessment, which usually excludes extreme events such as weather, declared emergencies, and disasters that affect over 10% of the utility's customers. Since microgrids can improve the reliability of an electrical distribution system through enhanced system resourcefulness and controllability, this activity recommends a technology development centered around how to optimally place and operate the microgrids so as to improve the reliability of electrical distribution to certain quantifiable level (e.g., improvement of SAIFI, SAIDI, CAIFI, and CAIDI). This includes quantifying the reliability of microgrid itself, especially the reliability and variability of its DERs, i.e., PV, wind turbines, batteries, internal combustion engines, etc. One approach to producing this technology is to demonstrate how microgrids, especially networked microgrids, can help to improve the reliability of distribution and transmission systems by providing them with reserves, i.e., capacity reserve, operational reserve, regulation reserve, etc. It is important to note that there are legal and regulatory barriers preventing the use of microgrids and networked microgrids as ancillary services which need to be addressed for this approach to succeed. Finally, to encourage the adoption of microgrids, new business models for pricing the reliability benefit of microgrids to distribution and transmission system need to be established.

*Advanced techno-economic analysi*s. This technology development focuses on the capability to perform technoeconomic analysis to develop cost-optimal microgrid architectures that account for tradeoffs between performance dimensions such as resilience, sustainability, and efficiency. That is, robust, expansive, and computationally efficient technoeconomic modeling is foundational to achieving microgrid deployment at-scale. Although tools have evolved to support detailed analysis of several tradeoffs between these dimensions for some stakeholders, there remains difficulty in supporting techno-economic analysis that internalizes the broad and diverse value streams of microgrids for all stakeholders. Fundamentally, improved coupling of the following elements would allow a more robust trade-space analysis including multiple objectives for multiple stakeholders:

- Application of multi-dimensional trade-space analysis across all stages of planning, informing decision-making as microgrid design moves from concept to detailed design and to operation
- Incorporation of tradeoffs when considering microgrids installed in-front-of versus behind-the-meter, including the ability to represent both wholesale and retail markets within a single design optimization.
- Deeper consideration of the nonlinearities involved during grid-islanded operation within true 'black-sky' plus 'blue-sky' co-optimization of conceptual design parameters. For instance, models should incorporate load behavior adaptations during emergency conditions.
- Additional consideration of grid-responsive load as a resource, including electrical and thermal energy storage and grid-interactive efficient buildings (GEB) modules. Furthermore, representation of how these resources differ in operations during grid-tied versus grid-islanded conditions.
- Representation of utility distribution-scale microgrids, customer (behind-the-meter) microgrids, and networked microgrids within a single platform
- Incorporation of additional consequence-focused metrics, such as economic and social values of resilience to the load entities
- Incorporation of additional stakeholder objectives, for instance delivering insight for planners representing customers, city governments, or state governments. Especially, incorporation of approaches that reveal how microgrids enable equitable service to customers, especially equitable support of social needs during disruptions.

Many of the above enhancements have examples of important single advancements within existing tools, however if these features are not coupled to some extent within a standardized unified framework (Section 2.1) it becomes extremely difficult if not impossible to deeply understand the performance tradeoffs.

Imposing stability requirements. Historically, distribution systems have seldom experienced stability issues because the substation provides a strong voltage source and distribution systems have a limited number of DERs. However, for microgrids and distribution islands with high penetration of DERs, dynamic stability becomes an operational concern that propagates into how a distribution system is planned or designed. Commercial and national laboratory MPDT typically, once a plan, design, or operation schedule is determined, study microgrid dynamic stability based on conventional bulk power system approaches. These include electromagnetic transient (EMT) simulations and positive-sequence transient stability simulation. These approaches are reasonable given the current state-of-practice, but there remain significant obstacles in accurately modeling the dynamics in full-size, three-phase unbalanced distribution systems. This recommendation suggests new models and simulation tools that enable dynamic simulation of microgrids that have unbalanced load distributions, different types of DERs, and loads with various control and protection schemes. This technology will allow design and planning tools to account for the stability of proposed distribution feeder operation modes, like intentional islanding, and microgrid designs. Some of this work is currently underway, for example, the RONM project is developing integrated modeling of DER dispatch and network configuration to disallow combinations that are unstable.

