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MicrogridUP Software Playbook: A User Guide

PREPARED BY:

NRECA Research

NRECA

America's Electric Cooperatives

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Overview

The MicrogridUP software is a microgrid planning tool that enables military installations and utility privatization (UP) system owners to quickly and accurately determine microgrid investment options to improve installation resilience. The MicrogridUP Playbook is a step-by-step software user manual to guide U.S. military energy managers, military advisors and contractors, and utilities through the microgrid design process using the MicrogridUP software.

From 2021-2024, NRECA Research developed the MicrogridUP software, leveraging previously funded Department of Energy (DOE) and national laboratory projects. MicrogridUP supports military installation energy resilience, defined by the U.S. Department of Defense (DoD) as "the ability to prepare for and recover from energy disruptions that affect mission assurance on military installations."[1] With decreasing costs for renewable generation and energy storage, military planners are exploring microgrids as a resilient and increasingly cost-effective energy management solution to ensure continuity of critical loads.

What is a Microgrid?

A microgrid, as defined by the U.S. DOE, is: "a group of interconnected loads and distributed energy resources that acts as a single controllable entity with respect to the grid. It can connect and disconnect from the grid to operate in grid-connected or island mode."

While other microgrid planning tools are available, they may lack the robust elements needed to fully anticipate hardware, software, and budgeting needs for the complex microgrid configurations needed to provide continuity of operations for large and/or critical military loads. The MicrogridUP tool fills this gap by enabling planners to enter the complete set of data needed to design microgrids and networks of microgrids for multibuilding sites at military installations, including:

- Resilience requirements (e.g., 14-day resilience requirement for U.S. Army installations)
- Load characterization
- Existing energy sources
- Gas and electric rates
- All relevant installation circuits—low voltage (building), medium voltage (distribution), and high voltage (transmission)

This software uses standard assumptions and data requirements to the extent possible, while allowing maximum design flexibility. Based on user inputs and locational data, MicrogridUP solves the key computational problems in large installation microgrid design—optimal distribution design and generation mix. Prior to release, the tool was field-validated at four diverse military installations.

[1] https://www.govinfo.gov/content/pkg/USCODE-2019-title10/html/USCODE-2019-title10-subtitleA-partIV-chap173-subchapI-sec2911.htm

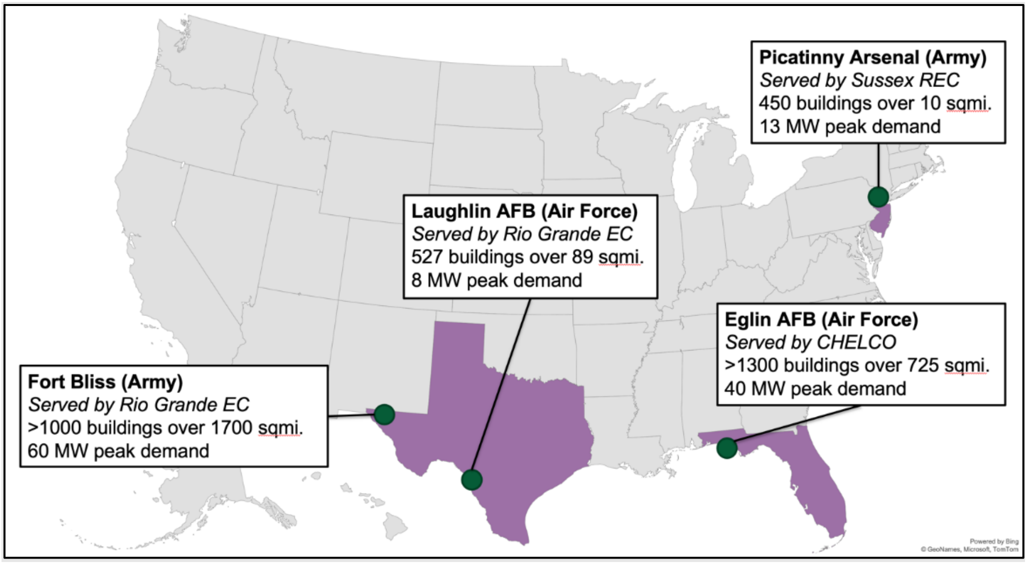


Figure 1. Four test installations and the utilities that serve them through UP contracts.

Key goals of the MicrogridUP tool are:

- Increasing resilience—100% of critical load is supported through a proposed microgrid design solution, including microgrids or networks of microgrids to serve a single critical load (e.g., server control room, a single building (e.g., hospital), a group of buildings (e.g., military headquarters or remote artillery range), an entire campus or military base, or a city block or neighborhood.
- Reducing labor requirements and soft costs to design an appropriate microgrid—Optimization using MicrogridUP modeling results in a 30% (approximate) reduction in labor hours for design tasks, related engineering, and other soft costs compared to existing methods.
- Producing accurate cost estimates for the lifecycle of microgrid solution(s)—Realistic cost expectations developed to enable user to implement the proposed microgrid solution at the military installation.

MicrogridUP is a technical software designed for use by distribution engineers and other microgrid planners with similar expertise. Although tailored to a military use case, MicrogridUP can also be used by energy services companies and utilities for large industrial or commercial use cases.

The software is a web application installed by the user on a local system using Docker (details provided in Docker Requirements section). All files stay on the local system; no information is shared beyond the system on which it is installed. For information on microgrid cybersecurity, see the 2020 Sandia National Laboratories Report entitled *Cybersecurity of Networked Microgrids: Challenges, Potential Solutions, and Future Directions*.

Prerequisites

Docker Requirements

MicrogridUP is a web application that is installed on a local system using Docker, a software platform designed to run containerized applications. This means that MicrogridUP can run on any Mac, Windows, or Linux system that supports Docker. You must install Docker Desktop software before you can install and run MicrogridUP.

For Docker Desktop system requirements, see the appropriate link below for your operating system:

- **Mac**: https://docs.docker.com/desktop/install/mac-install/
- **Windows**: https://docs.docker.com/desktop/install/windows-install/
- **Linux**: https://docs.docker.com/desktop/install/linux-install/

MicrogridUP Hardware and Software Requirements

As mentioned above, MicrogridUP can run on any Mac, Windows, or Linux system that supports Docker Desktop software. See the links above in Docker Requirements for supported platforms.

Note: Because MicrogridUP is a containerized web application, all files and data used in the analysis stay on the local system. No information is shared beyond the system on which MicrogridUP is installed.

MicrogridUP Input Data Requirements

The quality of the outputs that MicrogridUP generates is directly related to the quality of the input data it receives. The table below specifies ideal and minimum required input data.

With the **Ideal** level of data in the table below, MicrogridUP can return results for every load in the system. The **Minimum Required** level of data allows for circuit-level modeling of potential microgrids.

If additional sources of data become available during the evaluation process, they can be incorporated later.

Most fields in the MicrogridUP software include default values, which are listed and described in Microgrid Specifications in Appendix A. The software will output more accurate projects and estimates if you provide actual data for each **Data Type** below.

Data Type	Ideal	Minimum Required	Supported File Formats
Meter Data for Base	One year of 15-minute AMI data	One year of monthly energy consumption per building and SCADA load profiles for individual feeders	.csv
Circuit	Windmil/ Cymedist model	Substation and feeder data to manually construct a circuit model	.dss
GIS	Shapefile	GIS coordinates for loads	.kml, .shp, etc.
Cost of Power	Full rate schedule	Energy (kWh) and demand (kW) charges	.csv
Resilience Requirements	Specific resilience targets in numbers like SAIDI	Critical loads identified	.csv
Outage Statistics	Data from all historical outages, including locations and equipment	No outage data	.csv

For additional descriptions of input data requirements and uses, see Appendix A: Descriptions of Input Data Requirements.

Installation

MicrogridUP is a web application using Docker, a software platform designed to run containerized applications. To use MicrogridUP, you must first install the Docker Desktop software. Then you will download and install the MicrogridUP app.

To install MicrogridUP:

1. Install Docker Desktop using the instructions at the appropriate link below:

   Mac: https://docs.docker.com/desktop/install/mac-install/
   Windows: https://docs.docker.com/desktop/install/windows-install/
   Linux: https://docs.docker.com/desktop/install/linux-install/

   Note: MicrogridUP is a Linux container, not a Windows container.

2. Open a command prompt and enter this command to download the MicrogridUP app:

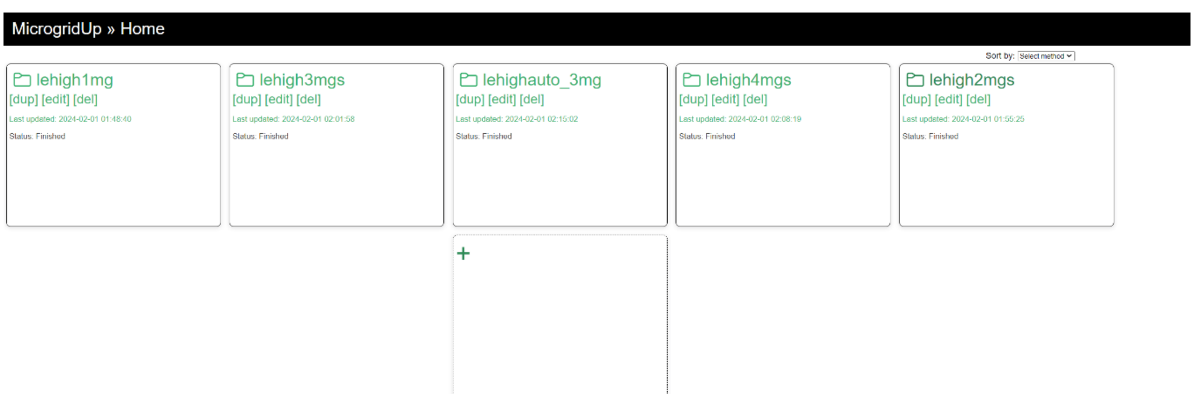
   ```
   docker pull ghcr.io/dpinney/microgridup:main
   ```

3. To start MicrogridUP, run this command:

   ```
   docker run -d -p 5001:5000 --name mgucont ghcr.io/dpinney/microgridup:main
   ```

4. Once the command completes, open a web browser and navigate to http://127.0.0.1:5001.

   The MicrogridUP app should open to the Home screen below.

