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METHODOLOGY FOR DEVELOPING A MICROGRID

REPORT

Energy Security Project (ESP)

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Rev D

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ACRONYMS

AMR	Automatic Meter Reading
BESS	Battery Energy Storage System
CAPEX	Capital Expenditures
DER	Distributed Energy Resources
DSO	Distribution System Operator
DTU	Distribution Terminal Unit
GIS	Geographic Information System
ID	Identification
IEC	International Electrotechnical Commission
kA	Kiloampere
km	Kilometer
KPI	Key Performance Indicator
kV	Kilovolt
kVA	Kilovolt-Ampere
kVAR	Kilovolt-Ampere Reactive
kW	Kilowatt
kWh	Kilowatt-Hour
LCOE	Levelized Cost Of Energy
LV	Low Voltage
MGMS	Microgrid Management System
MILP	Mixed-Integer Linear Programming
MV	Medium Voltage
MVAR	Megavolt-Ampere Reactive
MW	Megawatt
OPEX	Operational Expenditures
PV	Photovoltaic
Pval	Present Value
RES	Renewable Energy Sources
RF	Radio Frequency
RTU	Remote Terminal Unit
s	Seconds
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCADA	Supervisory Control And Data Acquisition
SoC	State of Charge
VAR	Volt-Ampere Reactive
VOLL	Value Of Lost Load

EXECUTIVE SUMMARY

This guide provides a comprehensive framework for the development and implementation of microgrid systems, particularly in regions like Ukraine that face frequent power disruptions due to geopolitical issues. It focuses on integrating efficient and sustainable distributed energy resources (DER) such as solar photovoltaic (PV), gas generators, biofuel, and diesel generators at the distribution system operator level. The aim is to build microgrids capable of withstanding extreme conditions while enhancing local energy systems and community resilience.

This guide builds on successful strategies implemented in different parts of the world, focusing on increasing the resilience of the electricity supply for selected regions. The strategies included here are geared toward:

- **Enhancing resilience and reliability**: Strengthening local network resilience against blackouts and brownouts and ensuring a reliable power supply during large-scale and long outages through grid-scale solutions and robust design and analysis techniques.

- **Promoting energy independence:** Reducing dependence on external power supplies by utilizing locally available renewable resources and developing decentralized power sources, thus enhancing local energy security and autonomy.

- **Optimizing operational effectiveness:** Providing detailed methodologies for integrating DER. This includes conducting essential analyses like load-flow, short-circuit, and stability assessments to adapt to changing load demands and ensure the microgrid's effectiveness under various scenarios.

- **Using adaptive design and management:** Incorporating flexible and efficient microgrid management systems that can quickly adapt to changing conditions and repair schedules, critical for post-conflict recovery and stabilization. This involves integrating renewable and distributed generation to promote sustainability and reduce the environmental impact.

This report is structured to systematically navigate through the critical phases of microgrid design, including:

- Initial planning and data collection, focusing on understanding the specific energy demands and infrastructure capabilities at the local level.

- Detailed modeling and simulation of microgrid operations to optimize performance and reliability under both normal and stressed conditions.

- Implementation strategies that consider both technical and economic feasibility, especially pertinent to regions experiencing conflict or recovery.

CHALLENGES: POWER BALANCING AND FREQUENCY SUPPORT

Islandable microgrids face significant challenges, particularly in power balancing and frequency support. These challenges are crucial for maintaining operational stability and efficiency, especially when disconnected from the main grid.

- Power balancing

  - Demand-supply matching: Microgrids must dynamically balance supply and demand to maintain system stability. This involves sophisticated control systems capable of handling the variability introduced by renewable energy sources and abrupt shifts in load demand.
  - Storage Integration: Properly sized and managed battery energy storage systems (BESS) are crucial for stabilizing the microgrid by absorbing excess energy during low-demand periods and supplying energy during peak demand.

- Frequency support
  - Maintaining frequency stability: In island mode, microgrids must independently maintain frequency stability, a challenging task due to their smaller scale and lower inertia.
  - Advanced control strategies: Techniques such as droop control and virtual inertia are implemented to stabilize grid frequency by providing essential inertia and damping.

DISPATCHABLE DISTRIBUTED ENERGY TECHNOLOGIES FOR BALANCING

To address these challenges, microgrids can utilize various dispatchable DER technologies:

- **Gas turbines**: These offer rapid response capabilities for quick adjustments in power output to manage supply-demand fluctuations. They also provide fuel flexibility, being able to operate on natural gas, biogas, and hydrogen.
- **Combined heat and power systems**: These systems enhance overall energy efficiency by simultaneously generating electricity and thermal energy. They can adapt their output based on the current electrical and thermal demands, aiding in power balancing and frequency support.
- **Gas/diesel/dual-fuel generators**: These are reliable backup power sources that can operate independently of the grid, ensuring continuous power supply. Their widespread availability and proven technology facilitate rapid deployment and maintenance.
- **Biomass energy systems**: These systems use organic materials as fuel to produce energy, offering a sustainable and renewable source of power that contributes to the balancing of microgrid energy supplies.
- **Battery energy storage systems**: BESS are crucial for managing the intermittency of renewable generation. They enable energy arbitrage by storing energy during low-demand periods and releasing it during peak demand, optimizing energy usage across the microgrid.

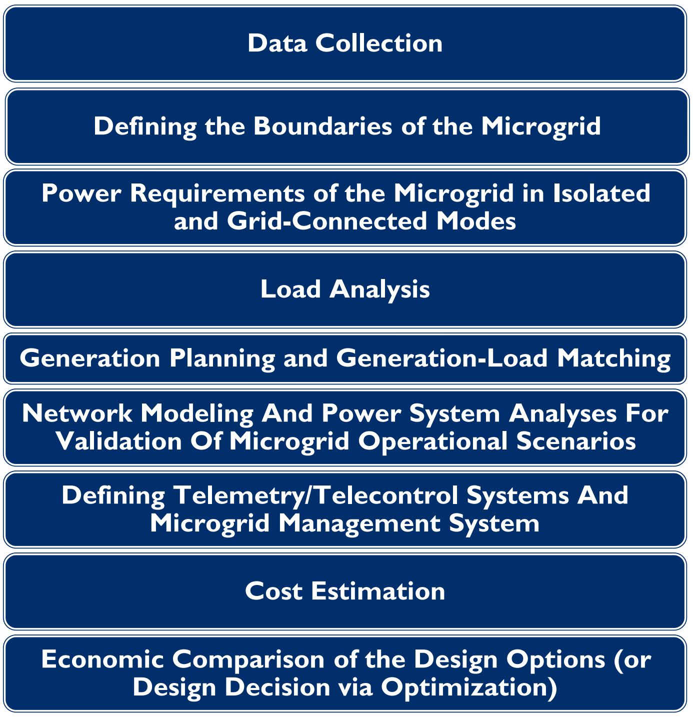
METHODOLOGY OVERVIEW

The recommended methodology begins with a thorough assessment of the proposed region, including comprehensive data collection on energy consumption, resources, and infrastructure, followed by geographical, environmental, and demand criticality analyses. This foundational work is critical for informing subsequent phases such as energy source identification, load prioritization, and community mapping, ensuring the project aligns with local needs and regulatory frameworks.

Technical development phases encompass security, risk management, design, and costing, with a strong focus on selecting appropriate technologies for generation, storage, and distribution facilities. The operational philosophy centers around durability, uninterrupted supply ability, and the selection of DER to meet specific community or operational site needs. The integration of smart grid technologies and a BESS underpins the flexibility, scalability, and efficiency of the microgrid.

MAIN STEPS FOR DEVELOPING CONCEPTUAL DESIGN

Key technical steps include:



1. **Data collection**: Collecting rigorous data on network infrastructure, load demands, and DER capabilities to inform the design and modeling phases. This involves gathering information on energy consumption, resources, and existing infrastructure.

2. **Defining the boundaries of the microgrid**: Using a multi-criteria decision-making tool to evaluate and prioritize regions based on network vulnerability, load criticality, and DER integration potential. This step clearly defines the microgrid boundaries and optimizes them for efficiency and resilience.

3. **Power requirements of the microgrid in isolated and grid-connected modes**: Designing configurations that optimize reliability, cost-effectiveness, and environmental impact, supported by the selection of appropriate DER configurations and sizing determinations. This includes understanding the power demands in both isolated and grid-connected scenarios.

4. **Load analysis**: Analyzing load profiles under normal and peak operational states to ensure sufficient generation and load-following capacity. This step involves detailed load studies to match generation with demand effectively.

5. **Generation planning and generation-load matching**: Optimal placement and integration of DER, which are crucial for enhancing grid efficiency and stability, reducing losses, and improving load management through strategic connection point selection. This involves planning for both existing and new generation sources to meet the microgrid's needs.

6. **Network modeling and power system analyses for validation of microgrid operational scenarios**: Performing detailed simulations to validate the microgrid's operational scenarios under various conditions. This step ensures that the microgrid design is robust and can handle different operational challenges.

7. **Defining telemetry/telecontrol systems and microgrid management systems**: Implementing robust telemetry and telecontrol systems, integrated with microgrid management systems, for real-time monitoring and control, which enhance operational reliability and responsiveness. This includes setting up the necessary communication and control infrastructure.

8. **Cost estimation**: Careful selection and integration of new equipment based on detailed technical and operational analysis. This ensures the microgrid's compatibility and functionality, addressing both current and future energy demands. This step involves estimating the costs associated with different design options and equipment.

9. **Economic comparison of the design options (or design decision via optimization)**: Comparing different design scenarios to optimize financial viability and technical performance. This involves using tools and methodologies to make informed decisions about the best design options based on economic and operational criteria.

ITERATIVE PROCESS FOR FINALIZING THE CONCEPTUAL DESIGN SOLUTION

Main block 1: Define scenario. This is a highly iterative phase with sub-tasks shown in a general sequence, but findings in any given area may require updates to adjacent subjects. The initial step involves characterizing the system and setting goals, resulting in establishing a boundary around the geographic extents. This block also collects and refines overarching goals, including physical parameters and target key performance indicators (KPI). Within the established boundary, the next step is to evaluate the infrastructure. Using the guides in this document, critical loads and infrastructure are identified and prioritized specific to the candidate microgrid region. Following the critical inventory assessment, it is necessary to evaluate and define the configuration options as well as the system boundary and the DER and storage requirements.

Main block 2: Design a solution. This phase takes the findings from the previous phase and quantifies a conceptual microgrid layout. A combination of renewable and conventional generators is analyzed to serve peak load values of critical load (or all infrastructure in some cases), and a system is defined. Costs are estimated, and performance is evaluated. Detailed in the subsequent conceptual design, this block reveals viability, trade-off opportunities, and cost limitations. If no reasonable conceptual path forward is found, the microgrid project developers could return to the previous phase to reevaluate the data.

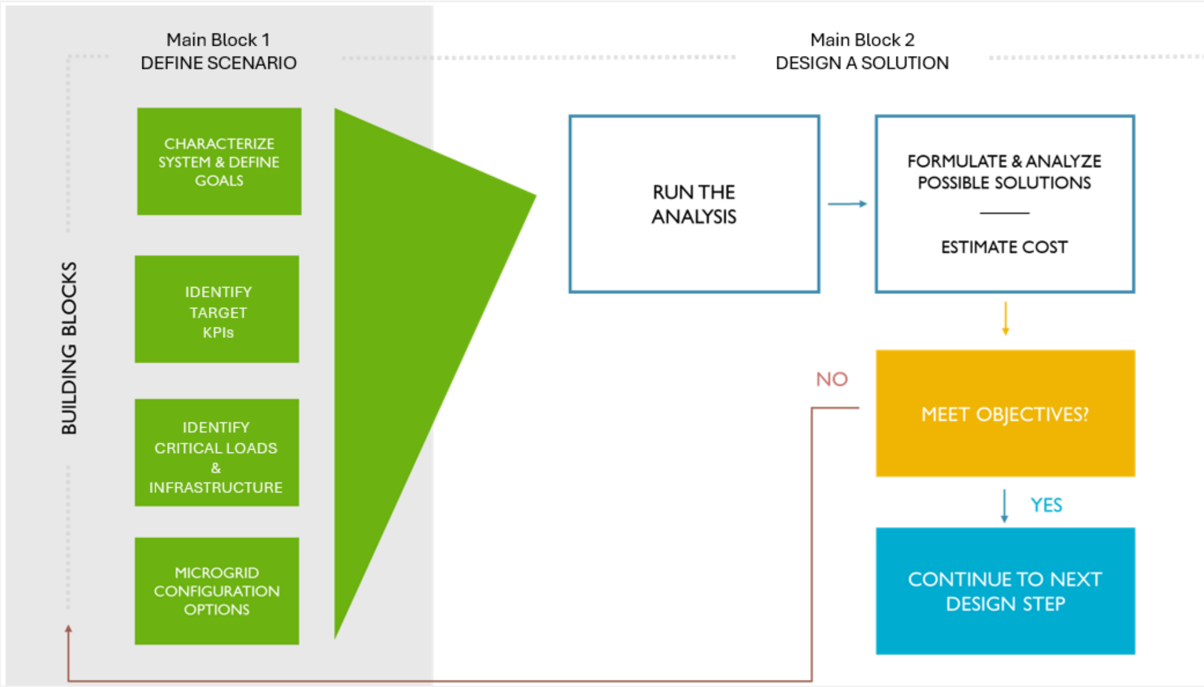


Figure 1: Iterative process for balancing the KPIs and microgrid solution design

OPTIONS FOR MICROGRID DESIGN OPTIONS AND CONFIGURATION

Microgrid configuration and design flexibility: The guide details an array of microgrid configurations designed to enhance the reliability, efficiency, and sustainability of electricity supply. Stakeholders can tailor microgrid designs to meet specific operational requirements and adapt to geographical, economic, and environmental conditions. This decision-making process involves evaluating multiple dimensions such as sizing, energy sources, management strategies, and control systems, each offering distinct advantages suited to particular scenarios.

Comprehensive overview of options: The table below categorizes potential microgrid configurations, outlining key aspects such as the demand to be met, the endurance of off-grid operations, types of DER, and management strategies. These configurations are designed to optimize performance across various metrics such as system resilience, cost-effectiveness, and environmental impact, thereby ensuring that the microgrid not only meets current energy demands but is also scalable and adaptable to future changes.

SUMMARY OF MICROGRID CONFIGURATION OPTIONS TO BE CONSIDERED

KEY ASPECTS	OPTIONS				
Sizing/demand to be met by the microgrid	Critical Loads Only	Critical + Non-Critical Loads	Daytime Loads Only	Full Load (Day & Night)	
Expected off-grid endurance of microgrid operations	2 Hours	8 Hours	24 Hours	1 Month	Indefinite
DER type/source	Solar PV + Battery	Diesel + Battery	Gas Generator Set + Battery	Solar + Diesel + Gas	Solar PV + Gas Generator Set

SUMMARY OF MICROGRID CONFIGURATION OPTIONS TO BE CONSIDERED					
KEY ASPECTS	OPTIONS				
Topology of generation	Centralized	Decentralized	Hybrid	Modular	Portable
Management of microgrid borders	Static/Defined	Dynamic/Adaptive			
Control strategies	Centralized	Decentralized	Peer-to-peer		
Takeover of microgrid	Manual Takeover at Site	Manual Takeover via Telecontrol	Autonomous/Hot Standby	Time Programmed	

Strategic approach to microgrid design: Understanding these options enables planners and engineers to design microgrids that are efficient and resilient, capable of integrating seamlessly with existing energy infrastructure or operating independently as stand-alone systems. This strategic approach is essential for addressing the growing complexity and evolving challenges of modern energy systems, promoting more sustainable and reliable energy solutions.

Key performance indicators: The guide also introduces a set of KPIs that provide essential metrics to assess and compare the performance, efficiency, and resilience of different microgrid designs. These KPIs facilitate a tailored analysis that aligns with specific project needs, ensuring that the evaluation process is both thorough and adaptable. These KPIs assess:

- **Endurance and autonomy**: The duration a microgrid can operate independently during peak loads without external support.
- **Capacity management**: Ability to handle and prioritize critical loads during standard and high-demand scenarios.
- **System responsiveness**: Time and effectiveness in transitioning between connected and island modes, including system stability.
- **Resource utilization**: Efficiency in using DER and maintaining operations during component failures.
- **Sustainability**: Contribution of renewable energy sources to the microgrid's total energy output.
- **System control and monitoring**: Effectiveness of control systems in providing timely and accurate operational feedback.
- **Scalability**: The microgrid's potential for expansion without significant infrastructural changes.
- **Economic benefits**: Cost savings from grid-connected operations like demand response and peak shaving.
- **Power quality**: Adequacy of voltage and frequency levels during islanded operations to ensure safety and functionality.

This report elaborates on the key recommendations for selecting the optimal main configuration, structured into the following primary components:

Identify Critical and Non-Critical Loads

Start by identifying and categorizing the critical and non-critical electrical loads within the distribution network portion that has been selected as a candidate region.

This includes an assessment of the electrical demand for each transformer and feeder to understand their power requirements and criticality in terms of access to uninterrupted supply.

Assess Existing Grid & Generation Capabilities

Review the existing power system, including generation assets and distribution systems.

Evaluate the location of existing generators, storage systems, and spare circuit-breaker bays.

This assessment helps use existing components effectively, minimizing the need for new construction and reducing costs.

Determine Optimal Microgrid Isolation Points

Select electrical switching points based on the location of critical loads, existing grid and generation.

The choice of switching points should aim to include all critical loads within the microgrid while considering the cost-effectiveness of integrating or excluding certain non-critical loads based on their geographic dispersal and connection feasibility.

Incorporate New Generation Sources

Define the boundaries to include new generation or storage sources planned for the microgrid.

The physical and electrical connection points of these new assets should align with the overall design to optimize the microgrid's operational efficiency and resilience.

TECHNO-ECONOMIC COMPARISON OF MICROGRID DESIGN OPTIONS

Given the unique challenges and objectives of microgrid projects, especially those designed for resilience rather than straightforward financial returns, this study recommends shifting the focus from the overall feasibility of microgrid projects to a more nuanced approach. Comparing alternative design options and optimizing the microgrid configuration and sizing is preferable to solely assessing their broad economic feasibility.

Instead, consider two alternative approaches for evaluating microgrid designs: the objective function and optimization approach and the levelized cost of energy comparison approach.

The objective function and optimization approach utilizes advanced optimization techniques like mixed integer-linear programming to explore various configurations, aiming to minimize total ownership costs while maximizing system efficiency and reliability.

The levelized cost of energy approach provides a clear metric to compare economic performance across different microgrid designs, facilitating the identification of the most cost-effective configurations.

The techno-economic comparison of alternative microgrid configurations needs to be thoroughly assessed, considering both initial capital expenditures and ongoing operational expenditures. The objective is to minimize these costs while maximizing system efficiency and load coverage (and other KPIs presented in this report). This could be achieved through strategic DER selection and sizing as well as through the implementation of advanced control systems that optimize the operational expenditure over the system's life cycle.

PROJECT IMPLEMENTATION PLANNING

A well-structured implementation plan is essential for the successful deployment of microgrids. The process begins with project setup, which includes defining the project's scope and identifying all relevant stakeholders. Detailed planning follows, focusing on technical feasibility studies and system design to optimize the microgrid for local conditions.

Each phase is designed to transition smoothly to the next, with a high-level estimated duration provided to stakeholders to support timely and efficient project completion. This comprehensive and adaptable framework is crucial for establishing microgrids that are technically viable, economically rational, and optimally integrated into existing infrastructure, especially in regions like Ukraine where resilience and reliability are critical due to ongoing conflict.

Recommended timelines for the main phases of the implementation cover the following, although these timelines may vary significantly based on several factors, such as the availability of existing DER, the scale of the microgrid, the intricacies of project financing, and the efficiency of the tender process, regulatory approvals, and stakeholder engagement.

1. **Design and tender period**
   - Starts with the completion of conceptual design and includes activities such as system studies, environmental impact assessment, and the tendering process.
   - **Duration**: Approximately three months, starting with Month 1 and finishing by the end of Month 3.
2. **Contract and pre-construction period**
   - Involves finalizing contracts, detailed site surveys, and preparations for construction.
   - **Duration**: Roughly three months, spanning Month 3 to Month 6.
3. **Implementation stage**
   - Covers all major construction activities, including the installation of the main components and system integration.
   - **Duration**: Extends over four months, from Month 6 to Month 10.
4. **Initial energization and commissioning progress**
   - Involves the initial energization, testing, and final adjustments leading to the operational handover.
   - **Duration**: Lasts about two months, from Month 10 to Month 12.

These phases collectively encompass the full 12-month period planned for microgrid project implementation, structuring the progression from conceptual design to full operational commissioning.

Considering the existing capacity deficit in Ukraine, generation and storage systems can be commissioned at an early stage of microgrid project development to work synchronously with the main grid.

CONCLUSION

These guidelines provide a comprehensive and adaptable framework for the development of microgrids, designed to navigate the complexities of distribution-level design with a focus on practical, scalable solutions. By underscoring their technical viability, economic rationality, and solution optimization, this framework promotes the integration of advanced technologies and renewable energy sources. Through careful planning, the employment of sophisticated analytical tools, and the proper selection of components, the guide aims to foster the deployment of DER and microgrids as a fundamental element of sustainable and resilient energy infrastructure. This is particularly pertinent for communities like those in Ukraine, where the prevailing conditions of conflict necessitate robust and reliable power solutions capable of contributing to regional stability and energy independence.

1. DATA REQUIREMENTS FOR MICROGRID PROJECT PREPARATION

The process of data collection and evaluation is a critical initial step in the microgrid development methodology. The information gathered will inform subsequent analyses, such as microgrid sizing, generation and load balancing, cost analysis, network modeling and analyses for validation of design, and automation system design, as well as identifying and optimizing the new system components (investments) required for the implementation of the microgrid.

When the candidate region for the microgrid project is pinpointed, acquiring comprehensive data on the electrical infrastructure becomes essential. Securing a full digital network model is paramount. This model encompasses a detailed schematic of the existing network, capturing all electrical components and their interconnectivity. In the absence of an existing digital model, one must be developed from the ground up.

Subsequently, it is necessary to ascertain the precise coordinates of all transformers and distribution lines within the boundaries of the candidate microgrid region. Any spare feeders at medium-voltage (MV) substations, switching centers, and transformer substations should be identified for contingency planning. Furthermore, investment plans that outline the next five years for the electrical distribution network need to be compiled to ensure alignment with the future trajectory of the microgrid project.

Information pertaining to the status, capacity, type, and geographical location of existing distributed generators is also essential. This encompasses solar, cogeneration, diesel generators, and other forms of embedded generation. Connection points to the network, ownership details, capacity factors, and historical production profiles provide a clear picture of existing generation assets. Detailed information regarding inverter technologies for solar power plants, as well as automation and protection systems in current power plants, is also required to understand the operational landscape.

To effectively design a microgrid that meets the diverse demands of the entire distribution network, it is essential to collect comprehensive load data—both hourly and peak—from transformer centers, feeders, and transformers across all candidate regions. This expansive approach ensures that the microgrid can adapt its operational boundaries dynamically and maintain supply continuity to both critical and non-critical loads dispersed throughout the network. Classification of customers, ranging from critical to non-critical, is crucial in prioritizing energy supply and facilitating effective load-generation balance calculations. This involves not only documenting the total number of customers and their consumption patterns but also meticulously mapping their connection points to the electrical network, including substations, MV feeders, distribution transformers, and service points. By capturing detailed load data for all network components, not just those directly connected to critical loads, the design ensures that the microgrid operates within the proper operational limits at all hours, enhancing reliability and system adequacy across the distribution grid.

Ensuring that existing systems for automation, supervisory control and data acquisition (SCADA), metering, and protection are adequate for a potentially expanded or modified network requires a thorough inventory. This includes a detailed list of equipment within the distribution and low-voltage (LV) electrical networks and their associated processes related to protection philosophy.

Moreover, considering the regional context where warfare and security threats are a concern, the evaluation process must take into account factors such as physical security measures for grid components, redundancy in critical infrastructure, and the potential for cyber threats. These elements are critical to enable the microgrid to withstand and adapt to the unique challenges presented by its environment.

Lastly, preparing a comprehensive unit price list and technical specifications for all potential equipment in the microgrid project helps to create a clear budgetary framework for project execution. This catalog serves as a reference for procurement and aids in the financial planning of the project.

While the table below presents a set of general recommended data items to be collected, actual data requirements may vary from site to site. Tailoring the data collection process to the specific needs and conditions of each site ensures that the microgrid solution is both appropriate and optimized for its intended environment.