Protection-aware microgrid planning and design. Today, protection tools, such as fault current calculators, determination of the impacts of large motor starts or transformer inrush, determination of settings or parameters for protective devices, and calculation of arc flash incident energies, are used to ensure that distribution feeders respond to failures gracefully, isolate faults, and prevent system collapse. Given the importance of protection in microgrid systems, industry, has begun to integrate microgrid techno-economic and deep-circuit simulation with protection models (like those used in MPDT). A general strategy for research and development for protection systems in microgrids and systems with microgrids is covered in the strategy document entitled, *Advanced microgrid control and protection*. Here, this recommendation focuses on technology developments that are required to ensure that MPDT account for protection systems and their requirements. Specifically, this report recommends the following capability developments:

- A model of load dynamics and protection systems responding to load changes. Load types are becoming increasingly varied and given the relatively low level of fault currents in microgrids, some load changes could be misidentified as faults by protection systems.
- A model of DER dynamics and transient responses. These features are control-dependent, and thus, a microgrid must be designed to ensure that the installed protection system responds currently under a variety of operations scenarios. This includes high-fidelity representations of the DER under faults for current limiting, angle of the current injection, and ride-through behavior.
- Coordination between the microgrid's protection and the protection of the distribution feeder it is connected to.
- Planning capabilities so that tools that can incorporate co-design of the power-electronics controls for inverter-based resources with protective equipment.
- Planning capability that supports the ability to model and design new microgrid protection schemes that are more robust to changing conditions such as load types, inverter-based resources, and networked microgrids.

- A capability to model next-generation protection technologies such as solid-state circuit-breaker technologies and pulse-reclosing technologies. This will allow microgrids to contribute in a wider range of operating scenarios.
- A capability to optimally design protection schemes for arbitrary microgrid designs, DER configurations, critical loads, and fault currents. This will support more flexibility when it comes to microgrid design and operation scenarios that are allowed.
- A capability to model and protect DC microgrids. Most tools are focused on AC systems.

Work in this area has begun in the Microgrid R&D program, such as integration of protection modeling into RONM to disallow network configurations that cannot be properly protected, which should be built upon to support these new developments.

Resilience modeling in coupled design and operations. Resilience is a term that is used to refer to performance during low-probability, high-impact events and contrasts with reliability which is used to refer to performance during high-probability, low-impact events. Resilience quantifies the state of a system before, during, and after extreme events, as well as the transition process between states. Thus, tools for resilience modeling incorporate elements of preparation before an extreme event, operations during an extreme event, and the response and recovery after an extreme event. Resilience modeling has long been an important motivator for R&D efforts (see RONM, LPNORM, and a variety of industry tools, etc.) in MPDT tools, and building on the successful outcomes of these prior efforts, the following recommendations are made. First, it is recommended that continued efforts be made to establish specific and standardized metrics for assessing resilience. Only with widely accepted metrics can the resilience benefits of microgrid(s) be quantified. This recommendation enables the development of optimization and simulation tools that utilize these metrics to make microgrid recommendations that further the resilience goals of microgrid stakeholders. Specifically,

- An optimization model for selecting microgrid resilience enhancement options given resource constraints on budget and time that account for stakeholder preferences and customization. The rich history of the Microgrids R&D program, such as Risk-controlled Expansion and Planning with Distributed Resources (REPAIR), provides a strong foundation for such work.
- An approach for coordinating microgrid(s) and ADMS to improve restoration and recovery, in particular in situations where the communication system is partially or completely damaged, e.g., building off the communication recovery model of LPNORM [27].
- A new business model for incorporating legal and regulatory requirements, e.g., requirements to prevent customer back-feeds during outages, to assess the relative pros and cons associated with such requirements.
- A co-simulation capability for modeling physical and cyber systems during an extreme event. The interplay between these two systems is crucially important for understanding the resilience capabilities, or lack thereof, microgrids have during an extreme event.

