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Engineering Microgrids Amid the Evolving Electrical Distribution System

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Abstract: Non-wires alternatives and microgrid technologies are maturing and present great opportunities for electric utilities to increase the benefits they offer to their customers. They have the potential to decrease the cost of resolving traditional electrical system loading issues, contribute to carbon emissions reductions, and improve the electrical distribution system's resilience to extreme weather events. The authors of this manuscript present a review of the research on microgrids and their practical applications. This is leveraged with the past work of the authors of this manuscript and other authors to develop specific objectives for microgrids, practical criteria for engineers to consider when deploying microgrids, stochastic methods to optimize microgrid designs, and black start requirements. This guidance is then used for the design of actual networked microgrids being deployed with adaptive boundaries.

Keywords: microgrid; adaptive networked microgrids; non-wires alternatives; distributed energy resource; sectionalizing; energy justice; stochastic methods

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Citation: Sharma, S.; O'Donnell, J.; Su, W.; Mueller, R.; Roald, L.; Rehman, K.; Bernstein, A. Engineering Microgrids Amid the Evolving Electrical Distribution System. *Energies* **2024**, *17*, 4764. https://doi.org/10.3390/en17194764

Received: 27 August 2024
Revised: 13 September 2024
Accepted: 19 September 2024
Published: 24 September 2024

1. Introduction

The increasing penetration of distributed energy resources (DER) as well as policy trends are steering the power grid to a more distributed future. It is expected that around 30–50% of the generation assets will be connected at the distribution level in the next 10 years [1]. This trend along with technical advances are making microgrids a viable option to improve the performance and efficiency of the electrical distribution system.

A microgrid is a group of interconnected devices (loads, generators, and distributed energy resources) within clearly defined electrical boundaries that act as a single controllable entity [2]. A microgrid can operate in either grid-connected or islanded mode depending on the overall grid conditions. Microgrids are traditionally considered as critical resources for improving the resilience of the electrical grid during emergencies. However, the role of microgrids in the future electrical grid is not limited to pure resilience considerations. In particular, evolving concepts such as networked and dynamic microgrids are transforming the microgrid concept into an essential building block of the future grid as a system of systems. As a result, microgrids are becoming an essential element of virtual power plants (VPP) and therefore contributing to decarbonization of the future grid.

To achieve the goals of this paper, it first presents an overview of microgrid concepts and examples of real microgrids that are operating in the United States. It then discusses the different objectives that can be achieved by standalone and networked microgrids.

Finally, guidelines and methods are presented to engineer practical microgrid systems and demonstrate the applications of those guidelines and methods with illustrative examples.

The result of this work is to provide engineers with the critical objectives for microgrids with practical implementation considerations, including source and sectionalizing placement, black start requirements, data availability, and others. Predominantly deterministic microgrid optimization techniques are also replaced with time-efficient probabilistic practices that consider the practical reality of areas with low DER penetration being adjacent to areas with high DER penetration. All of this is grounded in the lessons learned from actual real-world deployments of two sets of adaptive networked microgrids.

2. State of the Art

Section 2.1 considers the research that has been completed and is available in publications, Section 2.2 summarizes some key microgrid applications, and Section 2.3 recaps the state of the art. Section 2.4 describes some of the authors' relevant work and how the work described in this manuscript contributes to the overall body of knowledge.

2.1. Literature Review

This section reviews the research relevant to this manuscript.

The Department of Energy (DOE) defines a microgrid as "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode" [2]. Microgrids are increasingly becoming an area of interest in research, and some consider them a foundational element of the future electrical grid [3]. Reference [3] goes on to describe a microgrid as a small number of DERs connected to a single power subsystem, with the DERs including both renewable and conventional resources, and it notes that microgrids have gained popularity in recent years as a result of technological improvements in small-scale power generation. Microgrid research and development make them a promising addition to the future electrical distribution system, and this section presents some of that research.

The authors of [3] define the six components of microgrids as generation, storage, energy management system, loads, controller, and point of common coupling and define a framework for classifying microgrids based on seven elements: controls (centralized, decentralized, or distributed), size (low, medium, and large based on generation capacity), power supply (AC, DC, or AC-DC coupled), source (renewable, fossil, or hybrid), load (residential, commercial, or industrial), location (urban or remote), and application (military, campus, community, island, or direct energy). Reference [3] also describes the key requirements for the controls with a focus on seven components: power balance, transition, protection, power transmission, optimization, synchronization, and stability. The authors of [4] consider microgrids as an essential interface to connect renewable energy resources to the traditional distribution system. They present the challenges of microgrid controls in categories of operation, compatibility, integration of renewable sources, protection, regulation, and integration of consumer energy management systems. Reference [5] starts by describing several aspects of microgrids, including a classification method, and then presents the challenges with AC microgrid protection, including dynamics in fault current magnitude, faults/events during grid connected mode, faults/events during islanded mode, islanding condition detection, blinding of protection, protection devices/switch selection, false tripping/spurious separations, and re-synchronization/auto-recloser problems. The authors also propose solutions to these challenges with analysis of the merits and demerits of each. Reference [6] provides an overview of the challenges with AC microgrids, including sympathetic tripping, reduction of response time or loss of sensitivity, reclosing schemes miscoordination and fuse problems, exceeding short circuit level, and undetected islanding problems, and then the authors present methods and standards to address these challenges with an analysis of each. Figure 1 illustrates the basic components of a microgrid.

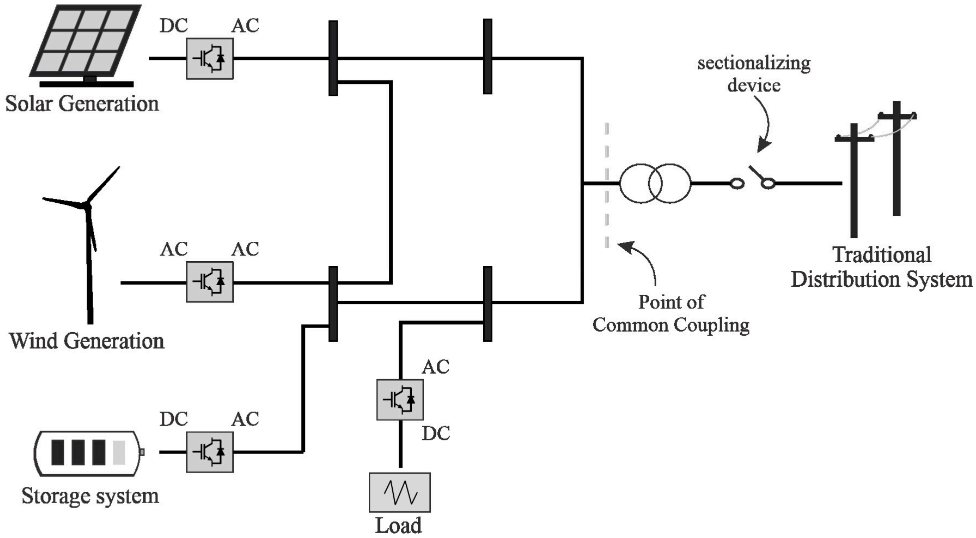


Figure 1. An illustration of the components of a single microgrid.

It is clear from a review of the available research that microgrids are a topic of strong interest, and there has been a focus on the design of stand-alone/conventional microgrids. Reference [7] provides a roadmap for microgrid design with considerations for operational efficiency, economic efficiency, resiliency, and sustainability. The authors propose a phased process that includes a feasibility assessment phase, a planning phase, a modernization and integration phase, a design and modeling phase, an innovation and implementation phase, and an operation and maintenance phase. Reference [8] describes a framework for microgrid design that is focused on social, economic, technical, legal, and regulatory criteria. Reference [9] provides an overview of optimization methods as they are applied to microgrids. Reference [10] optimizes the design of a microgrid based on load and generation for a day in one-second time steps. Twenty-four representative day-types are used by [11] to optimize microgrid controls. Day-ahead optimization of real-time microgrid operation is developed in [12] using stochastic methods considering the uncertainty of renewable sources.

The common perception [13,14] is that each microgrid is a personalized energy system of any size, made up of any available DERs. Standard and customized microgrids have proven their ability to increase reliability and resilience but at a high monetary and labor cost. Recently, more attention has been paid to more reconfigurable and networked systems (Figure 2) in which some components and subsystems can be pieced together and reconfigured like LEGO blocks. Table 1 compares standard and customized microgrids with more reconfigurable and networked microgrids. The more-reconfigurable and networked microgrids are designed with adjustable electric boundaries and dynamic topologies through a combination of smart switches, grid-forming inverters, mobile generators, and energy storage devices. The boundaries of the microgrids on the same electrical circuits are designed to be adaptive during operation, as opposed to existing approaches where microgrid boundaries are static (i.e., not varying over time). Ultimately, they will empower local communities to improve the use and sharing of local energy resources during both normal operation (e.g., large-scale integration of electric vehicles) and emergency conditions (addressing cold snaps/heat waves, natural disasters, and wildfires).

The focus of microgrid research has started to move past stand-alone microgrid operation and has shifted toward multiple microgrids collaborating to serve customers. There are several terms to describe these microgrids, including nested microgrids, networked microgrids, collaborative microgrids, and adaptive networked microgrids (ANM). ANMs are becoming an increasing focus of research because of the potential reliability and other benefits they promise for end users.

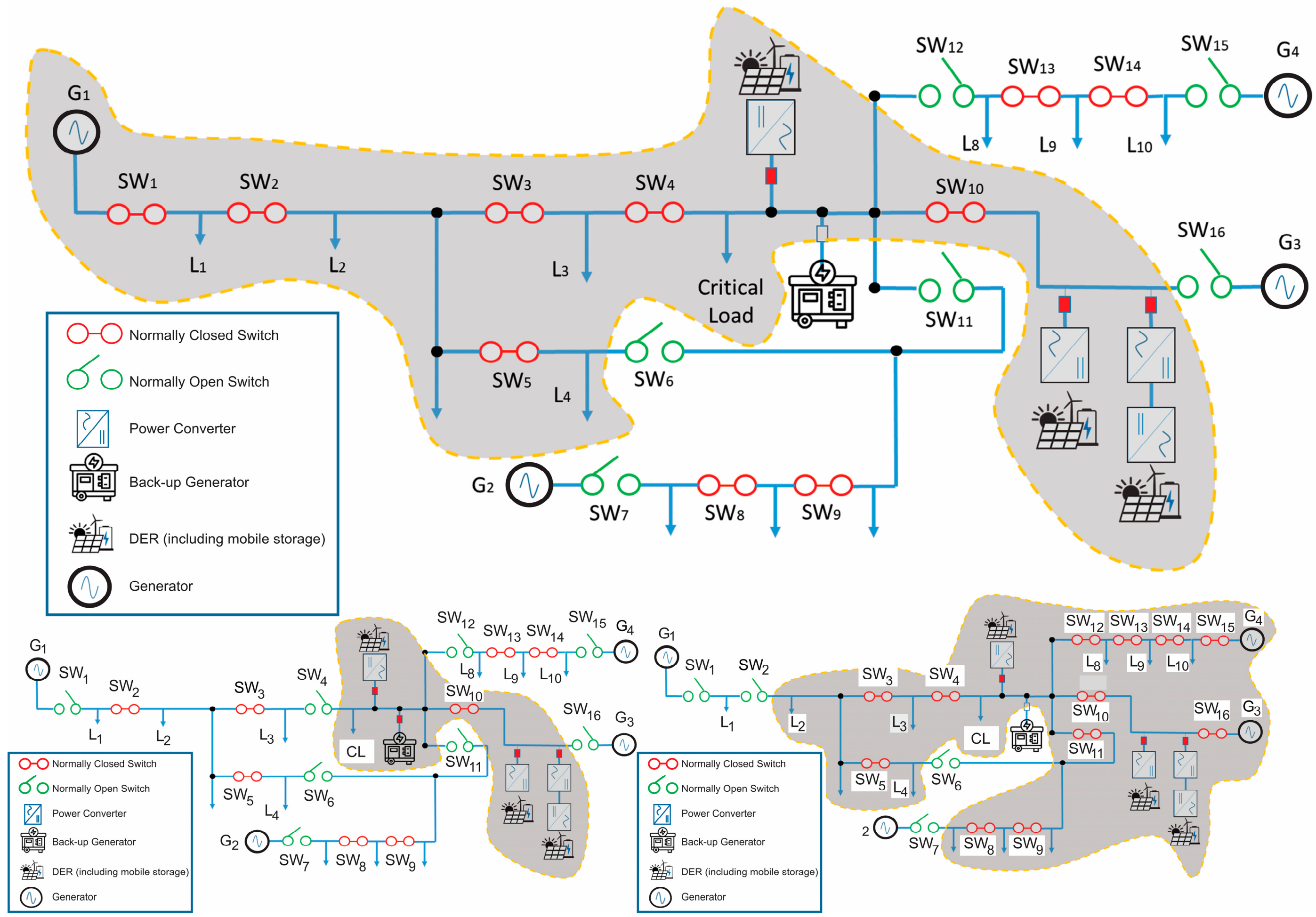


Figure 2. An illustration of the networked microgrid with dynamically changing electric boundaries.

Table 1. A comparison of standalone and networked microgrids.