TABLE 1: RECOMMENDATIONS ON DATA ITEMS TO BE COLLECTED FOR MICROGRID DESIGN

DATA ITEM	DESCRIPTION	STUDY/PURPOSE OF USE	MAIN DATA OWNER AND DATA FORMAT
Digital network model	Full schematic of existing network architecture, including all electrical components and connectivity	Essential for conducting power system analyses and identifying the power transfer capabilities of existing conductors and transformers or determining necessary upgrades for increased capacity	Distribution system operator (DSO), in the form of DIgSILENT PowerFactory or similar software
Geographic data	Coordinates and physical addresses of all high- and medium-voltage substations	Critical for the optimal physical allocation of critical loads and generation assets within the network	DSO, Geographic Information System (GIS) maps (vector data)
	Coordinates of all distribution transformers (MV/LV)	Integral for precise network mapping and planning of distribution infrastructure	DSO, GIS maps (vector data)
	Detailed maps showing the routes of all overhead and underground distribution lines	Necessary for accurate planning and routing of new distribution lines and ensuring redundancy and reliability in the grid layout	DSO, GIS maps (vector data)
	Granular topographical data to aid in planning the physical layout of new grid components, considering vulnerability to attacks	Utilized for advanced planning of physical grid components' layout, taking into account geographical challenges and potential security vulnerabilities	Municipality or local authorities, maps
	Maps showing redundancy in critical infrastructure to identify areas lacking in backup systems and requiring enhancement	Employed to identify weak points in the network lacking redundancy and to design enhancements to improve grid reliability and resilience	Municipality or local authorities, maps
Substation and distribution line details	Inventory of spare feeders available in MV substations	Vital for identifying existing infrastructure that can be repurposed or upgraded to support microgrid operations and sectionalizing points	DSO, tabular data or single-line diagrams
	Status and capacity of all existing distribution embedded generators, including type (solar, cogeneration, diesel, etc.), capacities, geographical	Required for a comprehensive assessment of existing and potential generation sources, including both dispatchable and variable options, ensuring sufficient capacity to meet electrical load requirements while	DSO, tabular data (DSO is assumed to collect this data from DER owners/operators and to keep it up to date)

TABLE 1: RECOMMENDATIONS ON DATA ITEMS TO BE COLLECTED FOR MICROGRID DESIGN			
DATA ITEM	DESCRIPTION	STUDY/PURPOSE OF USE	MAIN DATA OWNER AND DATA FORMAT
	locations, and network connection points	considering operational characteristics, fuel availability, and cost implications	
	Detailed loading data for each substation, feeder, and transformer	Critical for high-resolution load data analysis, ensuring accurate sizing and optimal performance in both grid-connected and islanded operational modes	DSO, tabular data (from SCADA, automatic meter reading (AMR), or other telemetry system)
	Peak load data for distribution transformers (MV/LV)	Essential for determining the maximum load handling capability and planning upgrades or reinforcements in the distribution network	DSO, tabular data (from SCADA or AMR or via peak measurement campaigns)
	Existing physical security measures for grid components and evaluation of their effectiveness, focusing on areas that have experienced previous disruptions	Necessary for assessing the current security posture of grid components and planning improvements to enhance protection against future disruptions	DSO, unstructured data
Distributed energy resources (DER)/ generation data	Complete list of all distributed generation sources with precise coordinates	Required for a comprehensive assessment of generation sources, facilitating optimal integration into the microgrid and ensuring geographic suitability	DSO, tabular data (DSO is assumed to collect this data from DER owners/operators and keep it up to date)
	Power generation capacity and type of each source	Essential for evaluating the contribution of each generation source to overall grid stability and reliability	
	Historical performance and outage data for each generation source, if available	Critical for analyzing past performance and reliability metrics to predict future behavior and optimize maintenance schedules	DER owners, tabular data
	Availability and storage locations for alternative fuels that can be used for generators, particularly focusing on gas, diesel, biomass, or other locally sourced fuels that may be more accessible during disruptions	Important for ensuring fuel supply security and planning for contingencies in generator operations during grid disruptions	DSO or microgrid project developer, unstructured data
Investment and future planning	Documentation of already committed distribution investments for the next five years, detailing the scope, expected outcomes, and timelines	Critical for aligning microgrid development plans with future grid investments, ensuring coherence and synergy in infrastructure development	DSO, tabular data from distribution network development plan
Equipment and component inventory	Comprehensive equipment-type library detailing specifications and models of all hardware components within the network	Essential for verifying compatibility and ensuring the availability of necessary components for microgrid implementation	DSO, tabular or software format (e.g., DIgSILENT)
	Unit price lists for critical distribution network components including substations, both overhead	Used to support financial planning and procurement processes, ensuring cost-effective acquisition of essential components for microgrid deployment	DSO, tabular data

TABLE 1: RECOMMENDATIONS ON DATA ITEMS TO BE COLLECTED FOR MICROGRID DESIGN			
DATA ITEM	DESCRIPTION	STUDY/PURPOSE OF USE	MAIN DATA OWNER AND DATA FORMAT
	and underground distribution lines, power transformers, distribution transformers, circuit breakers, fuses, current and voltage transformers, and relays		
Energy and demand data for critical loads	Peak and average energy consumption: data on both peak and average energy consumption for each critical service such as hospitals, water treatment plants, and communication centers	Required for accurate load forecasting and demand-side management, ensuring the microgrid can meet the critical load requirements under various operational scenarios	DSO, data from AMR or manual meter readings
	Energy usage patterns: time-of-day and seasonal variations in energy usage for these facilities	Utilized for detailed load profiling and optimizing the operation of the microgrid to match consumption patterns	DSO, data from AMR or manual meter readings
	Backup power specifications: specifications and capacity of existing backup power solutions (e.g., diesel generators, uninterruptable power supply) at each critical facility	Critical for ensuring that backup power systems are adequate to support critical loads during grid outages	DSO, data from AMR or manual meter readings
Load-shedding capabilities	Load-shedding protocols: detailed descriptions of current load shedding protocols including which loads are shed, the sequence of shedding, and under what conditions	Essential for designing effective load-shedding schemes to maintain grid stability and reliability during peak load conditions or emergencies	DSO, unstructured data
	Effectiveness records: historical records of load-shedding instances, including duration, affected areas, and effectiveness in reducing demand on the grid	Utilized for evaluating the performance of load-shedding protocols and refining them to enhance grid stability	DSO, tabular data from operational records
Critical load priority index	Service criticality ratings: a list of critical services ranked by the necessity of maintaining uninterrupted power, including justification for rankings based on public health and safety impacts	Used to prioritize load shedding and ensure that critical services remain operational during both grid-connected and island modes	DSO or microgrid project developer, tabular data
	Infrastructure dependency matrix: data showing the dependency of critical services on each other (e.g., hospitals depending on water treatment plants)	Employed to ensure that interdependent critical services are prioritized appropriately in microgrid operations and contingency planning	DSO or microgrid project developer, tabular data
Load and customer data	Typical load profiles for various customer categories	Critical for accurate modeling of demand and consumption patterns for different customer segments, aiding in demand-side management and load forecasting	DSO, load profiles
	Number of customers and detailed consumption statistics for each customer	Essential for understanding the distribution of load across different	DSO, tabular data

TABLE 1: RECOMMENDATIONS ON DATA ITEMS TO BE COLLECTED FOR MICROGRID DESIGN			
DATA ITEM	DESCRIPTION	STUDY/PURPOSE OF USE	MAIN DATA OWNER AND DATA FORMAT
	category, which may include residential, commercial, and industrial sectors	customer categories and planning tailored demand-response strategies	
System protection and monitoring	Detailed list of protection relay attributes and settings, including enabled protection schemes/types and typical relay parameters	Essential to ensure that adequate protection schemes are in place to safeguard the microgrid against faults and maintain reliable operation	DSO, tabular data
	Information on fault clearing times for different parts of the network	Critical for designing protection systems that ensure rapid fault clearance, minimizing disruption and damage to the grid infrastructure	DSO, tabular data
	Specifications and capabilities of existing SCADA, energy analyzers, substation automation, and metering systems and solutions to understand whether there is any need for further upgrades or any new functionality	Necessary for assessing the integration of existing systems into the microgrid management framework and identifying required upgrades or new functionalities	DSO, existing system description documents
Existing telemetry and telecontrol systems	Any existing systems for SCADA, grid AMR, etc., that should be considered either to be part of the microgrid management system or be integrated into the newly designed monitoring and control system	Essential for real-time monitoring and control of the microgrid, ensuring seamless integration of existing telemetry and telecontrol systems	DSO, existing system description documents
Existing reliability and performance of the main grid	Historical data on grid reliability and performance indices (e.g., SAIFI, SAIDI)	Critical for ensuring that proposed microgrid solutions enhance overall system reliability and resilience, informed by site-specific reviews of current systems and maintenance practices	DSO, tabular data

To ensure alignment with industry-leading power system analysis and simulation software such as DIgSILENT PowerFactory, PSS Sincal, DAKAR, and others, the table below outlines the necessary technical attributes for various existing DER, substations, transformers, and distribution lines. It covers essential data categories including general information, electrical characteristics, operational data, connection details, unique identifiers, location coordinates, ownership details, types, and commissioning dates of system components. Additionally, it provides detailed information such as rated capacities, number of units, inverter specifications, power factor settings, and connection schemes. Operational metrics such as historical generation data, capacity factors, maintenance schedules, and environmental operating limits are also detailed to facilitate the effective integration of these components into power system models.

By methodically gathering and leveraging this data, practitioners can conduct precise simulation and analysis scenarios essential for evaluating system performance, identifying potential upgrades, and ensuring robust operation under varying conditions.

TABLE 2: TECHNICAL ATTRIBUTES TO BE COLLECTED FOR THE EXISTING SYSTEM COMPONENTS

MAIN SYSTEM COMPONENTS	DATA CATEGORY	KEY ATTRIBUTES
Existing DER	General information	**Name/ID**: Unique identifier for the DER **Location (coordinates)**: Latitude and longitude **Owner**: Name of the entity that owns the DER **Type (solar, wind, diesel, etc.)**: Specific type of DER **Commissioning date**: Date when the DER was connected to the grid
	Electrical characteristics	**Rated capacity (MW)**: Nominal power output **Number of units**: Total number of generating units **Inverter specifications**: Type (e.g., central, string) Capacity (kW/MW) Maximum power point tracking range Control mode (voltage, power factor, etc.) **Power factor (cos ϕ)**: Typically set point and possible operating range **Reactive power capability (MVAR)**: Range of reactive power control (either cos ϕ or MVAR range would be enough) **Voltage level (kilovolt - kV)**: Connection voltage level **Connection scheme:** Diagram of the DER connection (direct line connection or connection through a transformer or substation, etc.) **Ramp rate limits (MW/min)**: Rate of change of power output
	Operational data	**Historical generation data (hourly, daily, monthly)**: Time series data of generation **Capacity factor**: Average power output divided by rated power **Availability factor**: Percentage of time the unit is operational **Maintenance schedule**: Planned maintenance periods (if there any predefined plans) **Operational constraints (e.g., temperature, wind speed)**: Environmental limits for operation
	Connection details	**Connection point (e.g., substation, feeder)**: Specific grid connection point **Grid connection agreement**: Terms of grid connection **Protection settings (e.g., relay settings)**: Specific protection parameters **Control system details (e.g., SCADA integration)**: Communication and control system details **Impedance (complex impedance (resistance + reactance): R+jX)**: Impedance of the connection line and/or transformer
MV substations	General information	**Name/ID**: Unique identifier for the substation **Location (coordinates)**: Latitude and longitude **Owner/operator**: Entity responsible for the substation (DSO vs. third party) **Commissioning date**: Date when the substation was commissioned
	Electrical characteristics	**Voltage levels (primary and secondary)**: Nominal voltage levels (e.g., 35/6 kV) **Transformer ratings (MVA)**: Apparent power rating

TABLE 2: TECHNICAL ATTRIBUTES TO BE COLLECTED FOR THE EXISTING SYSTEM COMPONENTS		
MAIN SYSTEM COMPONENTS	DATA CATEGORY	KEY ATTRIBUTES
		Number of transformers: Total number of transformers in the substation **Impedance (%Z)**: Percentage impedance of transformers **Cooling type (oil natural air forced, oil natural air natural, etc.)**: Cooling method **Short circuit level (kiloampere - kA)**: Maximum short circuit current **Protection systems**: **Relay types and settings**: Specific protection relay models and settings **Circuit breaker specifications**: Ratings and types **Isolation and earthing systems**: Grounding details **Busbar configuration**: Single bus, double bus, etc. **Other switchgear type and ratings**: Rating and types of disconnector and load break switch equipment
	Operational data	**Load data**: Peak, average, and minimum load values **Historical load profiles**: Time series load data **Maintenance records**: History of maintenance activities **Reliability data (SAIFI, SAIDI)**: System reliability indices
	Topology data	**Single-line diagrams or** • **Incoming and outgoing feeders**: Details of feeders connected to the substation • **Connection to transmission network**: Points of connection to higher-voltage network **SCADA and monitoring systems**: Main parameters of control and monitoring systems
Distribution transformers (transformer points) (MV/LV)	General information	**Name/ID**: Unique identifier for the transformer **Location (coordinates)**: Latitude and longitude **Owner/operator**: Entity responsible for the transformer (DSO vs. third party) **Commissioning date**: Date when the transformer was commissioned
	Electrical attributes	**Rated power (kilovolt-ampere - kVA)**: Nominal power rating **Primary and secondary voltages (kV)**: Voltage levels on both sides **Impedance (%Z)**: Percentage impedance **Cooling type**: Oil natural air forced, oil natural air natural, etc. **Tap changer details (on-load, off-load)**: Tap changer specifications **Vector group**: Phase displacement group **Short-circuit impedance (R+jX)**: Impedance values for short-circuit studies
	Operational data	**Load data**: Peak, average, and minimum load values **Historical load profiles**: Time series load data
	Protection and control	**Protection systems (relay settings)**: Specific relay settings and types **Circuit breaker specifications**: Ratings and types **Earthing details**: Grounding method and resistance (if available) **Control systems (remote/local control)**: Control system details

TABLE 2: TECHNICAL ATTRIBUTES TO BE COLLECTED FOR THE EXISTING SYSTEM COMPONENTS		
MAIN SYSTEM COMPONENTS	DATA CATEGORY	KEY ATTRIBUTES
Distribution line	General information	**Line ID/name**: Unique identifier for the line **Route description**: Physical description of the route **Owner/operator**: Entity responsible for the line **Commissioning date**: Date when the line was commissioned
	Electrical attributes	**Voltage level (kV)**: Nominal voltage level **Conductor type and size**: Type (e.g., aluminum conductor steel reinforced) and cross-sectional area **Length of line (kilometer - km)**: Total length of the line **Impedance (R+jX per km)**: Resistance and reactance per kilometer **Thermal rating (current capacity in ampere)**: Maximum current capacity **Grounding system**: Earthing details (if available)
	Operational data	**Load data:** Peak, average, and minimum load values **Historical load profiles**: Time series load data **Fault history**: Record of faults and outages (if available) **Maintenance records**: History of maintenance activities (if available) **Reliability data (SAIFI, SAIDI)**: System reliability indices (if available)
	Protection and control	**Protection systems (relay settings)**: Specific protection relay settings **Switchgear details**: Types and ratings of switchgear equipment **Sectionalizers/reclosers**: Details of automatic sectionalizing equipment **SCADA integration**: Details of SCADA system integration

2. IDENTIFYING THE MICROGRID BORDERS

The process of defining microgrid boundaries begins with a thorough assessment of the local electrical distribution network. This involves identifying and categorizing the critical and non-critical electrical loads within the area selected as a candidate for a microgrid. A detailed understanding of the power requirements and criticality of each transformer and feeder is crucial, as it determines which facilities require an uninterrupted power supply.

2.1. NETWORK VULNERABILITY ASSESSMENT FOR MICROGRID IMPLEMENTATION

The first step is to evaluate the network's vulnerability. This process includes analyzing the electrical grid's susceptibility to disruptions affecting power supply and stability. Identifying operational scenarios is crucial for microgrid function. These scenarios encompass blackouts, brownouts, N-1 contingency (N-1), or in high mission-critical cases N-2 contingency (N-2), and large-scale distribution outages.

Assessing the probability of various outage severities involves probabilistic analysis. This helps prioritize regions based on their susceptibility to disruptions.

A historical analysis of past outages, including blackouts, brownouts, and N-1/N-2 contingencies, provides insights into grid reliability and typical challenges.

Regions particularly vulnerable to external threats, such as war or natural disasters, require an evaluation of potential impacts on the power grid.

Analyzing the grid's capacity to handle single- and dual-component failures (N-1 and N-2 contingencies) identifies areas where grid resilience is lacking.

Geospatial analysis using GIS tools overlays data on a regional map, pinpointing areas most vulnerable based on outage probability, historical data, and contingency risks. This visual representation aids in identifying regions with the highest need for microgrid interventions.

2.2. CATEGORIZING AND GROUPING EXISTING LOADS AND GENERATION

Once the candidate region is decided, the logical step is to organize existing loads and any available generation resources. This is achieved by employing existing or potentially new electrical isolation components, such as switches or breakers, within the distribution system. These components play a crucial role in defining the microgrid's boundaries by serving two primary functions:

- Determining isolation points: They help select the specific points in the distribution network that will act as gatekeepers for the microgrid, effectively isolating it from the main grid during operational shifts or power outages.
- Segregating loads: They help identify which loads, both critical and non-critical, lie downstream of these isolation points and are therefore included within the microgrid.

The placement of these isolation points is strategic and dependent on multiple factors, including the location of critical loads and existing generation capabilities. The decision-making process considers:

- Location of critical loads: The positioning of critical loads often dictates the selection of the isolation point. For instance, a microgrid might be designed to encompass all critical infrastructure within a single isolated segment to ensure its uninterrupted functionality during grid failures.

- Cost considerations: Utilizing existing infrastructure for isolation points can be more cost-effective than creating new installations. This includes not only the physical components but also the integration of these points within the existing network layout.
- Existing and new generation integration: The inclusion of existing generation assets and the potential addition of new energy sources can influence how boundaries are expanded or contracted. Integrating new generation facilities might require adjusting the existing boundary to accommodate these sources efficiently.
- Current and projected electricity demands are assessed across different regions, considering demographic and economic growth trends. Special attention is given to areas with potential high growth in critical sectors such as industrial zones and commercial hubs, where increased load demand may exceed the existing grid's capacity. This step helps identify areas that would benefit most from the stability and capacity enhancements provided by microgrids.

2.3. ANALYZE LOAD CRITICALITY FOR MICROGRID IMPLEMENTATION

This step evaluates critical infrastructure such as hospitals, data centers, public services, and defense systems to determine the potential impact of power disruptions on their operations. This analysis needs to include evaluating the value of lost load (VOLL) and economic activity in the region to quantify the cost of power outages to these critical services. By assessing load criticality, regions where power reliability is paramount can be prioritized for microgrid installation.

Critical infrastructure needs to be identified and categorized to understand where power reliability is most necessary to sustain essential functions and services. This includes:

- Hospitals and medical centers: Facilities providing critical health services, including emergency rooms, intensive care units, and other medical services reliant on stable power
- Data and telecommunication centers: Major data centers and telecommunication hubs essential for maintaining communication systems, especially during emergencies
- Public services: Key public service facilities such as water treatment plants, sewage facilities, and emergency services like fire and police stations, which require continuous power for public safety and health
- Defense facilities: Military bases and defense-related installations where power reliability is crucial for national security operations
- Industrial facilities: Major industrial operations that significantly impact the local or regional economy, particularly those involving high levels of automation and critical manufacturing processes

A high-level assessment of the economic impact and VOLL is recommended once critical loads have been identified. This needs to include:

- Economic activity assessment: Evaluating overall economic activity in the region, focusing on how power reliability influences industrial output, employment, and economic stability, is recommended.

- Optional VOLL evaluation: Calculating the VOLL for critical services to provide a quantified estimate of the economic cost associated with power outages is recommended. This evaluation may not be conducted universally but needs to be applied in regions with precise economic impact data.

- High-level economic impact overview: For regions where detailed VOLL calculations are not feasible, a general assessment of potential economic impacts based on historical outage data and the presence of critical infrastructure is recommended to provide sufficient insight to prioritize regions based on economic risks associated with power outages.

2.4. SELECTING MICROGRID ISOLATION POINTS

Determining optimal microgrid isolation points is crucial for integrating a microgrid with existing power systems. This process ensures all critical loads are included within the microgrid while evaluating the cost-effectiveness of incorporating or excluding non-critical loads based on their geographic distribution and connectivity feasibility.

- Inclusion of critical loads: The primary focus is to encompass all essential services—like hospitals and emergency response centers—within the microgrid to guarantee uninterrupted power during grid failures.

- Cost-effectiveness and non-critical loads: The inclusion of non-critical loads, such as residential and non-essential commercial facilities, is assessed for cost-effectiveness. These loads are integrated only if they do not disproportionately increase the microgrid's complexity and cost relative to the benefits they bring.

- Leveraging existing infrastructure: The selection of electrical switching points, where the microgrid disconnects from the main grid, relies heavily on the existing grid layout and available generation assets. Optimal points are those that minimize the need for new construction and efficiently connect to existing generation resources.

- Network configuration optimization: The process involves using modeling tools to simulate various scenarios, helping to refine the configuration of the microgrid. The goal is to ensure it meets critical needs efficiently and remains adaptable for future expansions.

2.5. TOPOLOGICAL OPTIONS FOR MICROGRID BORDERS

Potential topological options could be considered to identify the microgrid border to support the scalability and adaptability of the microgrid within the distribution network. *Figure 2* presents different types of microgrid configurations, organized by the scale and complexity of integration with existing electrical infrastructure.

1. Full substation-level microgrid (purple zone): This configuration encompasses the entire area served by a distribution or subtransmission substation. It includes all feeders and generation sources connected at this level, facilitating comprehensive control over generation and distribution within this boundary. This type of microgrid is capable of supporting an extensive

area with multiple loads and generation types, ensuring robust resilience and energy management at a larger scale.

2. Full feeder-level microgrid (green zone): This smaller, more focused area within the substation-level microgrid includes all loads and generation sources along a single feeder line. It offers specific, feeder-based control, allowing for targeted energy management and resilience strategies. This setup is suitable for areas with critical loads that benefit from dedicated management, such as industrial zones or large commercial districts.
3. Partial feeder-level microgrid (blue zone): Representing a segment of a feeder, this microgrid type includes only a portion of the loads and generation resources found along a specific feeder line. It is ideal for localized energy solutions where only certain sections of a feeder require enhanced reliability and control, such as a hospital campus or a small residential area with critical needs.
4. Single-load microgrid (orange zone): The smallest scale illustrated, this microgrid type is dedicated to a single critical load, such as a hospital, data center, or emergency services facility. It typically includes one or more local generation sources directly connected to the load, maximizing control over power quality and supply continuity for essential services.

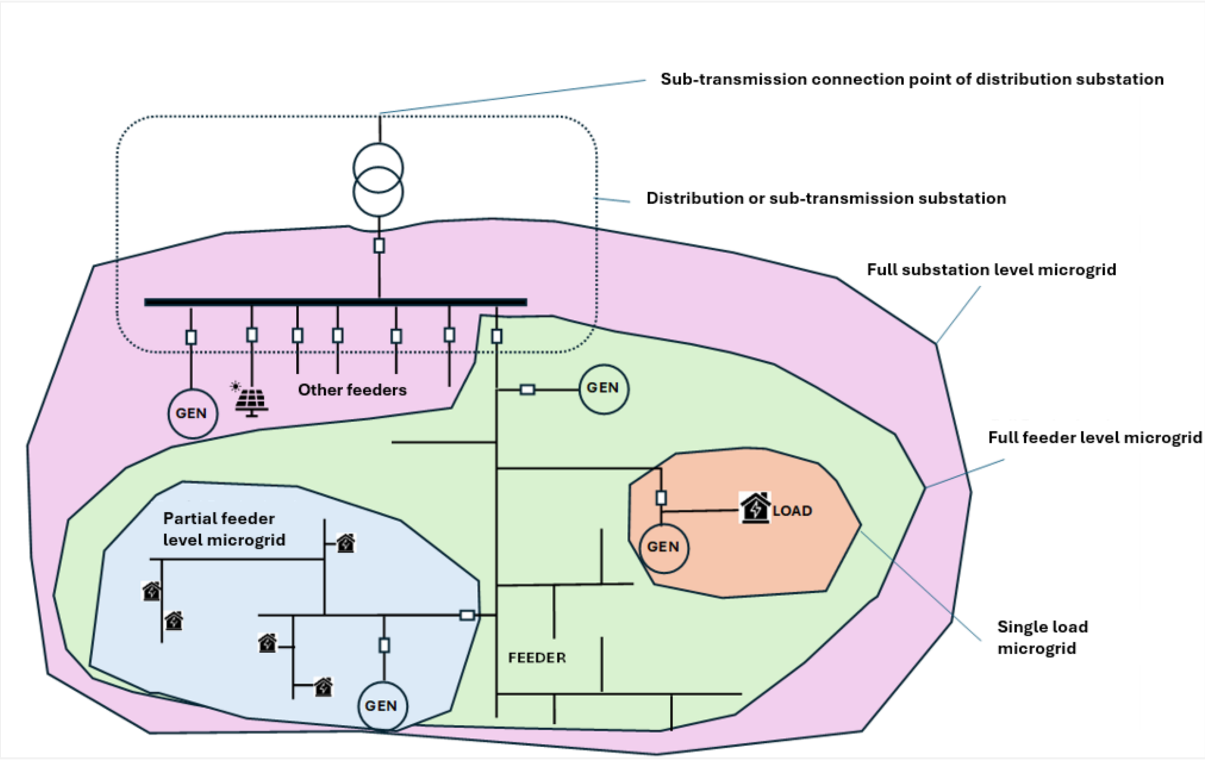


Figure 2: Different potential types of microgrid borders

The application of these principles can vary widely based on the project's goals and the specific scenarios envisaged. For instance:

- A microgrid might include diverse forms of generation like diesel generators, gas motors, and solar photovoltaic (PV) arrays, each connected at different points within the distribution system.