   For next steps, see Using MicrogridUP.

5. To stop using the MicrogridUP app:
   a. Run `docker stop mgucont` at a command prompt.
   b. Close Docker Desktop.
6. To start the app again:

a. Open Docker Desktop.
b. Run `docker start mgucont` at a command prompt.
c. Open a web browser and navigate to http://127.0.0.1:5001.

To upgrade, repeat steps 2-4 above. To retain your project data, migrate the folder /data/projects/ from the original container to the new one before deleting the old container.

Using MicrogridUP

General Guidance/Tips

MicrogridUP is a robust optimization model that incorporates a wide range of input data. Due to the complexity of the underlying calculations, **expect long processing times**—from 30 minutes for simple queries to six hours or longer for more complex scenarios.

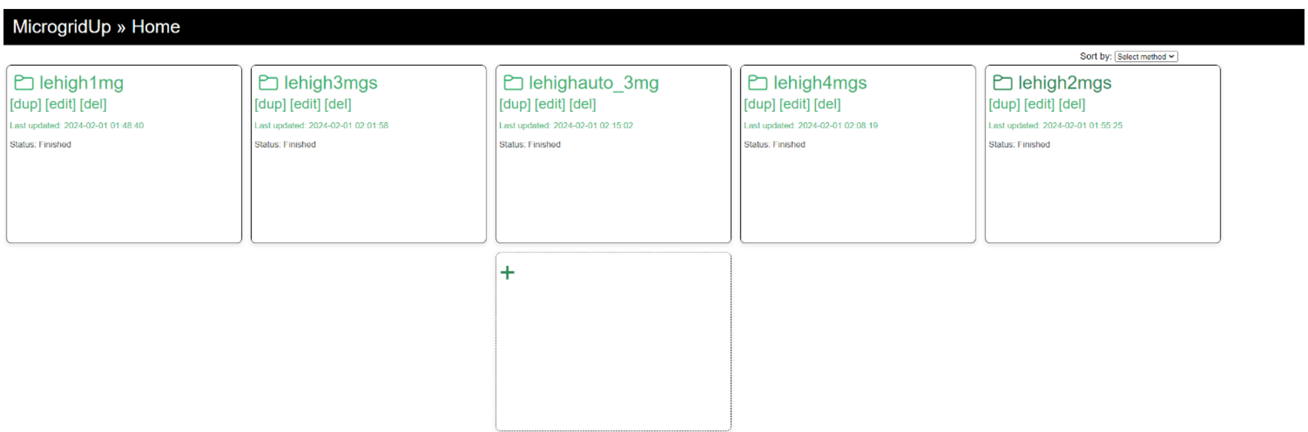
In addition, **optimization models like MicrogridUP can fail** for many reasons, for example if a proposed scenario is not feasible or requires too long to process.

To mitigate these issues, we suggest the following approaches to using MicrogridUP:

- Start small and build up. When creating a complex project, it may be helpful to first run MicrogridUP with a smaller subset of data. Then gradually increase the complexity by adding additional critical loads, circuits, etc. in later projects.
- Run complex scenarios overnight.

Working with Projects

When opening MicrogridUP, you should see the Home screen below.



Each box on this screen represents a completed project. A **project** consists of a set of input data and the microgrid design created by MicrogridUP based on that data. MicrogridUP includes five example projects (lehigh 1-5) to demonstrate the functionality of the software. You can create a different project for each installation, or create multiple projects for the same installation to test different sets of assumptions or inputs.

From the Home screen you can:

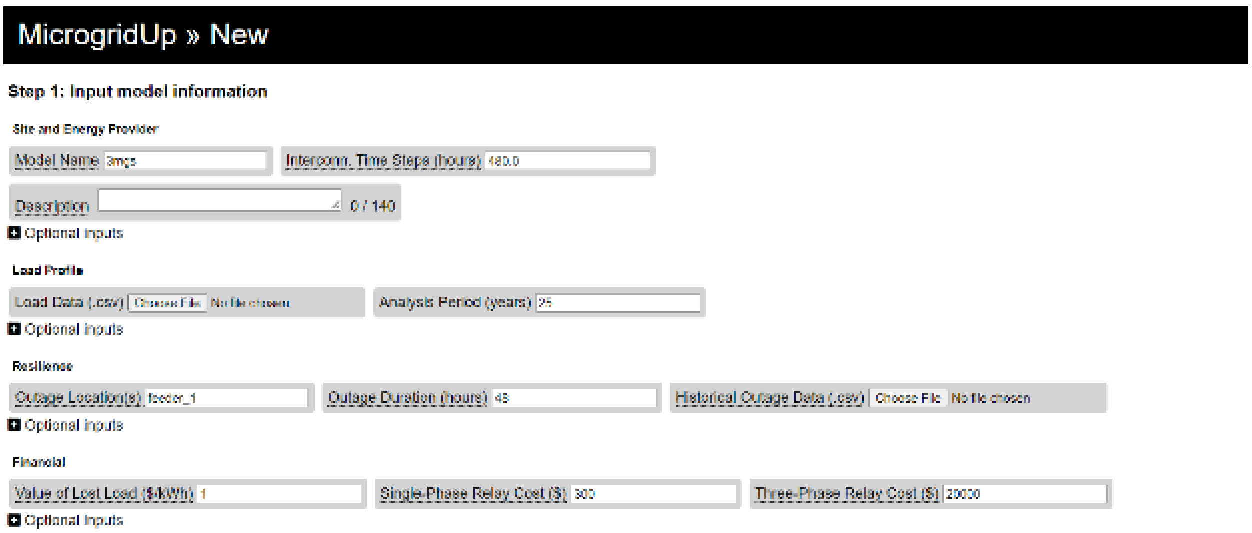
- Create a new project. See Creating a New Project.
- View the output of an existing project by clicking its title. See Outputs for more information.
- Duplicate, edit, or delete an existing project.

Creating a New Project

Step 1: Input project information

1. From the MicrogridUP Home screen, click the empty square with the + character. The MicrogridUP > New screen opens.

   Many of the fields in a new project have default values, but these can be changed.



2. Enter a **Project Name**. This name will be used to identify this project on the Home screen.
3. Complete the rest of the fields in the Step 1 section.

   Note: The **Load Data** file must be a CSV file with one load per column. The top row must contain the load name, and the next 8,760 rows contain hourly load data in kW. Each load described in the circuit definition (.dss) file in the next step must have a corresponding column in the Load Data file and the names must match exactly.

   Tip: Hover over a field label for more information about that field. For detailed information, see Table 1 in the Microgrid Specifications section of Appendix A.

Step 2: Specify existing circuit

In this step, you will characterize the distribution system and designate any critical loads.

MicrogridUP uses OpenDSS to model the distribution system so a .dss file is required. This file can have varying levels of detail, depending on the type of analysis to be done. The most basic level shows the substation and feeders, along with transformers, regulators, switches and loads. A more detailed model might include individual buildings/loads and downstream distribution system elements. Any distributed energy resources (solar, prime generators, combined heat and power (CHP) generators, energy storage systems) to be used in the microgrid also need to be included in the .dss file.

To add a circuit file to MicrogridUP, you can either upload an existing .dss file or generate a file by manually specifying the elements and values in the circuit. To gain familiarity with the software, we recommend manually building a simplified circuit file with a single substation and feeder.

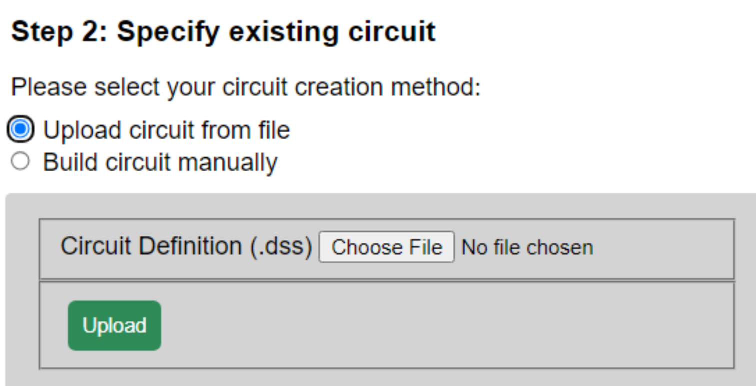
Note: Whether a .dss file is imported or manually generated, each load described in the file must have a corresponding column in the Load Data file (from Step 1: Input project information) and the names must match exactly.

To upload a circuit file:

1. Under Step 2, click **Upload circuit from file**.
2. Click **Choose File**, then browse to the .dss file location and select it.