Microgrid Attribute	Standalone Microgrid	Networked Microgrid
Control strategy	Time-invariant control law	Time-varying adaptive control law
Electric boundary	Pre-defined	Dynamic and may even have overlay
Physical topology	Fixed and static	Flexible (changing over time)
Communication	Fixed directed graph	Variable directed graph
AC-OPF solver	Dedicated to a given topology	Needs to be much more robust against dynamically changing topologies
Contingency analysis	Computationally expensive	Extremely high computational cost

Reference [15] describes a difference between conventional microgrids with fixed boundaries and microgrids with smart, flexible, and dynamic boundaries. The authors of [15] focus on microgrid controller design by comparing four scenarios of microgrid operation: grid connected, multiple islanded microgrids, merged islanded microgrids with small boundaries, and merged islanded microgrids with large boundaries. They also define key decisions for the design of microgrids with dynamic boundaries, including recloser placement, asset sizing, grounding, and protection design. Reference [15] also tests the presented concepts with hardware-in-the-loop systems and a deployment with the Electrical Power Board (EPB) in Chattanooga, Tennessee. Reference [16] develops an objective function to be optimized for microgrid deployment and design. The objective function developed by the authors of [16] includes system considerations (load blocks, power flow, operational constraints, and topology constraints), microgrid controllability (no microgrids, static microgrids, expanding microgrids, and networking microgrids), limiting wildfire ignition risk, and equity-aware load shedding. Reference [14] describes a framework for dynamic formation and operation of networked microgrids toward the goals of improving transmission and distribution system real-time resilience, integrating and efficiently leveraging large amounts of renewables and DERs, allowing wide-scale electrification, increasing distributed and decentralized decision-making, and improving equity and energy justice. There have been some experiments with ANMs as well, as described in [17,18]. Optimizing the size of the components of networked microgrids using a 24 h period with 15 min time steps is the focus of [19]. Twenty-four-hour day-ahead predictions of wind speed, solar radiation, load demand, and electricity market price are used in a two-stage model to optimize output power and trading opportunities of nested microgrids in [20]. Reference [21] develops a comprehensive and multistep formulation of networked microgrids response over a several hour period to power interruptions due to severe weather events. It includes analysis of 1000 scenarios to show the adaptiveness of the proposed approach.

2.2. Application Review

This section reviews some key microgrid applications.

2.2.1. Fremont Fire Stations Microgrid

The city of Fremont is in California and located next to the San Francisco Bay. Fremont is located on the Hayward fault, which means that the area is prone to earthquakes [22]. Natural disasters cause many issues for the highly populated city, so the fire stations must be ready when the earthquakes hit and must have the power to perform their critical responsibilities [22]. Three microgrids have been established at three different Fremont fire stations. Initially, only one microgrid was created, as the first one was used as a pilot, so the learnings could be used for the other two microgrids [22]. Each microgrid contains a 40 kW solar canopy and 95 kWh battery energy storage [23]. The microgrids are helping the city meet its climate action plan target. These microgrids are reducing greenhouse gas emissions by approximately 80,000 pounds/year, and approximately $30,000/year of savings are expected for all three fire stations, which is better than what was anticipated. These microgrids have created more jobs for the community as well [22].

2.2.2. Brooklyn Microgrid

The Brooklyn Microgrid (BMG) in New York City is one of the most known and unique microgrids in the United States. The BMG uses solar energy from solar panels on top of buildings that "prosumers" own, and those prosumers can sell the power to the local area "consumers" using a mobile app [24]. The local microgrid creates a more reliable and efficient grid for the communities in the area [24]. Reference [25] notes that the BMG is connected to the traditional grid to balance supply and demand since the microgrid can under- or oversupply the community.

2.2.3. Marine Corps Air Station Miramar Microgrid

The Marine Corps Air Station (MCAS) Miramar Microgrid is located in San Diego, California. The microgrid supports the loading at the air station, but it can support the traditional utility grid as well [26]. Reference [26] notes that during a heat wave, the MCAS Miramar Microgrid was utilized to provide power to the normal grid in nearby regions to ensure that there were fewer rolling blackouts due to the high peak demand from the increased temperatures of that heat wave. The microgrid consists of solar energy, landfill gas, energy storage, and diesel and natural gas-fired power plants [27]. Reference [27] notes that the landfill gas is purchased from a separate power plant through a purchase agreement. All of these components for this microgrid can support the load in the air station, which has hundreds of buildings in island mode for up to 21 days [27].

2.2.4. Kodiak Island Microgrid

Kodiak Island is in Alaska and is now known for its wind turbine renewable energy. Reference [28] describes Alaska as having one of the most expensive energy rates for residential customers. There are six wind turbines that generate 1.5 MW each at their maximum output [29]. In other words, a total of 9 MW can be produced by the microgrid, and it serves approximately 20% of Kodiak Island's annual energy needs [29].

2.2.5. Borrego Springs Microgrid

The Borrego Springs Microgrid is well known. The microgrid is supplied by two local solar farms, additional solar panels on customer rooftops, and batteries [30]. Furthermore, San Diego Gas & Electric (SDG&E) converts the excess and unused solar energy into hydrogen that is stored to use later for up to eight hours [30]. The microgrid is typically not in use or is operating in parallel with the normal grid [31]. The microgrid can be operated on its own to support customers if outages occur in the area [31].

2.2.6. Chattanooga Microgrid

The Chattanooga Microgrid is located in Tennessee and will provide backup power for police and fire services [32]. The microgrid uses both solar panels and diesel generators [33]. The solar panels are on top of police services headquarters [33]. The Chattanooga Microgrid uses the existing well-established smart utility grid and reroutes power when an outage or fault is detected [32]. This "smarter smart grid" makes the grid more reliable and flexible for any unexpected future outage [32].

2.2.7. Bronzeville Microgrid

The Bronzeville Microgrid is a pilot that demonstrated that microgrids can be utilized to support underserved communities [34]. This $25 M microgrid initiative has proven to be a great asset for the Bronzeville community, and it will be a model for future microgrids across the country [35]. The area experienced many catastrophic storms and temperature spikes in the past, for which the microgrid was predicted and has proven to create better resiliency for the community [34,35]. The microgrid can be islanded from the main grid or be grid connected, which ensures that there is support during planned outages, unplanned outages, high temperatures, and other conditions [35,36]. The microgrid consists of natural-gas-fired generators, rooftop solar systems, and battery storage to support a total load of approximately 7 MW [34–36].

2.2.8. Summary of Microgrid Applications

There are microgrids built all around the United States, and more are expected to come in the near and distant future. Microgrids are expected to be a future additional component to every normal utility grid to create better reliability and reduce carbon emissions. Many energy companies are looking at different opportunities and ways to build future microgrids to create a more reliable grid that every customer deserves and needs. Table 2 summarizes the review of key microgrid installations discussed in this manuscript. An "X" in Table 2 indicates that the characteristic described in the column is an attribute of the installation.

Table 2. Summary of key microgrid installations.

Organization	Location	Site	All Renewable Sources	Dynamic Boundaries	Multiple Microgrids	Goal
CEC	Fremont, CA, USA	Fire Stations	X		X	Reliability, ensure fire station has power during emergencies
LO3 Energy	Brooklyn, NY, USA	Remote Community	X	X		Reliaibility, local energy, lower energy costs
SDG&E	San Diego, CA, USA	Marine Corps Air Station Miramar		X		Reliability, ensure operations had power during missions
KEA	Kodiak Island, AK, USA	Remote Community	X		X	Reliability, reduce rates
SDG&E	Borrego Springs, CA, USA	Remote Community	Future			Reliability, fully renewable in future
EPB of Chattanooga	Chattanooga, TN, USA	Airport		X	X	Reliabilty, ensure power during emergencies
Bronzeville Microgrid	Chicago, IL, USA	College Campus and Surrounding Community			X	Reliabilty, clean energy

2.3. State of the Art Summary

Advances in microgrid technology and the promise of improved reliability have led to a great deal of interest in microgrids in both research and application. There is significant variation in the design of these microgrids based on geography, weather patterns, historic reliability issue root causes, energy justice considerations, and many other factors. There are also many models for how to classify microgrids and design them and the overall objective function for the deployments. Furthermore, the potential of microgrids has led to a vision that includes them as a basic building block for the future electrical system. In that vision, advanced controls, communications, and protection would allow microgrids to collaborate and be optimized to best serve customers after a significant weather event results in damage to traditional infrastructure.

For microgrids to move from a promising new technology to regular deployments and basic building blocks for the electrical system, standard approaches are needed; and those standard approaches must be grounded in real-world applications. That is the purpose of the work described in this manuscript.

2.4. Previous Work and New Contributions

This section describes the authors' previous relevant work, how the work described in this document builds on those previous efforts, and the new contributions included in this manuscript.

2.4.1. Previous Work

The work in this manuscript builds on the authors' previous work on load forecasting, stochastic methods, controls and protection, energy justice considerations, and design optimization [14,16,37–41].

2.4.2. Building on Previous Work and New Contributions

The methods presented in this document build on previous work to make the following contributions to the overall body of knowledge.

1. They develop the critical objectives for microgrids and present the practical implementation of microgrid design to meet those objectives.
2. They study the practical experiences of sourcing and sectionalizing placement, black start requirements, and data availability limitations in actual microgrid deployments with the need to serve critical loads while weighing energy equity concerns.
3. They replace predominantly deterministic techniques based on day-ahead time horizons or representative load shapes for the design of stand-alone and collaborative microgrids with time-efficient probabilistic practices based on load forecasts for months into the future.
4. They consider the practical reality of areas with low DER penetration being adjacent to areas with high DER penetration. Considering this experience from actual microgrid deployments in the optimization methods offers the opportunity to improve the reliability of low DER penetration areas, which can also be lower income level areas.
5. The use of the methods is presented with actual real-world deployments of two sets of adaptive networked microgrids.

3. Microgrid Objectives

The installation of microgrids can serve a range of possible objectives. While initially implemented primarily to provide power in remote areas without grid connection, microgrid technology increasingly serves a range of other purposes, from local grid decarbonization to grid resiliency purposes, and often a combination of both [42].

This paper is particularly focused on microgrids embedded in the traditional distribution system, where the existing distribution grid (owned and operated by an electric utility) forms the backbone infrastructure for the development of new, networked microgrids. Leveraging existing utility-owned infrastructure is arguably the cheapest way to make microgrid technology available to a large number of customers and presents an opportunity for microgrids to enhance the already high reliability benefits customers receive from the traditional system. The development of such microgrids requires the involvement of the utility in the design and operation of the microgrid and associated energy resources, including siting and installation of microgrid-enabling technologies, such as grid-forming DERs, control systems, and devices, including new sectionalizing devices or grid capacity upgrades. These assets can be supplemented by community solar and customer-sited, utility-owned resources to allow the local community more ownership and control of the microgrid development, thus promoting fruitful collaborations between the utility and its customers.

In developing the microgrid, the first step should be to decide what the overall objective of the development is, and that objective development should consider the criticality of the load to be served by the microgrid for the community. For example, utilities must consider the impact of pumping stations, hospitals, police stations, and fire stations to provide critical services to the community. Some examples of objectives include the following:

- Reduce outage times and frequency: A utility may initiate microgrid development to reduce outage frequency and outage times in a certain area without the need to build or reinforce lines. With the capacity to operate in islanded mode, communities (or parts of communities) that are served by infrastructure that is susceptible to weather events, such as part of a feeder with long lines through wooded areas, can avoid power outages.
- Improve resiliency: A utility may initiate microgrid development to improve resiliency of a feeder during extreme weather events. With the capacity to operate in islanded mode, it can be quicker and easier to restore power to all or some of the community in the case of significant impact, e.g., storms, flooding, or fires, that otherwise may cause prolonged outages.
- Improve power quality: A utility may initiate microgrid development to improve local power quality. Through proper resource placement and additional control capabilities with microgrid development, a utility can actively utilize local resources to manage power quality issues, such as low or high voltage magnitudes or voltage imbalance.
- Increase DER hosting capacity and promote local DER build-out: A utility may initiate microgrid development to increase DER hosting capacity. The same control capabilities that enable improved power quality can also be leveraged to support larger populations of DERs in the feeder. Over time, this can spur DER build-out by local customers, thus further improving the ability of the feeder to operate in islanded mode.
- Meet local demand for renewable energy: Many local communities desire to be served by primarily renewable energy. By coupling microgrid development with community solar or other forms of community-owned and/or customer-sited resources, the utility can partner with the community on achieving their local goals.

In a microgrid, there may at times be too little energy available to serve all customers. It is therefore important to consider not only the overall benefits and costs of installing the microgrid but also which customers receive those benefits and shoulder the cost of deployment. For example, in a post-storm grid restoration setting, the presence of DERs and how they are operated (i.e., whether they serve their specific customer's location or are integrated in a local microgrid) will impact which customer groups experience the longest power outages [43]. This may be compounded by other effects, such as socio-economic status and vulnerability of different customer groups. For example, customers who rely on power for medical purposes may need to leave their homes sooner than other residents, leading to a spike in hospital admissions [44–47]. Similarly, residents in areas of high socio-economic status are typically better positioned to cope with the consequences of power outages (consider how more resourced customers sought out hotels during the power outages following Winter Storm Uri in Texas), while residents of lower socio-economic status may struggle with additional expenses related to alternative shelter and the cost of restocking their refrigerator once the power outage ends.

To incorporate such considerations in microgrid design and operation, researchers have suggested prioritizing serving electricity to both commonly considered critical loads, such as emergency responders or community centers that provide services to residents during power outages [48,49] and areas with higher social vulnerability and less ability to cope with the consequence of power outages [16]. This aligns with the Justice40 initiative, which requires 40% of federal spending to flow to disadvantaged communities (DACs). However, a challenge with the data on social vulnerability and disadvantaged communities is low spatial granularity. Values are typically aggregated to the census tract level, although there may be significant variability within an individual census tract. Some more granular information is available on a nationwide scale, including the area deprivation index (ADI), which is available on the scale of census block groups (much smaller units than census tracts) [50,51]. An even better option for utilities may be to work directly with the information they have about their customers and their vulnerabilities, including information regarding which customers are on energy assistance programs or on programs for medically vulnerable customers, though privacy considerations may preclude use of such data under certain circumstances.

