SANDIA REPORT
SAND2022-11264
Printed August 2022

Sandia National Laboratories

Optimal Portfolio Design of Distributed Energy Resources on Puerto Rico Distribution Feeders with Long Outages after Hurricane Maria

ProsumerGrid Inc.
Marcelo F. Sandoval
Jorge Hernández
Santiago Grijalva

Sandia National Laboratories
Robert J. Broderick
Efraín O'Neill-Carrillo

June 2022

Prepared by
Prosumer Grid, Inc.
for
Sandia National Laboratories
Albuquerque, New Mexico
87185 and Livermore,
California 94550

Issued by Sandia National Laboratories, operated for the United States Department of Energy by National Technology & Engineering Solutions of Sandia, LLC.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone:	(865) 576-8401
Facsimile:	(865) 576-5728
E-Mail:	reports@osti.gov
Online ordering:	http://www.osti.gov/scitech

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Rd
Alexandria, VA 22312

Telephone:	(800) 553-6847
Facsimile:	(703) 605-6900
E-Mail:	orders@ntis.gov
Online order:	https://classic.ntis.gov/help/order-methods/

Optimal Portfolio Design of Distributed Energy Resources on Puerto Rico Distribution Feeders with Long Outages after Hurricane Maria

Marcelo F. Sandoval, Jorge Hernández, Santiago Grijalva
ProsumerGrid, Inc.
777 Atlantic Drive NW
Atlanta, GA 30332-0250

Robert J. Broderick, Efraín O'Neill-Carrillo
Photovoltaics and Distributed Systems Integration
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-1033

ABSTRACT

This work details a project to design reliable, resilient, and cost-effective networked microgrids considering grid constraints and resilience metrics focused on Puerto Rico distribution feeder locations with long outages after Hurricane Maria. The project consisted primarily of modeling and simulation tasks that accomplished the following objectives:

1. Selected 10 distribution feeder models in vulnerable areas. The sample feeders are geographically distributed across Puerto Rico and vary in length to capture the wide variety of feeders on the island.
2. Determined the optimal location and sizing of distributed energy resources (DERs) on the identified distribution feeders. The systems considered as part of the microgrid solutions were solar photovoltaic (PV), battery energy storage systems (BESS) and distributed fossil fuel generation (DFFG).
3. Estimated the cost-benefit of the proposed DER portfolios.
4. Provided a set of final recommendations that inform decision making on how to do targeted planning analysis for microgrids that can supply energy to critical infrastructures.

ACKNOWLEDGEMENTS

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Office of Energy Agreement Number 34951 and the Office of Electricity (OE) support through an interagency agreement with FEMA.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

This page left blank

EXECUTIVE SUMMARY

Distributed Energy Resources (DERs) are transforming the electric industry. In particular, adoption of these resources is rapidly growing and being driven by technology, economic, and regulatory changes. If properly sized, sited, and coordinated, DERs have the unique capability to provide a range of services and benefits to electricity users and the electric grid. Determining the optimal combination of DERs that are the most cost effective (investment and operational), providing the highest expected benefits, and having the highest capability to meet forecasted demand is a significant challenge. Adding the goal of making the system resilient to expected grid disconnection from the electric utility is a very complex problem to solve due to the large number of decision variables and parameters that need to be considered.

The objective of the study was to determine the optimal (least cost, reliable and resilient) portfolio of DERs, solar PV, energy storage, and distributed fossil fuel generation that can meet the critical demand in a specific location while minimizing the total costs (investment and operational). Because the optimal portfolio of DERs depends on the expected load to be served, the economics of DER costs, electric utility price, and other variables, a robust set of assumptions was developed for the baseline case and a set of corresponding sensitivities was also developed to test how much the solutions varied based on input assumptions.

In this work, we conducted modeling and simulation to design resilient and cost-effective microgrids focusing on ten Puerto Rico feeder locations with long outages after Hurricane Maria. The research team identified the set of ten representative feeders that met the following criteria: 1) include areas that took the longest to restore after Hurricane Maria, typically around eight months, 2) have critical infrastructure such as hospitals, clinics, shelters, that are of key importance to keep operating during grid outages and 3) have relatively diverse geographic distribution across the island.

The strategic goal of the modeling and simulation was to find an optimal microgrid solution that balanced the following three metrics:

- **Resilience:** to develop a local energy supply portfolio that can supply electricity during extreme conditions, including weather and natural disasters, to meet the critical loads in each outage area.
- **Economics:** to develop an energy supply portfolio that is cost effective in terms of capital and operational expenses.
- **Sustainability:** to develop an energy supply portfolio that considers maximizing renewables generation and minimizing emissions.

The key questions addressed in this study were: What investments in DERs are needed to meet the forecasted demand for the next 20 years while considering frequent and long grid outages? What types and capacities of these DER resources should be installed? And what are the resulting total costs, benefits, and net present value of the DER portfolio selected?

This project accomplished several objectives. First, the team determined the optimal location and sizing of DERs at ten areas on the selected distribution feeders to create microgrids. Second, we demonstrated a two-stage stochastic optimization model for minimizing the net present cost of a DER portfolio located at each feeder to satisfy facility peak demand over a 20-year time horizon, while taking into consideration operational constraints (power balance), financial constraints (timing and value of DER capital investments), resilience constraints (expected restoration times) and DER locational/operational constraints. Finally, we estimated the cost-benefit of the proposed DER portfolios and describe a set of final design recommendations and sensitivity tradeoffs that can inform decision making on how to perform targeted planning analysis for a larger number of resilient and cost effective microgrids in the future.

This analysis was completed in the 2020-2021time frame using cost source data that reaches back to as early as 2017, so future analysis will need to apply updated technology and fuel supply costs to the methodology and approaches we describe in this report. Our analysis was focused on the least cost approach for a utility centric resilience investment strategy, so we did not constrain our scenarios to the 75% renewable energy minimum for microgrids in the PR microgrid regulations. Finally, the estimation of critical facilities for each of the 10 communities was based on GIS information and our best estimate on a five-point priority scale, so future in depth analysis at any of these sites will need targeted stakeholder engagement to refine the critical facility analysis.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
AMR	Advanced Meter Reading
ARPA-E	Advanced Research Project Agency - Energy
ATB	Annual Technology Baseline
BESS	Battery Energy Storage Systems
CHP	Combined Heat & Power
CO_2	Carbon Dioxide
DER	Distributed Energy Resources
DFFG	Distributed Fossil Fuel Generation
DLMP	Distribution Locational Marginal Prices
DOE	U.S. Department of Energy
DR	Demand Response Devices
DSO	Distribution System Operators
EIA	Energy Information Administration
EPRI	Electric Power Research Institute
ESS	Energy Storage Systems
EV	Electric Vehicles
GIS	Geographic Information System
HC	Hosting Capacity
IEEE	Institute of Electrical and Electronics Engineers
IPCC	Intergovernmental Panel on Climate Change
IRP	Integrated Resource Planning
ISO	Independent System Operator
LBNL	Lawrence Berkley National Laboratory
LMP	Locational Marginal Price
LNG	Liquified natural gas
LNVA	Locational Net Value Analysis
MILPM	Mixed Integer Linear Programming Model
NREL	National Renewable Energy Laboratory
NSF I-Corps	National Science Foundation Innovation Corps
NWA	Non-Wire Alternatives
OH	Overhead Line
PG	ProsumerGrid, Inc.
PREPA	Puerto Rico Electric Power Authority
PV	Photovoltaic

Abbreviation	Definition
R&D	Research and development
SNL	Sandia National Laboratories
T/D	Transmission and Distribution
TOU	Time-Of-Use
UG	Underground Line
U.S.	United States
UCESS	Utility Controlled Energy Storage Systems
VOLL	Value of Lost Load

1. INTRODUCTION

In this work, we conducted modeling and simulation to design resilient and cost-effective networked microgrids on the distribution system focusing on Puerto Rico feeder locations with long outages after Hurricane Maria. This project accomplished several objectives. It selected ten distribution feeder models that were geographically distributed across Puerto Rico and varied in length to capture the wide variety of feeders on the island. The team then determined the optimal location and sizing of distributed energy resources (DERs) on the identified distribution feeders to create microgrids. The systems considered as part of the microgrid solutions were solar photovoltaic (PV), battery energy storage systems (BESS) and distributed fossil fuel generation (DFFG). The estimated cost-benefit of the proposed DER portfolios was determined, and a set of final recommendations was provided that informs decision making on how to perform targeted planning analysis for microgrids that can supply energy to critical infrastructure.

The research team consisting of representatives of ProsumerGrid (PG) and Sandia National Laboratories identified a set of ten representative feeders that collectively: 1) include areas that took the longest to restore after Hurricane Maria, 2) have critical infrastructure such as hospitals, clinics, shelters, and 3) have relatively diverse geographic distribution in the island. The resilient energy supply of critical infrastructures such as hospitals, clinics, shelters is of utmost importance during major weather or catastrophic events.

The objective of the study was to determine the optimal (least cost, reliable and resilient) portfolio of DERs including solar PV, energy storage, and DFFG that can meet the critical demand in a specific location while minimizing the total costs (investment and operational). Because the optimal portfolio of DERs depends on the expected load to be served, the economics of DER costs, electric utility price, and other variables, a set of assumptions was developed for the baseline case and a set of corresponding sensitivities was also developed to test how much the solutions varied based on input assumptions.

The general strategic goals included the following:

- Resilience: to develop a local energy supply portfolio that can supply electricity during extreme conditions, including weather and natural disasters, and can deliver electricity with the right quantity at the right time to supply critical loads.
- Economics: to develop a local energy supply portfolio that is cost effective in terms of capital and operational expenses.
- Sustainability: to develop a local energy supply portfolio that considers renewables and emissions.

2. METHODOLOGY

2.1. Context for Optimization-Based Distributed Energy Resources Planning

The Puerto Rico Energy Bureau (PREB) (Regulation on Microgrid Development- 9028, 2018) defines DER to mean Distributed Generation or electric Energy Storage: Distributed generation means an electric power generation facility in Puerto Rico connected to the distribution infrastructure or to a microgrid and/or producing power for self-supply or sale; Energy storage means any resource located in the microgrid that is capable of receiving electric energy from the electric power grid or any other generation resource, for later injection of electricity back to the electric power grid or to serve any load. These definitions are also consistent with relevant energy laws such as the Puerto Rico Energy Public Policy Act (Act17-2019).

Using the above definition, resources such as solar PV systems, energy storage systems (ESS), fuel-based generators, and fuel cells can be considered as DERs. Figure 1 shows several DER examples. In this study, we define a portfolio of DERs as a set of solar photovoltaic (PV), battery energy storage systems (BESS) and distributed fossil fuel generation (DFFG).

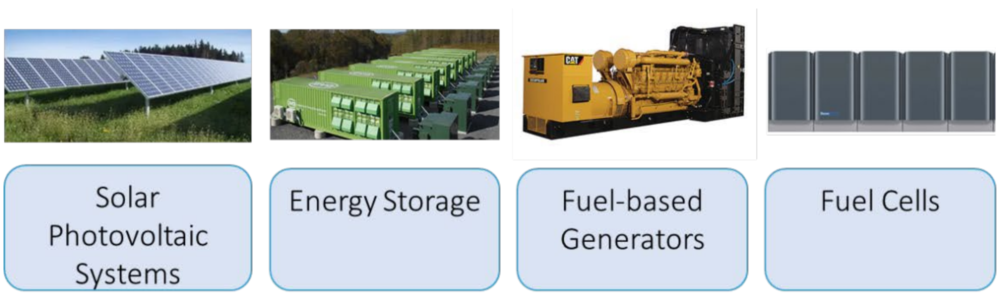


Figure 1. Distributed Energy Resources Examples

The rational for choosing these three resource options was based on wanting to have technology options that were accessible and commercially available and could demonstrate least cost, resilient operation and accommodate both seasonal and daily variation in renewable energy resources while also allowing long periods in microgrid only operation. We address the sensitivities around DFFG options by explicitly modeling a carbon cost scenario, a low-cost renewable energy scenario and the viability of low carbon emissions with an LNG solution.

DERs are transforming the electric industry, see Figure 2. In particular, private adoption of these resources is rapidly growing and being driven by technology, economic, and regulatory changes. If properly sized, sited, and coordinated, DERs have the unique capability to provide a range of services and benefits to electricity users and the electric grid. For example, electricity users can benefit from reduced demand charges, minimized bill costs, and increased resilience. Distribution power systems would see benefits from deferred system upgrades while transmission systems would be better able to provide energy services and ancillary services (if coincident with local grid need). And power generation would be better able to avoid the construction of peaking generators (if coincident with system peak).

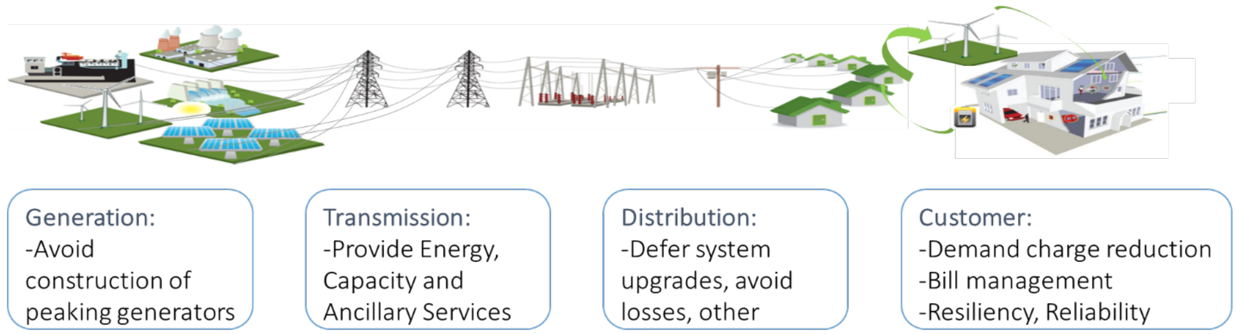


Figure 2. DERs Services at Generation, Transmission, Distribution Electric Systems

Determining the optimal combination of DERs that are the most cost effective (investment and operational), providing the highest expected benefits (less energy non-served, highest avoided energy cost), and having the highest capability to meet forecasted demand is a significant challenge. Adding the goal of making the system resilient to expected grid disconnection from the electric utility is a very complex problem to solve due to the large number of decision variables and parameters that need to be considered.

In this study, we used optimization methods to determine the type and capacity of DERs that must be deployed in a microgrid footprint on each feeder to maximize the benefits while reducing total costs and increasing resilience. Optimization is a technique that has been broadly used in the electricity industry as part of long-term planning for bulk power generation. For this study, we utilized the ProsumerGrid Planning Studio (See Appendix A) which provides a methodology for long-term DER planning at the distribution-level.

The following questions are addressed in the study:

1. What investments in DERs should be made to meet the forecasted demand for the next 20 years while considering the possible unavailability of the main grid for a certain period of time?
2. What types and capacities of these DER resources should be installed?
3. What are the resulting total costs (total capital investment and operational costs) and the net present value of those costs for the DER portfolio selected?

2.2. Optimal DER Planning Method

In this section we describe the DER optimization method utilized in this study. DER options include solar PV, energy storage, and DFFG. The modeling steps consists of approximating the underlying DER capacity planning decision problem using mathematical expressions.

The optimization approach consists of the following steps, widely used in optimization methodologies for long term energy capacity planning:

1. Modeling: Build a mathematical model of the feeder, critical infrastructure demand, and DERs.
2. Data Collection: Analyze available quantitative data to be used as inputs to the mathematical model.
3. Solve the model: Use a numerical method to solve the mathematical model.
4. Solution Analysis: Infer the actual decision from the solution to the mathematical model and conduct sensitivity analysis.

2.2.1. *Optimization Problem*

A particularly important consideration in optimizations is deciding how much detail to consider while maintaining numerical tractability of the mathematical model. The modeling step requires some simplifying assumptions to be able to solve the model.

The key components of the optimization model are:

1. The decision variables (i.e., DER type, how many DER units, and what DER capacity should be installed?)
2. The constraints that specify restrictions and interactions between the decision variables (i.e., power and energy balance, maximum generation outputs and network limits).
3. The objective function that quantifies the criteria for choosing the best solution (i.e., the values of the decision variables that minimize the objective function are the “best” among a set of decision values defined by the constraints in the optimization model).

In this project we used a two-stage stochastic optimization model for minimizing the net present cost of a DER portfolio operated by a feeder to satisfy a facility peak demand over a multi-year time horizon, while taking into consideration operational constraints (power balance), financial constraints (timing and value of DER capital investments), resilience constraints (expected restoration times) and the following additional parameters: forecasts (solar PV output profiles, load profiles), DER locational, and operational constraints. The time horizon for this study is 20 years. For each year, the 24-hour load profiles of a representative day are considered at 1-hour granularity.

2.2.2. *Scenarios*

There are two scenarios simultaneously considered: 1) grid connected operations and 2) grid-disconnected operations, that estimate the occurrence of outages due to normal maintenance downtime and potential emergency conditions such as hurricanes during the planning horizon as shown in Table 1. Each scenario is weighted by a corresponding probability of occurrence. The probability for grid disconnected operations is assumed to be equal to the number of hours of expected restoration time divided by the total number of hours in the planning horizon (20 years). Sensitivities to two outage times will be analyzed: 6 months and 1 month.

Table 1. Grid Connected and Grid Disconnected Scenarios

Scenario	Power Exchange with The Grid, P_x	Scenario Probability
Grid Connected	P_x	1−(Restoration Time/Total Hours)
Grid Disconnected	$P_x = 0$	Restoration Time Hours/Total Hours

2.2.3. Objective Function

The objective function seeks a first-stage decision that minimizes first-stage DER investment costs and the expected cost of the second-stage decision (expectation of the sum of the operational costs resulting from the optimal operation of DER under the two scenarios). We note that costs due to electric utility permitting and interconnection are not considered in the model, but rather the problem seeks to find the optimal DER investment assuming existing infrastructure capacity. Also, this work assumes that the existing distribution infrastructure can be used for each of the microgrids. Thus, the cost of new distribution lines was not included as a decision variable in the analysis

2.2.4. First Stage Decision Variables

The following first-stage decision variables are to be determined for each node and phase:

- Capacity size of solar photovoltaic
- Capacity size of energy storage
- Capacity size of DFFG

2.2.5. Second Stage Decision Variables

The study uses a temporal granularity of one hour and a spatial granularity of the distribution feeder circuit. The following second-stage decision variables are to be determined for each period t in each year y, at each node n, at each phase p, under each scenario ω:

- Power exchange with the grid at the point of interconnection (i.e., grid-tied with the electric utility distribution system)
- Power produced by each generator
- Power produced by each solar PV unit
- Power discharged by each storage device
- Power charged by each storage device
- Energy level in each storage device
- Power delivered to each load demand

2.2.6. Model Constraints

The following constraints are considered:

- Line Capacities: The power flow on each line and on each phase needs to be less or equal than the corresponding conductor thermal limit.
- Node Power Balance Per Phase: The sum of total power injected per phase at a given node of the distribution circuit needs to be equal to the sum of the total power leaving the node on the same phase.
- Distributed Generator Capacities: For each generator, the output power is constrained by the maximum generation capacity.
- Storage Energy Balance: The energy stored at each time step is equal to the energy stored in the previous time step plus (minus) the charge (discharge) efficiency of the storage device multiplied by the charge (discharge) power in the current time step.

- Storage Final Charge: The energy stored at the beginning of the day needs to be equal to the energy stored at the end of the day.
- Charge and Discharge Rate Limits: The charge and discharge power set points of each storage unit need to be less than the maximum charge and discharge rates, respectively.
- Energy Capacity: The energy stored in each storage unit needs to be between its minimum and maximum energy capacity limits.
- Solar PV Output: Solar PV output is limited by its forecasted values. Solar PV can be curtailed, which assumes that the PV resource is interfaced with the grid through a smart inverter.
- Maximum and Minimum Demand Response Available: The proportion of flexible demand served is bounded by the maximum and minimum flexible demand at each load location.
- Maximum Size of DERs with respect to Local Load: This parameter is circuit dependent and is used to model space constraints for solar PV.
- Resources lifetime (e.g., number of charges / discharges of the storage solution)

2.2.7. Model and DER assumptions

The network is modeled per single feeder and each node with a load is given all DER technologies as options. All sizes of DERs in the range of the distribution system loads are considered. We assume that the DERs have the necessary controls to receive operational commands to be dispatched and that their costs include such operational capability.

2.3. Requirements and Assumptions

2.3.1. Feeder Locations Requirements

SNL generated an initial dataset of 42 locations whose outage time was between 2-8 months after the initial event. (Figure 3) This dataset contains the latitude and longitude coordinates of polygons areas determined by SNL methodology using nighttime satellite imagery. (Lugo-Alvarez, Broderick, & Ortiz-Rivera, 2020).

The SNL methodology utilized nighttime satellite imagery to track the grid recovery after a major blackout by comparing a baseline satellite image before any outages to images taken in the weeks and months after a major blackout caused by Hurricane Maria. NASA's satellite imagery provides high quality composite images, that have been processed to remove all light sources that are not man made: fires, reflections on clouds, reflections of the moon, etc. Using this data and comparing the various images, SNL was able to identify outage areas across the entire island of Puerto Rico. The next step in the process was to combine these outage areas with population and infrastructure GIS data to identify 42 locations that likely have the need for resilient microgrid projects to mitigate the long outages suffered in these areas.

Based on this data, ProsumerGrid identified 136 feeders that intersected these polygons locations. (see Table 2) The research team then identified ten feeder locations, taking into consideration the locations of critical infrastructures and geographical diversity.

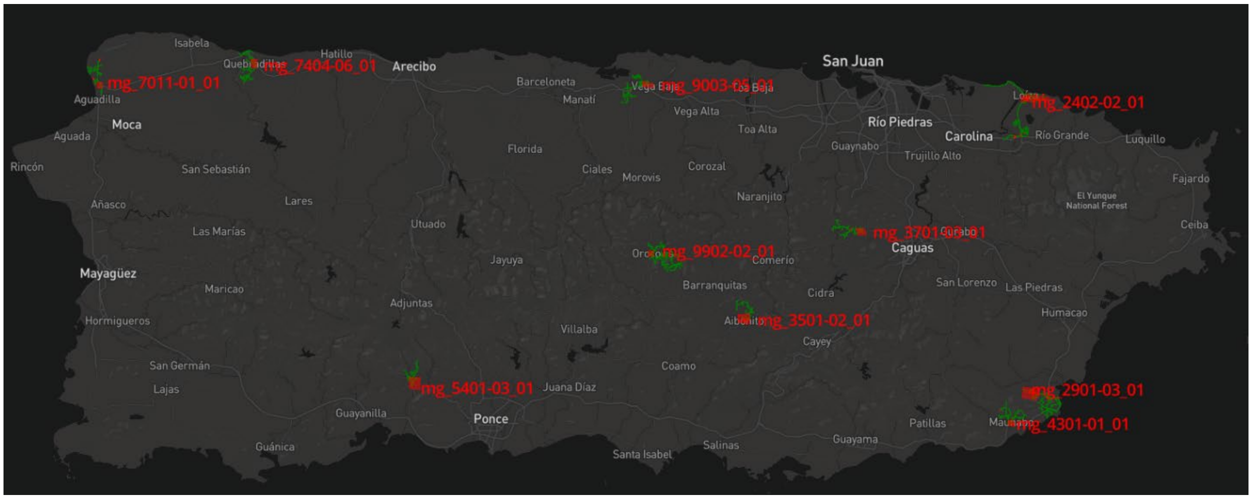


Figure 3. Geographical Distribution of Selected Feeders

Table 2. Selected Feeder Locations

No	Location	Municipality	Feeder Identifier	Powered by May 2018 (8 months)
1	Northeast	Loiza	2402-02	Yes
2	Southeast	Yabucoa	2901-03	No
3	Southeast	Maunabo	4301-01	No
4	East	Aguas Buenas	3701-03	No
5	Center	Aibonito	3501-02	No
6	Center	Orocovis	9902-02	No
7	North	Vega Baja	9003-05	No
8	South	Penuelas	5401-03	Yes
9	Northwest	Quebradillas	7404-06	Yes
10	Northwest	Aguadilla	7011-01	Yes

The SNL research team reviewed a map, done by other researchers, with the sectors in Puerto Rico that had no power by May 2018 (and beyond). The map was developed from publicly available outage data from the U.S. Department of Energy Situation Reports from September 2017 to April 2018, and official social media data from the Puerto Rico Electric Power Authority and the U.S. Army Corp of Engineers (Castro-Sitiriche, Burgos-Rivera, & Burgos-Citron, 2019). These data were the best available publicly at the time and were geographically located over a Puerto Rico map showing local municipalities. The map was only a tool to narrow the candidate feeders from those identified from Sandia's previous satellite imagery work. Six of the ten representative feeders are close to areas that had no power as of May 2018. Comprehensive data on exact locations with outages restored before May 2018 were not available at the time our work was completed, so restoration time of the other four feeders was unknown. These four selected feeders did not have power for at least two months and were chosen based on the number of critical infrastructures and geographical location.

The SNL research team also made three important observations. First, that the feeders are usually in an "urban" area even within a mountain region (e.g., near City Hall or the town's square). Usually, those specific locations got power before the more rural zones of that specific town. However, critical infrastructures/services are usually provided near the town's square. So instead of locating the microgrids exactly on the community that got power last, the representative microgrids locations were selected based on the proximity to the critical loads that would serve those communities and others. Furthermore, if these microgrids are to be utility-owned/operated, it makes sense to locate them where they would benefit more people. Second, using satellite imagery to identify sectors without power is a good approach when other sources of outage data are unavailable. However, it is possible that some satellite images showing dark areas may have had some parts of the community power restored for residential/commercial loads. Public lighting is served from separate circuits that might have not been a priority at the moment of restoration. Third, this work assumes that the existing distribution infrastructure can be used for each of the microgrids. Thus, the cost of new distribution lines was not included as a decision variable in the analysis. These three observations are important considerations for the use and application of this report.

2.3.2. Sustainability, Resilience, Economic Metrics and Requirements

Table 3 describes the sustainability, resilience and economic objectives, assumptions, and requirements.

Table 3. Sustainability, Resilience, and Economic Requirements

Requirement Type	Required Data	Assumption(s)
Sustainability Metrics:	Percent of Minimum Renewable Energy	**No minimum** renewable energy constraint. There is an existing microgrid rule that requires 75% of energy to come from renewables under normal operating conditions. This is not imposed as a constraint as our analysis was focused on the least cost approach for a utility centric resilience investment strategy, so we did not constrain our scenarios to the 75% renewable energy minimum for microgrids.
Resilience Metrics:	Percent of Critical Load to be supplied in Grid Disconnect-Mode	All critical loads based on the critical priority value inside of the outage area need to be supplied. A sensitivity was created to filter out all loads that are not labeled critical.
	Outage time	Outage time of 28 days per year for each of the 20 years in the analysis timeframe: 13440 hours

Requirement Type	Required Data	Assumption(s)
	Priority Values for Critical Infrastructure	On a 0-1 scale, Critical infrastructure has a priority greater than 0.75, other loads have a priority lower than 0 .75
Economic Metrics:	Total Capital and Operational costs	Total capital and operational costs for 20 years
	Net Present Value (NPV)	Net present value of the total cash flows for the planning period
	Project life (planning horizon T in years)	20 years
	Discount rate (%)	8.35% (baseline from PREPA) 0% (low discount rate sensitivity)

2.3.3. Demand Parameters

Long-term demand forecasts were provided by PREPA as determined by Siemens for the 2019 Integrated Resource Plan Study (IRP). The forecasted estimate is a demand decrease for the long-term forecast, with a median of -0.024% per year. PREPA has established that the peak demand as of September 2018 was 10% below the 2016 peak level. We will consider a flat demand for the baseline case and the decreasing demand scenario of -2% per year as the demand sensitivity scenario.

Regarding distribution circuit demand profiles, for some feeders, load profiles obtained by feeder head power meters were provided by PREPA. Those profiles have hourly granularity for one year (2016). For other distribution circuits, the load profiles were not provided but only the peak demand was given. We note that PREPA did not have power meters installed at all the feeders on their system at the time of this report. PREPA also provided the system level demand profile, which was utilized to approximate the feeder level demand profile for the feeders that did not have time series demand data. Although PREPA has Advanced Meter Reading (AMR) infrastructure to remotely read customer energy meters, the data is currently not integrated with distribution circuit load data. The distribution circuit models consider only the primary network, which is the current approach used by most utilities in the United States (U.S.). Secondary circuit modeling is usually a requirement to model individual customer loads on distribution feeders based on smart meter readings. (Peppanen, Reno, & Broderick, 2016) Therefore, ProsumerGrid utilized load allocation, which is the common method used to model the circuit loads in many applications such as PV hosting capacity studies (Reno, Ellis, Quiroz, & Grijalva, 2012) and feeder load modeling. (Singh & E., 2010) In load allocation, the known feeder-level demand (peak and profile) is assigned proportionally to the capacities of the service transformers, including three-phase and single-phase transformers. Both active and reactive power demand were allocated in this manner. Existing solar PV systems were present in some of the use cases and were modeled according to profiles provided by PREPA.

Regarding demand response in Puerto Rico, there was no comprehensive study that has assessed the opportunities on the island at the time of our analysis. The success of numerous demand response programs in various regions of the U.S. and many other countries around the world would indicate that demand response can be a significant resource to contribute to grid economics and reliability. In the model used for this study, flexible demand is not considered.

2.3.4. Solar Photovoltaic Parameters

The solar model consists of the following parameters: solar PV profile, operational cost, and investment cost. Also, a maximum capacity of the PV device is assumed to model space limitations. The solar PV profiles were provided by PREPA, consisting of solar power hourly estimates for one year (2018). The investment costs were obtained from the National Renewable Energy Laboratory's (NREL) 2018 Annual Technology Baseline (ATB) Low Case. (NREL, 2018)

Due to the requirement for resilience, solar needs to be combined with storage and be able to be islanded. When combined with storage, solar production higher than the demand is expected to charge the battery. PV would then be curtailed under two conditions: a) when the load at the point of common coupling is exceeded, and the battery is fully charged and, b) when the system is islanded, and the battery is fully charged. Both conditions are considered in the determination of the optimal PV (and other DERs) capacity. Also, there are specific fixed operational costs considered that include cleaning, maintenance, etc. The parameters for each solar PV device are presented in Table 4.

Table 4. Solar PV Assumptions

Parameter	Value
Solar PV hourly profile for period *t*, at node *n*, phase *p*, in year *y*, and scenario *ω*, [kW]	Hourly Profile
Fixed operating cost of solar PV device w, [$/kW-year]	10
Investment cost of solar PV device w, [$/kW] (Commercial)	1830
Investment cost of solar PV device w, [$/kW] (Residential)	2700
Variable operating cost of solar PV device w, [$/kWh]	0.001
Constraint on Maximum Capacity of PV device, [kW]	Circuit-dependent

2.3.5. Energy Storage Parameters

The energy storage model considers the following parameters:

- Power Ratings [kW AC]: Maximum charge and discharge rates. For many energy storage technologies in the scale of this study (customer scale), maximum charge and discharge rates are equal and are reported in terms of one value "Power Rating (kW AC)" in energy storage datasheets.
- Energy Rating [kWh or h]: This parameter is also called energy capacity. If it is reported in hours [h], it shows the maximum duration that energy storage can be charged or discharged at its maximum rating during that duration.
- Initial energy and final energy [kWh]: These parameters determine the available stored energy in the energy storage at the beginning and end of the optimization horizon. These parameters are optimally determined by the optimization model for a typical day and then are given to the optimization model as inputs to solve for the planning horizon. For each day, we assume that the initial energy and final energy of each storage device are equal to fifty percent of the full energy capacity that is determined by the optimization model.
- Roundtrip efficiency [%]: Charging and discharging the energy storage is a process that is not perfectly efficient. This means that not all the energy is stored and not all the stored energy can

be converted back because of conversion losses. The ratio of the output energy that is converted from one unit of input energy determines the roundtrip efficiency. For example, an energy storage with a roundtrip efficiency of 90% needs 1kWh of input energy to generate 0.9kWh of output energy. Roundtrip efficiency is equal to the multiplication of charge and discharge efficiencies. Since most of the energy storage datasheets report only the roundtrip efficiency, it is assumed that charge and discharge efficiencies are both equal to the square root of the roundtrip efficiency.

- Investment cost [$/kWh]: This parameter is also called capital cost and shows the cost to purchase an energy storage system and includes the cost of storage modules (e.g., battery cells), balance of system (e.g., container), power conversion system (e.g., inverter) and related costs. (Lazard) Note that it does not include the cost of land and grid integration.
- Operational cost for charging/discharging output power [$/kWh]: This parameter models the cost of energy required to compensate the losses. It also factors in the degradation of energy storage assuming that the output energy reduces the life of the storage that is modeled with a per kWh cost.
- Maintenance cost [$/kW/year]: Depending on the size and the technology of energy storage, a maintenance cost is assumed that is incurred every year.

The above parameters are collected from an extensive pool of datasheets of commercially available energy storage technologies and public reports. All costs used in this analysis come from these reports and any future studies will need to update cost assumptions with more recent industry vetted data. (Bruce, Kamath, & Jean-Marie, 2011), (Zakeri & Sanna, 2015), (Aneke & Meihong, 2016), (Abedi & Kwang, 2015), (Atanasoae, 2017), (Carnegie) (Cole, 2016), (Colthorpe, 2017), (Diorio , 2015), (Farhadi & Osama, 2016), (Agency, 2017), (Kintner-Meyer, 2013), (Anchal & Kulkarni, 2017), (Merchant, 2017), (Poonpun & Jewell, 2008), (Romm, 2017) Two of the most commonly used technologies are reviewed for this study: Li-ion batteries, Lead Acid batteries.

Table 5 summarizes the findings of energy storage technology parameters. For each technology and each parameter, several values are reported in various sources. It also provides the range of available data from all the reviewed sources and the average of that range is reported in parentheses. Note that the power and energy ratings are reported for each storage module and higher values can be deployed by using multiple modules.

Table 5. Energy Storage Technology Parameters

Technology	Li-ion	Lead Acid
Power Rating [kW]	30 - 1000	350 - 5000
Energy Capacity [kWh]	up to 4000	up to 20000
Roundtrip efficiency [%]	86 - 98 (92)	60 - 80 (70)
Investment cost – Battery [$/kWh]	232 – 523 (378)	315 – 540 (428)
Investment cost – Other, e.g. EPC [$/kWh]	168 – 377 (273)	235 – 410 (322)
Operational cost for charging/ discharging output power [$/kWh]	0.007	0.007
Maintenance cost [$/kW/year]	2.5	1 – 4 (2.5)

These parameters are the inputs of the optimization problem. The outputs are the number of each storage technology to be used and their capacity in terms of maximum charge and discharge rates that are within the available range shown in Table 5. The maximum energy in the storage devices is assumed to be up to four hours at the optimal charge and discharge powers. This is consistent with several commercial solutions available that offer flexibility by energy, footprint and voltage and that demonstrate scalability from a few kW (residential solutions) to large scale MW (grid scale energy storage solutions for long duration applications with continuous power supply >=3 hours). (LG Chem, Energy Solutions Company ESS Battery Division.) The 4-hour Li-ion Battery Storage operational costs and investment costs come from the Siemens 2018 Q1 National Forecast- Low Case used in the PR Grid Redesign Study. (Sandoval & Grijalva, 2019)

Other than the parameters used in the optimization model, energy storage physical parameters such as dimensions and weight are also important for the optimal planning. Table 6 compares the physical parameters of commercially available storage solutions. Data is collected from energy storage provider datasheets. The storage technology of all the reported solutions is Lithium-ion since it has the highest energy density (kWh/kg) among currently available battery solutions. It is noted that these solutions weigh about 17 to 34 kg per kWh. This must comply with the mechanical resistance of the site.

Table 6. Energy Storage Physical Parameters

Provider	Power [kW AC]	Energy [kWh]	Dimensions (W*D*H) [m]	Weight [kg]
Energport	120	240	3, 2.4, 2.4	8000
Energport	500	1000	6, 2.4, 2.4	26500
Energport	1000	2000	12, 2.4, 2.4	42000
Skid Solutions	250	500	3.1, 1.2, 2.25 + 4.7, 1.8, 2.8	2720 + 6130 = 8850
Skid Solutions	500	1000	4.6, 1.2, 2.25 + (4.7, 1.8, 2.8)*2	4600 + 6130*2 = 16860
SungrowSamsung	250	500	6.85, 2.44, 1.18	10000
SungrowSamsung	250	1000	11.95, 2.44, 1.18	17500
SungrowSamsung	500	1000	11.95, 2.44, 2.46	20000
SungrowSamsung	500	2000	11.95, 2.44, 2.46	35000

2.3.6. *Distributed Fossil Fuel Generation Parameters*

DFFG including natural gas, diesel, and propane share some common properties of requiring fuel storage or access to fuel networks. We use a generic DFFG model that requires parameters of investment costs, and variable operational costs including fuel and emissions. The maximum DFFG capacity assumed per node depends on the specific circuit. Similar to solar PV and energy storage, by default every node is given the option of DFFG limited to twice the peak load. Then, the optimization decides the optimal capacity based on local node demand, DER costs, and operational and circuit constraints.

2.3.6.1. Conventional Generation, Propane

Propane in Puerto Rico is delivered by trucks to customers and is primarily used for cooking and other applications. There are many propane distribution companies that operate in Puerto Rico. The 2018 cost of the 100-pound propane cylinder (23.6 gallons) delivered at customer premises in Puerto Rico ranged from $75 to $85 in 2018. (Vera Rosado, 2018) Assuming that a gallon of propane can generate as much as 23.0 kwh of electricity, the cylinder can produce 542.8 kWh, which represents a fuel cost of about $ 0.1473/kWh. The propane-based Combined Heat & Power (CHP) system installed at the Hospital Concepción uses propane and has a fuel cost of $0.16/kWh (CHP Association, 2017) including transportation. We assume a fuel cost of $0.16/kWh for propane DFFG in this study. We note that for this study, the thermal benefits of CHP are not captured since it would require detailed assessment of the customer heat loads. The installation of accessories, such as a transfer switch, are assumed to double the cost of the generator. The investment cost of a propane generator for this study is assumed to be $ 2750/kW.

2.3.6.2. Conventional Generation, Natural Gas

When one is looking for a fuel supply alternative that provides a reliable source for small to medium size generation on the distribution system, natural gas fired generation is generally a good candidate. It is normally fast starting, runs on demand, is relatively efficient, has lower emissions, and is cost-effective in most situations. On the U.S. mainland, there are considerable examples of stand-by or backup generation for hospitals, commercial facilities, and industrial sites as well as microgrids both islanded and interconnected to the grid which use natural gas as their fuel source. Typical costs assumed for this study are: operational cost is estimated to be 0.124$/kWh, the capital cost is about 1000 $/kW and the non-fuel operation and management (O&M) costs are 56$/kW/year.

Natural gas provided by liquified natural gas (LNG) shipments (delivered by sea from Trinidad and Tobago), are used for central station power generation at Eco-Eléctrica's plant. Puerto Rico does not have a network of gas pipelines or gas distribution lines. There was one proposal to build a pipeline from the Peñuelas LNG facility to the north shore over the mountains. Another proposed pipeline would go from the Peñuelas LNG facility to the Aguirre power plant in Salinas, PR. Those plans were scratched, but their purpose was to supply existing power plants, allowing the conversion of the oil/diesel plants, not for a broad gas distribution system.

Natural gas use is also growing as a backup for industrial facilities being delivered in cryogenic containers and through "virtual pipelines." (Crowley, 2018) (3.0: LNG Distributed Production and Virtual Pipeline, 2017) Usually, the storage capacity of those installations allows for two days to one week of generation. Crowley currently delivers LNG to a few industrial clients that have a DFFG in their facilities. At the time this report was written they announced the inauguration of an LNG facility in Peñuelas. From the LNG facility, operators will load natural gas in its liquid form onto 10,000-gallon ISO containers for over-the-road transport to customer facilities around the island. Upon arrival at the customer's site, the LNG will be re-gasified and used for power generation and energy consumption.

The research team decided to investigate the viability of containerized LNG and therefore all the scenarios in this report assume that LNG is readily available on site. Presently such a scenario is possible in locations where LNG can be delivered by land. This might not be the case in mountainous regions of PR. There might also be limits on the capacity of current LNG suppliers to deliver the fuel to a large number of users.

2.3.6.3. Conventional Generation, Diesel

The use of diesel as a fuel supply for small to medium sized generators on the distribution system is a viable alternative for Puerto Rico. Diesel generators have been used for many years on the U.S. mainland and in Puerto Rico as backup power sources or for completely stand-alone facilities not connected to the distribution grid. Diesel for small generators played a very important role during the recovery from Hurricane Maria. (NY Times, 2017) There are currently a large number of suppliers of diesel generators. Diesel fuel is available in Puerto Rico both on the main island and the islands of Vieques and Culebra. In Puerto Rico, there are well-established distribution networks including receiving terminals, storage facilities and delivery trucks. The major concerns with using diesel for this application are a) price volatility, b) exhaust emissions and noise disturbance, and c) the ability to have enough on-site storage or fuel supply to support an extended electric grid outage.

Diesel as a fuel source for small and medium sized distributed generation is currently feasible and would appear to be for the foreseeable future. Diesel generators are considered very reliable even for the smaller sizes. The capital cost of diesel generators is $ 850/kW for diesel. (NREL, 2018) (Generac) Current diesel fuel prices fluctuate from 2.00 to 2.46 $/gal, or $ 0.199/kWh. The operational fuel cost is about 0.199/kWh.

2.3.6.4. Assumed Distributed Generator Parameters

Propane, natural gas and diesel are viable options for the study locations. The parameters defined for DFFG are presented in Table 7.

Table 7. Distributed Generation Assumptions

Parameter/Generator Fuel Type	Propane	Natural Gas	Diesel
Nominal capacity of distributed generator *g*, [kW]	100 kW	100 kW	100 kW
Constraint on Maximum generation of distributed generator *g*, [kW]	System-dependent	System-dependent	System-dependent
Operational cost of distributed generator (fuel) *g*, [$/kWh]	0.16 $/kWh	0.124 $/kWh	0.199 $/kWh
Investment cost of distributed generator g, [$/kW]	2750 $/kW	1000 $/kW	800 $/kW
Fixed costs of distributed generator g, [$/kW-year]	56 $/kW-year	56 $/kW-year	56 $/kW-year

2.3.6.5. Emissions Parameters

A strategic objective for Puerto Rico is to reduce its CO_2 emissions. Most of Puerto Rico's current generation fleet is fossil-fuel based and relatively old, with significant CO_2 emissions. The deployment of DERs, in particular a high penetration of renewable energy such as solar PV, has the potential to significantly reduce CO_2 emissions. In order to assess the value of DERs in reducing emissions, it is necessary to estimate the cost of emissions by various fuel types. In addition, distributed generation fueled by natural gas, diesel or propane also produces CO_2. Incorporating the cost of CO_2 allows the optimization model to also weigh sustainability versus economic objectives. Emissions is a key element considered in this study for the analysis of optimal DER portfolios.

In order to estimate the costs of CO^2, we analyzed several reports that estimate values for CO_2 resulting from the electric power generation sector. For this study, the horizon of the portfolio assessment is 20 years. We investigated costs for 2020 and 2030. The European Union has developed prices that are recommended to be used by the member countries at $28/metric ton and $38/metric ton for 2020 and 2030, respectively. (European Commission, 2017) The Intergovernmental Panel on Climate Change Panel (IPCC) recently released a special report (Intergovernmental Panel on Climate Change, 2018) that suggests broader adoptions for the costs of CO_2 and encourages aggressive actions towards carbon reduction. Low and high scenarios for the cost of CO_2 are discussed in the ICCP report. An article from the New York Times (Stam, 2018) discusses the risk faced by oil companies and the values for the cost of CO^2 that they use for long-term infrastructure investments. Reports (ERCOT, 2018), (Silva, 2018), (NYISO) provide the cost of CO_2 for various ISOs in the U.S. and a report (Social Cost of Carbon Pricing of Power Sector CO2) from EPRI also provides estimated values. The values for the cost of CO_2 provided by these various reports for 2020 and 2030 are summarized in Table 8.

Table 8. Analysis of Key Reports on Cost of CO_2 Emissions

Reference Study	$/metric ton	$/metric ton
	Year 2020	Year 2030
General Price Utilized in Europe	28	38
IPCC 2018 Recommendation Low	40	50
IPCC 2018 Recommendation High	80	100
Shell and BP feasibility projects	40	40
ERCOT	5	21.2
ISONE	20	35
NYISO	40.4	56
EPRI	15	25
Average without ICCP High	26.91	37.89

The average cost of CO_2 for 2020 and 2030 is calculated and presented in the last row of Table 8. This average was computed without considering the row corresponding to the IPCC 2018 high recommendation, because this scenario is ambitious and not very likely in practice due to policy and political considerations. (IPCC) The resulting averages are $26.91/metric ton and $37.89/metric ton for 2020 and 2030, respectively. Therefore, a $30/metric ton was considered for the simulations in this study.

The amount of CO_2 emissions depends on the fuel type used by the generating source. According to the Energy Information Administration (EIA), the CO_2 emissions in pounds of CO_2 per million BTU is given in Table 9.

Table 9. CO_2 Produced with Different Types of Fuel

Fuel Type	CO^2 Emissions	Average Heat Rate
	CO_2 pounds per MBTU	MBTU/MWh
Coal	210.6	10.46
Diesel	161.3	7.81
Propane	139	13.42
Natural gas	117	11.55

2.3.7. *Distribution Circuit Network Model*

This section describes how the model of the distribution circuit network model (the wires) was developed. Distribution circuits (feeders) represent the power system from the distribution substation down to the customer point of common coupling or service meter. We followed the commonly used modeling approach for distribution circuits which includes modeling the primary circuits (medium voltage) from the distribution circuit slack bus at the substation up to the service transformers modeled as complex loads. (Kersting, 2007), (Gonen, 2008) This model is the most widely used in the industry since most utilities do not model secondary circuits (from the low voltage secondary of the service transformer to the customer meter).

The distribution circuit models developed for this project are based on PREPA's GIS database records, which include the following main types of records:

1. Primary Circuit Records: which provide the necessary information for nodes, list of phases, conductor types and underground versus overhead lines. These records also contain the coordinates of the circuit nodes, which were transformed to latitude and longitude values.
2. Service Transformer Records: which include references to the distribution circuit number, coordinates, transformer capacity and type.
3. Poles Records: including coordinates and pole types.
4. Substation Records: which include transformer rating and type and coordinates.

These records were cleaned and processed to obtain distribution circuit network models that are radial, three-phase, unbalanced, suitable for AC 3-phase power flow analysis. The following steps and considerations were utilized to generate the circuit models:

2.3.7.1. Node Number Cleaning

A few node number inconsistencies were found with repeated node names having different coordinates and vice-versa: various points had different (although almost exact) coordinates with the same name. The data processing was therefore not done by node number, but by coordinates. New node numbers were assigned when needed and propagated to the various model records.

2.3.7.2. Line Parameters

Fifty-six different conductor types were identified in PREPA's database. These conductor types were mapped to known conductor classes to obtain their parameters and formatted according to Gridlab-D line configuration formats. Scripts were used to generate the needed configuration types based on the list of phases for each line. In the case of underground lines, the line parameters were modeled directly using admittance matrix formats as is common in modeling software. (CYME, 2018), (EPRI, 2018)

2.3.7.3. Feeder Topology and Connectivity

All of PREPA feeders are radial. There are some underground loops, but they are always operated open. Thus, the underground and overhead line records combined for a distribution circuit should result in a graph that has a tree structure. A few inconsistencies were identified for the feeders where the graph was not connected (there were missing line records). In most cases these were poles that were close to each other, for example a street corner, but the connectors were not modeled. Scripts were used to identify the case of nodes very close to each other. In a few cases there were missing line records that spanned tenths of feet (a typical distance of a line segment). In those cases, virtual lines with parameters of the surrounding lines were inserted to restore graph connectivity. Graph algorithms were utilized to verify graph connectivity and nodal and line phase consistency. The layouts of the resulting distribution circuits were confirmed using ProsumerGrid's georeferenced maps, which are based on Mapbox.