- In scenarios where new generation sources like solar are added, the boundaries might be adjusted to include these assets, sometimes requiring a re-evaluation of the most cost-effective points for electrical isolation.

2.6. DYNAMIC BORDER MANAGEMENT OF THE MICROGRID

Dynamic border management of microgrids allows for the sophisticated division of the power distribution system into smaller, self-sufficient units with flexible boundaries that can be adjusted in real-time based on current operational conditions. This adaptability enhances resiliency and is particularly advantageous in scenarios with high renewable energy sources, where it optimizes the utilization of available renewable energy. However, despite its benefits, this method introduces significant complexity and, due to intricate implementation requirements, may not always be the preferred design option.

Key aspects of dynamic border management include segmentation, dynamic boundaries, load prioritization, operational scenarios, mathematical formulations for switching actions, and the evaluation of resiliency metrics, defined below. This detailed approach ensures that critical loads are supplied during outages and the overall network remains robust and adaptable.

1. Segmentation: The distribution system should be divided into smaller, self-sufficient microgrids with flexible boundaries.

2. Dynamic boundaries: Flexible boundaries should be preplanned to adapt during normal operation or emergencies. Automated switches and control agents can adjust microgrid boundaries dynamically based on operational conditions.

3. Mixed-integer linear programming: MILP is used to determine optimal switching actions for adjusting boundaries and supplying critical loads.

4. Load prioritization:

   – Classification: Loads should be classified into critical loads, medium-critical loads, and non-critical loads based on their importance to grid stability.

   – Objective function: The objective function should aim to maximize the supply to critical loads during outages.

5. Operational scenarios:

   – Scenario planning: Various operational scenarios (daytime, nighttime) should be considered, each with different load demands and generation capabilities.

   – Simulation: Simulation tools (e.g., DIgSILENT DPL scripts, MATLAB, GridLAB-D) should be used to validate the operational feasibility of the microgrid configurations.

6. Mathematical formulation for defining possible switching actions for dynamic grid border management of the microgrid(s) as follows:

Power demand equations

$$P_{Source} = \Delta_n * (\sum P_i - \sum P_{DG_m})$$

$$Q_{Source} = \Delta_n * (\sum Q_i - \sum Q_{DG_m})$$

Where:

- P_{Source} and Q_{Source}: Source real and reactive power
- Δ_n: Deficiency coefficient for scenario n
- P_i and Q_i: Real and reactive power demand at node i
- P_{DG_m} and Q_{DG_m}: Real and reactive power output of distributed generation in microgrid m

Cluster formation constraints

$\sum \alpha_{i_m}$ = 1 for all i in N

α_{i_m} = 1 for i = m, for all i in N, m in M

Where:

- α_{i_m}: Binary variable indicating if node i belongs to microgrid m

Power flow constraints

- Voltage limits

  $|V_i^{min}| \leq |V_i| \leq |V_i^{max}|$

  Where:

  - V_i: Voltage at node i
  - V_i^{min} and V_i^{max}: Minimum and maximum allowable voltages

- Branch capacity limits

  $|I_F^i| \leq |I_F^{imax}|$ and $|I_R^i| \leq |I_R^{imax}|$

  Where:

  - I_F^i and I_R^i: Forward and reverse current flow capacities in the i[th] branch
  - I_F^{imax} and I_R^{imax}: Maximum allowable currents

- Distributed generation (DG) power constraints

  $P_{DG_{min}} \leq P_{DG} \leq P_{DG_{max}}$

$Q_{DG_{min}} \leq Q_{DG} \leq Q_{DG_{max}}$

Where:

- P_{DG} and Q_{DG}: Real and reactive power capacities of distributed generation
- $P_{DG_{min}}$ and $P_{DG_{max}}$: Minimum and maximum allowable real power
- $Q_{DG_{min}}$ and $Q_{DG_{max}}$: Minimum and maximum allowable reactive power

7. Resiliency metrics: The composite resiliency score could be used to evaluate the overall resilience of the microgrid configurations. This score will be based on several key metrics:

   – Diameter: The diameter of a network is the longest shortest path between any two nodes. A smaller diameter indicates a more resilient microgrid, as it implies shorter paths for power distribution and quicker fault isolation.

   – Betweenness centrality: Betweenness centrality measures the extent to which a node lies on the paths between other nodes. High betweenness centrality nodes are critical for maintaining connectivity in the network. Identifying these nodes helps strengthen the network's resilience by protecting critical points.

   – Algebraic connectivity: Algebraic connectivity, or the second smallest eigenvalue of the Laplacian matrix of the network, reflects the robustness of the network. Higher algebraic connectivity indicates a more resilient network, as it suggests better overall connectivity and fault tolerance.

8. Analytic hierarchy process: The analytic hierarchy process could be used to assign weights to the resiliency metrics and calculate a composite score for each microgrid configuration. This involves:

   – Defining criteria: Establish criteria based on the chosen resiliency metrics (diameter, betweenness centrality, algebraic connectivity).

   – Pairwise comparison: Perform pairwise comparisons between the criteria to establish their relative importance. This comparison is usually based on expert judgment and involves assigning numerical values to the importance of one criterion over another.

   – Calculating weights: Use the pairwise comparison matrix to calculate the weights for each criterion. These weights reflect the relative importance of each metric in the overall composite score.

   – Scoring configurations: Evaluate each microgrid configuration against the defined criteria. Multiply the score for each criterion by its respective weight and sum the results to obtain the composite resiliency score.

9. Automated switches and control points

   – Automated switches (could be remote-controlled reclosers for overhead lines) should be placed at key nodes to facilitate dynamic boundary adjustments.

- Control agents should be assigned to coordinate DER and manage information exchange between clusters. Agents can dynamically adjust the boundaries of microgrids to optimize the system's resiliency.

10. Dynamic reconfiguration

    - Preplanned boundaries should be established for various scenarios (e.g., daytime and nighttime operations).

    - Real-time data and automated systems should be used to adjust boundaries based on current conditions, ensuring optimal performance and resiliency.

11. Algorithm for dynamic boundaries

    - Initialization starts with preplanned microgrid boundaries based on normal operating conditions.

    - Continuous monitoring of the power system's state, including load demand and generation availability, is essential.

    - When a disturbance is detected, MILP should be used to determine the best boundary adjustments to isolate faults and maintain supply to critical loads.

    - Boundary adjustments should be implemented using automated switches, ensuring the microgrids operate in their most resilient configurations.

12. Simulation and validation

    - Tools like MATLAB should be used to simulate different microgrid configurations and validate their performance under various scenarios.

    - The proposed configurations should meet all operational constraints and maximize resiliency.

13. Operational procedures

    - Microgrid configurations should be regularly updated based on load demand and generation capacity.

    - In an emergency, microgrid boundaries and switch statuses should be quickly adapted to isolate faults and maintain supply to critical loads.

3. OPTIONS FOR MICROGRID CONFIGURATION DESIGN AND PARAMETERS

3.1. POTENTIAL OPTIONS FOR MICROGRID CONFIGURATION DESIGN

Microgrid configurations are designed to provide tailored energy solutions that enhance the reliability, efficiency, and sustainability of electricity supply in diverse environments. By evaluating various configuration options, stakeholders can optimize microgrid designs to meet specific operational requirements and adapt to geographical, economical, and environmental conditions. This decision-making process involves considering multiple dimensions such as sizing, energy sources, management strategies, and control systems, each offering distinct advantages and suited to particular scenarios.

The table outlined here presents a comprehensive overview of potential microgrid configurations, categorizing them into several key aspects such as the demand to be met by the microgrid, the endurance of off-grid operations, types of DER, and management strategies. These aspects are critical for ensuring that the microgrid not only meets the current energy demands but is also scalable and adaptable to future changes. Each configuration option is associated with specific operational capabilities and is designed to optimize performance across various metrics such as system resilience, cost-effectiveness, and environmental impact. The selection of the right configuration is crucial for achieving a balance between operational demands and sustainability objectives, thereby ensuring the long-term success of microgrid implementations.

Understanding these options enables planners and engineers to design microgrids that are not only efficient and resilient but also capable of integrating seamlessly with existing energy infrastructure or operating independently as stand-alone systems. This strategic approach to microgrid design is essential for addressing the growing complexity and evolving challenges of modern energy systems, promoting more sustainable and reliable energy solutions.

TABLE 3: SUMMARY TABLE FOR MICROGRID CONFIGURATION OPTIONS TO BE CONSIDERED

KEY ASPECTS	OPTIONS				
Sizing/demand to be met by the microgrid	Critical Loads Only	Critical + Non-Critical Loads	Daytime Loads Only	Full Load (Day & Night)	
Expected off-grid endurance of microgrid operations	2 Hours	8 Hours	24 Hours	1 Month	Indefinite
DER type/source	Solar PV + Battery	Diesel + Battery	Gas Generator Set + Battery	Solar + Diesel + Gas	Solar PV + Gas Generator Set
Topology of generation	Centralized	Decentralized	Hybrid	Modular	Portable
Management of microgrid borders	Static/Defined	Dynamic/Adaptive			
Control strategies	Centralized	Decentralized	Peer-to-peer		
Takeover of microgrid	Manual Takeover at Site	Manual Takeover via Telecontrol	Autonomous/Hot Standby	Time Programmed	

1. **Sizing/demand to be met by the microgrid**

   – Critical loads only: The microgrid is designed to support only essential services and critical infrastructure.

   – Critical + non-critical loads: Extends support beyond critical loads to include non-essential services, enhancing operational flexibility.

   – Daytime loads only: Focuses on providing power during daytime hours, typically aligned with peak solar production periods.

   – Full load (day and night): Ensures continuous operation, covering all loads throughout the day and night, maximizing availability.

2. **Expected off-grid endurance of microgrid operations**

   – 2 hours: Suitable for short-term outages, primarily ensuring continuity during brief interruptions.

   – 8 hours: Supports a full workday, useful in regions with frequent but short-lived grid instability.

   – 24 hours: Designed to maintain operations for a full day without grid support, ideal for areas with extended grid failures.

   – 1 month: Provides long-term resilience, suitable for extreme conditions or areas with seasonal grid issues.

   – Indefinite: The microgrid is capable of operating independently of the grid indefinitely, typically with substantial renewable energy sources and storage capacity.

3. **DER type/source**

   – Solar PV + battery: Utilizes PV panels and battery storage, emphasizing sustainability and renewable sources.

   – Diesel + battery: Combines traditional diesel generators with batteries, offering reliability with some energy storage benefits.

   – Gas generator set + battery: Integrates gas-powered generation with battery storage, balancing efficiency and lower emissions.

   – Solar + diesel + gas: A hybrid approach using solar, diesel, and gas to ensure high reliability and variable load management.

   – Solar PV + gas generator set: Pairs solar power with gas generators, providing a balance of renewable and reliable gas energy.

4. **Topology of generation**

   – Centralized: A single, central source of power generation, simplifying management but potentially increasing vulnerability.

- Decentralized: Multiple generation sources distributed throughout the microgrid, enhancing resilience and reducing transmission losses.
- Hybrid: Combines both centralized and decentralized elements, optimizing both resilience and efficiency.
- Modular: Features plug-and-play components that can be scaled or reconfigured as needed.
- Portable: Mobile generation equipment that can be relocated as required, suitable for temporary or emergency situations.

5. **Management of microgrid borders**
   - Static/defined: Fixed boundaries with predefined connections and disconnections from the main grid.
   - Dynamic/adaptive: Flexible boundaries that can change based on load demands, generation capacity, and other conditions.
   - Peer-to-peer: Allows for autonomous trading and sharing of energy between different entities within the microgrid.
6. **Control strategies**
   - Centralized: All control decisions are made from a central point, simplifying coordination but may increase response times to local changes.
   - Decentralized: Control is distributed among various components, enhancing responsiveness and local optimization.
   - Peer-to-peer: Employs a networked approach where components communicate and make decisions without central oversight, fostering resilience and flexibility.
7. **Takeover of microgrid**
   - Manual takeover at site: Operations can be manually taken over by personnel on-site, allowing for direct human intervention.
   - Manual takeover via telecontrol: Remote manual control, providing flexibility and immediate response without needing on-site presence.
   - Autonomous/hot standby: Fully automated systems capable of self-managing during critical situations without human intervention.
   - Time programmed: Operations switchover is pre-scheduled or triggered by specific conditions, offering predictability and planned responses.

Below is a detailed guideline that outlines the key aspects and decision-making criteria that should be considered to ensure a robust and efficient microgrid design.

TABLE 4: ASPECTS OF DECISION-MAKING CRITERIA	
ASPECT OF MICROGRID DESIGN	DECISION-MAKING CRITERIA
Sizing/demand to be met by the microgrid	1. Criticality of loads, 2. Available generation capacity 3. Energy storage capabilities 4. Cost implications
Expected off-grid endurance of microgrid operations	1. Historical outage durations 2. Risk assessment of potential threats 3. Fuel storage capacity 4. Renewable energy integration potential 5. Mission criticality of load
DER type/source	1. Local resource availability (solar irradiance, fuel supply) 2. Environmental considerations 3. Initial and operational costs 4. Reliability and maintenance requirements 5. Space constraints
Topology of generation	1. Geographic distribution of loads 2. Scalability requirements 3. Resilience needs 4. Existing infrastructure 5. Operational flexibility
Management of microgrid borders	1. Load variability 2. System complexity 3. Operational requirements 4. Control system capabilities 5. Future expansion plans
Control strategies	1. System size and complexity 2. Communication infrastructure 3. Desired level of autonomy 4. Cybersecurity considerations
Takeover of microgrid	1. Personnel availability and expertise 2. Response time requirements 3. Remote monitoring capabilities 4. Automation level desired 5. Regulatory compliance with grid code and technical regulations

Sizing/demand to be met by the microgrid

- Criticality of loads: Focus on ensuring power delivery to essential services that are crucial for safety and critical operations.
- Available generation capacity: Assess the total capacity of all available generators and renewable energy sources to meet demand effectively.
- Energy storage capabilities: Evaluate the adequacy of batteries and other storage technologies to support power continuity during grid failures or peak demand periods.
- Cost implications: Consider both the initial investment and ongoing operational costs associated with different sizing options.

Expected off-grid endurance of microgrid operations

- Historical outage durations: Utilize past outage data to estimate potential future outages and define required endurance capacities.
- Risk assessment of potential threats: Analyze risks from natural disasters, cyber-attacks, or equipment failures that might affect grid stability.
- Fuel storage capacity: Determine necessary fuel reserves to sustain operations during prolonged grid failures.
- Renewable energy integration potential: Assess the feasibility of incorporating renewable energy sources to enhance sustainability and reduce reliance on traditional fuels.
- Mission criticality of load: Identify mission-critical loads that must remain operational to maintain essential services.

DER type/source

- Local resource availability: Examine the availability of local resources like solar irradiance and fuel supplies.
- Environmental considerations: Evaluate the environmental impacts of deploying specific DER to ensure sustainable practices.
- Initial and operational costs: Analyze costs associated with the installation, maintenance, and operation of DER.
- Reliability and maintenance requirements: Assess the reliability of each DER option and the maintenance efforts required.
- Space constraints: Factor in the physical space requirements for installing DER systems.

Topology of generation

- Geographic distribution of loads: Plan generation sites based on the spatial distribution of demand within the microgrid area.
- Scalability requirements: Design the system with scalability in mind to accommodate future demand increases or technological advancements.
- Resilience needs: Ensure the infrastructure is robust enough to withstand various disruptions and maintain continuous operation.
- Existing infrastructure: Leverage existing infrastructure to optimize costs and enhance system efficiency.
- Operational flexibility: Allow for adjustments in operational strategy based on dynamic conditions or demand changes.

Management of microgrid borders

- Load variability: Manage demand fluctuations effectively by adjusting power supply strategies.
- System complexity: Address complexities in integrating multiple energy sources and managing their interactions.
- Operational requirements: Meet specific operational demands based on the microgrid's purpose and scale.
- Control system capabilities: Ensure the control systems can effectively manage the dynamic operational environment of the microgrid.
- Future expansion plans: Consider potential future expansions and the ability to integrate new technologies without significant redesign.

Control strategies

- System size and complexity: Develop control strategies that are appropriate for the size and complexity of the system.
- Communication infrastructure: Establish a robust communication network to support effective control and monitoring.
- Desired level of autonomy: Determine the appropriate level of automation needed to minimize manual intervention while maintaining reliability.
- Cybersecurity considerations: Implement strong cybersecurity measures to protect the system against digital threats.

Takeover of microgrid

- Personnel availability and expertise: Ensure that adequately trained personnel are available for system operation and emergency management.
- Response time requirements: Set up protocols for rapid response to system disruptions or failures.
- Remote monitoring capabilities: Utilize advanced technologies for remote system monitoring and management.
- Automation level desired: Integrate automation to enhance system responsiveness and operational efficiency.
- Regulatory compliance: Comply with all relevant grid codes and technical regulations to ensure the microgrid operates legally and safely.

3.2. KEY PERFORMANCE INDICATORS FOR COMPARING MICROGRID CONFIGURATION DESIGN OPTIONS

In evaluating microgrid configurations, a set of KPIs provides essential metrics to assess and compare the performance, efficiency, and resilience of different designs. While not all KPIs need to be applied simultaneously in every assessment scenario, this comprehensive set ensures that stakeholders can select the most relevant metrics based on specific operational goals, environmental conditions, and regulatory requirements. This flexibility allows for a tailored analysis that aligns with particular project needs, making the evaluation process both thorough and adaptable.

The chosen KPIs encompass a broad range of measurable outcomes, from technical performance and energy efficiency to economic viability and environmental impact. They are designed to provide a quantitative foundation for decision-making, facilitating comparisons between different microgrid models and configurations under various conditions.

TABLE 5: KPIS FOR COMPARING MICROGRID CONFIGURATION DESIGN OPTIONS

KPI	DESCRIPTION
Off-grid system endurance	Measures the maximum duration (in hours or days) that the microgrid can operate independently under peak critical load conditions without external grid support.

TABLE 5: KPIS FOR COMPARING MICROGRID CONFIGURATION DESIGN OPTIONS	
KPI	DESCRIPTION
Peak critical load served	Quantifies the microgrid's capacity to handle peak demand loads (measured in kW or MW) of critical systems during both standard and heightened operational scenarios.
Load shedding level	Assesses the percentage of total load that can be disconnected (shut off) to prioritize critical operations under energy scarcity conditions, ensuring core functionalities are maintained.
Restoration time and proper transition	Measures the time required (in seconds or minutes) to transition from grid-connected to island mode after an outage and, similarly, the time to revert back to grid power with assessments of transition smoothness and system stability.
Optimized DER load factor	Evaluates the load factor of DER, aiming for a high percentage usage rate over time to reduce instances of underutilization and improve overall efficiency.
N-1 contingency	Defines the microgrid's ability to maintain critical load operations (as a percentage of total capacity) in the event of failure of any significant DER component, ensuring continuous operation.
Degree of renewable energy contribution	Measures the percentage of the microgrid's total energy output that is generated from renewable sources, highlighting the system's sustainability and reliance on renewable energy.
Operational visibility	Evaluates the effectiveness of the microgrid's control systems by quantifying the delay in system monitoring feedback (in real-time seconds) and the accuracy of operational data representation.
Expandability and reconfigurability	Assesses the microgrid's capacity for expansion in terms of additional load and infrastructure integration, quantified by the percentage increase in load or generation capacity without requiring significant infrastructure overhaul.
Grid-connected and economic applications	Measures the economic benefits derived from grid-connected operations such as cost savings from demand response and peak shaving activities, expressed as a percentage reduction in energy costs.
Power quality	Monitors the variation in voltage and frequency levels within acceptable industry standards during islanded operations, aiming to keep these variations within a tight percentage range to ensure the stability and safety of connected loads.

When selecting the optimal microgrid configuration, it is imperative to conduct a systematic evaluation that considers multiple factors critical to the project's success. This decision-making process is guided by a structured methodology that involves defining criteria, evaluating options, and calculating weighted scores to objectively assess each potential configuration. The instructions outlined below provide a step-by-step approach to this evaluation process, considering all relevant aspects such as resilience, cost efficiency, and environmental impact. This comprehensive analysis helps stakeholders make informed decisions that align with both immediate needs and long-term strategic goals of the microgrid installation.

- Define criteria weights: Weights should be assigned to each criterion reflecting its importance relative to the microgrid's objectives, such as enhancing resilience, minimizing costs, or maximizing environmental benefits.
- Evaluate each option: Each design option should be evaluated on a scale from 1 to 5 based on how well it meets the criteria, using data from simulations and pilot projects where available.
- Calculate weighted scores: The impact of each design option should be quantified by multiplying its score by the criterion's weight, followed by summing these to derive a total score that will guide decision-making.

- Decision analysis: The optimal design choice might not be determined solely by the highest score but should also consider strategic factors like future scalability, potential regulatory changes, and integration with existing infrastructure.

4. POWER REQUIREMENTS OF THE MICROGRID IN ISOLATED AND GRID-CONNECTED MODES

Microgrids are designed to enhance resilience by operating in two distinct modes: isolated and grid-connected. Each mode has unique power requirements, especially in terms of maintaining stability and reliability during disruptions. This section details the technical aspects of these requirements, focusing on ensuring a resilient power supply.

4.1. ISOLATED MODE

In isolated mode, a microgrid operates independently from the main power grid. This mode is essential during grid outages or in remote areas without grid access. The key power requirements are as follows:

- Meeting power demand equations
  - $P_{Source} = \Delta_n * (\sum P_i - \sum P_{DG_m})$
  - $Q_{Source} = \Delta_n * (\sum Q_i - \sum Q_{DG_m})$

  Where:
  - P_{Source} and Q_{Source}: Source real and reactive power
  - Δ_n: Deficiency coefficient for scenario n
  - P_i and Q_i: Real and reactive power demand at node i
  - P_{DG_m} and Q_{DG_m}: Real and reactive power output of distributed generation in microgrid m
- Adequate generation capacity: The generation capacity must exceed peak load requirements to ensure continuous operation during island mode. This includes incorporating dispatchable generation sources to meet varying load demands promptly. Redundancy through N-1 or N-2 scenarios enhances resilience, allowing the system to sustain operation even if one or more generation sources fail.
- Load management: Dynamic load management is essential to prevent overloading and ensure continuous supply. This involves real-time monitoring and control of loads, prioritizing critical loads over non-critical loads. Demand-response strategies can be employed to adjust load profiles according to available generation capacity.
- Stability and control: Voltage and frequency stability are paramount. Advanced control systems are required to regulate voltage and frequency within acceptable limits. Inverter-based DER should be equipped with control algorithms to provide grid-forming capabilities, ensuring a stable and resilient power supply.
- Merit order of DER: The microgrid should optimize the use of DER based on availability, cost, and environmental impact. Renewable energy sources should be utilized first, followed by stored energy, and finally, non-renewable generators if needed.

- Management of in-rush currents: Generators must be sized to effectively manage in-rush currents, which are typically when transformers are energized and motors start. This sizing ensures the system can handle sudden increases in demand without operational disruption.

- Reactive power supply: All generation sources must supply both real and reactive power to meet the power factor requirements of the microgrid. Proper selection and sizing of generation equipment ensure sufficient reactive power is available, enhancing stability and efficiency.

  Furthermore, reactive power can be supplied by power factor correction capacitors, inverters, dynamic volt-ampere reactive (VAR) compensators, and other sources. In islanded systems, reactive power is generally provided by the generators that are connected, although some systems also incorporate capacitors at substations to help correct the power factor directly at the transformer secondary distribution points. These capacitors can adjust their output based on the load's power factor requirements and are often designed to mitigate the inductive losses of transformers.

  Distributed capacitors in island mode are beneficial as they decrease the reactive power demand from generators and reduce overall system losses by supplying reactive power close to where it is needed. Generators are typically rated with a power factor of 0.8; for example, a generator rated at 1,200 kW/1,500 kVA could provide up to 900 kVAR to a load with a lagging power factor. However, if the system has a leading power factor—indicative of more capacitive than inductive loads—the generator's capacity could be strained, potentially affecting system stability. Ideally, the total load's power factor should be nearly unity, slightly lagging, which is a critical consideration in the engineering design and analysis of island modes.

- Contingency planning and load growth: Generators should include a contingency factor (typically 15 percent to 20 percent above peak load) to handle unexpected load spikes and future growth. This foresight prevents operational inefficiencies and potential damage, ensuring scalability with increasing demands.

- Harmonics and load balancing: While harmonic distortion is not typically a major concern for microgrids designed for resilience, it can still impact long-term operation and efficiency. Nonlinear and unbalanced loads can generate harmonic currents, distorting electrical waveforms and causing inefficiencies.

  Under typical utility-connected conditions, the low impedance of the source mitigates significant harmonic impacts. However, in microgrids powered by generators with higher source impedance, like diesel or gas, harmonic effects can be amplified, potentially leading to higher voltage drops and destabilizing the generators.

  To address harmonic distortion, particularly in the long-term operation of microgrids, the use of harmonic filters, both passive and active, could be considered. Passive filters use reactors and capacitors to target and eliminate specific harmonics, while active filters dynamically counteract harmonics by injecting opposing currents. These mitigation strategies help maintain operational stability and protect equipment within the microgrid.