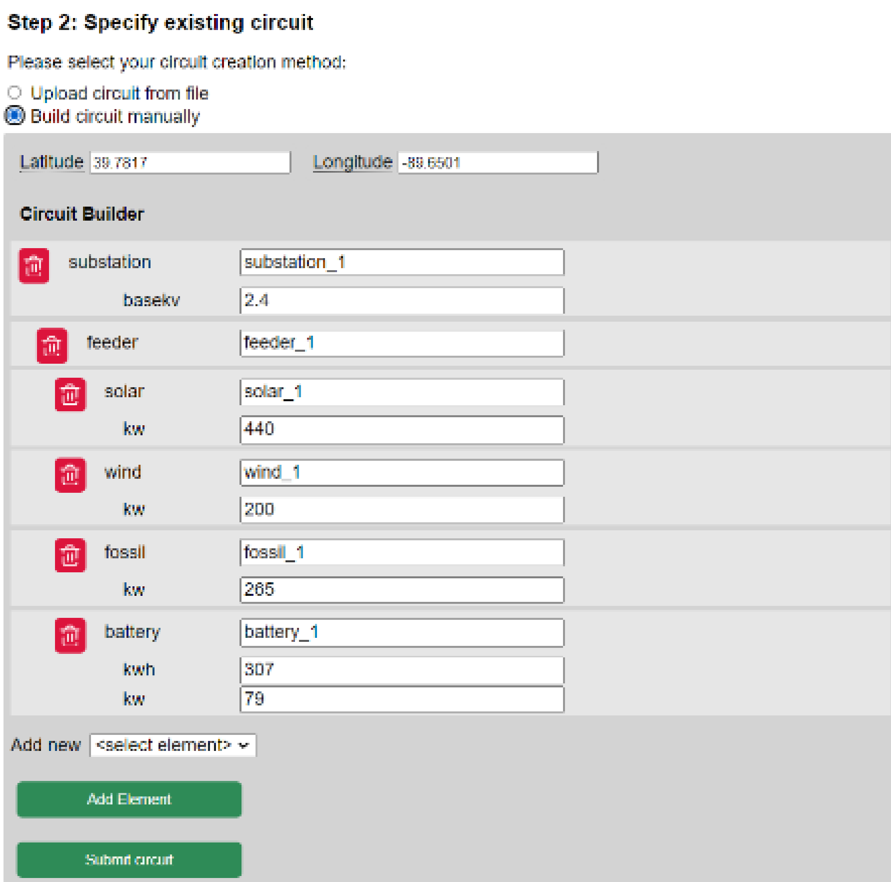
   When selecting a .dss file, consider the following:

   - Make sure any Windmil/Cymdist model used to generate the file is complete and without errors or the translation will fail.
   - `gen_bus` in the .dss file must have loads directly attached, otherwise the bus will not have a KV rating in the .dss tree structure and consequently MicrogridUP will fail to run.
   - If existing distributed generation is included, you must specify whether the load values include the distributed generation, or whether it is accounted separately.
3. Click **Upload**.
4. After successfully uploading the circuit file, select all critical loads from the list below the Circuit Definition dialog. **Critical loads** are loads which must be powered during outages or other resiliency events.



To Build a Circuit Manually:

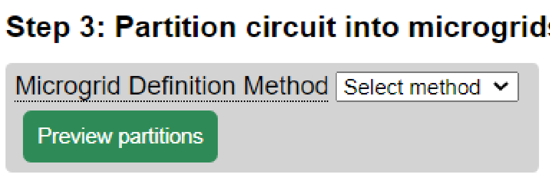
1. Under Step 2, click **Build circuit manually**.
2. In the Circuit Builder, specify a **Latitude** and **Longitude**. These will be used to calculate the available wind and solar resources. Please choose a lat/long pair inside the boundaries of the circuit being modeled, such as the location of the substation.
3. When the Circuit Builder opens, it is populated with sample elements. You can edit or delete these, or add additional elements.
    a. To create an element, click **Add Element**. Complete the fields to describe the element, then click **Add Element** again.
    b. To edit an existing element, give it a new name or change its other values.
    c. To delete an element, click the red Trash icon next to it.
4. When you have finished configuring the circuit, click **Submit circuit**.
5. After successfully submitting the circuit, select all critical loads from the list below the Circuit Builder dialog. **Critical loads** are loads which must be powered during outages or other resiliency events.



Step 3: Partition circuit into microgrids

In this step, you can explore different methods for partitioning your circuit into microgrids and choose one that best fits your environment.

1. Under Step 3, select a **Microgrid Definition Method**.

   For more information about each of these methods, see the tooltips beside each method.

   Note: Increasing the number of microgrids in the project increases processing time.
2. Click **Preview partitions** to see the number and locations of the microgrids that will be modeled using the specified method.

Step 4: Select technologies to be used in microgrids

Next select the types of energy and/or storage technologies to be used.

1. Under Step 4, select one or more technologies.

   As you select each box, additional fields for that option are displayed with default values. For detailed information, see Table 2 in the Microgrid Specifications section of Appendix A.
2. If necessary, change the default values for each technology.

Step 5 (Optional): Override technology parameters per-microgrid

By default, the values specified in Step 4 (for example, available fuel) are applied globally to all microgrids. In this step, you can override these global values for some parameters and assign different values to different microgrids if desired.

For example, if you want to restrict generation options in a given location (e.g., no wind near flight facilities but allowed at other locations) that can be done in this input.

1. Under Step 5, select the microgrid you want to modify.
2. To modify the value for a parameter:
   a. Click the green + icon.
   b. Select the parameter you want to modify from the list.
   c. Enter the new value for the parameter.

   Tip: For parameter descriptions, hover over a field label in Step 4.
3. Repeat these steps for each parameter on each microgrid you want to override.

   You can override values for all of the available parameters on **each** microgrid. If you don't specify a value here, the microgrid will continue to use the default value for that parameter specified in Step 4.
4. After entering values for all desired parameters, click **Run project** to start processing.

   MicrogridUP will display a status screen with the progress of the modeling process. This screen will refresh automatically to show the most recent data. Once the run is complete (which may take 30 minutes to several hours), the results will be displayed automatically. For more information on these results, see Outputs.

Outputs

MicrogridUP produces the following outputs for each modeled microgrid project: overview of the economics and resilience of the design; one-line and GIS displays of the proposed microgrid solution; results of the interconnection and control simulations; and detailed design results. Each output is on a separate tab—Overview, Map, Interconnection, Control, Microgrids, Files, and Inputs—and most output tabs include graphs or images. Where relevant, tabular outputs are also included for easy export to other tools such as Microsoft Excel.

Overview

The Overview tab provides results of the full design with the following outputs:

- Financial Summary—summary of capital expenditures for microgrid(s) and the net present value (NPV). Positive net present values show that demand and energy services provided by the microgrids pay back more than the original capital investment.
- Microgrid Load and Generation—breakdown of existing generation and loads.
- Microgrid Generation Mix, Existing and New—suggested new generation additions and how this compares to the load that needs to be served
- User Warnings—warnings about assumptions made within MicrogridUP (such as decommissioning of storage, which can't be integrated due to power limitations).
- Distribution Upgrades needed to create Microgrids—detailed list of all distribution upgrades that will be necessary to host the microgrids.

Figure 1. Screenshot of sample graphs from Overview tab

Map

The Map tab includes a GIS map of modeled microgrid or network of microgrids, with different colors indicating distinct microgrids. This image illustrates how the buildings and circuit align and displays the circuit and microgrid boundaries along with geospatial map tiles. You can inspect each of the generation resources added to the circuit model and their detailed specifications. Should you need to manually adjust the circuit, the overlaid one-line interface allows full editing support.

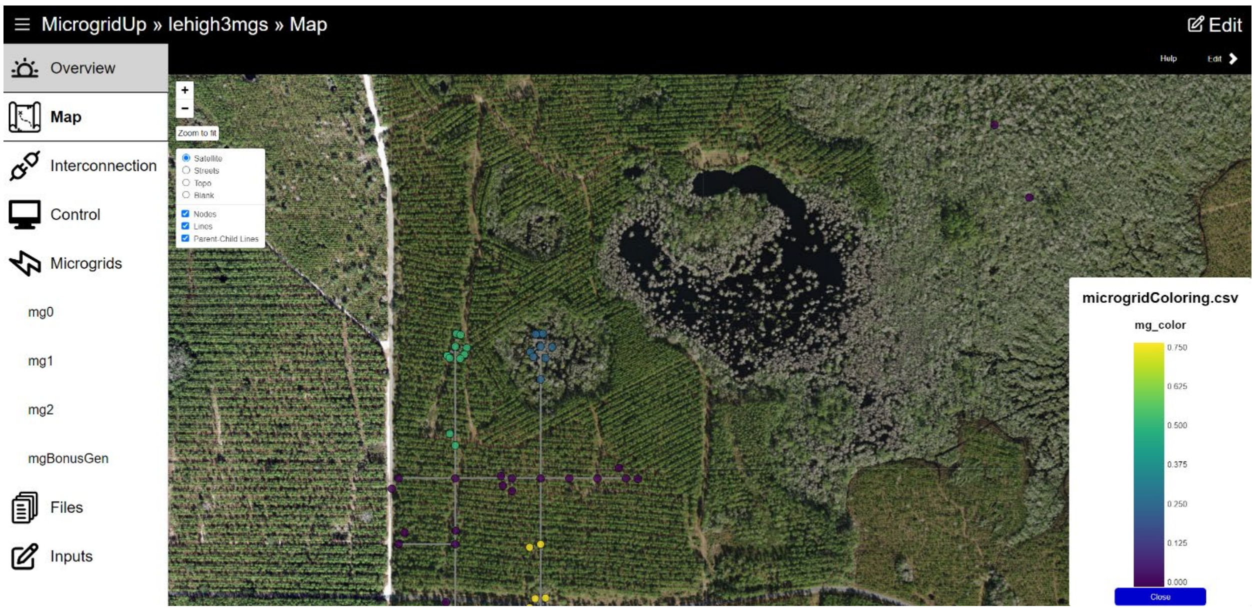


Figure 2. Screenshot of sample microgrid map from Map tab

Interconnection

The Interconnection tab displays quasi-static load-flow simulation results for the project under normal (no fault) operations along with a hosting capacity analysis for each microgrid. The Interconnection tab includes graphics depicting:

- Generator Output—maximum kW of new uncontrolled generation (i.e., renewables) that can be interconnected.
- Load Voltage—maximum voltage of critical loads.
- Voltage Source Output—confirmation that the timeseries voltages under normal operating conditions are within the ANSI band.
- Tap Position—tap setting on voltage regulators on the circuit. This can be used to verify new generation does not lead to excessive tap changer operation.
- Traditional Hosting Capacity By Bus—total kW capable of interconnection at each bus on the circuit.