2.3.7.4. Voltage Regulation

Voltage regulator parameters and settings were not provided. The simulation assumes that the voltage at the distribution circuit slack bus is equal to 1.05 pu and that any voltage regulators are at their nominal position.

2.3.7.5. Power Flow Validation

A three-phase, unbalanced power flow solution is obtained for each distribution feeder. All the per-phase complex voltages and lines flows are analyzed for thermal overloads and voltage violations. Sensitivity of complex load changes to voltage magnitude are recorded. This sensitivity is utilized in the determination of needed reactive power compensation due to DER variability.

2.3.7.6. Substation and Sub-transmission Mapping

PREPA provided a partial mapping of the distribution circuit names to the loads modeled in the PSS®E software case for Transmission & Sub Transmission. These mappings are used to determine the substation and point of connection of the feeder to the sub transmission network.

2.3.7.7. Visualization

Based on the coordinates of the various objects modeled on the feeder, a geo-json representation was developed for visualization of feeder quantities. This visual model is used to support the visualization of DER models as well as the optimal grid redesign.

2.3.8. Sensitivities

The previous subsections have described the assumptions for the distribution circuit DER optimization used to determine the optimal type, location, and size of DERs on the distribution circuits. For each assumption, corresponding justification and rationale have been presented supporting the values as a "best assumption estimate" to be used for the baseline. The baseline is defined as the most likely assumptions for the optimal DER solution based on our analysis. To emphasize, the use of the optimization approach allows the evaluation of a very large number of possibilities when selecting a) the optimal locations from a set of potentially large number of locations on the circuit, b) the types, from a set of solar PV, energy storage and DFFG and c) the size, from all the viable ranges of values for size of each DER.

Since there is uncertainty to the input assumptions selected for the model, it is appropriate to run sensitivity analysis for several key input assumptions. This enables answering questions such as: what would happen to the DER portfolio selected if demand in Puerto Rico is lower than expected? In order to provide a robust set of results to enable decisions, we considered the sensitivities in the simulations shown in Table 10 for this study.

Table 10. Five Sensitivity Scenarios Considered in the Simulation

Sensitivity	**Restore Time (h)**	**Diesel CO2 Cost ($/kWh)**	**Natural Gas CO2 Cost ($/kWh)**	**Propane CO2 Cost ($/kWh)**	**Load Priority Threshold**	**Discount Rate (%)**	**Load Growth (%/year)**	**Average Utility Price ($/kWh)**	**DER Cost Reduction (%)**
Baseline	13440	0	0	0	1	8.35	0	0.21	0
CO2 Cost	13440	0.0218	0.0112	0.0228	1	8.35	0	0.21	0
High Priority Loads	13440	0	0	0	0.75	8.35	0	0.21	0
Low DER Cost and Discount Rate	13440	0	0	0	1	0	0	0.21	-6
Decreasing Demand	13440	0	0	0	1	8.35	-2	0.21	0
Low Utility Price	13440	0	0	0	1	8.35	0	0.12	0

3. ANALYSIS RESULTS

3.1. Overview of Microgrid Results

This chapter describes in detail a single microgrid to illustrate the optimal DER portfolio analysis results. For each of the ten microgrids the following results were obtained:

1. Microgrid and Parent Feeder Data:
    a. Microgrid ID, Swing Node,
    b. Nominal Voltage (kV),
    c. Number of Nodes,
    d. Number of OH Lines,
    e. Number of UG Lines,
    f. Number of Loads,
    g. Electrical Length (mi),
    h. Total MW,
    i. Microgrid Plot
2. Critical Infrastructure Data:
    a. Name, Type (shelter, clinic, hospital, telecom tower),
    b. Real Power per Phase,
    c. Priority Level,
    d. Critical Infrastructure Time Series Profiles Plots

There are a total of five sensitivities analyzed:

1. Low Utility Electricity Price
2. Low DER Cost and Discount Rate
3. High Priority Loads
4. CO2 Costs
5. Decreasing Demand

For each sensitivity, the following results were obtained:

1. Optimal Selected Capacity by DER Option
2. DER portfolio total capital costs, input costs
3. Grid-connected and grid outage lifetime operating costs
4. Total Capital Operating and Capital Costs
5. Power Schedules

The locations of the feeders with the ten microgrids studied are shown Figure 4:

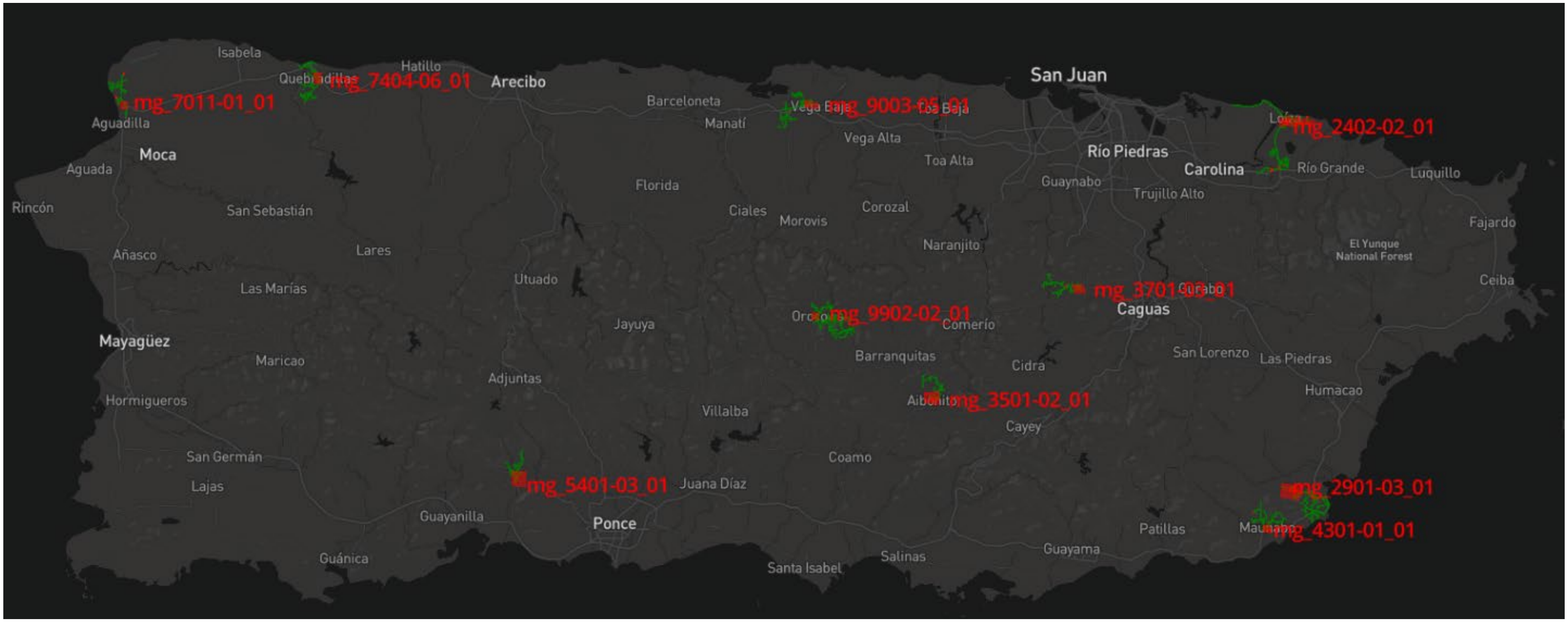


Figure 4. Locations of feeders with ten microgrids studied

The summary of the baseline optimal selected capacity by DER option for each microgrid is shown Table 11, while the summary of the baseline DER portfolio total capital and operational cost NPV for each microgrid is shown in Table 12.

Table 11. Summary of the Baseline Optimal Selected Capacity by DER Option for each Microgrid

Optimal Selected Capacity by DER Option and Microgrid (Baseline)											
Microgrid Municipality		**Loiza**	**Yabucoa**	**Maunabo**	**Aguas Buenas**	**Aibonito**	**Orocovis**	**Vega Baja**	**Peñuelas**	**Quebradillas**	**Aguadilla**
Microgrid Identifier		**9902-02**	**9003-05**	**7404-06**	**7011-01**	**5401-03**	**4301-01**	**3701-03**	**3501-02**	**2901-03**	**2402-02**
DER #	**DER Option**	**(kW)**	**(kW)**	**(kW)**	**(kW)**	**(kW)**	**(kW)**	**(kW)**	**(kW)**	**(kW)**	**(kW)**
1	commercial_pv	1,050	717	1,200	817	1,900	1,050	1,400	2,200	2,200	3,600
2	residential_pv	0	0	0	0	0	0	0	0	0	0
3	lead_acid	0	0	0	0	0	0	0	0	0	0
4	li_ion	67	33	200	83	217	133	67	183	233	167
5	diesel	0	0	0	0	0	0	0	0	0	0
6	natural_gas	900	600	1,000	500	1,400	900	1,300	1,400	1,600	3,200
7	propane	0	0	0	0	0	0	0	0	0	0

Table 12. Summary of Baseline DER Portfolio Total Capital and Operational Cost NPV for each Microgrid

DER Portfolio Total Capital and Operational Cost NPV by Microgrid (Baseline)										
Microgrid Municipality	**Loiza**	**Yabucoa**	**Maunabo**	**Aguas Buenas**	**Aibonito**	**Orocovis**	**Vega Baja**	**Peñuelas**	**Quebradillas**	**Aguadilla**
Microgrid Identifier	**9902-02**	**9003-05**	**7404-06**	**7011-01**	**5401-03**	**4301-01**	**3701-03**	**3501-02**	**2901-03**	**2402-02**
Total NPV ($K)	17,056	11,570	20,212	11,164	27,959	17,535	23,830	30,720	33,100	58,304

3.2. Discussion of Sample Microgrid Results

In this section a description of the microgrid results for Orocovis municipality microgrid 9902-02_01 will be provided which exemplifies the method of analysis and the results obtained for the rest of the microgrids. The results for the other nine microgrids studied are presented in Appendix B.

The Orocovis municipality microgrid was selected as it highlights many of the significant results obtained from this study which include: 1) the viability of high renewable penetration microgrids, 2) the cost savings that fossil fuel generation can provide and 3) the identification of key technical and economic scenario sensitivities that result in different outcomes.

3.2.1. Orocovis Microgrid 9902-02 Case Data

Microgrid 9902-02 (Figure 5) is in the center of Puerto Rico in the Orocovis Municipality. This location was not restored eight months after the hurricane event. The microgrid footprint was estimated using the satellite nighttime imagery data that defined the outage region. The geographic boundary was then modified by looking at logical points for installing switches to electrically island that area of the feeder.

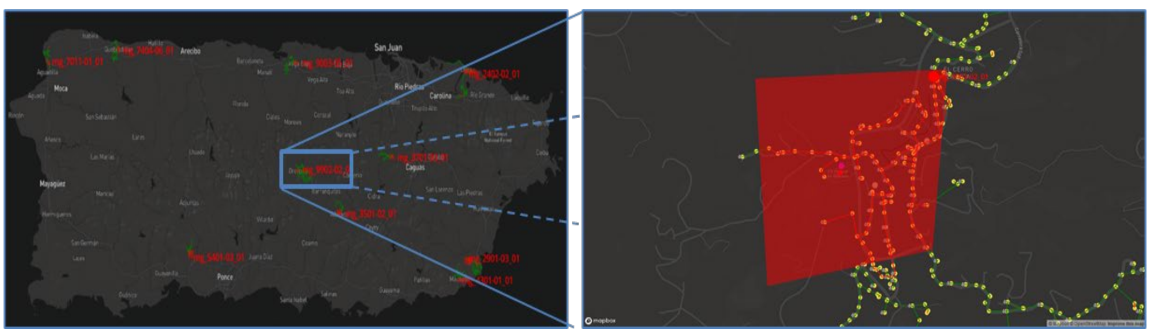


Figure 5. Orocovis Microgrid 9902-02 Site Location

The microgrid has a nominal voltage of 8.32 KV and contains 120 nodes, 109 overhead (OH) lines, ten underground (UG) lines, and 56 loads. The circuits span an electrical length of about 2.8 miles. The total active power of the load is estimated at about 0.895 MW which is about a third the parent feeder load of 2.8 MW with 32 miles of electrical length and over 900 nodes. This portion of the feeder where the microgrid is located is a dense load pocket compared to the other sections of the very long parent feeder. Table 13 and

Table 14 summarize the data for both the microgrid footprint and the parent feeder. The total peak MW load within the microgrid footprint selected is 0.895 MW, which is approximately 32% of the feeder peak load. Determining the microgrid footprint is a balancing process of minimizing MW demand and therefore generator costs while at the same time picking up the loads that are critical to the community's resilience.

Table 13. Orocovis Microgrid 9902-02 Data

Microgrid ID	mg_9902-02_01
Swing Node	15580839
Nominal Voltage (kV)	8.32
Number of Nodes	120
Number of OH Lines	109
Number of UG Lines	10
Number of Loads	56
Electrical Length (mi)	2.807
Total MW	0.895

Table 14. Orocovis Microgrid 9902-02 Parent Feeder Data

Feeder ID	9902-02
Swing Node	1000243601
Nominal Voltage (kV)	8.32
Number of Nodes	922
Number of OH Lines	901
Number of UG Lines	20
Number of Loads	345
Electrical Length (mi)	31.956
Total MW	2.757

3.2.2. *Orocovis Microgrid 9902-02 Critical Infrastructure Data*

Microgrid 9902-02_01 contains five critical loads that include a hospital, a clinic and three schools categorized as shelters. The hospital has an estimated per phase peak power of 21.353 KW and the clinic of 9.151 KW. The three shelters have an estimated per phase peak power of 27.423 KW. Table 15 summarizes the critical infrastructure data.

Table 15. Orocovis Microgrid 9902-02 Critical Infrastructure Data

Name	Type	Power A (kW)	Power B (kW)	Power C (kW)	Priority Level
CENTRO DE SALUD INTEGRAL DE OROCOVIS	hospital	21.353	21.353	21.353	100
SALUD INTEGRAL EN LA MONTANA INC.	clinic	9.151	9.151	9.151	100
ESC ALBERTO MELENDEZ TORRES	shelter	27.423	27.423	27.423	75
ESC S. U. MATRULLAS	shelter	27.423	27.423	27.423	75
ESC. S. U. ANA DALILA BURGOS ORTIZ	shelter	27.423	27.423	27.423	75

The study used sample profiles from other hospitals in the island for the clinics and hospital and considered a small hotel profile for the shelters as shown in Figure 6 to create a 24-hour load profile.

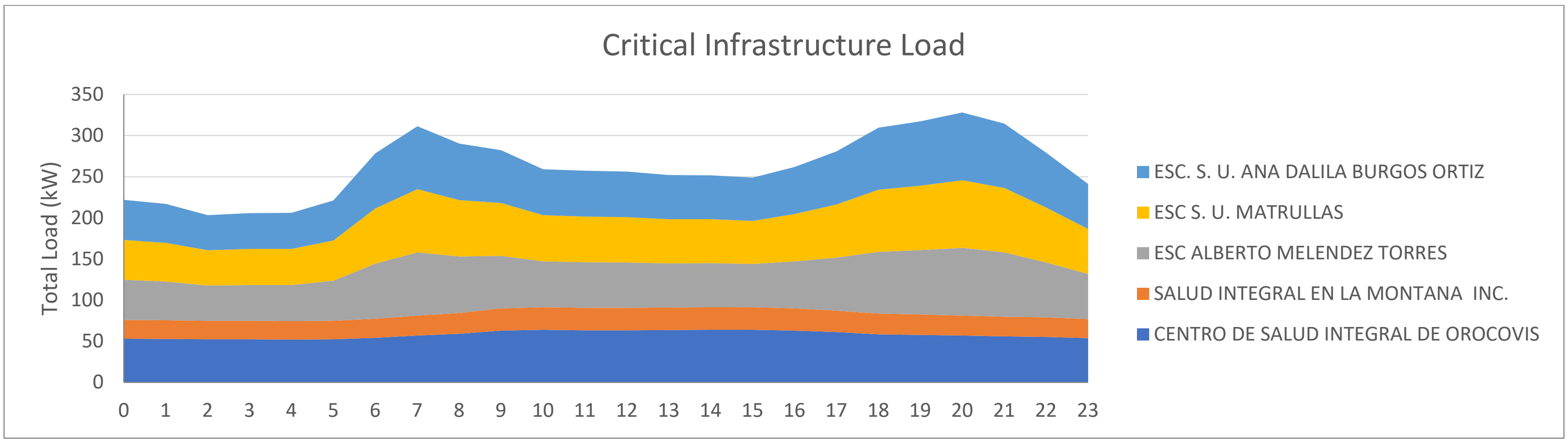


Figure 6. Orocovis Microgrid 9902-02 Critical infrastructure Load Profiles

3.2.3. *Orocovis Microgrid 9902-02 Baseline Results*

This baseline scenario considers the following baseline parameter: outage time of 28 days per year for each of the 20 years in the analysis time for a total restore time of 13,440 hours. Other baseline parameters include: no CO2 costs, no load priority threshold (i.e., all loads are served by the microgrid), a discount rate of 0.0835, no DER cost reduction, no load growth and a utility price of $0.21/kWh as described in Section 2. Optimal DER results show that a combination of 1,050 KW commercial solar PV, 67 KW of lithium-ion energy storage with a 4 hour energy capacity, and 900KW of conventional generation natural gas are the least cost combination of DERs to supply energy to the microgrid location as summarized in Table 16.

Table 16. Orocovis Microgrid 9902-02 Baseline Optimal DER Capacities

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	PV	1,050
2	residential_pv	PV	0
3	lead_acid	storage	0
4	li_ion	storage	67
5	diesel	generator	0
6	natural_gas	generator	900
7	propane	generator	0

The baseline microgrid capacity result is 100% composed of DER options, so it does not import nor export energy to the grid. It essentially runs as an independent microgrid. The net present value of the total capital and operating cost is $17,055,806. The total capital cost is obtained from the multiplication of the optimal selected capacity for each DER option by the capital cost of each resource. The operational costs result from the combination of the grid connected and grid outage lifetime energy throughputs multiplied by the resource operating cost as shown in Table 17 and Table 18.

Table 17. Orocovis Microgrid 9902-02 Baseline DER Portfolio Total Capital and Operating Costs

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	37,490	17,935	4,205,871	4,186,315
2	0	0	0	0
3	0	0	0	0
4	8,810	4,214	369,767	365,172
5	0	0	0	0
6	12,404,751	5,934,192	18,974,878	12,504,319
7	0	0	0	0
Total:	**12,451,051**	**5,956,341**	**23,550,516**	**17,055,806**

In the baseline, it is assumed that 92.329% of the planning horizon (48 weeks per year) the microgrid will operate in grid connected mode and 7.671% of the planning horizon (4 weeks per year) will be operated in the grid disconnected mode. Table 18 describes the lifetime operating cost under these two scenarios. The distinction between grid connected mode and grid disconnected mode in this 100% DER microgrid design is nonexistent for this case as the microgrid is fully independent from the gid, but becomes important in other scenarios, so for constancy we will show the breakout for all cases.

Table 18. Orocovis Microgrid 9902-02 Baseline DER Portfolio Grid Connected & Grid Outage Lifetime Operating Costs

	Grid Connected (Pr = 92.329%)			Grid Outage (Pr = 7.671%)		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	34,614	34,614	16,559	2,876	2,876	1,376
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	1,162	8,134	3,891	97	676	323
5	0	0	0	0	0	0
6	92,364	11,453,154	5,478,966	7,674	951,597	455,226
7	0	0	0	0	0	0
Total	**128,141**	**11,495,902**	**5,499,416**	**10,647**	**955,149**	**456,925**

Figure 7 shows the DER power schedule dispatch for a 24 hour period. Energy storage assets are sized to maximize solar PV output while at the same time absorbing solar variability and excess power during peak solar production times. Conventional fossil fueled generation represents a significant portion of both capacity and generation.

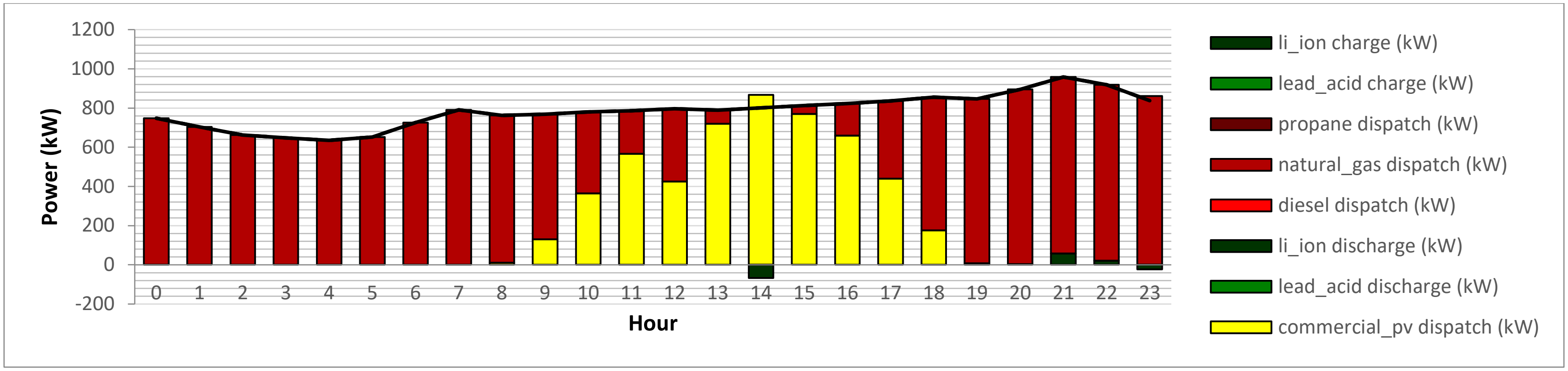


Figure 7. Orocovis Microgrid 9902-02 Baseline Time-Series Power Schedules

In summary, the baseline scenario is primarily a fossil fueled generation microgrid with approximately 72% of the total energy being provided (both Grid Connected and Grid Outage) over the 20-year planning period by natural gas generators with 28% provided by the solar/battery system. The NPV capital cost is ~$11.1 million and NPV operating cost over the 20-year planning period is ~ $5.9 million.

3.2.4. Orocovis Microgrid 9902-02 Low Utility Electricity Price Sensitivity Results

The Low Utility Electricity Price Sensitivity includes the same parameters as the baseline, but it also incorporates a lower average electricity price of 0.12 $/kWh as described in Section 2. This electricity price was found to be the one at which the electric grid is cost competitive compared to all other DER portfolios. Optimal DER results show the same amount of energy storage and solar. Conventional natural gas and diesel generation is selected. The results are summarized in Table 19.

Table 19. Orocovis Microgrid 9902-02 Low Utility Electricity Price Sensitivity: Optimal DER Capacities

DER Asset #	DER Option	DER Type	Optimal Selected Capacity (kW)
1	commercial_pv	pv	1,050
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	67
5	diesel	generator	800
6	natural_gas	generator	100
7	propane	generator	0
8	grid power exchange	--	--

The net present value of the total capital and operating cost is $16,365,364. (Table 20) This is $690,442 (~4%) less expensive than the baseline result $17,055,806. This is mainly because of the lower cost of the electric grid price that offers an alternative to the natural gas generator. In the baseline case, the utility price is not cost effective and therefore the Natural Gas generator supplies most of the energy in both grid connected and grid disconnected modes. In this scenario, utility power is more cost effective than a natural gas generator during grid connected mode and a mix of diesel and natural gas is more cost effective in grid disconnected mode. Since the natural gas generator has higher investment cost and lower operational cost, diesel becomes more cost effective when the number of operating hours for the natural gas generator declines.

Table 20. Orocovis Microgrid 9902-02 Low Utility Electricity Price Sensitivity: DER Portfolio Total Capital and Operating Costs

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	37,490	17,935	4,205,871	4,186,315
2	0	0	0	0
3	0	0	0	0
4	7,200	3,444	368,157	364,402
5	1,271,423	608,224	6,369,919	5,706,720
6	159,712	76,403	889,726	806,417
7	0	0	0	0
8	11,082,201	5,301,509	11,082,201	5,301,509
	12,558,026	**6,007,516**	**22,915,874**	**16,365,364**

In the Low Utility Electricity Price Sensitivity (Table 21), the lifetime energy throughput in the grid connected scenario is slightly lower than the baseline and it is slightly higher in the grid disconnected scenario. In the grid connected scenario, the electric grid replaces the natural gas generators operations. The following table summarizes the lifetime operating costs. The total lifetime energy throughput for grid connected mode is about 92,352 MWhs which results in a lifetime NPV operating cost of $5,320,957.

Table 21. Orocovis Microgrid 9902-02 Low Utility Electricity Price Sensitivity: DER Grid Connected & Grid Outage Lifetime Operating Costs

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	34,614	34,614	16,559	2,876	2,876	1,376
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	863	6,039	2,889	166	1,161	555
5	0	0	0	6,389	1,271,423	608,224
6	0	0	0	1,288	159,712	76,403
7	0	0	0	0	0	0
8	92,352	11,082,201	5,301,509	0	0	0
	127,829	**11,122,854**	**5,320,957**	**10,719**	**1,435,172**	**686,558**

Figure 8 and Figure 9 show the Low Utility Electricity Price Sensitivity: Time-Series Power Schedules for grid connected and the grid outage scenarios. This sensitivity is the only case where there is a different and more cost effective power dispatch in the grid connected scenario vs the grid outage scneario. In both scenarios, the solar power output is maximized, and storage is charged to cope with solar variability above the load. The electric grid and the distributed generators are used to provide most of the energy supply during the morning and the late afternoon and night.

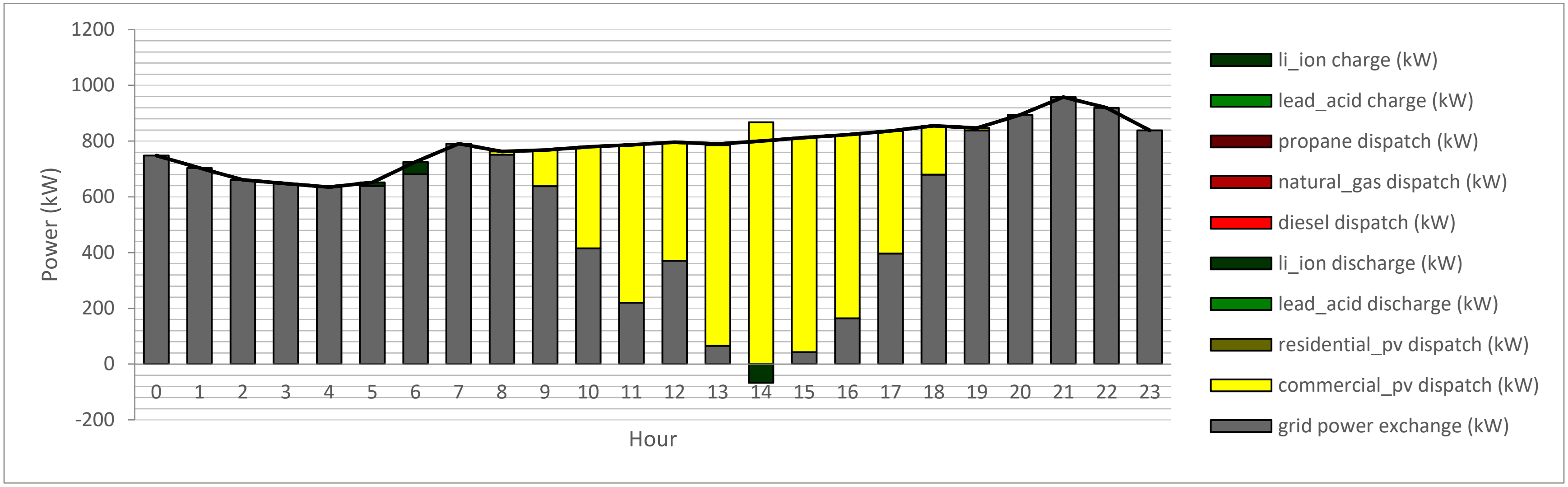


Figure 8. Orocovis Microgrid 9902-02 Low Utility Electricity Price Sensitivity: Time-Series Power Schedules Grid Connected Scenario

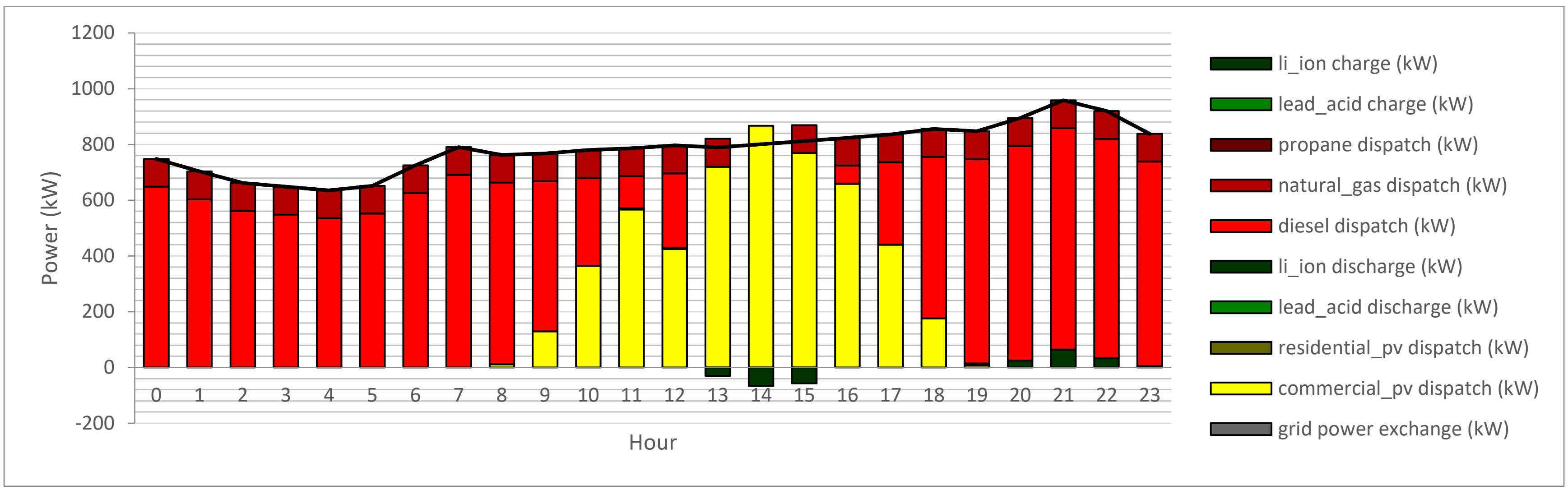


Figure 9. Orocovis Microgrid 9902-02 Low Utility Electricity Price Sensitivity: Time-Series Power Schedules Grid Outage Scenario

In summary, the Low Utility Electricity Price scenario results in a dramatic change in the type of DER generation with the utility grid supplying the dominate share of energy in the grid connected case and diesel generation substituting for most of the natural gas generation and providing the dominate amount of energy in the gid disconnected case. This new combination of diesel and natural gas results in a lower total investment and operational cost for the grid disconnected case.

3.2.5. Orocovis Microgrid 9902-02 Low Solar and Storage Costs and No Discount Rate Sensitivity Results

This sensitivity includes the same baseline parameters, and it assumes that there is a lower cost associated with DER resources such as solar and energy storage (-6% lower cost) and no discount rate is assumed. A zero-discount rate means that all future costs for fuel and battery replacement will be equivalent to year one cost. This scenario attempts to cover the case where the electric utility has immediate access to capital from grid recovery funds or similar sources that prioritize low emissions DERs and the interest rate environment is very low. Optimal DER results show that the amount of solar is about two times the capacity selected in the baseline. The amount of energy storage is more than 15 times larger compared to the baseline. Finally, the natural gas generator is about half the size compared to the baseline. The results are summarized in Table 22.

Table 22. Orocovis Microgrid 9902-02 Low Discount Rate Sensitivity: Optimal DER Capacities

DER Asset #	DER Option	DER Type	Optimal Selected Capacity (kW)
1	commercial_pv	PV	2,367
2	residential_pv	PV	0
3	lead_acid	storage	0
4	li_ion	storage	983
5	diesel	generator	0
6	natural_gas	generator	500
7	propane	generator	0

The net present value of the total capital and operating cost is $17,005,252. This is $50,554 (~0.02%) less expensive than the baseline result $17,055,806. This is mainly because of the lower cost associated with solar and energy storage and their low operating costs. The total capital and operating costs are summarized in Table 23.

Table 23. Orocovis Microgrid 9902-02 Low Discount Rate Sensitivity: DER Portfolio Total Capital and Operating Costs

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	83,254	83,254	4,887,588	4,887,588
2	0	0	0	0
3	0	0	0	0
4	416,773	416,773	3,026,540	3,026,540
5	0	0	0	0
6	7,031,124	7,031,124	9,091,124	9,091,124
7	0	0	0	0
	7,531,152	**7,531,152**	**17,005,252**	**17,005,252**

In the Low Solar and Storage Costs and No Discount Rate Sensitivity , the lifetime energy throughput of solar is two times higher compared to the baseline. The amount of energy storage energy throughput is 50 times higher than the baseline. The natural gas energy throughput is half compared to the baseline. Table 24 summarizes the lifetime operating costs.

Table 24. Orocovis Microgrid 9902-02 Low Discount Rate Sensitivity: DER Portfolio Grid Connected & Grid Outage Lifetime Operating Costs

	Grid Connected (Pr = 92.329%)			Grid Outage (Pr = 7.671%)		
DER Asset #	Lifetime Energy Throughput (MWh)	Lifetime Operating Cost ($)	Lifetime Operating Cost (NPV$)	Lifetime Energy Throughput (MWh)	Lifetime Operating Cost ($)	Lifetime Operating Cost (NPV$)
1	76,868	76,868	76,868	6,387	6,387	6,387
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	54,972	384,802	384,802	4,567	31,972	31,972
5	0	0	0	0	0	0
6	52,353	6,491,750	6,491,750	4,350	539,374	539,374
7	0	0	0	0	0	0
	184,192	**6,953,420**	**6,953,420**	**15,304**	**577,732**	**577,732**

Figure 10 shows the DER portfolio power schedules. The solar dispatches are significantly higher compared to the baseline due to the lower capital costs and the zero-discount rate assumption.

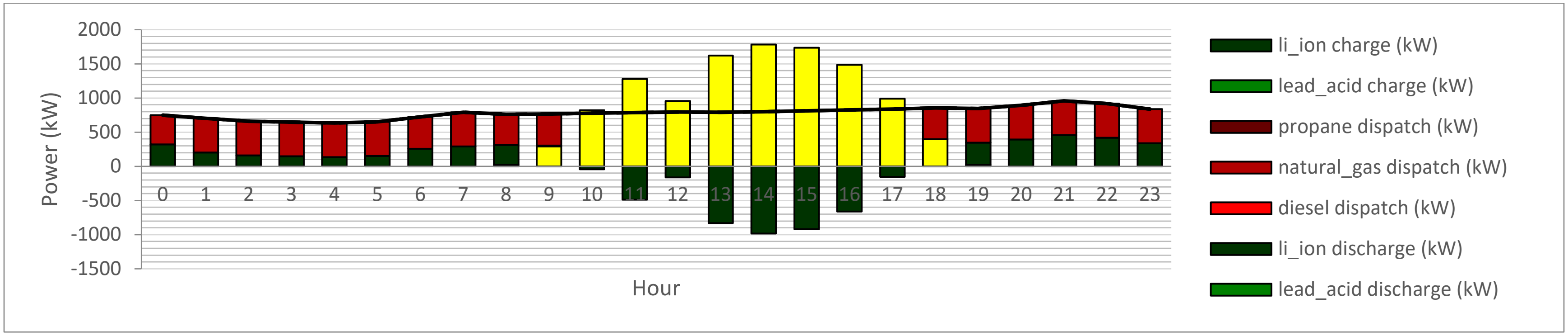


Figure 10. Orocovis Microgrid 9902-02 Low Discount Rate Sensitivity: Time-Series Power Schedules

In summary, the Low DER Cost and No Discount Rate Scenario results in a higher capacity of solar and energy storage being selected with respect to the baseline and a lower total operational and investment cost. A 6% cost reduction for solar and storage results in 2.25 higher capacity for solar and 14.67 more capacity of energy storage and 0.02% less total cost.

3.2.6. Orocovis Microgrid 9902-02 High Priority Loads Sensitivity Results

The High Priority loads sensitivity scenario includes the same baseline parameters but assumes that only critical loads with a priority higher than 0.75 will be served such as hospitals, clinics, shelters and telecom towers as described in Section 2. Optimal DER results show the same amount of energy storage is selected equal to the baseline. However, the amount of solar and conventional natural gas generation is about 33% of the capacity needed in the baseline. The reason is that less capacity is needed to satisfy the peak capacity and energy constraints associated only with the critical loads. The results are summarized in Table 25.

Table 25. Microgrid 9902-02_01 High Priority Loads Sensitivity: Optimal DER Capacities

DER Asset #	DER Option	DER Type	Optimal Selected Capacity (kW)
1	commercial_pv	PV	400
2	residential_pv	PV	0
3	lead_acid	storage	0
4	li_ion	storage	67
5	diesel	generator	0
6	natural_gas	generator	300
7	propane	generator	0

The net present value of the total capital and operating cost is $6,315,427. This is about 37% of the cost in baseline result $17,055,806 because the peak demand of only the critical loads is about 37% of the baseline peak load. The total capital and operating costs are shown in Table 26.

Table 26. Orocovis Microgrid 9902-02 High Priority Loads Sensitivity: DER Portfolio Total Capital and Operating Costs

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	14,302	6,842	1,602,257	1,594,796
2	0	0	0	0
3	0	0	0	0
4	23,829	11,399	384,786	372,357
5	0	0	0	0
6	4,511,536	2,158,231	6,701,579	4,348,274
7	0	0	0	0
	4,549,668	**2,176,473**	**8,688,622**	**6,315,427**

In the High Priority Loads Sensitivity, the lifetime energy throughput of all resources is about 39% of the lifetime energy throughput of the baseline due to the demand change and the different load shapes. The lifetime energy throughput and operating cost in both grid-connected and grid-disconnected scenarios are shown in Table 27.

Table 27. Orocovis Microgrid 9902-02 High Priority Loads Sensitivity: DER Portfolio Grid Connected & Grid Outage Lifetime Operating Costs

	Grid Connected (Pr = 92.329%)			Grid Outage (Pr = 7.671%)		
DER Asset #	Lifetime Energy Throughput (MWh)	Lifetime Operating Cost ($)	Lifetime Operating Cost (NPV$)	Lifetime Energy Throughput (MWh)	Lifetime Operating Cost ($)	Lifetime Operating Cost (NPV$)
1	13,205	13,205	6,317	1,097	1,097	525
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	3,143	22,001	10,525	261	1,828	874
5	0	0	0	0	0	0
6	33,592	4,165,446	1,992,668	2,791	346,090	165,563
7	0	0	0	0	0	0
	49,940	**4,200,652**	**2,009,510**	**4,149**	**349,016**	**166,962**

Figure 11 shows the DER portfolio power schedules. In the morning, the natural gas generator supplies most of the load. In the middle of the day, the solar power output is maximized, and storage is charged to cope with solar variability above the load. In the late afternoon, the energy storage is discharged, and the rest of the energy is satisfied by the natural gas generator.

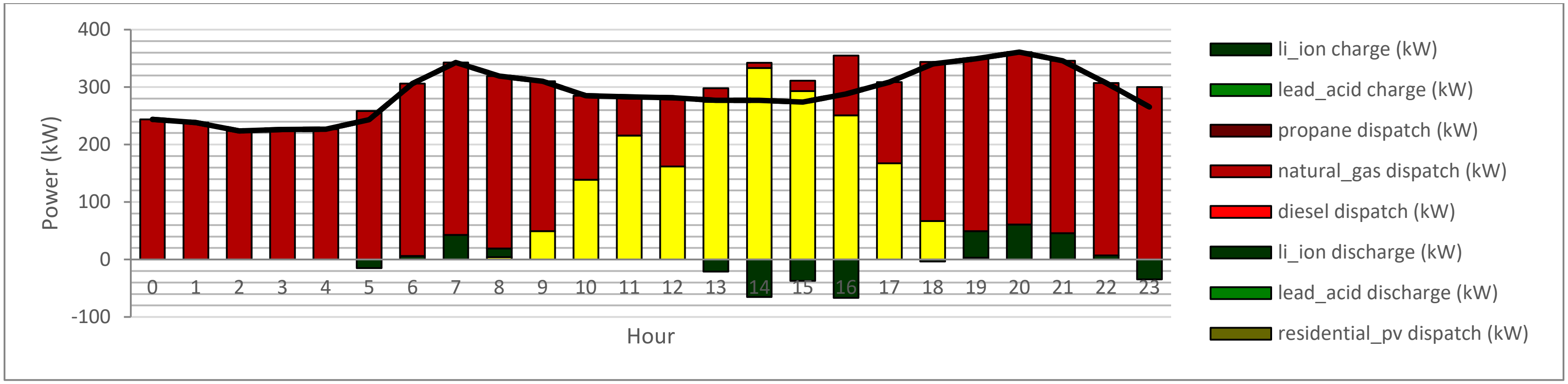


Figure 11. Orocovis Microgrid 9902-02 High Priority Loads Sensitivity: Time-Series Power Schedules

In summary, the high priority load scenario results in a dramatic change in the amount of solar and conventional natural gas generation required as the amount of energy the microgrid needs to provide is approximately 61% less than the baseline. This very different load profile and energy requirement results in the net present value of the total capital and operating cost of $6,315,427 which is about 37% of the baseline cost of $17,055,806 matching the change in peak demand of the critical loads at 37% of the baseline peak load.

3.2.7. Orocovis Microgrid 9902-02 CO^2 Cost Sensitivity Results

The CO^2 cost sensitivity includes the same baseline parameters, and it incorporates the following variable CO^2 cost for conventional generators: Diesel CO^2 Cost 0.0218 ($/kWh), Natural Gas CO^2 Cost 0.0112 ($/kWh), Propane CO^2 Cost 0.0228 ($/kWh) as described in Section 2. Optimal DER results show the same amount of energy storage and conventional natural gas generation. However, an additional 83 (kW) of solar are selected compared to the baseline because it is more cost effective to dispatch solar compared to distributed generators with higher CO^2 costs. The results are summarized in Table 28.

Table 28. Orocovis Microgrid 9902-02 CO2 Cost Sensitivity: Optimal DER Capacities

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	PV	1,133
2	residential_pv	PV	0
3	lead_acid	storage	0
4	li_ion	storage	67
5	diesel	generator	0
6	natural_gas	generator	900
7	propane	generator	0

The net present value of the total capital and operating cost is $17,763,862. This is $708,056 (~4%) more expensive than the baseline result $17,055,806. This is mainly because of the additional solar installed and the CO_2 Cost. The total capital and operating costs are summarized in Table 29.

Table 29. Orocovis Microgrid 9902-02 CO2 Cost Sensitivity: DER Portfolio Total Capital and Operating Costs

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	39,963	19,118	4,539,168	4,518,322
2	0	0	0	0
3	0	0	0	0
4	8,810	4,214	369,767	365,172
5	0	0	0	0
6	13,190,839	6,310,241	19,760,966	12,880,368
7	0	0	0	0
	13,239,612	**6,333,573**	**24,669,901**	**17,763,862**

In the CO_2 Cost Sensitivity (Table 30), the lifetime energy throughput of energy storage is similar to the baseline. However, the solar is dispatched 36,898 (MWh) in grid connected scenario and 3,066 (MWh) in grid outage scenario which is 6% higher compared to the baseline scenario. The natural gas generator was dispatched 3% less compared to the baseline scenario due to the higher CO2 costs.

Table 30. Orocovis Microgrid 9902-02 CO2 Cost Sensitivity: DER Portfolio Grid Connected & Grid Outage Lifetime Operating Costs

	Grid Connected (Pr = 92.329%)			Grid Outage (Pr = 7.671%)		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	36,898	36,898	17,651	3,066	3,066	1,467
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	1,162	8,134	3,891	97	676	323
5	0	0	0	0	0	0
6	90,081	12,178,939	5,826,168	7,484	1,011,900	484,073
7	0	0	0	0	0	0
	128,141	**12,223,971**	**5,847,710**	**10,647**	**1,015,641**	**485,863**

Figure 12 shows the DER power schedules. The solar dispatches are slightly higher compared to the baseline due to lower operational costs compared to natural gas generation.

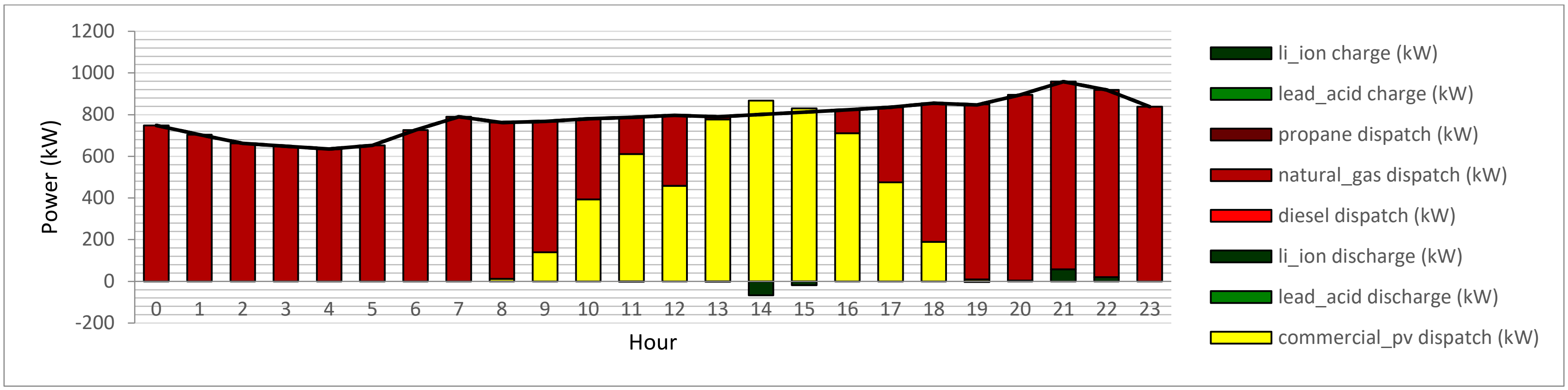


Figure 12. Orocovis Microgrid 9902-02 CO2 Cost Sensitivity: Time-Series Power Schedules

In summary, the CO_2 cost scenario resulted in a more renewable microgrid with 6% more solar MWh produced, but also a resulting cost increase of 4% compared to the baseline results. Note that for the natural gas generator, MWh decreased due to the additional solar, but the lifetime operating costs for the natural gas generator still increased due to the CO_2 costs.

3.2.8. *Orocovis Microgrid 9902-02 Decreasing Demand Sensitivity Results*

The decreasing demand sensitivity includes the same baseline parameters, and it assumes that the demand in the future years will decrease -2% per year as described in Section 2. Optimal DER results show the same amount of energy storage, solar and conventional natural gas generation. The reason is that the same capacity is needed to satisfy the peak capacity and energy constraints during the first year. The results are summarized in Table 31.

Table 31. Orocovis Microgrid 9902-02 Decreasing Demand Sensitivity: Optimal DER Capacities

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	1,050
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	67
5	diesel	generator	0
6	natural_gas	generator	900
7	propane	generator	0

The net present value of the total capital and operating cost is $16,228,889. This is $826,917 or (5%) less expensive than the baseline result $17,055,806 because the demand decreases yearly reducing total operating costs. The total capital and operating costs are summarized in Table 32.