Microgrid cybersecurity planning and design. While formerly passively controlled, distribution systems and the microgrid technologies that support them are increasingly adopting advanced control systems to manage their networks. This has created a need for capabilities that augment MPDT with analysis of potential cybersecurity vulnerabilities these control systems introduce [29] [30]. To achieve these capabilities, the recommendation is made for:

- The development of Software-Defined Networking (SDN) technologies for microgrid cyber systems. SDN provides a secure/virtual cloud environment that, in test settings [31], shows evidence of self-healing to establish new communication routes when cyber penetration is detected, automatically avoids suspicious devices in the microgrid, establishes application-specific filtering in the switches, and enables on-demand path establishment for control commands to limit attacker's capabilities. This is a potentially attractive technology to secure microgrids from cyber-attacks.
- Develop solutions based on cryptography for devices that are commonly present in microgrids. For example, the Trusted Execution Environment (TEE) architecture that uses ASICs as a trusted hardware module and Trusted Platform Module (TPM) secure software for DER inverters could be designed to be capable of providing physical attestation and closed-loop control mechanisms. The feasibility of encrypting communication information of microgrid components with minimum end-to-end latency have been validated and tested in an emulated distribution system developed by NREL [32].
- Develop a set of cybersecurity valuation studies that identify the drivers for microgrid cybersecurity investment, determine security needs, and explore vulnerability assessment of microgrids. This will provide a mechanism to justify and estimate cybersecurity budgets.

Planning for microgrid grid services. Microgrid participation in grid services and markets requires developing new modeling tools to match industry trends such as modeling of generation resources in the microgrid with new fuels (apart from natural gas and diesels), integration of storage and EVs, aggregation of microgrids and DERs into VPPs, new applications enabling microgrids to provide grid services and constraint management, different tariff schemes, e.g., time of use (TOU), real-time prices, and seasonality, N-k contingency analysis, and sensitivity analysis for multiple business models. This recommends the development of capabilities linked to assessing flexibility in microgrid operation and determine ways to integrate microgrids tightly into the power system and markets.

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

Integrated microgrid design. Develop a capability for identifying the boundaries of a microgrid and designing its structure and a capacity to maximize the reliability and/or resilience of a distribution feeder for user-defined constraints. While many of the features of such a tool exist under the Microgrids R&D portfolio (see, e.g., LPNORM and ReNCAT), the aim of this target is to demonstrate that important key features of the portfolio can be extracted or accessed directly to produce a capability at the intersection of tools in the portfolio. It is expected that this target can be accomplished in 1-3 years.

Dynamic models of microgrids. Develop a microgrid simulation library that enables dynamic simulation of full-size, three-phase unbalanced distribution systems and microgrids with different types of DERs and loads under various control and protection schemes. This library should be accomplished in the first year. In the next two-three years, this capability should be integrated with an existing Microgrid R&D planning tool to examine how high penetration of microgrids with various DERs and loads impact the dynamic behaviors of the distribution system and recommend modifications to the microgrid or distribution system to avoid any adverse behavior identified by the dynamical model.

Aggregated DERs and microgrids. Develop a capability to support the integration of microgrids, a group of microgrids, dynamic reconfiguration, aggregated DERs and VPPs within utility systems to support grid services and satisfy the network constraints. Such a capability also supports the determination of how to dynamically construct microgrid boundaries that leverage existing DERs on distributions feeders. Accounting for grid services requires increasingly flexible optimization approaches for microgrid operations and DER dispatch. Often, power flow tools that support optimization are not computationally efficient enough to simulate grid service requests and DER response. Thus, it is recommended that when modeling grid services and grid impacts, the microgrid program should move beyond network models and power flow tools and take advantage of new network modeling and optimization tool for distribution networks. For example, the optimization-based network model, PowerModelsDistribution.jl [13], for simulations with microgrid and VPP models.

End-to-end planning and design with operations and recovery. This target focuses on combining capabilities that support an approach for optimally designing and placing microgrids for improving blue-sky operations and black-sky recovery. Such an approach can leverage the developments of the RONM project that has focused on the black-sky portion and provide a capability that balances efficiency, reliability, resilience, sustainability, security, and flexibility. By building on known approaches, it is expected that such a target can be accomplished in 2-3 years.

2.4 Enabling Technologies and Concepts

Section 2 has largely identified recommendations for the microgrid R&D program on the topic of planning and design tools; however, there are enabling technologies and concepts whose continued adoption and advancement will help to support the goals and outcomes of these recommendations. These enabling activities and developments are outlined here.