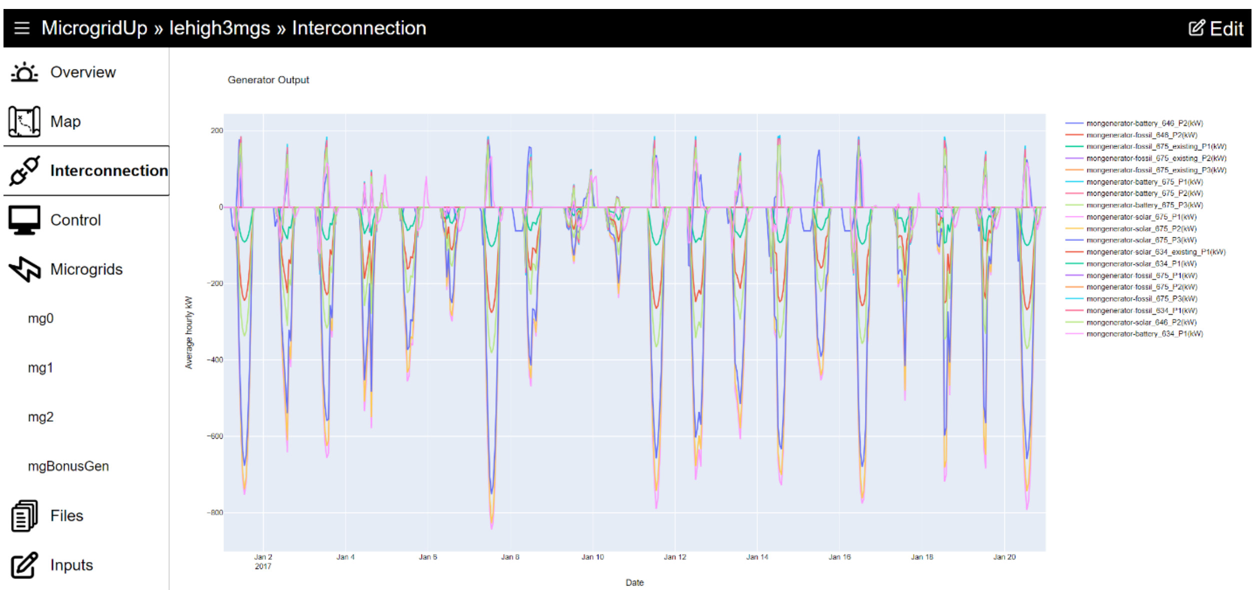


Figure 3. Screenshot of sample graph from Interconnection tab

Control

The Control tab provides detailed results of how the microgrid(s) will perform during the user-specified critical outage, e.g., a 7-day loss of power from the bulk power system during the time of highest load and lowest renewable output. The Control tab includes graphics depicting:

- Generator Output—maximum output required of generators.
- Load Voltage—maximum voltage of critical loads.
- Tap Position—tap setting on voltage regulators on the circuit. This can be used to verify new generation does not lead to excessive tap changer operation.
- Battery Cycles During Analysis Period—number of battery cycles during the critical outage.
- Fossil Genset Loading Percentage—fossil generator loading during the critical outage.
    - Note: If battery cycles or generator loading exceed the limits of the hardware during a critical outage, MicrogridUP modifies the generator design to modify expected battery lifetime or increase minimum generator size.
- Diesel and Natural Gas Equivalent Consumption During Outage by Microgrid—fuel requirements for the fossil generators on the microgrids. This is used to calculate the amount of fuel storage needed, which impacts price as well as land required to develop the microgrid.
- Inrush Current Report— predicted inrush current required to black start each microgrid. In the case of a renewable-only microgrid, inrush cannot be supplied by generators or economically via storage, so MicrogridUP calculates a capacitor bank size and adds it to the total cost of the microgrid. Inrush calculations use circuit information from the user inputs.

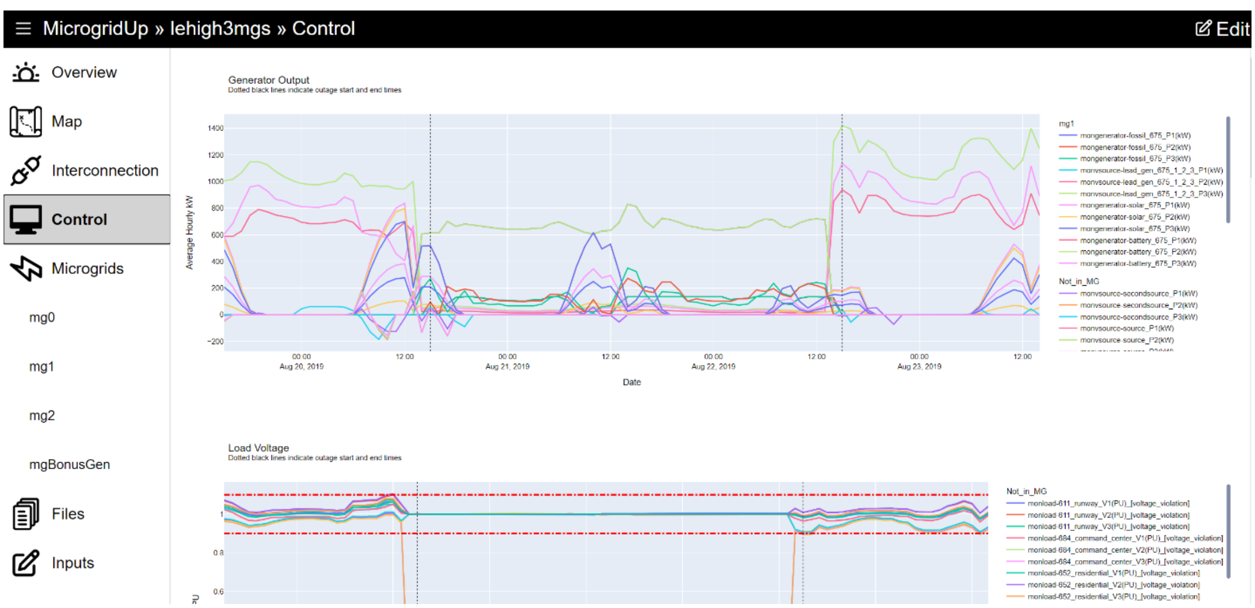


Figure 4. Screenshot of sample graphs from Control tab

Microgrids

The Microgrids tab includes detailed annual results for the generation additions and annual energy consumption and generation. Because outages are infrequent and outage costs are difficult or impossible to calculate, the economics of normal operation will dominate those of operation during an outage. The Microgrids tab includes outputs for each individual microgrid in the system, with graphics depicting:

- Lifetime Financial Comparison Overview
- Generation Overview
- Generation Serving Load
- Solar Generation Detail
- Wind Generation Detail
- Fossil Generation Detail
- Storage Charge Source
- Storage State of Charge
- Resilience Overview – Longest Outage Survived
- Outage Survival Probability
- Input Data

Figure 5. Screenshot of sample graphs from Microgrids tab

Files

The Files tab includes a list of files used and generated the MicrogridUP analysis.

Inputs

The Inputs tab displays all input values provided by the MicrogridUP user.

Appendix A: Descriptions of Input Data Requirements

Appendix A provides additional information on MicrogridUP's input data requirements, default values (where relevant), definitions, and usage or purpose of different data inputs. MicrogridUP includes techno-economic analyses from the National Renewable Energy Laboratory's Renewable Energy Optimization Tool (REopt®), available from: https://reopt.nrel.gov/. Because of this overlap, we provide links to the REopt Web Tool User Manual for additional information on certain inputs.