Table 32. Orocovis Microgrid 9902-02 Decreasing Demand Sensitivity: DER Portfolio Total Capital and Operating Costs

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	30,367	15,445	4,198,748	4,183,825
2	0	0	0	0
3	0	0	0	0
4	7,136	3,629	368,093	364,587
5	0	0	0	0
6	10,047,848	5,110,350	16,617,975	11,680,477
7	0	0	0	0
	10,085,351	**5,129,424**	**21,184,817**	**16,228,889**

In the Decreasing Demand Sensitivity (Table 33), the lifetime energy throughput of energy storage, solar and natural gas distributed generator are about 19% less than the baseline. This is consistent with a -2% decreasing demand assumption over 20 years.

Table 33. Orocovis Microgrid 9902-02 Decreasing Demand Sensitivity: DER Portfolio Grid Connected & Grid Outage Lifetime Operating Costs

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	28,038	28,038	14,260	2,330	2,330	1,185
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	941	6,589	3,351	78	547	278
5	0	0	0	0	0	0
6	74,815	9,277,054	4,718,323	6,216	770,794	392,027
7	0	0	0	0	0	0
	103,794	**9,311,681**	**4,735,934**	**8,624**	**773,671**	**393,490**

Figure 13 shows the DER portfolio power schedules. The dispatch of solar, energy storage and distributed generation shows a similar pattern like the baseline. This is consistent with the least cost operation of the DER portfolio.

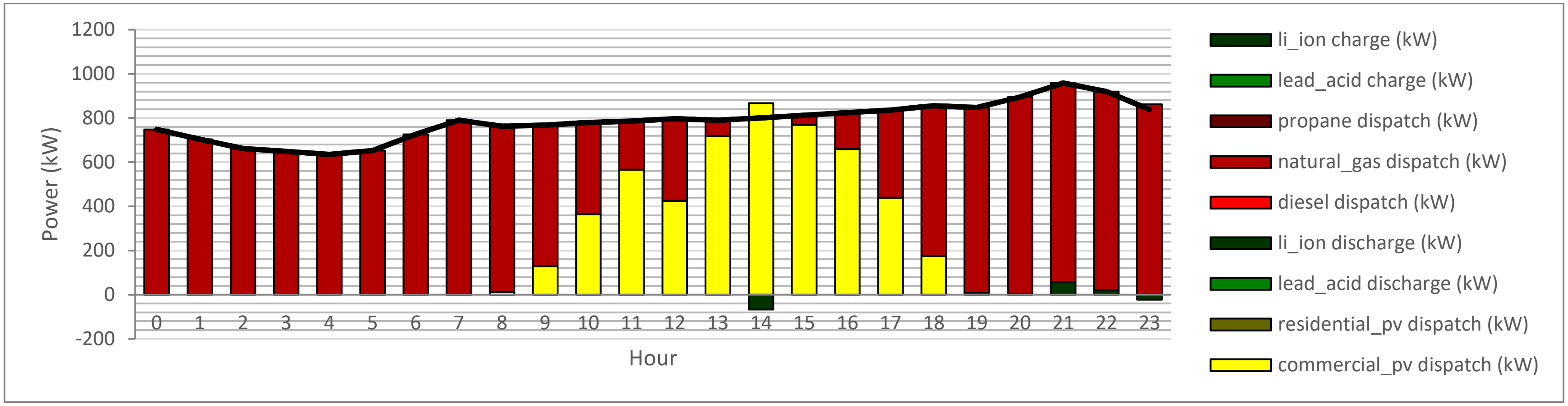


Figure 13. Orocovis Microgrid 9902-02 Decreasing Demand Sensitivity: Time-Series Power Schedules

In summary, the decreasing demand scenario results in the same amount of energy storage, solar and conventional natural gas generation as the baseline because the same capacity is needed to satisfy the peak capacity and energy constraints during the first year. The net present value of the total capital and operating cost is 5% less expensive than the baseline result because the demand decreases result in 19% less energy needed over the 20-year period which reduces the total operating costs.

4. CONCLUSIONS AND FUTURE WORK

4.1. Conclusions

This report presents the modeling and simulation of resilient and cost-effective networked microgrids on the distribution system focusing on ten Puerto Rico feeder locations with long outages after Hurricane Maria. The distribution feeder models were geographically distributed across Puerto Rico and varied in length to capture the wide variety of feeders on the main island. All feeders serve critical infrastructure such as hospitals, clinics and shelters.

This report selected 10 study locations: The study locations were selected from 42 areas previously identified with nighttime satellite imagery (Lugo-Alvarez, Broderick, & Ortiz-Rivera, 2020). The imagery was utilized to contrast ambient public lighting levels before and after Hurricane Maria to identify electrical outage areas. Given the limited access to outage data from PREPA during the project, these areas were independently identified using this satellite-based method to determine the portions of the electrical feeders that took the longest to restore. The 10 study areas were selected as representative study areas based on considerations such as restoration time, the number of critical infrastructures, distribution feeder data availability, and geographic distribution across PR. While these representative study areas are important areas for microgrid development consideration, additional analysis will be needed for program development and funding allocation to prioritize the most needy and beneficial locations for future resiliency investment.

Feasibility of stand-alone microgrids in Puerto Rico: At the time this study was made, there had been claims and a handful of examples of the feasibility of stand-alone microgrids in Puerto Rico, under both blue sky and black sky scenarios. However, there was not a publicly available report or analysis that showed how and why stand-alone microgrids were feasible in the Puerto Rican context. This report fills that void by providing an analysis framework that could be replicated for other locations. Furthermore, the microgrid stand-alone operation mode was favored in most instances and found to be economically advantageous based on the assumptions of costs and technology described in the report. Connection to the main grid was only found to be optimal when the rate was set to a low value of 12 cents/kWh, which is significantly less than current retail rates in Puerto Rico. This indicates the potential near term need for a different or expanded business model for the local utility as a facilitator of resilience through more distributed energy resources.

The objective of the study: The focus of this analysis was to determine the optimal (least cost, reliable and resilient) portfolio of DERs, solar PV, energy storage, and distributed generation that can meet the critical demand in a specific location while minimizing the total costs (investment and operational).

Both blue and black sky scenarios were considered and compared. The results showed that resilience solutions can additionally provide very significant value and services under normal operating conditions, and such services must be considered when making investments decisions.

This study results show the importance and feasibility of using an optimization-based approach to perform targeted DER planning in PR. This study has unique characteristics that include: 1) simultaneously considering the grid connected and grid disconnected scenarios, 2) analyzing multiple DER options, costs and constraints, 3) performing long-term capacity decisions while simultaneously considering operational hour by hour dispatch.

Crucial data assumptions and sensitivities: The results show that the selected DER and capacities are sensitive to the data assumptions. Given the complexity of the problem a single parameter assumption can influence the DER types, selected portfolio capacities, and total expected investment and operational cost. As shown in this study, an integrated optimization-based approach is needed to guide decision making.

The key sensitivities we evaluated that dramatically changed the results were low utility electricity price, high priority loads and low discount rate & reduced RE costs. These sensitivities caused the optimization to choose very different generation strategies over a wide range of total costs. The CO_2 costs sensitivity and decreasing demand assumptions were less impactful as they resulted in only incremental changes to the generation mix and economics of the baseline scenario.

We note that costs due to electric utility permitting and interconnection are not considered in the models, but rather the problem seeks to find the optimal DER investment assuming existing infrastructure capacity. Also, this work assumes that the existing distribution infrastructure can be used for each of the microgrids. Thus, the cost of new distribution lines was not included as a decision variable in the analysis

Key next steps for identifying the best places to put resiliency investments. The results from these 10 feeders can guide the analysis for other locations by providing a clear methodology to optimally align resilience, economics and sustainability goals. The results from this work also point to the need for discussion about the use of existing infrastructure by microgrids. The Puerto Rico microgrid rule currently does not allow this, but states that "The Commission will monitor market development and will determine at a later time if further action on this matter is required". The feasibility of stand-alone operation shown in this report for many microgrid scenarios, the need for increased resilience and the 100% renewable goal in Puerto Rico indicate that market conditions may soon require this issue to be revisited as shown also by ongoing dockets in front of PREB.

4.2. Future Work

This study explored the optimal DER portfolio planning while considering the microgrid locations, the circuit models, the DER locational and temporal constraints for 10 representative feeders in Puerto Rico. There are several future areas of research, including:

1) **Locations**

   Future work can expand the number of locations analyzed to more feeders that took the longest to restore and developing a rating system for the locations based on 1) number of critical infrastructure, 2) priority of critical locations, 3) duration of outage, and 4) power flow metrics such as line overloads, over/undervoltage. The selection of locations can be based on historical data and local communities needs and requirements.

2) **Microgrid boundary and distribution lines**

   This work took the microgrid boundary as an input, future work can focus on determining the tradeoff of expanding the microgrid boundary to serve more loads vs the cost of switching devices. Furthermore, this work assumed that the existing distribution infrastructure can be used for each of the microgrids. Thus, the cost of new distribution lines was not included. Since the current microgrid rule does not allow this, future work could include cost scenarios where new infrastructure is included, and/or an emphasis on proving the socio-economic and resilience benefits of allowing the use of existing infrastructure.

3) **DER Options: Energy Storage**

This work did not consider degradation effects of energy storage, future work can focus on analyzing the effects of degradation (due to cycling, depth of discharge) of energy storage and corresponding replacement costs on the type, capacity, and location of the DER portfolio.

4) **DER Options: Renewables**

This work included a representative day assumption for solar profiles, future work can focus on analyzing the effect of the 75% rule (minimum requirement of renewable energy) and considering seasonality profiles (different profiles for seasons, months, weeks of the year, days, etc.).

5) **DER Options: Conventional Generation**

This work included distributed generation. Future work can focus on considering stricter emissions constraints and the degradation and replacement costs for specific devices. Furthermore, this study assumed that LNG is readily available on site. Presently such scenario is possible on locations where LNG can be delivered by land. Future work can evaluate how limits on LNG availability affect the design of microgrids, especially in mountainous regions of Puerto Rico. This could include limits on the capacity of current LNG suppliers to deliver the fuel to a large number of users and long periods without LNG supply due to road obstructions after a major disaster.

6) **Grid Electricity Price**

This work used an average assumption for the grid price, future work can focus on considering a more granular average electricity price and electricity tariffs (energy and demand) for a particular location and the customer class. Future work should also evaluate the effect of increased electric rates and likely future increases due to fuel scarcity and raising LNG price environment.

7) **Grid Connected (Blue-sky) vs Grid Disconnected (Resilient Event) Scenarios**

This work used initial assumptions about DERs during resilient events, future work can focus on determining the expected outage times from other models and imposing a maximum number of hours that the DERs can run continuously during an outage event.

8) **Number of Hours of Operational Data within the Year and Time Granularity**

This work used a representative day during the year at hour granularity, future work can focus on using larger number of hours of operational data within the year (8760, one week/month, four weeks during the year, two weeks during the year, two days during the year) and using 15 mins granularity.

9) **Microgrid to Grid Services**

This work used avoided costs to determine specific benefits, future work can focus on considering distribution capacity deferral services and energy, capacity and other local distribution services.

10) Multi-System Co-simulation

This work focused on electricity infrastructure; future work can focus on creating a co-simulation of water and electricity infrastructure, using ProsumerGrid software tool for DER power generation, storage, consumption, and distribution and WNTR for water infrastructure simulation.

11) Stakeholder Engagement

This work focused on ten example study locations but did not gather onsite stakeholder inputs for each of the ten representative systems as that was out of scope for this feasibility focused study. All future work to develop conceptual microgrid designs for these areas or any other areas will need extensive stakeholder engagement to better understand needs and priorities of specific communities.

APPENDIX A. AN INTEGRATED GRID+DER PLANNING STUDIO™ SOFTWARE BY PROSUMER GRID

A.1. Overview

DERs such as solar and wind energy systems, ESS, flexible demand devices and electric vehicles are expected to continue growing massively in the coming years. DER deployments are driven by: regulatory pressure and sustainability objectives for a low carbon economy, technology and economics improvements and the emergence of prosumers who have changed their traditional behavior from energy consumers to an agent that can generate, store, or transport electricity and want a more sustainable, resilient, and reliable energy supply. Motivated by the confluence of these regulatory, economic, technological and social forces, the electric power industry is witnessing a paradigm shift from disintegrated generation-transmission-distribution planning model to a more integrated and customer centric focus with a strong emphasis on DERs. This new model has not only caused the whole electric utility industry to rethink its approach to energy delivery and its business models, but it has also made it quite evident that a more advanced set of planning tools are needed in order to continue to provide reliable, affordable, and environmentally-sustainable energy.

Through the financial support of the U.S. Department of Energy (DOE) Advanced Research Project Agency - Energy (ARPA-E) OPEN 2015 and various research and development (R&D_ subcontracts with national labs (including SNL, EPRI, and NREL) and industry sponsors, ProsumerGrid, Inc. has developed an innovative software tool that allows electric utility engineers, planners, strategists, research institutions, consulting firms, and policy makers to perform advanced simulations and planning studies of electric grids with massive amounts of conventional and DERs such as conventional fuel-based generators, solar PV, energy storage, demand response, small-scale generators, CHP, wind, electric vehicles, and microgrids.

After conducting more than 100 interviews though the National Science Foundation Innovation Corps (NSF I-Corps) program and additional interactions with electric utilities, research institutions, regulators, microgrid designers, energy planners, the ProsumerGrid team discovered that current software tools could not answer critical questions such as: 1) how to simulate the simultaneous impact of multiple DER types operating autonomously or coordinated on particular high-fidelity transmission and distribution (T/D) locations, 2) how to simulate the integrated operation of T/D+DER systems, 3) how to create an optimal DER portfolio (where, when, what size and what DER type) to satisfy a specific grid or resource need, 4) how to assess the avoided costs and operational and capital expenditures of deploying DER, and 5) how to design a reliable DER portfolio that is resilient during extreme whether events. ProsumerGrid software provides value to clients by answering these critical questions

ProsumerGrid's tool represents a quantum leap in the industry's capability to analyze, design, or redesign complex, emerging DER-based electricity grids. This analysis helps to ensure that the DER-based grid operates with the desired levels of resilience and sustainability at optimal and affordable cost.

A.2. ProsumerGrid Software Core Modules

ProsumerGrid is developing a software system that combines high-fidelity T/D power flow models, and DER techno-economic models with robust risk-averse stochastic (long and short-term) optimization algorithms. It provides unprecedented analytical capabilities supporting applications such as: 1) Optimal Long-Term Capacity Expansion Planning of T/D grids with DER, 2) Integrated T/D with Optimal DER Energy Scheduling, Unit Commitment and Production Costing, 3) Non-wire Alternatives (NWA) Analysis, 4) DER Services Locational Net Value Analysis (LNVA), 5) DER Hosting Capacity (HC) Analysis, 6) Optimal Sizing and Sitting of DER Portfolios, and 7) Optimal Resilient Microgrid DER Planning. The software tool allows decision makers to simulate and plan the electric grid while considering the operational characteristics of millions of DERs on the grid.

The tool is designed to be user friendly from the standpoint of data acquisition, data entry, and execution of analysis/planning studies (use cases). The tool has the following core modules:

A.2.1. Data Management and Translation Module

The data exploration mode allows the user to import, convert, and integrate network models with millions of DERs from various relevant formats such as CYMDIST, GridLAB-D, OpenDSS, Milsoft Windmil (NRECA's OMF Conversion Tool), PowerWorld, PSS/E, and GIS databases. An example is shown in Figure 14.

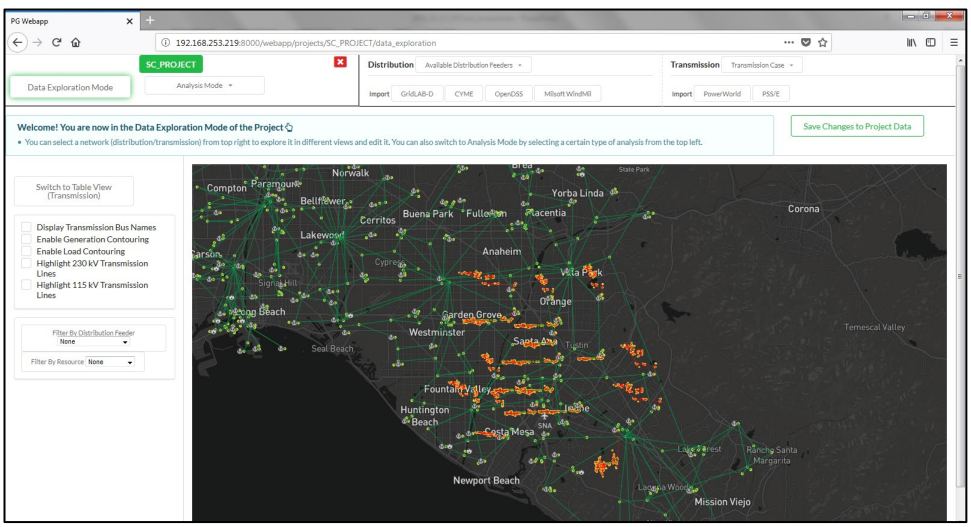


Figure 14. Data Exploration Mode: Integrated T/D View

A.2.2. Web-Based Visualization Module

The web-based visualization mode supports exploration and editing of DER-based T/D power system scenarios through geo-referenced as well as tabular views. It depicts line loadings, generation locations, load locations, and all distribution resources.

ProsumerGrid Planning Studio currently has six Analysis Modules for performing specific planning studies:

A.2.3. Time-Series Distribution Power-flow Module

The time-series distribution power-flow module allows the user to conduct time-series power-flow (three-phase, unbalanced) of distribution feeders, populated with various types of DERs and advanced smart controllers such as smart inverters for voltage regulation and volt/VAR dispatch. An example is shown in Figure 15.

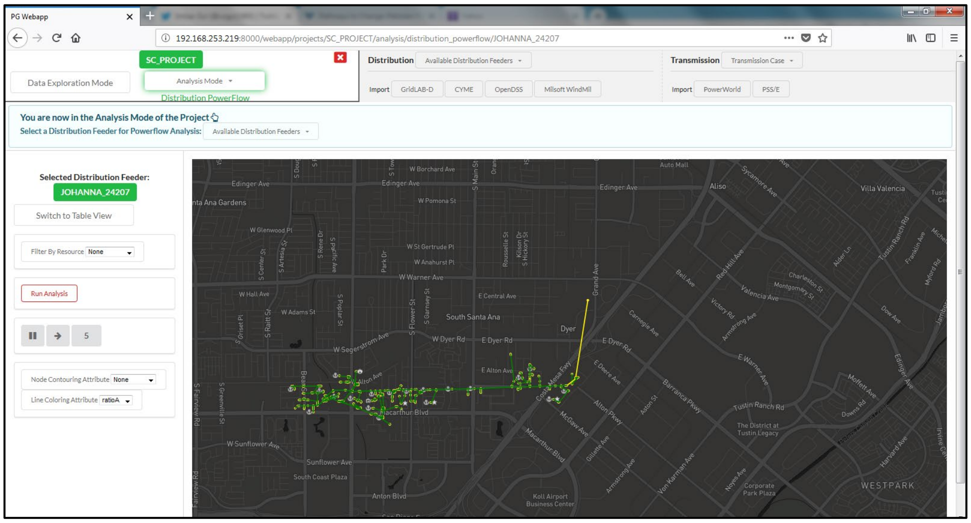


Figure 15. Distribution Power Flow Line Loading Sample Visualization

A.2.4. Time-Series, Integrated T&D Power-flow Modul

The time-series, integrated R&D power-flow module allows the user to conduct time-series, integrated (interconnected) transmission and distribution power-flows for a transmission system and a set of distribution feeders and it supports analysis of sub-transmission loop flows and the duck-curve phenomenon. An example is shown in Figure 16.

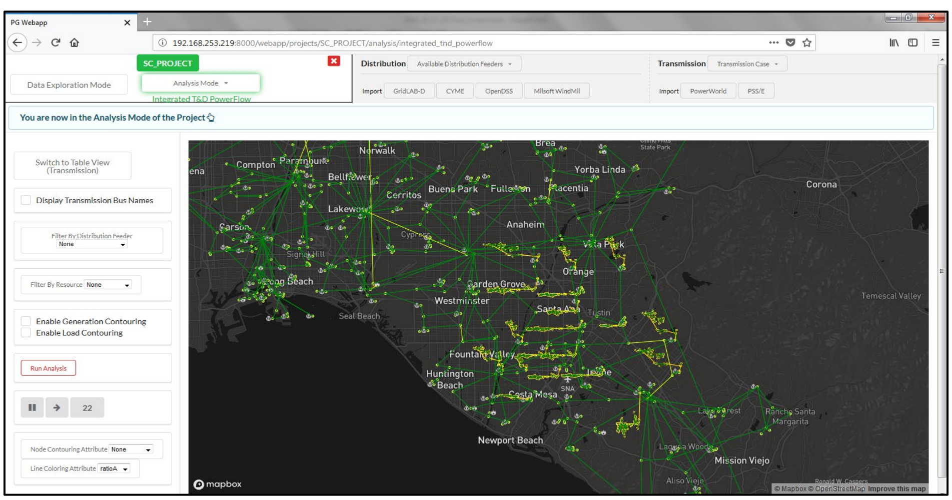


Figure 16. Integrated T/D Power Flow Line Loading Sample Visualization

A.2.5. *Optimal DER Scheduling Module (Economic Dispatch, Unit Commitment and Production Costing)*

The optimal DER scheduling module allows the user to determine the optimal schedule of operations for DERs (such as charging/discharging of storage, PV curtailment, demand response, and generation dispatch) on a system during a specific planning horizon (i.e. 8760-hour period, 24-hour period, single-hour period, etc.) and at a specific temporal granularity (i.e. hourly, 15-minutes, etc.). This analysis module considers the circuit model, wholesale price, load forecast and PV forecast while suggesting the optimal schedule of DER operations. The analysis can be configured to solve the following problems: an economic dispatch, a unit commitment, production costing or an energy scheduling. An example is shown in Figure 17.

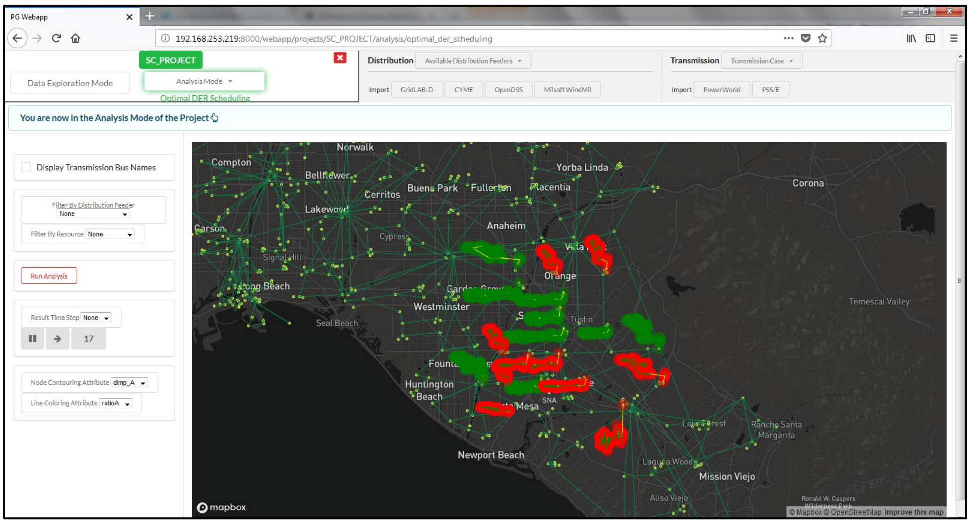


Figure 17. Optimal DER Scheduling DLMP Sample Visualization

Sample use cases include:

- Optimal Schedule of Generation Fleet and Energy Storage Systems at Transmission-level: This use case simulates the optimal operation of bulk generation fleet and energy storage systems.
- DERs Managed to Minimize Operational Costs: This use case simulates how optimal management of DERs can be used to minimize operational costs.
- DERs Managed to Shape Feeder Load: This use case simulates how optimal management of DERs can be used to shift peak load to improve the load shape.
- Optimization of DERs and Utility Controlled Distributed Energy Storage: This use case simulates the optimal management of Utility Controlled Energy Storage Systems (UCESS) deployed on the distribution grid to allow their use for the following two functions:
  - Use of UCESS by the utility for distribution grid reliability and optimization needs.
  - Bidding of UCESS assets (or portion of) to the wholesale market when not needed for reliability and optimization purpose.

An example is shown in Figure 18.

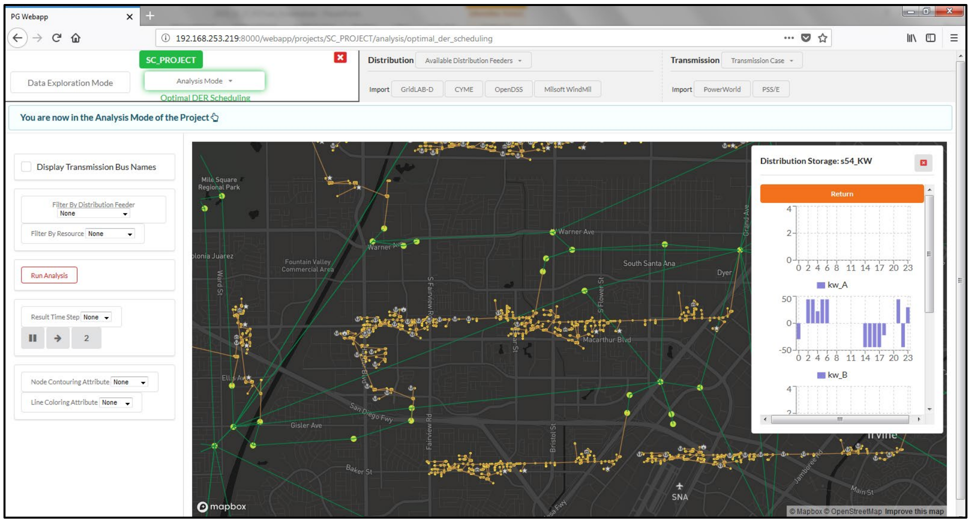


Figure 18. Optimal Scheduling of Energy Storage Sample Visualization

A.2.6. DER Project Non-Wires Alternatives Assessment Module

The DER project NWA assessment module assesses the avoided costs and adequacy of proposed DER projects as NWA to traditional capital investments made by an electric utility. It uses a stochastic optimization model to create an optimal utility DER portfolio from the optimal combination of DER projects proposed. It simulates the effects of the aggregated combination of DER proposals to provide ISO and DSO services. An example is shown in Figure 19.

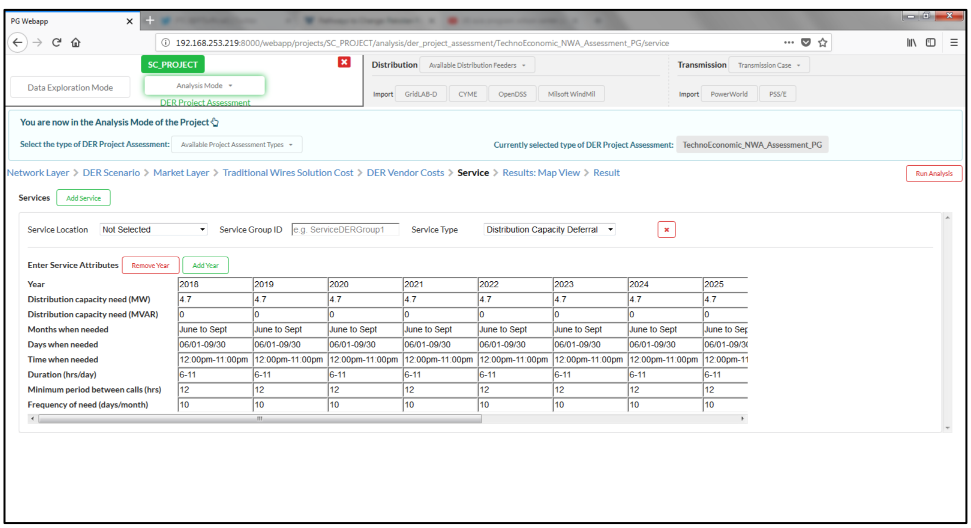


Figure 19. NWA Service Attributes Sample Visualization

A.2.7. Optimal DER Portfolio Planning Module

The optimal DER portfolio planning module allows the user to determine the optimal combination of a set of DER options (DER type, capacity and location) for a grid subsystem (with both transmission and distribution components) by considering the costs associated with various DER options, available DER service monetization options, and a utility's long-term planning criteria.

The Optimal Sizing and Sitting of DER (Distributed Energy Storage and Solar PV) for Distribution Systems and Resilient Microgrid Planning (Figure 20) use case determines the least-cost optimal combination (type, capacity, and location) of distributed energy storage and solar PV that minimizes investment costs and expected operational costs.

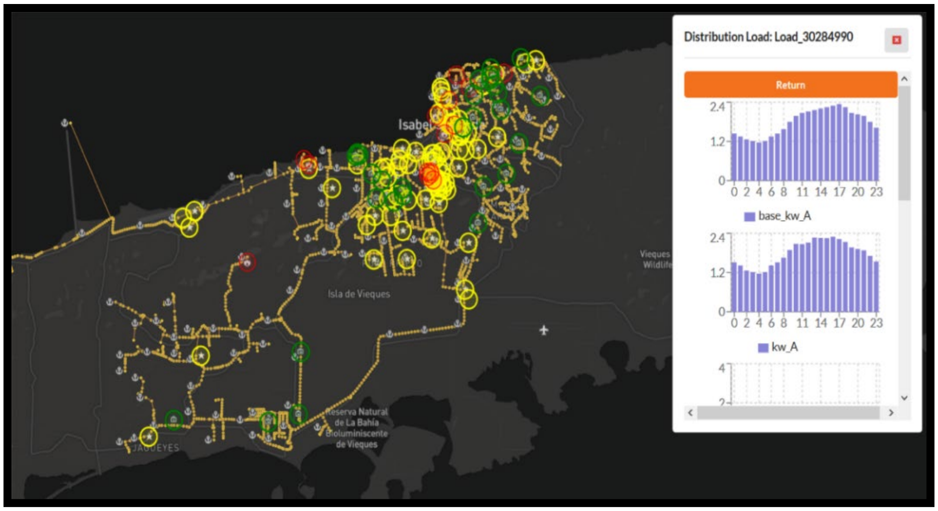


Figure 20. Optimal Distribution-Level DER Portfolio Planning Visualization

The Optimal Long Term Capacity Expansion applied to Integrated T-D-DER Planning (Figure 21) use case determines the most cost effective combination of conventional generation resources and energy storage, solar PV, wind, fuel cells, while observing the network parameters, operational constraints, and financial considerations.

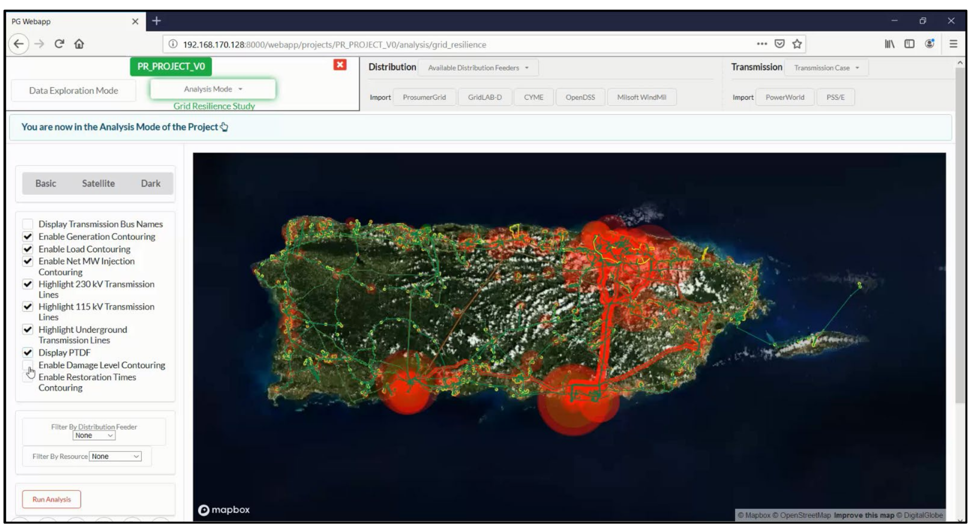


Figure 21. Optimal Transmission-level Resource Planning Visualization

A.2.8. Multi-Agent Market Simulation

The multi-agent market simulation module allows the user to simulate the operation of emerging multi-agent, DER-based Markets including Distribution System Operators (DSO) at the physical, informational, and market (locational price) levels. This simulation capability allows the user to compare and evaluate various proposed market rules and configurations. (Figure 22)

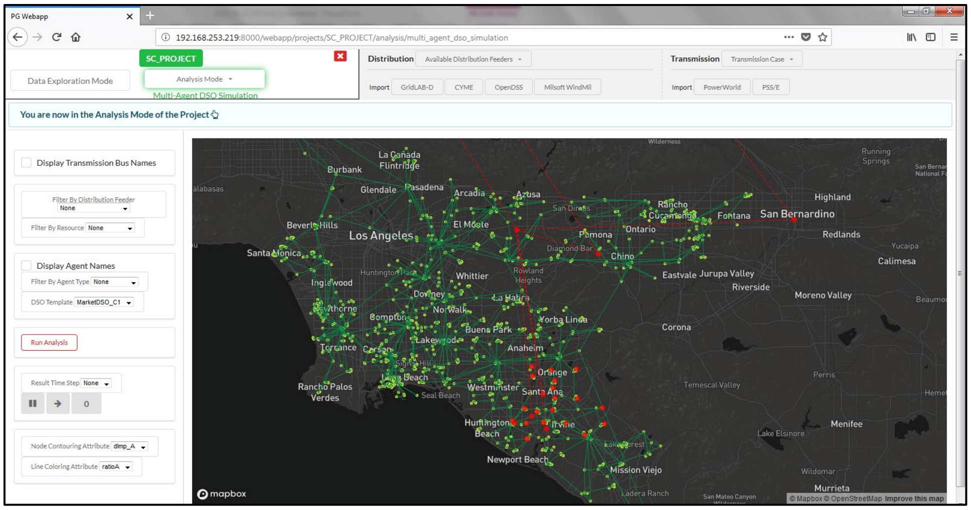


Figure 22. Sample Multi-Agent DSO Simulation

A.3. ProsumerGrid Software Summary of Unique Capabilities

ProsumerGrid software offers many improvements and advantages to traditional planning software: (Figure 23)

- Integrated simulations of complex transmission and distribution systems with DERs
- Groundbreaking optimization algorithms that support massively scalable optimization of millions of resources, while observing all the physical limits of the grid as well as resource and market constraints.
- Integrated layered approach that captures system physics, control options, system-level coordination, market operations, DER costs and financial considerations. This supports the testing of various grid and market architectures with different information flow schemes, market designs, and policy decisions.
- A robust risk-averse stochastic optimization approach that considers uncertainty of input parameters such as demand, price, grid outage, and takes into consideration simultaneously multiple scenarios, services, and DER types.
- Scalable computing resources (high performance computing native) and flexible deployment (local or cloud deployment options).
- Interactive, web-based and GIS-based visualization that provides a user-friendly system "design studio" environment for decision makers.

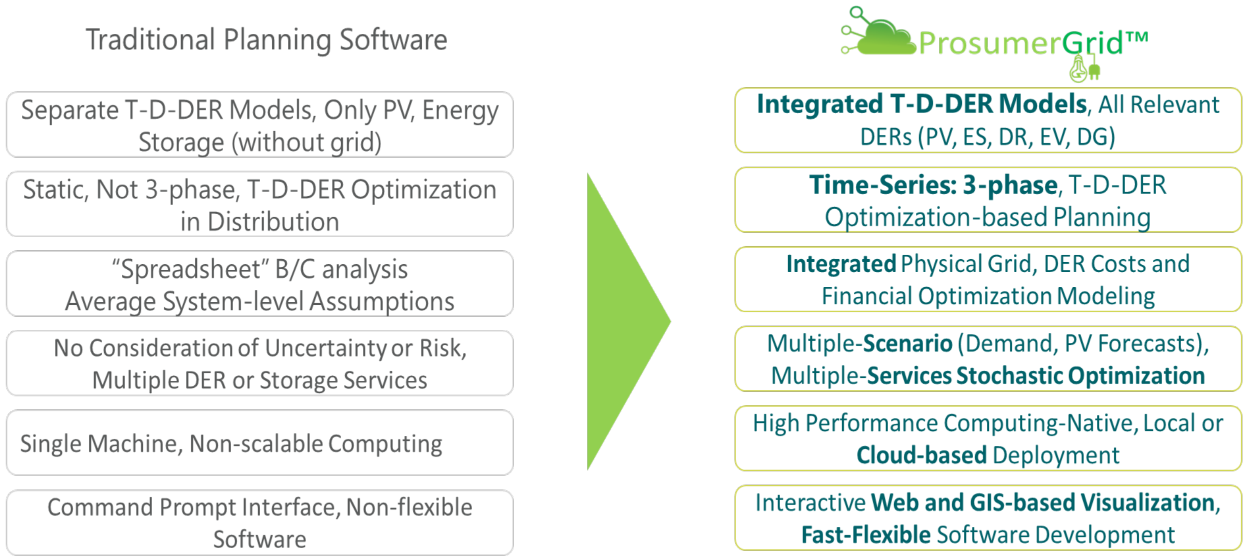


Figure 23. ProsumerGrid Unique Advantages

A.4. Optimal DER Portfolio Planning for Microgrids Analysis Workflow

As shown in Figure 24, the ProsumerGrid software analysis workflow includes the following steps: 1) importing the data corresponding to circuit models, DERs, time-series profiles, price signals, financial parameters, planning criteria and optimization options; 2) selecting the analysis type, configuring the analysis and setting the scenario parameters, 3) running the analysis and visualizing results. The following section provides details about the inputs and outputs associated with the microgrid use-case.

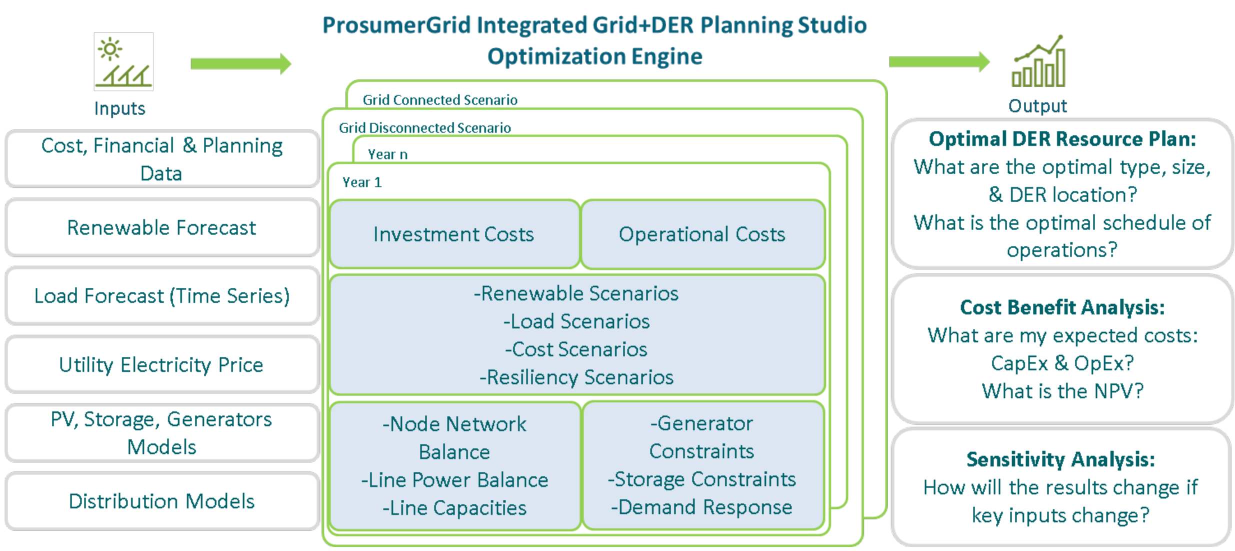


Figure 24. Analysis Workflow

A.4.1. Analysis Inputs

A.4.1.1. Microgrid Site Location Inputs

The microgrid bounds can be specified in a couple ways. First, limits can be specified with polygons whose vertices are specified in latitude and longitude. Second, a list of feeders with potential locations can be provided and then a prioritization analysis can be conducted based on the number of critical infrastructure, a higher ranking score based on critical infrastructure values, or higher values of line or voltage limit violations.

A.4.1.2. Distribution Feeder Circuit and Critical Loads Inputs

The distribution feeder data and critical loads can be specified in several ways. It can be specified with a standard distribution feeder model in Cymedist (*.stsx) or Gridlab-D (*.glm) formats. To visualize the model, if node latitude and longitude fields are not included in the feeder model, then an Excel file is required with the following records: node_name, longitude, latitude. It can also be specified with a list of nodes that form the microgrid (nodes that remain energized during islanding), or with a list and priority of any critical loads.

A.4.1.3. Distributed Energy Resources Options Inputs

DERs supported include solar PV, ESS, wind, DFFG, electric vehicles (EV), and flexible demand response devices (DR). DERs can be defined at single nodes in the circuit. They can be single phase or three-phase. Any number and type of DER candidates can be assigned to a single node and to the feeder. Certain features of the DERs, such as nominal capacity, maximum total capacity, location, and DER make can be specified. The most comprehensive type of analysis, e.g. Optimal DER Portfolio, determines the optimal size, type and location of DERs in the feeder, e.g. the size, type, location are decision variables of the optimization. DERs' operation can be modeled using different approaches:

- Fixed injections or injection profiles
- Optimized schedule of operations based on DERs locational and temporal constraints using linear constraints.
- Optimized schedule of operations based on DERs locational and temporal constraints using mixed integer-linear constraints (for example in the case of unit commitment).

For planning purposes, there are two types of DERs:

- Existing DERs
- Candidate DERs

Table 34 illustrates the main input fields for DERs. Using the parameters below different technology, fuel types, and installation options can be specified, for example:

- Different technology types of energy storage systems such as: lithium-ion, lead acid, sodium sulfur, super capacitors, flow batteries.
- Different fuel types for distributed generators such as: natural gas, diesel, propane.
- Different solar PV system installation types such as: commercial, residential, rooftop, ground-mounted, community solar.

Table 34. Sample DER Input Parameters

DFFG	Solar PV	Wind	Energy Storage
name	name	name	name
owner_type	owner_type	owner_type	owner_type
owner	owner	owner	owner
fuel_type	size_type	size_type	size_type
size_type	nominal_max_kW	nominal_max_kW	nominal_max_kW
nominal_max_ kW	max_total_kW	max_total_kW	nominal_max_kWh
max_total_kW	fraction_of_load	fraction_of_load	max_total_kW
fraction_of_load	power_factor	power_factor	fraction_of_load
power_factor	capital_cost	capital_cost	charge_duration
capital_cost	fixed_operating_cost	fixed_operating_cost	charge_efficiency
fixed_operating_cost	variable_operating_cost	variable_operating_cost	discharge_efficiency
variable_operating_cos t	location	location	dod
location	specific_nodes	specific_nodes	num_cycles
specific_nodes			power_factor
			init_soc
			capital_cost
			fixed_operating_cost
			variable_operating_cost
			location
			specific_nodes

A.4.1.4. *Time-Series Profiles Inputs*

- Load Profiles: There are various ways to specify the load. The simplest way is by feeder (e.g., based on historical substation measurements) that is proportionally assigned to the loads (static value specified in the power flow case). In this option all the loads have the same "shape." Loads can also be specified individually (e.g. based on smart meters). The minimum profile is 24 hours for one day, but it can also be one year at one hour, 15- or five-minute granularity. The accuracy of the optimization will be higher with more comprehensive profiles.
- Solar Profiles: Similarly, a single profile can be applied to all the PVs in the feeder in proportion to their size. Or individual profiles can be used for each PV. The profile can range from one day at one-hour granularity, or for one year up to one-min granularity.
- Wind Profile: Similar to solar PV profiles.
- Customer Prices and Rates: If the objective is to minimize customer price, rates can be modeled in detail for each individual load or by types of loads (residential, etc.). The rates model can capture flat rates to Time-Of-Use (TOU), seasonal rates, rates with demand charges, and any type of real-time pricing.
- LMP: If the objective is to minimize the electric-distribution utility operational cost, the LMP can be specified as input at the specific distribution substation.

A.4.1.5. *Long-Term Profiles Inputs*

Long term profiles can be specified in two ways. The first is with forecasts, which are usually long-term (10-30 year) profiles of demand, PV, and wind, and the prices are used for long-term optimization if the forecast is available. The second is with growth factors. These can be applied to the different referential time-series profiles.

A.4.1.6. *Service Prices and Avoided Costs Profiles Inputs*

The incorporation of DERs in the distribution feeder will result in a different exchange of power and services with the main grid. The following inputs associated with avoided cost per MWh are inputs for one year at one-hour granularity:

- System Avoided Cost of Ancillary Services
- System Avoided Costs of CO^2
- System Avoided Costs of Capacity
- System Avoided Costs of Energy
- System Avoided Costs of Renewable Portfolio Standard
- Services specifications:
  - Enabled services: regulation up, down, spinning and non-spinning reserve, distribution capacity deferral
  - Service price or cost
  - System service requirements
  - Resources allowed to participate in the specific service

A.4.1.7. *Financial Parameters Inputs*

The following are financial parameters utilized during the simulation.

- Planning_horizon
- Maximum_total_investment_cost
- Enable_traditional_project_deferral
- Lifetime_of_investment_years
- Start_year
- Base_year
- Traditional_project_invested_capital
- Year_the_investment_is_committed
- Revenue_requirement_scaling_factor
- Discount_rate
- Inflation_rate_for_investment
- Periodicity_of_investment_in_years

A.4.1.8. *Planning Criteria Inputs*

The following are additional planning criteria parameters.

- Griddisconnect_scenario_probability
- Gridconnect_scenario_probability
- Restore_time
- VOLL

Depending on the use case, it can be assumed that:

- The microgrid is optimally designed to be grid connected as well as islanded (i.e., in this case both gridconnect and griddisconnect probabilities are specified),
- The microgrid is designed to be autonomous (i.e., in this case by setting the griddisconnect_scenario_probability to 1),
- The microgrid is designed to be operating during a certain outage time (two hours, 24 hours, one week, six months, etc.) can be specified as restore time, and;
- Optionally, the value of loss load can be specified, and the corresponding energy not served decision variable can be determined.

A.4.1.9. *Optimization Options & Additional Constraints Inputs*

The optimization options include both the Mixed Integer Linear Programming Model (MILPM) and the Linear Programming Model (LPM). In the case of the MILPM, integer variables are specified to add discrete values of the DER units and the parameters can be specified as either Optimality Gap or Solution Time. In the case of the LPM, the MILP constraints are relaxed, and a linear model is used to obtain insights about the microgrid DER portfolio.

A.4.2. Microgrid Assessment Outputs

Below, we describe the outputs of the most common types of analysis.

A.4.2.1. *Time-Series Power Flow Outputs*

Determines the three-phase power flow results for all nodes and lines associated with the microgrid. The outputs include:

- Voltage
- Current
- Power flows in lines
- Line-limit values
- Voltage-limit values

A.4.2.2. *Optimal Energy Scheduling Outputs*

Determines the optimal schedule of all the DERs connected to the feeder/microgrid, which can range from a single hour to one day hourly, to one year (e.g. at one-hour granularity). The outputs include:

- Curtailable solar PV active power injection at each time point.
- Curtailable wind active power injection at each time point.
- Energy storage charge and discharge and energy stored at each time point.
- Demand response power at each time point (including demand shift).
- DFFG dispatch at each time point.
- Total microgrid or feeder energy exchange with the main grid at each point in time.
- Per resource operating cost at each point in time.
- Total system operating costs at each point in time.
- Per resource and system total horizon operating costs.
- List of binding constraints including device and circuit capacities and operational limits.
- Distribution locational marginal prices (DLMP) for each node and phase at each point in time.
- DER scheduling charts.