  Moreover, an engineering assessment, including harmonic-producing equipment and the magnitude of harmonics produced, could be added to the design activity for selecting appropriate filter sizes and locations. This assessment ensures that harmonic filters are strategically placed to optimize their effectiveness, enhancing the overall power quality and stability of the microgrid.

4.2. GRID-CONNECTED MODE

In grid-connected mode, a microgrid operates in conjunction with the main power grid, allowing for power exchange. This mode offers flexibility and enhances overall grid resilience. The key power requirements are as follows:

- Grid synchronization: The microgrid must synchronize its voltage, frequency, and phase with the main grid to ensure seamless operation. Synchronization protocols and control systems are required to manage the transition between isolated and grid-connected modes.

- Peak load management: During periods of high demand, the microgrid can draw additional power from the main grid to meet local needs. Conversely, during periods of low demand, excess power generated within the microgrid can be exported to the main grid.

- Merit order of DER: Similar to the case in isolated mode, the use of DER should be optimized based on availability, cost, and environmental impact, with a preference for renewable energy sources.

- Uninterrupted transition requirements: For critical operations requiring seamless power continuity, microgrids must be equipped to transition between grid-connected and island modes without interruption. Specialized generation sources and control systems capable of rapid load pickup are necessary.

- Technical considerations are as follows:

  Power flow constraints

  – Voltage limits

  $|V_i^{min}| \leq |V_i| \leq |V_i^{max}|$

  Where:

  - Vi: Voltage at node i
  - V_i^{min} and V_i^{max}: Minimum and maximum allowable voltages

  – Branch capacity limits

  $|I_F^i| \leq |I_F^{imax}|$ and $|I_R^i| \leq |I_R^{imax}|$

  Where:

  - I_F^i and I_R^i: Forward and reverse current flow capacities in the ith branch
  - I_F^{imax} and I_R^{imax}: Maximum allowable currents

  Distributed generation power constraints

  $P_{DG_{min}} \leq P_{DG} \leq P_{DG_{max}}$
  $Q_{DG_{min}} \leq Q_{DG} \leq Q_{DG_{max}}$

Where:

- P_{DG} and Q_{DG}: Real and reactive power capacities of distributed generation
- $P_{DG_{min}}$ and $P_{DG_{max}}$: Minimum and maximum allowable real power
- $Q_{DG_{min}}$ and $Q_{DG_{max}}$: Minimum and maximum allowable reactive power

4.3. TRANSITIONING BETWEEN MODES

Transitioning between isolated and grid-connected modes requires careful coordination and advanced control strategies to ensure stability and continuity of supply. Key considerations include:

- Seamless transition: The microgrid control system must detect grid disturbances and initiate a seamless transition to isolated mode. Similarly, when the main grid stabilizes, the microgrid must synchronize and reconnect without causing disruptions.
- Control strategies: Hierarchical control strategies, including primary, secondary, and tertiary controls, manage the transition between modes. Primary control ensures immediate response to changes, secondary control adjusts setpoints, and tertiary control optimizes overall operation.
- Protection mechanisms: Protection mechanisms such as relays and circuit breakers must be in place to isolate faults and protect equipment during transitions. Fast-acting protection systems are essential to minimize the impact of disturbances.

5. LOAD STUDIES

In microgrid design, ensuring the system's capacity to support peak load demands of critical systems during both normal and peak activities is paramount. This includes managing not only critical but also non-critical loads that cannot be segregated. To ascertain the microgrid's capability, a comprehensive analysis of the load profile in different operational states—normal and peak—is essential. This ensures that there is sufficient generation and load-following capacity available to meet these demands without compromising system stability.

The analysis extends to encompass specific load types that pose unique challenges. Step loads, highly nonlinear loads, motor loads, and high-VAR inductive loads require special attention due to their potential to disrupt system stability and efficiency. These loads are evaluated under both grid-connected and island operational modes to ensure that the microgrid can maintain functionality across different scenarios. This evaluation includes both projected and actual or tested requirements, providing a robust framework for understanding and planning the microgrid's capabilities.

In scenarios with high renewable energy integration, the adaptability of the microgrid becomes crucial. An adaptive border strategy can effectively extend the operational boundaries of the microgrid during high-renewable-energy hours, optimizing the utilization of available renewable energy and reducing reliance on non-renewable sources.

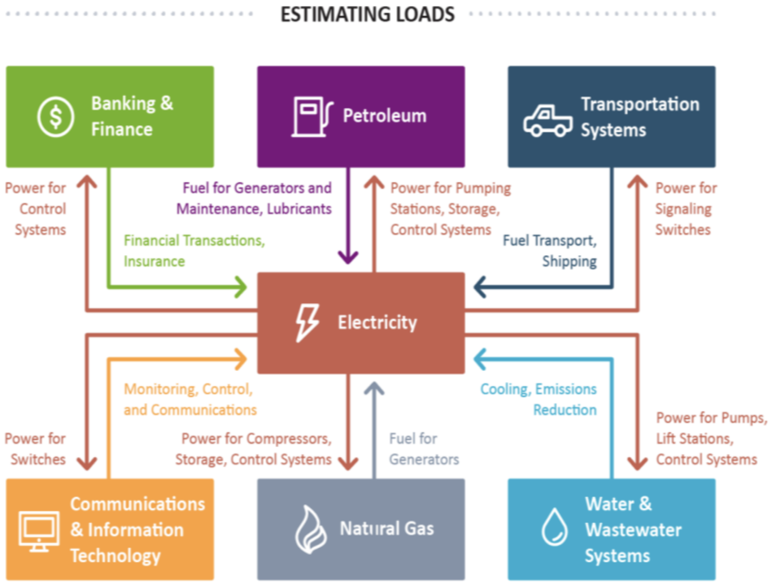
Load shedding is another critical component in microgrid management, particularly for enhancing the endurance of higher-priority loads. Implementing load shedding via transformer or feeder switching provides a methodical approach to manage load distribution actively. This not only maximizes the off-grid endurance of critical loads but also supports the overall energy resilience of the system. The strategy includes detailed plans for sequential restoration at substation breakers or employing under-frequency load shedding, which are tailored to maintain power to essential facilities even during disruptions.

Moreover, in situations involving non-critical loads that are not easily segregable, the design must carefully evaluate the trade-offs. This involves considering whether to incorporate additional load-shedding switchgear, which can help manage these loads more effectively at the expense of potential increases in system and generation costs. This decision is crucial for ensuring that the microgrid can provide reliable service without excessive financial burdens, balancing cost against reliability and sustainability.

Prioritization Strategy

Facilities identified as critical loads should be ranked highest and included in the microgrid design, as they are essential for maintaining public health, safety, and welfare during power outages. These critical facilities are indispensable during emergency conditions and must be guaranteed uninterrupted power supply. Conversely, facilities categorized as non-critical can be disconnected during events like grid outages, optimizing resource allocation and ensuring that power is reserved for essential services.

Recommended Examples of Critical Load Selection



- Public health and safety infrastructure: Critical water services necessary for public health and firefighting, wastewater treatment for public health, and associated operational needs such as stormwater pumping infrastructure.

- Communication infrastructure: Key components necessary to maintain communication during emergencies, including infrastructure for internet, telephone, radio, and TV stations, as well as data centers. Priority may vary based on the specific role of these services in emergency response.

- Emergency response services: Essential infrastructure for police, fire, ambulance services, and emergency response operations centers that coordinate critical emergency communications.

- Healthcare facilities: Hospitals, at-risk patient care centers, pharmacies, and ambulance services that provide vital healthcare services and need to remain fully operational to ensure public health.

- Public services and safety: Grocery stores, gas stations, and shelters, including schools used as shelters, which support community resilience and provide essential supplies and refuge in emergencies.

- Transportation infrastructure: Critical transportation control systems, including those for traffic, railways, and aviation facilities, which are crucial for safe and efficient movement during emergencies.

- Support for critical business operations: Other necessary business operations that significantly impact community functioning or economic stability, which may include utilities and services critical to societal well-being.

6. GENERATION ANALYSIS AND GENERATION-LOAD MATCHING

Selecting generation sources for a microgrid is a critical design decision. During operation, these sources will be managed to maintain stability and power quality. The final choice of generation sources is influenced by power requirements, available renewable energy resources, existing generation assets, regionally available fuel sources, air emissions, and economic return. Balancing technical capabilities to meet load with other project priorities such as costs, sustainability, and redundancy is essential.

6.1. GENERATION ANALYSIS

Advanced microgrids often combine generation sources into hybrid systems. These systems can dispatch and curtail generation as needed, capturing the benefits of both dispatchable and variable generation. For example, a system may optimize renewable resources to minimize operating costs while curtailing them to maintain power quality. Characteristics of hybrid power systems:

- Low renewable energy contribution: Dispatchable generation runs at all times, with renewables reducing the net load. Typically, no control system is required.
- Medium renewable energy contribution: Dispatchable generation runs continuously. At high renewable contributions, additional load is added, or renewables are curtailed to avoid overgeneration. A basic control system is required.
- High renewable energy contribution (with storage): Renewables and storage can power loads without engine generators, which can be shut off unless needed. Basic control systems are required.
- High renewable energy contribution (without storage): Engine generation can be shut down or act as a spinning reserve. Sophisticated control systems are necessary.

TABLE 6: ATTRIBUTES OF MICROGRIDS WITH RENEWABLE ENERGY SOURCES (RES)

RES LEVEL IN MICROGRID	OPERATIONAL CHARACTERISTICS	RES CONTRIBUTION TO PEAK LOAD	RES CONTRIBUTION TO ANNUAL ENERGY	MATURITY LEVEL
Low	• Dispatchable generation runs at all times • Renewables reduce net load on dispatchable generation • All renewable energy goes directly to load • Often, no control system present	Less than 30%	Less than 20%	High, many examples at large and small scale
Medium	• Dispatchable generation runs almost at all times • Renewables reduce the net load on dispatchable generation • Additional load added or renewable energy curtailed at high contributions • Basic control system typically required	30%–75%	20%–50%	High, many examples at large and small scale
High (with energy storage)	• Renewable energy and storage can power load without engine generators	50%–100%	50%–100%	High, mostly at small scale

RES LEVEL IN MICROGRID	OPERATIONAL CHARACTERISTICS	RES CONTRIBUTION TO PEAK LOAD	RES CONTRIBUTION TO ANNUAL ENERGY	MATURITY LEVEL
	• Engine generators used mainly to charge storage during low renewable periods • Basic control system required minimum • Renewable generation can exceed peak loads, with excess energy stored			
High (without energy storage)	• Engine generation can be shut down or reserved when renewable energy meets load requirements • Additional components required for power quality when a generator is off • Requires sophisticated control system	50%–100%	50%–100%	Low to medium, few examples, mostly at small scale

6.2. EXISTING GENERATION SOURCES

Integration of existing generation assets: Utilizing existing generation facilities can significantly reduce new capital expenditures (CAPEX). It is essential to assess the technical suitability, reliability, and remaining operational lifetime of these assets. Key technical parameters include:

- Capacity (kW): The maximum output the generator can produce.
- Efficiency (%): The ratio of useful power output to the total power input.
- Maintenance records: Historical data on maintenance and repairs, helping predict future performance.

By evaluating these parameters, project teams can determine the feasibility of using existing generation assets.

General characteristics: Existing generation assets must be evaluated for their type, size, operating restrictions, and historical reliability. Assets near the end of their useful life or with poor reliability may not be suitable. Important parameters include:

- Age (years): The number of years the generation asset has been in operation.
- Operating hours (hours/year): The average annual operating hours.
- Failure rate (failures/year): The frequency of failures, affecting reliability and maintenance costs.

By assessing these characteristics, project teams can determine the feasibility and suitability of existing generation assets.

Ownership and operational constraints: The ownership structure of generation assets significantly impacts their integration into the microgrid. Units under power purchase agreements will need both technical and contractual modifications to enable operation when islanded from the main grid. Key considerations include:

- Contractual terms: Agreements outlining responsibilities and limitations.
- Control rights: The extent of control the microgrid operator has over the assets.
- Maintenance responsibilities: The division of maintenance tasks between the installation and third-party owners.

Addressing these constraints ensures the effective integration and management of generation assets.

Strategic placement within the distribution system: Existing generation sources must be strategically placed within the microgrid's designated electrical boundaries. This ensures optimal operational scenarios by including both generation sources and critical loads within the isolation points. Important factors include:

- Proximity to critical loads (meters): The distance between generation sources and the loads they serve.
- Interconnection points: Locations where generation sources connect to the microgrid.
- Fault isolation capabilities: The ability to isolate faults and prevent them from affecting the entire microgrid.

By considering these factors, project teams can enhance the microgrid's operational efficiency and reliability.

Control system compatibility: Existing generation sources must be compatible with the microgrid control system. This often requires additional controls and communication infrastructure. Key parameters include:

- Response time (seconds): The time it takes for the control system to respond to changes.
- Communication protocols (Modbus, IEC104, etc.): Standards used for communication between control systems and generation assets.
- Control flexibility: The ability to adjust control parameters for different operational scenarios.

Ensuring compatibility is crucial for seamless integration and effective management.

Generator control modes: When integrating both existing generator facilities and new DER into microgrids, several control modes are critical for maintaining system stability and efficiency.

- Base load mode is used for continuous power supply at constant real power output and fixed power factor, suitable for both traditional and new generators synchronized with the utility's frequency.
- Variable load mode adapts well to renewable DER like solar, allowing power output to fluctuate based on resource availability.
- Isochronous mode is essential for ensuring a generator or a group of generators maintains a stable frequency regardless of load changes, particularly useful in isolated systems without grid support. This mode helps in situations where consistent power quality and frequency stability are critical.

- Isochronous load-sharing mode further enhances the benefits of isochronous mode by distributing load changes among multiple generators to stabilize frequency collectively, ideal for complex microgrids with mixed-generation assets.

- Droop mode provides a flexible response to changing loads by adjusting the generator's frequency and output. This mode is vital for systems where load varies significantly, helping to balance the generation dynamically without central frequency control, especially in stand-alone microgrids.

Paralleling standby generators: Utilizing existing central or standby generation assets within a microgrid can enhance its capacity while reducing CAPEX. However, it is essential to consider whether these generators can operate in parallel with a microgrid. Most standby generators lack the necessary governor/excitation controls and paralleling switchgear, which are crucial for microgrid integration, necessitating additional investments in equipment and communications infrastructure.

Critical factors for integrating standby generators include:

- Synchronization capabilities: Ensuring the generator can match the microgrid's frequency and voltage.

- Governor/excitation controls: Mechanisms to manage the generator's output.

- Switchgear ratings (kA): The ability of switchgear to handle high current levels.

Additional considerations include generator controls and compatibility, characteristics of automatic transfer switches, system protection settings, and local utility interconnection requirements. If standby generators are considered viable for microgrid integration, it is crucial to establish a "do-no-harm" scenario to avoid increasing the risk of damage to these generators. For instance, if microgrid communications fail or a fault occurs in the distribution system, the standby generators should be able to function independently during an outage.

Operational risk management in standby generators: A "do-no-harm" operational scenario must be defined for standby generators used in the microgrid. This ensures they function effectively as stand-alone assets during outages without increased risk of damage. Key parameters include:

- Fault tolerance: The ability to withstand faults without significant damage.

- Load-handling capacity: The maximum load standby generators can handle.

- Fail-safe mechanisms: Systems to protect generators from damage in the event of control system failures or faults.

Controllability: Existing generation sources must be controllable by the microgrid control system. This often involves retrofitting with new control systems and communication infrastructure. Key parameters include:

- Control precision (%): The accuracy of control adjustments.

- Latency (milliseconds): The delay between a control command and the generator's response.

- Scalability: The ability to expand control systems for additional generation sources or loads.

Ensuring controllability is crucial for maintaining stability and optimizing performance.

Economic dispatch: To enhance the economic viability of the microgrid, existing generation assets should provide economic benefits while connected to the grid, such as peak shaving or grid services. Resources with lower operating costs and fewer restrictions, like natural gas generators, are preferable. Important parameters include:

- Fuel cost ($/kWh): The cost of fuel used by the generators.
- Emissions (gCO_2/kWh): The environmental impact of the generators.
- Operational flexibility: The ability to adjust generation output based on economic conditions and grid demands.

6.3. NEW GENERATION SOURCES

Selecting new generation sources for a microgrid involves detailed analysis and careful planning to ensure that the system can meet its power requirements effectively and efficiently. New dispatchable generation sources are typically sized based on peak load requirements minus the capacity of existing dispatchable generation. This sizing process must consider factors such as in-rush currents, future growth, and redundancy requirements to ensure reliability and stability.

Dispatchable generation assets: Dispatchable generation assets, such as gas motors and diesel generators, are crucial for meeting the continuous power needs of the microgrid. These sources must be reliable, flexible, and capable of responding quickly to changes in load demand. When selecting dispatchable generation assets, it is important to consider the following:

- Fuel availability and cost: The availability and cost of fuel, such as natural gas or diesel, are critical factors. The assessment should cover the local supply infrastructure, fuel transportation logistics, and long-term price stability.
- Emissions and environmental impact: The emissions profile and environmental impact of each generation source must be evaluated. Diesel generators, for example, may have higher emissions compared to natural gas engines, which could affect permitting and regulatory compliance.
- Operational efficiency and maintenance requirements: Gas engines typically offer higher efficiency and lower maintenance costs compared to diesel generators. Maintenance intervals, spare parts availability, and ease of repair are important factors.
- Scalability and redundancy: The generation assets must be able to be scaled up to meet future load growth and include redundancy to enhance system reliability. Redundant systems can ensure continuous operation even if one unit fails.

Flexibility and reliability considerations: Operational flexibility, defined by how quickly a DER can ramp up or down, is crucial, especially in microgrids with high renewable penetration where variability is high. Reliability metrics, such as uptime and maintenance schedules, are also essential to ensure a continuous power supply. Assessing these metrics helps in selecting generation sources that can adapt to load changes and maintain stability.

Single vs. multiple units: Deciding between one large unit or multiple smaller units impacts redundancy, scalability, and resilience. Multiple smaller units can offer improved reliability through redundancy, ensuring power supply continuity even if one unit fails, and can better match localized demand variations. Conversely, a single larger unit might benefit from economies of scale in terms of capital and operational costs but could increase risk by creating a single point of failure. This decision should balance the benefits of scalability and reliability against cost efficiency and risk management.

Renewable generation assets: Renewable generation sources offer several advantages, including lower energy costs, reduced environmental impact, and the provision of a self-sufficient energy resource. When selecting renewable generation assets, it is important to consider the location, availability of resources, technology type, permitting requirements, offtake agreements, and financing options. Tools like the U.S. National Renewable Energy Laboratory (NREL) System Advisor Model and HOMER Pro are valuable for evaluating the feasibility of these renewable energy projects. They provide detailed insights into the potential performance and economic viability of different renewable energy technologies.

Energy storage: Battery energy storage systems (BESS) play a crucial role in modern microgrids by providing an immediate response to load changes and helping to maintain system stability. BESS can also be used for black start capabilities, enabling the microgrid to restart independently after a complete shutdown. In addition to these operational benefits, BESS can offer revenue-producing activities such as peak shaving and demand response. By reducing peak demand and participating in demand-response programs, microgrids with BESS can lower energy costs and generate additional income, enhancing the overall economic performance of the system.

New generation sizing: New generation sources are often necessary when the existing generation is insufficient to meet the microgrid's needs. The required new dispatchable generation capacity can be calculated as follows:

$$G_{new} = P_{\text{peak}} - G_{\text{existing\_dispatchable}}$$

Where:

- G_{new}: New generation capacity required
- P_{peak}: Peak load for the selected load
- $G_{\text{existing\_dispatchable}}$: Capacity of existing dispatchable generation

Dispatchable generation assets: Dispatchable generation assets are critical for meeting the continuous power needs of the microgrid. The required capacity can be determined using:

$$G_r = P_{\text{L}} - G_{\text{existing\_dispatchable}}$$

Where:

- G_r: Required dispatchable generation capacity
- P_{L}: Peak load
- $G_{\text{existing\_dispatchable}}$: Existing usable dispatchable generation

New dispatchable sources should be sized based on peak demand minus existing generation, incorporating considerations like in-rush currents, future growth, and redundancy needs.

Load selection and load management: Microgrids should be designed to meet peak load demands selectively, reducing unnecessary CAPEX on generation capacity. Strategies such as load shedding during peak times or no-renewables hours can minimize the need for larger generation capacities, thereby reducing costs.

$$P_{eff} = P_L \times \text{Coverage Ratio}$$

Where:

- P_{eff}: Effective peak load
- P_L: Peak load
- Coverage ratio: Proportion of the peak load that needs to be covered (e.g., 90 percent)

Fuel supply considerations: Assessing the capacity and pressure of existing natural gas systems or the availability of other fuels is crucial. Ensuring an adequate and reliable fuel supply supports the continuous operation of dispatchable generators.

Renewable generation considerations: When designing the microgrid, site-specific availability of renewable energy sources, technology suitability, and economic feasibility should be considered. Tools and databases like renewable atlases can be used to explore renewable energy potential.

Energy storage sizing: Energy storage systems are essential for providing immediate response to load changes and maintaining system frequency. The required storage capacity can be calculated as:

$$S_r = \Delta_L \times \text{t}$$

Where:

- S_r: Required storage capacity
- Δ_L: Maximum load variation
- t: Desired backup duration

Generation-load matching: Balancing load and generation is crucial, particularly in island mode. The microgrid controller must ensure that generation matches load while maintaining voltage and frequency within acceptable limits. This balance is dynamic due to variations in building systems, occupancy, and renewable generation.

Available generation capacity and storage generation capacity must meet the dynamic load at all times:

$$G_{\text{available}} + S_{\text{gen}} \geq L_{\text{t}}$$

Where:

- $G_{\text{available}}$: Available generation capacity
- S_{gen}: Storage generation capacity
- L_{t}: Dynamic load at time t

Detailed modeling (preferably on an hourly or 15-minute basis) is advised to match microgrid loads with generation capabilities accurately. Tools like HOMER can be used for this practice, but tailored scripts in basic solvers such as MS Excel can also be employed.

7. NETWORK MODELING AND POWER SYSTEM ANALYSES FOR VALIDATION OF MICROGRID OPERATIONAL SCENARIOS

After finalizing the microgrid configuration and design, it is crucial to validate its operation within proper operational limits in both island and grid-connected modes across diverse scenarios. This step ensures that the conceptual design meets performance criteria. Utilizing advanced simulation tools like DIgSILENT PowerFactory, the validation process involves comprehensive network modeling and power system analyses.

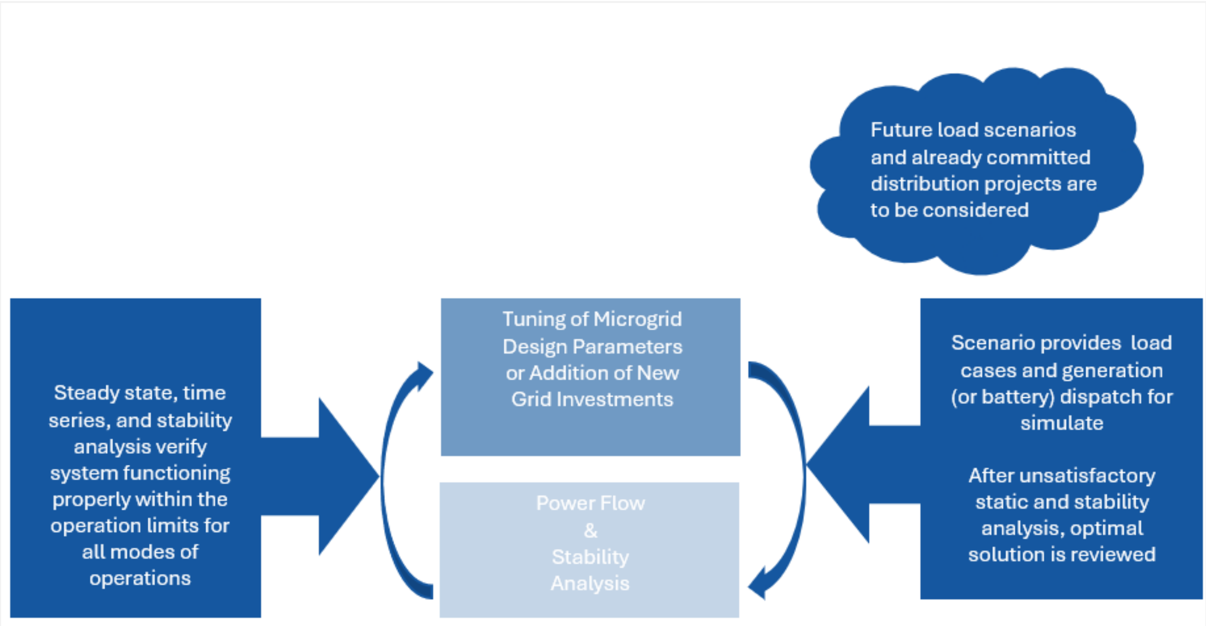


Figure 3: Iterative process for ensuring the microgrid design is adequate

Data collection is the first step in network analysis and modeling for a microgrid. This foundational task gathers all relevant information about the existing energy infrastructure, including details on energy consumption patterns, the physical layout of the current network, a detailed asset list of networks with their parameters and asset ages, and specifics about existing DER. Collecting comprehensive and accurate data is crucial for creating a realistic model of the microgrid, which forms the basis for all subsequent analyses and decisions.