User Goals

- Description: Resilience and operational goals for the target facilities. Includes providing for both long-term outages and shorter-term disruptions. Includes specific requirements/restrictions for distributed generation options (especially renewable generation goals and net-metering status). Should be coordinated with the base utility and water plan.
- Use: Design of the microgrid options depends on the user's resilience requirements as well as restrictions on the use of new fossil and renewable generation.
- Source: Customer

Circuit File

- Description: Full Windmil/Cymdist data model (including GIS data showing physical locations of buildings and other assets).
- Use: MicrogridUP does an economic analysis which includes selected existing generation equipment, then runs a power-flow model using full circuit data.
- Source: Owner of distribution system

Existing Distributed Generation

- Description: Optional list of existing distributed generation, both renewable and fossil-based (e.g., combined heat and power (CHP), solar, wind, and energy storage.) Renewable generation should include type and capacity (both DC and AC if applicable). Fossil generation should include type, fuel source, fuel storage capacity, and age. This category also includes existing backup generation that could be used in microgrid operations.
- Use: MicrogridUP does an economics analysis which includes existing distributed generation sources that could be used with the microgrid.
- Source: Customer

Distribution System Equipment Specifications

- Description: Technical specifications of equipment in existing distribution system which might need to be used in the microgrid, including any existing capabilities for providing distribution system and building-level load management. Equipment includes applicable switches, relays, and load control options for feeders, line sections, building, or sub-building loads.

- Use: Required for power-flow analysis, especially to identify equipment which may need to be upgraded/replaced for a microgrid project.
- Source: Customer, owner of distribution system (likely multiple documents)

Critical Loads

- Description: Prioritized list of critical loads, defined as loads that must be powered during resiliency events. These loads must be identified with facilities on the circuit model.
- Use: Critical loads are used to determine the most cost-effective solutions. Prioritized lists are used to implement "Fast Load Shedding" control schemes, if necessary.
- Source: Customer

Is your military base able to sub-meter individual buildings and loads?
Sub-metering allows the installation to control which buildings or portions of a circuit may be "islanded," or included inside the microgrid.
What: Loads that must be supported during an external outage.
Need: Defined size, duration, location, to be able to design an optimal microgrid.

Metering Data

- Description: At least one year of historical load data for both electricity and gas consumption.
- Use: Historical load data is used to simulate system performance in both the economic optimization and power-flow modeling parts of MicrogridUP. One year of detailed data is needed both to show load profiles (time of use over a single day) and seasonal variations in total energy requirements.
- Source: Customer and customer utilities

Full Rate Schedule

- Description: Details of the electric utility rate structure, include rate name, fixed charges, energy charges (kWh), and demand charges (kW). Details should include time-of-use energy rates, seasonal variation in energy and demand, coincident/non-coincident demand charges if applicable, net metering or distributed generation "buy-in" options, and gas supply contract.
- Use: MicrogridUP uses these rates to estimate and optimize operating costs for future microgrids including savings from renewable generation. The data is also used to estimate the value of ancillary services such as net-metered energy and peak shaving.
- Source: Customer and customer utilities

Outage Statistics

- Description: Data from all historical outages, including locations and equipment (optional)
- Use: This information is needed to define goals for the microgrid and to evaluate the ability of the microgrid to manage resilience events of differing durations.
- Source: Customer

Weather Data

- Description: MicrogridUP accesses weather data, especially solar insolation and wind resource, through the REOpt performance software; there is no need to supply it separately.
- Use: This data is used to calculate performance of existing and proposed renewable generation.
- Source: MicrogridUP

Resilience Metrics and Microgrid Siting

- Description: A core input to MicrogridUP is the minimum survival time for critical loads (e.g., 336 hours in the case of Army resilience goals) which is called the Critical Outage. Each load in the project is classified as critical or non-critical. During outage simulations, MicrogridUP commands the microgrid to shed the non-critical loads. The result is a set of microgrids sized precisely for the critical loads, minimizing capital cost. Our military partners have validated that this is the most important resilience metric overall for mission success and continuity.
- Use: MicrogridUP also calculates average outage survival time for a given microgrid solution considering outages of all possible lengths and starting hours. This often exceeds the critical survival time, which is an ancillary benefit of microgrid deployments.
- Source: Customer

Microgrid Specifications

The microgrid is specified in two steps. First, it is segmented by specifying a “FAULTED_LINE” variable to be a switch that can disconnect a subset of the distribution system circuit from all voltage sources. Second, any loads that are “downstream” of the microgrid isolation switch and included in the critical load file are added to the microgrid specification, which is in turn added to the .dss model file.

The user interface allows the user to specify design options for each microgrid, as well as economic conditions used in the financial analysis. Table 1 shows the software’s default values and descriptions in Step 1 of the interface. Table 2 shows the default values and descriptions for Step 4.

Table 1. Fields Used in Step 1 of the MicrogridUP Interface

Field Name	Default Value	Description
Project Name	(blank)	Project names must be entirely lowercase.
Interconn. Time Steps (hours)	480.0	Defines the length of the interconnection analysis. Example – if time steps are 15 minutes, 480 would define a five-day analysis.
Description	(blank)	Include an optional description of the project. Max 140 characters.
Energy Cost ($/kWh)	0.12	Energy charge per kWh.

Wholesale Cost ($/kWh)	0.034	To turn off energy export/net-metering set wholesale Cost to 0 and excess PV gen will be curtailed.
Demand Cost ($/kW)	20	Demand rate per kW.
DG Can Curtail	Yes	Allows for excess distributed generation to be automatically curtailed.
DG Can Export	Yes	Allows for excess distributed generation to be sold back to the grid.
Use URDB Rate?	No	The electricity rate can be selected from a list of rates available in the location entered. The rates are downloaded from the Utility Rate Database (URDB). If available, the most common rates are listed at the top of the list. Due to data limitations in some parts of the country, the full list of rates includes rates available within 25 miles of the location specified. **This value, or a custom annual, monthly or detailed rate, is required.** Utility rates that are not in URDB can only be modeled as custom rates. For more information, please see the The REopt Web Tool User Manual.
URDB Label	5b75cfe95457a3454faf0aea	If you want to use a URDB rate that isn't available in the dropdown list for your selected location, you can enter a URDB label that corresponds to an unlisted rate. This label can be found in the URL for the URDB rate on the Open EI website. For example, the label for the rate found at the URL https://openei.org/apps/IURDB/rate/view/5e6134175457a3cf56019407would be entered as just the label 5e6134175457a3cf56019407.
Load Data (.csv)	(none)	Please upload a .csv file representing the hourly load shape. See https://github.com/dpinney/microgridup/blob/main/docs/input_formats.md for formatting details.
Analysis Period (years)	25	The financial life of the project in years. Salvage value is not considered. Units: years. **This value is not required.** Note for energy storage: 25-year project life, with 10-year battery life, replaced once. For more information, please see The REopt Web Tool User Manual.

Year	2017	Baseline year of data collection.
Outage Location(s)	670671	Node number in distribution map where typical outage would take place.
Outage Duration (hours)	48	The number of hours the electric outage lasts. The system will be sized to minimize the lifecycle cost of energy, with the additional requirement that it must also sustain the critical load during the outage period specified. **This input is required to complete the optimization for energy resilience. The input must be a number between 0 and 8759.** For more information, please see [The REopt Web Tool User Manual.]()
Historical Outage Data (.csv)	(none)	Please upload a .csv file representing historical outages. See https://github.com/dpinney/microgridup/blob/main/docs/input_formats.md for formatting details.
Maximum REopt Run-time (seconds)	240	Please enter a number 30-86400. A greater maximum REopt run-time could result in more precise REopt results. A maximum REopt run-time that is too short could result in an error.
Value of Lost Load ($/kWh)	1	Specify the value of lost load during a power outage in $/kWh.
Single-Phase Relay Cost ($)	300	Specify the cost of a single-phase relay in $.
Three-Phase Relay Cost ($)	20000	Specify the cost of a three-phase relay in $.
O+M Escalation (% per year)	0.025	Please enter a number 0-1 for the Annual nominal O&M cost escalation rate. Format 0.XXX
Discount Rate (% per year)	0.083	The rate at which the host discounts the future value of all future costs and savings. Note this is an after tax discount rate if the Host is a taxable entity. Units: decimal percent. **This value is not required.** For more information, please see the [The REopt Web Tool User Manual.]() Discount rate: a percent value that represents the cooperative's internal cost of capital. A

		cooperative's cost of capital is a combination of equity and debt, calculated on a weighted basis, also known as Weighted Average Cost of Capital (WACC). The cost of capital represents how much the value a dollar would change over time and in the future, but calculated to equal the value of today's dollar, or Net Present Value (NPV). Projects that have higher savings in the early years will have a higher NPV than projects with savings that occur at the end of project, assuming they are of the same term in years. When comparing multiple options, they should all have the same discount rate so that their respective NPVs will be comparable. If the discount rate is part of the negotiable contract, then different discount rates can be used. Higher discount rates will typically result in lower NPVs when compared on an equal basis. MicrogridUP uses discounting when calculating the optimum dispatch. Changing your discount rate will sometimes change how much of a specific resource the model will specify, though the amount might not vary very much.