A.4.2.3. *Optimal DER Services Stacking Outputs*

Determines the optimal operational services stacking for all DERs. The outputs include

- All the outputs of Optimal Energy Scheduling PLUS.
- Selected wholesale and distribution-level services: Frequency regulation up and down, reserve, and distribution capacity deferral services for each DER at each point in time.
- Value streams for each DER and service type.
- Total system value for each service type.
- Locational marginal prices of DER services at each point in time.

A.4.2.4. *Optimal DER Portfolio Outputs*

Optimal DER Portfolio determines the optimal type, size and location of sets of DERs in a distribution feeder or microgrid that can satisfy two objectives. The first is it minimizes the net total present costs (capital and operational) of energy supply while satisfying the line-thermal limits, the DERs locational and temporal constraints (max output power, max energy, time-series profiles, etc.), and the service constraints (what DERs are allowed to participate, etc.). The second objective is it maximizes the present value of long-term benefits (i.e. avoided energy, capacity, etc.) minus cost (capital, operational).

Because the ultimate long-term value of the DERs option depends on how the DERs are operated day by day, the outputs of the Optimal Energy Scheduling are a byproduct of the Optimal DER Portfolio calculation. Specific types, locations, and sizes of DERs can be filtered or constrained. For instance, market or regulator rules may require DFFG to be at least one MW, certain critical facilities are required to have a certain type of DER, etc.

The Optimal DER Portfolio provides the following outputs:

- The outputs of Optimal Energy Scheduling PLUS.
- Optimal type, size, and locations of DERs that minimizes C or maximizes B-C.
- Visualization of the optimal DERs.
- Total costs including, capital, O&M, etc.
- Realized system avoided costs of Ancillary Services, CO^2, Capacity, Energy, and Renewable Portfolio Standards.
- Net Present Value of optimal DER solution.
- Benefit/Cost Metrics of optimal DER solution.
- Optionally, multiple sensitivities to DER, financial or planning parameter, (i.e. high-mid-low capital or operating costs, growing-decreasing-stagnant demand, high-mid-low outage times, disconnection probabilities, VOLL, etc.).

A.5. Improvements to ProsumerGrid Software during the Project

ProsumerGrid uses a software development strategy that is based on agile values and principles. The four core values are:

- Individuals and interactions over processes and tools
- Working software over comprehensive documentation
- Customer collaboration over contract negotiation
- Responding to change over following a plan

The twelve agile principles are:

1. Our highest priority is to satisfy the customer through early and continuous delivery of valuable software.
2. Welcome changing requirements, even late in development. Agile processes harness change for the customer's competitive advantage.
3. Deliver working software frequently, from a couple of weeks to a couple of months, with a preference to the shorter timescale.
4. Businesspeople and developers must work together daily throughout the project.
5. Build projects around motivated individuals. Give them the environment and support they need and trust them to get the job done.
6. The most efficient and effective method of conveying information to and within a development team is face-to-face conversation.
7. Working software is the primary measure of progress.
8. Agile processes promote sustainable development. The sponsors, developers, and users should be able to maintain a constant pace indefinitely.
9. Continuous attention to technical excellence and good design enhances agility.
10. Simplicity--the art of maximizing the amount of work not done--is essential.
11. The best architectures, requirements, and designs emerge from self-organizing teams.
12. At regular intervals, the team reflects on how to become more effective, then tunes and adjusts its behavior accordingly." (Agile Alliance)

ProsumerGrid uses an agile software product development methodology called Scrum. Scrum is an agile software product development practice that has relatively little overhead and tries to not take too much time away from production. Scrum uses an approach that is both iterative and incremental. This enhances predictability and mitigates risk. A Scrum team consists of a product owner, the development team, and the scrum master. A key role in Scrum is the product owner, whose primary task is to make decisions about the product and the product backlog. In this case, ProsumerGrid and SNL project managers shared the roles of product owners for specific features. The Scrum development team is cross functional and self-organizing. Team members perform a variety of tasks like doing both coding and testing. ProsumerGrid uses Scrum's three principles: transparency, inspection, and adaptation. Transparency means that all the team members are aware of every part of the project and agree on common standards such as the definition of a completed task. In ProsumerGrid, a completed task is one that has been designed, coded, tested, integrated, and documented. The second principle is inspection. Scrum encourages frequent inspection of work products and progress to detect any potential deviations from planned expectations. Finally, the third principle is adaptation. This principle means that the team must adjust and adapt to prevent further deviation whenever the product development is starting to stray from the vision.

ProsumerGrid uses four specific Scrum techniques for inspection and adaptation: sprint planning, daily scrum, sprint review, and sprint retrospective. All of these events are time boxed, meaning that there is a maximum time for the duration of these events. This contributes to maintain the allotted time and adjust the scope, rather than extending the scope and eventually delaying releases. A sprint is a development phase that in ProsumerGrid consists of two four-week periods, in which a working prototype is delivered. Each sprint consists of the four events/techniques previously mentioned. Spring planning occurs at the beginning of the current sprint to determine what tasks will be completed in that sprint. The daily scrum is a meeting that occurs every other day, so that developers can talk about what tasks they will be doing, what resources they need to accomplish these tasks and whether there are any specific challenges that need to be solved. The sprint review takes place at the end of the sprint. During a sprint a sprint goal is set. This represents the big picture of what is planned to be achieved during the specific sprint. Suggestions that will change the sprint goal will go in the backlog and can be implemented in future sprints if the task is prioritized. A schematic view of the scrum methodology is shown in Figure 25.

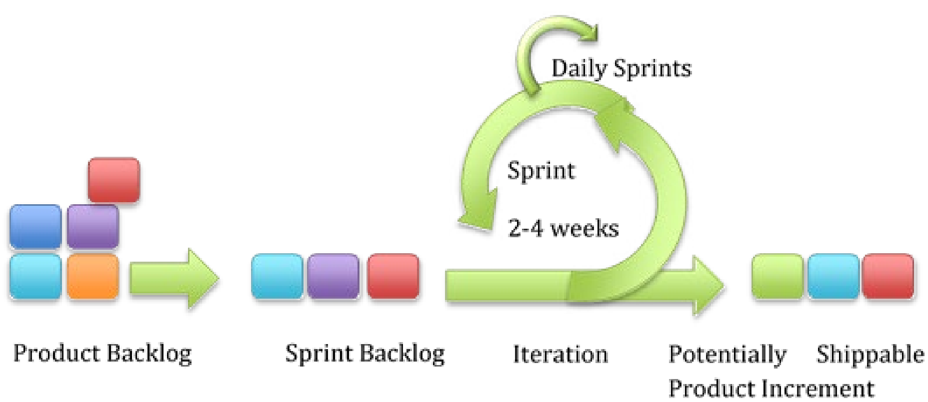


Figure 25. ProsumerGrid Scrum Methodology

A key scrum and agile technique used in ProsumerGrid is the product backlog. The product backlog basically is a collection of software development tasks that need to be implemented. It consists mostly of user stories, but it also includes work tasks, knowledge tasks, and bug fix tasks. A user story is a simple way of expressing software requirements. User stories are meant to keep all the requirements of the system in a consistent format of three parts: the who, the what and the why. The first part of the user story is the specific stakeholder which in this project was the research team at SNL. The second signifies the task or function the stakeholder wants to resolve using the product. For example, the requirement to visualize the critical infrastructure in the case. The final part signifies the why of the requirement. Other items included in the product backlog include work tasks, knowledge tasks and bugs. Work tasks include things like setting up a product testing server. They consist of physical to-do items that are not directly related to developing the product features. A knowledge task is a to-do item for things that need to be learned or researched. Bugs are errors in the code that require attention. Using the above described agile methodologies and techniques ProsumerGrid uses an iterative and incremental approach for software development that covers the specific software engineering activities of requirements elicitation, prioritization and analysis, code design, development and integration; and test development, execution, reporting and client demonstrations.

The set of requirements from the Optimal DER Portfolio Planning Project by ProsumerGrid and SNL resulted in numerous key findings and improvements to ProsumerGrid's software. These requirements resulted in software design, development, system integration and testing in ProsumerGrid's Optimal Grid+DER Planning Studio ™.

Table 35 lists the improvements that were implemented in the ProsumerGrid's Optimal Grid+DER Planning Studio ™ and specifies the version of the software where these improvements are or will be available.

Table 35. Improvements to the Grid+DER Planning Studio

Number	Description	Integrated Grid+DER Planning Studio™ version
1	Inputs: Implementation of maximum size of DERs by total combined DER MW.	Optimal Grid+DER Planning Studio™ v1.3
2	Inputs: Implementation of microgrid polygon locations whose vertices are specified by lat-long values	Optimal Grid+DER Planning Studio™ v1.3
3	Microgrid formation using graph theoretic methods	Optimal Grid+DER Planning Studio™ Analytical Engine v1.4
4	Output: Microgrid name and network visualization and filtering	Optimal Grid+DER Planning Studio™ v1.3
5	Output: Customized microgrid report in excel format containing sensitivity results, capacities, costs estimation and time-series plots	Optimal Grid+DER Planning Studio™ v1.3
6	Output: Microgrid polygons visualization	Optimal Grid+DER Planning Studio™ v1.3
7	Output: Critical infrastructure visualization	Optimal Grid+DER Planning Studio™ v1.3

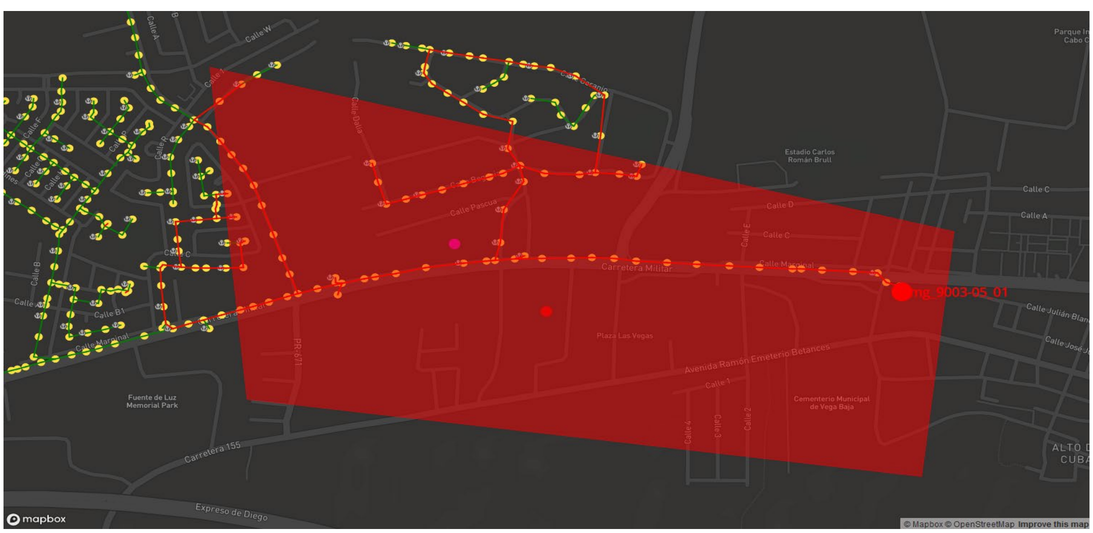
APPENDIX B. MICROGRID RESULTS

B.1. Vega Baja Microgrid 9003-05 Results

B.1.1. Vega Baja Microgrid 9003-05 Case Data

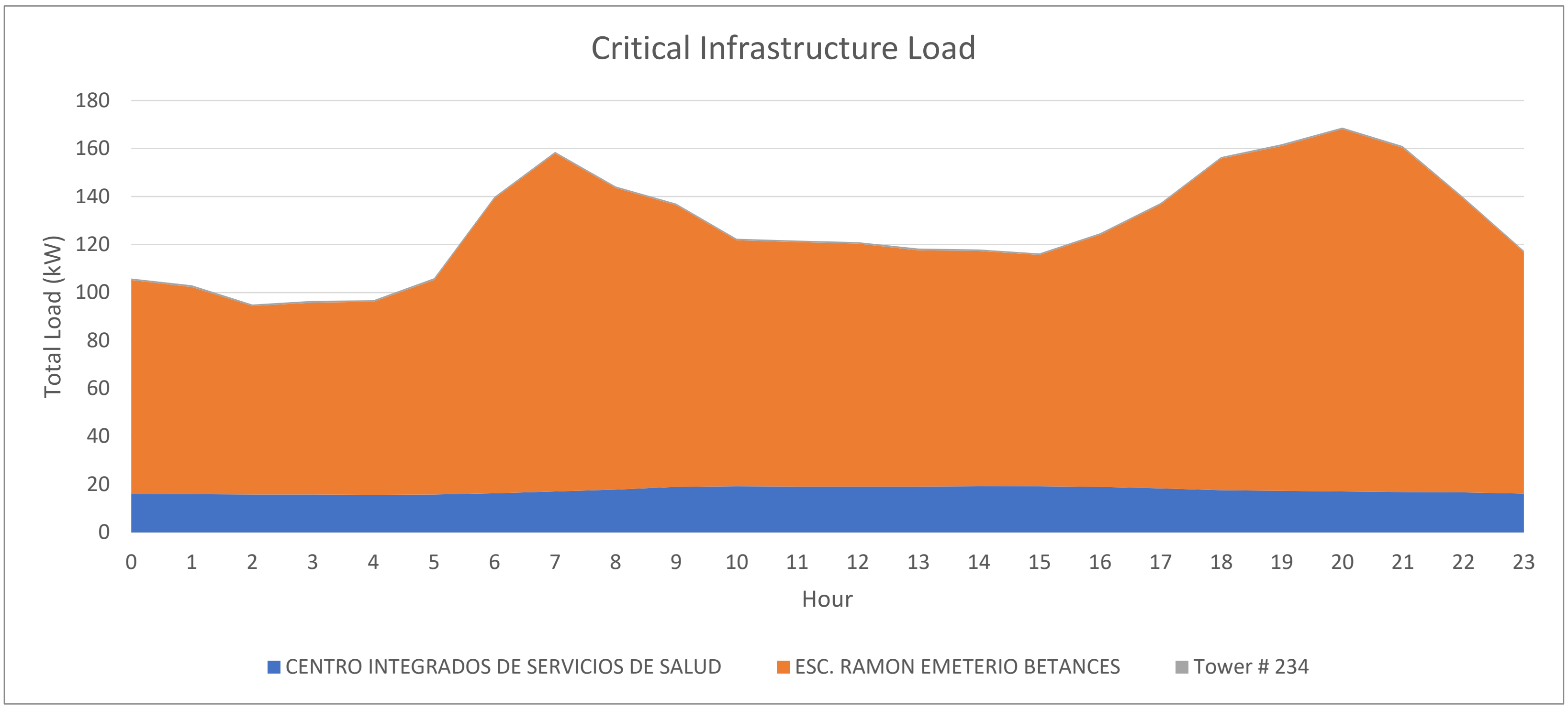
Microgrid Data	
Microgrid ID	mg_9003-05_01
Swing Node	15934143
Nominal Voltage (kV)	8.32
Number of Nodes	114
Number of OH Lines	113
Number of UG Lines	0
Number of Loads	33
Electrical Length (mi)	3.146
Total MW	0.602

Parent Feeder Data	
Feeder ID	9003-05
Swing Node	15934143
Nominal Voltage (kV)	8.32
Number of Nodes	750
Number of OH Lines	743
Number of UG Lines	6
Number of Loads	245
Electrical Length (mi)	20.113
Total MW	3.024



B.1.2. Vega Baja Microgrid 9003-05 Critical Infrastructure Data

Critical Infrastructure Data					
Name	**Type**	**Power A (kW)**	**Power B (kW)**	**Power C (kW)**	**Priority Level**
CENTRO INTEGRADOS DE SERVICIOS DE SALUD	clinic	6.415	6.415	6.415	100
ESC. RAMON EMETERIO BETANCES	shelter	50.332	50.332	50.332	75
Tower # 234	telecom tower	0.216	0.216	0.216	50

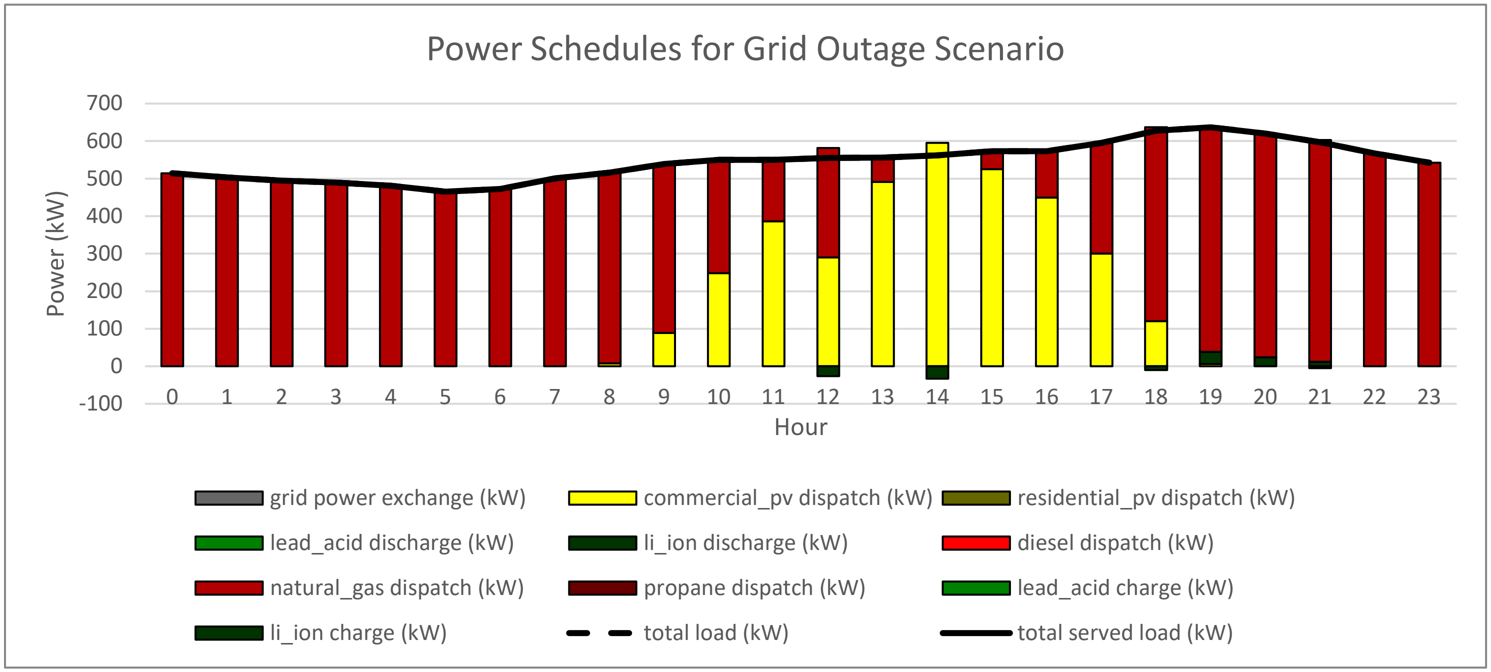


B.1.3. Vega Baja Microgrid 9003-05 Baseline Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	717
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	33
5	diesel	generator	0
6	natural_gas	generator	600
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	23,648	23,648	11,313	1,965	1,965	940
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	969	6,780	3,243	80	563	269
5	0	0	0	0	0	0
6	64,569	8,006,518	3,830,163	5,365	665,230	318,233
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	89,185	**8,036,945**	**3,844,719**	**7,410**	**667,758**	**319,442**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	25,612	12,253	2,870,698	2,857,338
2	0	0	0	0
3	0	0	0	0
4	7,343	3,513	187,822	183,992
5	0	0	0	0
6	8,671,748	4,148,396	13,051,833	8,528,481
7	0	0	0	0
8	0	0	0	0
	8,704,704	**4,164,161**	**16,110,352**	**11,569,810**

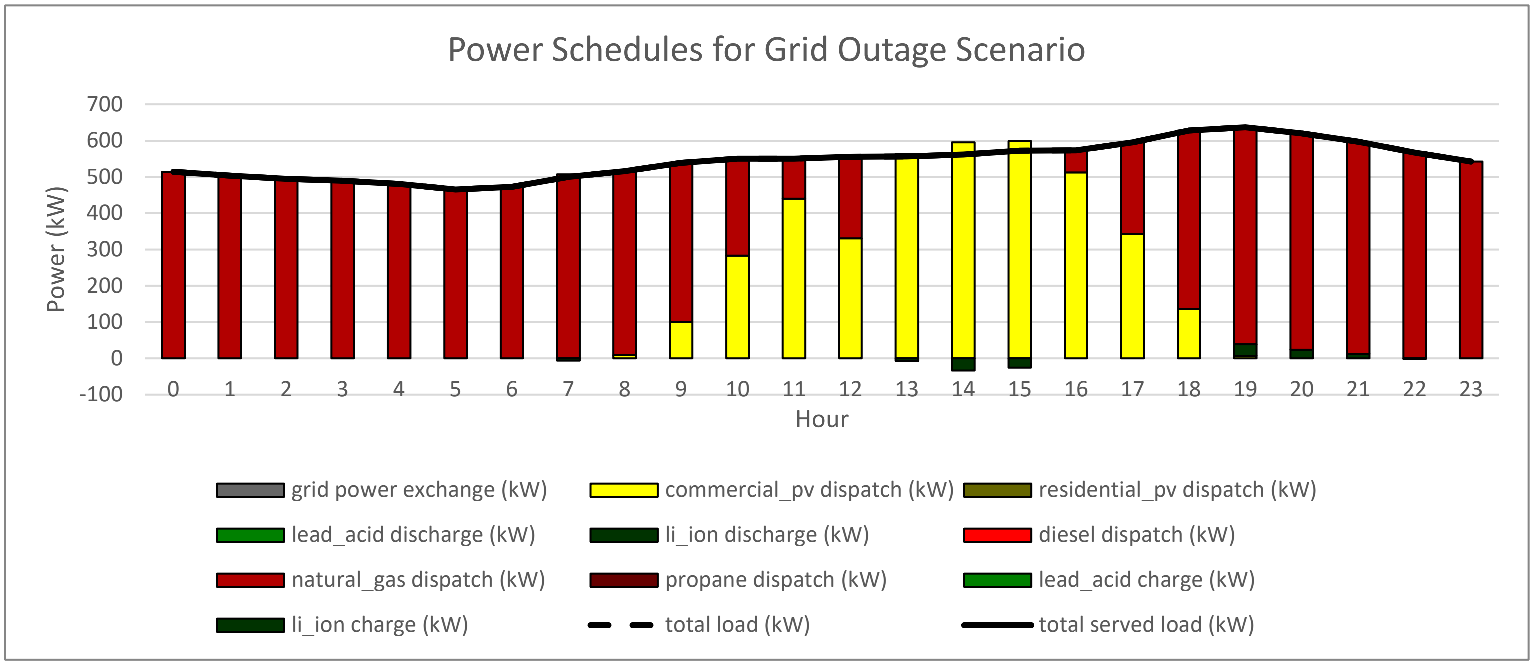


B.1.4. Vega Baja Microgrid 9003-05 CO2 Cost Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	817
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	33
5	diesel	generator	0
6	natural_gas	generator	600
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			Grid Outage (Pr = 7.671%)		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	26,388	26,388	12,623	2,192	2,192	1,049
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	959	6,712	3,211	80	558	267
5	0	0	0	0	0	0
6	61,828	8,359,202	3,998,880	5,137	694,533	332,251
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	89,175	**8,392,302**	**4,014,714**	**7,409**	**697,283**	**333,567**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	28,580	13,672	3,270,654	3,255,746
2	0	0	0	0
3	0	0	0	0
4	7,270	3,478	187,749	183,957
5	0	0	0	0
6	9,053,735	4,331,131	13,433,820	8,711,216
7	0	0	0	0
8	0	0	0	0
	9,089,585	**4,348,281**	**16,892,222**	**12,150,918**

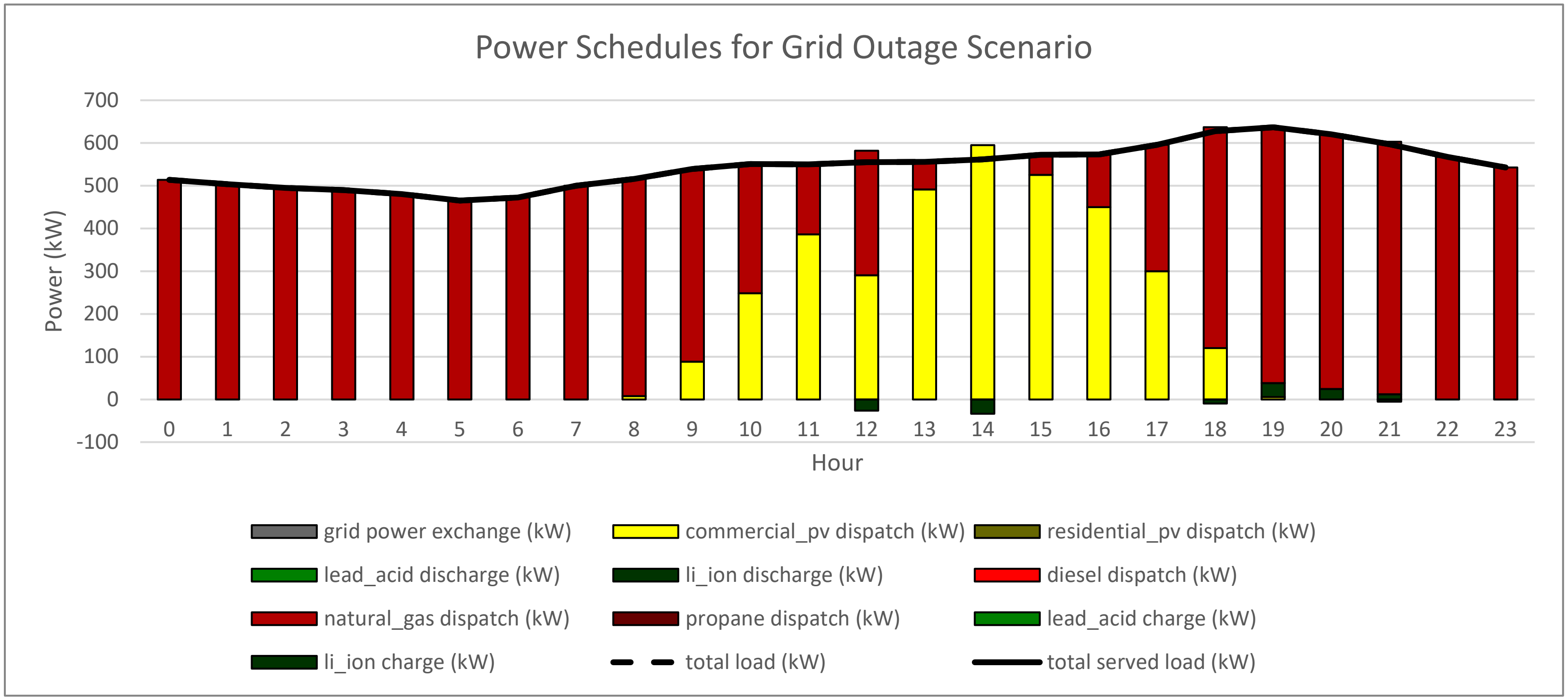


B.1.5. Vega Baja Microgrid 9003-05 Decreasing Demand Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	DER Option	DER Type	Optimal Selected Capacity (kW)
1	commercial_pv	pv	717
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	33
5	diesel	generator	0
6	natural_gas	generator	600
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	19,155	19,155	9,742	1,591	1,591	809
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	785	5,492	2,793	65	456	232
5	0	0	0	0	0	0
6	52,301	6,485,280	3,298,422	4,345	538,836	274,053
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	72,240	**6,509,926**	**3,310,957**	**6,002**	**540,884**	**275,094**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	20,746	10,551	2,865,831	2,855,637
2	0	0	0	0
3	0	0	0	0
4	5,948	3,025	186,427	183,504
5	0	0	0	0
6	7,024,116	3,572,475	11,404,201	7,952,560
7	0	0	0	0
8	0	0	0	0
	7,050,810	**3,586,052**	**14,456,459**	**10,991,700**

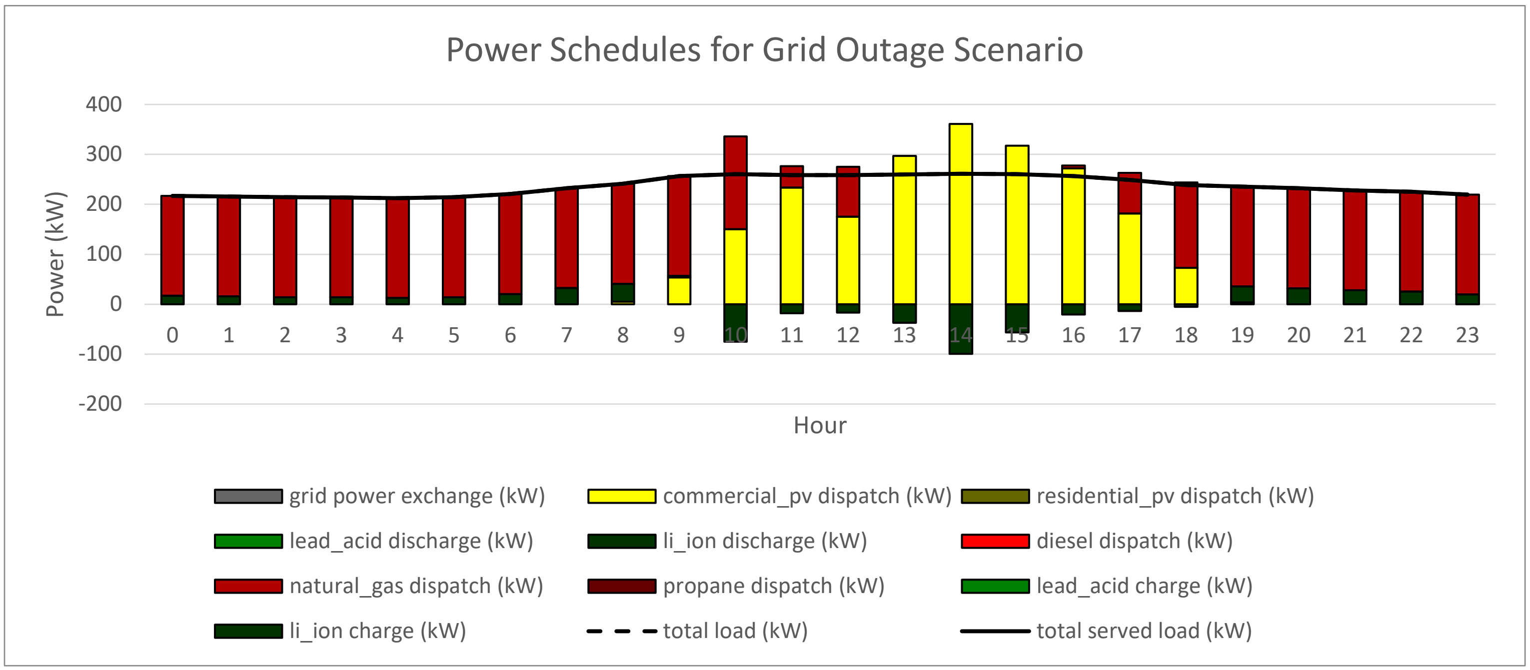


B.1.6. Vega Baja Microgrid 9003-05 High Priority Loads Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	433
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	100
5	diesel	generator	0
6	natural_gas	generator	200
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	14,305	14,305	6,843	1,189	1,189	569
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	4,451	31,160	14,906	370	2,589	1,238
5	0	0	0	0	0	0
6	24,178	2,998,093	1,434,230	2,009	249,100	119,164
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	42,935	**3,043,558**	**1,455,979**	**3,567**	**252,877**	**120,972**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	15,494	7,412	1,735,778	1,727,696
2	0	0	0	0
3	0	0	0	0
4	33,748	16,145	575,185	557,581
5	0	0	0	0
6	3,247,193	1,553,394	4,707,221	3,013,422
7	0	0	0	0
8	0	0	0	0
	3,296,436	**1,576,951**	**7,018,184**	**5,298,699**

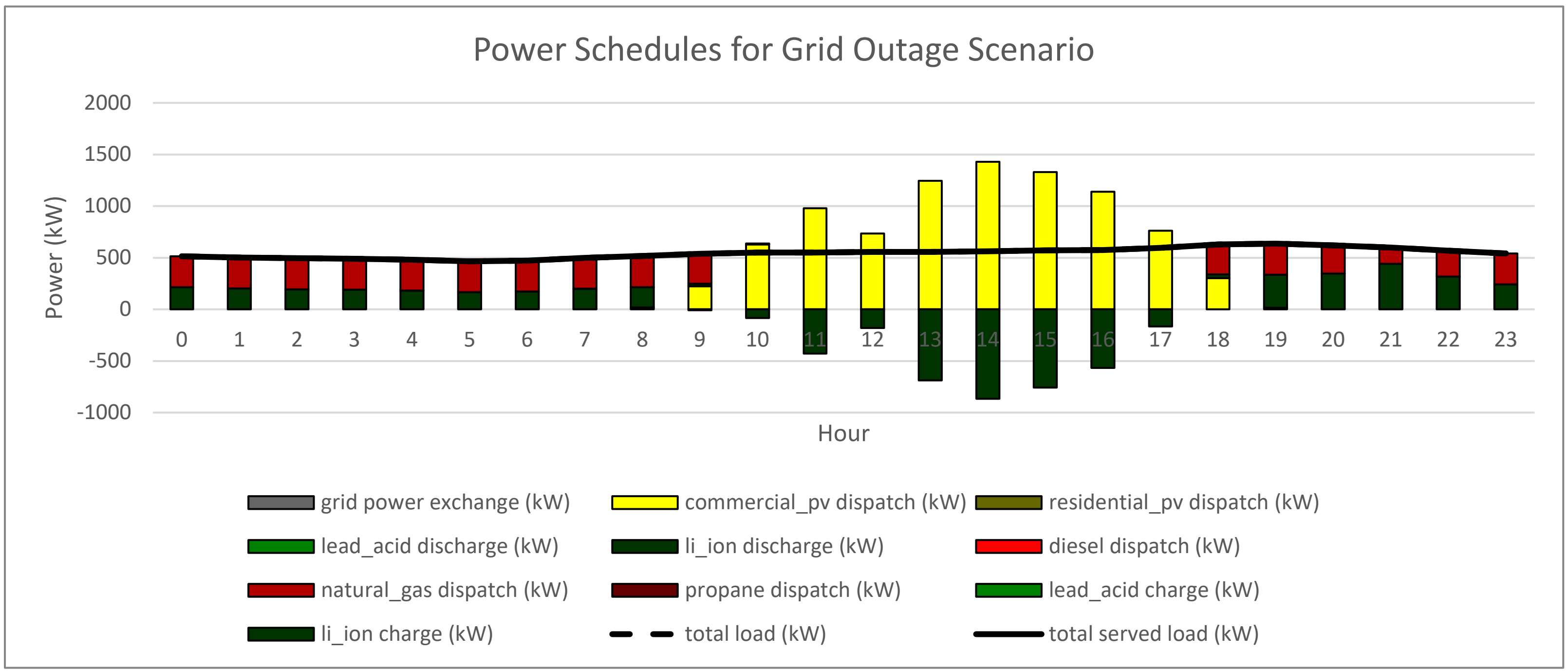


B.1.7. Vega Baja Microgrid 9003-05 Low Discount Rate Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	1,817
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	867
5	diesel	generator	0
6	natural_gas	generator	300
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	59,403	59,403	59,403	4,936	4,936	4,936
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	48,505	339,536	339,536	4,030	28,211	28,211
5	0	0	0	0	0	0
6	30,794	3,818,464	3,818,464	2,559	317,261	317,261
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	138,702	**4,217,403**	**4,217,403**	**11,524**	**350,407**	**350,407**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	64,339	64,339	3,752,172	3,752,172
2	0	0	0	0
3	0	0	0	0
4	367,746	367,746	2,667,880	2,667,880
5	0	0	0	0
6	4,135,725	4,135,725	5,371,725	5,371,725
7	0	0	0	0
8	0	0	0	0
	4,567,810	**4,567,810**	**11,791,777**	**11,791,777**

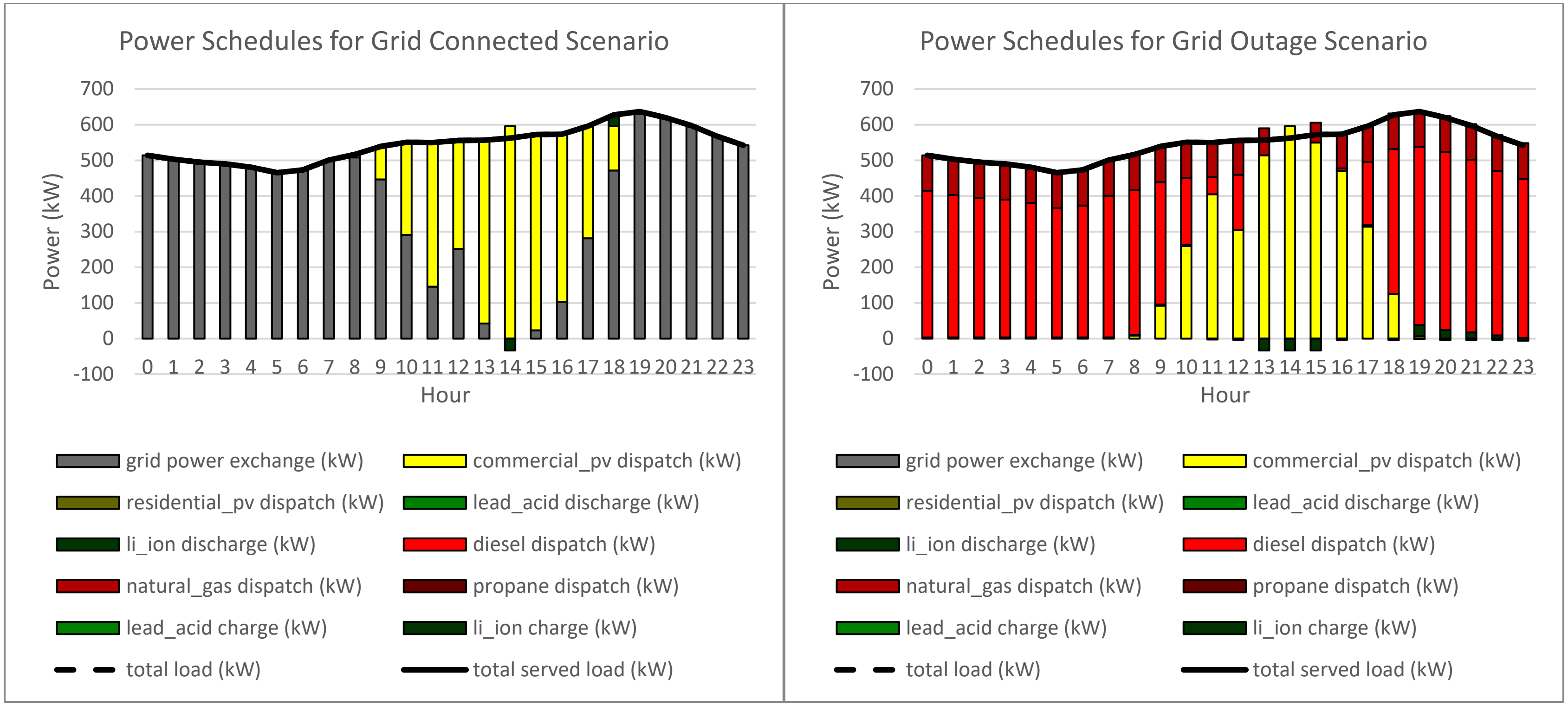


B.1.8. Vega Baja Microgrid 9003-05 Low Utility Electricity Price Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	750
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	33
5	diesel	generator	500
6	natural_gas	generator	100
7	propane	generator	0
8	grid power exchange	--	--

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	24,561	24,561	11,749	2,041	2,041	976
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	431	3,020	1,444	143	1,004	480
5	0	0	0	4,042	804,307	384,765
6	0	0	0	1,250	154,970	74,135
7	0	0	0	0	0	0
8	63,633	7,635,962	3,652,896	0	0	0
	88,625	**7,663,543**	**3,666,090**	**7,476**	**962,321**	**460,356**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	26,602	12,726	3,004,016	2,990,140
2	0	0	0	0
3	0	0	0	0
4	4,024	1,925	184,502	182,404
5	804,307	384,765	3,990,867	3,571,325
6	154,970	74,135	884,984	804,149
7	0	0	0	0
8	7,635,962	3,652,896	7,635,962	3,652,896
	8,625,864	**4,126,446**	**15,700,332**	**11,200,913**



Power Schedules for Grid Connected Scenario
Power (kW)
Hour
Power Schedules for Grid Outage Scenario
Power (kW)
Hour
grid power exchange (kW)
commercial_pv dispatch (kW)
residential_pv dispatch (kW)
lead_acid discharge (kW)
li_ion discharge (kW)
diesel dispatch (kW)
natural_gas dispatch (kW)
propane dispatch (kW)
lead_acid charge (kW)
li_ion charge (kW)
total load (kW)
total served load (kW)

B.2. Quebradillas Microgrid 7404-06 Results

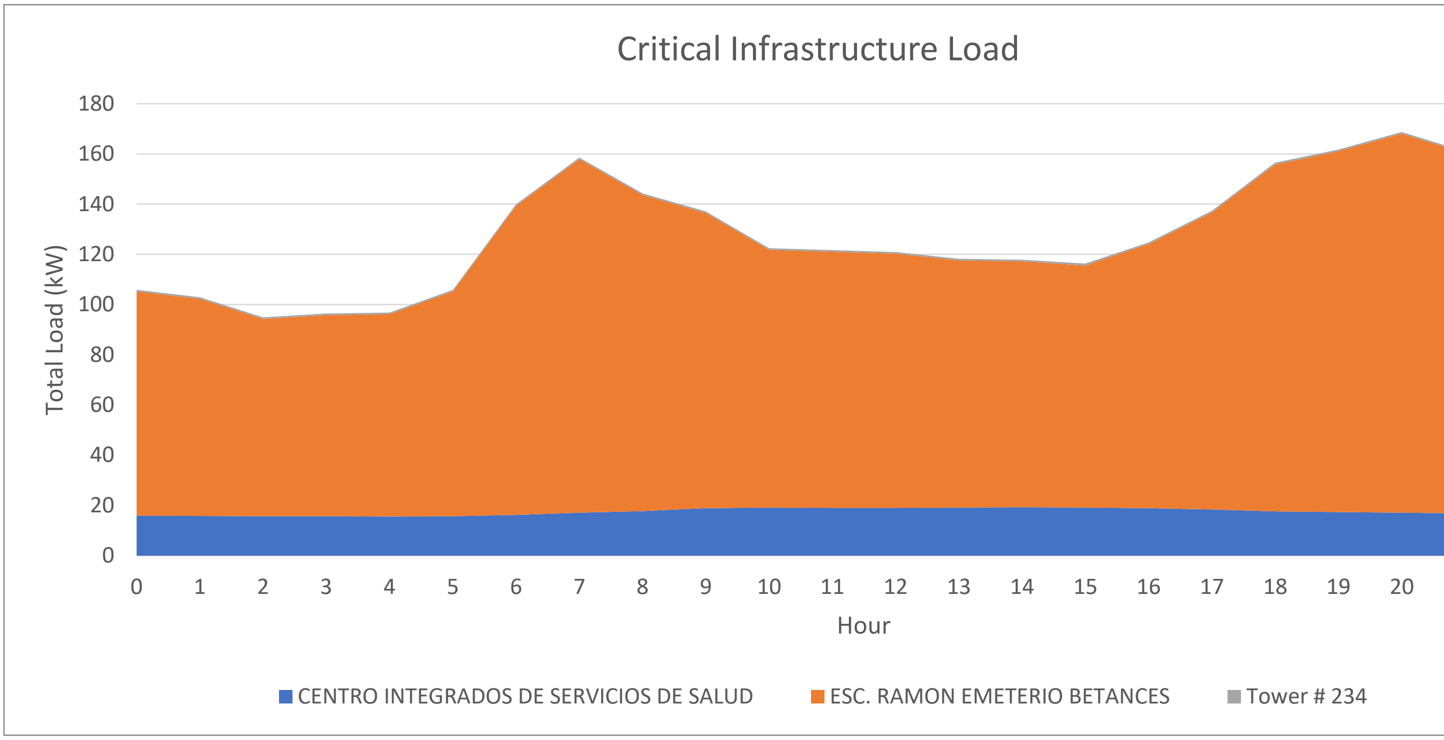
B.2.1. Quebradillas Microgrid 7404-06 Case Data

Microgrid Data	
Microgrid ID	mg_7404-06_01
Swing Node	27613139
Nominal Voltage (kV)	4.16
Number of Nodes	261
Number of OH Lines	192
Number of UG Lines	68
Number of Loads	96
Electrical Length (mi)	4.538
Total MW	1.095

Parent Feeder Data	
Feeder ID	7404-06
Swing Node	27613139
Nominal Voltage (kV)	4.16
Number of Nodes	753
Number of OH Lines	682
Number of UG Lines	70
Number of Loads	272
Electrical Length (mi)	19.872
Total MW	2.171

B.2.2. Quebradillas Microgrid 7404-06 Critical Infrastructure Data

Critical Infrastructure Data					
Name	**Type**	**Power A (kW)**	**Power B (kW)**	**Power C (kW)**	**Priority Level**
CENTRO INTEGRADOS DE SERVICIOS DE SALUD	clinic	6.415	6.415	6.415	100
ESC. RAMON EMETERIO BETANCES	shelter	50.332	50.332	50.332	75
Tower # 234	telecom tower	0.216	0.216	0.216	50

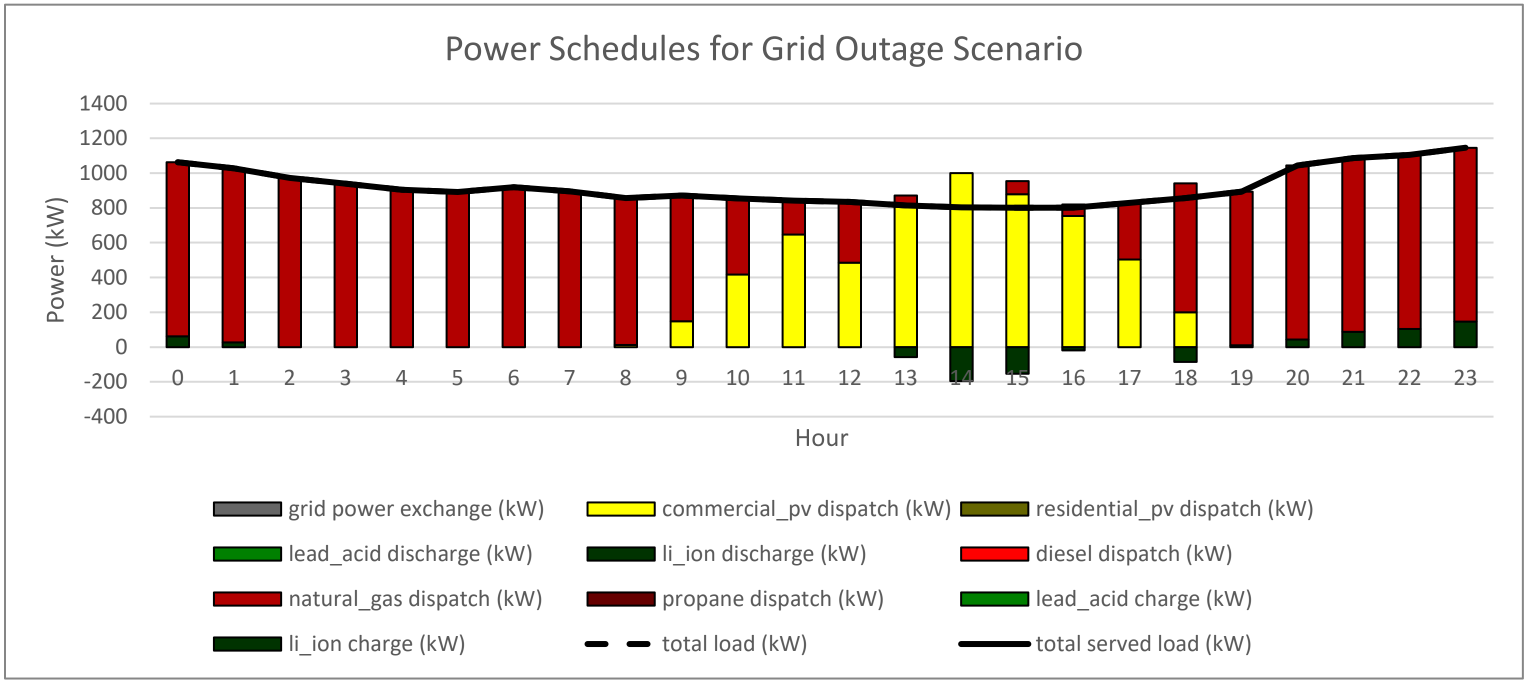


B.2.3. Quebradillas Microgrid 7404-06 Baseline Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	1,200
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	200
5	diesel	generator	0
6	natural_gas	generator	1,000
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	39,615	39,615	18,951	3,291	3,291	1,575
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	6,643	46,501	22,245	552	3,864	1,848
5	0	0	0	0	0	0
6	109,273	13,549,908	6,482,013	9,079	1,125,808	538,565
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	155,532	**13,636,024**	**6,523,209**	**12,923**	**1,132,963**	**541,988**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	42,906	20,526	4,806,770	4,784,389
2	0	0	0	0
3	0	0	0	0
4	50,365	24,094	1,133,238	1,106,966
5	0	0	0	0
6	14,675,716	7,020,577	21,975,858	14,320,719
7	0	0	0	0
8	0	0	0	0
	14,768,988	**7,065,197**	**27,915,865**	**20,212,074**