Digital network model development is crucial for effectively visualizing and simulating the microgrid's performance across various conditions. This process begins with the selection of sophisticated modeling tools like DIgSILENT PowerFactory, which facilitates the creation of a detailed virtual representation of the microgrid. The model integrates collected data to depict the microgrid's operational and structural aspects, enabling comprehensive simulations of network behavior. These simulations are vital for identifying potential issues and testing different scenarios in a risk-free environment. The process includes validating the model by comparing simulated results with actual data to ensure accuracy and conducting sensitivity analyses to pinpoint critical performance drivers. This systematic approach significantly aids in the planning and optimization of the microgrid design, ensuring that the system can respond effectively to various operational challenges.

Steady-state analyses are performed to understand the microgrid's behavior under normal operating conditions. This involves evaluating the network's performance when the demand and supply are balanced and stable. Insights gained from steady-state analyses help ensure that the microgrid can reliably meet energy demands, highlighting areas where adjustments or enhancements may be necessary for optimal operation.

Load-flow analysis is a crucial steady-state analysis in network modeling, providing detailed insights into how electrical power flows through the microgrid under various loading scenarios. It helps determine voltage levels at different points in the network, identify potential bottlenecks, and evaluate the impact of integrating new DER. By simulating specific loading conditions, such as peak and off-peak periods, this analysis identifies issues like voltage drops, load imbalances, and congestion points. It also assesses how new DER affect power flow patterns and overall system performance. Developing mitigation strategies to address these issues ensures the microgrid operates efficiently and maintains stability under diverse scenarios.

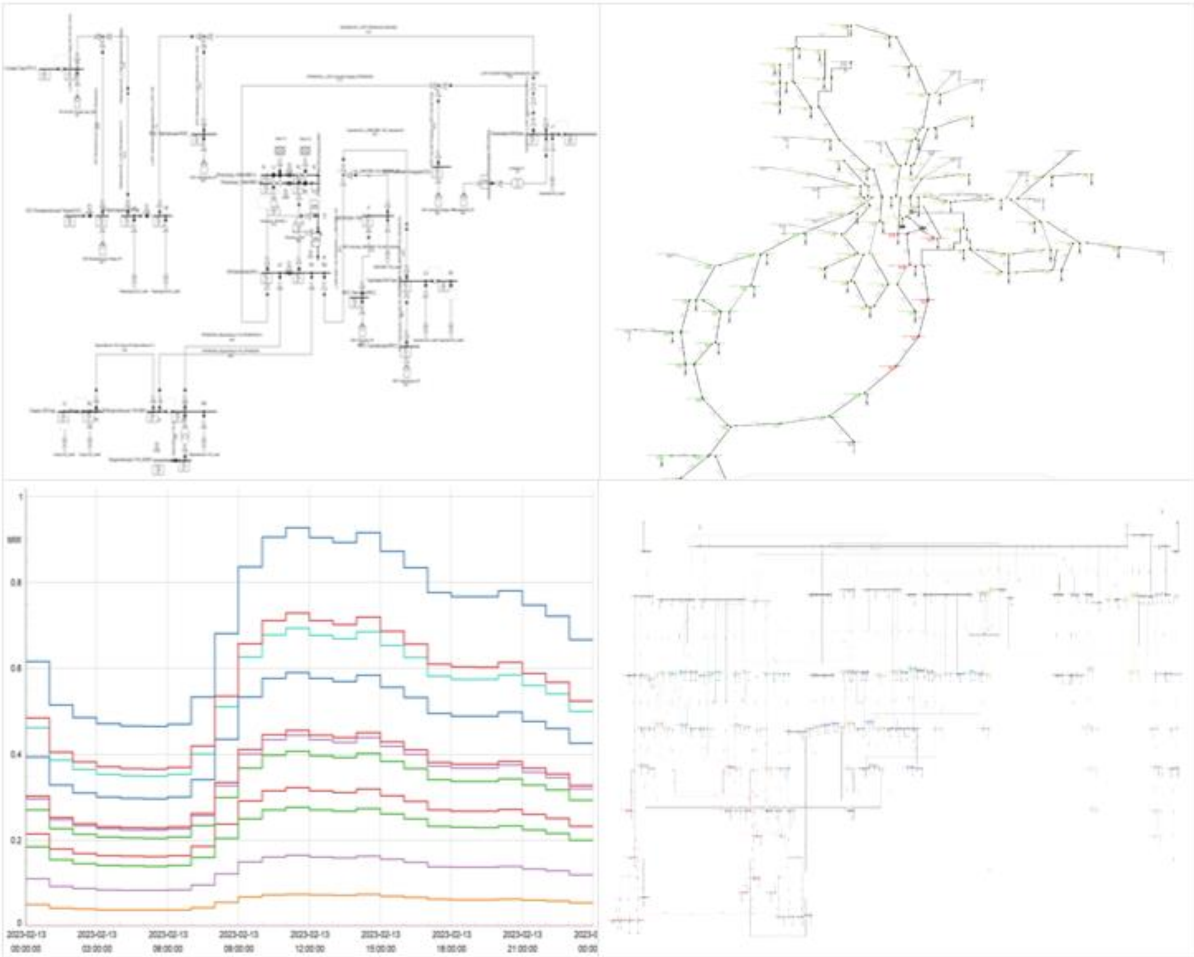


Figure 4: Network modelling and power system analysis

Quasi-dynamic analysis extends the insights provided by load-flow analyses by incorporating changes over time, though not at the full temporal resolution of dynamic simulation. This approach is particularly useful for evaluating how the microgrid responds to fluctuations in demand or supply over different periods, allowing for the anticipation and mitigation of potential issues that could arise from variability in renewable energy sources or changing consumption patterns.

The objective of quasi-dynamic analysis is to simulate the microgrid's response to temporal changes in demand and supply patterns, especially when integrating fluctuating renewable energy sources. By using load profiles that vary over time, this method reflects changes in both demand and generation, such as increased loads during daytime hours in residential areas or decreased loads overnight in commercial districts.

Time periods and scenarios are defined to account for the variability in demand and supply, including the intermittent nature of renewable energy sources and varying load demands throughout the day and year. Simulations model the microgrid's behavior over these periods, capturing fluctuations in renewable energy generation and load demand. Various operational strategies, such as adjustments of renewable and conventional generation outputs, battery storage utilization, grid reconfiguration, and changes in microgrid boundaries, are tested over time to observe their impacts.

Analyzing the simulation results helps identify potential operational issues and areas where the microgrid may not perform optimally under varying conditions. This analysis ensures that designs are not only theoretically sound but also practically viable, significantly reducing the risk of operational failures and enhancing overall sustainability. Based on insights from the simulation, control strategies and operational parameters are adjusted to improve the system's resilience and adequacy, ensuring reliable support for dynamic energy conditions.

Short-circuit analysis is essential for assessing the safety and resilience of a microgrid. This analysis identifies the potential impacts of fault conditions, such as short circuits, on the network, including the maximum fault currents that could be encountered. The insights gained are critical for selecting appropriate protective equipment and designing fault management strategies to ensure the safety of both the microgrid and its users.

The objective of short-circuit analysis is to evaluate the microgrid's response to various fault scenarios by identifying potential fault currents and their effects on network components. Fault scenarios, including different types and locations of faults, are defined to comprehensively assess the microgrid's response to potential electrical faults. Simulations are conducted to determine fault currents and their impact on network components, analyzing how faults propagate through the microgrid and the resultant stresses on electrical components.

The analysis identifies areas where fault currents exceed the ratings of equipment and pose safety risks. Appropriate protective devices and coordination settings are then selected to mitigate the impacts of these faults, minimizing damage and disruption. Fault management strategies are developed to enhance the overall safety and reliability of the microgrid under fault conditions, designed to quickly isolate faults, minimize their impact, and restore normal operations swiftly and safely.

Protection coordination ensures the microgrid's protection system is well-coordinated, considering the dynamic integration of DER, variable power flow directions, and potential microgrid boundary reconfigurations. It involves evaluating existing protection settings and devices, such as relays, circuit breakers, and fuses, to assess their performance under various operational scenarios, including DER integration, which can alter fault currents and power flow. Simulation tools model different power flow scenarios, including reverse power flow, and the impact of microgrid reconfiguration on protection settings. This analysis includes the types of DER, such as solar PV, diesel generators, gas turbines, and energy storage systems. Developing a coordination plan for all protective devices ensures they operate in the correct sequence, minimizing outage areas and protecting equipment. Using software like DIgSILENT PowerFactory automates setting calculations and adjustments, ensuring optimal coordination across all scenarios.

The electrical systems power flow model should be used for several different analyses. In particular, the model should be used to perform parallel protection studies. In this case, "parallel" refers to the fact that two complete protective device coordination studies must be carried out: one in grid-connected mode and one in island mode. The parallel protection studies should be used to determine new settings for the distribution system protective relays and protective devices.

Voltage stability analysis is a supportive component in assessing a microgrid's ability to maintain stable voltage levels under various operational conditions. This analysis ensures that the microgrid can handle sudden changes in load or generation without experiencing voltage collapse or significant fluctuations, particularly important due to the unique configurations and high penetration of renewable energy sources in microgrids.

The primary goal of voltage stability analysis is to validate that the microgrid can sustain stable voltage levels across different scenarios. This includes both steady-state and dynamic conditions, focusing especially on transitions between grid-connected and island modes. Such transitions are critical, as they can introduce significant fluctuations in voltage levels.

To achieve this, scenarios that potentially challenge voltage stability, such as sudden large-scale disconnections of DER or abrupt changes in load, are identified and modeled. These simulations use advanced tools like DIgSILENT PowerFactory to analyze the microgrid's response to these conditions, pinpointing areas within the network that are prone to voltage instability, such as nodes with weak connections or areas far from generation sources.

Furthermore, the impact of integrating new DER on voltage stability is assessed to determine whether these resources contribute to or mitigate potential instabilities. Various DER, such as solar PV, diesel generators, gas motors, and energy storage systems, are analyzed for their specific characteristics and their effect on the microgrid's voltage stability.

Dynamic stability assessment is essential for assessing the stability of generators in response to variations in generation or load within a power system. This analysis becomes particularly crucial in the context of microgrid planning for two main reasons. Firstly, any changes in load or generation within a microgrid can constitute a significant portion of the microgrid generator's capacity. This means that even small fluctuations can have substantial impacts. Secondly, in a microgrid, at least one generator must regulate voltage and frequency, roles typically handled by the utility in grid-connected mode. This requirement makes dynamic stability analysis critical for the proper calibration of generator controls.

A fundamental aspect of this analysis involves monitoring the rotor angle dynamics among the microgrid's generators. It is vital to ensure that these rotor angles remain stable; otherwise, the generators might become unstable and disconnect from the system, leading to potential power disruptions. By conducting thorough dynamic stability analysis, planners can identify and mitigate risks, enhancing the reliability and efficiency of the microgrid under varying operational conditions.

In developing a microgrid, a comprehensive approach to network analysis and modeling is indispensable. This process, beginning with detailed data collection and progressing through sophisticated analyses, enables the identification of optimal design and operational strategies. By thoroughly understanding the microgrid's behavior under a variety of conditions, developers can ensure that the final system is not only efficient and sustainable but also robust and capable of delivering reliable power under both normal and fault conditions.

8. DEFINING TELEMETRY/TELECONTROL SYSTEMS AND MICROGRID MANAGEMENT SYSTEMS

8.1. DESIGN CONSIDERATIONS FOR MICROGRID TELEMETRY AND TELECONTROL

Designing an effective telemetry and telecontrol system for a microgrid is important for adequate observability/controllability, operational reliability, and enhanced system responsiveness. Telemetry and telecontrol systems enable real-time data collection, monitoring, and control of various microgrid components, facilitating dynamic management and operational decision-making. By implementing sophisticated monitoring and control mechanisms, a microgrid can ensure optimal performance, enhanced system resilience, and improved integration of DER.

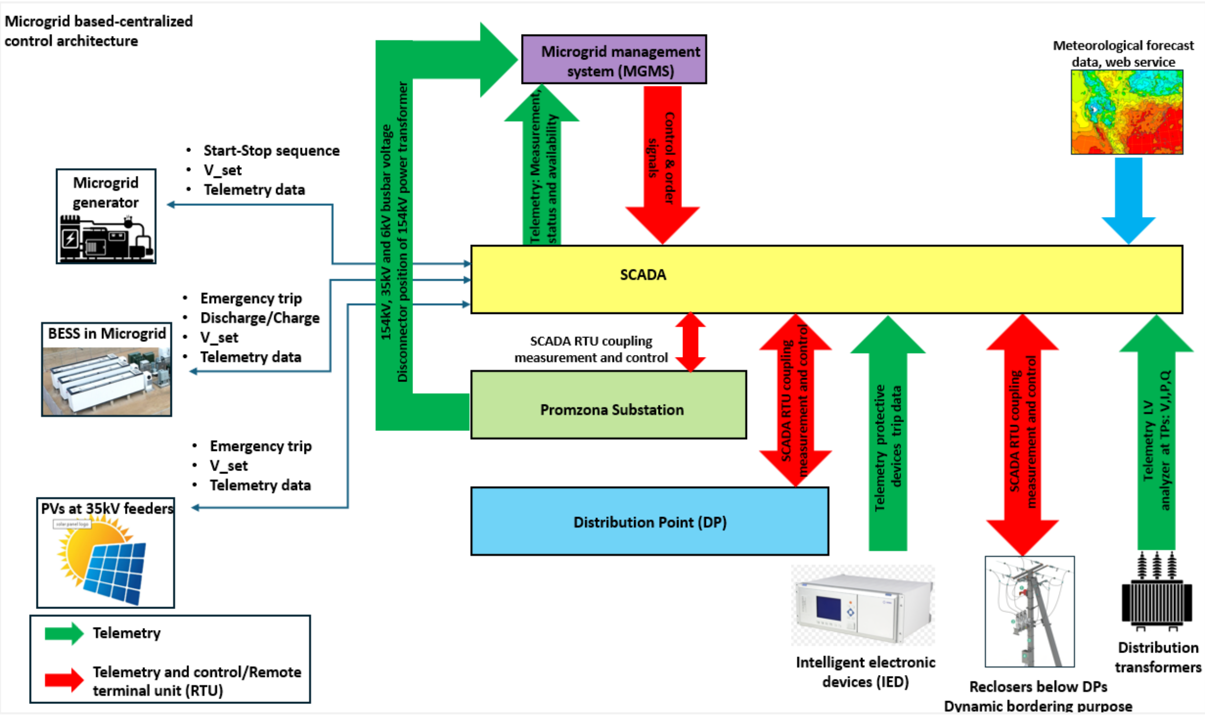


Figure 5: Example of solution topology for telemetry/telecontrol of a microgrid

Main feeder monitoring and control: Ensuring efficient power distribution and maintaining observability and controllability in microgrid operations are essential. Implementing robust monitoring and control mechanisms for main feeders involves deploying sensors and control devices capable of real-time data acquisition and control actions. These mechanisms provide critical insights into power flows, enabling precise management of electricity distribution within the microgrid. By continuously monitoring the main feeders, operators can quickly detect and respond to any anomalies, ensuring the stability and reliability of the microgrid.

Switching station monitoring and control: Maintaining operational reliability and enhancing system responsiveness requires advanced systems for monitoring and control at switching stations. These systems monitor the status and performance of switching devices, allowing for rapid intervention in case of faults or operational changes. By integrating intelligent electronic devices and SCADA systems, operators can execute control commands remotely, optimizing the flow of electricity and maintaining system stability. Effective monitoring at switching stations also enables proactive maintenance, reducing the risk of unexpected failures.

Addition of new switching points: Increasing the flexibility and resilience of the microgrid network involves introducing new switching points, such as reclosers or additional switching substations. These new points enhance the microgrid's ability to reconfigure itself in response to faults or maintenance needs. This strategic addition provides greater flexibility in managing power flows and isolating sections of the network for maintenance without disrupting the overall operation. It ensures that the microgrid can adapt to changing conditions and maintain high levels of reliability and resilience.

Monitoring solutions for MV/LV transformers and load points: Optimizing performance and enabling early detection of potential issues are achieved by deploying comprehensive monitoring solutions for MV and LV transformers and load points. These solutions include installing sensors and data acquisition systems that track key performance indicators such as voltage, current, and temperature. By continuously monitoring these parameters, operators can identify and address issues before they escalate, ensuring optimal performance and extending the lifespan of critical equipment.

Telemetry and telecontrol in DER sites: Facilitating the seamless integration of DER sites with the SCADA/microgrid management system (MGMS) is essential for effective microgrid management. This involves installing communication devices and control systems that enable real-time data exchange and remote control of DER. By integrating DER sites into the SCADA/MGMS framework, operators can manage renewable energy sources and storage systems more effectively, optimizing their contribution to the overall energy mix and enhancing grid stability.

SCADA integration solutions: Ensuring robust integration of grid automation with SCADA is a key consideration. This may involve using substation controllers, remote terminal units (RTUs), mini-RTUs, distribution terminal units (DTUs), protocol converters, and basic remote-read metering (AMR meters). These technologies enable comprehensive data collection and control across the microgrid, allowing all components to be integrated into a unified management system. The seamless integration of these devices ensures that the microgrid operates efficiently and responds promptly to operational demands.

Protection scheme: Microgrids are typically implemented within distribution networks that have a radial design or are operated in a radial meshed design. The distribution network protection scheme relies mainly on overcurrent protection, with settings strongly dependent on grid supply at the interphase point. When transitioning to an islanded microgrid system, there might be a significant shift in fault current due to separation from the grid. New protection schemes must be analyzed and confirmed to ensure existing relays comply with the new microgrid configuration, especially with small-scale generation.

Recalculating fault currents and tuning protection relays, if they have features to change settings according to the operational mode, are essential steps. In off-grid microgrids, step load changes exhibit weaker responses compared to on-grid schemes, necessitating the resizing of protection areas to handle small load losses in case of feeder faults. Heavily loaded feeders might need reclosers or breakers to prevent simultaneous loss of all feeder loads.

If any underfrequency load-shedding protection is installed, it must be adjusted or disabled to accommodate the microgrid's wider frequency range during transient events or load changes.

Voltage protection settings must also be checked and adjusted to match the wider voltage variations typical of microgrid operations. Installing new intelligent electronic devices and relays capable of operating in both microgrid and on-grid states is beneficial, allowing for multiple overcurrent settings that can be dynamically switched based on commands from the MGMS. Additionally, interlocking and out-of-phase switching considerations are crucial for ensuring safe ring operation scenarios.

8.2. MICROGRID MANAGEMENT SYSTEM AND FUNCTIONALITIES

A microgrid is a collective of interconnected loads and DER delineated by distinct electrical boundaries. It functions as a unified and controllable entity concerning the larger electrical grid. A microgrid possesses the capability to connect to or disconnect from the main grid, facilitating its operations in both grid-connected and islanded modes. The following figure provides a general diagram of a microgrid and its components. Some but not all resources are applicable to all microgrid designs.

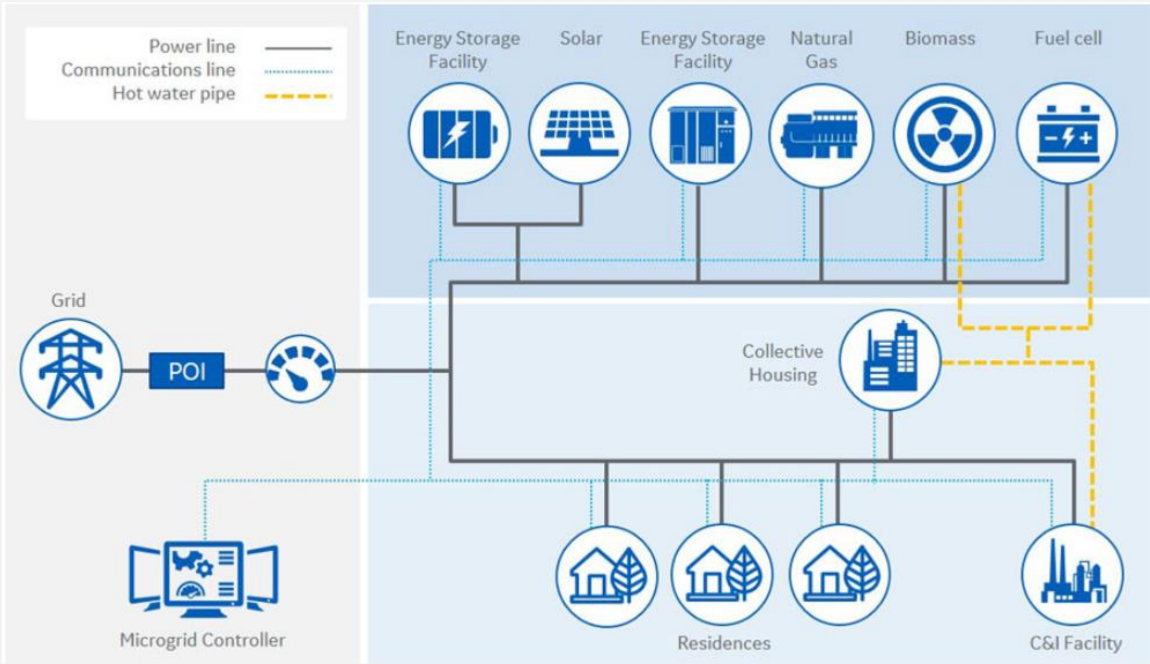


Figure 6: Microgrid management system solution[1]

Centralized control of the microgrid is performed via an MGMS and SCADA, where the entire control decision process occurs. The MGMS communicates with the main SCADA to receive all the telemetric and forecast data. However, in order to avoid false switching or synchronization of the power generator, MGMS measures the subtransmission and distribution voltage status at a main substation and the switch position of the power transformer (if the high-/medium-voltage substation is part of the design).

All these conditions are checked before the transition to a microgrid state.

- Initiation sequence: A microgrid system operates in ready mode during normal grid operation. Telemetric functions are online; however, all the autonomous switching functions are to be disabled. Operator-intended control actions could be ordered via SCADA human-machine

[1] Microgrid Solutions (gegridsolutions.com)

interface. To start initiating microgrid operation, the separation of the microgrid from the main grid is the basic condition in the enabling sequence. There is no online transition to microgrid and no grid parallel operation. A microgrid is conditioned to be enabled at an interruption of power at the substation and the opening of transformer switches.

- Scope of dynamic border: The dynamic border is ranked to supply critical, less critical, and non-critical load accordingly. The MGMS receives the topological status of network total load forecast, PV generation, and BESS status, which are processed in SCADA. The load forecast and PV generation forecast are expected to be done in SCADA, while the dynamic border and operation mode are to be decided by the MGMS. Boundary transitions are ordered from the MGMS and sent to SCADA.

- BESS-PV management: Load forecasting and PV generation forecasting are performed in SCADA and input to the MGMS, which calculates whether the PV is to be interrupted or the charge/discharge state of the BESS.

An MGMS is a sophisticated amalgamation of control mechanisms, software tools, and protocols designed to harness the capabilities of modern microgrids. It stands as the cerebral center, orchestrating various components and energy resources to achieve seamless operations. Below are the detailed requirements regarding its structure and capabilities.

System architecture and functions: An MGMS operates on multi-tiered architecture that fuses real-time data acquisition, advanced analytics, control algorithms, and human-interactive interfaces. The system's modular design allows for scalability and adaptability, providing an extensive range of functionalities to manage microgrid operations effectively.

Microgrid management is facilitated by an effective MGMS tool, which is tasked with overseeing the operation of the microgrid in both island and grid-connected modes. It encompasses various functionalities crucial for ensuring the optimal performance and stability of the microgrid. This study considers the following applications of the MGMS:

- Control and optimization module
- Energy management module
- Advanced protection and resilience module
- Human-machine interface and visualization
- Black start sequence
- PV management
- BESS management
- Generation set management
- Load management

Control and optimization module: This module is essentially the brain of the MGMS, incorporating advanced predictive control algorithms to anticipate future conditions and optimize operations accordingly. It utilizes complex mathematical models to simulate various scenarios, incorporating renewable generation forecasts, load predictions, and market signals. Optimization algorithms work to minimize operational costs while adhering to constraints like battery life, thermal limits of equipment, and regulatory requirements. The control strategies derived from these algorithms are executed in real time, ensuring energy resources are dispatched in the most efficient manner.

Energy management module: This segment of the MGMS serves to balance generation and demand continuously, engaging DER in a symphony of supply-side management. It includes features like real-time monitoring of energy flows, state-of-charge management for batteries, and demand-side management capabilities. It can also dynamically adjust to changing conditions, such as sudden load drops or spikes, by altering generation outputs or storage discharge rates. This module's intelligent design supports the integration of intermittent renewable resources while maintaining power quality and reliability.

Advanced protection and resilience module: This safety-centric module is tailored to enhance the microgrid's capability to withstand and quickly recover from disruptions. It integrates fault detection, isolation, and recovery mechanisms that use high-speed communication to isolate faults almost instantaneously. This module also employs layered defense strategies against cyber threats, including encryption, intrusion detection systems, and continuous monitoring for anomalies in data patterns that could indicate cyber-attacks.

Human-machine interface and visualization: This module provides the operators with comprehensive situational awareness through real-time visualizations, dashboards, and control interfaces. It translates complex data and system diagnostics into intuitive graphical representations, allowing for easy interpretation and quick decision-making. The human-machine interface is designed for ergonomic interaction, offering customizable views to suit different operational roles and preferences.