4. Engineering Microgrids

Engineering microgrids involves intricate planning to integrate various renewable energy sources, energy storage systems, and control mechanisms to ensure reliable, efficient, and resilient power distribution within a localized area. It requires expertise in electrical engineering, power systems, control theory, and renewable energy technologies to design, optimize, and maintain microgrid systems tailored to specific community or industrial needs.

This section describes important considerations while engineering microgrids. These includes studying the efficient placement of sectionalizers and DERs to get the optimum benefit of dynamic microgrids.

4.1. Data Availability

Data availability for microgrid and DER placement can vary depending on factors like geographic location, infrastructure, and regulatory environment. Typically, the engineer needs data on energy consumption patterns, existing power infrastructure, renewable energy potential, demographics, and land availability. Tools like Geographic Information System (GIS) software and machine learning algorithms can help analyze and model this data for optimal microgrid placement. In particular, environmental justice evaluation of rural and urban areas is conducted to identify populations facing and/or vulnerable to environmental and energy burden and will help select areas with valuable data. This information is more area-based instead of individual circuit-based data. Another important consideration is the placement of medical customers and prioritizing those areas. A challenge faced by utilities, however, is in gathering data about social vulnerability and disadvantaged communities, which is currently a small amount of individual pieces of information. In order to get the best data in such a situation, it would be best for the utility to use the available customer data in its databases. As data availability evolves, this may change, but currently, it is best that vulnerability be considered based on specific information like critical loads and customers on energy assistance programs.

4.2. Sectionalizing and DER

The placement of sectionalizing devices and DERs are key aspects of microgrid design. This section describes key considerations for this determination.

4.2.1. Sectionalizing Placement

Sectionalizing helps with the installation of microgrids on distribution circuits by allowing for easier management and control of power distribution. By dividing the circuit into sections, it becomes simpler to isolate and troubleshoot any issues that may arise, ensuring the stability and reliability of the microgrid system. Additionally, sectionalizing can improve system flexibility, allowing for more efficient integration of renewable energy sources and localized power generation within the microgrid.

Sectionalizing aids microgrids with dynamic boundaries by providing flexibility in configurations. With dynamic boundaries, the microgrid's layout and connection points may shift due to various factors like demand fluctuations or renewable energy availability. Sectionalizing allows for easy reconfiguration of the microgrid, ensuring optimal distribution of power and maintaining system stability as the boundaries evolve. It enables swift isolation of problematic sections and facilitates seamless integration of new energy sources or loads within the microgrid, efficiently adapting to evolving requirements.

Several types of sectionalizing devices can be used for microgrid installations, including the following:

1. Reclosers: These devices automatically interrupt and restore power in response to faults, allowing for quick isolation of affected sections and restoration of unaffected areas.
2. Remote-controlled switches: These switches are not automated but can be operated remotely, allowing for efficient reconfiguration of the microgrid layout without manual intervention in the field.
3. Manual switches: These manual switches are placed strategically along the circuit to isolate specific sections, enabling targeted maintenance or fault isolation. The isolation and operation of these switches require crews to make the change in the field.
4. Fault indicators: These devices provide visual or remote indication of faults along the circuit, helping operators in the field to quickly locate and address issues.

Practical Considerations

By deploying a combination of these devices, microgrid operators can effectively manage and control power distribution, ensuring reliable operation and improving power quality issues and rapid response to changing conditions. Below are the practical considerations for the placement of the sectionalizers:

- Load distribution: Sectionalizers should be strategically placed to ensure balanced load distribution across the circuit to reduce the outage timing and frequency, optimize efficiency, and minimize overloads.
- Improve reliability and power quality: Sectionalizers should be placed at locations that improve the power quality of the area by localizing and isolating faults on distribution lines. By strategically locating sectionalizers, utilities can minimize the impact of faults, reduce outage durations, and enhance system reliability. This proactive approach aids in maintaining consistent voltage levels, reducing momentary interruptions, and improving overall power quality for consumers. For this guideline, it is critical that engineers understand the location of faults and the probability that those faults are to occur.
- Accessibility: Ensure that sectionalizers are easily accessible for maintenance and troubleshooting purposes. They should be placed in locations that are truck accessible and near major intersections as much as possible.
- Sectionalizer locations: Poles with little to no other equipment installed should be selected or placed to allow for the installation of sectionalizers.
- Easements: Locations for sectionalizers should be selected with consideration for the ability to obtain easements from customers.

Customer-Focused Considerations

As described in Section 3, the criticality of the load for the community should be considered for microgrids to be most beneficial. This includes deploying a combination of sectionalizers that are critical customer-focused, such as focused on medical customers and critical loads. Below are the customer-focused considerations:

- Medical customers: Placement of sectionalizers on an electric circuit with medical customers, such as hospitals, clinics, and medical facilities, should be selected to ensure uninterrupted and reliable supply of electricity, which is essential for patient care and safety.
- Critical loads: sectionalizers should be placed on the circuit to provide reliable service to critical loads such as government buildings, pumping stations, police stations, and fire stations.
- Energy assistance: customers on energy assistance programs could be given preference considering the potentially disproportionate impact of outages on these customers.
- Fault detection: sectionalizers should be located at points that consider where faults are most probable to occur, such as areas prone to equipment failure or tree hazards.
- Aesthetics: Aesthetics considerations for placing sectionalizers on an electric circuit involve ensuring that these devices blend harmoniously with their surroundings and do not detract from the visual appeal of the environment.
- Boundary balance of load: The sectionalized load should be able to be served by the contained DERs.

4.2.2. DER Placement

This section describes some of the key aspects to consider for DER placement. Section 4.3 describes the sizing of these components.

- Installed DERs: Including forecasted DER (e.g., customer installation of solar panels, wind turbines, or other DERs) in areas with ample renewable energy potential to maximize generation output.
- Available property to install DERs: Research to find the property that would fit the need for the required DER.
- Community engagement: Engage with local communities, stakeholders, and customers to solicit input and address concerns regarding DER placement.
- Load profile: Analyze the load profile of the electric circuit to identify areas with high energy demand or potential for load balancing. Place DERs strategically in locations where they can effectively offset peak demand or provide ancillary services to improve grid stability.
- Promote local DERs: Considering the benefits of microgrids, promoting the installation of DERs at customer sites to eventually help other sections of the circuit can be considered.
- Fault location: The DERs must be placed considering the probability of faults occurring. For example, a centralized DER will not support areas with frequent service drop issues.

4.3. Optimizing Renewable Generation to Serve Load

Using the Monte Carlo simulations from [40,41] to design stand-alone and collaborative microgrids has the potential to reduce their costs while maximizing their benefits. For that reason, engineering analysis was completed with stochastic principles to design stand-alone microgrids and collaborative microgrids that are currently being deployed.

4.3.1. Stand-Alone Microgrids

Stand-alone microgrids will be the first microgrid problem for which stochastic analysis will be explored, specifically optimizing the cost and performance of actual microgrids that are initially being deployed as stand-alone microgrids.

Stand-Alone Microgrid Configuration

As shown in Figure 3, the stand-alone microgrid for this optimization formulation can be operated as grid connected or grid isolated. It is also being installed with only renewable sources, specifically solar and storage.

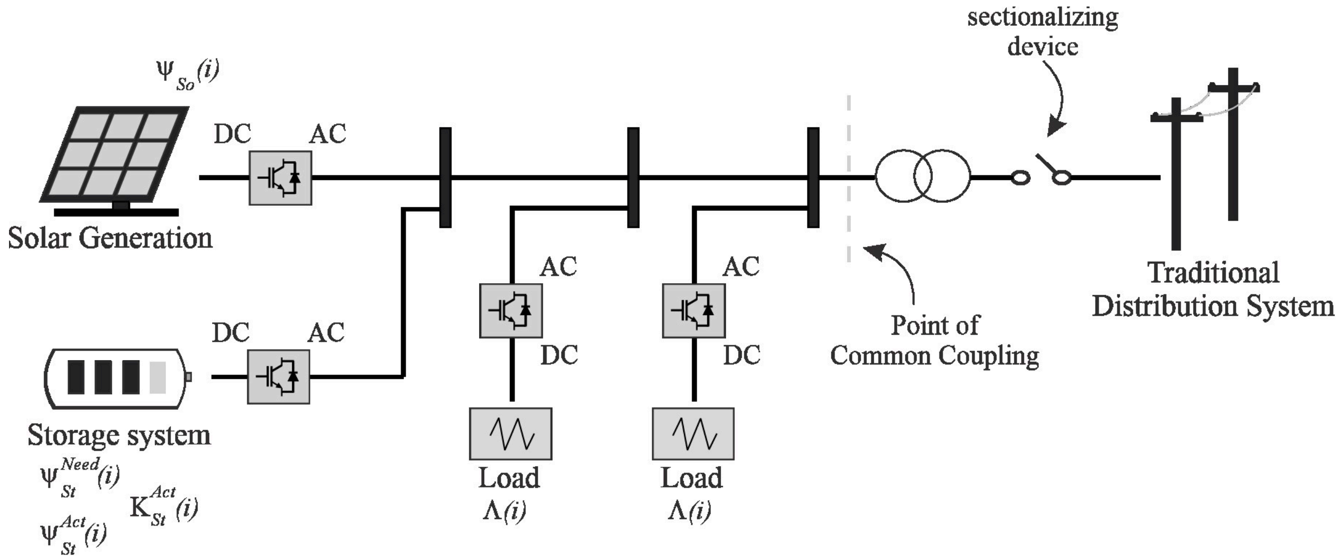


Figure 3. The composition of stand-alone microgrids.

Stand-Alone Microgrid Optimization Formulation

This work builds on the Monte Carlo simulations for Area 2 in [40,41]. This includes 1000 simulations per day for a 152-day forecasting period to provide 152,000 scenarios, each consisting of one day with 24 hourly load values for each transformer in the area.

Approximately 80 of the transformers in the feeder have been selected for a microgrid deployment based on the criticality of the load for the community being served. This microgrid will be referred to as Microgrid A. The load is next aggregated for the transformers included in Microgrid A for each of the 152,000 scenarios. This provides the load data needed for the optimization problem and is referred to as Λ in Equation (1).

A regression model is created next using the actual historical output of a comparable solar array with a historical measure of solar irradiance. The solar array and solar data source are both near the area for the microgrid deployments that are the subject of this study. The parameter ψ in Equation (1) is the result of the regression analysis with the Monte Carlo-derived solar irradiance data as input. This value describes the available solar power as a ratio of the installed capacity. It provides a ratio that can be scaled up or down based on the size of the solar deployment. Again, there are 152,000 scenarios for ψ, each consisting of one day with 24 hourly values.

The total load, Λ, and the available solar, ψ, in Equation (1) provide the input needed for the optimization. The load, Λ, is included in kW, and the available solar, ψ, is a unitless ratio to which the maximum output of a solar array in the units of kW will be applied. The indexing variable i is used to iterate through the hours of a day that comprise a scenario.

$$\begin{gathered} \Lambda(i) \in \mathbb{R} \\ \psi(i) \in \mathbb{R},\ 0 \leq \psi(i) \leq 1 \\ i \in \mathbb{W},\ 0 \leq i \leq 23 \end{gathered} \tag{1}$$

The output variables for the optimization are shown in Equation (2), which defines the design space for the problem. The parameter Ψ_{So}^{Max} represents the maximum available power output of the solar deployment in kW, and K_{St}^{Max} represents the maximum energy storage capacity in kWh of the battery not considering the depth of discharge limitations.

$$\begin{aligned} \Psi_{So}^{Max} &\in \mathbb{W} \\ K_{St}^{Max} &\in \mathbb{W} \end{aligned} \quad (2)$$

The objective of the optimization is to minimize the cost and the number of scenarios that cannot be fully served by the microgrid. Equation (3) defines the objective space for the problem. The modeled market price for the community solar scale deployments from [52] provides the cost for solar as \$1761/kW_{DC} and the cost of storage as \$492/kWh (rounded to \$500/kWh for the remainder of this analysis). As described in [53], inverter efficiency ranges from 95% to 98%. Using 95%, the cost of solar is \$1854/kW_{AC} (rounded to \$1900/kW_{AC} for the remainder of this analysis).

$$\begin{gathered} E \equiv Installation\ Expeditures \\ E = \left(\frac{\$1900}{\text{kW}}\right) \times \Psi_{So}^{Max} + \left(\frac{\$500}{\text{kWh}}\right) \times K_{St}^{Max} \\ N \equiv Percent\ of\ Scenarios\ Not\ Fully\ Served \end{gathered} \quad (3)$$

There are several intermediate variables required for the optimization calculations. They are shown in Equation (4). $\Psi_{So}(i)$ is the scaled-up output of the solar regression model in kW. $\Psi_{St}^{Need}(i)$ is in kW, and it describes the power required from the storage to meet the load offset by the solar output at time period i. Considering the equipment limitations, $\Psi_{St}^{Act}(i)$ describes the available power (kW) from the storage at time period i, and $K_{St}^{Act}(i)$ describes the available energy from the storage at time period i.

$$\begin{gathered} \Psi_{So}(i) \ \in \ \mathbb{R} \\ \Psi_{St}^{Need}(i) \in \mathbb{R} \\ \Psi_{St}^{Act}(i) \in \mathbb{R} \\ K_{St}^{Act}(i) \in \mathbb{R} \\ i \in \mathbb{W},\ 0 \le i \le 23 \end{gathered} \quad (4)$$

The problem constraints based on the equipment limitations are provided by Equation (5). As described in [53–57], battery degradation is a function of depth of discharge. The operating range for the storage in this problem was chosen as [15%, 85%] based on depth of discharge limitations, and the maximum output and charging capability of the battery was selected as 25% of the capacity rating ($E/4$).