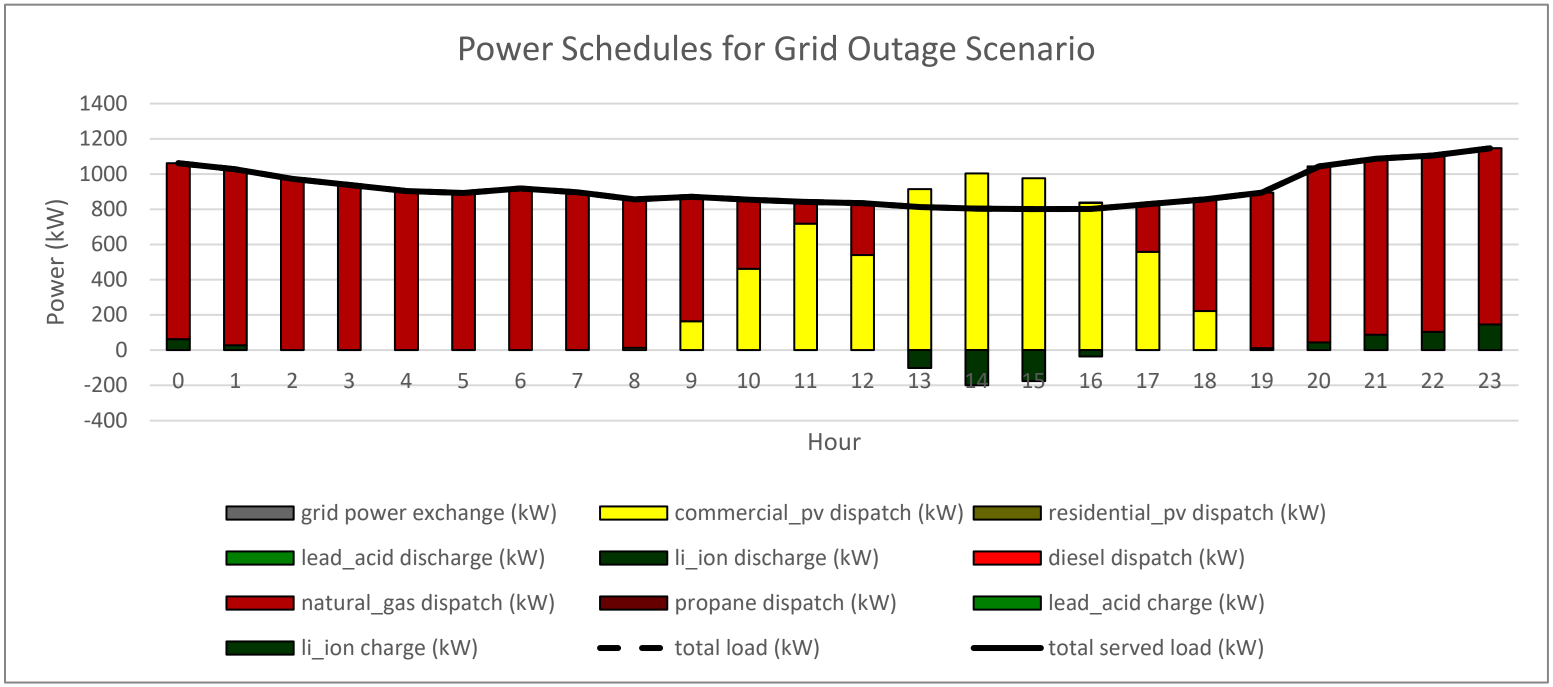


B.2.4. Quebradillas Microgrid 7404-06 CO2 Cost Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	1,333
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	200
5	diesel	generator	0
6	natural_gas	generator	1,000
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	43,294	43,294	20,711	3,597	3,597	1,721
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	6,643	46,501	22,245	552	3,864	1,848
5	0	0	0	0	0	0
6	105,595	14,276,430	6,829,567	8,773	1,186,172	567,442
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	155,532	**14,366,225**	**6,872,523**	**12,923**	**1,193,633**	**571,011**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	46,891	22,432	5,340,072	5,315,613
2	0	0	0	0
3	0	0	0	0
4	50,365	24,094	1,133,238	1,106,966
5	0	0	0	0
6	15,462,602	7,397,008	22,762,743	14,697,150
7	0	0	0	0
8	0	0	0	0
	15,559,858	**7,443,534**	**29,236,053**	**21,119,729**

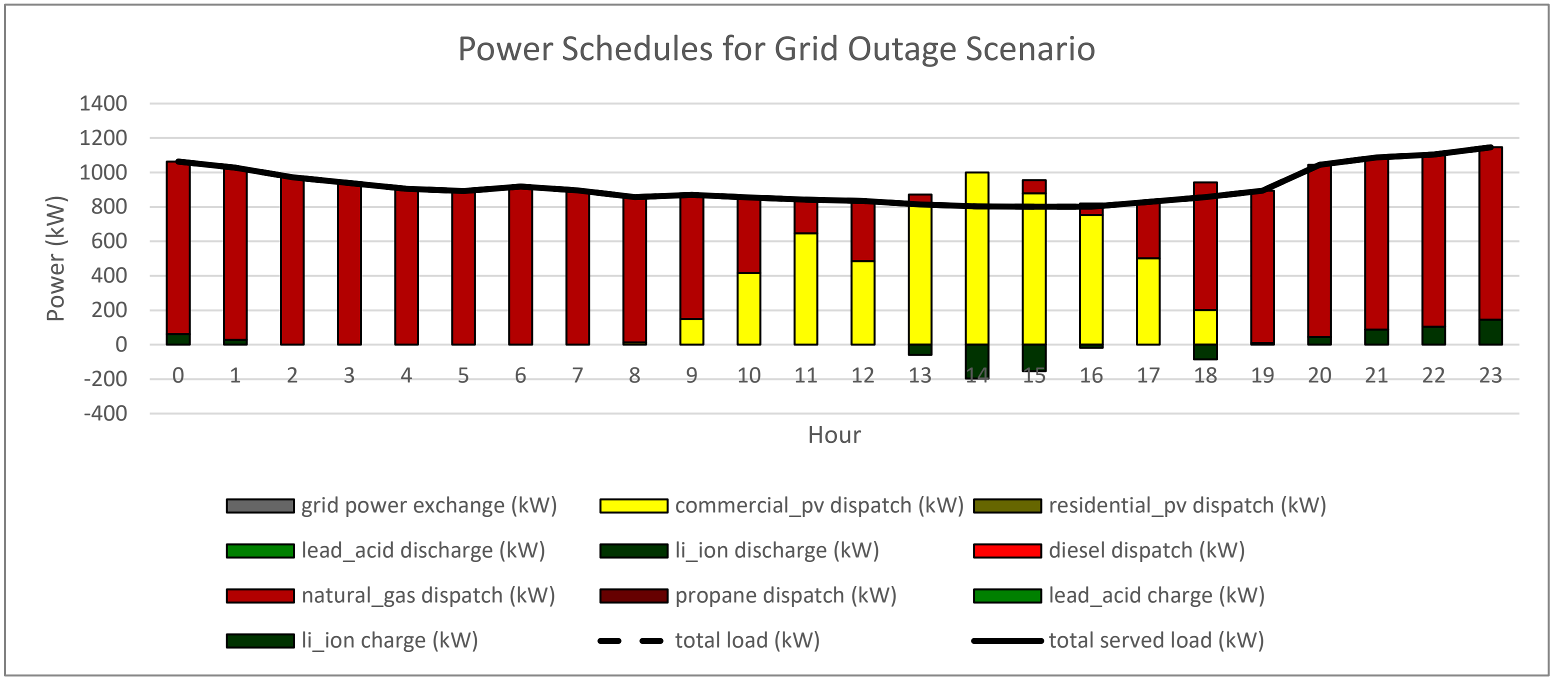


B.2.5. Quebradillas Microgrid 7404-06 Decreasing Demand Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	1,200
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	200
5	diesel	generator	0
6	natural_gas	generator	1,000
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	32,088	32,088	16,320	2,666	2,666	1,356
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	5,381	37,666	19,157	447	3,130	1,592
5	0	0	0	0	0	0
6	88,511	10,975,425	5,582,117	7,354	911,905	463,796
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	125,981	**11,045,180**	**5,617,594**	**10,467**	**917,700**	**466,744**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	34,754	17,676	4,798,618	4,781,540
2	0	0	0	0
3	0	0	0	0
4	40,796	20,749	1,123,668	1,103,621
5	0	0	0	0
6	11,887,330	6,045,913	19,187,472	13,346,054
7	0	0	0	0
8	0	0	0	0
	11,962,880	**6,084,337**	**25,109,757**	**19,231,215**

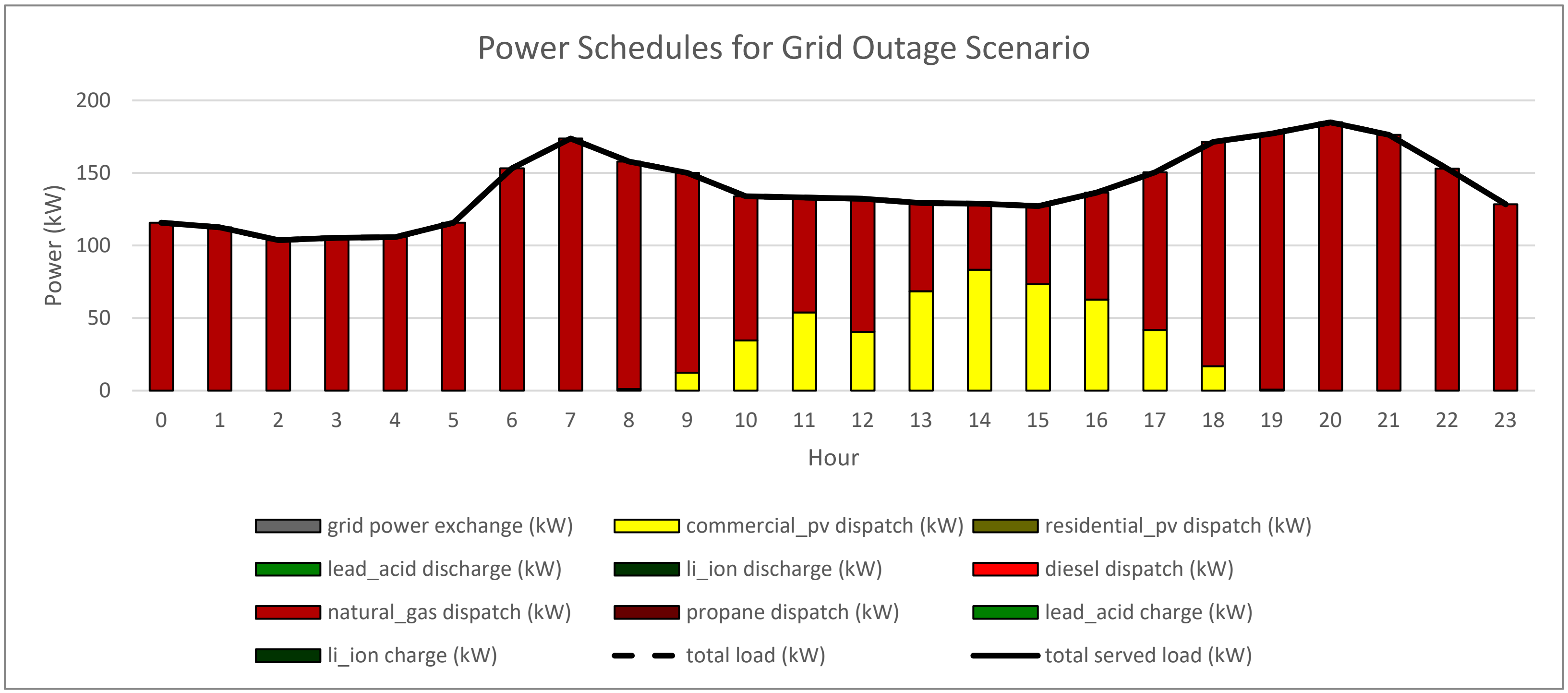


B.2.6. Quebradillas Microgrid 7404-06 High Priority Loads Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	100
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	0
5	diesel	generator	0
6	natural_gas	generator	200
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	3,301	3,301	1,579	274	274	131
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	19,324	2,396,192	1,146,292	1,606	199,090	95,241
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	22,625	**2,399,493**	**1,147,871**	**1,880**	**199,364**	**95,372**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	3,576	1,710	400,564	398,699
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	2,595,282	1,241,533	4,055,311	2,701,561
7	0	0	0	0
8	0	0	0	0
	2,598,858	**1,243,243**	**4,455,875**	**3,100,260**

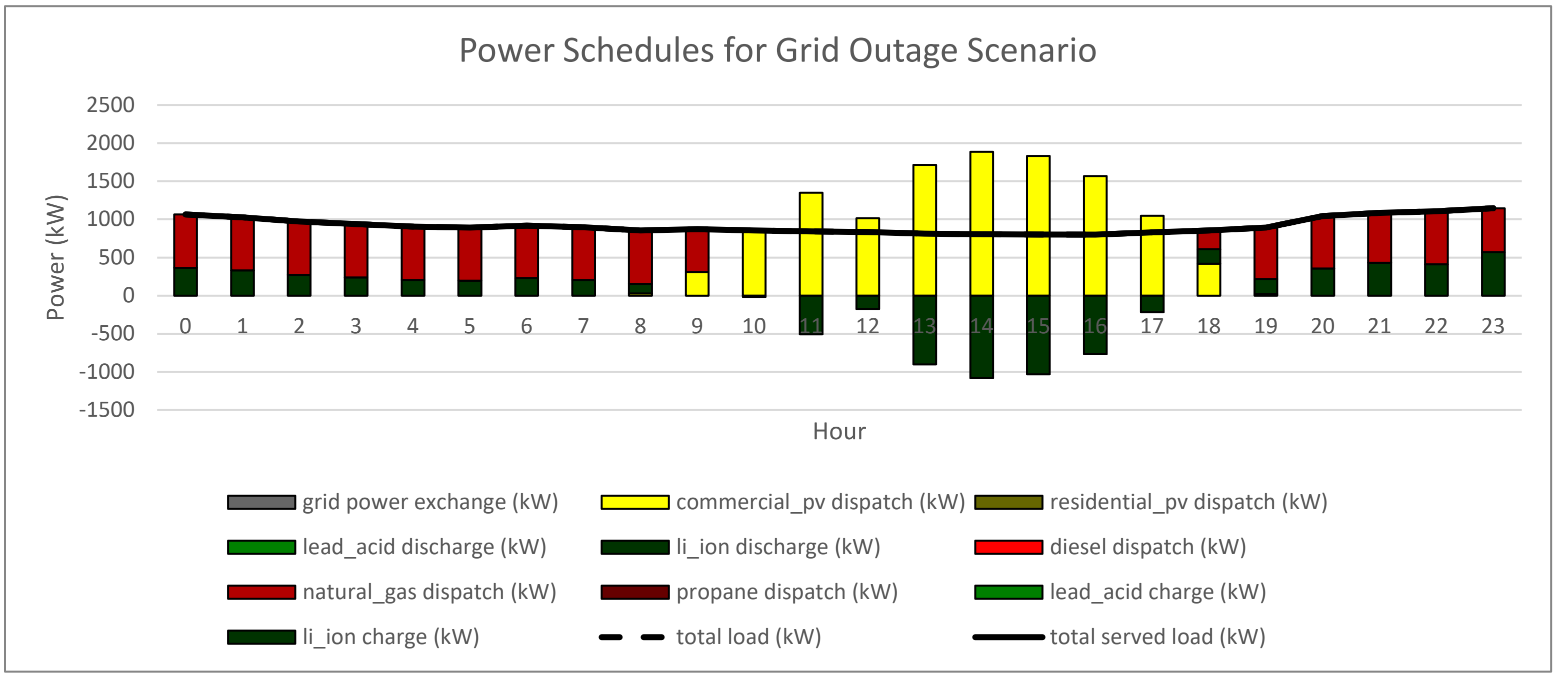


B.2.7. Quebradillas Microgrid 7404-06 Low Discount Rate Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	2,500
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	1,083
5	diesel	generator	0
6	natural_gas	generator	700
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	81,212	81,212	81,212	6,748	6,748	6,748
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	60,858	426,008	426,008	5,056	35,395	35,395
5	0	0	0	0	0	0
6	69,935	8,671,935	8,671,935	5,811	720,517	720,517
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	212,006	**9,179,155**	**9,179,155**	**17,615**	**762,660**	**762,660**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	87,960	87,960	5,162,960	5,162,960
2	0	0	0	0
3	0	0	0	0
4	461,403	461,403	3,336,570	3,336,570
5	0	0	0	0
6	9,392,452	9,392,452	12,276,452	12,276,452
7	0	0	0	0
8	0	0	0	0
	9,941,815	**9,941,815**	**20,775,981**	**20,775,981**

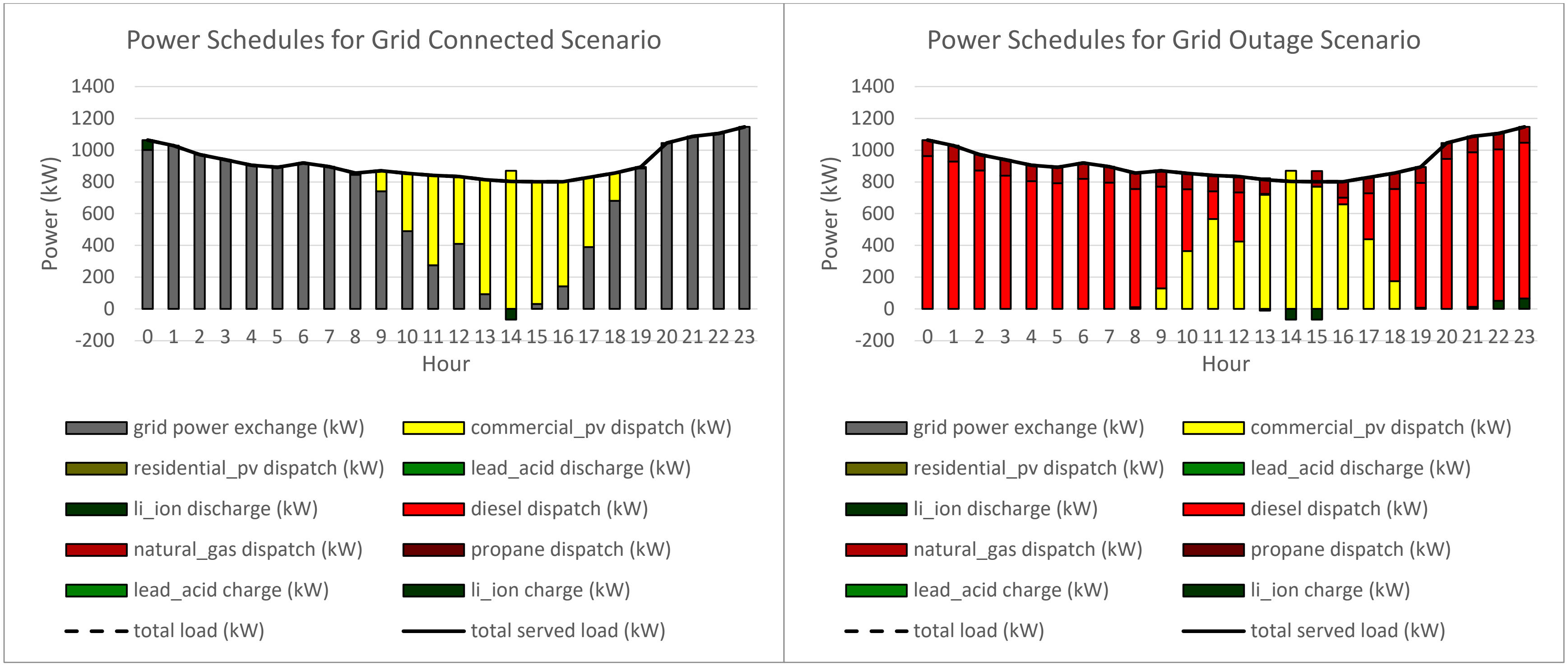


B.2.8. Quebradillas Microgrid 7404-06 Low Utility Electricity Price Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	1,050
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	67
5	diesel	generator	1,000
6	natural_gas	generator	100
7	propane	generator	0
	grid power exchange	--	--

	Grid Connected (Pr = 92.329%)			Grid Outage (Pr = 7.671%)		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	34,632	34,632	16,567	2,877	2,877	1,377
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	863	6,039	2,889	154	1,081	517
5	0	0	0	8,189	1,629,708	779,621
6	0	0	0	1,287	159,597	76,348
7	0	0	0	0	0	0
8	114,016	13,681,884	6,545,148	0	0	0
	149,510	**13,722,555**	**6,564,604**	**12,508**	**1,793,264**	**857,862**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	37,509	17,944	4,205,890	4,186,324
2	0	0	0	0
3	0	0	0	0
4	7,120	3,406	368,077	364,364
5	1,629,708	779,621	8,002,828	7,152,741
6	159,597	76,348	889,612	806,362
7	0	0	0	0
8	13,681,884	6,545,148	13,681,884	6,545,148
	15,515,819	**7,422,466**	**27,148,291**	**19,054,938**

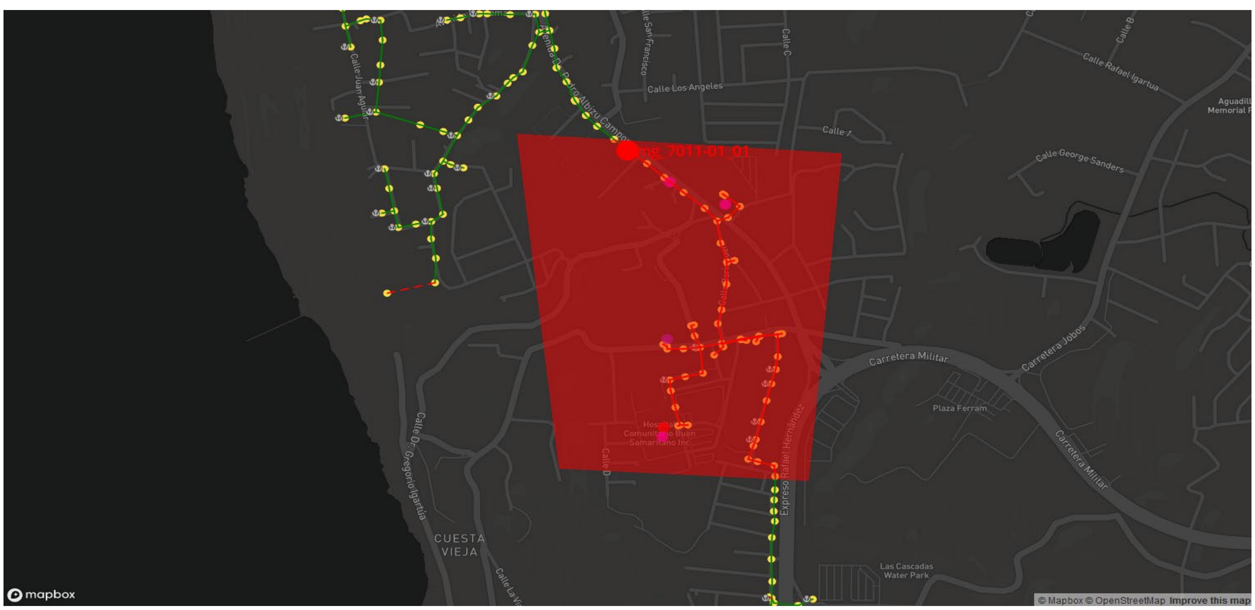

Power Schedules for Grid Connected Scenario
Power Schedules for Grid Outage Scenario
Power (kW)
Hour
1400
1200
1000
800
600
400
200
0
-200
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
grid power exchange (kW)
commercial_pv dispatch (kW)
residential_pv dispatch (kW)
lead_acid discharge (kW)
li_ion discharge (kW)
diesel dispatch (kW)
natural_gas dispatch (kW)
propane dispatch (kW)
lead_acid charge (kW)
li_ion charge (kW)
total load (kW)
total served load (kW)

B.3. Aguadilla Microgrid 7011-01 Results

B.3.1. Aguadilla Microgrid 7011-01 Case Data

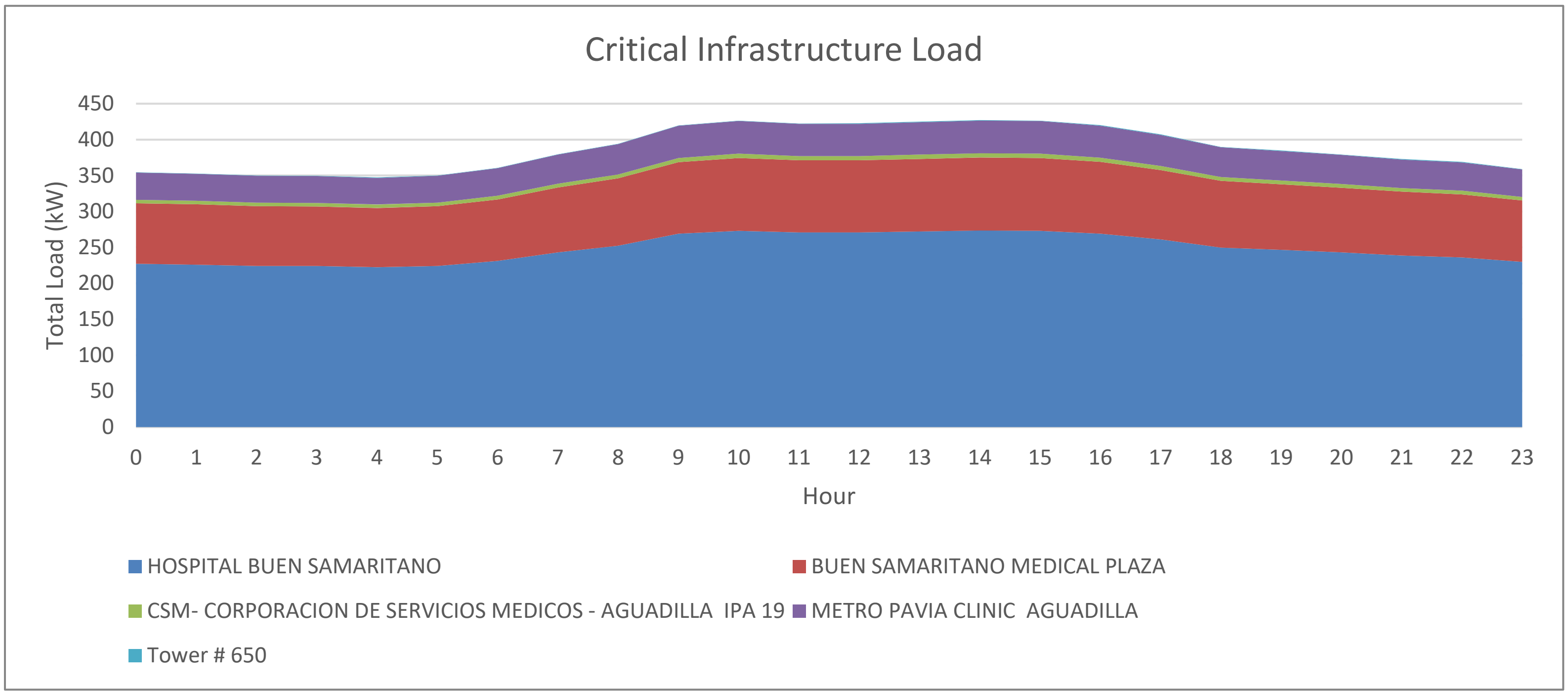
Microgrid Data	
Microgrid ID	mg_7011-01_01
Swing Node	31147549
Nominal Voltage (kV)	13.2
Number of Nodes	57
Number of OH Lines	48
Number of UG Lines	8
Number of Loads	12
Electrical Length (mi)	1.332
Total MW	0.541

Parent Feeder Data	
Feeder ID	7011-01
Swing Node	1000297325
Nominal Voltage (kV)	13.2
Number of Nodes	661
Number of OH Lines	519
Number of UG Lines	141
Number of Loads	206
Electrical Length (mi)	15.152
Total MW	3.701



B.3.2. Aguadilla Microgrid 7011-01 Critical Infrastructure Data

Critical Infrastructure Data					
Name	**Type**	**Power A (kW)**	**Power B (kW)**	**Power C (kW)**	**Priority Level**
HOSPITAL BUEN SAMARITANO	hospital	91.209	91.209	91.209	100
BUEN SAMARITANO MEDICAL PLAZA	clinic	33.832	33.832	33.832	100
CSM- CORPORACION DE SERVICIOS MEDICOS - AGUADILLA IPA 19	clinic	1.992	1.992	1.992	100
METRO PAVIA CLINIC AGUADILLA	clinic	15.127	15.127	15.127	100
Tower # 650	telecom tower	0.216	0.216	0.216	50

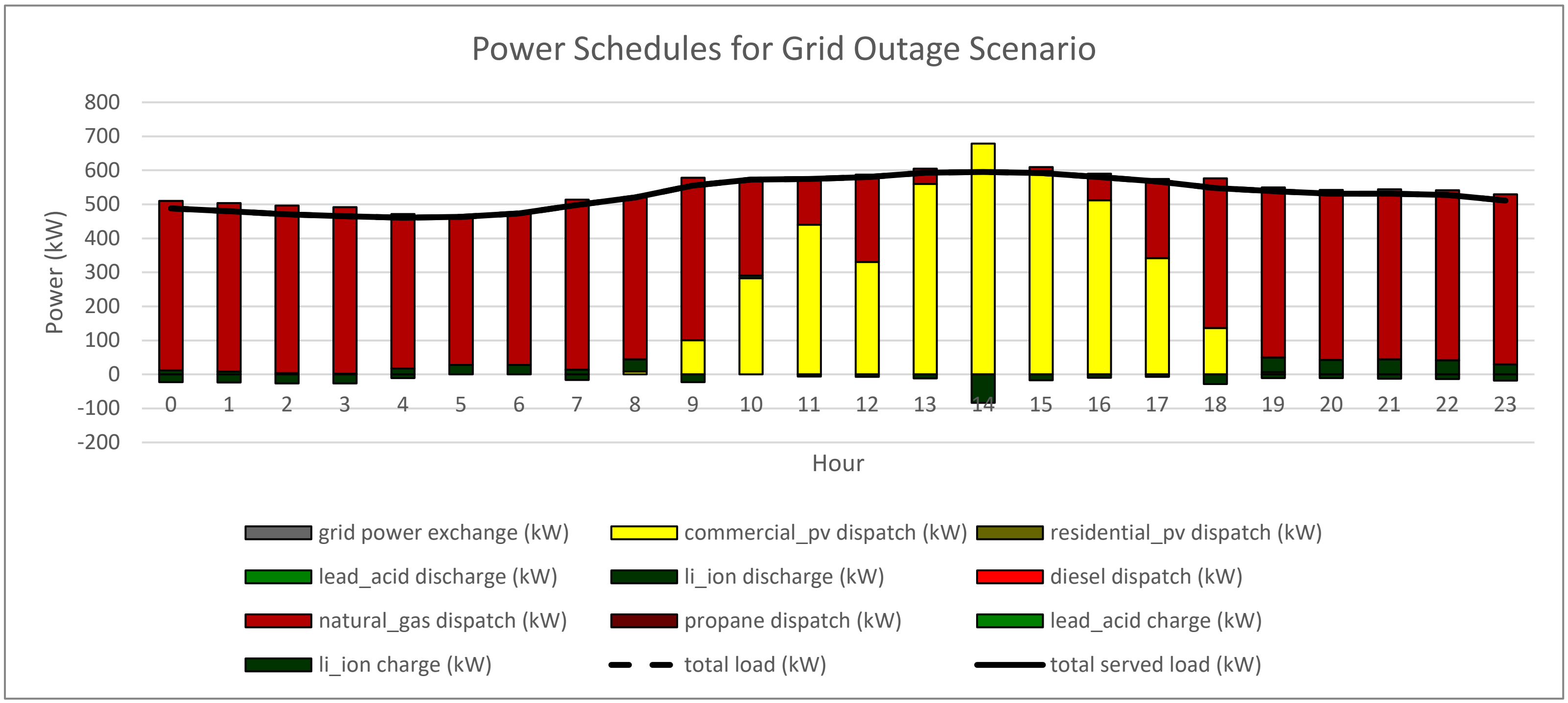


B.3.3. Aguadilla Microgrid 7011-01 Baseline Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	817
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	83
5	diesel	generator	0
6	natural_gas	generator	500
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**			
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Total Lifetime Operating Cost ($)**
1	26,949	26,949	12,892	2,239	2,239	1,071	29,188
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0
4	5,037	35,259	16,867	419	2,930	1,401	38,189
5	0	0	0	0	0	0	0
6	58,970	7,312,342	3,498,082	4,900	607,554	290,642	7,919,896
7	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0
	90,956	**7,374,550**	**3,527,841**	**7,557**	**612,722**	**293,114**	**7,987,272**

DER Asset #	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	13,963	3,271,262	3,256,037
2	0	0	0
3	0	0	0
4	18,269	489,385	469,466
5	0	0	0
6	3,788,724	11,569,966	7,438,795
7	0	0	0
8	0	0	0
	3,820,956	**15,330,613**	**11,164,297**

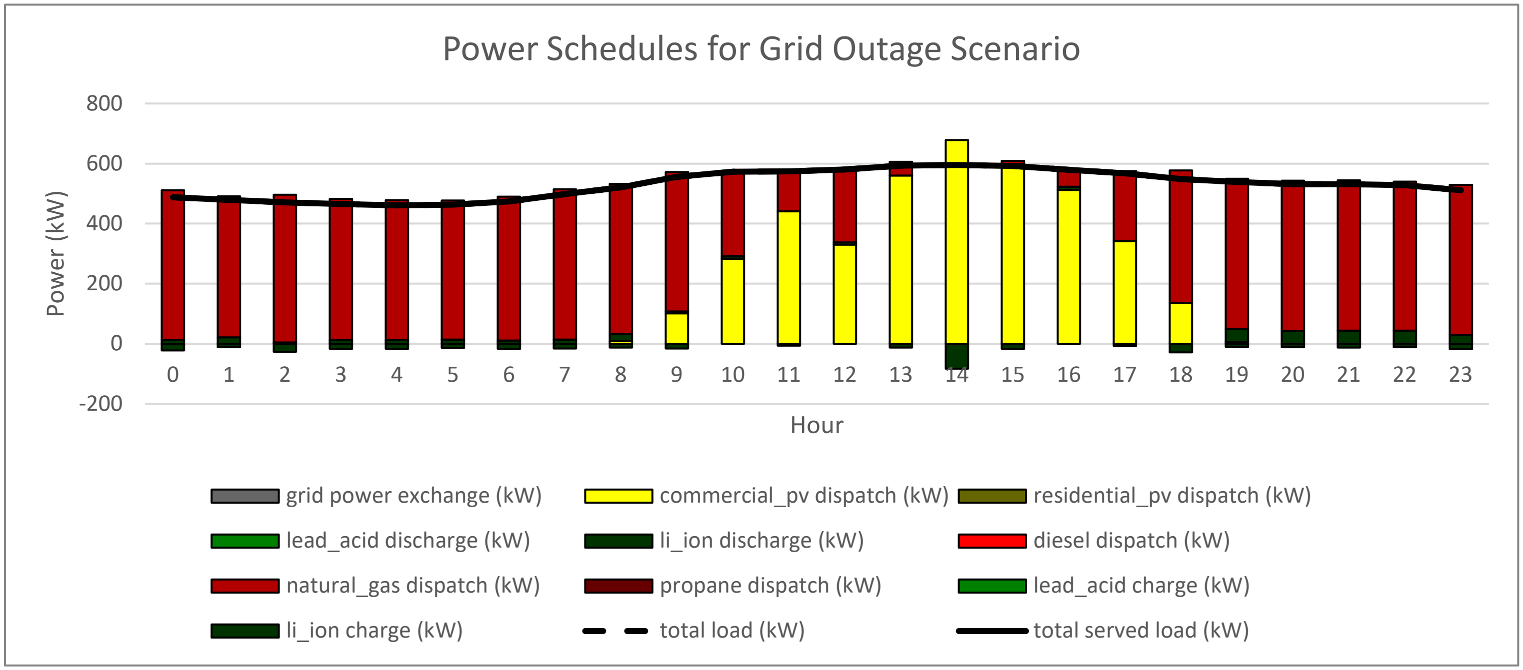


B.3.4. Aguadilla Microgrid 7011-01 CO_2 Cost Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	817
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	83
5	diesel	generator	0
6	natural_gas	generator	500
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			Grid Outage (Pr = 7.671%)		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	26,949	26,949	12,892	2,239	2,239	1,071
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	5,037	35,259	16,867	419	2,930	1,401
5	0	0	0	0	0	0
6	58,970	7,972,812	3,814,038	4,900	662,429	316,893
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	90,956	**8,035,019**	**3,843,797**	**7,557**	**667,598**	**319,366**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	29,188	13,963	3,271,262	3,256,037
2	0	0	0	0
3	0	0	0	0
4	38,189	18,269	489,385	469,466
5	0	0	0	0
6	8,635,241	4,130,931	12,285,312	7,781,002
7	0	0	0	0
8	0	0	0	0
	8,702,617	**4,163,163**	**16,045,959**	**11,506,504**

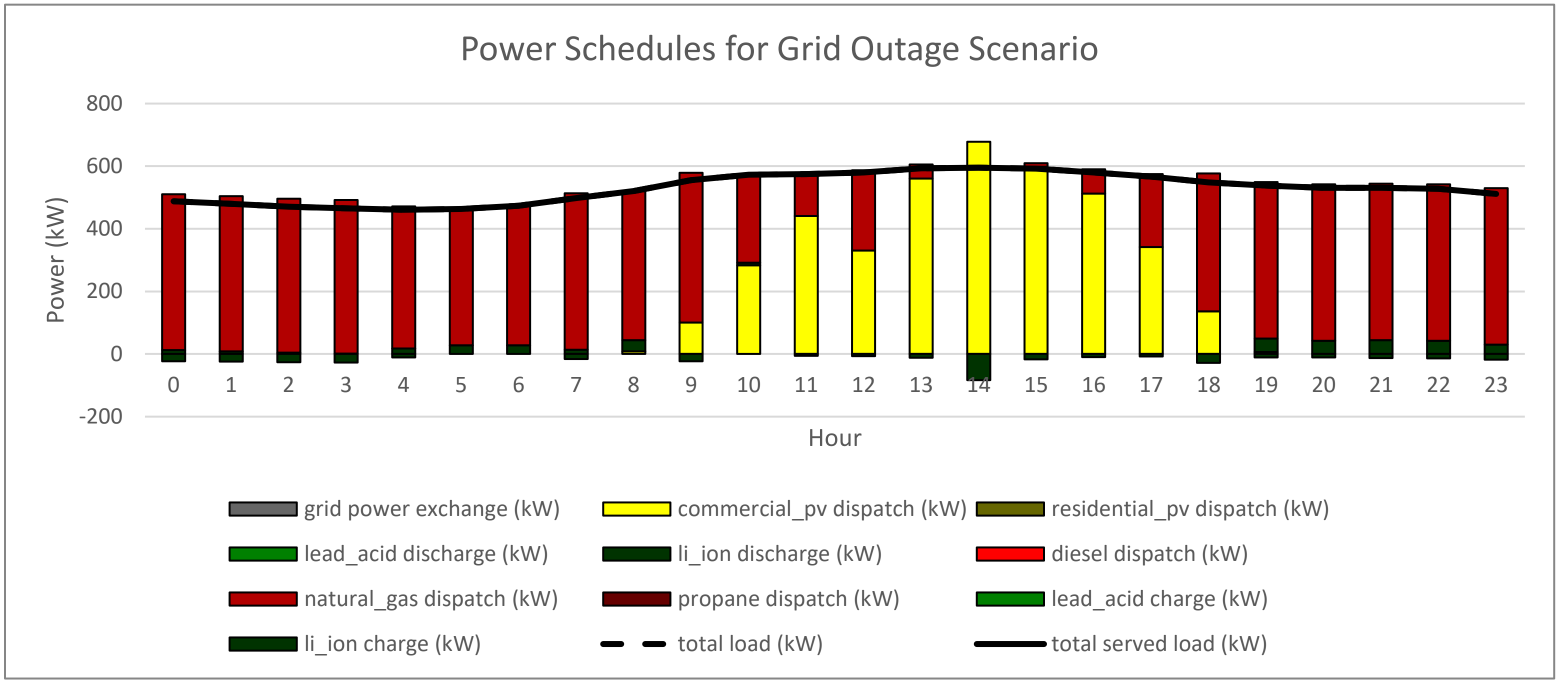


B.3.5. Aguadilla Microgrid 7011-01 Decreasing Demand Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	817
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	83
5	diesel	generator	0
6	natural_gas	generator	500
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	21,829	21,829	11,102	1,814	1,814	922
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	4,080	28,560	14,526	339	2,373	1,207
5	0	0	0	0	0	0
6	47,766	5,922,997	3,012,444	3,969	492,118	250,292
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	73,675	**5,973,385**	**3,038,072**	**6,121**	**496,305**	**252,421**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	23,642	12,024	3,265,716	3,254,098
2	0	0	0	0
3	0	0	0	0
4	30,933	15,732	482,130	466,929
5	0	0	0	0
6	6,415,115	3,262,737	10,065,186	6,912,807
7	0	0	0	0
8	0	0	0	0
	6,469,690	**3,290,493**	**13,813,032**	**10,633,835**

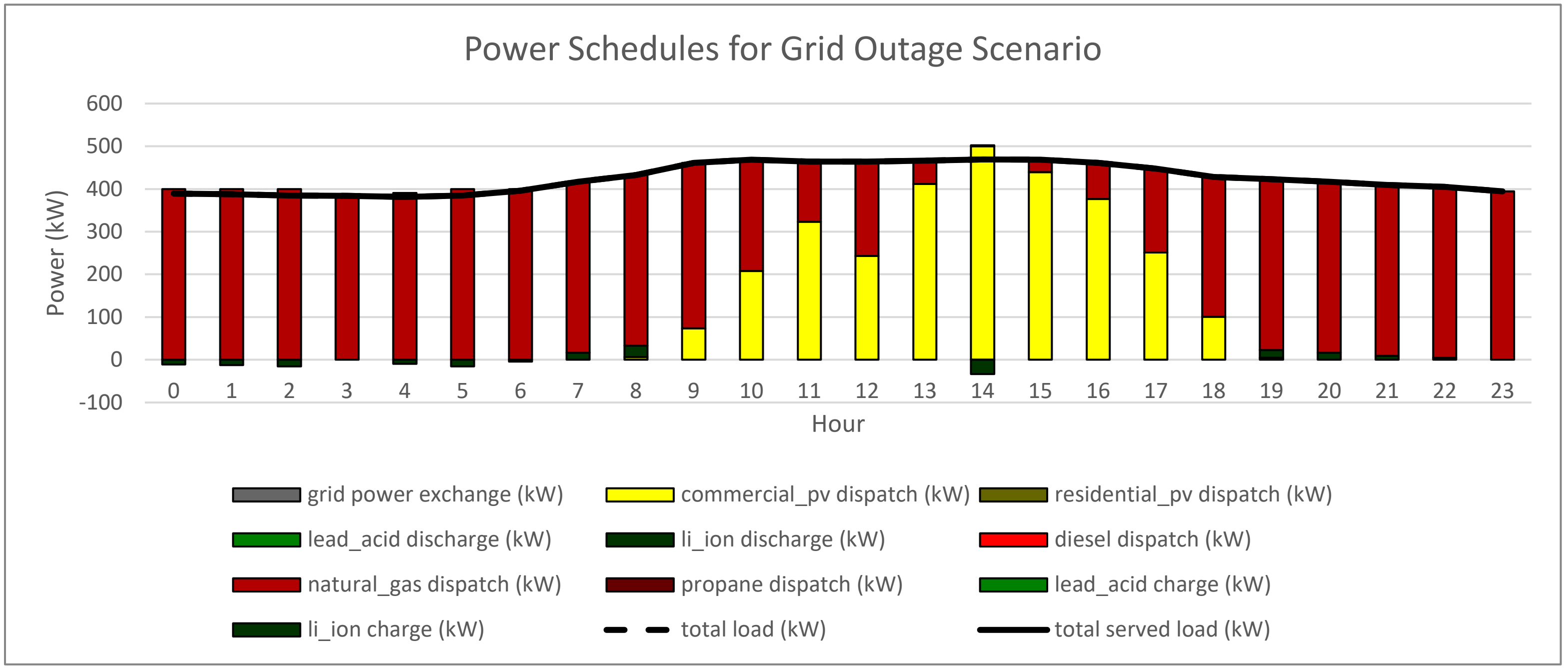


B.3.6. Aguadilla Microgrid 7011-01 High Priority Loads Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	600
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	33
5	diesel	generator	0
6	natural_gas	generator	400
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	19,808	19,808	9,476	1,646	1,646	787
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	1,301	9,109	4,357	108	757	362
5	0	0	0	0	0	0
6	49,026	6,079,220	2,908,181	4,073	505,098	241,629
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	70,135	**6,108,136**	**2,922,014**	**5,827**	**507,501**	**242,779**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	21,453	10,263	2,403,385	2,392,195
2	0	0	0	0
3	0	0	0	0
4	9,865	4,719	190,344	185,198
5	0	0	0	0
6	6,584,319	3,149,810	9,504,375	6,069,867
7	0	0	0	0
8	0	0	0	0
	6,615,637	**3,164,792**	**12,098,104**	**8,647,259**