Black start sequence: Black start sequence capability refers to the capacity of a microgrid, operating independently without a grid connection, to commence its power generation and gradually restore energy supply while off-grid. In such scenarios, the black start sequence function depends on the primary energy source, such as a grid-forming inverter (if one exists) or a generator equipped with isochronous speed control.

The MGMS incorporates specific control logic operations to facilitate power restoration:

- Initial control steps to assess electrical status and positioning
- Activation of the primary energy source (e.g., a power generator)
- Powering up the main electrical bus once the primary source stabilizes
- Systematic reconnection of loads based on predetermined priority levels

PV management: PV management involves regulating the output of PV power within a microgrid. The MGMS oversees PV power generation by curtailing its production in specific situations, such as instability due to excessive power output, the need to prevent power export to the grid, or generation setback feed issues. To ensure safe operation, the disconnection mechanism in *Figure 7* can be adopted as a safeguard.

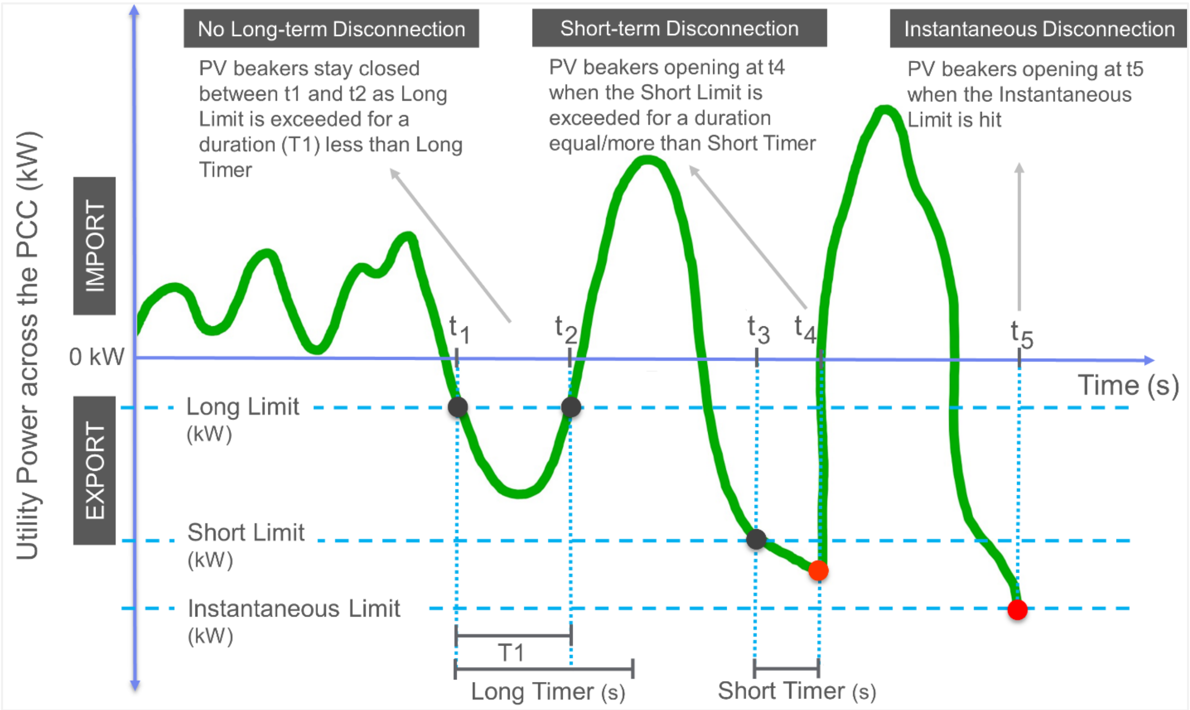


Figure 7: PV management[2]

The mechanism can activate PV breakers if there are any concerns regarding PV curtailment. It operates based on three thresholds and associated timers (long, short, instantaneous). It applies to both utility power and generation setback feed power, where "power" denotes utility power (e.g., export power) across the point of common coupling and generation setback feed power.

Long-term disconnection:

- If the power value falls between the long limit and short limit (both in terms of kW) for a duration shorter than the long timer(s), PV breakers remain closed.
- If the power value falls between the long limit and short limit (kW) for a duration equal to or exceeding the long timer(s), PV breakers are gradually opened.

Short-term disconnection:

- If the power value falls between the short limit and the instantaneous limit (kW) for a duration shorter than the short timer(s), PV breakers remain closed.
- If the power value falls between the short limit and the instantaneous limit (kW) for a duration equal to or exceeding the short timer(s), PV breakers are gradually opened.

[2] Power Management Under Islanded Conditions - 0100DB2302 Microgrid Flex Design Guide (schneider-electric.com)

Instantaneous disconnection:

If the power value exceeds the instantaneous limit (kW), PV breakers are gradually opened.

If parameters are inconsistently configured, the MGMS will raise an alarm, adhering to the following hierarchy:

- Long limit (kW) > short limit (kW) > instantaneous limit (kW)
- Long timer(s) < short timer(s)

The abrupt appearance or disappearance of sources immediately impacts PV power generation, causing rapid fluctuations. Such fluctuations can trigger instability problems, particularly when operating in island mode. For instance, a sudden surge in PV power output could result in the unwanted backfeeding of the generation set. Consequently, the MGMS consistently regulates PV production by constraining sudden increases and gradually increasing PV power levels in increments to prevent frequency spikes.

BESS management during low state-of-charge (SoC) conditions: The following strategies are applicable to systems equipped with BESS and PV setups.

Method 1 - load shedding and BESS operation

In scenarios where the BESS operates at a low SoC and there is limited or no solar PV availability, there might not be adequate power to maintain a network with stable voltage and frequency. In such cases, the MGMS will command the disconnection of sheddable loads before the BESS reaches its minimum SoC, while the BESS remains in grid-forming mode and can be charged with PV production. Once the BESS SoC exceeds a predetermined threshold, the load management function will automatically reconnect all loads.

Method 2 - BESS hibernation and manual restart

In situations where the BESS operates at a low SoC and solar PV availability is limited or absent, there may not be sufficient power to maintain a network with stable voltage and frequency. In this scenario, the MGMS will issue a command to completely shut down the system. This involves transitioning the BESS to offline mode and disconnecting all sheddable loads before the BESS reaches its minimum SoC. When solar PV becomes available again, the microgrid may be restarted using one of the following methods:

- Manual restart by the operator when solar production is available
- Automatic restart by the MGMS when the utility is restored

Generation set management: When a generation set functions as a grid-forming resource, it operates independently of the supervisory controller's commands. Therefore, the active power output of the generation set depends on the characteristics of the loads and local resources connected to the busbar. To control the active power output of the generation set within predetermined boundaries, the only viable option is to manage the loads and local resources. In this context, the MGMS regulates generation set operation within its minimum and maximum acceptable power limits by controlling the BESS and PV systems and/or shedding certain loads. An example of this scenario is illustrated in *Figure 8*, where PV power is curtailed to ensure the generation set operates above its minimum acceptable power level.

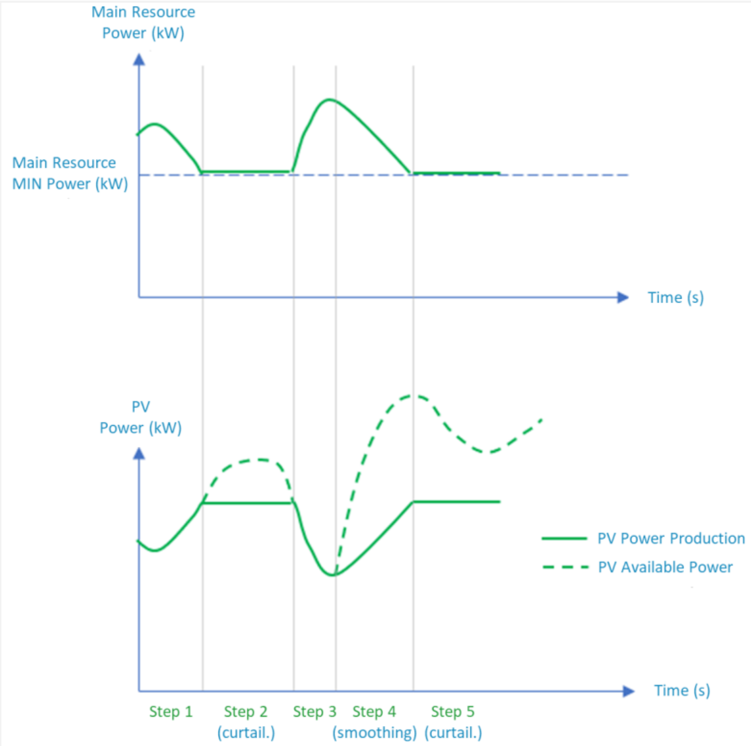


Figure 8: Generation set management[3]

The MGMS facilitates the coordinated operation of both PV and BESS with a generation set, serving as a grid-forming resource. This integration helps reduce fuel consumption and carbon dioxide (CO_2) emissions. In instances where the BESS is depleted or solar production is insufficient, customers can utilize a mobile generation set for emergency loads.

Load management: During off-grid operation, the microgrid system may encounter an unbalanced state where the total load surpasses the maximum available supply. This imbalance can lead to potential overloads on the remaining DER, potentially resulting in a complete disruption of the microgrid's operation.

In off-grid scenarios, the MGMS assumes responsibility for maintaining overall system stability. Depending on prevailing system conditions, it may issue commands to shed loads to sustain system stability. Additionally, the MGMS automatically restores loads whenever feasible.

Load shedding based on power

When the power output of the grid-forming resource (such as a generation set or BESS) reaches very high levels, nearing its nameplate capacity, the MGMS initiates load shedding progressively. This action aims to prevent a compromise of the reserve margin. *Figure 9* shows how this functionality is used to keep reserved power within an acceptable margin through three steps.

[3] Power Management Under Islanded Conditions - 0100DB2302 Microgrid Flex Design Guide (schneider-electric.com)

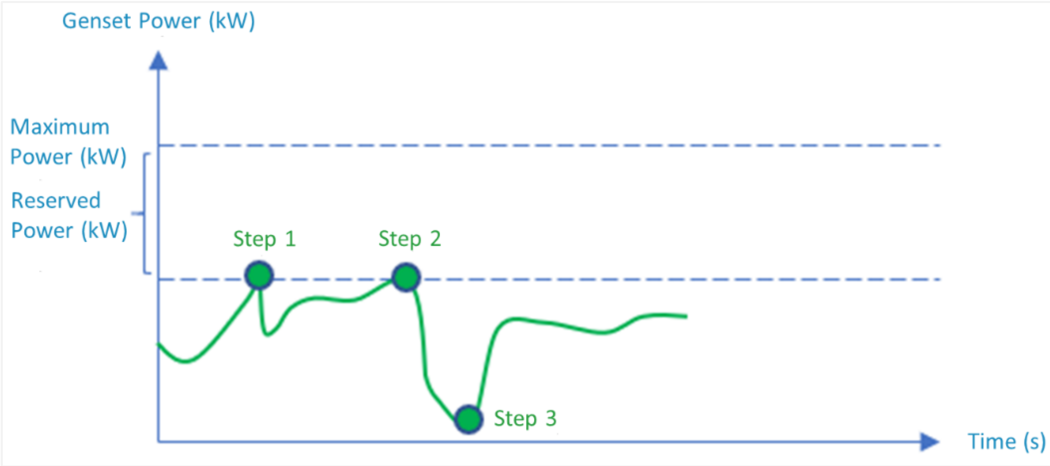


Figure 9: Load shedding based on power

- Step 1: When the reserved power of the generation set diminishes to a level considered too small, the MGMS takes action by disconnecting the lowest-priority load.
- Step 2: Same as Step 1.
- Step 3: When the reserved power of the generation set exceeds a threshold considered excessive, the MGMS automatically reconnects the highest-priority load.

Load shedding/reconnection based on energy

When the SoC of the BESS drops to a low level, the MGMS adopts a systematic approach to manage loads. Initially, it sheds all non-essential loads to alleviate the strain on the BESS. If the SoC remains insufficient, the MGMS proceeds to shed essential loads. Ultimately, if the SoC reaches the minimum acceptable level (SoC_min), all loads are shed. Load priorities can be adjusted using the local human-machine interface.

In scenarios where the BESS serves as the primary or anchoring resource, if its spinning reserve is deemed adequate and its SoC surpasses the predefined threshold, the MGMS begins reconnecting loads in sequence. The MGMS introduces an adjustable delay between two consecutive load reconnections.

The load shedding/reconnection mechanism described above is depicted in *Figure 10*, with the following steps explained in detail.

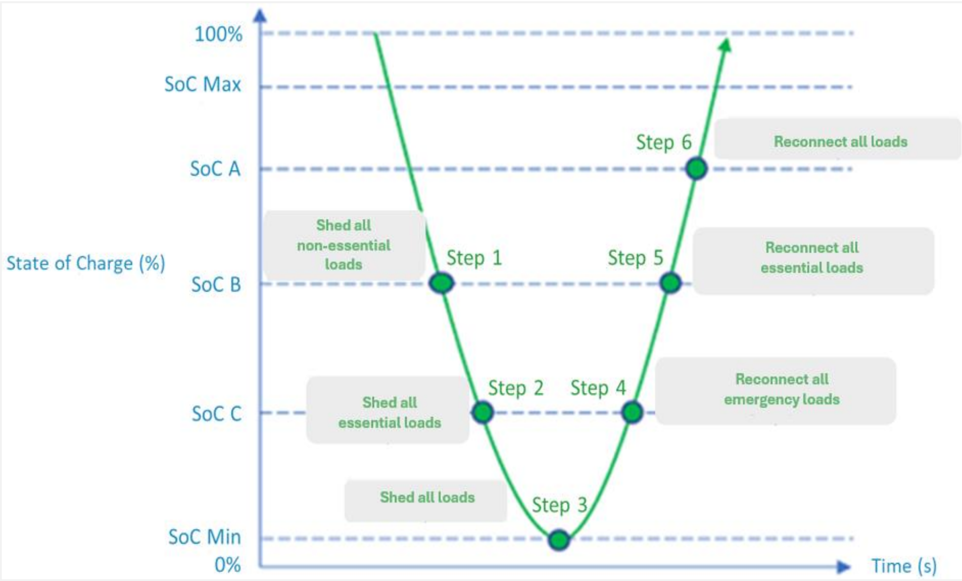


Figure 10: Load shedding/reconnection based on energy

Step 1. If SoC < $\mathrm{SoC}_{\mathrm{Essential}}$ load and reaches $\mathrm{SoC}_{\mathrm{B}}$, MGMS sheds all non-essential loads.

Step 2. If SoC < $\mathrm{SoC}_{\mathrm{Emergency}}$ load and reaches $\mathrm{SoC}_{\mathrm{C}}$, MGMS sheds all essential loads.

Step 3. If SoC < $\mathrm{SoC}_{\mathrm{min}}$, MGMS sheds all loads.

Step 4. If SoC > $\mathrm{SoC}_{\mathrm{min}}$ and reaches $\mathrm{SoC}_{\mathrm{C}}$, MGMS reconnects all emergency loads, one by one, if BESS spinning reserve allows.

Step 5. If SoC > $\mathrm{SoC}_{\mathrm{Emergency}}$ load and reaches $\mathrm{SoC}_{\mathrm{B}}$, MGMS reconnects all essential loads, one by one, if BESS spinning reserve allows.

Step 6. If SoC > $\mathrm{SoC}_{\mathrm{Essential}}$ load and reaches $\mathrm{SoC}_{\mathrm{A}}$, MGMS reconnects all loads, one by one, if BESS spinning reserve allows.

8.3. STEPS FOR TELEMETRY/TELECONTROL DESIGN

Step 1: Design of an MGMS integrated with SCADA

- The process starts by defining the functionality requirements for the MGMS, focusing on communication, control, and optimization. A detailed analysis of the microgrid ecosystem identifies key components and their interdependencies, laying the groundwork for a conceptual design of the MGMS architecture that incorporates advanced communication and control techniques.
- An important part of this step involves assessing the existing distribution SCADA system to determine if integration with the MGMS is feasible or if there is a need to design and procure a new combined SCADA and MGMS solution. This assessment ensures that the system

architecture is not only robust but also compatible with existing infrastructure, leading to a more streamlined integration and deployment process.

- A conceptual design for the MGMS architecture must be developed, incorporating advanced techniques for communication, control, and optimization.
- Next the developer finalizes the design and prepares technical specifications for implementation.

Step 2: Design of telemetry and telecontrol points

- Main feeder monitoring and control: Both monitoring and control mechanisms are established for main feeders to ensure efficient power distribution and observability/controllability in microgrid operations.
- Switching station monitoring and control: Advanced systems for monitoring and control at switching stations are crucial for maintaining operational reliability and enhancing responsiveness within the microgrid.
- Addition of new switching points: New switching points, potentially including reclosers or new switching substations, are considered to increase the flexibility and resilience of the microgrid network.
- Monitoring solutions for MV/LV transformers and load points: These are critical for optimizing performance and early detection of potential issues, contributing to the overall stability of the microgrid.
- Telemetry and telecontrol in DER sites: Extending these capabilities to DER sites facilitates their seamless integration with the SCADA/MGMS and enhances the manageability of the microgrid.
- SCADA integration solutions: Appropriate technology is selected for SCADA integration of grid automation; this could include options like substation controllers, RTUs, mini-RTUs, DTUs/protocol converters, and basic remote-read metering (AMR meter).
- Communication solutions: A communication framework is designed, primarily utilizing radio frequency (RF) technology with a cellular network backup, to ensure reliable data transmission and robust control across all telecontrol points of the microgrid.

8.4. DESIGNING COMMUNICATION ARCHITECTURE FOR MICROGRID TELEMETRY/ TELECONTROL

Robust and efficient communication architecture is essential for the effective operation of microgrids, as it facilitates real-time telemetry and telecontrol across various components. The following considerations outline the design principles and key features of ideal communication architecture for microgrids.

Integration of fiber optics, RF, and cellular technologies: Integrating multiple technologies, including fiber optics, RF, and cellular technologies, is recommended to ensure fast and reliable data exchanges across all nodes of the microgrid.

- Fiber optics: Fiber optics provide high-speed, high-capacity data transmission with minimal latency, making them ideal for critical data exchanges between central control units and major components such as power generation sources and substations. Utilizing existing fiber optic strands in current cables or installing new fiber optic cables in spare ducts can be a cost-effective strategy.

- Radio frequency: RF communication is used for wireless communication in areas where laying fiber optics is impractical. RF supports moderate data rates and can cover wide areas, making it suitable for remote monitoring and control of DER.

- Cellular technologies: Cellular networks offer flexible and scalable communication solutions, especially useful for mobile or temporary installations. These networks ensure reliable connectivity for remote sites and maintain data transmission even in areas lacking other infrastructure.

Redundancy and failover mechanisms: To maintain continuous operations even during network disruptions, redundancy and failover mechanisms should be implemented within the communication framework. This ensures that critical communication links remain operational and that the microgrid can continue to function effectively under adverse conditions.

- Redundant communication paths: Establishing multiple communication paths for key connections allows data to be rerouted in case of a failure in the primary path.

- Failover protocols: Automated failover protocols are recommended to detect communication failures and switch to backup systems without human intervention, minimizing downtime and maintaining operational continuity.

Support for centralized and distributed control strategies: The network should be structured to support both centralized and distributed control strategies, optimizing the performance of the microgrid and ensuring its adaptability to different operational scenarios.

- Centralized control: The communication network should enable a central control unit to oversee and manage the entire microgrid, making high-level decisions based on comprehensive system data.

- Distributed control: Local control units within the microgrid need to operate autonomously, making real-time adjustments to optimize performance and respond to local conditions. The communication architecture should support data sharing and coordination between these distributed units and the central control unit.

Field testing and validation: Field testing of the communication infrastructure needs to be conducted under various environmental and operational conditions to validate its performance and reliability.

- Environmental testing: Communication systems should be tested in different environmental conditions, such as extreme temperatures, humidity, and electromagnetic interference, to ensure they can withstand and perform reliably in real-world scenarios.

- Operational testing: The infrastructure should be tested during normal and emergency operational conditions to assess its responsiveness, latency, and data integrity. This includes simulating network failures and observing the effectiveness of redundancy and failover mechanisms.

Compliance with IEC 62351: Adherence to the IEC 62351 standard is recommended, as it provides guidelines for securing communication protocols in power systems. This standard focuses on ensuring the confidentiality, integrity, and availability of data and includes measures for authentication, encryption, and secure management of keys and certificates.

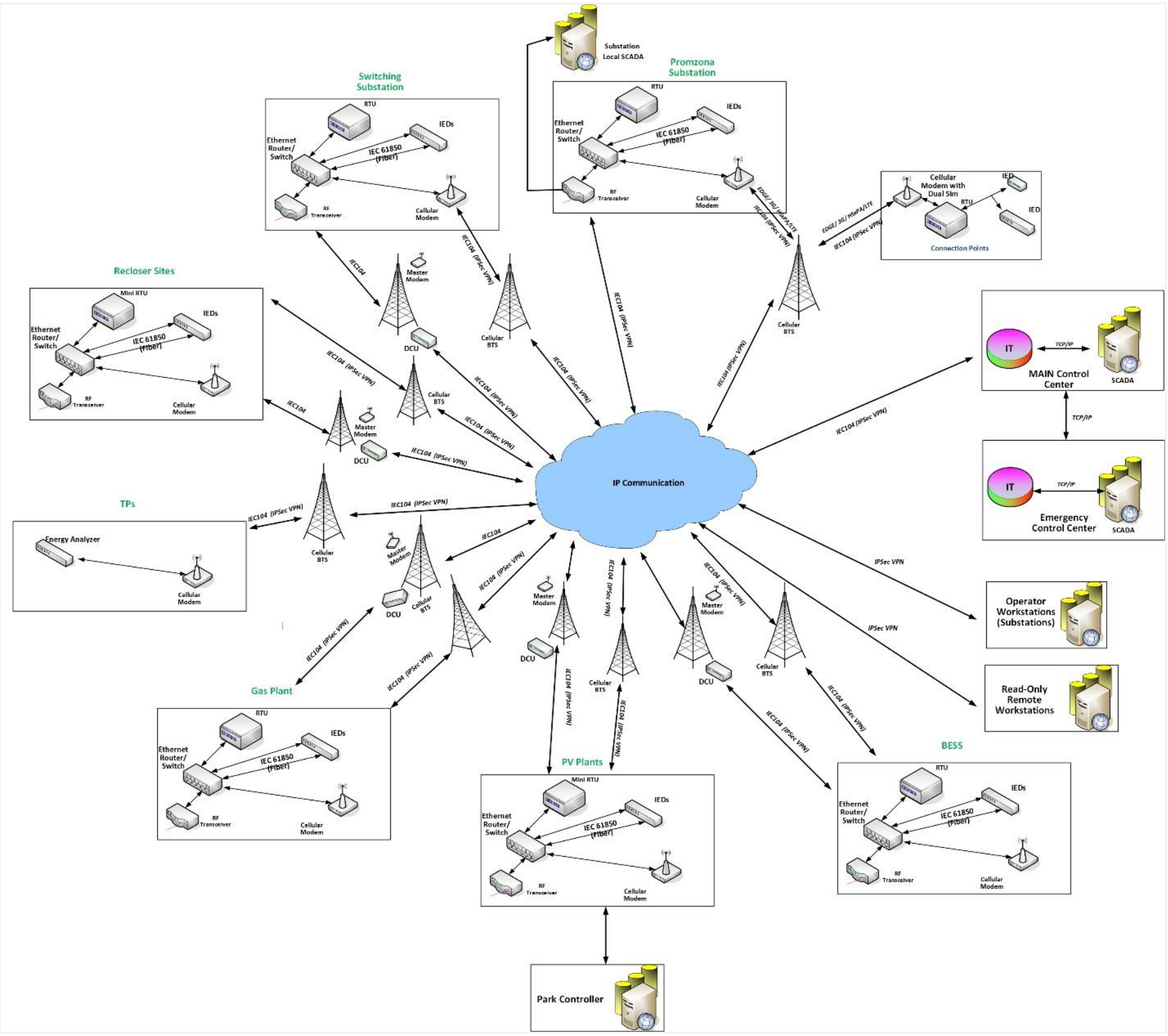


Figure 11: Example of communication architecture

8.5. CYBERSECURITY RECOMMENDATIONS FOR MICROGRID DESIGN

Providing robust cybersecurity for microgrid systems is critical to maintaining their reliability, integrity, and resilience against potential cyber threats. This section outlines key recommendations and technical requirements for securing microgrid control systems and their management infrastructure. The recommendations include measures for physical and logical access control, adherence to standardized cybersecurity frameworks, network segmentation, hardware and software hardening, and the implementation of secure authentication and encryption protocols. Additionally, the technical requirements for MGMS cybersecurity emphasize secure authentication, data encryption, intrusion detection, patch management, audit and logging capabilities, redundancy, secure configuration management, and regular security assessments. By following these guidelines, microgrid operators can significantly enhance the cybersecurity posture of their systems, ensuring continuous and secure operations.

- Physical and logical access control: It is essential to ensure that both physical and logical access to microgrid control systems are strictly controlled. Critical components should be physically secured, and stringent access control policies should be implemented to restrict unauthorized access to the system's network and devices.