$$\begin{gathered} K_{St}^{Act}(i) \ \ge \ 0.15 \times K_{St}^{Max} \\ K_{St}^{Act}(i) \ \le \ 0.85 \times K_{St}^{Max} \\ \Psi_{St}^{Act}(i) \ \le \ 0.25 \times K_{St}^{Max} \\ \Psi_{St}^{Act}(i) \ \ge -0.25 \times K_{St}^{Max} \\ i \in \mathbb{W},\ 0 \le i \le 23 \end{gathered} \quad (5)$$

There are several equalities needed for the hour-by-hour determination, as shown in Equation (6).

$$\begin{gathered} \Psi_{St}^{Need}(i) = \Lambda(i) - \Psi_{So}(i) \\ \Psi_{So}(i) = \Psi_{So}^{Max} \times \psi(i) \\ K_{St}^{Act}(0) = 0.85 \times K_{St}^{Max} \\ \lambda(i-1) = \begin{cases} -0.25 \times K_{St}^{Max} & if \quad \lambda(i-1) < -0.25 \times K_{St}^{Max} \\ \Lambda(i-1) - \Psi_{So}(i-1) & otherwise \\ 0.25 \times K_{St}^{Max} & if \quad \lambda(i-1) > 0.25 \times K_{St}^{Max} \end{cases} \\ K_{St}^{Act}(i) = \begin{cases} 0.15 \times K_{St}^{Max} & if \quad K_{St}^{Act}(i) < 0.15 \times K_{St}^{Max} \\ K_{St}^{Act}(i-1) - \lambda(i-1) & otherwise \\ 0.85 \times K_{St}^{Max}(i) & if \quad K_{St}^{Act}(i) > 0.85 \times K_{St}^{Max} \end{cases} \\ i \in \mathbb{W},\ 0 \le i \le 23 \end{gathered} \quad (6)$$

Whether a design can fully meet or fails to meet a scenario depends on the storage's ability to satisfy the load minus the solar contribution. This has a power demand component and an energy component. Each of these must be satisfied for every hour of the day for the design to fully satisfy the scenario. If the criterion shown in Equation (7) for available storage power or the criterion shown in Equation (8) for available storage energy is met for any hour of the day in a scenario, that design is established as a failure for that scenario. It should be noted that solar output can be curtailed, so tests for charging too quickly and overcharging are not needed.

$$\begin{gathered} \Psi_{St}^{Need}(i) \ \geq \ 0.25 \times K_{St}^{Max} \\ i \in \mathbb{W}, \ 0 \leq i \leq 23 \end{gathered} \tag{7}$$

$$\begin{gathered} \Psi_{St}^{Need}(i) \ \geq \ K_{St}^{Act}(i) - 0.15 \times K_{St}^{Max} \\ i \in \mathbb{W}, \ 0 \leq i \leq 23 \end{gathered} \tag{8}$$

Stand-Alone Microgrid Optimization Results

The optimization described in Section "Stand-Alone Microgrid Optimization Formulation" was run using the Non-Dominated Sorting Genetic Algorithm (NSGA-II), which is described in references [58–60] with all 152,000 scenarios. This generated the Pareto front with 100 points shown in Figure 4 in approximately one hour and two minutes after 50 iterations.

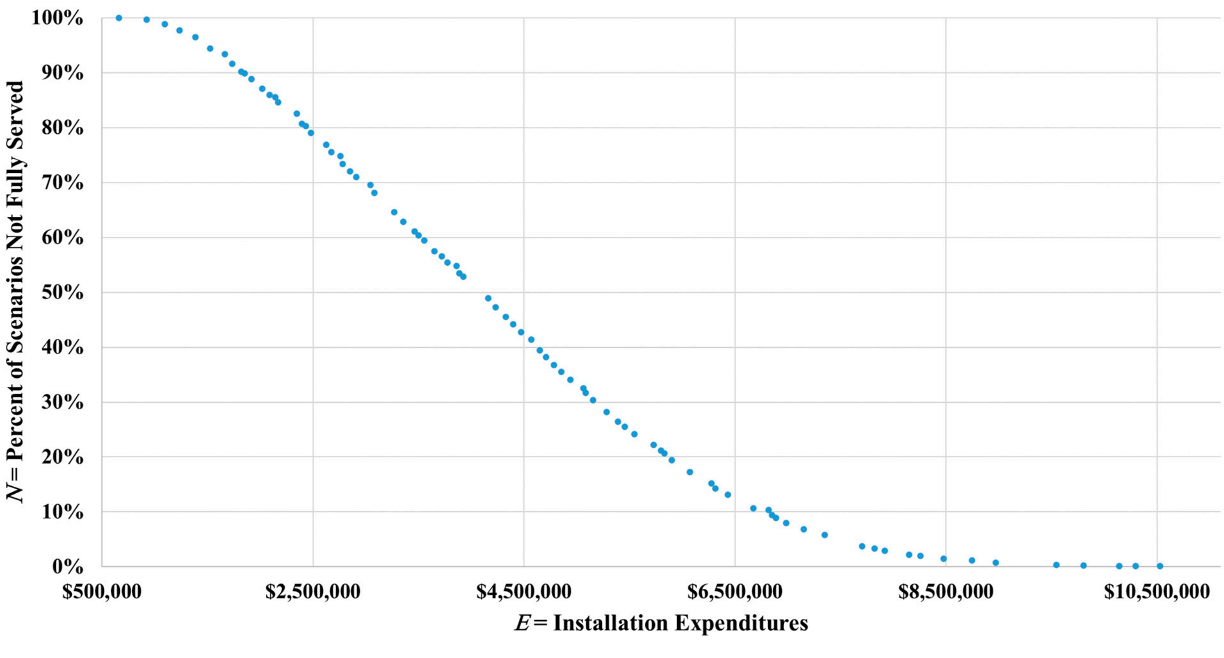


Figure 4. The Pareto front for Microgrid A using all 152,000 scenarios and the CPU.

Because a scalable solution that could run on centralized computing elements and grid-edge devices is desired, since engineering analysis is more efficient with a reduced time to develop the Pareto front, and due to the need to complete frequent studies with uncertain customer adoptions of new technologies; several experiments were run to determine more time-efficient methods that did not sacrifice accuracy. Some of the key areas of focus for the experiments included sampling methods from the comprehensive scenarios, number of iterations for the algorithm to run, number of points on the Pareto front, the need for a final assessment with all 152,000 scenarios, and CPU versus GPU usage. Figure 5 shows the results of those experiments. The learnings from the experiments include that GPU usage greatly reduces the processing time, designing based on peak load scenarios does not produce accurate results, and designing based on randomly selected scenarios does produce accurate results.

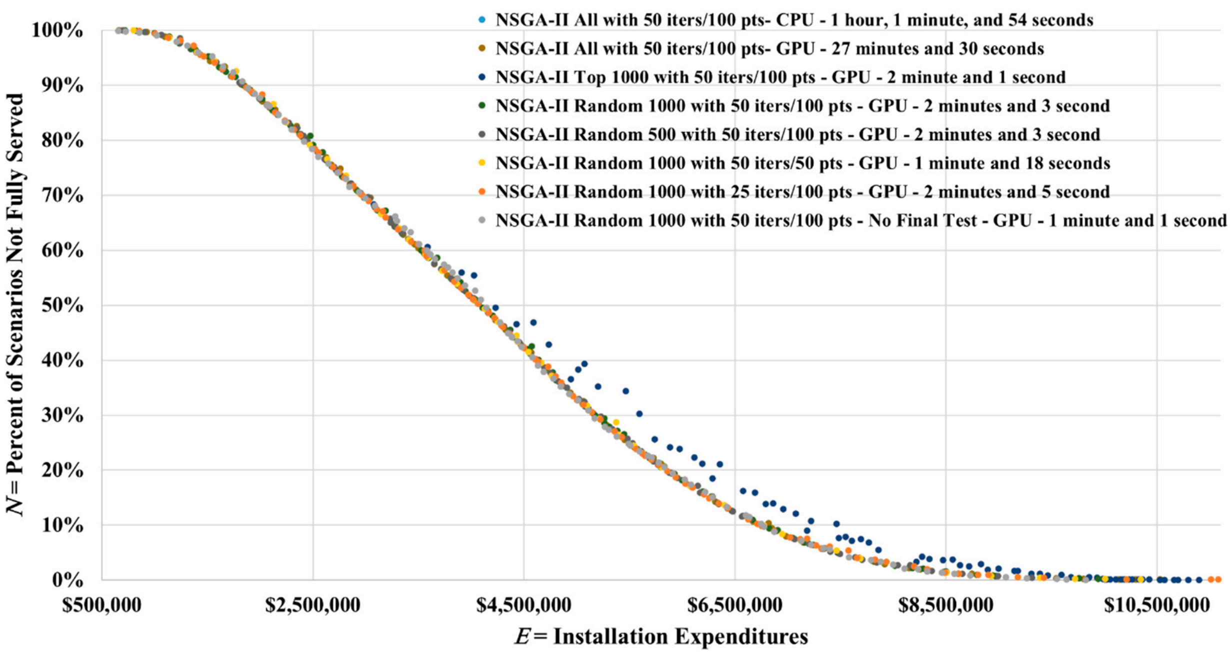


Figure 5. The Pareto fronts for Microgrid A created with different methods.

Based on a review of the results of the experiments, NSGA-II with 1000 randomly selected scenarios, 100 points, 50 iterations, and using GPU resources was selected as the best balance between accuracy and time to generate the Pareto front. It required approximately two minutes to run, which included time for a final assessment of all 100 design points on the Pareto front for all 152,000 scenarios.

Figure 6 shows a comparison between the initial approach and the revised approach. It shows that the Pareto fronts are nearly identical with a 97% reduction in time.

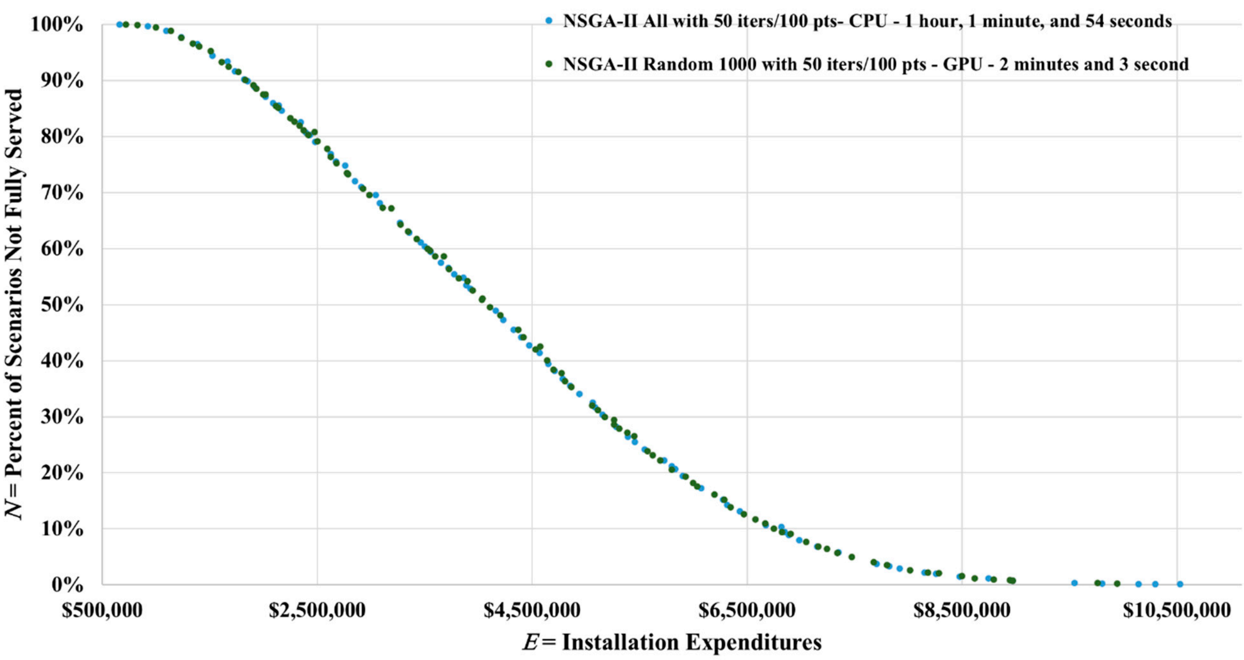


Figure 6. A comparison of the Pareto fronts for Microgrid A based on all scenarios and the revised approach.

As shown in Figure 7, the design point in the objective space can be determined based on the specific situation and criticality of the load in the microgrid. The point at which marginal costs start to increase for improvements in *N* (point of diminishing returns) should be considered and was selected as the design point for the remainder of this analysis. The blue dashed line in Figure 7 and similar figures is drawn to be approximately parallel to the linear portion of the curve. It is included to help highlight the point of diminishing returns.