Advanced smart grid devices. Over the next 5-10 years, it is expected that vendors will continue to introduce smart devices, such as software-defined switches and controllers, which will be used to improve the utility of microgrids. The recommendations outline a plan for supporting flexible software architectures of existing and new tools so that models of new devices can be introduced without complete software rewrites. However, detailed models and APIs of devices, their limitations, and their capabilities are needed so that the benefits of the device to a microgrid are properly assessed. One way of incentivizing vendors to provide this information are to use the capabilities of the Microgrid R&D program to produce case studies that demonstrate how the new devices benefit a microgrid or a distribution feeder with a microgrid.

Artificial intelligence and machine learning. Artificial Intelligence (AI) and Machine Learning (ML) are expected to continue to make advances with new technology introductions that may impact the Microgrids R&D program. There are increasing amounts of data in microgrid deployments which the industry is using to develop new ways of controlling and managing microgrids and distribution feeders [33]. Such developments should be carefully monitored as potential opportunistic directions for microgrid planning and design R&D, in particular, as industry continues to find new ways to leverage AI and ML technologies in microgrids.

Advanced smart control systems. Hand-in-hand with advanced devices and AI technologies are expectations of developments of increasingly complex and sophisticated control systems. Examples include (but are not limited to) power-electronics-intensive microgrids with increased rates of interactions, dynamic islanding through DC or controllable AC links, and advanced automation strategies for edge-intelligent fast-responding inverters that securely coordinate in real time. However, like the individual smart devices, publication of or providing documentation on the control approach will help the program to assess the benefits and limitations of new control systems. The recommended focus on flexible and interoperable software will help promote agility in the microgrid program and stay at the forefront of modeling advanced control systems and their impact on planning and design.

Education, technology transfer, and industry adoption. Research and development in many fields often experiences a “valley of death”, where it is challenging for research to make the transition to practice. While the microgrid R&D program has experienced successes in bridging these gaps (see, e.g., transitions of capability to NRECA’s Open Modeling Framework (OMF), the program’s heavy emphasis on industry engagement and peer review, DER-CAM's commercialization, etc.), the program should continue to monitor and adopt the latest new ideas in education, training manuals, and tool usability to promote trust in the research. Industry is a willing partner here, accepting of advice on how to use tools, and suggesting of projects and case studies where the research can be showcased to encourage adoption.

Hardware-in-the-loop simulation. Planning and design tools rely on computer models and computer simulation to identify design choices, planning results, and operational outcomes. Computer simulations are approximations of physical systems and these outcomes require validation and verification of solution plausibility. The microgrids R&D program (see RONM) often leverages scalable hardware-in-the-loop platforms for validation and verification and these platforms should continue to be used as intermediary between software validation and field testing.

Customer impact models. Industry and the academic fields have developed and are developing sophisticated economic models on how utility costs and revenues affect the electricity rates offered to consumers. These models are a source of calculations for consumer savings and energy equity which, in turn, drive the outcomes of microgrid planning and design tools. As customer impact models continue to improve, these should be used to continue to augment the techno-economic capabilities of microgrid tools.

4 Use Case and Scenario Examples

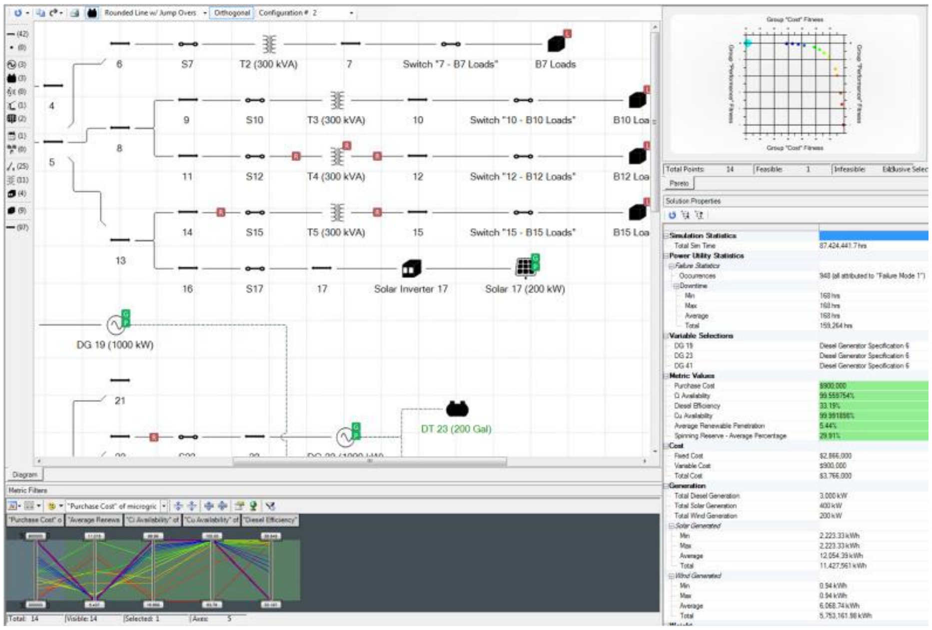
Use cases and scenarios are important drivers of efforts in MPDT. They are used to demonstrate tool usage, provide concrete examples of a tool’s value, and provide immediate support and recommendations on microgrid planning. This section describes a few microgrid use cases and scenarios and how they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