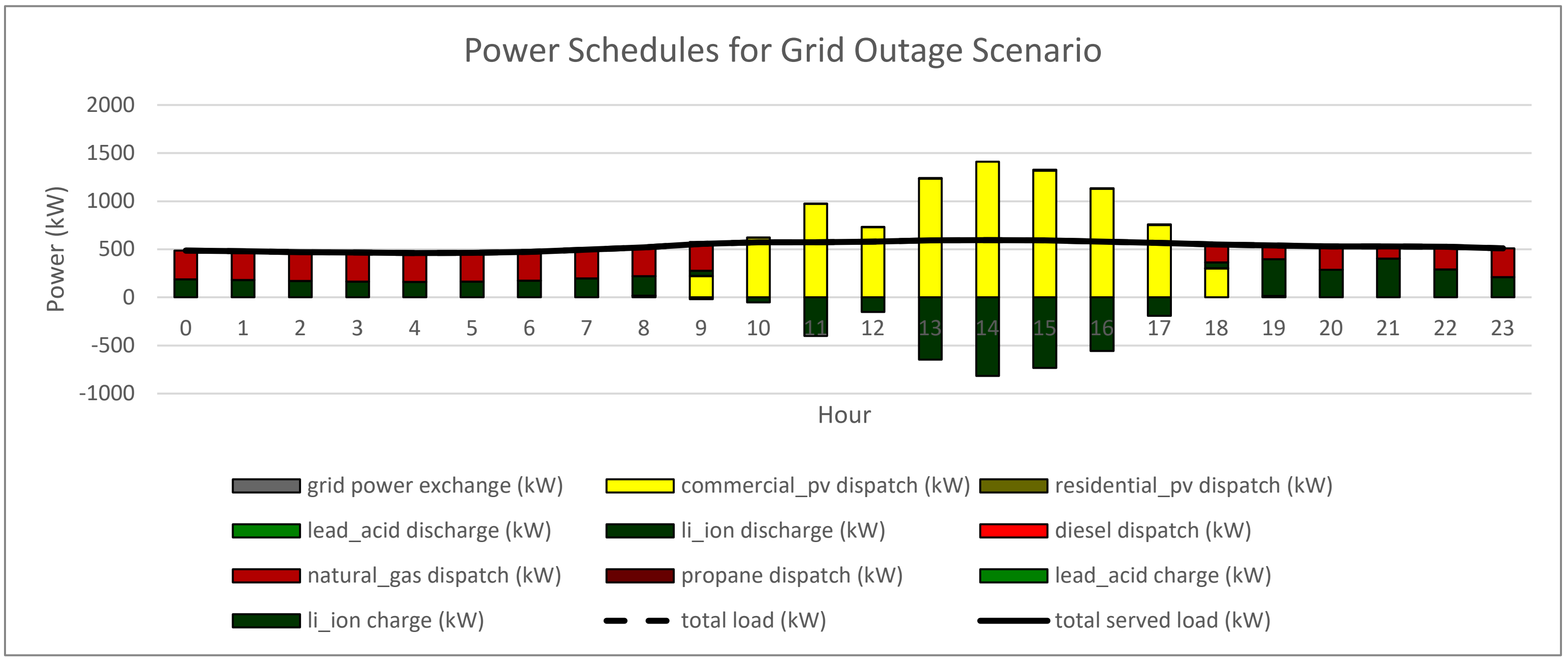


B.3.7. Aguadilla Microgrid 7011-01 Low Discount Rate Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	1,800
2	residential_pv	pv	10
3	lead_acid	storage	0
4	li_ion	storage	817
5	diesel	generator	0
6	natural_gas	generator	300
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	58,747	58,747	58,747	4,886	4,886	4,886
2	330	330	330	23	23	23
3	0	0	0	0	0	0
4	46,208	323,456	323,456	3,839	26,875	26,875
5	0	0	0	0	0	0
6	28,558	3,541,197	3,541,197	2,373	294,224	294,224
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	133,843	**3,923,729**	**3,923,729**	**11,120**	**326,007**	**326,007**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	63,632	63,632	3,717,632	3,717,632
2	353	353	29,353	29,353
3	0	0	0	0
4	350,330	350,330	2,517,764	2,517,764
5	0	0	0	0
6	3,835,421	3,835,421	5,071,421	5,071,421
7	0	0	0	0
8	0	0	0	0
	4,249,736	**4,249,736**	**11,336,170**	**11,336,170**

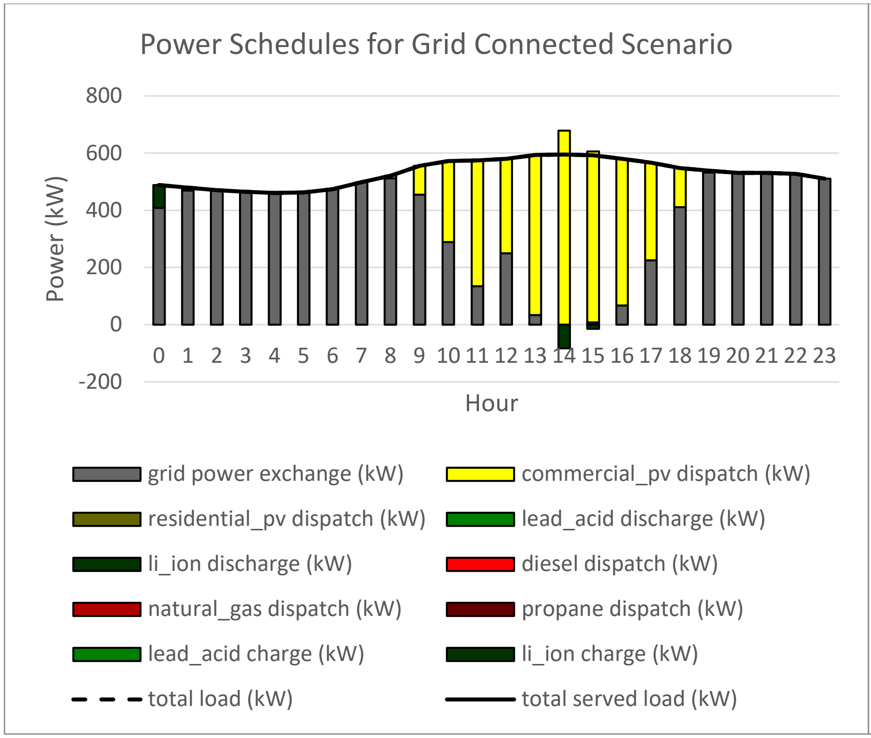


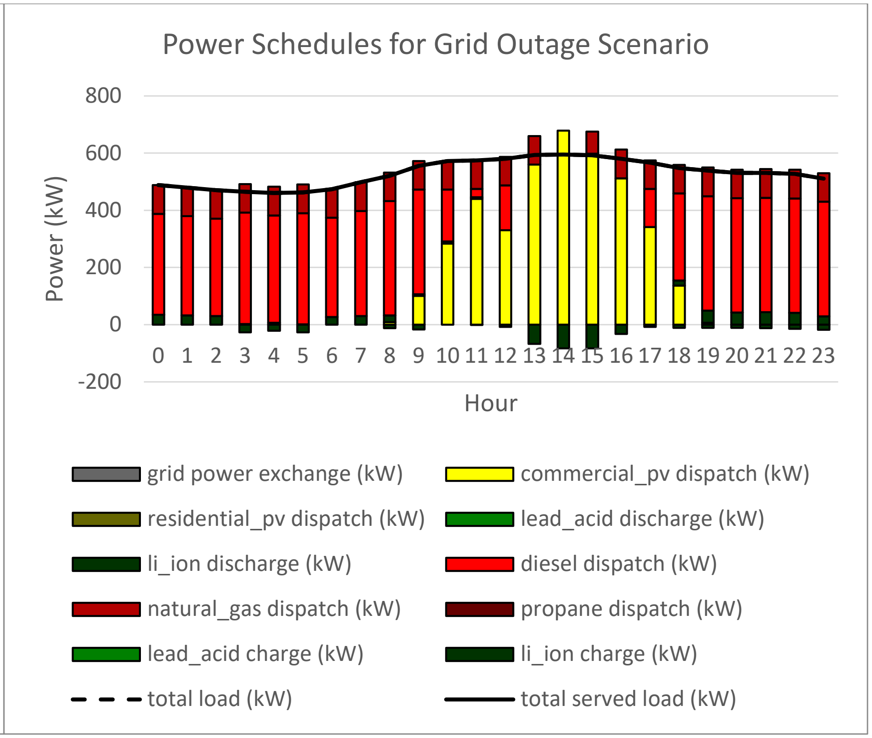
B.3.8. Aguadilla Microgrid 7011-01 Low Utility Electricity Price Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	817
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	83
5	diesel	generator	400
6	natural_gas	generator	100
7	propane	generator	0
8	grid power exchange	--	--

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	26,949	26,949	12,892	2,239	2,239	1,071
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	1,260	8,820	4,219	499	3,491	1,670
5	0	0	0	3,628	721,910	345,348
6	0	0	0	1,275	158,135	75,649
7	0	0	0	0	0	0
8	58,813	7,057,575	3,376,207	0	0	0
	87,022	**7,093,343**	**3,393,318**	**7,641**	**885,775**	**423,738**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	29,188	13,963	3,271,262	3,256,037
2	0	0	0	0
3	0	0	0	0
4	12,311	5,889	463,508	457,086
5	721,910	345,348	3,271,158	2,894,596
6	158,135	75,649	888,149	805,663
7	0	0	0	0
8	7,057,575	3,376,207	7,057,575	3,376,207
	7,979,119	**3,817,055**	**14,951,652**	**10,789,588**


Power Schedules for Grid Connected Scenario
800
600
400
200
0
-200
Power (kW)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour
grid power exchange (kW)
commercial_pv dispatch (kW)
residential_pv dispatch (kW)
lead_acid discharge (kW)
li_ion discharge (kW)
diesel dispatch (kW)
natural_gas dispatch (kW)
propane dispatch (kW)
lead_acid charge (kW)
li_ion charge (kW)
total load (kW)
total served load (kW)


Power Schedules for Grid Outage Scenario
800
600
400
200
0
-200
Power (kW)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour
grid power exchange (kW)
commercial_pv dispatch (kW)
residential_pv dispatch (kW)
lead_acid discharge (kW)
li_ion discharge (kW)
diesel dispatch (kW)
natural_gas dispatch (kW)
propane dispatch (kW)
lead_acid charge (kW)
li_ion charge (kW)
total load (kW)
total served load (kW)

B.4. Peñuelas Microgrid 5401-03 Results

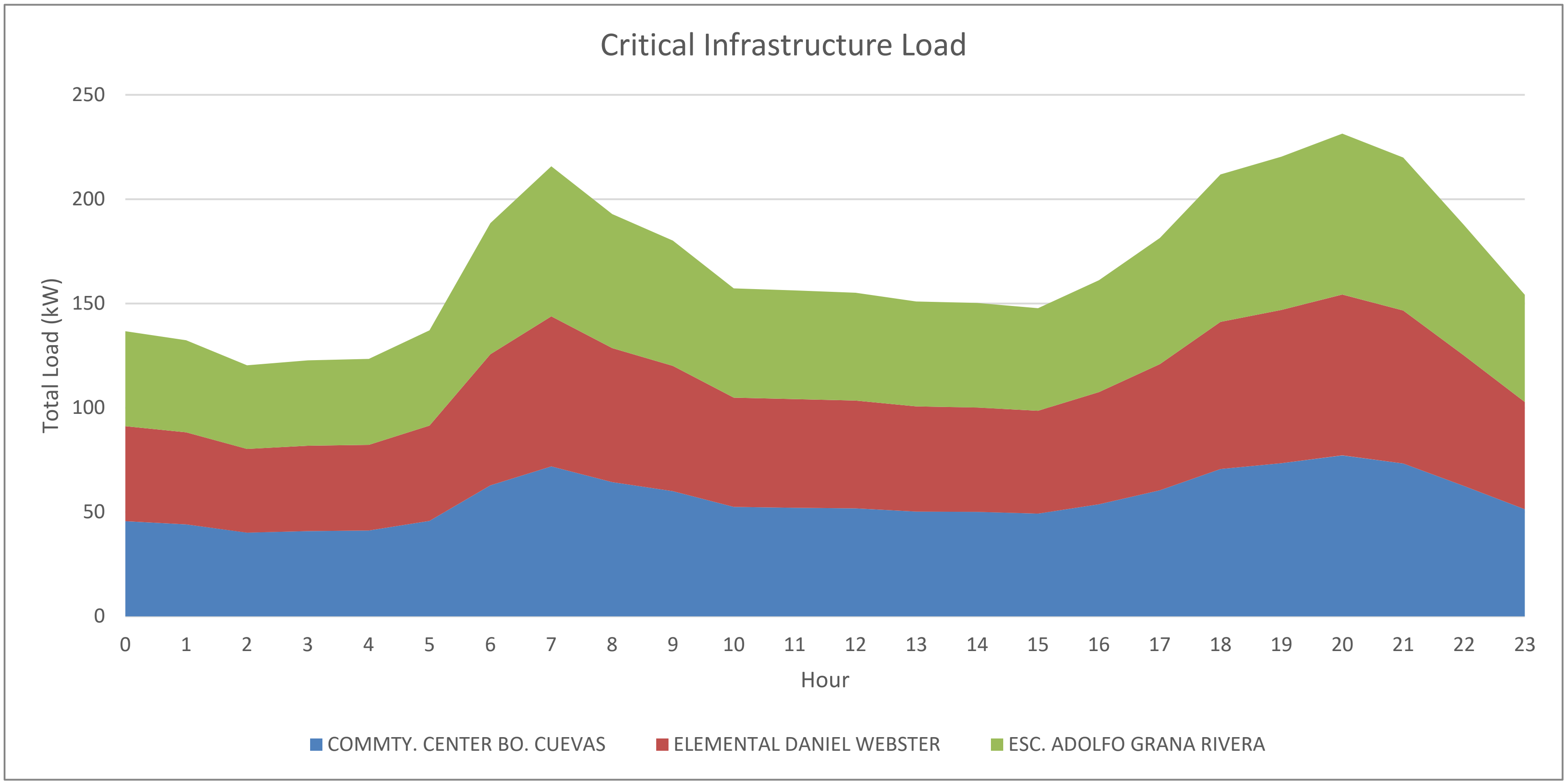
B.4.1. Peñuelas Microgrid 5401-03 Case Data

Microgrid Data	
Microgrid ID	mg_5401-03_01
Swing Node	11149161
Nominal Voltage (kV)	4.16
Number of Nodes	297
Number of OH Lines	286
Number of UG Lines	10
Number of Loads	127
Electrical Length (mi)	7.386
Total MW	1.433

Parent Feeder Data	
Feeder ID	5401-03
Swing Node	11149161
Nominal Voltage (kV)	4.16
Number of Nodes	403
Number of OH Lines	390
Number of UG Lines	12
Number of Loads	174
Electrical Length (mi)	13.135
Total MW	1.544

B.4.2. Peñuelas Microgrid 5401-03 Critical Infrastructure Data

Critical Infrastructure Data					
Name	**Type**	**Power A (kW)**	**Power B (kW)**	**Power C (kW)**	**Priority Level**
COMMTY. CENTER BO. CUEVAS	shelter	25.711	25.711	25.711	75
ELEMENTAL DANIEL WEBSTER	shelter	25.711	25.711	25.711	75
ESC. ADOLFO GRANA RIVERA	shelter	25.711	25.711	25.711	75

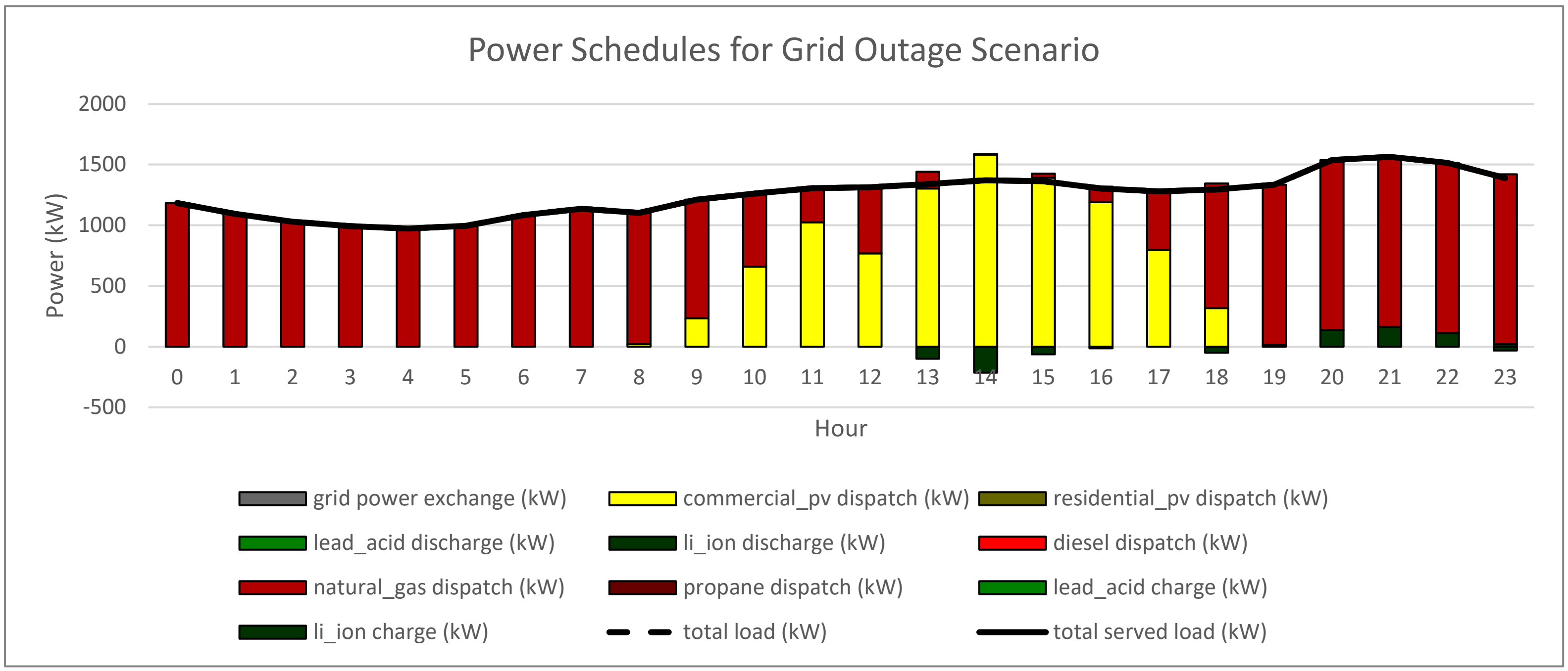


B.4.3. Peñuelas Microgrid 5401-03 Baseline Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	1,900
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	217
5	diesel	generator	0
6	natural_gas	generator	1,400
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	62,724	62,724	30,006	5,211	5,211	2,493
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	6,138	42,964	20,553	510	3,570	1,708
5	0	0	0	0	0	0
6	139,582	17,308,134	8,279,875	11,597	1,438,065	687,942
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	208,443	**17,413,822**	**8,330,434**	**17,319**	**1,446,846**	**692,143**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	67,935	32,499	7,610,719	7,575,283
2	0	0	0	0
3	0	0	0	0
4	46,534	22,261	1,219,646	1,195,373
5	0	0	0	0
6	18,746,199	8,967,817	28,966,397	19,188,015
7	0	0	0	0
8	0	0	0	0
	18,860,668	**9,022,577**	**37,796,762**	**27,958,671**

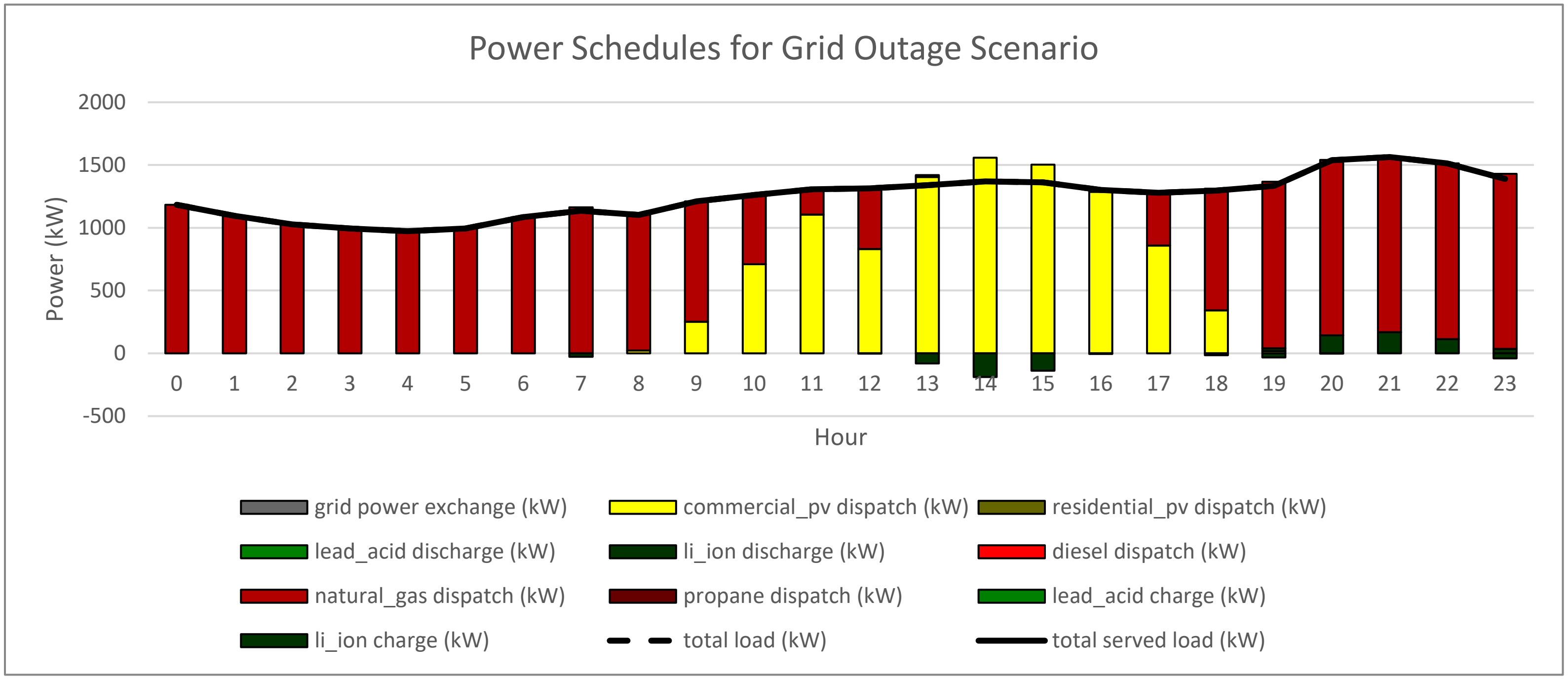


B.4.4. Peñuelas Microgrid 5401-03 CO2 Cost Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	2,050
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	217
5	diesel	generator	0
6	natural_gas	generator	1,400
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	66,864	66,864	31,986	5,540	5,540	2,650
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	6,823	47,761	22,848	567	3,968	1,898
5	0	0	0	0	0	0
6	135,470	18,315,556	8,761,806	11,272	1,523,925	729,016
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	209,157	**18,430,182**	**8,816,641**	**17,378**	**1,533,433**	**733,565**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	72,403	34,636	8,210,670	8,172,903
2	0	0	0	0
3	0	0	0	0
4	51,730	24,746	1,224,842	1,197,858
5	0	0	0	0
6	19,839,482	9,490,822	30,059,680	19,711,020
7	0	0	0	0
8	0	0	0	0
	19,963,615	**9,550,205**	**39,495,191**	**29,081,782**

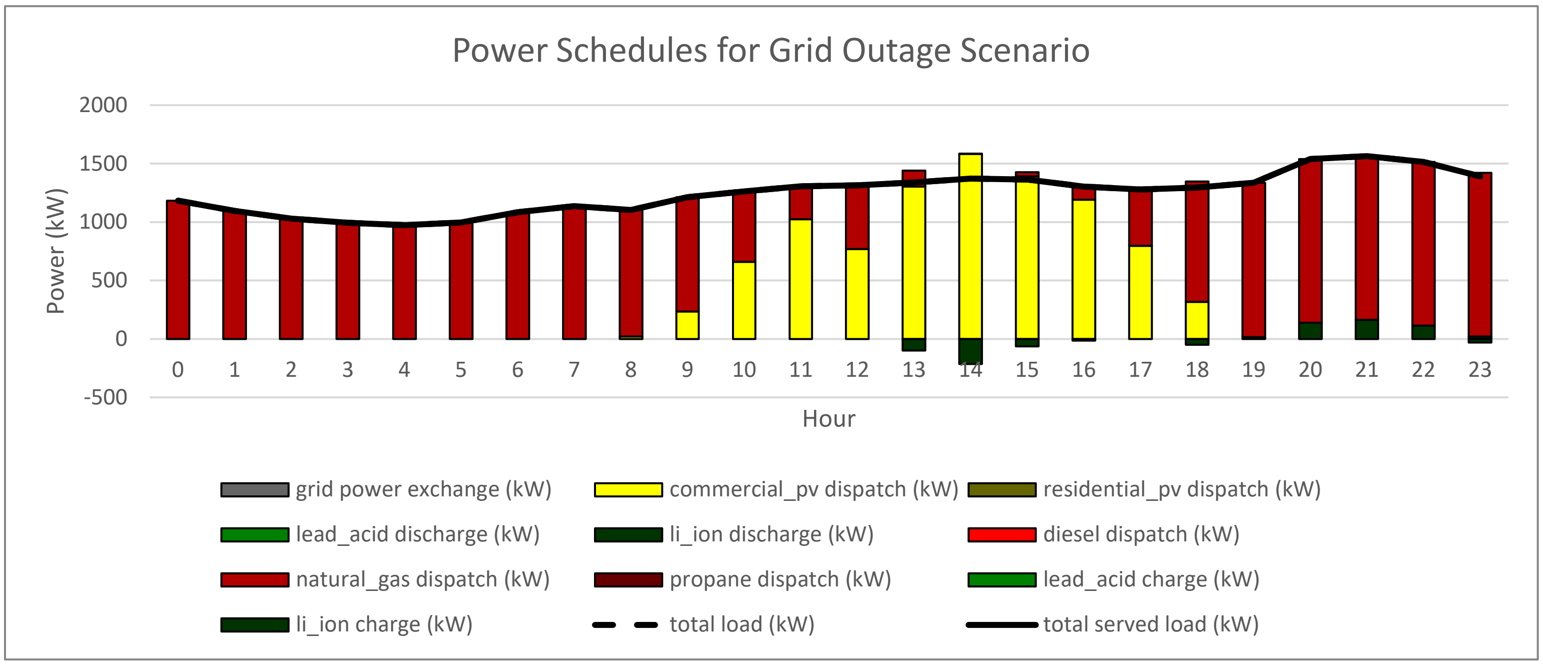


B.4.5. Peñuelas Microgrid 5401-03 Decreasing Demand Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	1,900
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	217
5	diesel	generator	0
6	natural_gas	generator	1,400
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	50,806	50,806	25,840	4,221	4,221	2,147
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	4,972	34,801	17,700	413	2,891	1,471
5	0	0	0	0	0	0
6	113,061	14,019,589	7,130,382	9,394	1,164,832	592,435
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	168,839	**14,105,196**	**7,173,922**	**14,028**	**1,171,945**	**596,053**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	55,028	27,987	7,597,811	7,570,771
2	0	0	0	0
3	0	0	0	0
4	37,693	19,171	1,210,805	1,192,282
5	0	0	0	0
6	15,184,421	7,722,818	25,404,619	17,943,016
7	0	0	0	0
8	0	0	0	0
	15,277,141	**7,769,975**	**34,213,235**	**26,706,069**

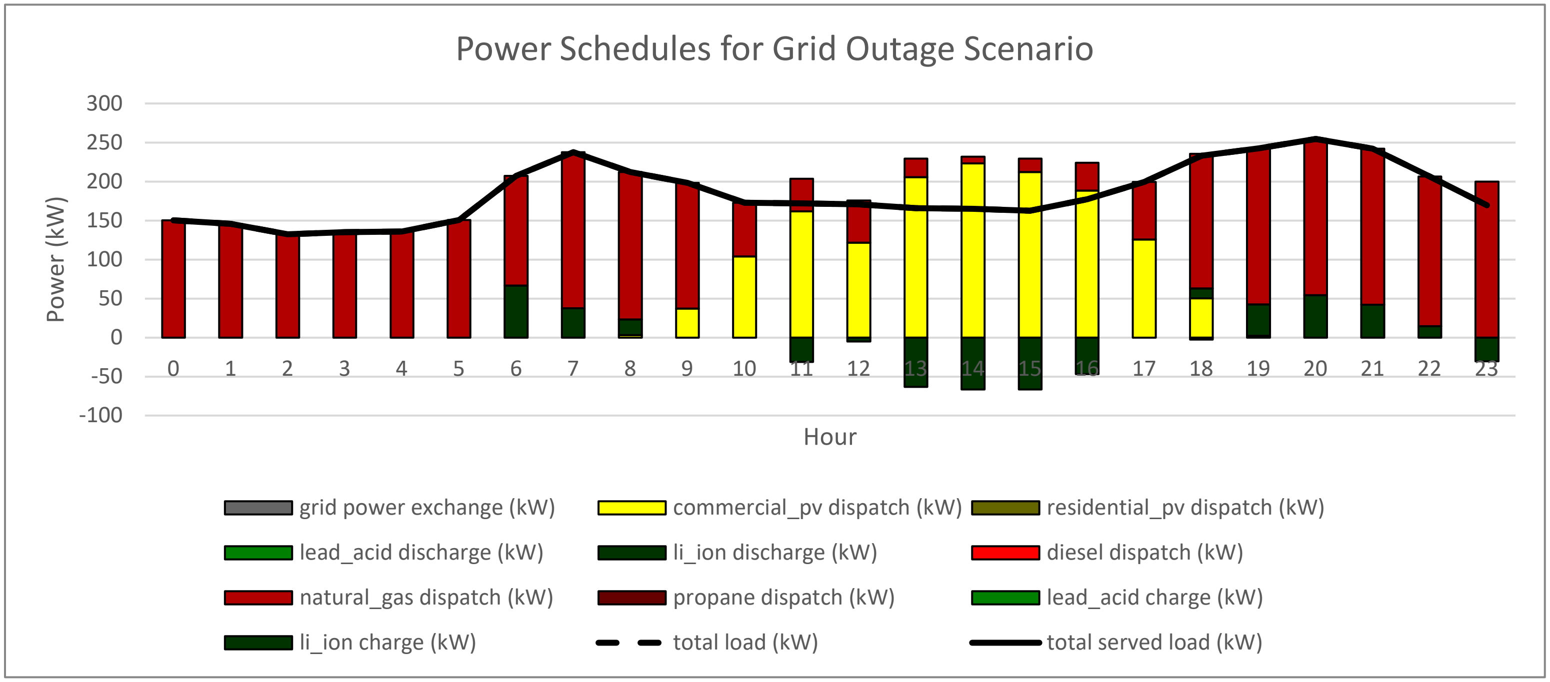


B.4.6. Peñuelas Microgrid 5401-03 High Priority Loads Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	300
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	67
5	diesel	generator	0
6	natural_gas	generator	200
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			Grid Outage (Pr = 7.671%)		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	9,674	9,674	4,628	804	804	384
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	4,051	28,354	13,564	337	2,356	1,127
5	0	0	0	0	0	0
6	20,411	2,531,010	1,210,786	1,696	210,292	100,599
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	34,136	**2,569,037**	**1,228,977**	**2,836**	**213,451**	**102,111**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	10,477	5,012	1,201,443	1,195,978
2	0	0	0	0
3	0	0	0	0
4	30,710	14,691	391,667	375,648
5	0	0	0	0
6	2,741,301	1,311,385	4,201,330	2,771,414
7	0	0	0	0
8	0	0	0	0
	2,782,488	**1,331,088**	**5,794,440**	**4,343,040**

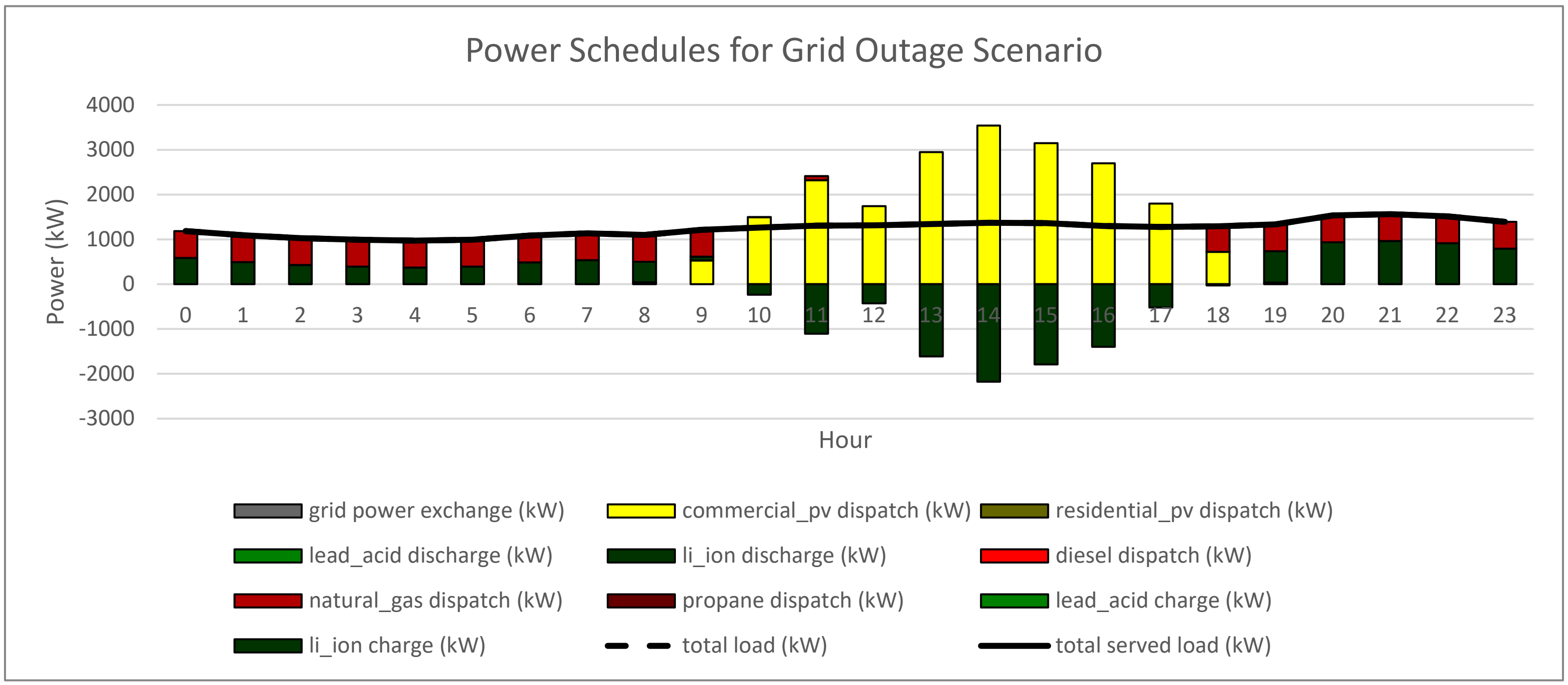


B.4.7. Peñuelas Microgrid 5401-03 Low Discount Rate Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	4,300
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	2,183
5	diesel	generator	0
6	natural_gas	generator	600
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	141,703	141,703	141,703	11,774	11,774	11,774
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	120,095	840,664	840,664	9,978	69,847	69,847
5	0	0	0	0	0	0
6	65,350	8,103,439	8,103,439	5,430	673,283	673,283
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	327,149	**9,085,806**	**9,085,806**	**27,181**	**754,904**	**754,904**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	153,477	153,477	8,882,477	8,882,477
2	0	0	0	0
3	0	0	0	0
4	910,511	910,511	6,705,078	6,705,078
5	0	0	0	0
6	8,776,722	8,776,722	11,248,722	11,248,722
7	0	0	0	0
8	0	0	0	0
	9,840,710	**9,840,710**	**26,836,277**	**26,836,277**

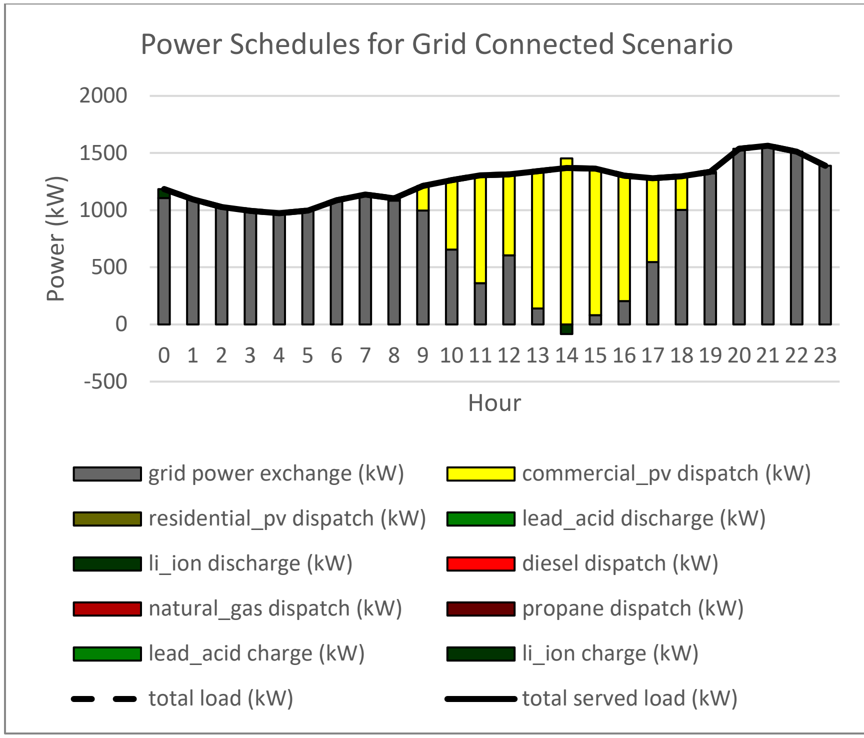


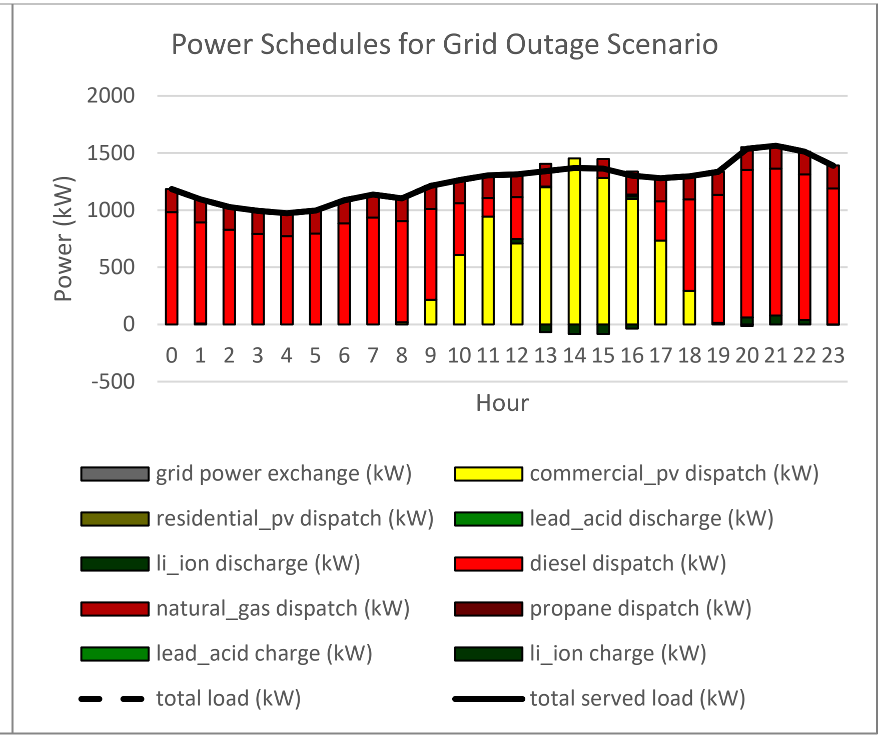
B.4.8. Peñuelas Microgrid 5401-03 Low Utility Electricity Price Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	1,750
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	83
5	diesel	generator	1,300
6	natural_gas	generator	200
7	propane	generator	0
8	grid power exchange	--	--

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	57,746	57,746	27,624	4,798	4,798	2,295
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	1,078	7,549	3,611	304	2,129	1,019
5	0	0	0	9,446	1,879,819	899,269
6	0	0	0	2,556	316,945	151,620
7	0	0	0	0	0	0
8	144,349	17,321,883	8,286,452	0	0	0
	203,173	**17,387,178**	**8,317,688**	**17,104**	**2,203,691**	**1,054,203**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	62,544	29,920	7,009,844	6,977,220
2	0	0	0	0
3	0	0	0	0
4	9,678	4,630	460,875	455,827
5	1,879,819	899,269	10,164,875	9,184,325
6	316,945	151,620	1,776,973	1,611,648
7	0	0	0	0
8	17,321,883	8,286,452	17,321,883	8,286,452
	19,590,869	**9,371,891**	**36,734,451**	**26,515,473**


Power Schedules for Grid Connected Scenario
Power (kW)
2000
1500
1000
500
0
-500
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour
grid power exchange (kW)
commercial_pv dispatch (kW)
residential_pv dispatch (kW)
lead_acid discharge (kW)
li_ion discharge (kW)
diesel dispatch (kW)
natural_gas dispatch (kW)
propane dispatch (kW)
lead_acid charge (kW)
li_ion charge (kW)
total load (kW)
total served load (kW)


Power Schedules for Grid Outage Scenario
Power (kW)
2000
1500
1000
500
0
-500
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour
grid power exchange (kW)
commercial_pv dispatch (kW)
residential_pv dispatch (kW)
lead_acid discharge (kW)
li_ion discharge (kW)
diesel dispatch (kW)
natural_gas dispatch (kW)
propane dispatch (kW)
lead_acid charge (kW)
li_ion charge (kW)
total load (kW)
total served load (kW)

B.5. Maunabo Microgrid 4301-01 Results

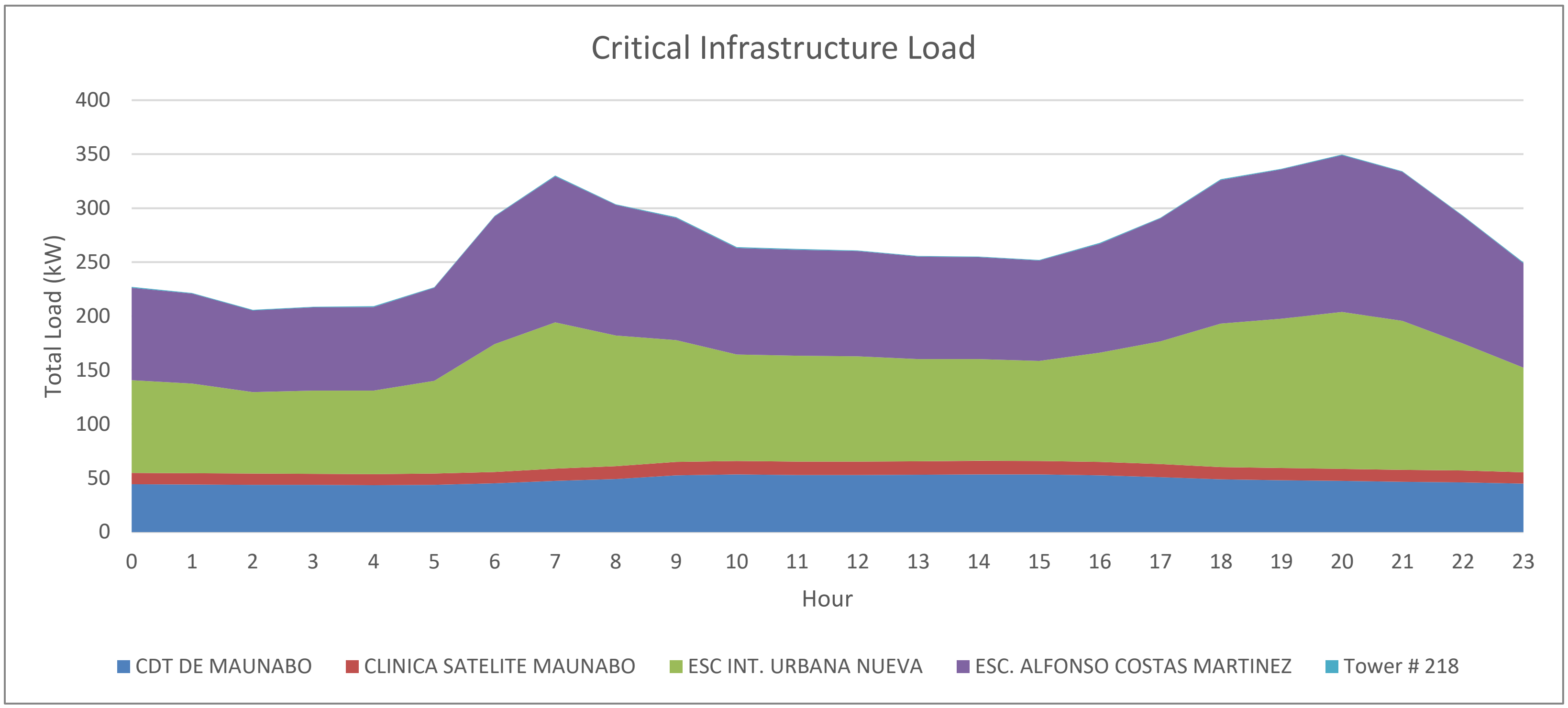
B.5.1. Maunabo Microgrid 4301-01 Case Data

Microgrid Data	
Microgrid ID	mg_4301-01_01
Swing Node	1000164881
Nominal Voltage (kV)	4.16
Number of Nodes	210
Number of OH Lines	176
Number of UG Lines	33
Number of Loads	72
Electrical Length (mi)	3.858
Total MW	0.933

Parent Feeder Data	
Feeder ID	4301-01
Swing Node	6672026
Nominal Voltage (kV)	4.16
Number of Nodes	610
Number of OH Lines	567
Number of UG Lines	42
Number of Loads	207
Electrical Length (mi)	17.508
Total MW	1.723

B.5.2. Maunabo Microgrid 4301-01 Critical Infrastructure Data

Critical Infrastructure Data					
Name	**Type**	**Power A (kW)**	**Power B (kW)**	**Power C (kW)**	**Priority Level**
CDT DE MAUNABO	clinic	17.786	17.786	17.786	100
CLINICA SATELITE MAUNABO	clinic	4.211	4.211	4.211	100
ESC INT. URBANA NUEVA	shelter	48.406	48.406	48.406	75
ESC. ALFONSO COSTAS MARTINEZ	shelter	48.406	48.406	48.406	75
Tower # 218	telecom tower	0.216	0.216	0.216	50