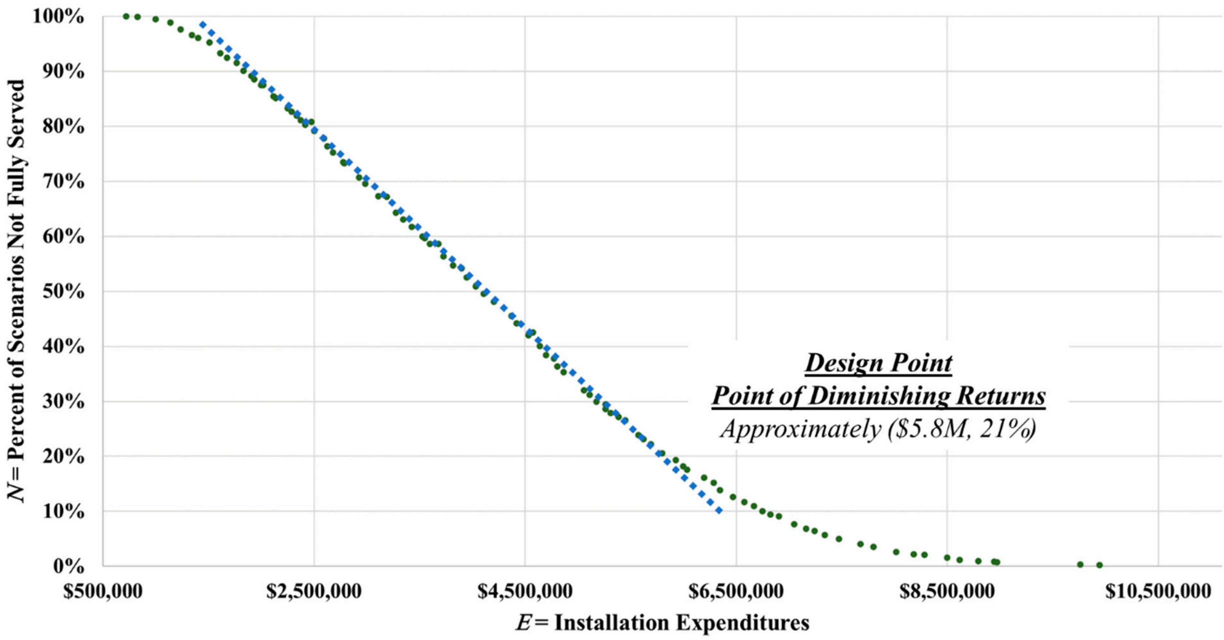


Figure 7. The design point for Microgrid A.

The optimization method was applied to a second smaller microgrid on the same circuit that is also being deployed to serve critical loads for the community. This microgrid will be referred to as Microgrid B. As shown in Figure 8, it also had a point of diminishing returns, which was again selected as the design point for this analysis.

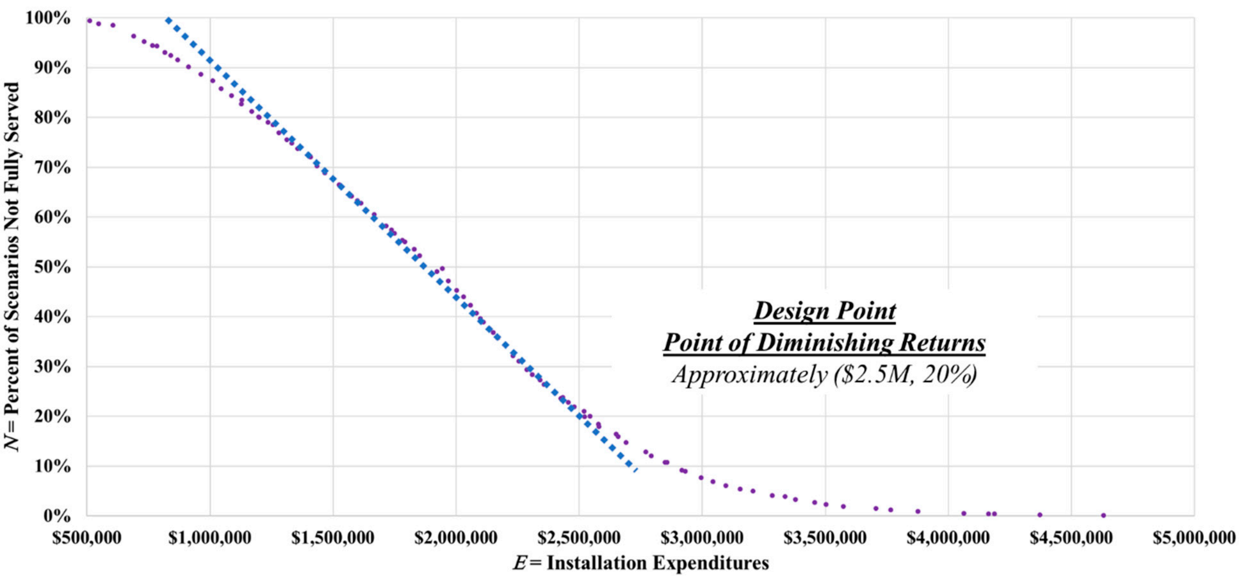


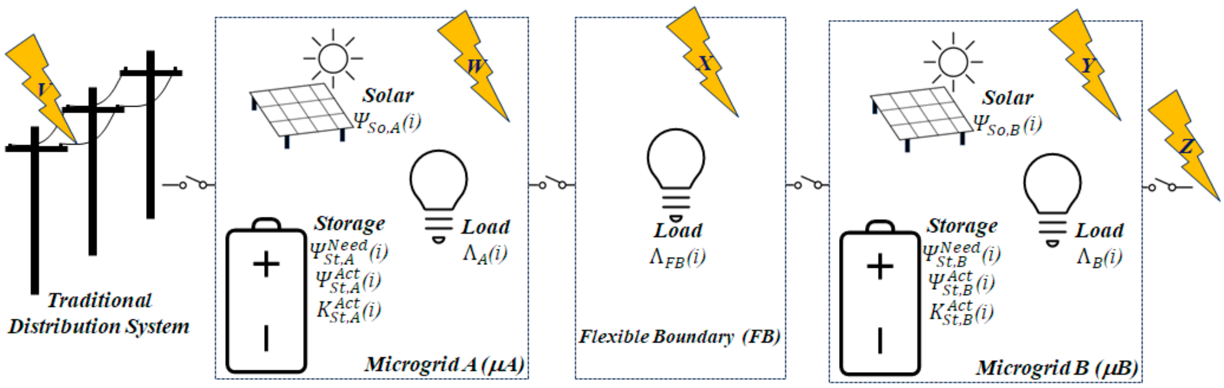
Figure 8. The design point for Microgrid B.

4.3.2. Networked Microgrids

In contrast to stand-alone microgrids; [15] describes networked, collaborative, nested, or adaptive networked microgrids as having multiple interface points with boundaries that can change and being adjacent to other microgrids with which collaborative solutions can be found. With the framework of stand-alone microgrids established, stochastic methods for networked microgrids can be developed.

Networked Microgrids Configuration

As shown in Figure 9, the networked microgrids configuration for this optimization formulation consists of two microgrids that can be operated grid connected or grid isolated. They are installed on the same distribution circuit and are separated by a flexible boundary. The flexible boundary is a practical reality of deploying microgrids and is the result of the fact that microgrids can only be installed where there is a significant presence of DER. Areas with high DER penetration can be a result of the included customers having higher disposable income levels and/or the presence of critical loads, such as hospitals or pumping stations, that will necessitate customer- or utility-owned DER deployments to serve the area in a microgrid. Flexible boundaries exist when there is low DER penetration or an absence of critical loads between areas with microgrids. Figure 9 models the actual deployments being used as the microgrid case studies in this document, which are more completely illustrated in Section 4.6.



Number of Transformers	µA	FB	µB
	80	50	66

Figure 9. The composition of the networked microgrids.

Again, these microgrids are being installed with only renewable sources and use the same modeled market price for the community solar scale deployments as described in the stand-alone microgrid formulation. The same solar regression model and battery limitations are also used in this case.

In Figure 9, the locations of faults have been labeled with V, W, X, Y, and Z, and these labels will be used to describe fault combinations in this section. The combinations of the faults V, W, X, Y, and Z in Figure 9 will result in additional combinations of the 152,000 scenarios to be optimized because they result in different collaborations between the microgrids, as shown in Table 3. In Table 3, 0 indicates that the fault has not occurred, and 1 indicates that the fault has occurred. Microgrid operation is highlighted by the bold lines and shows that there are nine combinations of the original 152,000 scenarios that have been developed for the operation of the microgrids based on fault location.

The microgrids will collaborate if they can serve their load and support other areas. If the collaboration does not allow the microgrid to serve its own load, it will not collaborate. This is illustrated in Tables 4–6. In Tables 4–6, a 0 indicates that the design does not fail the scenario, and 1 indicates that the design did fail the scenario.

Table 3. Microgrid collaborations that result from fault combinations. Bold and italic text highlights microgrid operation.

V	*W*	*X*	*Y*	*μA*	*FB*	*μB*
0	0	0	0	Grid Connected	Grid Connected	Grid Connected
0	0	0	1	Grid Connected	Grid Connected	No Service
0	***0***	***1***	***0***	Grid Connected	No Service	***Serving Itself***
0	0	1	1	Grid Connected	No Service	No Service
0	***1***	***0***	***0***	No Service	***Potential Service from B***	***Serve Itself and FB***
0	1	0	1	No Service	No Service	No Service
0	***1***	***1***	***0***	No Service	No Service	***Serve Itself***
0	1	1	1	No Service	No Service	No Service
1	***0***	***0***	***0***	***Serve Itself, FB, and B***	***Potential Service from A and B***	***Serve Itself, FB, and A***
1	***0***	***0***	***1***	***Serve Itself and FB***	***Potential Service from A***	No Service
1	***0***	***1***	***0***	***Serve Itself***	No Service	***Serve Itself***
1	***0***	***1***	***1***	***Serve Itself***	No Service	No Service
1	***1***	***0***	***0***	No Service	***Potential Service from B***	***Serve Itself and FB***
1	1	0	1	No Service	No Service	No Service
1	***1***	***1***	***0***	No Service	No Service	***Serve Itself***
1	1	1	1	No Service	No Service	No Service

Table 4. Collaboration logic for Microgrid A, Microgrid B, and the flexible boundary.

Individual Results			**Combined Results**		
μA_o = μA Alone	**μB_o = μB Alone**	**μT = μA, μB, and FB**	**μA_f = Collaborative Result for μA = μA_o and μT**	**μB_f = Collaborative Result for μB = μB_o and μT**	**FB For Fault = μT**
0	0	0	0	0	0
0	0	1	0	0	1
0	1	0	0	0	0
0	1	1	0	1	1
1	0	0	0	0	0
1	0	1	1	0	1
1	1	0	0	0	0
1	1	1	1	1	1

Table 5. Collaboration logic for Microgrid A and the flexible boundary.

Individual Results		**Combined Results**	
μA_o Alone	**μAFB = μA and FB Together**	**μA_f = Collaborative Result for μA = μA_o**	**FB = μA_o and μAFB**
0	0	0	0
0	1	0	1
1	1	1	1

Table 6. Collaboration logic for Microgrid B and the flexible boundary.

Individual Results		**Combined Results**	
μB_o Alone	**μBFB = μB and FB Together**	**μB_f = Collaborative Result for μB = μB_o**	**FB = μB_o and μBFB**
0	0	0	0
0	1	0	1
1	1	1	1

Networked Microgrids Collaboration Formulation

The stand-alone microgrid formulation remains useful for the case of networked microgrids with some substitutions and reconsideration for the failed scenarios metrics (N).

The definitions shown in Equation (9) will be used for the percentage of scenarios not fully served measures going forward.

$$\begin{array}{c} N_A \equiv Percent\ of\ Scenarios\ Not\ Fully\ Served\ by\ Microgrid\ A \\ N_B \equiv Percent\ of\ Scenarios\ Not\ Fully\ Served\ by\ Microgrid\ B \\ N_{FB} \equiv Percent\ of\ Scenarios\ Not\ Fully\ Served\ by\ Microgrid\ FB \end{array} \quad (9)$$

For the case of Microgrid A, Microgrid B and the flexible boundary combining, the substitutions in Equation (10) are useful.

$$\begin{array}{c} \Lambda(i) = \Lambda_A(i) + \Lambda_B(i) + \Lambda_{FB}(i) \\ \psi(i) = \psi(i) \\ \Psi_{So}^{Max} = \Psi_{So,A}^{Max} + \Psi_{So,B}^{Max} \\ K_{St}^{Max} = K_{St,A}^{Max} + K_{St,B}^{Max} \end{array} \quad (10)$$

For the case of Microgrid A and the flexible boundary combining, the substitutions in Equation (11) are useful.

$$\begin{array}{c} \Lambda(i) = \Lambda_A(i) + \Lambda_{FB}(i) \\ \psi(i) = \psi(i) \\ \Psi_{So}^{Max} = \Psi_{So,A}^{Max} \\ K_{St}^{Max} = K_{St,A}^{Max} \end{array} \quad (11)$$

For the case of Microgrid B and the flexible boundary combining, the substitutions in Equation (12) are useful.

$$\begin{array}{c} \Lambda(i) = \Lambda_B(i) + \Lambda_{FB}(i) \\ \psi(i) = \psi(i) \\ \Psi_{So}^{Max} = \Psi_{So,B}^{Max} \\ K_{St}^{Max} = K_{St,B}^{Max} \end{array} \quad (12)$$

The failed scenarios measures are determining the percentage of scenarios that cannot be fully served if the microgrid or flexible boundary needs service from a source other than the traditional distribution system. This only occurs if there are faults on the circuit, so only cases with faults need to be considered (i.e., the universe for the failed scenario measures only includes cases with faults). Because the probabilities of fault combinations are not the same, the failed scenarios measures need to be modified considering the fault combinations. Equation (13) provides the probabilities for the number of primary faults on a circuit given that there are faults on the circuit. In this section, *Prob*(*Event A*) will indicate the probability of Event A occurring, and *Prob*(*Event A* | *Event B*) will indicate the probability of Event A occurring given that Event B has occurred. From Equation (13), if a fault occurs on a circuit, it is much more probable that it is a single fault, and the contribution to *N* should be weighted accordingly.

$$\begin{array}{c} Prob(1\ fault|faults) = 0.83, \\ Prob(2\ faults|faults) = 0.12, \\ Prob(3\ faults|faults) = 0.03, \\ Prob(4\ faults|faults) = 0.01,\ and \\ Prob(\geq 5\ faults|faults) = 0.01 \end{array} \quad (13)$$