Table 2. Fields Used in Step 4 of the MicrogridUP Interface

Field Name	Default Value	Description
Solar Cost ($/kWh-DC)	1600	Fully burdened cost of installed PV system in dollars per kilowatt. **This value is not required.** For more information, please see [The REopt Web Tool User Manual.]()
Solar Power Max (kW-DC)	1000000000	REopt identifies the total system size that minimizes the lifecycle cost of energy at the site. The maximum new PV size limits the new PV system (not including any existing PV system) to no greater than the specified maximum. To remove the option of a new PV system from consideration in the analysis, set the

		maximum size to 0. If a specific sized new generator is desired, please enter that size as both the minimum size and also the maximum size. This value is not required. For more information, please see [The REopt Web Tool User Manual.]()
Solar Power Min (kW-DC)	0	REopt identifies the total system size that minimizes the lifecycle cost of energy at the site. The minimum new PV size forces a new PV system of at least this size to appear at the site (in addition to any existing PV system). If there is not enough land available, or if the interconnection limit will not accommodate the system size, the problem will be infeasible. The default value is 0 (no minimum size). If a specific sized new generator is desired, please enter that size as both the minimum size and also the maximum size. This value is not required. For more information, please see [The REopt Web Tool User Manual.]()
Solar MACRS Years	5	MACRS schedule for financial analysis. Possible inputs are 0, 5 and 7 years. Set to zero to disable accelerated depreciation accounting for solar.
Solar ITC (% as decimal)	0.26	Please enter a number 0-1 for the solar investment tax credit. Format 0.XX
Battery Capacity Cost ($/kWh-AC)	420	Energy capacity cost is the cost of the energy components of the battery system (e.g., battery pack). The amount of energy that a battery can store is determined by its capacity (kWh) while the rate at which it charges or discharges is determined by its power rating (kW). While PV system cost is typically estimated based on power rating (kW) alone, **battery costs are estimated based on both 28apacityy (kWh) and power (kW)**. The power components of the system (e.g., inverter, balance of system (BOS)) are captured by the power metric of $/kW and the energy components of the system (e.g., battery) are captured by the energy metric of $/kWh.

		This allows the capacity (kWh) and power (kW) rating of the battery to be optimized individually for maximum economic performance based on the load and rate tariff characteristics of the site. Some systems are optimized to deliver high power capacity (kW), while others are optimized for longer discharges through more energy capacity (kWh).
Battery Capacity Max (kWh-AC)	1000000	Specify the maximum desired battery capacity in kWh.
Battery Capacity Min (kWh-AC)	0	Specify the minimum desired battery capacity in kWh.
Battery Power Cost ($/kW-AC)	840	Power capacity cost is the cost of the power components of the battery system (e.g., inverter and balance of system (BOS)). The amount of energy that a battery can store is determined by its capacity [kWh] while the rate at which it charges or discharges is determined by its power rating [kW]. While PV system cost is typically estimated based on power rating [kW] alone, **storage costs are estimated based on both capacity [kWh] and power [kW]**. The power components of the system (e.g., inverter, BOS) are captured by the power metric of $/kW and the energy components of the system (e.g., battery) are captured by the energy metric of $/kWh. This allows the capacity (kWh) and power (kW) rating of the battery to be optimized individually for maximum economic performance based on the load and rate tariff characteristics of the site. Some systems are optimized to deliver high power capacity (kW), while others are optimized for longer discharges through more energy capacity (kWh). For example, assume the unit cost of power components is $1,000/kW, and the unit cost of energy components is $500/kWh.

		Consider a battery with 5 kW of power capacity and 10 kWh of energy capacity (5 kW/10 kWh). The total cost of the battery would be: (5 kW * $1,000/kW) + (10 kWh * $500/kWh) = $10,000. For more information, please see The REopt Web Tool User Manual.
Battery Power Max (kW-AC)	1000000000	Specify the maximum desired battery power in kW.
Battery Power Min (kW-AC)	0	Specify the minimum desired battery power in kW.
Battery MACRS Years	7	MACRS schedule for financial analysis. Possible inputs are 0, 5 and 7 years. Set to zero to disable accelerated depreciation accounting for solar.
Battery ITC (% as decimal)	0	Please enter a number 0-1 for the battery investment tax credit. Format 0.XX
Battery Replacement Power Cost ($/kW-AC)	410	Power capacity replacement cost is the expected cost, in today's dollars, of replacing the power components of the battery system (e.g. inverter, balance of systems) during the project lifecycle. **This value is not required.** For more information, please see The REopt Web Tool User Manual.
Battery Replacement Capacity Cost ($/kWh-AC)	200	Energy capacity replacement cost is the expected cost, in today's dollars, of replacing the energy components of the battery system (e.g. battery pack) during the project lifecycle. **This value is not required.** For more information, please see The REopt Web Tool User Manual.
Battery Power Replacement (years)	10	Energy capacity replacement year is the year in which the energy components of the battery system (e.g. battery pack) are replaced during the project lifecycle. The default is year 10. **This value is not required.** For more information, please see The REopt Web Tool User Manual.
Battery Capacity Replacement (years)	10	Power capacity replacement year is the year in which the power components of the battery system (e.g. inverter, balance of systems) are replaced during the project lifecycle. The default is year 10. **This value**

		is not required. For more information, please see The REopt Web Tool User Manual.
Genset Cost ($/kW)	500	Fully burdened cost of the new installed backup diesel generator in dollars per kilowatt. **This value is not required.** For more information, please see The REopt Web Tool User Manual.
Genset Max (kW)	1000000000	Specify max fossil generation in kW. Only specify if needed, as the optimization runs best if left unedited.
Genset Min (kW)	0	Specify minimum fossil generation in kW. Only specify if needed, as the optimization runs best if left unedited.
Fuel Available (Gal)	50000	Availability of diesel fuel in gallons for new and/or existing generator. **This field is not required.** For more information, please see The REopt Web Tool User Manual.
Min Gen Loading (% as decimal)	0.3	Please enter a number 0-1 for the the minimum fraction of rated total kVA load that must be maintained by the generator. >/= 0.3 recommended for extended diesel operation. Set to 0 for highest likelihood of success in solving optimization. Format 0.XX
Fuel Cost (diesel gal equiv)	3	Fully burdened cost of diesel fuel in dollars per gallon. **This value is not required.** For more information, please see The REopt Web Tool User Manual.
Genset Emissions Factor (lb CO2/gal)	22.4	Default fuel emissions factors, and their relevant units (lbs/MMBtu or lbs/gal), are determined by the fuel types entered in the Site and Utility Section. The fuel type for Generators is assumed to be diesel. Emissions factors are not required inputs. For more information, please see The REopt Web Tool User Manual.
Genset Annual O+M Cost ($/kW/year)	10	Estimated annual backup diesel generator operation and maintenance (O&M) costs per installed kilowatt (including both new and existing generators). Includes regular O&M based on calendar intervals including testing, stored fuel maintenance, and service contracts. **This value is not required.** For more information, please see The REopt Web Tool User Manual.

<table>
<tr><td>Genset Hourly O+M Cost ($/kWh/year)</td><td>0</td><td>Estimated non-fuel operation and maintenance (O&M) costs which vary with the amount of electricity produced (by both new and existing backup diesel generators). Variable O&M may include filters and oil changes, and other maintenance requirements based on engine run-hours. This value is not required. For more information, please see The REopt Web Tool User Manual.</td></tr>
<tr><td>Genset only runs during outage?</td><td>No</td><td>"No" signifies that fossil generator is enabled to run at any point in the year.</td></tr>
<tr><td>Fossil MACRS Years</td><td>0</td><td>MACRS schedule for financial analysis. Possible inputs are 0, 15 and 20 years. Set to zero to disable accelerated depreciation accounting for solar.</td></tr>
<tr><td>Wind Cost ($/kW)</td><td>4989</td><td>Fully burdened cost of installed wind system in dollars per kilowatt. The chart below gives the default system capital costs that are used by REopt for each wind size class. If a custom cost is entered, it will be used instead of the default cost. This value is not required. For more information, please see The REopt Web Tool User Manual.
<table>
<tr><td colspan="3">Wind CAPEX Defaults</td></tr>
<tr><td>Size Class</td><td>System Size Range</td><td>Base Cos</td></tr>
<tr><td>-</td><td>(kW)</td><td>($/kW)</td></tr>
<tr><td>Residential</td><td>0-20</td><td>$5,675</td></tr>
<tr><td>Commercial</td><td>21-100</td><td>$4,300</td></tr>
<tr><td>Midsize</td><td>101-999</td><td>$2,766</td></tr>
<tr><td>Large</td><td>>=1,000</td><td>$2,239</td></tr>
</table></td></tr>
<tr><td>Wind Power Max (kW)</td><td>1000000000</td><td>Specify the maximum desired generation in kW. Leave at default for full optimization on wind power.</td></tr>
<tr><td>Wind Power Min (kW)</td><td>0</td><td>Specify the minimum desired generation in kW.</td></tr>
<tr><td>Wind MACRS Years</td><td>5</td><td>MACRS schedule for financial analysis. Possible inputs are 0, 5 and 7 years. Set to zero to disable accelerated depreciation accounting for solar.</td></tr>
<tr><td>Wind ITC (% as decimal)</td><td>0.26</td><td>Please enter a number 0-1 for the wind investment tax credit. Format 0.XX</td></tr>
</table>

Appendix B: Technology-Specific Considerations for MicrogridUP Modeling

Appendix B provides an overview of various technologies commonly used in microgrids**.**

Diesel and Natural Gas Generators (Reciprocating Internal Combustion Engines (RICE))

RICE Rating

Diesel and natural gas generators are rated by their real power (kW) and apparent power (kVA) or power factor (kVA/kW). Generators are typically rated for standby use, prime power or continuous operation. A standby generator is used to provide backup power for a building or load and is typically designed to run less than 250 hours per year, with no more than 25 hours at the full standby rating.

A prime power generator has a more robust cooling system and typically a larger alternator, and is designed continuously at reduced load, or for longer periods of time (500-750 hours per year) at higher loads. Continuous power generators are designed to operate continuously at a constant power up to its full rating. They are typically not designed for variable loads. Prime and continuous generators often have extended lube oil capacities, which allow maintenance to be extended.