- Network segmentation and isolation: Implementing network segmentation to isolate critical systems from non-critical ones is important. This limits the spread of potential cyberattacks and helps protect sensitive control systems. Firewalls and intrusion detection systems should be used to monitor and control network traffic.

- Hardware and software hardening: Hardening all hardware and software components by disabling unnecessary services and ports, removing unneeded software, and applying security patches regularly is necessary. This reduces the potential attack surface and mitigates vulnerabilities.

- Password management and authentication: Enforcing strong password policies, including requirements for complexity, regular changes, and proper storage, is vital. Multi-factor authentication should be used to enhance security, allowing only authorized personnel to access the microgrid's control systems.

- Regular security updates: Timely application of security patches and firmware updates for all networked devices within the microgrid is essential. This practice helps close security gaps and protects against newly discovered threats.

- Incident response and recovery plans: Developing and maintaining an incident response plan that includes procedures for detecting, responding to, and recovering from cyber incidents is crucial. These plans should be regularly tested for effectiveness and readiness.

- Continuous monitoring and logging: Continuously monitoring and logging network traffic and system activities is important. These logs can be used to detect anomalies, enforce security policies, and provide forensic data in the event of a security breach.

- Use of secure communication protocols: Employing secure communication protocols, such as transport layer security/secure sockets layer (TLS/SSL,) for data transmission within the microgrid ensures data integrity and confidentiality during communication between different components of the microgrid.

- Compliance with IEC 62351: Adhering to the IEC 62351 standard, which provides guidelines for securing communication protocols in power systems, is essential. This standard focuses on protecting the confidentiality, integrity, and availability of data and includes measures for authentication, encryption, and secure management of keys and certificates.

Technical requirements for cybersecurity for MGMS

- Secure authentication and authorization: The MGMS must implement secure authentication mechanisms, such as multi-factor authentication, to verify the identity of users and devices. Role-based access control should be used to ensure that only authorized personnel have access to specific system functions and data.

- Encryption of data: All data transmitted within the MGMS, including control signals and operational data, should be encrypted using strong encryption algorithms. This protects the confidentiality and integrity of data, preventing unauthorized access and tampering.

- Intrusion detection and prevention systems: The MGMS should include intrusion detection and prevention systems to monitor network traffic for suspicious activities and potential security breaches. These systems should be capable of alerting operators and automatically responding to detected threats.

- Patch management: The MGMS must have a robust patch management process in place to keep all software and firmware up to date with the latest security patches. This helps mitigate vulnerabilities and protect against known exploits.

- Audit and logging capabilities: The MGMS should have comprehensive audit and logging capabilities to track user activities, system events, and security incidents. Logs should be securely stored and regularly reviewed to identify and address potential security issues.

- Redundancy and failover mechanisms: The MGMS should incorporate redundancy and failover mechanisms to ensure continuous operation and availability of critical functions in the event of a cyberattack or hardware failure. This enhances the system's resilience and reliability.

- Secure configuration management: The MGMS must maintain secure configuration management practices, including the use of configuration baselines and regular audits to ensure compliance with security policies and standards. Unauthorized changes to system configurations should be detected and prevented.

- Regular security assessments: Regular security assessments, including vulnerability assessments and penetration testing, should be conducted on the MGMS to identify and remediate potential security weaknesses. These assessments help maintain the security and resilience of the system.

9. IDENTIFICATION OF REQUIREMENTS FOR NEW EQUIPMENT

In the dynamic landscape of modern energy systems, the development of microgrids is a pivotal strategy to enhance energy resilience, efficiency, and sustainability. Microgrid design and implementation require rigorous consideration of various factors, ranging from operational philosophy to technological advancements. In this context, the selection and integration of new equipment play a crucial role in shaping the functionality and performance of microgrid systems. Aligned with the microgrid's operational principles and informed by network analysis and size determination studies, the selected equipment ensures optimal performance tailored to the microgrid's unique needs and requirements.

9.1. TYPES OF NEW EQUIPMENT

Additional DER: Additional DER are essential components of a microgrid, contributing to its energy generation capacity and overall flexibility. These resources, such as solar panels, gas generators, diesel generators, etc., enable the microgrid to harness both renewable and traditional energy sources, reducing dependency on centralized power grids and enhancing its resilience and sustainability.

Battery energy storage system: BESS play a critical role in stabilizing the microgrid by storing excess energy during periods of low demand and releasing it during peak demand or in the event of supply fluctuations. BESS helps to balance supply and demand, improve grid stability, and support renewable energy integration, thereby enhancing the microgrid's reliability and efficiency.

Low/medium-voltage overhead line: LV and MV overhead lines are essential components for transmitting electrical power within the microgrid. These lines facilitate the distribution of electricity from generation sources to end users, offering a cost-effective and efficient means of energy transfer, especially in rural or remote areas where underground cables may not be feasible.

Low/medium-voltage underground cable: In urban or densely populated areas, LV and MV underground cables offer a more aesthetically pleasing and space-saving alternative to overhead lines. These cables minimize visual impact, reduce the risk of damage from environmental factors or vandalism, and enhance the reliability of power distribution within the microgrid.

Remote terminal unit/mini RTU/cellular distribution terminal units: RTUs, mini RTUs, and cellular DTUs are critical components of the microgrid's monitoring and control infrastructure. These devices enable real-time data acquisition, telemetry, and remote-control functionalities, allowing operators to monitor and manage the microgrid's performance efficiently from a centralized location.

Energy analyzer (telemetry): Energy analyzers provide detailed insights into the microgrid's energy consumption, generation, and distribution patterns. These telemetry devices collect and analyze data on voltage levels, power quality, and energy flows, enabling operators to optimize system performance, identify inefficiencies, and make informed decisions to improve overall energy management.

Digital relay: Digital relays serve as protective devices within the microgrid, detecting and isolating faults to prevent damage to equipment and ensure the safety of personnel. These advanced relays offer fast and accurate fault detection capabilities, minimizing downtime and disruptions to the microgrid's operation while enhancing overall system reliability.

Radio frequency communication: RF communication systems enable wireless data transmission between various components of the microgrid, facilitating seamless communication and coordination. RF communication technology offers reliable and secure connectivity, allowing for real-time monitoring, control, and coordination of DER, distribution assets, and control devices.

Cellular: Cellular communication technology provides a robust and widely accessible means of connectivity for remote monitoring and control of microgrid assets. Cellular networks offer reliable coverage, high data transmission speeds, and secure communication channels, making them ideal for applications requiring remote access and control, such as smart grid management and asset monitoring.

Recloser: Reclosers are automatic circuit breakers equipped with intelligent control capabilities, designed to detect and isolate temporary faults in the microgrid's distribution network. These devices help minimize outage durations by automatically restoring power to unaffected sections of the grid after a fault has been cleared, improving overall system reliability and resilience.

Circuit breaker: Circuit breakers are essential safety devices within the microgrid, designed to protect electrical circuits from overcurrent and short circuits. These devices interrupt the flow of electricity in the event of a fault, preventing damage to equipment and mitigating the risk of fire or electrical hazards. Circuit breakers come in various types and configurations to suit different voltage levels and operational requirements within the microgrid.

Step-up/step-down transformer: Step-up and step-down transformers are used to adjust voltage levels within the microgrid, facilitating the efficient transmission and distribution of electrical power. Step-up transformers increase voltage levels for long-distance transmission, while step-down transformers reduce voltage levels for distribution to end users. These transformers play a vital role in maintaining power quality, minimizing losses, and ensuring compatibility between different components of the microgrid.

Incorporating these new equipment components into the microgrid design supports the system's reliability, efficiency, and resilience, ultimately enabling it to meet the energy needs of its users while adhering to environmental, economic, and operational objectives. Each piece of equipment contributes to the overall functionality and performance of the microgrid, underscoring the importance of careful selection and integration during the development process.

9.2. CONSIDERATIONS FOR IDENTIFYING POTENTIAL NEW COMPONENTS

The microgrid's operational philosophy, encompassing its objectives and operational requirements, must be thoroughly reviewed to ensure that new equipment selections align with these foundational principles. A comprehensive network analysis should pinpoint areas within the microgrid that could benefit from upgrades or additional equipment, aimed at enhancing overall functionality and efficiency. Size and capacity requirements for new equipment are determined based on a detailed assessment of the microgrid's current and projected load demands as well as its generation capacity. This ensures that the equipment chosen is capable of meeting the microgrid's operational demands effectively.

Potential new component 1: Additional DER

- The potential for integrating renewable energy into the microgrid (due to the determined demand scaling) needs to be carefully assessed, considering the microgrid's specific energy needs and load requirements. This assessment is vital for determining the necessity and scope for additional DER.

- Selection of additional DER, such as solar panels, diesel generators, gas generators, etc., is based on their ability to enhance the microgrid's energy generation capacity and its sustainability objectives. The choice of these systems is influenced by their compatibility with the existing energy infrastructure and their environmental impact.
- The optimal locations and capacities for these additional DER are determined by analyzing resource availability, geographic conditions, and the existing energy distribution network within the microgrid. This strategic placement ensures maximum efficiency and integration with the least disruption to the current system.

Potential new component 2: BESS

- Evaluating the need for energy storage based on the variability of renewable energy sources and the microgrid's load profiles is important for maintaining energy balance and stability.
- Specifying the capacity and performance requirements for the BESS is important to meet the operational demands of the microgrid.
- Selecting suitable battery technologies and configurations, considering factors such as charging/discharging rates, efficiency, and life cycle, is essential for optimizing energy storage and release.

Potential new component 3: Low/medium-voltage overhead line

- Identifying areas where new overhead lines are required to connect microgrid components is essential for expanding the network and enhancing connectivity between DER.
- Determining the voltage rating and capacity of the overhead lines based on load requirements is crucial to ensure they can handle the projected electrical loads without compromising performance or safety.
- Designing the overhead line route requires careful consideration of terrain, right-of-way, and environmental impact to minimize disruptions and adhere to local regulations.
- When procuring materials and equipment for the construction of the overhead lines, it is necessary to ensure quality and compatibility with existing infrastructure.

Potential new component 4: Low/medium-voltage underground cable

- Assessing areas where underground cables are needed for grid expansion or reliability improvement is important to support the growth and resilience of the microgrid.
- Specifying the voltage rating and capacity of the underground cables based on load requirements is critical to ensure that the infrastructure can adequately support energy distribution needs.
- Designing the underground cable route involves considering factors such as soil conditions, depth, and proximity to other utilities to avoid interference and potential hazards.

- When procuring materials and equipment for the installation of underground cables, it is necessary to meet specific technical and safety standards.
- Excavating trenches, laying cables, and backfilling trenches according to specifications are essential steps in the installation process that require precision and adherence to design plans.

Potential new component 5: Recloser

- Identifying locations where reclosers are needed for automatic fault detection and isolation is critical to maintaining the integrity and resilience of the microgrid during faults.
- Selecting recloser devices with appropriate ratings and settings for the microgrid's operating conditions is important to ensure they function optimally under various electrical loads and fault conditions.
- Installing and configuring reclosers at strategic points along the distribution network is required to maximize their effectiveness in isolating faults and minimizing outage areas.
- Testing recloser operation under various fault scenarios is necessary to ensure proper functionality and to verify that they are effectively enhancing grid reliability.

Potential new component 6: Circuit breaker

- Determining the need for circuit breakers to protect microgrid components from overcurrent and faults is essential for preventing equipment damage and ensuring safety.
- Selecting circuit breakers with suitable ratings and characteristics for the microgrid's voltage levels and load conditions is crucial to ensure they can adequately handle the electrical demands and fault conditions of the microgrid.
- Installing and configuring circuit breakers at key points within the microgrid is required to protect different sections of the grid effectively.
- Coordinating circuit breaker settings with other protection devices for coordinated operation is important to ensure a holistic protection strategy that enhances overall grid stability and safety.

Potential new component 7: Step-up/step-down transformer

- Evaluating the need for transformers to adjust voltage levels within the microgrid is crucial for efficient power distribution and minimizing energy losses.
- Determining the required voltage ratios and capacities for step-up and step-down transformers is necessary to match the generation and consumption profiles within the microgrid.
- Selecting transformers with appropriate specifications for the microgrid's voltage profile and load requirements is essential to ensure effective voltage regulation and compatibility with the connected equipment.
- Installing and commissioning transformers at relevant points within the microgrid is required to integrate them into the existing infrastructure seamlessly.

Potential new component 8: RTU/mini RTU/cellular DTU

- Determining the need for RTUs or DTUs for monitoring and control purposes is essential for effective microgrid management.
- Selecting the appropriate RTU or DTU based on communication requirements and system compatibility is crucial to ensure seamless integration and functionality within the microgrid.
- Installing and configuring the RTU or DTU at strategic locations within the microgrid is required to maximize coverage and control capabilities.
- Establishing communication protocols and interfaces with the MGMS is important for consistent and reliable data exchange.

Potential new component 9: Energy analyzer (telemetry)

- Identifying the need for energy analyzers to monitor system performance and energy flows is crucial for effective energy management within the microgrid.
- Selecting energy analyzer systems capable of providing telemetry data in real time is essential to track and optimize energy consumption and generation dynamically.
- Installing energy analyzers at key points within the microgrid to capture relevant data is necessary for detailed performance monitoring.
- Integrating energy analyzer data into the MGMS for analysis and optimization helps in making informed decisions to improve energy efficiency and reliability.

Potential new component 10: Digital relay

- Evaluating the existing protection system and identifying areas where digital relays are needed for improved fault detection and coordination is critical for system safety.
- Selecting digital relays with advanced protection features and communication capabilities is essential to enhance the protective functions of the microgrid.
- Installing and configuring digital relays at critical points within the microgrid provides robust protection against faults and abnormalities.
- Coordinating settings with other protection devices for reliable and coordinated operation enhances the overall stability of the microgrid.

Potential new component 11: RF communication

- Determining the need for RF communication systems for data transmission within the microgrid is important for establishing robust and flexible communication links.
- Selecting RF communication technologies suitable for the microgrid's operational requirements and environmental conditions is crucial for reliable performance.
- Installing RF communication equipment and establishing communication links between microgrid components facilitates seamless and uninterrupted data flow.

- Testing and optimizing RF communication performance to ensure reliable data transmission is essential for maintaining operational integrity.

Potential new component 12: Cellular communication components

- Assessing the need for cellular communication for remote monitoring and control of microgrid components is important for extending control beyond local networks.
- Selecting cellular communication technologies compatible with the MGMS is crucial for ensuring reliable and secure communications.
- Installing cellular communication devices and establishing connections with cellular networks provide a backup and extension to other communication forms.
- Implementing security measures to protect cellular communication from unauthorized access is essential to safeguard system data and operations.

While integrating new equipment into a microgrid design, it is important to recognize that not all these components are required for every microgrid. The selection of additional equipment should be guided by specific operational needs, system capacity, and the overall design philosophy of the microgrid. Each component offers potential benefits but should be considered based on the particular objectives and constraints of the microgrid project. This approach ensures that the integration of new equipment enhances the microgrid's functionality, efficiency, and resilience without unnecessary complexity or cost.

10. COST ESTIMATION

Cost estimation is a fundamental aspect of microgrid design, providing the financial framework necessary for project planning and decision-making. Accurate cost estimation accounts for all potential expenses, helping stakeholders budget effectively and evaluate the economic viability of a microgrid project. This section outlines the key components and considerations involved in estimating the costs associated with designing and implementing a microgrid.

Components

When estimating the cost of a microgrid, it is essential to consider a comprehensive range of components, which can be broadly categorized into electrical system components, energy generation and storage, controls and communications, new buildings or renovations, system integration, cybersecurity, operation and maintenance, engineering design, system studies, and general project costs.

- Electrical system components
  - New sectionalizing switches, circuit breakers, relays, and cables: These components are essential for ensuring reliable power distribution and protection within the microgrid. Costs can vary based on the specifications and quality of the equipment required.
- Energy generation and storage
  - BESS: Includes costs for batteries, battery management systems, and installation.
  - Gas and diesel generators: Accounts for the cost of the generators, installation, and any necessary ancillary equipment like exhaust systems and fuel storage.
  - PV systems: Includes costs for solar panels, mounting structures, inverters, and integration into the existing grid.
- Controls and communications
  - Communication lines and microgrid controllers: These costs include hardware, software, and installation expenses.
  - Supervisory control and data acquisition systems: Hardware and software for real-time system monitoring and control must be priced out.
  - Microgrid management systems: Includes the costs of advanced management software and necessary computing infrastructure.
- New buildings or renovations
  - Microgrid control room and related facilities: The cost of constructing new buildings or renovating existing structures to house control equipment and personnel must be included. This also covers utilities and site preparation costs.
- System integration

  - Holistic integration of electrical, mechanical, and building control systems: Integration costs cover the expenses associated with ensuring all systems work seamlessly together. This involves significant planning, engineering, and labor.

- Operation and maintenance
  - Costs per hour of operation for diesel generator maintenance and other equipment: Ongoing operation and maintenance costs must be considered, including routine maintenance, repairs, and replacements.

- Engineering design costs
  - Professional fees for engineering design services: This includes the costs of hiring engineers to design the microgrid, develop detailed plans, and oversee the project.

- System study costs
  - Protection, interconnection, and other system studies: Includes the costs of studies to assess protection schemes, interconnection requirements, and other technical aspects, which are essential for ensuring the microgrid's safety and reliability.

- General project costs
  - Safety, project management, general provisions, overhead, and profit: These are additional costs associated with ensuring the project is completed safely, on time, and within budget. They also include contractor overhead and profit margins.

Typical steps for a cost estimation study

- Comprehensive scope definition: The first step is to clearly define the scope of the project. This involves outlining all the components and systems that will be included in the microgrid, ensuring that every necessary element is considered from the outset.

- Detailed bill of quantities listing: Next, a detailed bill of quantities should be created. This list should be based on the architectural and functional specifications of the microgrid, ensuring that every required component is accounted for in detail.

- Market pricing: For accurate cost estimation, current market prices for each component must be obtained. This often involves contacting multiple suppliers to get competitive bids or quotes. Additionally, the costs for any custom components or specialized technology that are specific to the microgrid's design must be included in the estimate. This ensures that any unique requirements are adequately considered in the cost planning.

- Detailed breakdown of costs: All potential expenses should be itemized, covering equipment, materials, labor, and regulatory fees. This detailed breakdown helps understand the total financial requirement and identify areas where cost savings might be achieved.

- Installation and integration costs: Estimating labor costs for the installation is crucial. This includes the staffing required for physical installation, electrical integration, and system testing. Furthermore, costs associated with integrating new components with existing infrastructure should be considered. This may involve additional hardware or modifications to ensure seamless integration.

- Permitting and compliance: Securing permits and ensuring regulatory compliance can incur significant costs. This includes environmental assessments and regulatory fees required to ensure the project meets all local and national requirements. These costs must be included in the overall budget.
- Contingency planning: Finally, it is important to include a contingency budget. This budget accounts for unexpected expenses or changes in the project scope, providing a financial buffer to handle any unforeseen issues that may arise during project implementation.

11. ECONOMIC COMPARISON OF THE DESIGN OPTIONS (OR DESIGN DECISION VIA OPTIMIZATION)

A comprehensive techno-economic comparison of alternative design options involves evaluating the technical performance and economic viability of different microgrid configurations. This analysis considers capital and operational costs, system efficiency, reliability, and scalability. By comparing various energy sources, storage solutions, and control strategies, the optimal design can be identified, balancing cost-effectiveness with technical robustness through two possible approaches.

Objective function and optimization approach: In microgrid design, using an objective function and optimization approach involves creating a mathematical model that captures the intricate balance between cost, performance, and operational constraints of the microgrid components. The objective function is designed to minimize the total cost of ownership, including capital expenditures, operational costs, and maintenance, while maximizing system efficiency and reliability. Constraints may include renewable energy integration targets, energy storage capacities, and grid interconnection requirements. Advanced optimization techniques, such as MILP or genetic algorithms, are applied to explore various configurations of DER, storage systems, and load management strategies. This approach enables a precise, data-driven comparison of alternative microgrid designs, helping select the most cost-effective and technically sound option.

Comparison of levelized cost of energy for alternative design options: The levelized cost of energy (LCOE) approach in microgrid design provides a clear metric for comparing the economic performance of different design options. LCOE is calculated by dividing the total life-cycle costs of the microgrid, including initial capital investment as well as operations and maintenance costs, by the total energy produced over the system's lifespan. This method allows for a straightforward comparison of various configurations, such as different combinations of solar panels, wind turbines, battery storage, and backup generators. By focusing on the cost per unit of energy delivered, the LCOE approach helps identify the most economically viable microgrid design, taking into account factors like renewable energy penetration, energy storage efficiency, and load profiles. This ensures that the chosen design not only meets energy needs but also provides the best financial return over its operational life.

11.1. OBJECTIVE FUNCTION AND OPTIMIZATION APPROACH

The goal of this approach is to minimize the total life-cycle cost, incorporating capital, operational, maintenance, fuel, and control system costs as well as resilience and reliability metrics over the project's lifetime:

$$\text{Minimize } \mathrm{Z}$$

$$= \frac{\mathrm{C}_{\mathrm{cap}}(\mathrm{X}_{\mathrm{new}}, Y, Z, control) + \sum_{t=1}^{T}(\mathrm{C}_{\mathrm{op,t}}\left(\mathrm{X}_{\mathrm{new}}, \mathrm{X}_{\mathrm{old,}} Y, Z, \mathrm{S}_{\mathrm{t}}\right) + \mathrm{C}_{\mathrm{main,t}}\left(\mathrm{X}_{\mathrm{new}}, \mathrm{X}_{\mathrm{old,}} Y, Z\right)}{(1+r)^t + C_{control(z)} + C_{\mathrm{reliability}} + C_{\mathrm{resilience}}}$$

where:

- Z is the total cost.
- $\mathrm{X}_{\mathrm{new}}$ represents the capacity of new generation units.
- $\mathrm{X}_{\mathrm{old}}$ represents the capacity of existing generators.

- Y represents the capacity of BESS.
- Z represents other infrastructure components.
- $control$ encapsulates the cost elements related to control and automation systems.
- $\mathrm{S_t}$ represents the generation scheduling variables for all types of generators at time t.
- $\mathrm{C}_{\mathrm{cap}}$ is the capital cost function.
- $\mathrm{C}_{\mathrm{op,t}}$ is the operational cost in year t.
- $\mathrm{C}_{\mathrm{main,t}}$ is the maintenance cost in year t.
- $C_{control}$ is the control system cost function.
- $C_{\mathrm{reliability}}$ is the cost associated with reliability metrics.
- $C_{\mathrm{resilience}}$ is the cost associated with resilience metrics.
- r is the discount rate.
- T is the project lifetime.

Constraints:

1. Power balance constraint:

$$P_{gen,new,t}^{s_{new,t}} + P_{gen,old,t}^{s_{old,t}} + P_{RES,t}^{s_{RES,t}} + P_{RES,t} + P_{BESS,t} = P_{load,t}$$

for all t where $P_{gen,new,t}^{s_{new,t}}$, $P_{gen,old,t}^{s_{old,t}}$, and $P_{RES,t}^{s_{RES,t}}$ are the power outputs from new conventional, old conventional, and renewable energy sources, respectively, which depend on their respective dispatch decisions $s_{new,t}$, $s_{old,t}$ and $s_{RES,t}$.

2. Generator operating limits:

$$0 \leq x_{new} \leq x_{new,max} \text{ and } 0 \leq x_{old} \leq x_{old,max}$$

3. Battery operating and capacity limits:

$$0 \leq y \leq y_{max} \text{ and } SOC_{min} \leq SOC_t \leq SOC_{max}$$

4. Island operation duration:

$$\sum_{t=1}^{D}(P_{gen,new,t} + P_{gen,old,t} + P_{RES,t} + P_{BESS,t}) \geq \sum_{t=1}^{D} P_{load,t}$$

where D is the minimum duration of islanded operation required.

5. N-1 reliability compliance:

Ensure N-1 reliability compliance via power system simulations. This involves checking that the system can withstand the failure of any single component (generator, line, transformer, etc.) without causing a system-wide outage. The simulations must validate that the microgrid can maintain operational integrity under N-1 conditions.

6. Generator placement and sizing strategy:

To decide whether to deploy generation capacity centrally or in a decentralized manner, introduce binary decision variables d_central and d_decentral, which influence system design and costs:

$$d_{\mathrm{central}} + d_{\mathrm{decentral}} = 1$$

$$x_{\mathrm{new}} = x_{\mathrm{central}} \times d_{\mathrm{decentral}} + x_{\mathrm{decentral}} \times d_{\mathrm{decentral}}$$

where x_{central} and $x_{\mathrm{decentral}}$ are the capacities if centralized or decentralized, respectively.

7. Control system cost dependency:

The cost of the control system may vary depending on whether a centralized or decentralized approach is chosen due to different needs for communication, monitoring, and management technologies:

$$C_{\mathrm{control(z)}} = C_{\mathrm{central}} \times d_{\mathrm{decentral}} + C_{\mathrm{decentral}} \times d_{\mathrm{decentral}}$$

Optimization strategy: This model involves a complex decision-making layer, not only about the size and dispatch of generation and storage assets but also about the optimal structuring and control of these assets across potentially multiple sites or nodes within the microgrid. This involves solving a larger-scale mixed-integer nonlinear programming problem due to the binary decisions regarding centralization versus decentralization and the nonlinearities involved in cost functions and operational constraints.