With these data and assuming that all faults are equally probable, the probabilities for different fault combinations can be determined using Equation (14). Equation (14) follows from the fact that the number of unique combinations of α items being placed into ρ bins is $\frac{\alpha!}{\rho!(\alpha-\rho)!}$. For example, a combination of two faults from the five provides the following ten qualifying sets: VW, VX, VY, VZ, WX, WY, WZ, XY, XZ, and YZ. Using $\frac{\alpha!}{\rho!(\alpha-\rho)!} = \frac{5!}{2!(5-2)!} = 10$ provides the same value, and the probability of any set of faults given that two faults have occurred is $1/10$.

$$Prob(fault\ mix|\rho\ faults) = \frac{1}{\binom{5}{\rho}}$$
$$with \binom{5}{\rho} = \frac{5!}{\rho!(5-\rho)!}\ for\ the\ identified\ faults\ (V,\ W,\ X,\ Y,\ and\ Z). \quad (14)$$

Equations (13) and (14) can be combined using conditional probability calculations to provide Equation (15). In Equation (15), $Prob(\mu G\ needed)$ is the probability that the microgrid is needed given that there are events on the circuit, and it is determined by summing the probabilities of the event combinations that lead to the microgrid being needed, as described in Table 3.

$$Prob(fault\ mix \wedge \rho\ faults) = Prob(fault\ mix|\rho\ faults) \times Prob(\rho\ faults)$$
$$Prob(fault\ mix \wedge \rho\ faults|\mu G\ needed) = \frac{Prob(fault\ mix \wedge \rho\ faults)}{Prob(\mu G\ needed)} \quad (15)$$

Applying Equations (13)–(15) to the nine combinations of faults results in Equation (16). Equation (16) weighs the contributions of the fault combinations to N by how probable those fault combinations are to occur.

$$N_A = 0.86 \times N_{A,V} + 0.06 \times N_{A,VY} + 0.06 \times N_{A,VX} + 0.02 \times N_{A,VXY}$$
$$N_{FB} = 0.47 \times N_{FB,W} + 0.47 \times N_{FB,V} + 0.03 \times N_{FB,VY} + 0.03 \times N_{FB,VW} \quad (16)$$
$$N_B = 0.31 \times N_{B,X} + 0.31 \times N_{B,W} + 0.02 \times N_{B,WX} + 0.31 \times N_{B,V} + 0.02 \times N_{B,VX} + 0.02 \times N_{B,VW} + 0.01 \times N_{B,VWX}$$

Stand-Alone Microgrid Design Performance with Collaboration

Figures 10–12 show the results of collaboration between the microgrids with comparable stand-alone designs of their counterparts (i.e., Microgrid A collaborating with a similarly performing Microgrid B, and Microgrid B collaborating with a similarly performing Microgrid A). Collaboration improves the performance from $N_A = 21\%$, $N_B = 20\%$, and $N_{FB} = 100\%$ to $N_A = 18\%$, $N_B = 18\%$, and $N_{FB} = 60\%$, respectively, while maintaining the cost at approximately \$8.3 M and with 85% of the total solar output and 66% of the total storage capacity in Microgrid A.

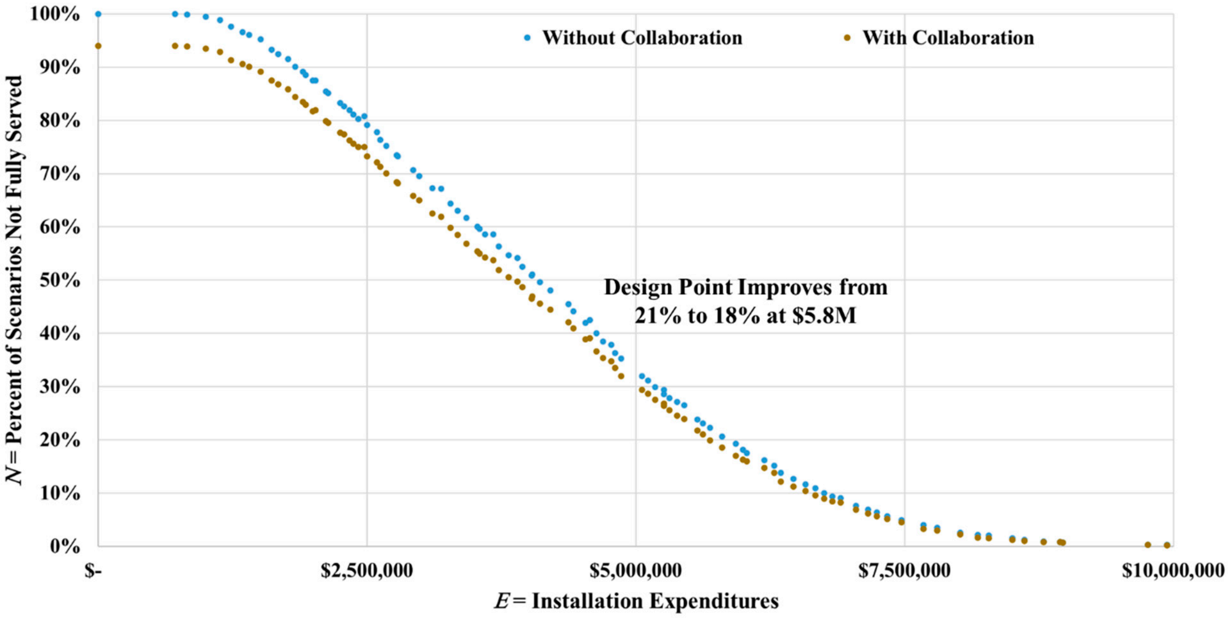


Figure 10. Microgrid A performance with collaboration with Microgrid B.

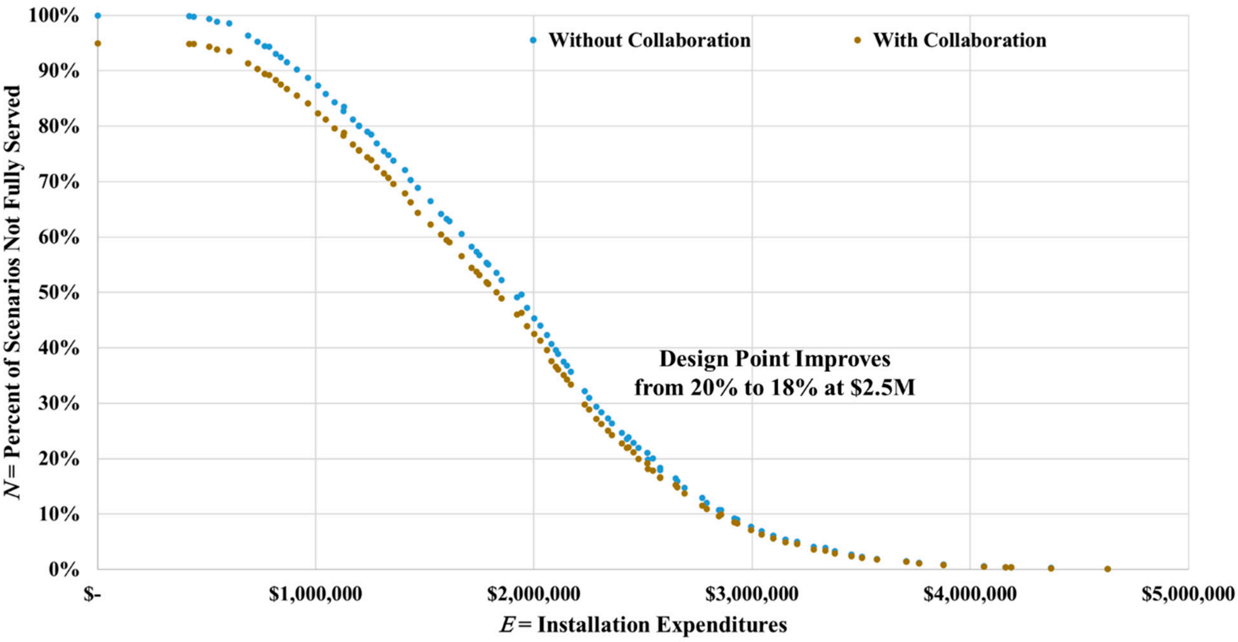


Figure 11. Microgrid B performance with collaboration with Microgrid A.

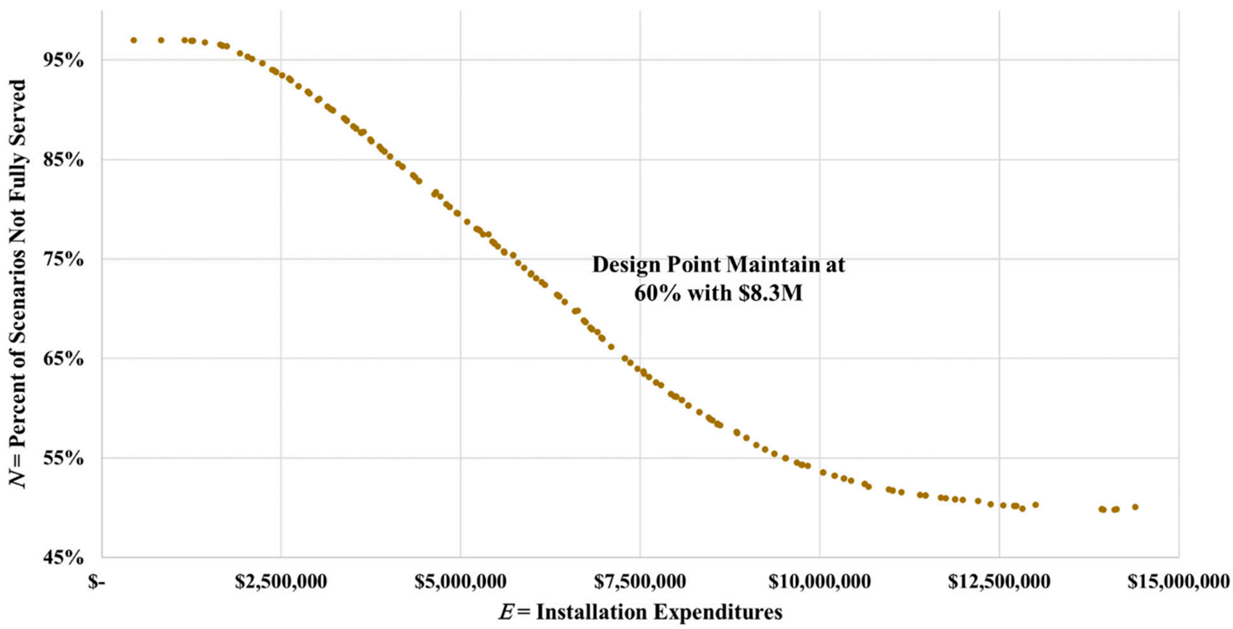


Figure 12. Service to the flexible boundary due to collaboration.

Networked Microgrid Optimized Design Considering Collaboration

The optimization of the design of the networked microgrids considering collaboration has a similar structure to the stand-alone microgrid formulation, as shown in Equations (17)–(21).

The input variables for the optimization are shown in Equation (17).

$$\begin{gathered} \Lambda_A(i) \in \mathbb{R} \\ \Lambda_B(i) \in \mathbb{R} \\ \Lambda_{FB}(i) \in \mathbb{R} \\ \psi(i) \in \mathbb{R},\ 0 \leq \psi(i) \leq 1 \\ i \in \mathbb{W},\ 0 \leq i \leq 23 \end{gathered} \quad (17)$$

The output variables for the optimization are shown in Equation (18), which defines the design space for the problem.

$$\begin{aligned} \Psi_{So,A}^{Max} &\in \mathbb{W} \\ K_{St,A}^{Max} &\in \mathbb{W} \\ \Psi_{So,B}^{Max} &\in \mathbb{W} \\ K_{St,B}^{Max} &\in \mathbb{W} \end{aligned} \tag{18}$$

N_A and N_B are the variables to be optimized, and together they form the optimization space for the problem.

As shown in Equation (19), inequality constraints were also added to consider the desire to improve on the stand-alone microgrid design's performance with collaboration at the same or lower cost. The cost of the microgrids was slightly over \$8,340,000, which was rounded to \$8.3 M. This led to the first constraint in Equation (19), which requires that the cost be less than \$8,350,000. N_A and N_B were both slightly higher than 18.4% and 18.3%, respectively, which were rounded to 18%. This led to the second and third constraints in Equation (19), which requires that the failed scenarios metrics both be less than 18.5%. This was further supported by using a ±20% range around the stand-alone microgrid design results to initialize the design space.

$$\begin{gathered} E - 8,350,000 \ \leq 0 \\ N_A - 0.185 \ \leq 0 \\ N_B - 0.185 \ \leq 0 \\ with \\ E \equiv E_A + E_B E_A = \left(\frac{\$1900}{\text{kW}}\right) \times \Psi_{So,A}^{Max} + \left(\frac{\$500}{\text{kWh}}\right) \times K_{St,A}^{Max} \\ E_B = \left(\frac{\$1900}{\text{kW}}\right) \times \Psi_{So,B}^{Max} + \left(\frac{\$500}{\text{kWh}}\right) \times K_{St,B}^{Max} \end{gathered} \tag{19}$$

There are several intermediate variables required for the optimization, which are shown in Equation (20).

$$\begin{gathered} \Psi_{So,A}(i) \in \mathbb{R} \\ \Psi_{St,A}^{Need}(i) \in \mathbb{R} \\ \Psi_{St,A}^{Act}(i) \in \mathbb{R} \\ K_{St,A}^{Act}(i) \in \mathbb{R} \\ \Psi_{So,B}(i) \in \mathbb{R} \\ \Psi_{St,B}^{Need}(i) \in \mathbb{R} \\ \Psi_{St,B}^{Act}(i) \in \mathbb{R} \\ K_{St,B}^{Act}(i) \in \mathbb{R} \\ i \in \mathbb{W}, 0 \leq i \leq 23 \end{gathered} \tag{20}$$

The problem constraints based on the equipment limitations are provided by Equation (21).

$$\begin{gathered} K_{St,A}^{Act}(i) \ \geq 0.15 \times K_{St,A}^{Max} \\ K_{St,A}^{Act}(i) \leq 0.85 \times K_{St,A}^{Max} \\ \Psi_{St,A}^{Act}(i) \leq 0.25 \times K_{St,A}^{Max} \\ \Psi_{St,A}^{Act}(i) \geq -0.25 \times K_{St,A}^{Max} \\ K_{St,B}^{Act}(i) \geq 0.15 \times K_{St,B}^{Max} \\ K_{St,B}^{Act}(i) \leq 0.85 \times K_{St,B}^{Max} \\ \Psi_{St,B}^{Act}(i) \leq \ 0.25 \times K_{St,B}^{Max} \\ \Psi_{St,B}^{Act}(i) \geq -0.25 \times K_{St,B}^{Max} \\ i \in \mathbb{W}, 0 \leq i \leq 23 \end{gathered} \tag{21}$$

The equalities in Equation (6) and tests in Equations (7) and (8) that are used for the stand-alone microgrid formulation can be used for the networked microgrid formulation with the substitutions described in Section "Networked Microgrids Collaboration Formulation".