RICE Generator Sizing and Minimum Loads

Operation of generators for extended periods at less than 30% loading for diesel models and 50% loading for natural gas models can cause a number of problems. For diesel generators, the primary effect is insufficient heat in the chamber, which causes incomplete combustion and result in “engine slobbering” or “wet stacking,” which is the release of a black, oily liquid from manifold joints. This can cause buildup of carbon in the cylinder or valves (“coking”), resulting in loss of engine performance, increased engine wear and increased maintenance costs. It can also result in increased emissions and damage to aftertreatment components such as oxidation catalysts, selective catalytic reduction components, or diesel particulate filters.

Natural gas engines do not “slobber,” but reduced gas pressure during loads below 50% of rating allows oil to work its way into the cylinder, leasing to ash deposits as well as valve, spark plug and cylinder ring carbonization. These in turn lead to changes in the compression ratio and detonation margin, resulting in increased wear and more emissions. The standard recommendation is to run diesel generators at more than 30% load for 30 minutes every four hours of operation, using dedicated load banks if necessary. Natural gas generators should not be run for more than 30 minutes at less than 30% load, or for more than two hours at loads between 30 and 50%.

RICE Maintenance

Engine/generators should be “exercised” at regular intervals when used in standby operation. They need to be maintained on a frequent basis when they are in operation. Daily tasks include checked fuel and oil levels, weekly tasks include checking/cleaning air and fuel filters and checking the cooling system. Diesel engine oil needs to be changed based on hours of operation of the engine. The standard oil sump allows for 250 hours of operation, extended sumps allow for 500 to 1,500 hours of operation. Used oil but be stored and disposed of properly.

"Top End Overhauls" to decarbonize valves, piston rings and fuel injectors, and to check top gaskets, are required at 1,500 to 5,000 hours intervals. Full engine overhauls (including bearings) are typically required every 6,000 to 10,000 hours of operation. Natural gas generators run cleaner than diesel engines so they typically have oil change intervals of at least 500 hours, but they also need additional maintenance on the electrical ignition system. Fuel storage is also a problem, especially for diesel generators, since diesel becomes sluggish at low temperatures and is prone to various things growing in diesel fuel that has been stored for an extended period of time.

RICE Decommissioning

Decommissioning can be as simple as towing a trailer-mounted generator away, but is generally more complex, including removal of the generator itself, the fuel tank and delivery pipes, and removal of all controls and electrical connections. It often involves dealing with hazardous materials which require special handling.

Combined Heat & Power (CHP)

Combined Heat and Power (CHP) systems use generators to supply electricity and then use the "waste heat" from these generators to provide additional energy. Usually, the energy is used for space heating or water heating, but it can also power an "absorption cooler" to provide cooling. Most CHPs use natural gas RICE generators, but there are also CHPs powered from microturbines and fuel cells. (Note: some co-op systems that use continuous diesel generators, especially in Alaska, have implemented sophisticated CHP systems.) Large CHP plants use megawatt-scale utility gas turbines. CHP systems have all of the issues associated with generators but add "plumbing" associated with heat recovery.

Other Generators

Microturbines

Microturbines are small (25-500 kW) gas turbines (basically jet engines) attached to generators. They typically have slightly higher efficiencies and lower emissions than RICE generators and are often combined with CHP to improve efficiency.

Fuel Cells

Fuel cells are solid state generators that produce DC electricity using hydrogen as a fuel. The hydrogen is often supplied from electricity using an electrolier or using methane (natural gas) via a reformer. The only waste product of a fuel cell is water. The DC is converted to AC via an inverter. Most fuel cells run best at constant loads. Fuel cells have high efficiencies, but the overall system efficiency is lower because of the energy needed to produce and store the hydrogen. Volkswagen has estimated that an electric car delivers 70-90% of the electricity generated to the powertrain, while fuel cell cars supply only 25-35% efficiency. Production of hydrogen using excess renewable energy has been proposed as a way of reducing the effects of this low efficiency.

PV Systems

PV System Design and Rating

Photovoltaic (PV) systems are rated in both DC power and AC power. The PV modules themselves generate DC energy, which must be converted to AC via an inverter. A typical PV array will have a DC rating of 120-150% of the AC rating of the inverter. If the DC output of the array exceeds the rating of the inverter, the extra energy is simply not generated by the array, a process called “clipping.” In typical operation, annual clipping in a system with a 1.4 DC/AC ratio is 2-4% of annual production.

There are three main types of inverters:

1. Central inverters—Large inverters (typically MW-scale) with connections to multiple subarrays. Field wiring is primarily DC. Central inverters require complex procedures to repair if they fail.
2. String inverters—A separate inverter for each series string, or small set of series strings. Although the string wiring is DC, much of the field wiring is AC, coming the outputs of multiple string inverters. String inverters range in size from 25 kW to 250 kW. String inverters have the advantage of “graceful degradation;” if one inverter fails, it does not affect the rest of the system so there is less urgency to fix it. In addition, the faulty inverter is simply replaced in the field and then repaired in a dedicated facility.
3. Module level inverters—A separate inverter for each module. Reduces the effects of shading but introduces additional complexity and failure modes though the use of a large number of inverters. This configuration is uncommon on commercial and utility-scale PV systems.

There are two primary types of array mounting systems:

1. Fixed systems are mounted on a structure at a fixed angle. This can be on a roof or on a ground mount structure, including parking canopies.
2. Tracking systems use small motors to keep segments of the array aimed directly at the sun as it moves across the sky each day.

The most common type of tracker is the single-axis tracker, which uses a north-south axis to rotate the array from east to west. Some designs use linkages to move multiple rows with a single motor, while others have multiple motors which track one row at a time. Dual axis trackers use a more complicated system to keep the PV array “normal” (i.e., aimed directly at) the sun. Although they produce the most energy per kW rating, they are much less common due to the extra costs and complexity. PV modules are 15-23% efficient, so they take up a good deal of space. A 1.4 MW-DC / 1.0 MW-AC fixed ground-mount system typically covers about six acres of land. Tracking systems take a slightly larger area due to interrow shading considerations.

Roof-mounted systems must allow for access pathways and roof obstructions such as skylights, ventilation outlets and HVAC systems. Structures must be designed for specific wind and soil conditions. Most PV system capital costs are described as “dollars per watt” where the “watt” refers to the DC datasheet rating of the PV array.

PV Performance and Warranties

The performance of a PV array is different than “conventional generators” since they are “intermittent passive” rather than “active” generators. Unlike conventional generators, which can be turned on and off as necessary, PV systems only generate power when the sun is available, and can only be turned off, and not turned on, whenever needed.

The output of a PV systems varies diurnally, that is, when the sun is shining, and that energy is variable depending on the time of day and the current sky clearness, which can produce dramatic changes in power output over very short periods on time. PV outputs also varies seasonally, producing less energy in the winter than in the summer. Because the performance of PV modules has a negative temperature coefficient (less power with increased cell temperature), PV arrays often produce the most energy during cool days in the late spring.

Finally, the performance of a PV array depends on the latitude and local climate, although systems in northern latitudes can sometimes produce as much annual energy as southern latitudes due to longer summer days and cooler temperatures. PV systems work with both direct and diffuse (cloudy) sunlight, but sites with clear skies are obviously much better. The best solar sites are high deserts because of the clear skies, reduced atmospheric absorption, and cooler temperatures. Single-axis trackers can provide up to 30% more energy on an annual basis than fixed tilt systems.

There are several high-quality PV performance estimation packages which use increasing sophisticated input data to produce performance estimates, but the simple fact is that the performance of a PV system ultimately depends on the local weather, which can vary widely from year to year.

PV modules degrade slowly over time, typically falling to 80-85% of initial power after a 20-25 year service life. PV modules usually carry warranties of up to 25 years with a guaranteed minimum output at end of life, although they can continue to produce power for many years after the official warranty period. However, PV systems typically have a shorter warranty period due to the inverters and other components of the system. Grid-tied PV systems include “anti-islanding” features which disconnect them from the grid when the grid becomes unstable. In a microgrid, the PV array is often coupled with a battery, which provides isolation from the grid but allows the PV array to continue to provide power to loads in the “island” formed by the battery. Some PV-battery systems tie the DC output of the array to the DC battery before the inverter (DC-coupled), others use separate inverters for the PV array and battery and tie the inverters together before connecting to the grid (AC-Coupled).

PV Maintenance

PV modules and inverters are solid state with few if any moving parts. This means that for fixed-mount systems, maintenance is limited to checking wiring connection and performance of minor components such as relays, fuses/circuit breakers, fans and relays. Most system have remote monitoring along with a local weather station so that performance can be compared with predictions. If the system as a whole is not performing as expected, the problem can be tracked down to a particular subarray or even string, depending on the resolution of the monitoring system.

Some modern systems use infrared cameras, either hand-carried or via drone, to look for “hot spots” in an array field which indicate fault modules or wiring. These hot spots are typically caused by faulty or damages modules or faulty wiring.

General maintenance typically involves opening combiner boxes, inverters and other electrical boxes, and checking for signs of corrosion or arc flash. Pyranometers in weather stations should be recalibrated or replaced every two years or according to manufacturer recommendation. Trackers typically require additional maintenance, although many modern trackers are made with sealed gearboxes to minimize this need. If trackers are required, the RFP should ask the vendor to describe all maintenance needs.