Tools and techniques: Advanced optimization software capable of handling mixed-integer nonlinear programming is required. Tools such as GAMS, Pyomo, or MATLAB (with appropriate solvers like CPLEX, Gurobi, or BARON) are suitable for formulating and solving this type of problem. The use of simulation-based optimization or scenario analysis might also be beneficial to handle uncertainties in operational conditions and cost estimations, especially when comparing fundamentally different system architectures like centralized versus decentralized systems.

11.2. COMPARISON OF LEVELIZED COST OF ENERGY FOR ALTERNATIVE DESIGN OPTIONS

This approach compares different microgrid configurations by calculating their LCOE and selecting the most cost-effective option.

Steps

- Define the scenarios: Identify different design scenarios for the microgrid, such as:
  - Scenario 1: Renewable energy sources (RES) + BESS
  - Scenario 2: Gas generator only

– Scenario 3: Gas + RES

– Scenario 4: Gas + RES + BESS

- Identify cost components: Separate costs into CAPEX and operational expenditures (OPEX).
- Calculate present value (PVal) of costs
  – Use the discount rate to calculate the present value of both CAPEX and OPEX over the project's lifetime.
  – Present value of CAPEX ($PVal_{CAPEX}$) is the sum of all initial capital costs.
  – Present value of OPEX ($PVal_{OPEX}$) is the sum of annual OPEX discounted over the project's lifetime.
- Calculate present value of energy production
  – Determine the present value of the total energy produced over the project's lifetime.
  – Present value of energy production ($PVal_{Energy}$) is the sum of annual energy production discounted over the project's lifetime.
- Compute LCOE for each scenario by dividing the total present value of costs by the total present value of energy production: LCOE = ($PVal_{CAPEX}$ + $PVal_{OPEX}$) / $PVal_{Energy}$
- Compare the LCOE values of scenarios. The scenario with the lowest LCOE is typically the most cost-effective option over the project's life cycle.

$$\mathrm{LCOE} = \Big(\sum_{t=0}^{T}(\mathrm{CAPEX_{grid}} + \mathrm{CAPEX_{RES}} + \mathrm{CAPEX_{disp}} + \mathrm{CAPEX}_{grid\_comp} + \mathrm{CAPEX_{control}} + \mathrm{OPEX_{grid,t}} + \mathrm{OPEX_{RES,t}} + \mathrm{OPEX_{disp,t}} + \mathrm{OPEX_{grid\_comp,t}} + \mathrm{OPEX_{control,t}} + \mathrm{OPEX_{fuel,t}} + \mathrm{OPEX_{BESS,t}} + \mathrm{VOLL_t})) \div ((1+r)^t \div \Big(\sum_{t=0}^{T} E_{new,t} + E_{old,t}\Big) \div (1+r)^t\,)$$

where:

– $\mathrm{CAPEX_{grid}}$ is the capital expenditure for grid infrastructure.

– $\mathrm{CAPEX_{RES}}$ is the capital expenditure for new renewable energy sources.

– $\mathrm{CAPEX_{disp}}$ is the capital expenditure for new dispatchable generation (e.g., gas motors).

– $\mathrm{CAPEX}_{grid\_comp}$ is the capital expenditure for new grid components.

– $\mathrm{CAPEX_{control}}$ is the capital expenditure for control and automation systems.

– $\mathrm{OPEX_{grid,t}}$ is the operational expenditure for grid infrastructure in year t.

– $\mathrm{OPEX_{RES,t}}$ is the operational expenditure for renewable energy sources in year t.

- $\mathrm{OPEX}_{\mathrm{disp,t}}$ is the operational expenditure for dispatchable generation in year t.
- $\mathrm{OPEX}_{\mathrm{grid\_comp,t}}$ is the operational expenditure for grid components in year t.
- $\mathrm{OPEX}_{\mathrm{control,t}}$ is the operational expenditure for control systems in year t.
- $\mathrm{OPEX}_{\mathrm{fuel,t}}$ is the fuel expenditure for conventional generation in year t.
- $\mathrm{OPEX}_{\mathrm{BESS,t}}$ is the operational expenditure for battery energy storage systems in year t.
- $\mathrm{VOLL}_{\mathrm{t}}$ is the cost of unmet demand (value of lost load) in year t.
- $E_{new,t}$ is the energy produced by a new generation in year t.
- $E_{old,t}$ is the energy produced by existing generation in year t.
- r is the discount rate.
- T is the project lifetime.

Calculation of present value (PVal)

To calculate the present value of costs and energy production:

- Present value of CAPEX:

$$\mathrm{PVal}_{\mathrm{CAPEX}} = \mathrm{CAPEX}_{\mathrm{grid}} + \mathrm{CAPEX}_{\mathrm{RES}} + \mathrm{CAPEX}_{\mathrm{disp}} + \mathrm{CAPEX}_{grid\_comp} + \mathrm{CAPEX}_{\mathrm{control}}$$

- Present value of OPEX:

$$\mathrm{PVal}_{\mathrm{OPEX}} = (\sum_{t=0}^{T}(\mathrm{OPEX}_{\mathrm{grid,t}} + \mathrm{OPEX}_{\mathrm{RES,t}} + \mathrm{OPEX}_{\mathrm{disp,t}} + \mathrm{OPEX}_{\mathrm{grid\_comp,t}} + \mathrm{OPEX}_{\mathrm{control,t}} + \mathrm{OPEX}_{\mathrm{fuel,t}} + \mathrm{OPEX}_{\mathrm{BESS,t}} + \mathrm{VOLL}_{\mathrm{t}})) \div ((1+r)^{t}$$

- Present value of energy production:

$$\mathrm{PVal}_{\mathrm{Energy}} = (\sum_{t=0}^{T} E_{new,t} + E_{old,t}) \div (1+r)^{t})$$

TABLE 7: TYPICAL TABLE FOR COMPARING LCOE OF DIFFERENT OPTIONS[4]

COST ITEM	RES + BESS	GAS GENERATOR ONLY	GAS + RES	GAS + RES + BESS
CAPEX				
Grid ($)	200	200	200	200
New RES ($)	1,000,000	0	500	500
Dispatchable generation ($)	0	600	600	600

[4] Figures are only illustrative to show the structure of the final comparison table.

TABLE 7: TYPICAL TABLE FOR COMPARING LCOE OF DIFFERENT OPTIONS[4]				
COST ITEM	RES + BESS	GAS GENERATOR ONLY	GAS + RES	GAS + RES + BESS
Grid components ($)	500	100	100	500
Control systems ($)	300	100	100	300
OPEX (per year)				
Grid ($)	20	20	20	20
New RES ($)	30	0	20	20
Dispatchable generation ($)	0	50	50	50
Grid components ($)	50	10	10	50
Control systems ($)	40	10	20	40
Fuel ($)	0	200	150	150
BESS ($)	200	0	0	200
VOLL ($)	20	50	30	20
Energy production				
Annual (kWh/year)	1,500,000	1,000,000	1,200,000	1,500,000
Lifetime (years)	20	20	20	20
LCOE ($/kWh)	**0.410**	**0.580**	**0.520**	**0.540**

11.3. NOTES ON TECHNO-ECONOMIC FEASIBILITY OF RESILIENCE WITH MICROGRID PROJECTS

When assessing the financial viability of microgrid projects, particularly those aimed at enhancing resilience, it is crucial to recognize that many microgrid resiliency projects may not yield a direct positive financial return purely based on economic savings. However, these projects can still be financially viable under certain conditions. A positive financial return often hinges on a unique mix of factors such as the installation location, available financial incentives, and the existing infrastructure at the site.

For installations where resiliency is a critical requirement, the financial metrics might not need to strictly align with typical cost-saving goals. In such cases, the value of a microgrid transcends direct economic returns. It enhances the installation's capability, reduces operational risks, and provides a form of insurance against disruptions. This is particularly relevant for facilities requiring uninterrupted power for critical operations.

Given the unique challenges and objectives of microgrid projects, especially those designed for resilience rather than straightforward financial returns, this study recommends shifting the focus from the overall feasibility of microgrid projects to a more nuanced approach. Comparing alternative design options and optimizing the microgrid configuration and sizing is preferable to solely assessing their broad economic feasibility for the following reasons.

- Resilience as a priority: For installations where uninterrupted power is critical, the primary value of a microgrid lies in its ability to enhance site capabilities, mitigate risks, and provide a reliable power supply during interruptions. This resilience offers an intrinsic value that may not be directly quantifiable in traditional economic terms but is crucial for operational continuity.

- Economic savings vs. strategic importance: In contexts where resilience is a mission-critical requirement, the economic analysis of microgrid projects should extend beyond simple cost savings. The inclusion of VOLL in economic assessments exemplifies this approach by monetizing the benefits of avoided outages, which may justify the investments from a strategic standpoint rather than a purely financial one.

- Optimization over feasibility: By focusing on optimizing microgrid design—such as adjusting the size and configuration—rather than proving broad economic feasibility, stakeholders can tailor systems to meet specific operational needs efficiently. This approach allows for the detailed evaluation of how different configurations impact the resilience and economic performance of the project, taking into account the unique circumstances of each site.

- Contextual viability: Recognizing that a positive financial return depends on factors such as location, existing infrastructure, and available incentives, it becomes essential to adapt each project to leverage these elements effectively. This targeted approach ensures that each microgrid design is optimized for both performance and cost-efficiency within its specific context.

Integrating VOLL into the techno-economic assessment can further justify the investment in microgrid projects from a broader perspective. VOLL represents the cost that consumers are willing to pay to avoid power interruptions, quantifying the economic impact of supply disruptions. By including VOLL, stakeholders can evaluate the economic benefits of enhanced reliability and resilience that microgrids provide, especially when these systems prevent significant losses during power outages. This approach not only highlights the intrinsic value of maintaining continuous operations in critical facilities but also aligns the financial evaluation with the strategic importance of operational continuity.

12. MICROGRID IMPLEMENTATION PLAN

12.1. ACTIVITIES

Implementing a microgrid requires a structured and systematic approach to ensure its success and sustainability. This section outlines the essential phases and activities involved, from initial environmental assessments and financial planning to site surveys, regulatory compliance, and the final commissioning of the microgrid. Each step is designed to address technical, financial, and operational challenges, ensuring the microgrid is efficient, reliable, and capable of meeting local energy demands. Numbers in parentheses correspond to tasks in the sample implementation plan in the next section. Through meticulous planning and execution, this implementation plan aims to establish a resilient and sustainable energy solution tailored to the specific needs of the community.

1. Design and tender period

- Completion of conceptual design (T01-T02)
  - Define project objectives and scenarios (T01)
    - Identify the overarching goals and specific objectives for the microgrid project.
    - Develop different scenarios for project implementation, considering various constraints and requirements.
  - Initial concept development and site identification (T02)
    - Develop the initial concept for the microgrid, including potential configurations and layouts.
    - Identify and evaluate potential sites for the microgrid installation based on suitability and feasibility.
    - Design the concept: The conceptual design stage is the initial stage, which includes the general architecture of the microgrid, identification of the scope, sizing (number of feeders, total load to be supplied, duration of supply), on-grid and off-grid features, operational flexibility, SCADA, and telecommunication. Installation of new components/systems or replacement of equipment like cabinets, instrumentation, and new lines/switchgear as well as the location of new installations are principally designed in this phase. Technical assessments and cost assessments are also specified, including the economic optimization of microgrid size and resource types. Technical specifications of primary components and functional specifications of systems/subsystems are included.
- System studies and configuration design (T03)
  - Conduct detailed system studies to understand the technical requirements and constraints.
  - Develop the microgrid configuration design, including selecting appropriate technologies and components.
- Environmental impact assessment (T04)

- Conduct an environmental impact assessment to identify potential environmental risks and mitigation strategies.
- Prepare and submit the environmental impact assessment report to relevant authorities for review and approval.

- Financial planning (T05)
  - Once the conceptual design output is received with the economic analysis and cost assessment, a financial assessment of the microgrid project is prepared for budgeting in accordance with the overall implementation schedule. This includes resource planning, submission for budgetary amendment, an update of the owner's company revenue if necessary (inserting project cost into the tariff if applicable), and approval of the budget from authorities. Additional stages may be considered for international financial resources based on the lender's requirements.
  - Secure necessary financial resources and approvals to ensure project viability.
- Site surveys and investigations (T06)
  - Conduct site surveys to gather data on topography, soil conditions, and existing infrastructure.
  - Perform geotechnical investigations and other relevant studies to inform the design and construction planning.
- Permitting and approvals (T07)
  - Obtain all necessary permits and approvals from local, state, and federal authorities.
  - Ensure compliance with zoning, land use, and environmental regulations.
- Tender preparation and announcement (T08)
  - Prepare comprehensive tender documents, including detailed project specifications, scope of work, and contract terms. The tendering stage requires approval from various departments within the owner organization and permitting organizations. The project owner may be bound by public procurement law, and predefined time intervals could be required for permits, issuance of tender documents, and contractual agreements. Environmental impact assessments and legal permits for site implementation must be acquired before the tender process. Tenders might be public and transparent, and objections from bidders could add time to the process.
  - Publicly announce the tender and invite bids from qualified contractors and suppliers.
- Tender evaluation and contract signing (T09)
  - Evaluate bids based on technical and financial criteria.
  - Select the most suitable contractor(s) and finalize the contract terms.
  - Sign the contract for construction with the selected contractor(s).

2. Contract and pre-construction period

- Preparation of complete project documentation set (T10)
  - Prepare and obtain approval for the complete set of project documents, including engineering design, electrical plans, and construction specifications.
  - The engineering design stage is mainly fed from the conceptual design output and is generally specified in the tender process and performed by the main contractor. After the tender process is completed, the main contractor prepares the engineering projects and secures approval from the owner/authorized department. Once approved, manufacturing, testing, site delivery, and implementation are performed.
- Land delivery and site preparation (T11-T12)
  - Delivery of land to the contractor (T11): Officially hand over the project site to the contractor for commencement of work.
  - Land settlement, mobilization, and machine park settlement (T12).
    - Conduct land settlement activities, including clearing and leveling the site.
    - Mobilize construction teams, equipment, and materials to the project site.
    - Set up temporary facilities, including offices, storage areas, and worker accommodations.
- Preparation and submission of implementation projects (T13)
  - Contractors prepare and submit detailed implementation and manufacturing project documents.
  - Authorities review and approve the submitted documents to ensure compliance with project requirements.

3. Implementation stage

The implementation stage covers the period after tender and land delivery up to acceptance tests and site installation. It includes procurement and acceptance of equipment, site delivery after approval, submission of work and mobilization plans, and execution of land works according to the work plan. Replacement of main components or installation of new systems requires planned outages, and coordination with regional dispatch centers (transmission or distribution system operator) may be necessary.

- Excavation and preparation of construction areas (T14-T15)
  - Excavation and preparation of substation, BESS, and generator area (T14): Excavate and prepare the designated areas for the substation, BESS, and generator installation.
  - Construction work outside substation (T15): Begin construction work outside the main project zone, including access roads and utility connections.
- Equipment procurement and manufacturing (T16-T17)

- Order and manufacturing of main equipment (T16): Place orders for the main equipment required for the microgrid and oversee the manufacturing process.
- Construction works in microgrid site(s) (T17): Commence construction works at the microgrid site(s), focusing on building the necessary infrastructure and installing components.

- Testing and shipping (T18-T19)
  - Type test/routine test of main components (T18): Conduct type tests and routine tests on the main components to ensure they meet quality and performance standards.
  - Shipping of equipment to land (T19): Coordinate the shipping of equipment to the project site, ensuring safe and timely delivery.
- Installation of secondary infrastructure and systems (T20-T21)
  - Install secondary infrastructure in substations and remote points, transformer points, control communication network (T20).
  - Install switchgear, control, and protection systems, as well as BESS and power generators (T21).
- Functional testing (T22): Perform functional site tests for all installed components and systems to ensure proper operation and integration.

4. Initial energization and commissioning progress

- Initial energization (T23)
  - Perform initial energization of the microgrid system in a controlled and monitored environment.
  - Ensure all safety protocols are in place and adhered to during energization.
- Energized site testing (T24)
  - Carry out energized site tests to simulate real-world operating conditions.
  - Monitor system performance, response times, and resilience to potential disruptions.
- Commissioning and trial operation (T25)
  - The contractor submits a commissioning request after completing installation works. Site tests may be applicable before initial energization. Initial energization and trial operation could be part of the commissioning or separate stages, depending on local practices. The microgrid, designed for emergency conditions, requires cooperation for trial operation, possibly separating the microgrid region from the national grid. Strong cooperation is required to avoid faulty operations or large-scale interruptions. Trial operations may take a few months with intermittent operations to verify all functions and capabilities.
  - Conduct trial operations of the microgrid system to validate its readiness for full-scale operation.

  - Monitor and document system performance, identifying any areas for improvement.
- Final adjustments and calibration (T26)
  - Make necessary adjustments and calibrations to optimize system performance.
  - Ensure all systems are functioning according to design specifications.
- Monitoring and final revision of settings (T27)
  - The trial operation will reveal any deviations from design results, providing opportunities to update settings or make minor changes. Successful completion of monitoring and revision confirms that the microgrid will operate securely and reliably during real operations when needed. Most monitoring and parameter tuning is performed during the trial operation interval.
  - Prepare comprehensive commissioning documentation, including test results, performance data, and final adjustments.
  - Submit documentation to relevant authorities for approval.
  - Hand over the fully commissioned microgrid system to the operations and maintenance team.
  - Provide training and support to ensure a smooth transition to operational status.

12.2. TYPICAL IMPLEMENTATION PLAN FOR MICROGRID PROJECT

Process	Task ID	Taks Name	Month 1	2	3	4	5	6	7	8	9	10	11	12
Design and tender period	T01	Completion of conceptual design	■											
	T02	Initial concept development and site identification	■	■										
	T03	System studies and configuration design	■	■										
	T04	Environmental impact assessment	■	■										
	T05	Financial planning	■	■										
	T06	Site surveys and investigations	■											
	T07	Permitting and approvals	■	■	■									
	T08	Tender preparation and announcement		■	■									
	T09	Tender evaluation and contract signing			■									
Contract and pre-construction period	T10	Preparation of complete project documentation set			■	■	■	■						
	T11	Delivery of land to the contractor			■									
	T12	Land settlement, mobilization, and machine park settlement							■					
	T13	Preparation and submission of implementation projects							■	■				
Implementation stage	T14	Excavation and preparation of substation, BESS, and generator area								■				
	T15	Construction work outside substation								■	■			
	T16	Order and manufacturing of main equipment						■	■	■				
	T17	Construction works in microgrid site(s)								■				
	T18	Type test/routine test of main components								■				
	T19	Shipping of equipment to land								■	■	■		
	T20	Install secondary infrastructure in subst. and remote points, trans. points, control comm. network									■	■		
	T21	Install switchgear, control, and protection systems, as well as BESS and power generators									■	■	■	
	T22	Functional testing										■	■	
Initial energization and commissioning progress	T23	Initial energization											■	
	T24	Energized site testing											■	■
	T25	Commissioning and trial operation												■
	T26	Final adjustments and calibration												■
	T27	Monitoring and final revision of settings												■

ANNEX. SOFTWARE TOOLS FOR MICROGRID DESIGN

The design and optimization of microgrids necessitate sophisticated software tools capable of modeling and analyzing various cost and performance aspects. These tools are crucial for evaluating different scenarios, integrating diverse technologies, and considering economic factors to ensure efficient microgrid operation. This section presents primary software tools used in microgrid design, focusing on cost and performance modeling, as well as power system simulation. The ability to model costs and performance accurately ensures that microgrids are not only technically feasible but also economically viable and sustainable over the long term.

MICROGRID COST AND SCENARIO MODELING TOOLS

In microgrid design, cost and scenario modeling tools play an important role in optimizing design and operational strategies. These tools enable comprehensive analysis of various configurations, facilitating informed decision-making.

Microgrid cost and performance modeling tools are essential for several reasons:

- Economic feasibility: These tools help determine the economic viability of a microgrid project by analyzing CAPEX, OPEX, and potential revenue streams. By simulating different scenarios, stakeholders can identify the most cost-effective solutions and avoid over-investment.

- Optimization of resources: Through detailed simulations, these tools allow for the optimization of resources, including the integration of renewable energy sources, energy storage systems, and conventional generators. This ensures that the microgrid can meet its load demands efficiently while minimizing costs.

- Scenario analysis: These tools enable the evaluation of various scenarios, such as different energy mix options, load profiles, and future demand projections. This flexibility helps in planning for uncertainties and adapting to changing conditions.

- Sensitivity analysis: Sensitivity analysis capabilities allow users to understand how changes in key parameters, such as fuel prices or load growth, impact the overall performance and costs of the microgrid. This is crucial for risk assessment and management.

Several examples of such tools include the following:

- Hybrid Optimization of Multiple Energy Resources (HOMER) is a widely used tool for optimizing the design of microgrids and hybrid power systems. It simulates different configurations of energy systems to find the most cost-effective solution. HOMER evaluates both off-grid and grid-connected systems, considering renewable energy sources, storage, and conventional generators.

- Microgrid Design Toolkit (MDT) was developed by Sandia National Laboratories and helps in designing and optimizing microgrids. It focuses on reliability, economic performance, and integration of renewable energy sources. MDT provides a platform for evaluating different microgrid architectures and their performance under various scenarios.

- MicrogridUp1 is designed for the rapid assessment and optimization of microgrid projects. It offers tools for scenario analysis, cost estimation, and performance benchmarking, making it suitable for both preliminary and detailed design stages.

- Renewable Energy Optimization (REopt): Developed by the U.S. National Renewable Energy Laboratory (NREL), REopt helps optimize energy systems for buildings, campuses, communities, and microgrids. It evaluates the integration of renewable energy sources and storage, providing recommendations for cost-effective and resilient energy solutions.

- XENDEE is a comprehensive platform for microgrid design and optimization. It integrates financial and engineering models to evaluate microgrid performance, focusing on cost savings, energy efficiency, and resilience. XENDEE supports the planning and deployment of microgrids by providing detailed economic and technical analyses.

- Distributed Energy Resources - Value Estimation Tool (DER-VET) is an open-source tool developed by the Electric Power Research Institute (EPRI). It evaluates the value of DER, including their integration into microgrids. DER-VET considers various value streams, such as energy savings, reliability, and environmental benefits, to support investment decisions.

POWER SYSTEM SIMULATION SOFTWARE

Power system simulation software is a key tool for the design and analysis of the electrical networks of microgrids. These tools facilitate detailed studies on various critical aspects such as load flow, stability, fault analysis, and the integration of DER. By enabling comprehensive simulations, they ensure that microgrid designs are both technically sound and capable of meeting operational demands.

- Load flow analysis determines the voltage, current, active, and reactive power flows in an electrical network under steady-state conditions. This analysis is essential for ensuring that the microgrid can handle expected loads without issues such as voltage drops or excessive losses. By modeling different scenarios, engineers can optimize the placement and capacity of components to improve efficiency and reliability.

- Stability studies evaluate how a microgrid responds to disturbances such as sudden load changes or the loss of a generation unit. These studies are vital for ensuring that the microgrid can maintain stable operation under varying conditions. By simulating dynamic behaviors, engineers can design control strategies and protection schemes that enhance the resilience of the microgrid.

- Fault analysis involves simulating fault conditions (e.g., short circuits) to understand their impact on the microgrid and to design appropriate protection systems. This analysis helps in identifying potential weak points in the network and in developing strategies to isolate faults quickly to prevent widespread outages and damage to equipment.

- Integration of DER such as solar panels, diesel generators, and energy storage systems into a microgrid presents unique challenges. Simulation tools enable detailed modeling of these resources, including their intermittent nature and interactions with the grid. By understanding these dynamics, engineers can optimize the integration of DER to enhance the microgrid's performance and sustainability.

Examples of power system simulation software include the following:

- DIgSILENT PowerFactory is a versatile and widely used power system analysis tool that supports the simulation of microgrids. It offers comprehensive features for load flow analysis, stability studies, fault analysis, and the integration of DER. PowerFactory is known for its accuracy and detailed modeling capabilities, making it a preferred choice for engineers.
- PSS®SINCAL, developed by Siemens, is a comprehensive power system simulator for planning, modeling, and analyzing electrical power or pipe grids, focusing on distribution and industrial networks. It offers extensive analysis functions, including power quality, frequency stability, distributed generation interconnection, protection coordination, and economics-driven design decisions.
- NEPLAN provides a comprehensive suite of tools for power system analysis and planning. It supports load flow, fault analysis, transient stability, and the optimization of distributed generation. NEPLAN is known for its user-friendly interface and versatile modeling capabilities, making it an excellent tool for microgrid design and optimization.
- CYME is designed for the analysis and planning of electrical networks, offering modules for load flow analysis, short-circuit analysis, harmonic analysis, and DER integration. CYME is extensively used for designing and optimizing microgrids, ensuring efficient and reliable operation.

Cost and performance modeling tools, such as HOMER and REopt, enable comprehensive economic and technical evaluations, ensuring microgrids are technically feasible and economically viable. Power system simulation software, including DIgSILENT PowerFactory and PSS®SINCAL, facilitates detailed analysis of electrical networks, ensuring microgrid designs are robust and capable of meeting operational demands. By leveraging these advanced tools, engineers can design efficient, resilient, and sustainable microgrids.