Designs based on optimization that consider collaboration improve the performance from $N_A = 18\%$, $N_B = 18\%$, and $N_{FB} = 60\%$ to $N_A = 18\%$, $N_B = 16\%$, and $N_{FB} = 59\%$, respectively, while maintaining the cost at approximately $8.3 M and with 99.8% of the total solar output and 61% of the total storage capacity in Microgrid A. To achieve these results, the optimization was run for 100 iterations to attempt to generate a Pareto front with 100 points using 1000 random samples, which required three minutes and 23 s.

Summary of Microgrid Results

The microgrid performance results are summarized in Table 7. This shows that the performance of microgrids that were designed for stand-alone purposes can be improved with collaboration. It also shows that considering collaboration in design can provide additional improvements in performance.

Table 7. Summary of Microgrid Performance.

Measure	Stand-Alone Design and Operation	Stand-Alone Design and Collaborative Operation	Collaborative Design and Operation
E	$8.3 M	$8.3 M	$8.3 M
N_A	21%	18%	18%
N_B	20%	18%	16%
N_{FB}	100%	60%	59%

4.4. Protection and Control

Modern microgrid control remains a pivotal subject focused on optimizing the management of a variety of energy sources and loads at scale. Centralized control systems lie at the foundation of this discourse, characterized by a principal controller that governs the entire microgrid operations [39,61]. These systems are renowned for their aptitude in optimization and efficient power dispatch, orchestrating a harmonious operation of all integral grid components [37,62]. However, they are not without their shortcomings, particularly a vulnerability to a single point of failure that can destabilize the entire system's operation. In contrast, distributed control systems offer an alternative paradigm, where control responsibilities are apportioned among multiple local controllers [63]. This approach not only facilitates enhanced scalability but also injects a level of flexibility that is often absent in centralized control systems. The inherent resilience of distributed systems stems from their architecture, which is meticulously designed to negate the risks associated with single points of failure, ensuring that the microgrid remains operational [64]. On the other hand, the hierarchical control strategy emerges as a hybrid, integrative solution, weaving together various levels of control into a cohesive framework. It intricately combines primary, secondary, and tertiary controls, each tailored to address a specific spectrum of operational needs, from instantaneous dynamic responses to the nuanced, progressive tasks of energy management and scheduling [65]. This multilayered approach guarantees a microgrid endowed with the agility to navigate short-term fluctuations while remaining anchored in achieving long-term operational objectives, fostering a balance between immediacy and strategic foresight.

These developments in microgrid control methodologies underscore the ongoing evolution in this field, each approach presenting a unique set of advantages and challenges and collectively contributing to the enrichment of strategies available for the optimization of decentralized energy systems. The capricious nature of renewables, marked by intermittency and variability, mandates the deployment of sophisticated control strategies adept at ensuring grid stability and an unwavering power supply [66]. The matrix of challenges is augmented by the imperative to achieve seamless integration with diverse energy sources, state-of-the-art storage technologies, and fluctuating load demands. In the realm of modern control systems, issues extending beyond the technical and operational domains begin to surface. For example, communication delays emerge as a notable concern, particularly within the context of distributed control systems. The essence of real-time control in upholding microgrid stability is indisputable.

Advanced control systems and protection mechanisms are intrinsically interconnected, their collaborative functions enhancing the resilience and efficiency of microgrids. Islanding capabilities serve as a motivating example of this synergistic relationship. This feature enables microgrids to autonomously detect disturbances and strategically disconnect from the main grid, mitigating risks and preserving operational integrity [67,68]. The increased integration of DERs into microgrid systems heralds a transformative era marked by a shift from traditional radial power flow to a more complex, bidirectional power flow [69–71]. This transition underscores a pivotal moment in the evolution of power distribution and management, precipitating a reassessment of established protective measures and controls. Conventional protection schemes, rooted in a landscape dominated by radial power flow and centralized power generation, are encountering limitations amidst the emerging dynamics of bidirectional power flow inherent in contemporary microgrids [69]. In this new era, the preservation of system integrity and the assurance of reliable power supply hinge on innovative, adaptive protection protocols that are responsive to the multifaceted challenges posed by DERs and their associated power flow patterns. The emerging assimilation of artificial intelligence (AI) and machine learning (ML) into microgrid control and protection represents a paradigm shift, instigating a transformative process that extends beyond operational enhancement to include proactive, predictive, and adaptive capabilities. These emerging technologies stand to redefine the contours of microgrid management, setting the stage for a future where grid systems are not just managed but also imbued with the intelligence to self-optimize, adapt, and evolve in real time.

As this landscape is navigated, the harmonization of advanced control systems and innovative protection schemes will be instrumental in realizing the aspirational vision of microgrids that are not only efficient and resilient but also intelligent, adaptive, and self-sustaining. The authors recognize the importance and complexity of control and protection work for ANNs. It is one of the major workstreams for the microgrid projects being used as case studies in this manuscript. Based on the potential for lost communications when the microgrids are most needed and balancing the need for the utility to provide proper oversight of grid operations, the authors have settled on a hybrid control and protection architecture that carefully includes centralized and distributed aspects. With the microgrid core infrastructure designed, further designing and testing of that hybrid control and protection architecture will be a key area of focus. The details of that work will be published in future manuscripts as the lessons are learned.

4.5. Black Start Capability

Black start capability refers to the ability for the microgrid to start up without an outside source from a state where the grid is deenergized. Black start capability needs to understand the topology of the system before de-energization to determine the bounds of the microgrid, the availability of DER resources, and the presence of potential loads. The control state, availability, and capabilities of DER, including the start-up and return to service criteria timing of DER, need to be known or directly controlled. The black start capability needs to be calibrated to consider a number of electrical factors, including cold load pickup and voltage and current imbalance. For a section of a distribution system that forms a microgrid, this presents a number of challenges that may not be present in smaller structured microgrids that are controlled by a single party. These issues arise from the variability of the DER connectivity and distribution system configuration where the initial parameters for starting up the microgrid may not be known or in the direct control of the microgrid. Predominately, this uncertainty would be present where multiple owners of load and generation may have conflicting priorities.

Potential mitigating solutions would include installing multiple types of storage, such as ultra-capacitors, flywheels, or small fast-response battery units that are separate from the long duration storage to economically optimize the energy storage by providing short duration inrush capability. Other potential areas of investigation would be assessing available technologies that could mitigate or clamp inrush at the load side or along the lines or soft start/staged start for problematic loads and automatic phase balancing technologies, including power electronics.

Staging the black start from grid-forming devices outwards to the extent of the microgrid would be a typical practice to further mitigate having major sources of inrush. However, it is likely during an inclement event that that state of the microgrid may be abnormal and some DER resources may not be available. Predicting the topology of the network and the instantaneous availability of DER resources in the moments prior to and immediately following black start may prove to be difficult, or worse, a faulted section that was not indicated through fault location may now be present. However, that could be aided by having an auxiliary communications and control network that has sufficient backup power to save the state of the DER and switching devices after de-energization, transmitting the state information to the microgrid controller, and using state measurement and topology discovery algorithms to reconstruct the new allowable extents and remaining capability of the microgrid prior to black start. While black start capabilities have been considered in the design of the infrastructure, this will be a topic for future work in the control and protection workstream.

4.6. Illustrative Examples

Below are illustrative examples for a rural setting and an urban setting for deployment of microgrids to create ANMs. These examples are similar to real-world deployments and were selected to provide a range of settings for microgrid design and operation. They illustrate the challenges with real-world microgrid design and how the methods, guidelines, and considerations described earlier are applied.

As mentioned in Section 3, particular critical customers were taken into consideration while placing sectionalizers and DERs, to make sure that the critical customers are restored first in an outage event. Please note that in the images below, the situation being described is the microgrid network in the event of circuit isolation from the traditional source, i.e., the substation and distribution circuit.

4.6.1. Rural Area Example

Figure 13 is a depiction of an example circuit in a rural setting. This project will create a set of dynamic networked microgrids. This infrastructure is needed because the area attracts tourists during the summer, and that tourism generates the majority of the annual revenue for the community.

The scope of work includes the installation of a new microgrid to collaborate with an existing microgrid in the area. Additional sectionalizing, communication equipment, controls, protection, and other infrastructure will also be installed. The scope will follow the considerations described earlier and is summarized in Table 8. Additionally, the dynamic microgrids will automatically pick up and shed load in the flexible boundaries (gray areas in Figure 13). Overall, the two microgrids will work together as ANMs to provide optimized reliability to the customers on this circuit, including critical loads (e.g., water treatment facilities, police stations, fire stations, and others).

4.6.2. Urban Area Example

Figure 14 is a depiction of an example circuit in an urban setting. This project will leverage existing solar and storage to create dynamic networked microgrids. The scope of work includes the installation of a new microgrid to collaborate with a microgrid to be formed leveraging the existing solar and storage in the area. Additional sectionalizing, communication equipment, controls, protection, and other infrastructure will also be installed. The scope will follow the considerations described earlier and is summarized in Table 9. Additionally, the dynamic microgrid will automatically pick up and shed load in the flexible ANM areas (gray areas in the image). Overall, the two resulting microgrids will work together as dynamic microgrids or adaptive networked microgrids to provide optimized reliability to the customers on this circuit.

Table 8. Summary of considerations for rural example.

Practical Considerations	
Load distribution	Rural area loads are sparse compared to urban area loads. This makes placing sectionalizers to ensure even distribution of load simpler.
Improve reliability and power quality	Locations on the circuit are picked to help any existing power quality issues in the area. With rural areas, the circuits are long and often run into low voltage issues near the ends. Placing DER near the ends of the circuit can address this concern.
Accessibility	The locations of the sectionalizers are truck accessible and easily operated by field crews. With more trees in the rural area, tree clearance is necessary.
Sectioniaizers location	The poles that are selected are clean for equipment installation with tree clearance in the rural area. Load flow studies must be completed for all scenarios to ensure that no infrastructure is overloaded during collaboration.
Easements	The locations for the installations have been selected where easements can likely be easily obtained.
Customer-Focused Consideration	
Medical customers	No medical facilities or customers are on the circuit to prioritize.
Critical loads	A critical load that serves the entire city will be served by Microgrid 2. Microgrid 1 will serve a critical business area for the community.
Fault detection	The reliability history of the circuit has been reviewed to maximize fault detection and isolation.
Aesthetics	Tourism provides a large portion of revenue for this community. For that reason, areas frequently visited by tourists have not been selected for overhead equipment installation.
Boundary balance	Boundaries are picked to balance load and contained DER.
DER Placement	
Installed DERs	DERs already installed on the circuit are evaluated in the engineering study to determine the location for additional installations. For this rural setting, microgrid 1 is in construction currently.
Property	There is more opportunity for available property in a rural area. Suitable property had been identified for this set of microgrids.
Community engagement	Start collaboration with the community before the execution phase.
Load profile	DER is placed to ensure stability based on historical load profiles.
Promote local DER	Work with regional community affairs to illustrate the benefits of local DER.
Fault location	In a rural setting, the circuit has long line miles, making it essential to review historical faults to prevent delay in restoration.
Protection and Control	
Control	Distributed controls will be placed at each DER and each microgrid. These controls will act autonomously in the event of communication disruptions. They will leverage guidelines from centralized processing elements when communications are maintained.
Protection	More protection devices are required, as the rural circuit is not very sectionalized. Fault studies are needed to determine the settings for protective devices, which will be based on the scenarios under which the microgrids will operate.
Black Start Capability Factors	
Topology of system	In all settings, the control and protection systems must maintain an accurate view of the current topology for both current operating conditions and potential black start needs.
Availability of DER	In a rural setting, the availability of property to potentially install multiple small battery storage units around the microgrids should be easier to find.
Electrical factors	Steady state and dynamic simulations will be completed to consider cold load pickup and voltage/current imbalance.