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 either impossible or not beneficial to connect these systems to a bulk grid. Grid-isolated microgrids can also serve as a scenario for modeling similarities with grid-connected microgrids that disconnect from the bulk grid. Most of the targets discussed in Section 2 benefit from using grid-isolated microgrid scenario examples as such case studies ensure that the capabilities can be applied to grids in isolation and ensure that the capabilities do not have built in assumptions about being grid-connected. Our primary recommendation for the program is to test the most advanced features of new developments on grid-isolated microgrid case studies because of these systems' relatively straightforward design needs. One need for advancement is in the area of resilience-inclusive optimal design with climate change drivers and the uncertainty embedded in these projections. Remote communities are often especially vulnerable to climate change impacts and therefore would benefit greatly from such an approach.

More specifically, one potentially interesting forward-looking case study centers on tradeoffs between resilience and de-carbonization. In many parts of the country, communities are expressing desires to become carbon neutral, with target dates ranging anywhere from 2030 to 2050 and beyond. Given this desire, we envision one case study centered around planning and (re)designing an existing grid isolated microgrid to achieve this goal as this will a) help a community achieve such a target and b) provide a unique opportunity to exercise new research and development. Unless a CO_2 capture technology is implemented, a remote community can become carbon neutral only if it replaces fossil fuel DERs with non-fossil alternatives such as solar and wind paired with an energy storage solution. In this case study, the goal is to update the isolated microgrid in the most cost effective manner, perhaps leveraging new energy storage solutions such as hydrogen paired with solar [34], to meet existing and new reliability and resilience metrics developed in this program. Given the nature of microgrids without conventional energy resources, the R&D target of *Dynamic models of microgrids* is an especially important one for this case study. 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.

We also recommend revisiting past grid isolated case studies as they are already configured to leverage existing MPDT and can be naturally used to demonstrate new enhancements. For example, as part of DOE's Grid Modernization Laboratory Consortium in 2017, NREL 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 is 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 fossil fuels 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 forward-looking projections of climate impacts within both the blue-sky and black-sky valuation approaches, as well as improved incorporation within optimal design of consequence-based 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 5: Microgrid Design Toolkit model highlighting 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 grid-tied at least part time, tools must be able to reflect how microgrid design parameters can generate revenue for the microgrid operator 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 nominally the microgrid will do so during a disruptive event.

Within DOE, case studies have been performed on grid-connected use cases using MPDT. For example, a recent analysis performed by the DOE-OE 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, low-cost, and low-GHG 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 grid-tied design optimization for least-cost operations separately from a grid-islanded design optimization for maximum resilience operation. By running these tools iteratively, a near-co-optimal design which balanced economic value, greenhouse gas emissions, 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 DOE's 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 co-optimization and microgrid design. So, it is recommended that case studies based on this (and the other) use cases plan for education and training. In future case studies for this use case, we expect the follow 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, flexibility, and sustainability leveraging both existing tools that support this co-optimization as well as the capabilities outlined in section 2.3 to improve the accuracy of the co-optimization.
- Ensure that the grid-tied microgrids be considered within the overall distribution planning processes, thereby exercising the targets of *Combined microgrid and distribution feeder planning*.
- 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. A case study here will help demonstrate how microgrid planning tools can be used to support rate planning activities and their impact to optimal microgrid design, thereby exercising the targets of *Planning for microgrid services*.
- Identify the optimal protection system that keeps the microgrid and its distribution feeder protected in both grid connected and grid-islanded mode, considering the relative merits of static vs. dynamic protection settings. A case study with this feature will support *Protection-aware microgrid planning and design*.
- Identify the most cost optimal cyber security features to include in microgrid to demonstrate the value of the targets of *Microgrid cyber security 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 technology 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 renewable energy sources, and increase market share—often more than the aggregate of what the microgrids can accomplish individually. Thus, it is a recommendation that new tool developments be assessed using case studies based on networked microgrid use cases.