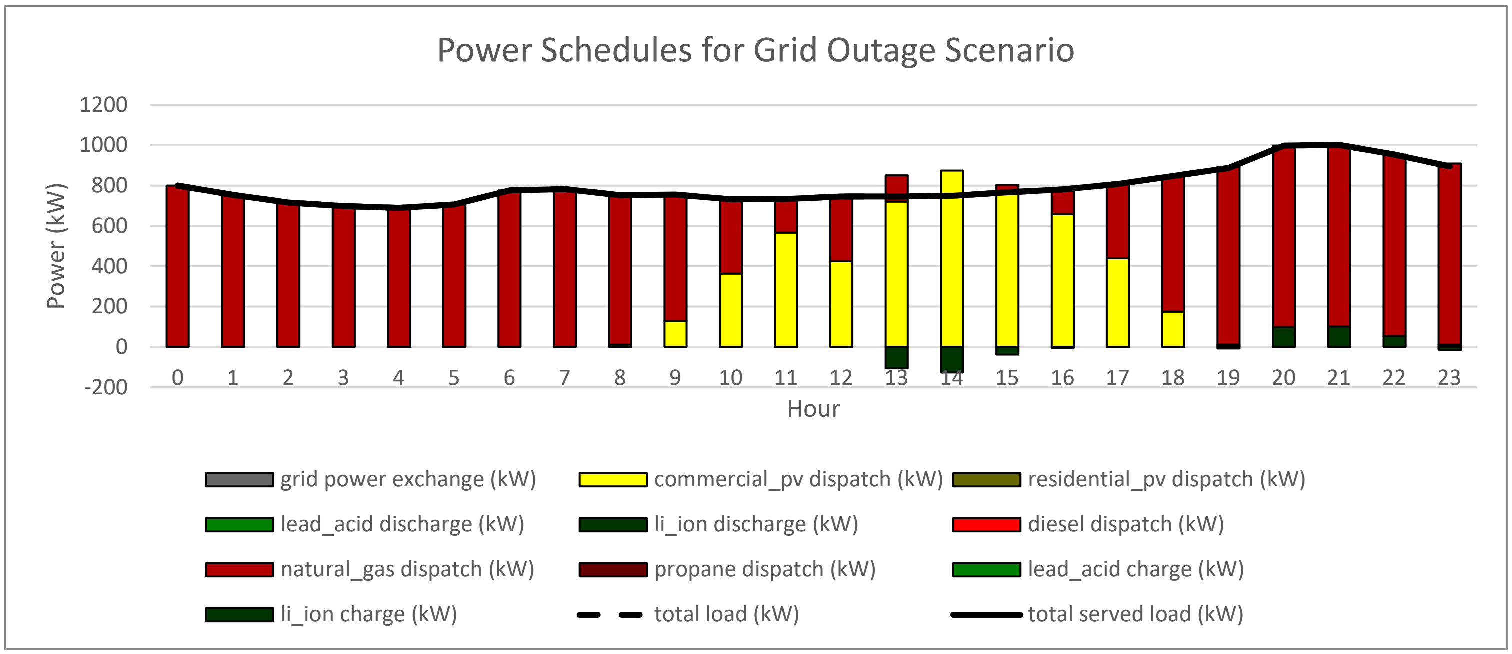


B.5.3. Maunabo Microgrid 4301-01 Baseline Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	1,050
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	133
5	diesel	generator	0
6	natural_gas	generator	900
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			Grid Outage (Pr = 7.671%)		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	34,663	34,663	16,582	2,880	2,880	1,378
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	3,812	26,681	12,764	317	2,217	1,061
5	0	0	0	0	0	0
6	94,058	11,663,185	5,579,441	7,815	969,048	463,574
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	132,533	**11,724,529**	**5,608,787**	**11,012**	**974,145**	**466,012**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	37,543	17,960	4,205,924	4,186,340
2	0	0	0	0
3	0	0	0	0
4	28,898	13,824	750,813	735,739
5	0	0	0	0
6	12,632,233	6,043,015	19,202,360	12,613,142
7	0	0	0	0
8	0	0	0	0
	12,698,674	**6,074,799**	**24,159,097**	**17,535,222**

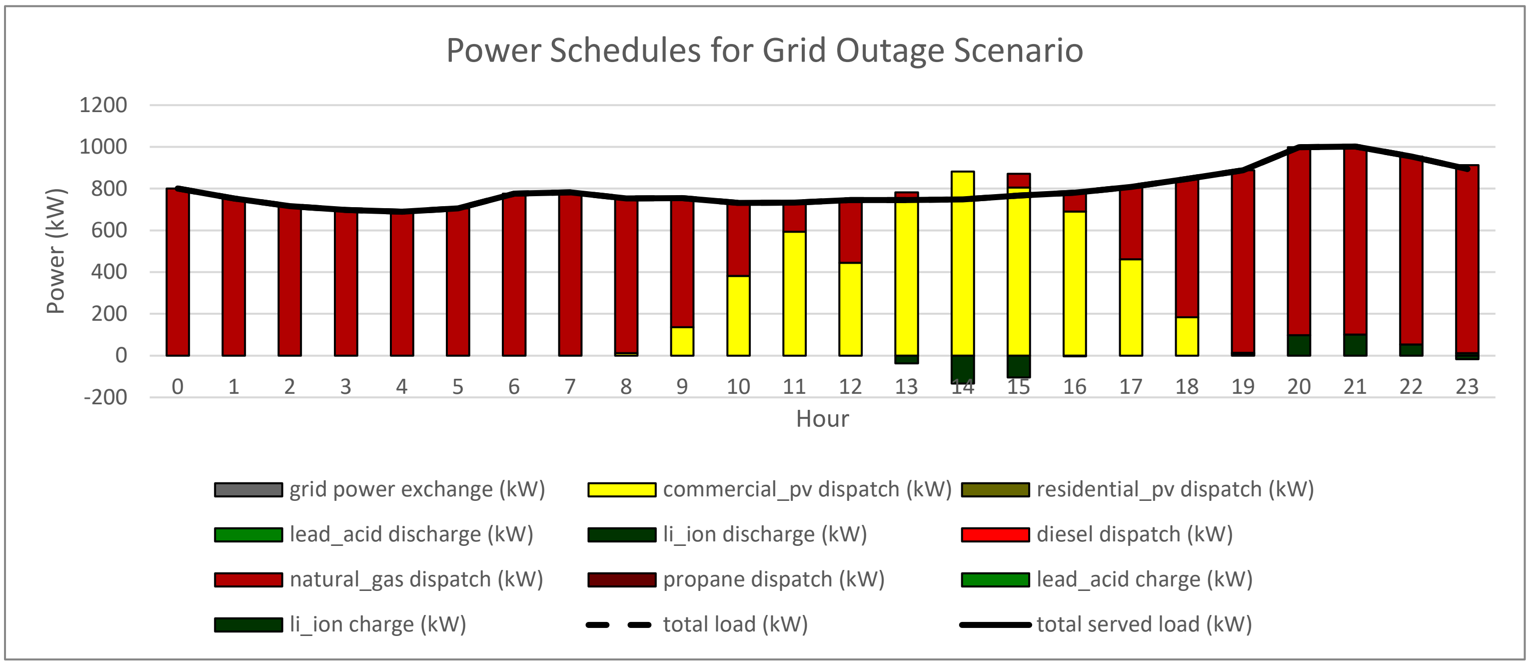


B.5.4. Maunabo Microgrid 4301-01 CO2 Cost Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	1,100
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	133
5	diesel	generator	0
6	natural_gas	generator	900
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	36,086	36,086	17,263	2,998	2,998	1,434
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	3,817	26,722	12,783	317	2,220	1,062
5	0	0	0	0	0	0
6	92,636	12,524,346	5,991,404	7,697	1,040,599	497,802
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	132,539	**12,587,154**	**6,021,450**	**11,012**	**1,045,817**	**500,298**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	39,084	18,697	4,405,959	4,385,572
2	0	0	0	0
3	0	0	0	0
4	28,942	13,845	750,857	735,760
5	0	0	0	0
6	13,564,945	6,489,206	20,135,072	13,059,333
7	0	0	0	0
8	0	0	0	0
	13,632,971	**6,521,748**	**25,291,888**	**18,180,665**

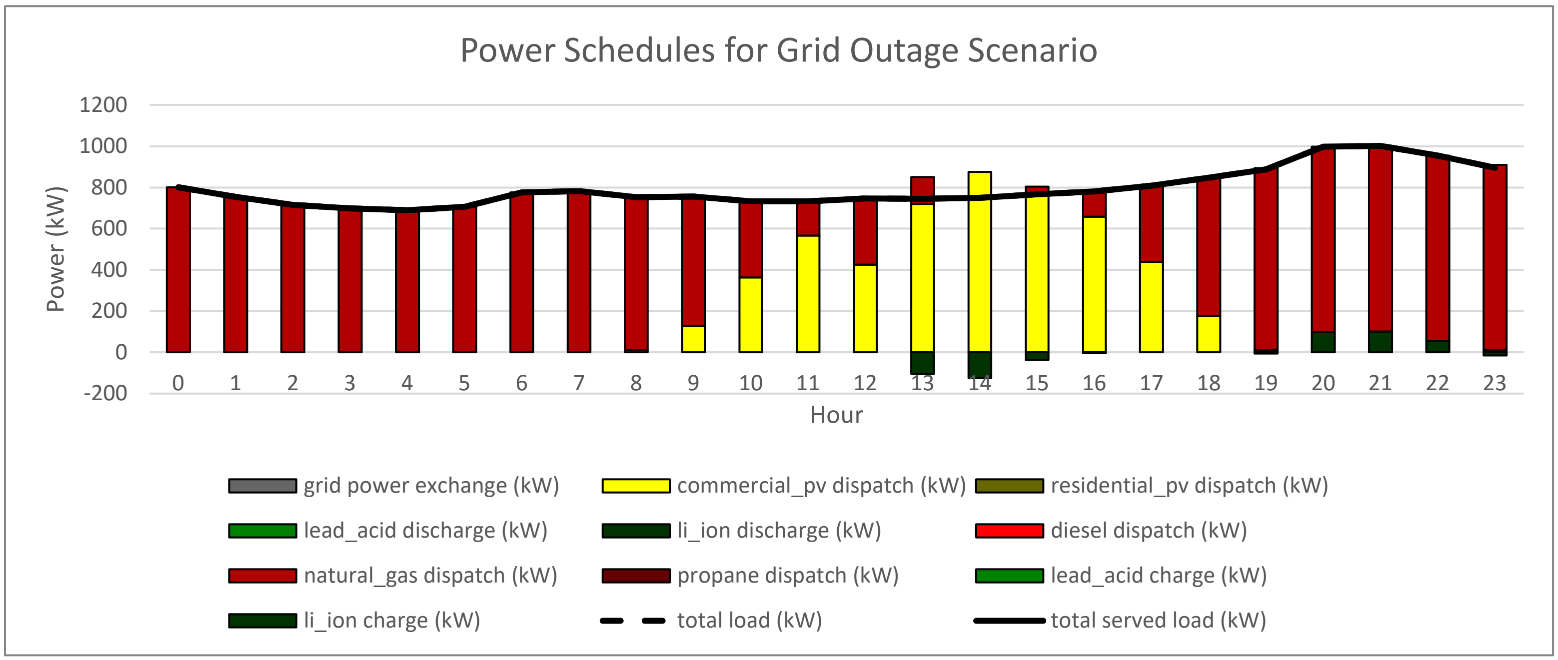


B.5.5. Maunabo Microgrid 4301-01 Decreasing Demand Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	1,050
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	133
5	diesel	generator	0
6	natural_gas	generator	900
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	28,077	28,077	14,280	2,333	2,333	1,186
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	3,087	21,612	10,992	257	1,796	913
5	0	0	0	0	0	0
6	76,187	9,447,180	4,804,849	6,330	784,929	399,216
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	107,352	**9,496,869**	**4,830,121**	**8,919**	**789,057**	**401,316**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	30,410	15,467	4,198,790	4,183,847
2	0	0	0	0
3	0	0	0	0
4	23,408	11,905	745,323	733,820
5	0	0	0	0
6	10,232,108	5,204,065	16,802,236	11,774,192
7	0	0	0	0
8	0	0	0	0
	10,285,926	**5,231,436**	**21,746,349**	**16,691,859**

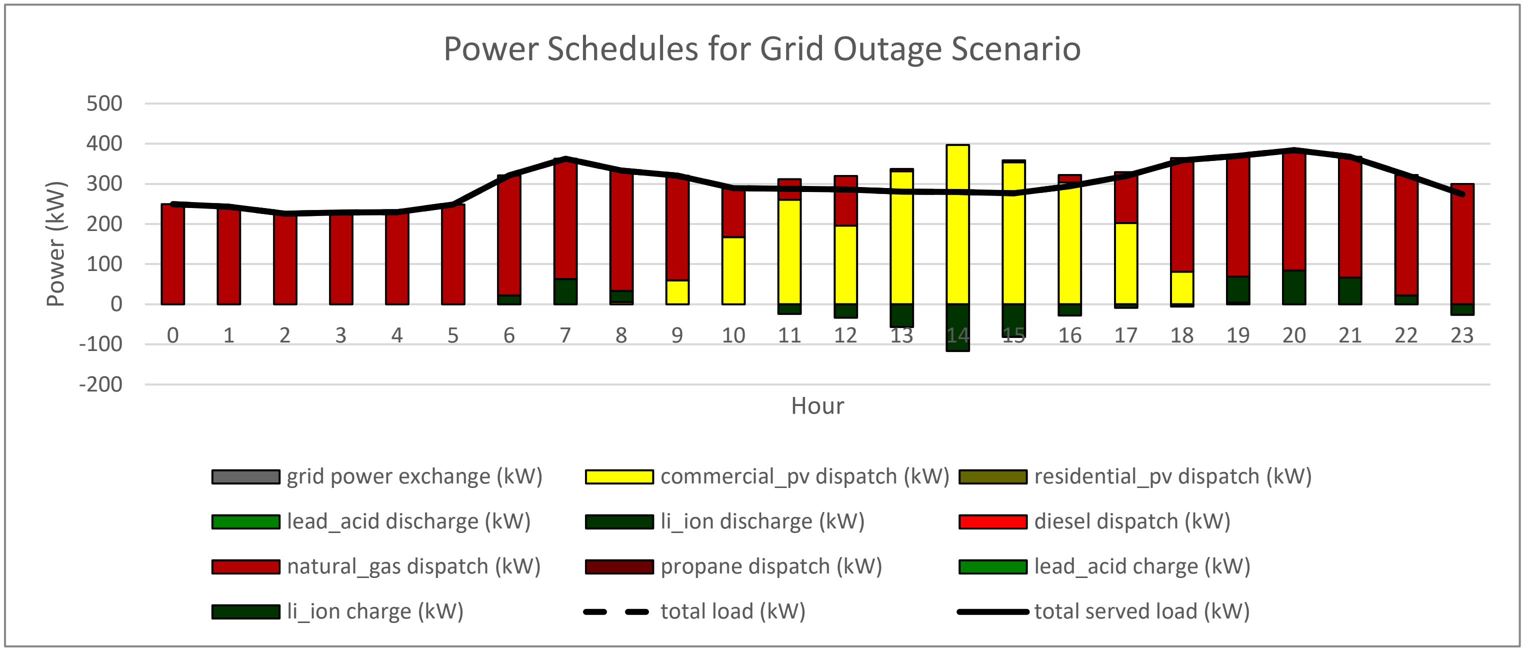


B.5.6. Maunabo Microgrid 4301-01 High Priority Loads Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	483
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	117
5	diesel	generator	0
6	natural_gas	generator	300
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	15,916	15,916	7,614	1,322	1,322	633
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	4,929	34,506	16,507	410	2,872	1,374
5	0	0	0	0	0	0
6	32,482	4,027,728	1,926,787	2,699	334,652	160,091
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	53,327	**4,078,150**	**1,950,908**	**4,431**	**338,846**	**162,097**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	17,238	8,246	1,936,016	1,927,025
2	0	0	0	0
3	0	0	0	0
4	37,378	17,881	669,054	649,557
5	0	0	0	0
6	4,362,380	2,086,878	6,552,422	4,276,920
7	0	0	0	0
8	0	0	0	0
	4,416,996	**2,113,005**	**9,157,492**	**6,853,501**

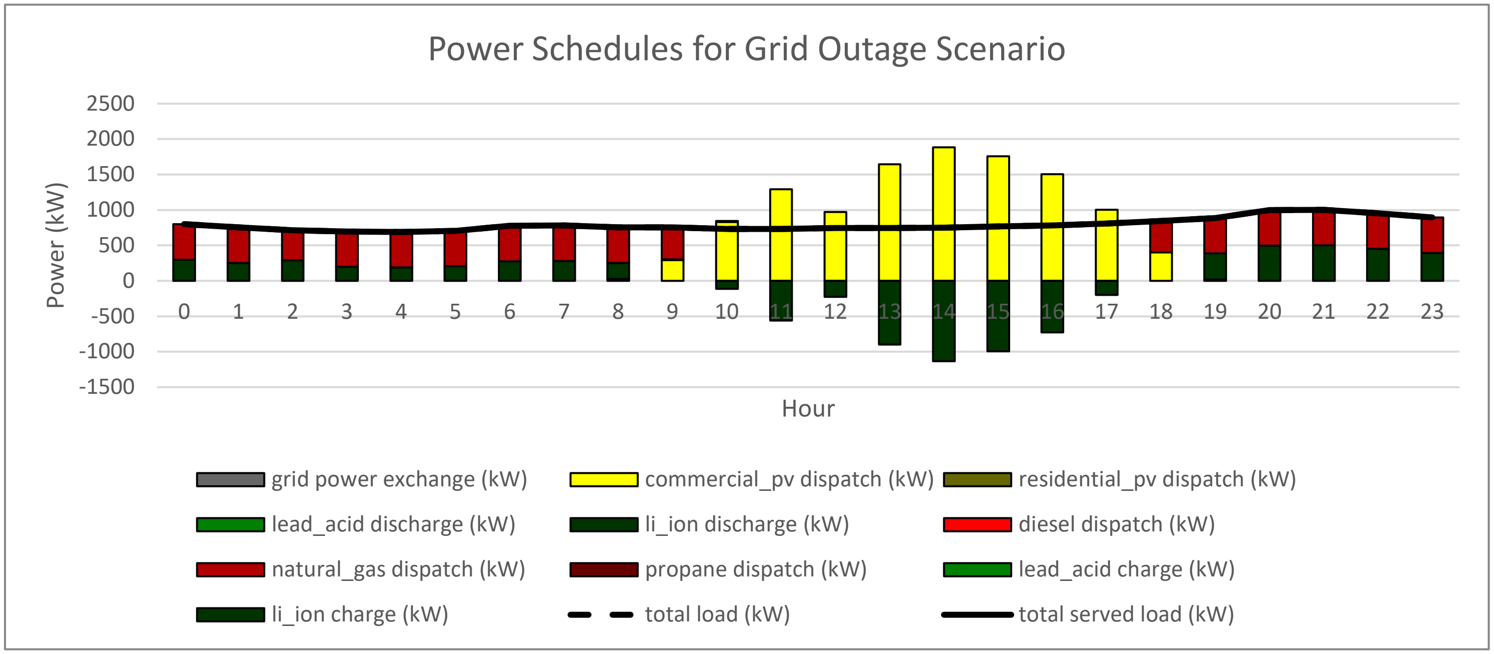


B.5.7. Maunabo Microgrid 4301-01 Low Discount Rate Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	2,400
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	1,133
5	diesel	generator	0
6	natural_gas	generator	500
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			Grid Outage (Pr = 7.671%)		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	78,444	78,444	78,444	6,518	6,518	6,518
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	62,698	438,884	438,884	5,209	36,465	36,465
5	0	0	0	0	0	0
6	52,731	6,538,599	6,538,599	4,381	543,266	543,266
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	193,872	**7,055,928**	**7,055,928**	**16,108**	**586,249**	**586,249**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	84,962	84,962	4,956,962	4,956,962
2	0	0	0	0
3	0	0	0	0
4	475,349	475,349	3,483,216	3,483,216
5	0	0	0	0
6	7,081,866	7,081,866	9,141,866	9,141,866
7	0	0	0	0
8	0	0	0	0
	7,642,177	**7,642,177**	**17,582,044**	**17,582,044**

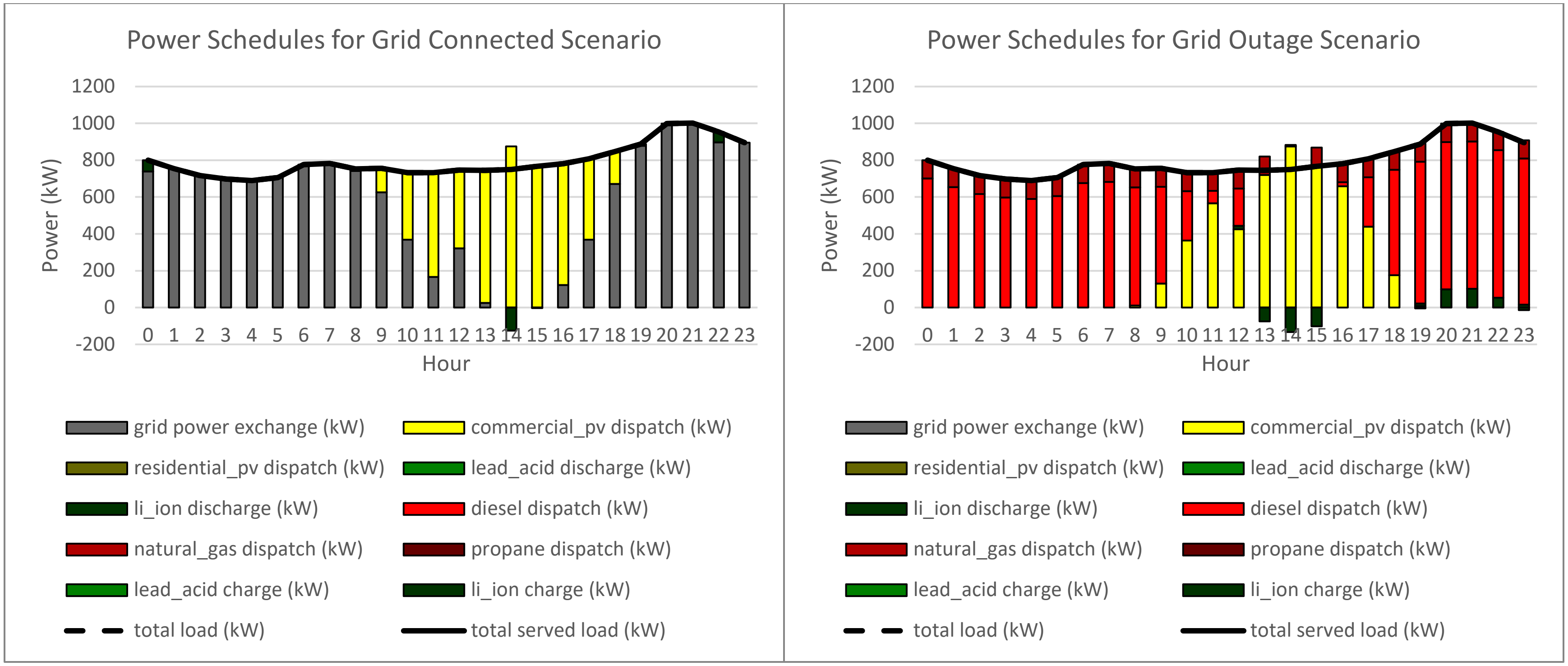


B.5.8. Maunabo Microgrid 4301-01 Low Utility Electricity Price Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	1,050
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	133
5	diesel	generator	800
6	natural_gas	generator	100
7	propane	generator	0
8	grid power exchange	--	--

	Grid Connected (Pr = 92.329%)			Grid Outage (Pr = 7.671%)		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	34,663	34,663	16,582	2,880	2,880	1,378
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	1,657	11,596	5,547	353	2,473	1,183
5	0	0	0	6,524	1,298,289	621,076
6	0	0	0	1,292	160,253	76,662
7	0	0	0	0	0	0
8	93,968	11,276,177	5,394,304	0	0	0
	130,288	**11,322,436**	**5,416,433**	**11,050**	**1,463,896**	**700,299**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	37,543	17,960	4,205,924	4,186,340
2	0	0	0	0
3	0	0	0	0
4	14,069	6,730	735,984	728,645
5	1,298,289	621,076	6,396,785	5,719,572
6	160,253	76,662	890,267	806,676
7	0	0	0	0
8	11,276,177	5,394,304	11,276,177	5,394,304
	12,786,332	**6,116,733**	**23,505,138**	**16,835,539**


Power Schedules for Grid Connected Scenario
1200
1000
800
600
400
200
0
-200
Power (kW)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour
grid power exchange (kW)
commercial_pv dispatch (kW)
residential_pv dispatch (kW)
lead_acid discharge (kW)
li_ion discharge (kW)
diesel dispatch (kW)
natural_gas dispatch (kW)
propane dispatch (kW)
lead_acid charge (kW)
li_ion charge (kW)
total load (kW)
total served load (kW)
Power Schedules for Grid Outage Scenario
1200
1000
800
600
400
200
0
-200
Power (kW)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour
grid power exchange (kW)
commercial_pv dispatch (kW)
residential_pv dispatch (kW)
lead_acid discharge (kW)
li_ion discharge (kW)
diesel dispatch (kW)
natural_gas dispatch (kW)
propane dispatch (kW)
lead_acid charge (kW)
li_ion charge (kW)
total load (kW)
total served load (kW)

B.6. Aguas Buenas Microgrid 3701-03 Results

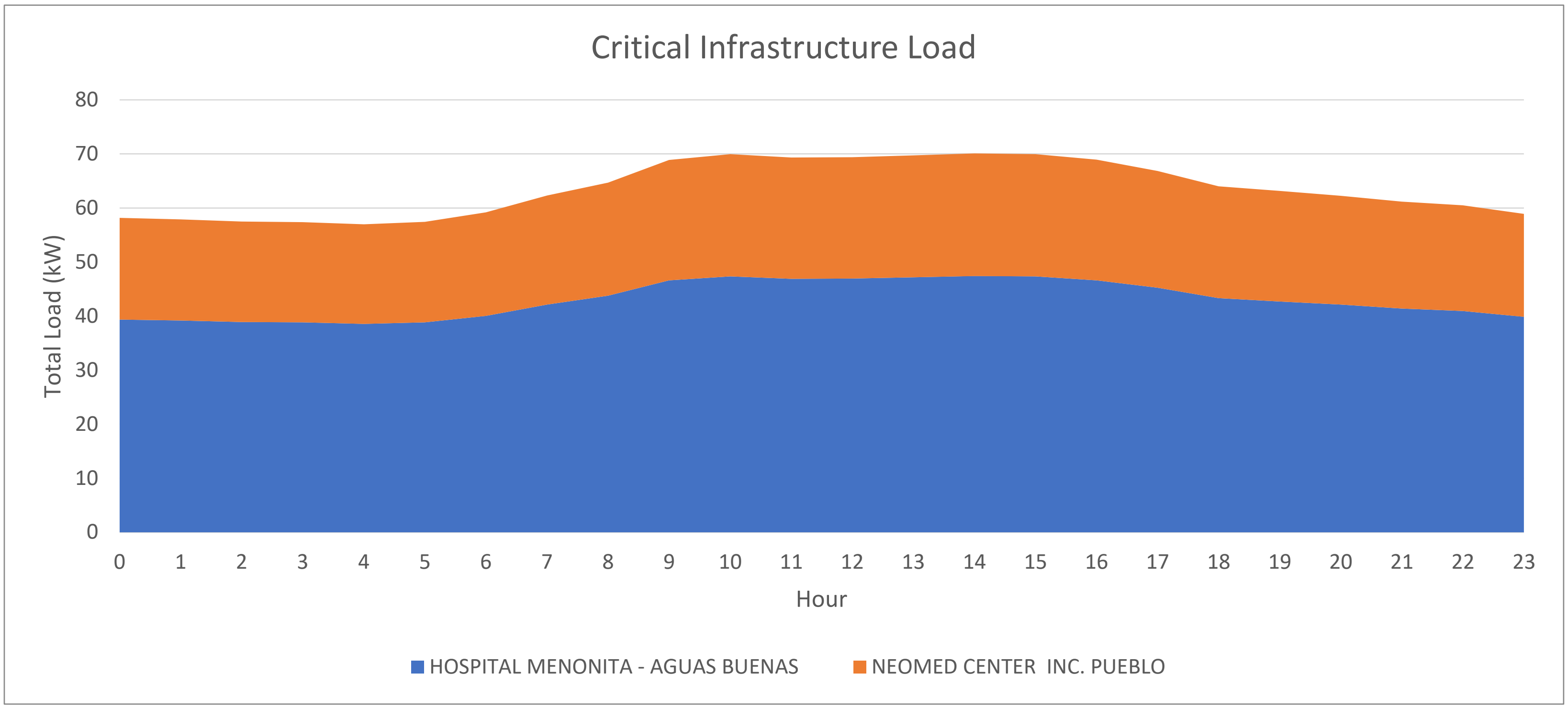
B.6.1. Aguas Buenas Microgrid 3701-03 Case Data

Microgrid Data	
Microgrid ID	mg_3701-03_01
Swing Node	1000342342
Nominal Voltage (kV)	8.32
Number of Nodes	226
Number of OH Lines	184
Number of UG Lines	41
Number of Loads	85
Electrical Length (mi)	4.543
Total MW	1.237

Parent Feeder Data	
Feeder ID	3701-03
Swing Node	1000342342
Nominal Voltage (kV)	8.32
Number of Nodes	569
Number of OH Lines	490
Number of UG Lines	78
Number of Loads	198
Electrical Length (mi)	15.701
Total MW	2.397

B.6.2. Aguas Buenas Microgrid 3701-03 Critical Infrastructure Data

Critical Infrastructure Data					
Name	**Type**	**Power A (kW)**	**Power B (kW)**	**Power C (kW)**	**Priority Level**
HOSPITAL MENONITA - AGUAS BUENAS	hospital	15.807	15.807	15.807	100
NEOMED CENTER INC. PUEBLO	clinic	7.557	7.557	7.557	100

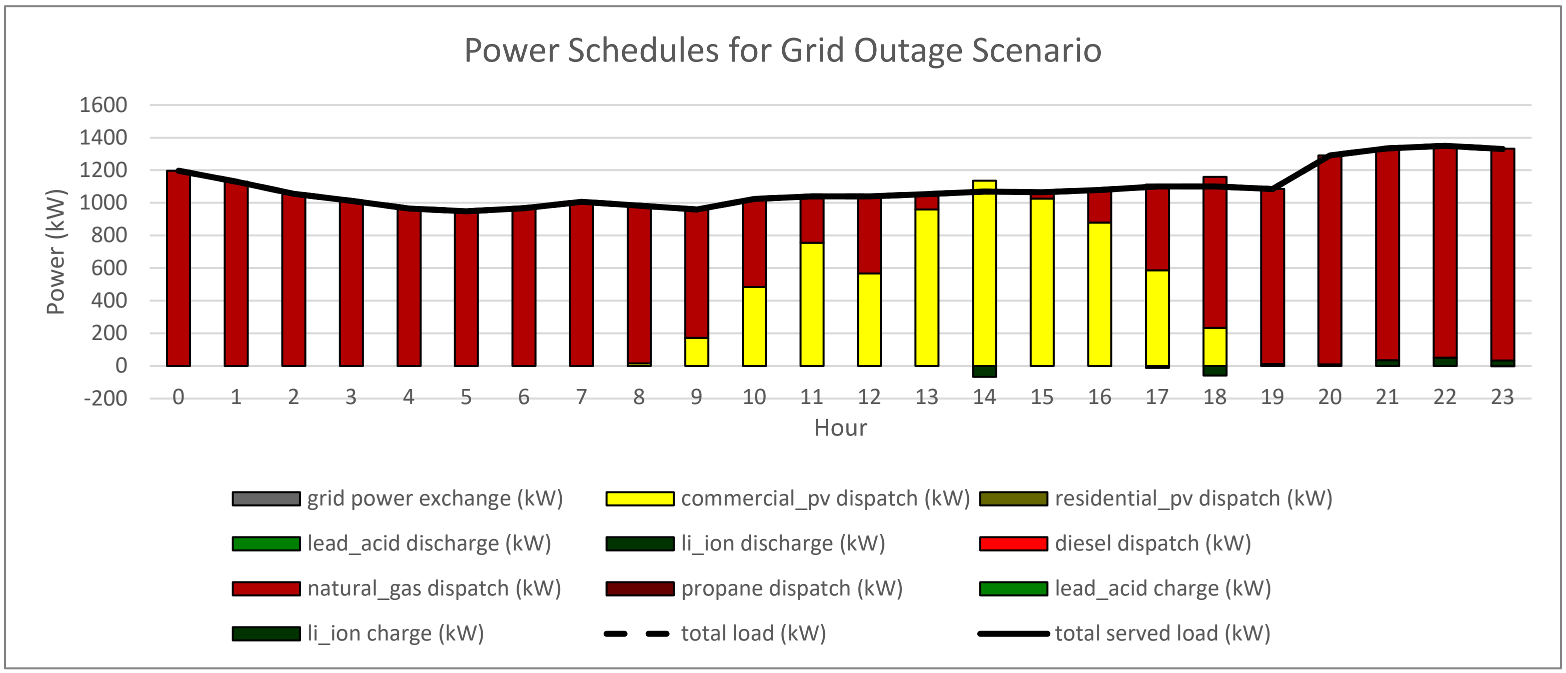


B.6.3. Aguas Buenas Microgrid 3701-03 Baseline Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	1,400
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	67
5	diesel	generator	0
6	natural_gas	generator	1,300
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			Grid Outage (Pr = 7.671%)		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	46,010	46,010	22,010	3,823	3,823	1,829
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	1,797	12,576	6,016	149	1,045	500
5	0	0	0	0	0	0
6	130,596	16,193,930	7,746,861	10,851	1,345,490	643,656
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	178,403	**16,252,516**	**7,774,888**	**14,823**	**1,350,357**	**645,985**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	49,833	23,839	5,607,673	5,581,680
2	0	0	0	0
3	0	0	0	0
4	13,621	6,516	374,578	367,473
5	0	0	0	0
6	17,539,420	8,390,518	27,029,604	17,880,701
7	0	0	0	0
8	0	0	0	0
	17,602,873	**8,420,873**	**33,011,855**	**23,829,854**

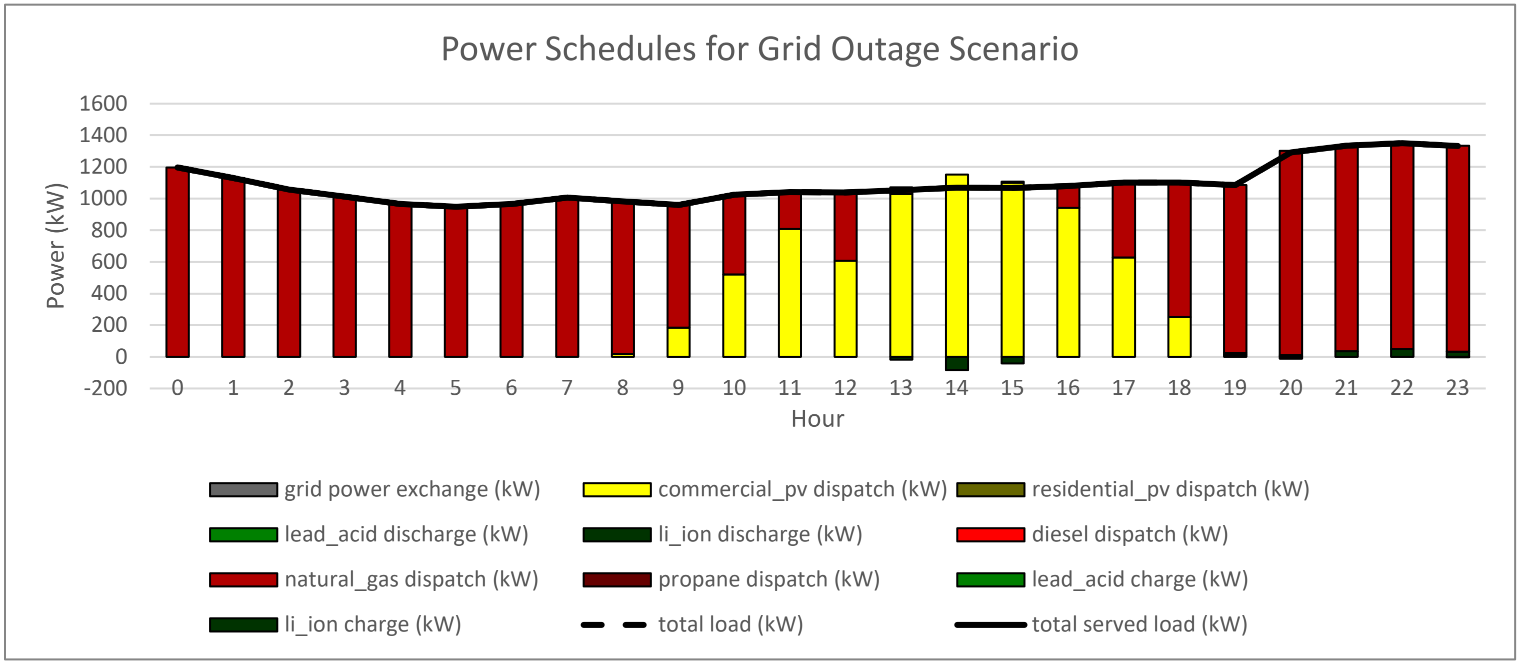


B.6.4. Aguas Buenas Microgrid 3701-03 CO2 Cost Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	1,500
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	83
5	diesel	generator	0
6	natural_gas	generator	1,300
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			Grid Outage (Pr = 7.671%)		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	48,862	48,862	23,375	4,060	4,060	1,942
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	2,011	14,077	6,734	167	1,170	560
5	0	0	0	0	0	0
6	127,753	17,272,197	8,262,683	10,614	1,435,079	686,514
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	178,626	**17,335,136**	**8,292,792**	**14,841**	**1,440,308**	**689,015**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	52,922	25,317	6,007,751	5,980,146
2	0	0	0	0
3	0	0	0	0
4	15,247	7,294	466,444	458,491
5	0	0	0	0
6	18,707,275	8,949,197	28,197,459	18,439,381
7	0	0	0	0
8	0	0	0	0
	18,775,444	**8,981,807**	**34,671,654**	**24,878,017**

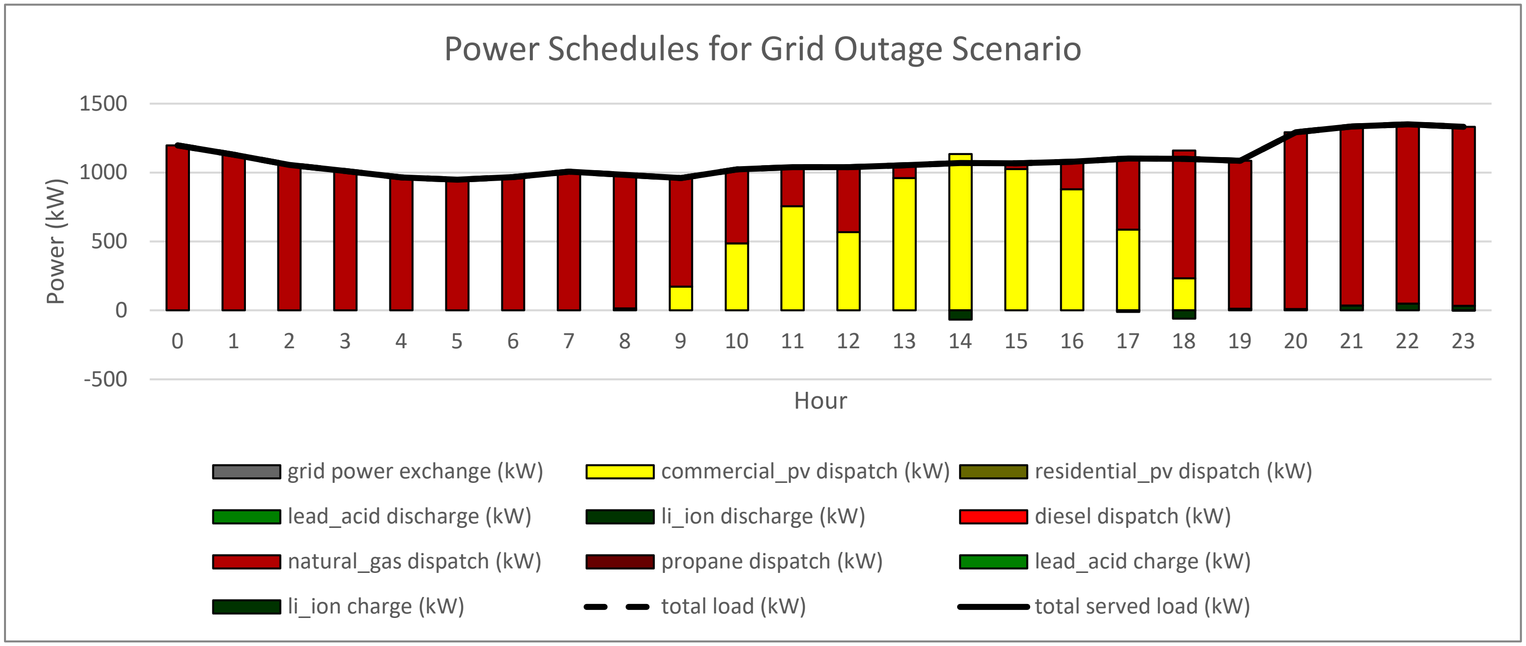


B.6.5. Aguas Buenas Microgrid 3701-03 Decreasing Demand Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	1,400
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	67
5	diesel	generator	0
6	natural_gas	generator	1,300
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			Grid Outage (Pr = 7.671%)		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	37,268	37,268	18,954	3,096	3,096	1,575
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	1,455	10,187	5,181	121	846	430
5	0	0	0	0	0	0
6	105,783	13,117,083	6,671,367	8,789	1,089,847	554,298
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	144,506	**13,164,538**	**6,695,502**	**12,006**	**1,093,789**	**556,303**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	40,364	20,529	5,598,205	5,578,370
2	0	0	0	0
3	0	0	0	0
4	11,033	5,611	371,990	366,569
5	0	0	0	0
6	14,206,930	7,225,664	23,697,114	16,715,848
7	0	0	0	0
8	0	0	0	0
	14,258,327	**7,251,805**	**29,667,309**	**22,660,787**

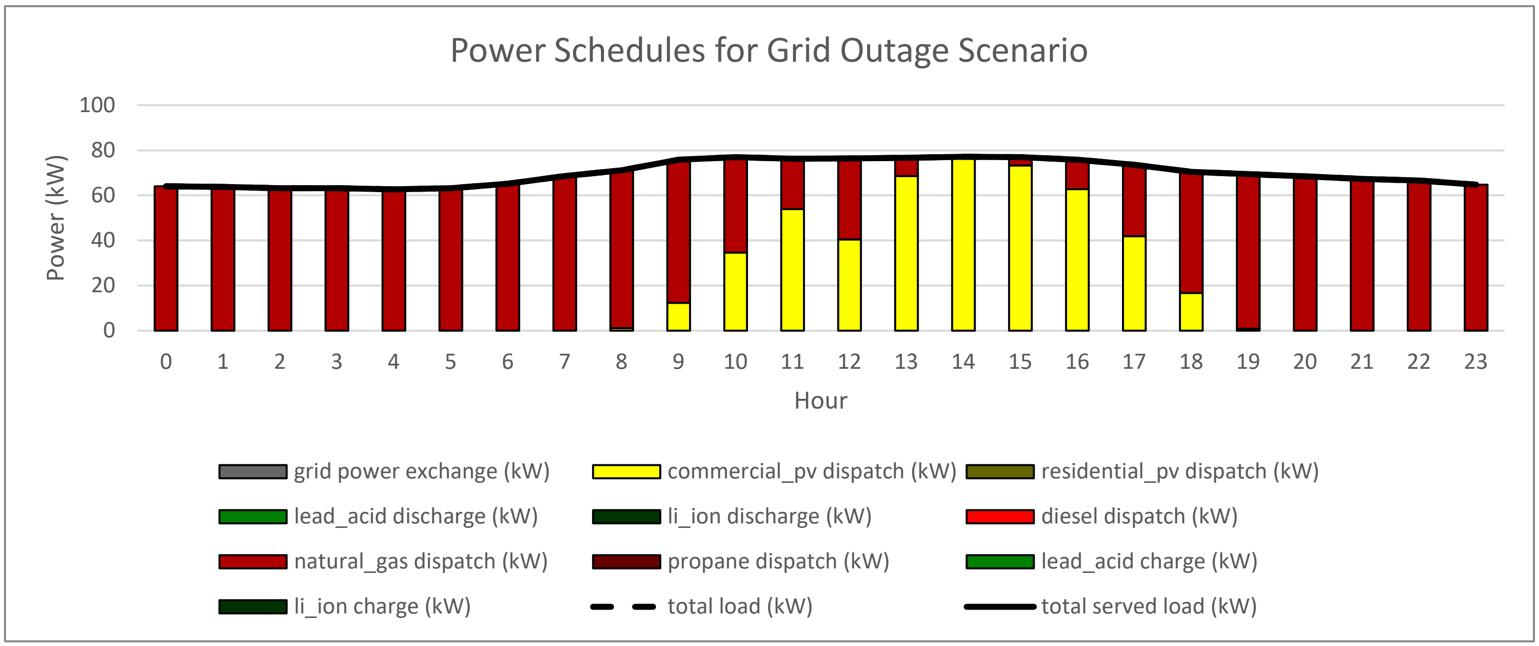


B.6.6. Aguas Buenas Microgrid 3701-03 High Priority Loads Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	100
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	0
5	diesel	generator	0
6	natural_gas	generator	100
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			Grid Outage (Pr = 7.671%)		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	3,260	3,260	1,559	271	271	130
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	8,044	997,481	477,175	668	82,877	39,647
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	11,304	**1,000,740**	**478,735**	**939**	**83,148**	**39,776**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	3,530	1,689	400,519	398,677
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	1,080,358	516,822	1,810,372	1,246,836
7	0	0	0	0
8	0	0	0	0
	1,083,888	**518,511**	**2,210,891**	**1,645,514**

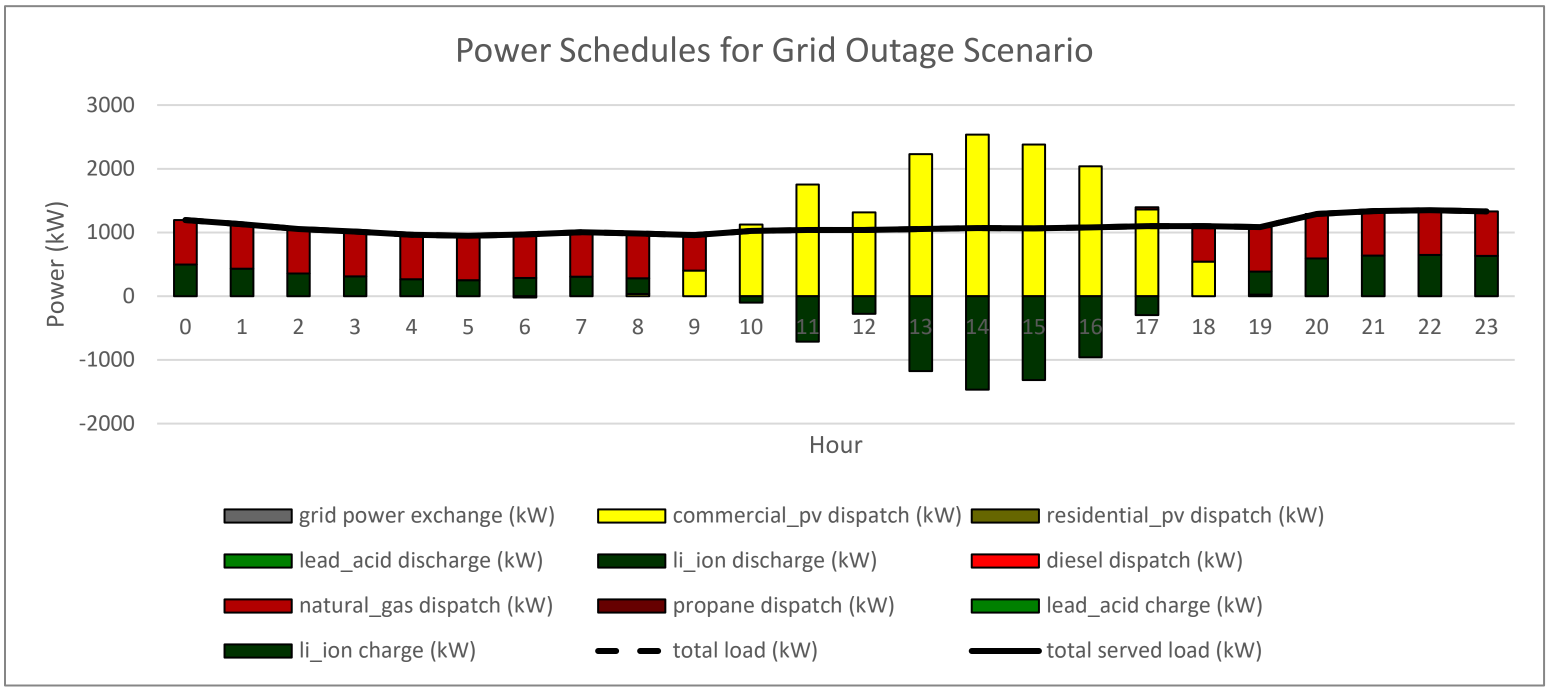


B.6.7. Aguas Buenas Microgrid 3701-03 Low Discount Rate Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	3,250
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	1,467
5	diesel	generator	0
6	natural_gas	generator	700
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	106,133	106,133	106,133	8,818	8,818	8,818
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	81,808	572,659	572,659	6,797	47,580	47,580
5	0	0	0	0	0	0
6	73,806	9,151,982	9,151,982	6,132	760,402	760,402
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	261,748	**9,830,774**	**9,830,774**	**21,748**	**816,800**	**816,800**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	114,952	114,952	6,712,452	6,712,452
2	0	0	0	0
3	0	0	0	0
4	620,239	620,239	4,512,772	4,512,772
5	0	0	0	0
6	9,912,384	9,912,384	12,796,384	12,796,384
7	0	0	0	0
8	0	0	0	0
	10,647,575	**10,647,575**	**24,021,608**	**24,021,608**