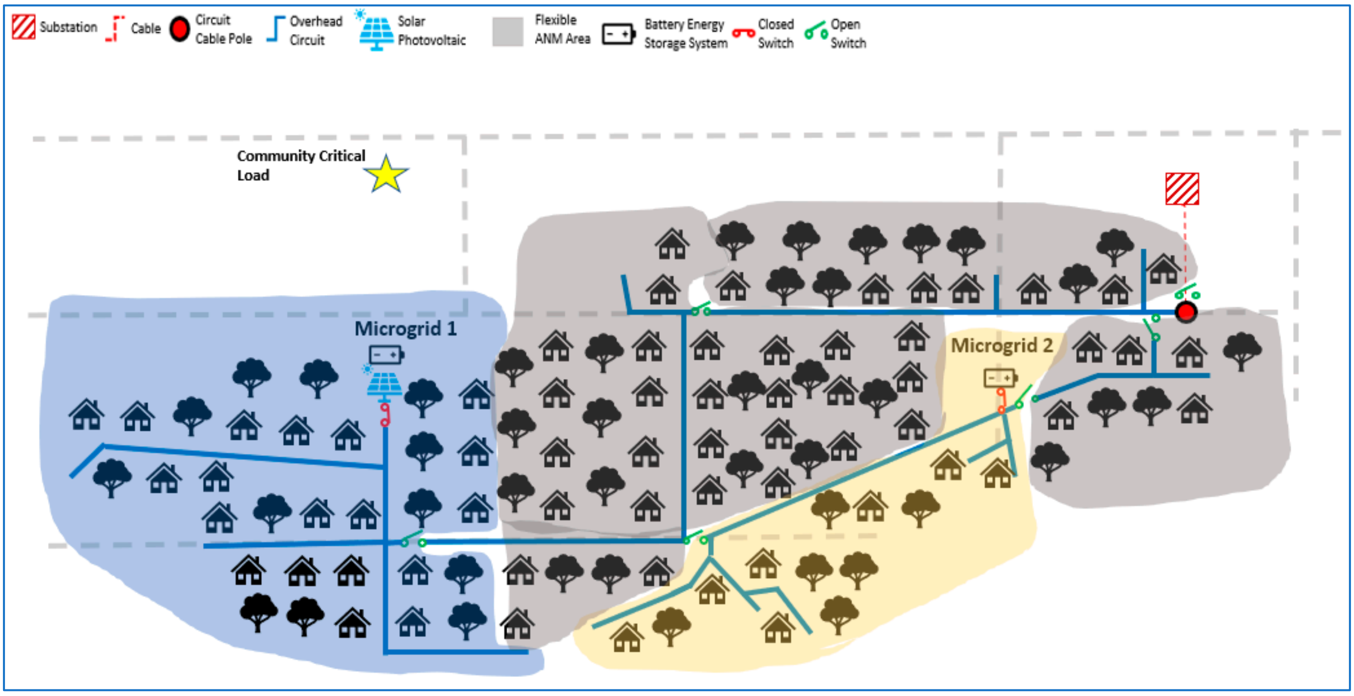


Figure 13. Illustration of a microgrid installed in a rural area.

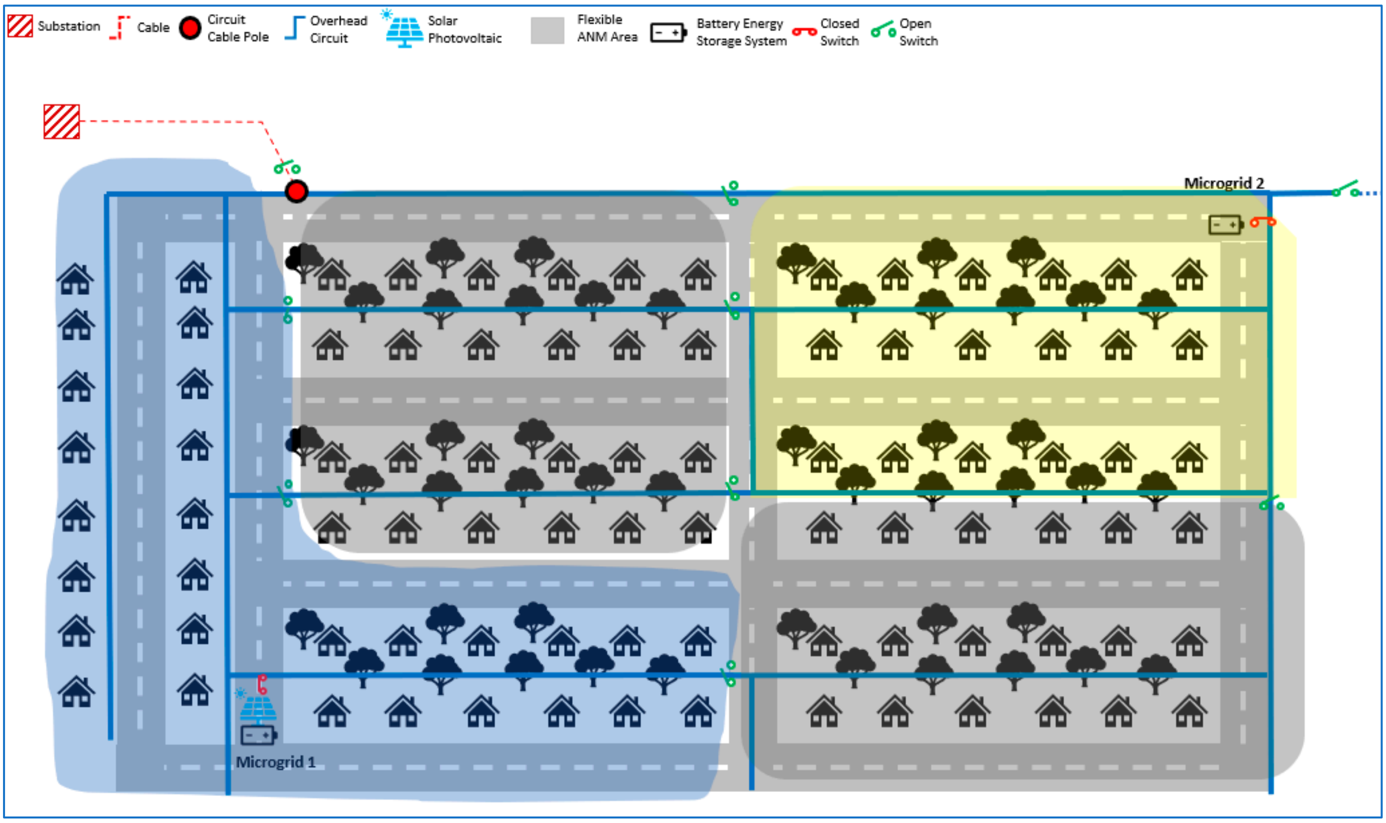


Figure 14. Illustration of a microgrid installed in an urban area.

Table 9. Summary of considerations for urban example.

Practical Considerations	
Load distribution	Urban areas are more densely populated. Sectionalizers are placed to ensure that load distribution is even, which may be a challenge.
Improve reliability and power quality	Locations are selected to resolve any power quality issue in the area. In urban areas, this is more likely to be a current issue.
Accessibility	The locations of the sectionalizers are truck accessible and easily operated by field crews. With lower tree density compared to rural areas, this is simpler.
Sectionalizers location	The poles that are selected are clean for equipment installation. Load flow studies must be completed for all scenarios to ensure that no infrastructure is overloaded during collaboration.
Easements	The locations for the installations have been selected where easements can likely be easily obtained. This may be more of a challenge with an urban setting due to the density of customers.
Customer-Focused Consideration	
Medical customers	No medical facilities or customers are on the circuit to prioritize.
Critical loads	No critical loads are connected to the circuit to prioritize.
Fault detection	The reliability history of the circuit has been reviewed to maximize fault detection and isolation.
Aesthetics	To maintain the beauty of the city, areas frequently visited and seen by city residents are avoided for installation of overhead equipment.
Boundary balance	Boundaries are picked to balance load and contained DER.
DER Placement	
Installed DERs	DERs already installed on the circuit are evaluated in the engineering study to decide the location for additional installations.
Property	Property available for DER installation will require coordination with customers. It is more challenging to find property in an urban area compared to a rural area. Suitable property has been identified for the case study being discussed.
Community engagement	Start collaboration with the community before the execution phase.
Load profile	DER is placed to ensure stability based on historical load profiles.
Promote local DER	Work with regional community affairs to illustrate the benefits of local DER.
Fault location	In an urban setting, the faults are more frequently at service drops. Additionally, it is easier to locate faults with the shorter circuits in an urban area.
Protection and Control	
Control	Distributed controls will be placed at each DER and each microgrid. These controls will act autonomously in the event of communication disruptions. They will leverage guidelines from centralized processing elements when communications are maintained.
Protection	Fewer protection devices are required because urban circuits are usually very sectionalized. Fault studies are needed to determine the settings for protective devices, which will be based on the scenarios under which the microgrids will operate.
Black Start Capability Factors	
Topology of system	In all settings, the control and protection systems must maintain an accurate view of the current topology for both current operating conditions and potential black start needs.
Availability of DER	In an urban setting, the availability of property to potentially install multiple small battery storage units around the microgrids will require research and is not as easy to find.
Electrical factors	Additional studies will be needed to make sure electrical factors are taken into consideration, such as cold load pickup and voltage/current imbalance.

5. Summary of Findings and Future Work

This section provides a summary of the findings from the present work and describes the authors' plans to extend this research.

5.1. Summary of Findings

After careful consideration of the available research and application of microgrids, this work has developed objectives for utilities to consider when deploying microgrids. The authors then extended those objectives to provide guidance for microgrid design. This included practical and customer considerations for the placement of sectionalizing and DER, black start, protection, and control. It also provided a stochastic optimization approach for the sizing of DER components, which balances the cost of the installation and the infrastructure's ability to serve load in fault conditions. These methods have resulted in a 97% reduction in the time to perform the optimization method, showed 3% to 4% improvements in the performance of microgrids due to collaboration, and presented how that collaboration can improve reliability for customers in areas with low DER penetration between the microgrids, which can include DACs. The practical use of the guidelines and methods is illustrated with real-world microgrid deployments.

5.2. Future Work

While this work has made contributions to the overall body of knowledge, as described throughout the document and summarized in Section 2.4.2, the authors recognize two primary needs to extend and further support the guidelines for microgrid design. First, the authors recognize a need to develop a comprehensive optimization approach for all the key considerations described in this manuscript for microgrid design. Second, the authors are developing and designing two sets of ANM deployments on distribution circuits in DTE Electric's service territory that use the guidelines described in this document and will use the learning to revise the comprehensive optimization approach that will be developed. The design of these two sets of ANMs will progress over the next few years through a series of engineering due diligence steps prior to the final commissioning and use of the ANMs. This will provide testbeds and real-life deployments to test, refine, and prove the guidelines described in this manuscript.

This manuscript focuses on the design and optimization of the overall microgrid infrastructure. The authors have noted other key aspects for the deployment of these systems, such as control and protection design, black start capability, transitioning between operating modes, and cybersecurity concerns. As the design of these aspects progresses, the lessons learned will be presented in future publications.

Author Contributions: Conceptualization, S.S., J.O., R.M., W.S., L.R. and A.B.; methodology, S.S., J.O., R.M., W.S., L.R. and A.B.; software, J.O.; validation, J.O.; formal analysis, S.S., J.O., R.M., W.S., L.R. and A.B.; investigation, S.S., J.O., R.M., W.S., L.R., A.B. and K.R.; resources, S.S., J.O., R.M., W.S., L.R., A.B. and K.R.; data curation, J.O.; writing—original draft preparation, S.S., J.O., R.M., W.S., L.R., A.B. and K.R.; writing—review and editing, S.S., J.O., R.M., W.S., L.R., A.B. and K.R.; visualization, S.S., J.O. and W.S.; supervision, S.S., J.O., R.M., W.S., L.R. and A.B.; project administration, S.S. and J.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding with the exception of the work of Dr. Roald and Dr. Bernstein, which is included in Section 3 of this manuscript. Dr. Roald and Dr. Bernstein's work was authored in part by NREL, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by DOE Office of Electricity, Microgrid Program. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work or allow others to do so, for the U.S. Government purposes.

Data Availability Statement: The data and electrical system configurations used in this research are confidential. The code and results are available.

Conflicts of Interest: Author Smriti Sharma, John O'Donnell, Richard Mueller and Khurram Rehman were employed by the company DTE Electric. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Nomenclature

Abbreviations	
ADI	Area Deprivation Index
AI	Artificial Intelligence
ANM	Adaptive Networked Microgrids
BMG	Brooklyn Microgrid
DACs	Disadvantaged Communities
DOE	Department of Energy
EPB	Electrical Power Board in Chattanooga, Tennessee
GIS	Geographic Information System
MCAS	Marine Corps Air Station
ML	Machine Learning
NSGA	Non-Dominated Sorting Genetic Algorithm
SDG&E	San Diego Gas & Electric
VPP	Virtual Power Plant
Key Variables Used with Microgrid Design	
E	Installation Expenditures
N	Percent of Scenarios Not Fully Served for a Stand-Alone Microgrid
N_A	Percent of Scenarios Not Fully Served by Microgrid A
N_B	Percent of Scenarios Not Fully Served by Microgrid B
N_{FB}	Percent of Scenarios Not Fully Served by Microgrid FB
$\Lambda(i)$	Load from 24 h Day Scenarios from Monte Carlo Simulations
$\psi(i)$	Solar Power Normalized to the Maximum Output
$\Psi_{So}(i)$	Actual Solar Power
$\Psi_{St}^{Need}(i)$	Power Output Needed from Storage to Serve a Scenario
$\Psi_{St}^{Act}(i)$	Power Output Available from Storage with Limitations
$K_{St}^{Act}(i)$	Energy Available from Storage with Limitations
Ψ_{So}^{Max}	Maximum Power Output for a Solar Deployment
K_{St}^{Max}	Energy Available from Storage without Limitations
$i \in \mathbb{W},\ 0 \leq i \leq 23$	used to index through the hours of a day that make up a scenario

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