Recent GMLC and Microgrid R&D 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, Citadel (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. Grey Sky: networks of microgrids collaboratively operating to support the bulk power system and to prevent bulk power system collapse.
3. Dark Sky: networks of microgrids operate to support critical end-use loads and self-assemble to provide increased resilience when service from the bulk system is interrupted.

4. Restoration: networks of microgrids coordinating with centralized efforts to provide black-start and other restoration 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. This will help to identify the "greater than the sum its parts" benefits of the networked system, thereby showcasing *Integrated microgrid design*.
- Model and optimize the control system to support the networking of the 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 Distribution Management System - Microgrid and Utility Interaction for Flexibility (Grid Services) and Resilience

ADMS and DERMS 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 recommendation to determine the ideal microgrid and distribution feeder design to take best integrate these systems. 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 of 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 DERs in concert with the wider distribution grid, a key component of the *aggregated DERs and microgrids* target.

- 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, also showcasing the *aggregated DERs and microgrid*s R&D effort.

- 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 an integration be planned to yield a successful result. This exercises *controller-aware optimization*.

Future extension of this research requires aggregation of multiple microgrids, BTM/ FTM DERs, VPPs and demand response enabled loads that are integrated with control center to support various grid services in varying time horizon (Figure 5). Argonne led "Beyond DERMS" is an attempt to demonstrate 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 DER deployments, load growth, electrification initiatives and distribution network changes using the same tools that they use for real-time operations.

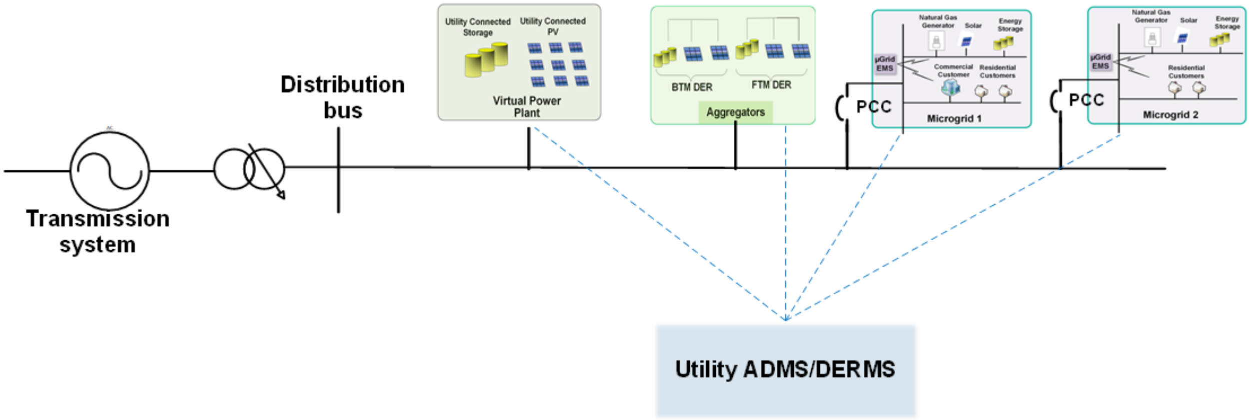


Figure 6: Flexible integration of grid service resources

3.5 Virtual Microgrids and Virtual Power Plants

Both microgrids and virtual power plants (VPP) involve aggregation and optimization of DERs. Aggregation is particularly useful in managing large numbers of DERs and enable them to provide grid services. 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 DERs are available. Meanwhile, the microgrid owner is free to innovate solutions for their specific operation and customers.

5 Justification of DOE Investment

The challenges, gaps, and tasks identified in this document outline a research and development path for the future of MDPT. 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 stakeholders to fully assess the potential benefits of a microgrid or a network of microgrids in their system. This type of DOE, academia, national lab, and industry partnership to further the state of practice has long provided success through the DOE's Microgrid R&D 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.

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