Another potential maintenance step is array cleaning. This is not typically necessary in environments with periodic rain but can be an issue in desert climates or sites with extended dry seasons. Washing modules is a tedious task and care must be taken not to add layers of residue which would further degrade performance. Robotic cleaners are becoming available, but they still require some manual operation and a good water source. Managing vegetative growth in array fields is an often-overlooked aspect of a large PV array. Techniques to manage growth include gravel, low profile ground covers, prairie/pollinator crops, or grass with sheep to manage the growth.

PV Decommissioning

PV systems typically have a service life of around 25 years. When this period is finished, they should either be repowered using new modules and electronics, or decommissioned, returning the site to its original condition for reuse. Decommissioning includes de-powering the system, removal of all modules, electronics, wiring and structures, recycling material as much as possible. PV module recycling is increasingly available in the U.S. as some landfills no longer accept PV panels, laws are changing to require recycling, recovered materials have monetary value, and new PV panels can be manufactured using recovered materials.

Wind Generators

Wind System Design and Rating

Modern wind generators use rotating turbine blades to convert wind to rotary power. There are many different wind turbine designs. The first classification is “horizontal axis,” with the blades either in from of or behind the generator on a horizontal shaft, and “vertical axis” with the generator at the base of a vertical shaft containing blades. These are often called VAWTs, Darius turbines or “egg-beaters.” This section will focus on horizontal axis turbines.

The generators in wind turbines are classified into 5 types:

1. Type 1 – Direct connection Squirrel Cage / Limited variable speed
2. Type 2 – Type 1 with variable resistor in rotor circuit / Limited Variable Speed
3. Type 3 – Doubly Fed Induction Generator with power electronics
4. Type 4 – Variable Speed with full power electronics

5. Type 5 – Variable Speed with speed/torque converter and synchronous generator

DC wind turbines are also available for off-grid, battery powered systems.

As wind power has become a more common part of the generation mix, the industry is migrating to larger and larger turbines, from 1 MW in 2000 to prototypes up to 13 MW in 2021. As a result, the market for small and mid-sized turbines (less than 1 MW) has declined. Used wind turbines in these sizes are available in limited quantities. Wind turbines are often installed in "farms" of multiple units.

Wind Performance and Warranties

Wind turbine performance is highly dependent on microclimate and tower height. It is very important to have an accurate estimate of the wind resource before investing in wind generation. The wind varies over the course of a day, from day-to day, and seasonally. Wind and solar can be complementary because often, the wind blows when the sun is not shining, but this is dependent on individual sites. Most modern turbines are Types 3-5, which have better efficiencies and have more capability to provide voltage and reactive power control.

Wind Maintenance

Wind turbine maintenance is typically performed twice a year and is similar to maintenance on other rotating machines except for the challenge of accessing equipment at the top of the tower.

Wind Decommissioning

Decommissioning of wind turbines is basically a reverse of the installation procedure. Wind turbine blade recycling processes are in development.[2]

Energy Storage Systems (ESS)

ESS Rating

There are four basic types of electrical energy storage—electrostatic (super-capacitors, superconducting magnetic energy storage), electromechanical (pumped hydro, compressed air, gravity-based systems, flywheels), electro-thermal (reversible heat pumps with thermal storage), and electrochemical (batteries). This section will focus on the last category.

Rechargeable electrochemical batteries are divided into two classes:

- Solid-state batteries—batteries of multiple technologies, including lead acid, lead-carbon, nickel-metal-hydride, various lithium technologies, sodium nickel chloride, and "liquid metal," among others. Typically, there is an electrolyte that interacts with an "electrode" with no moving parts or pumps.

[2] See: https://www.energy.gov/eere/wind/articles/carbon-rivers-makes-wind-turbine-blade-recycling-and-upcycling-reality-support

- Flow batteries—batteries that use pumped electrolyte to transfer energy, typically involving a membrane. The energy capacity is determined by the volume of electrolyte, and the "power rating" is determined by the size of the membrane and some other factors. These batteries have moving parts (pumps) and "plumbing" which introduces failure mechanisms not present in solid state batteries. There are two primary types of flow batteries— "redox" batteries, where the electrolyte is pumped through a membrane, and Zinc-Bromide batteries, where zinc is plated from the electrolyte onto a membrane. Redox batteries are similar in concept to hydrogen fuel cells.

All electrochemical batteries produce DC electricity, so the associated energy ESS require a DC to AC inverter and some method of charging the battery. These may be separate sets of power electronics or they may be combined into a bidirectional inverter.

Systems are rated both for power (kW/MW-AC – determined by the batteries and the power electronics) and energy (kWh/MWh-AC – determined by the batteries alone). Systems are occasionally described by power and hours (e.g., 500 kW/2 hours), but the energy/power rating is technically more accurate. It is important to note that any given battery can be used for more hours at lower power. The next most important rating is the cycle life versus depth of discharge, which is a measure of how many times the battery can be cycled to differently end capacities.

The most common batteries used for large scale microgrids are based on lithium-ion chemistries of various types. For example, Lithium NMC (nickel, manganese, cobalt) batteries are generally lighter, smaller and less expensive than LiFEPO4 (lithium iron phosphate), but these batteries have better cycling characteristics and are considered less susceptible to fire.

ESS Performance and Warranties

Energy storage systems are controlled via their power electronics, setting specific discharge and recharge rates. It takes more energy to recharge the battery than was delivered during discharge. This ratio is called the "AC round trip efficiency" (ACRTE) and is a combination of the battery DC efficiency and the efficiency of the power electronics. ACRTE varies widely among different battery types, ranging from 60% for some flow batteries up to 85-90% for advanced lithium batteries. Lithium batteries are typically rated for around ten years of life. Flow batteries are often rated for twenty or more years of life.

Most batteries also experience a decrease in energy storage capacity as they age. This can be due to usage (cycling) or due to general degradation of various chemicals and components such as separators. This degradation is expressed either as an annual percentage (e.g., 3% per year), or as a fraction of initial capacity at end-of-life (e.g., 70% of rated capacity after 10 years). Flow batteries (especially redox batteries) have much lower rates of degradation than lithium batteries, even with extensive deep cycling.

The physics of degradation means that there are two primary types of warranties on the battery component of the system. The first is simply to guarantee a specific capacity based on expected degradation. This is usually accompanied by requirements to monitor usage of the batteries to ensure that they operate within expected parameters. The second warranty guarantees full capacity at the end of life, which is accomplished by oversizing the initial capacity and then replacing modules within the warranty period to maintain rated capacity. The second method offers more useful capacity over the life of the battery, but it comes with an added cost, both for initial oversizing and for periodic replacement of modules.

ESS Maintenance

Solid state electrochemical energy storage systems require little active maintenance since there are few moving parts outside of relays and parts associated with HVAC systems designed to protect the batteries from extremes of temperature. Modern systems also include comprehensive monitoring of the batteries to spot early problems with battery modules that might lead to failure and consequent fires. Flow batteries require more maintenance since they include pumps and plumbing and must also be provided with containment of any unanticipated spillage. All energy storage systems require inspection of electrical and electronic components to identify corrosion and other problems.

ESS Decommissioning

Decommissioning batteries can be as simple as removing the ESS enclosures to a site where the individual components can be recycled or sent to landfills. Lithium battery recycling regulations are in development.[3] Although the batteries can be recycled, the cost of doing so is not compensated by the value of the recycled materials. Any contracts require posting a bond to cover the costs of decommissioning/recycling at end-of-life. This is problematic since the recycling technology is still immature so it is very difficult to estimate costs. Flow batteries have different recycling issues. For example, the electrolyte in Vanadium flow batteries, although toxic, can be completely recovered at end of life, and the balance of components are generally recyclable. Zinc and bromine from that category of flow batteries can also be recovered at end-of-life.

Codes and Standards

The following commercial standards may apply to equipment used in microgrids:

- UFC 3-600-01, 8 August 2016, Change 6, 6 May 2021—Fire Protection for Engineering Facilities
- UL9540-2020, 2nd edition—Standard for Safety Energy Storage Systems and Equipment
- UL1741-2020—Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources
- NERC Standard PRC-024-2—Generator Frequency and Voltage Protective Relay Settings
- IEEE 1547-2018—Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces
- IEEE Std 2030–2011 Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), and End-Use Applications and Loads

[3] https://www.epa.gov/hw/lithium-ion-battery-recycling

    - IEEE P2030.2 IEEE—Guide for the Interoperability of Energy Storage Systems Integrated with the Electric Power Infrastructure
    - IEEE 2030.2.1-2019—Guide for Design, Operation, and Maintenance of Battery Energy Storage Systems, both Stationary and Mobile, and Applications Integrated with Electric Power Systems
    - IEEE 2030.3-2016—Standard Test Procedures for Electric Energy Storage Equipment and Systems for Electric Power Systems Applications
    - IEEE 2030.7-2017—Standard for the Specification of Microgrid Controllers
    - IEEE 2030.8-2018—IEEE Standard for the Testing of Microgrid Controllers
    - IEEE 2030.9-2019—Recommended Practice for the Planning and Design of the Microgrid
- IEEE 519—Recommended Practice and Requirements for Harmonic Control in Electric Power Systems
- NFPA 1—Fire Code
- NFPA 70—National Electric Code
- NFPA 855—Standard for the Installation of Stationary Energy Storage Systems, 2020 edition
- ANSI C84.1—Electric Power Systems and Equipment – Voltage Ranges