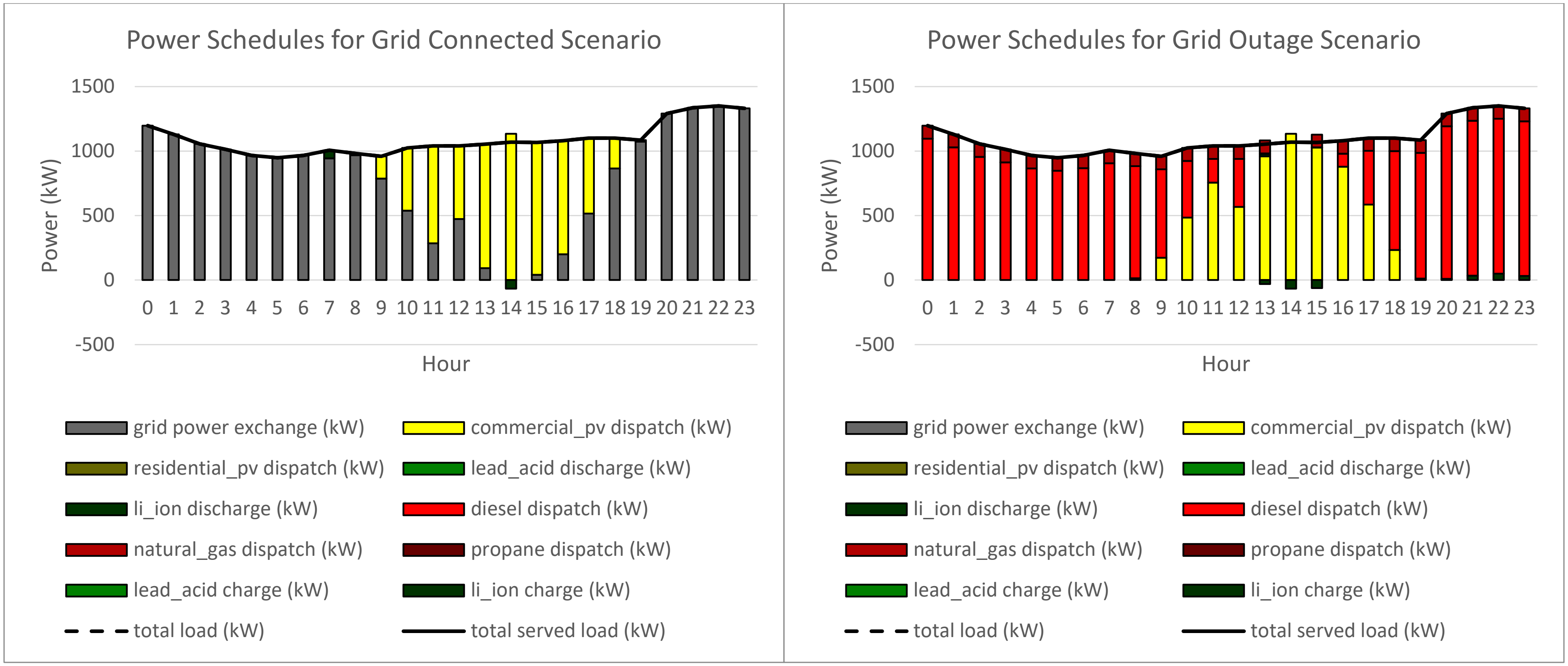


B.6.8. Aguas Buenas Microgrid 3701-03 Low Utility Electricity Price Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	1,400
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	67
5	diesel	generator	1,200
6	natural_gas	generator	100
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			Grid Outage (Pr = 7.671%)		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	46,010	46,010	22,010	3,823	3,823	1,829
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	863	6,039	2,889	170	1,192	570
5	0	0	0	9,564	1,903,156	910,433
6	0	0	0	1,288	159,712	76,403
7	0	0	0	0	0	0
8	130,557	15,666,876	7,494,729	0	0	0
	177,430	**15,718,925**	**7,519,628**	**14,845**	**2,067,883**	**989,235**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	49,833	23,839	5,607,673	5,581,680
2	0	0	0	0
3	0	0	0	0
4	7,231	3,459	368,188	364,417
5	1,903,156	910,433	9,550,900	8,558,177
6	159,712	76,403	889,726	806,417
7	0	0	0	0
8	15,666,876	7,494,729	15,666,876	7,494,729
	17,786,807	**8,508,863**	**32,083,364**	**22,805,419**

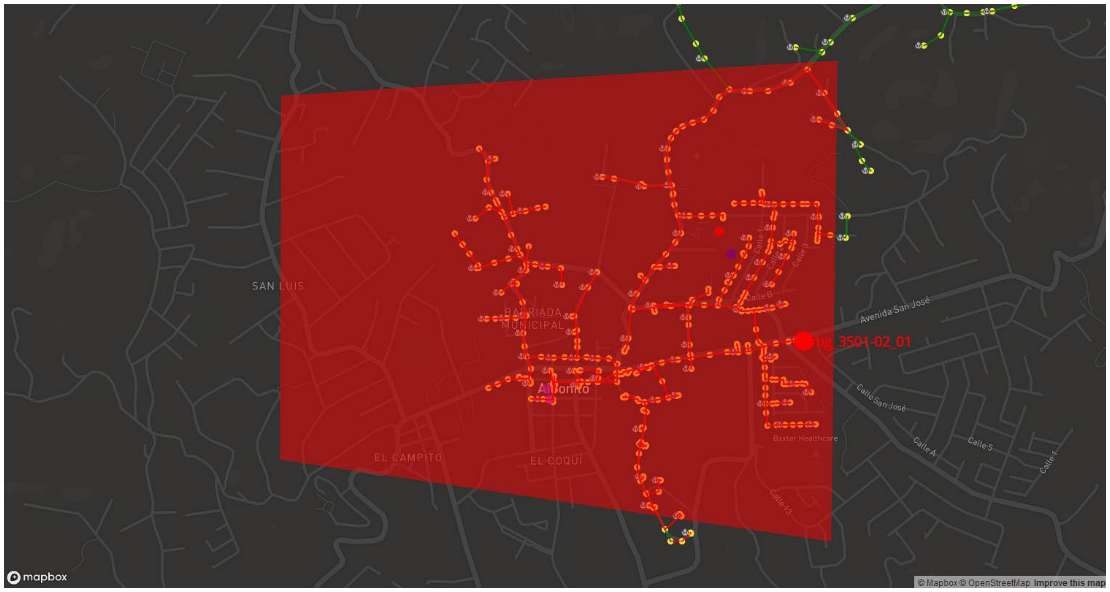

Power Schedules for Grid Connected Scenario
Power Schedules for Grid Outage Scenario
1500
1000
500
0
-500
Power (kW)
Hour
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
grid power exchange (kW)
commercial_pv dispatch (kW)
residential_pv dispatch (kW)
lead_acid discharge (kW)
li_ion discharge (kW)
diesel dispatch (kW)
natural_gas dispatch (kW)
propane dispatch (kW)
lead_acid charge (kW)
li_ion charge (kW)
total load (kW)
total served load (kW)

B.7. Aibonito Microgrid 3501-02 Results

B.7.1. Aibonito Microgrid 3501-02 Case Data

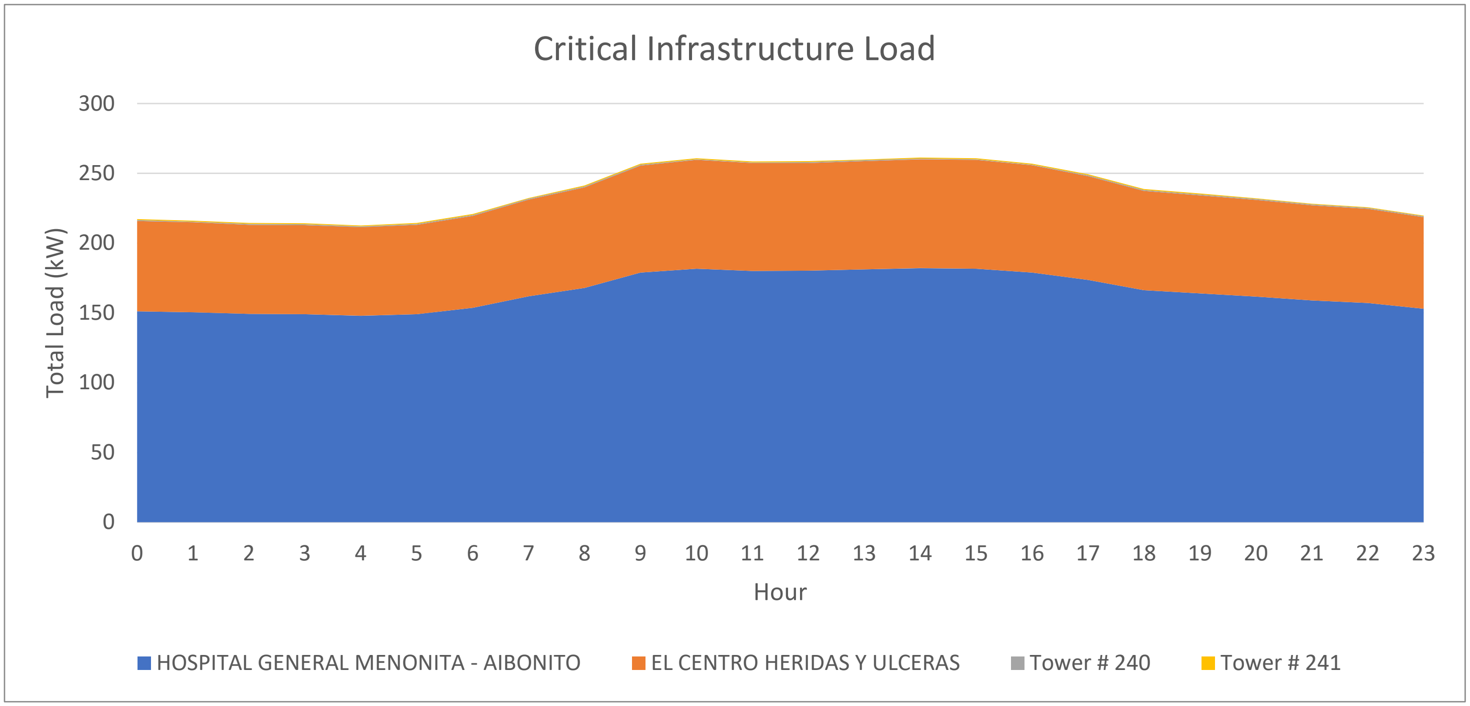
Microgrid Data	
Microgrid ID	mg_3501-02_01
Swing Node	1000342267
Nominal Voltage (kV)	8.32
Number of Nodes	348
Number of OH Lines	251
Number of UG Lines	96
Number of Loads	110
Electrical Length (mi)	6.307
Total MW	1.645

Parent Feeder Data	
Feeder ID	3501-02
Swing Node	1000342267
Nominal Voltage (kV)	8.32
Number of Nodes	516
Number of OH Lines	416
Number of UG Lines	99
Number of Loads	181
Electrical Length (mi)	13.486
Total MW	1.934



B.7.2. Aibonito Microgrid 3501-02 Critical Infrastructure Data

Critical Infrastructure Data					
Name	**Type**	**Power A (kW)**	**Power B (kW)**	**Power C (kW)**	**Priority Level**
HOSPITAL GENERAL MENONITA - AIBONITO	hospital	60.668	60.668	60.668	100
EL CENTRO HERIDAS Y ULCERAS	urgent care center	26.000	26.000	26.000	100
Tower # 240	telecom tower	0.216	0.216	0.216	50
Tower # 241	telecom tower	0.216	0.216	0.216	50

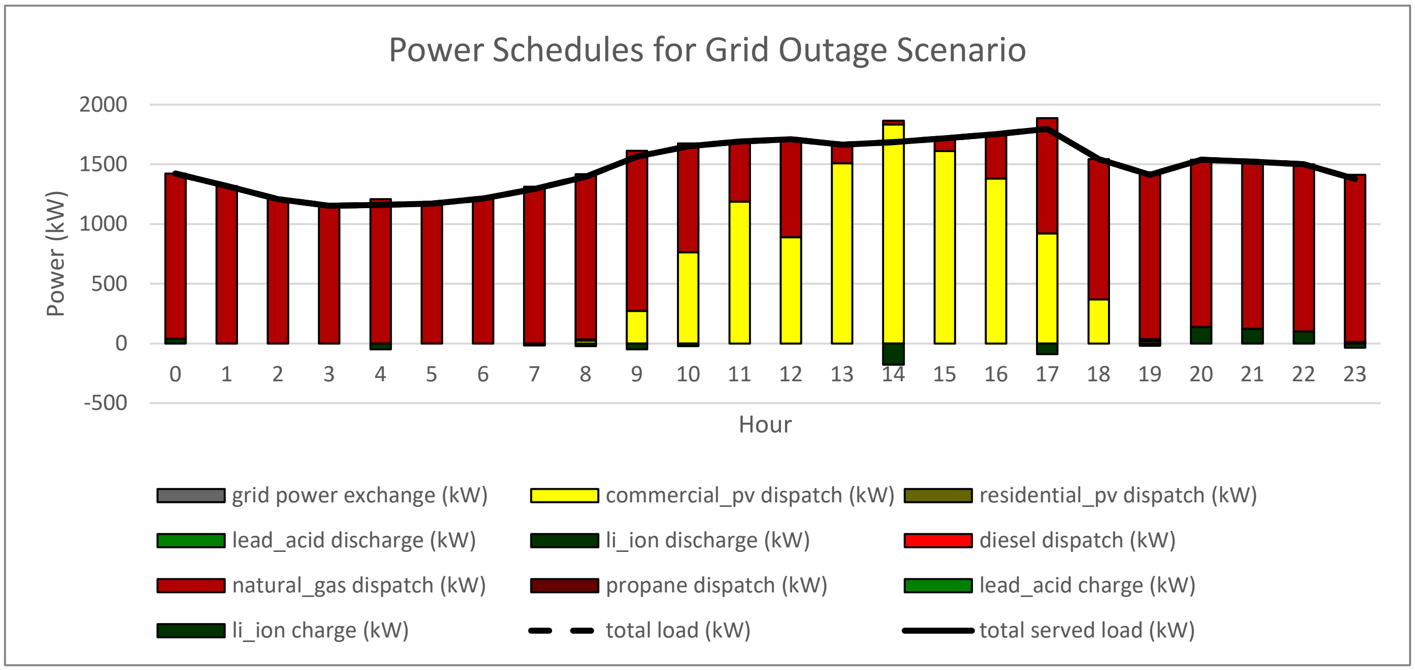


B.7.3. Aibonito Microgrid 3501-02 Baseline Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	2,200
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	183
5	diesel	generator	0
6	natural_gas	generator	1,400
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	72,628	72,628	34,744	6,034	6,034	2,887
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	6,282	43,973	21,036	522	3,654	1,748
5	0	0	0	0	0	0
6	166,741	20,675,858	9,890,929	13,854	1,717,875	821,798
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	245,650	**20,792,459**	**9,946,708**	**20,410**	**1,727,563**	**826,433**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	78,662	37,630	8,812,412	8,771,380
2	0	0	0	0
3	0	0	0	0
4	47,627	22,784	1,040,260	1,015,417
5	0	0	0	0
6	22,393,734	10,712,727	32,613,932	20,932,925
7	0	0	0	0
8	0	0	0	0
	22,520,023	**10,773,141**	**42,466,603**	**30,719,722**

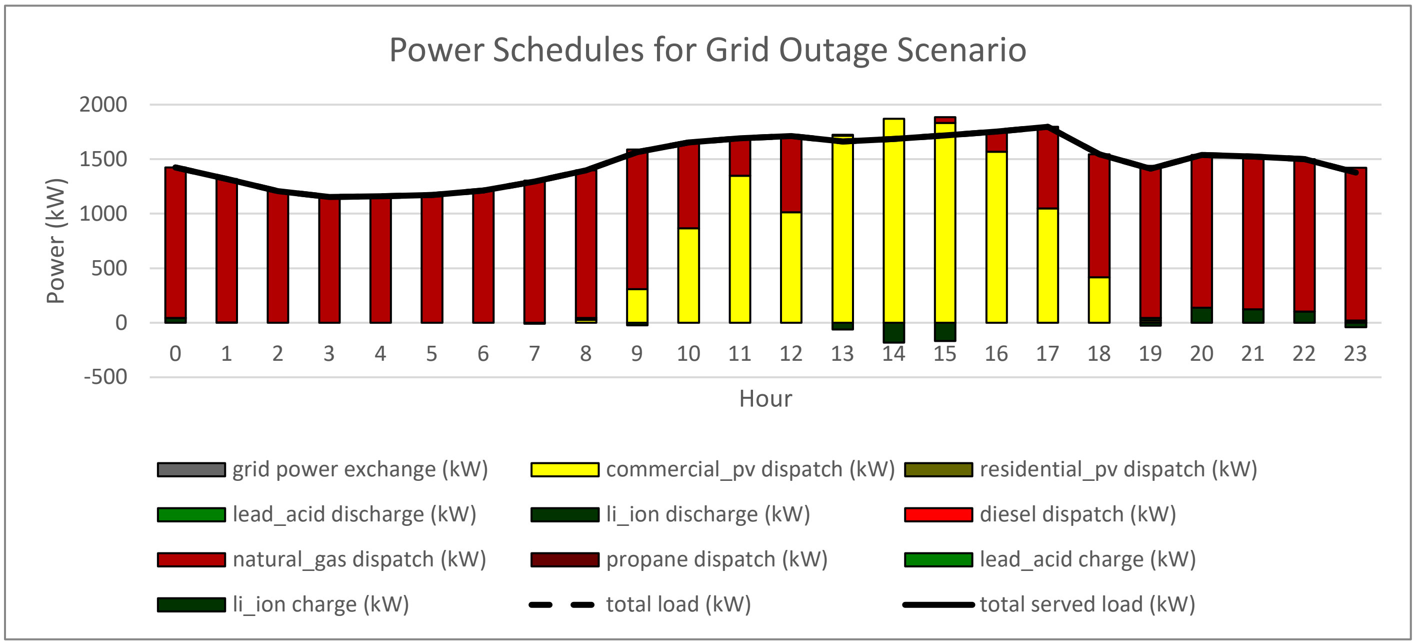


B.7.4. Aibonito Microgrid 3501-02 CO2 Cost Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	2,500
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	183
5	diesel	generator	0
6	natural_gas	generator	1,400
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	81,102	81,102	38,797	6,738	6,738	3,224
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	6,636	46,453	22,222	551	3,860	1,846
5	0	0	0	0	0	0
6	158,281	21,399,652	10,237,178	13,151	1,778,013	850,567
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	246,019	**21,527,207**	**10,298,198**	**20,441**	**1,788,611**	**855,637**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	87,840	42,021	10,012,556	9,966,737
2	0	0	0	0
3	0	0	0	0
4	50,313	24,069	1,042,946	1,016,702
5	0	0	0	0
6	23,177,665	11,087,745	33,397,863	21,307,942
7	0	0	0	0
8	0	0	0	0
	23,315,818	**11,153,834**	**44,453,364**	**32,291,381**

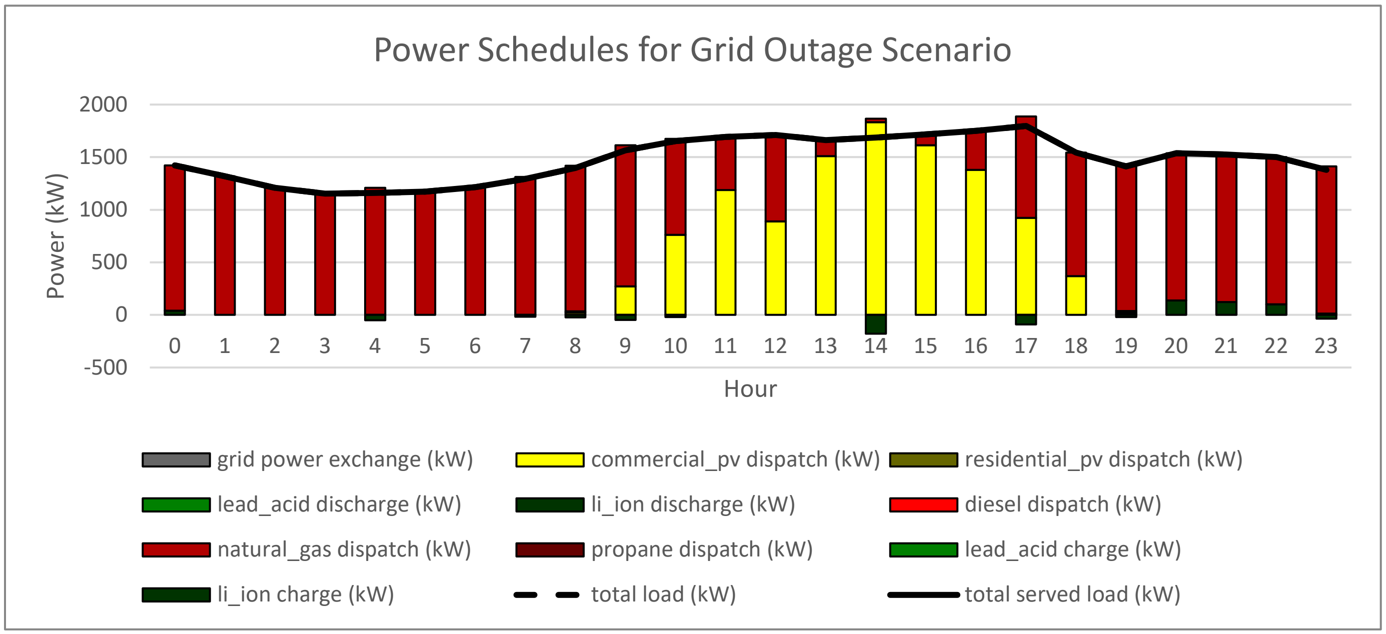


B.7.5. Aibonito Microgrid 3501-02 Decreasing Demand Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	2,200
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	183
5	diesel	generator	0
6	natural_gas	generator	1,400
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	58,828	58,828	29,920	4,888	4,888	2,486
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	5,088	35,618	18,116	423	2,959	1,505
5	0	0	0	0	0	0
6	135,060	16,747,445	8,517,774	11,222	1,391,479	707,708
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	198,977	**16,841,892**	**8,565,810**	**16,532**	**1,399,326**	**711,699**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	63,716	32,406	8,797,466	8,766,156
2	0	0	0	0
3	0	0	0	0
4	38,578	19,621	1,031,211	1,012,254
5	0	0	0	0
6	18,138,924	9,225,482	28,359,122	19,445,680
7	0	0	0	0
8	0	0	0	0
	18,241,218	**9,277,509**	**38,187,799**	**29,224,090**

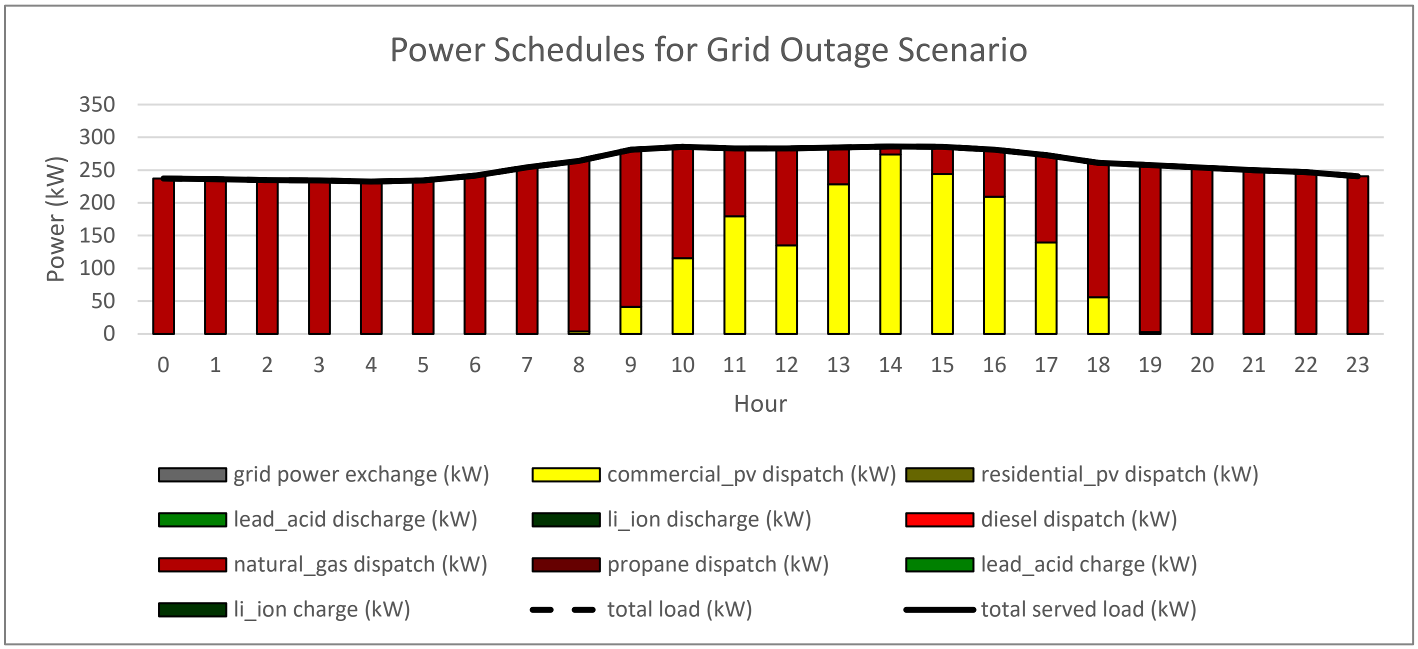


B.7.6. Aibonito Microgrid 3501-02 High Priority Loads Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	333
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	0
5	diesel	generator	0
6	natural_gas	generator	300
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			Grid Outage (Pr = 7.671%)		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	10,979	10,979	5,252	912	912	436
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	30,952	3,838,037	1,836,042	2,572	318,887	152,550
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	41,931	**3,849,016**	**1,841,295**	**3,484**	**319,800**	**152,986**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	11,892	5,689	1,335,187	1,328,984
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	4,156,924	1,988,592	6,346,967	4,178,634
7	0	0	0	0
8	0	0	0	0
	4,168,816	**1,994,281**	**7,682,154**	**5,507,618**

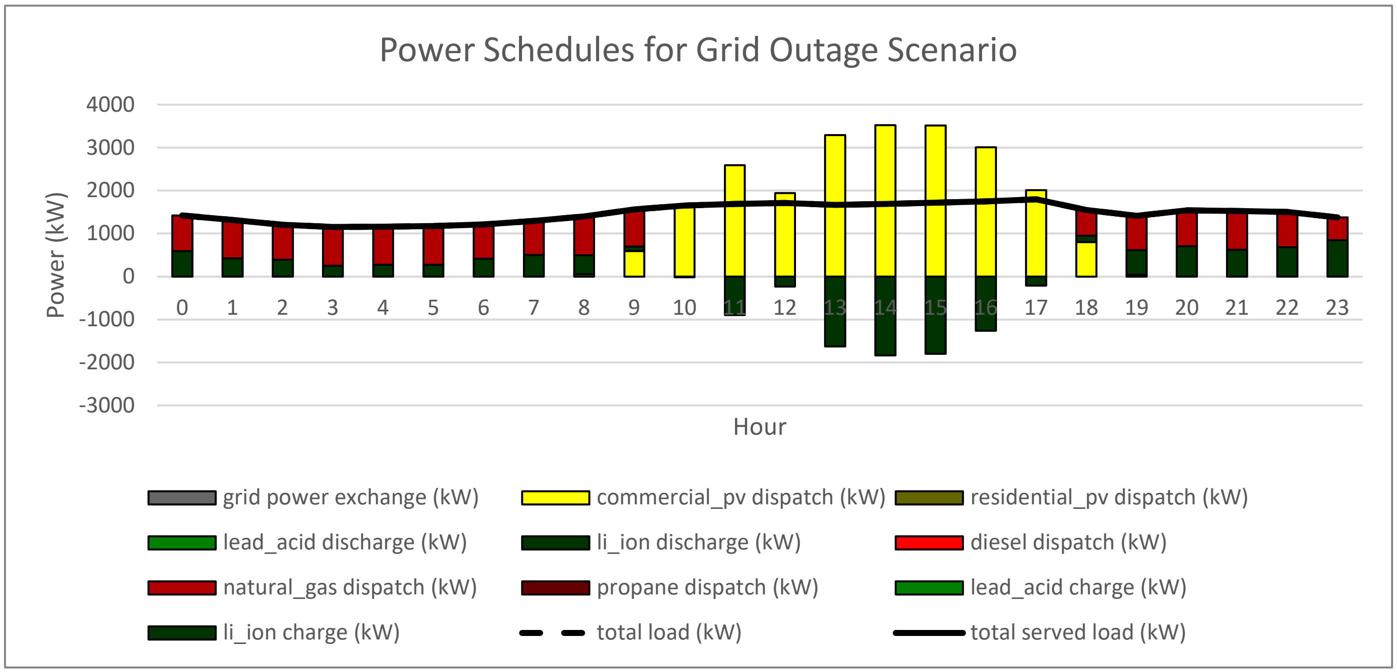


B.7.7. Aibonito Microgrid 3501-02 Low Discount Rate Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	4,800
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	1,833
5	diesel	generator	0
6	natural_gas	generator	900
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			Grid Outage (Pr = 7.671%)		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	155,240	155,240	155,240	12,898	12,898	12,898
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	101,958	713,705	713,705	8,471	59,299	59,299
5	0	0	0	0	0	0
6	88,115	10,926,262	10,926,262	7,321	907,820	907,820
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	345,313	**11,795,206**	**11,795,206**	**28,691**	**980,017**	**980,017**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	168,138	168,138	9,912,138	9,912,138
2	0	0	0	0
3	0	0	0	0
4	773,004	773,004	5,638,671	5,638,671
5	0	0	0	0
6	11,834,081	11,834,081	15,542,081	15,542,081
7	0	0	0	0
8	0	0	0	0
	12,775,224	**12,775,224**	**31,092,890**	**31,092,890**

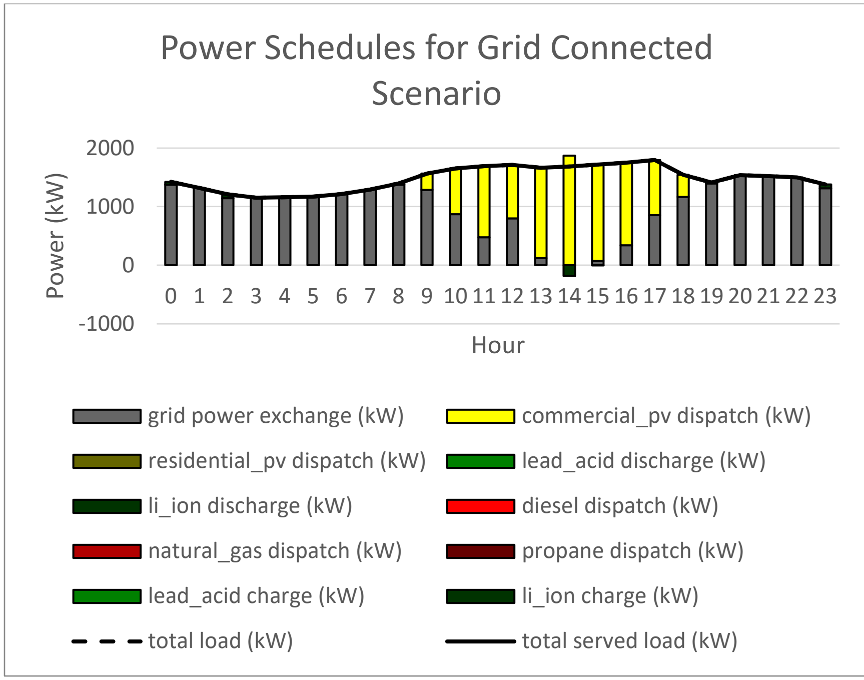


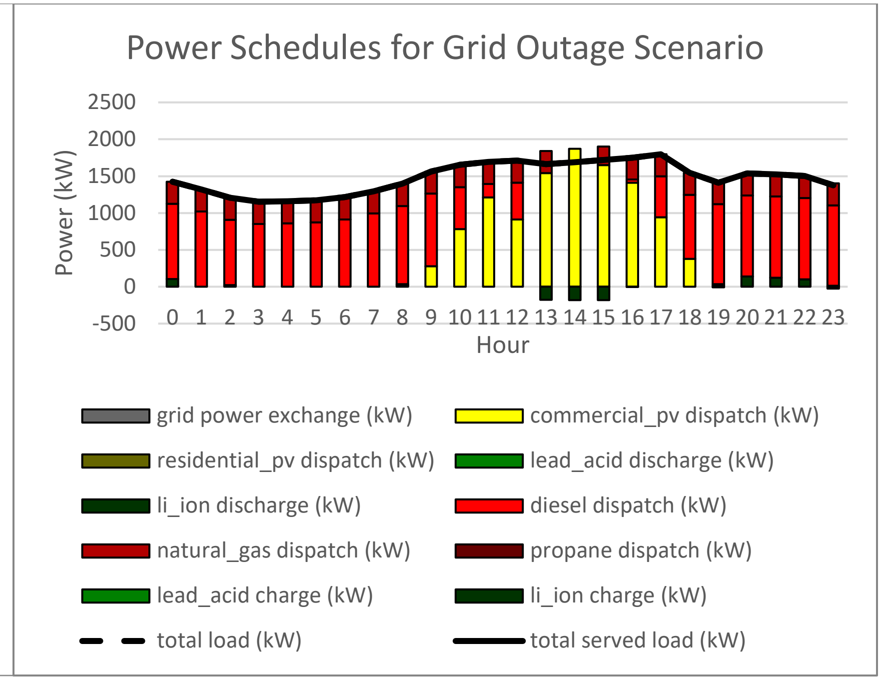
B.7.8. Aibonito Microgrid 3501-02 Low Utility Electricity Price Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	2,250
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	183
5	diesel	generator	1,100
6	natural_gas	generator	300
7	propane	generator	0
8	grid power exchange	--	--

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	74,252	74,252	35,521	6,169	6,169	2,951
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	2,434	17,036	8,150	624	4,368	2,090
5	0	0	0	9,886	1,967,226	941,083
6	0	0	0	3,838	475,858	227,641
7	0	0	0	0	0	0
8	164,956	19,794,725	9,469,412	0	0	0
	241,642	**19,886,013**	**9,513,082**	**20,516**	**2,453,621**	**1,173,765**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	80,421	38,472	9,012,665	8,970,716
2	0	0	0	0
3	0	0	0	0
4	21,404	10,239	1,014,037	1,002,872
5	1,967,226	941,083	8,977,658	7,951,515
6	475,858	227,641	2,665,900	2,417,684
7	0	0	0	0
8	19,794,725	9,469,412	19,794,725	9,469,412
	22,339,634	**10,686,847**	**41,464,986**	**29,812,198**


Power Schedules for Grid Connected Scenario
Power (kW)
2000
1000
0
-1000
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour
grid power exchange (kW)
commercial_pv dispatch (kW)
residential_pv dispatch (kW)
lead_acid discharge (kW)
li_ion discharge (kW)
diesel dispatch (kW)
natural_gas dispatch (kW)
propane dispatch (kW)
lead_acid charge (kW)
li_ion charge (kW)
total load (kW)
total served load (kW)

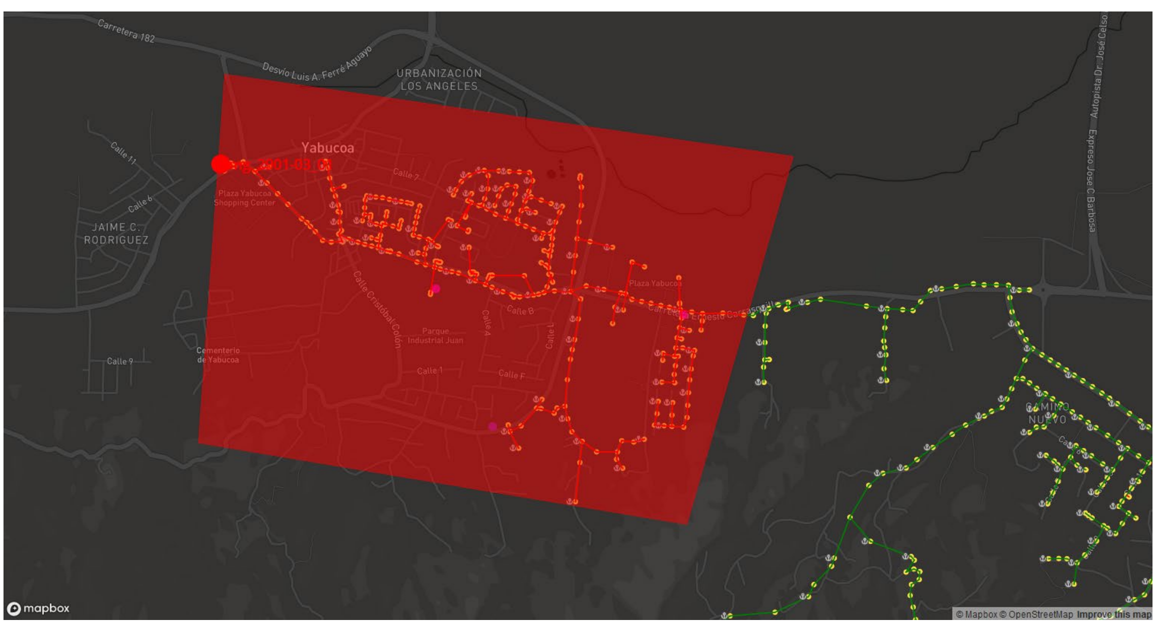

Power Schedules for Grid Outage Scenario
Power (kW)
2500
2000
1500
1000
500
0
-500
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour
grid power exchange (kW)
commercial_pv dispatch (kW)
residential_pv dispatch (kW)
lead_acid discharge (kW)
li_ion discharge (kW)
diesel dispatch (kW)
natural_gas dispatch (kW)
propane dispatch (kW)
lead_acid charge (kW)
li_ion charge (kW)
total load (kW)
total served load (kW)

B.8. Yabucoa Microgrid 2901-03 Results

B.8.1. Yabucoa Microgrid 2901-03 Case Data

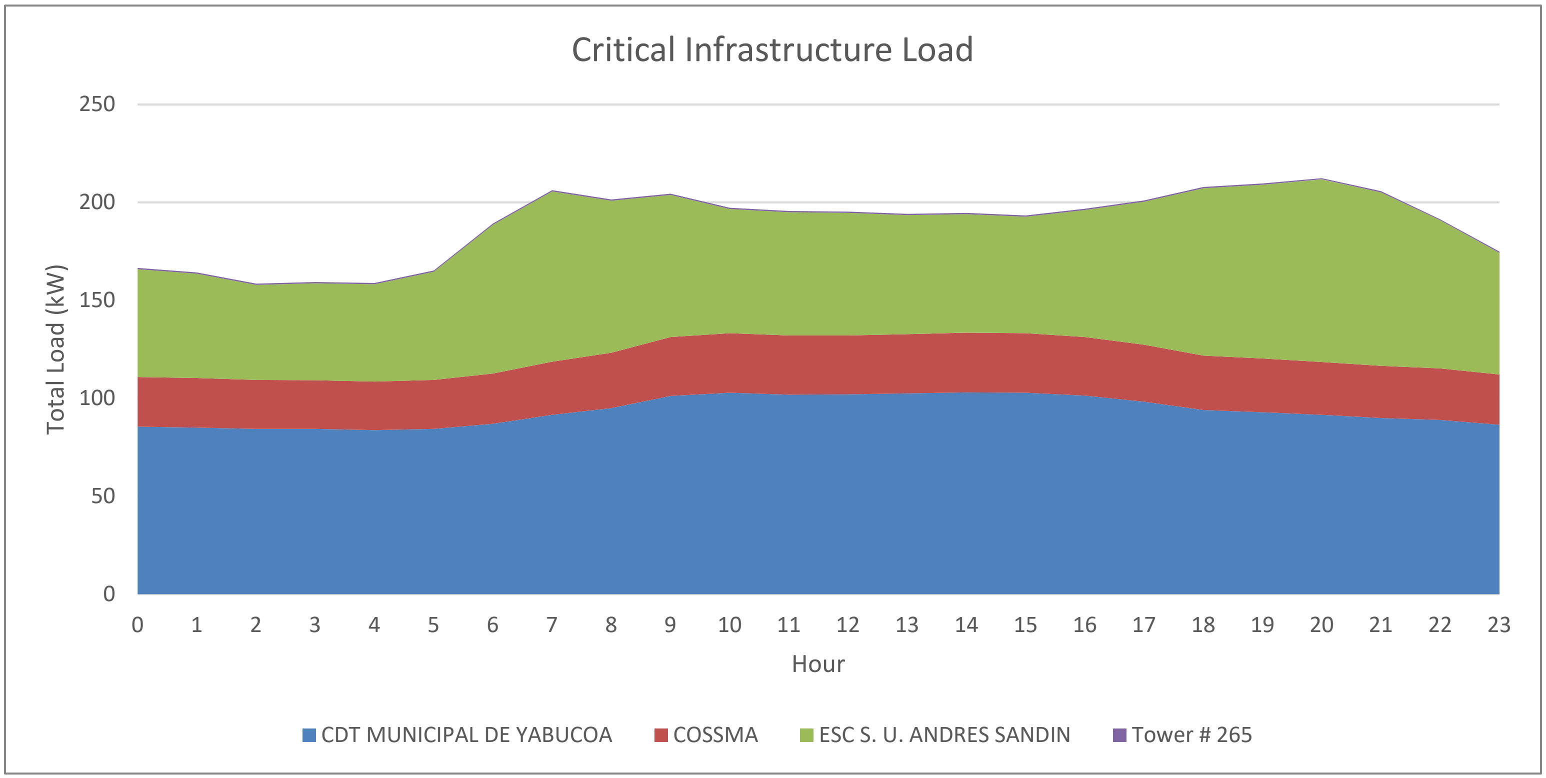
Microgrid Data	
Microgrid ID	mg_2901-03_01
Swing Node	1000341960
Nominal Voltage (kV)	8.32
Number of Nodes	295
Number of OH Lines	254
Number of UG Lines	40
Number of Loads	107
Electrical Length (mi)	7.236
Total MW	1.646

Parent Feeder Data	
Feeder ID	2901-03
Swing Node	1000341960
Nominal Voltage (kV)	8.32
Number of Nodes	858
Number of OH Lines	814
Number of UG Lines	43
Number of Loads	274
Electrical Length (mi)	26.695
Total MW	2.855



B.8.2. Yabucoa Microgrid 2901-03 Critical Infrastructure Data

Critical Infrastructure Data					
Name	**Type**	**Power A (kW)**	**Power B (kW)**	**Power C (kW)**	**Priority Level**
CDT MUNICIPAL DE YABUCOA	clinic	34.336	34.336	34.336	100
COSSMA	clinic	10.156	10.156	10.156	100
ESC S. U. ANDRES SANDIN	shelter	31.060	31.060	31.060	75
Tower # 265	telecom tower	0.216	0.216	0.216	50

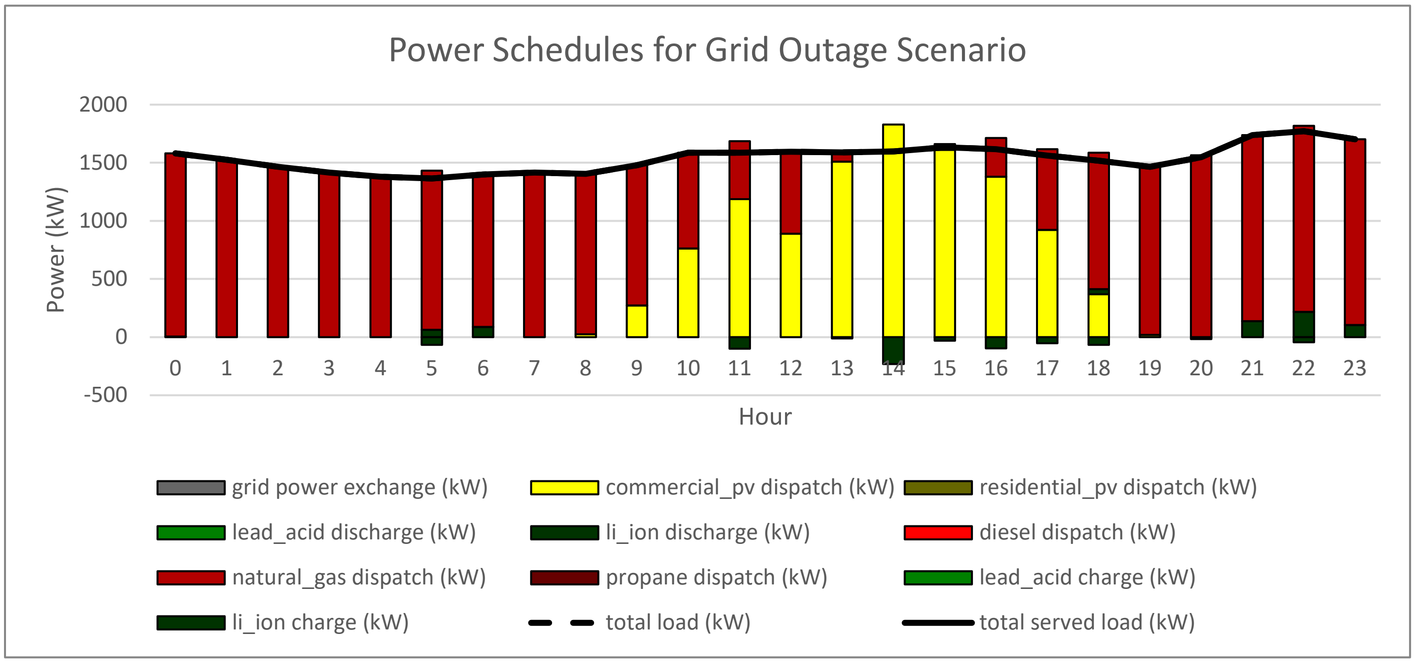


B.8.3. Yabucoa Microgrid 2901-03 Baseline Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	2,200
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	233
5	diesel	generator	0
6	natural_gas	generator	1,600
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	72,534	72,534	34,699	6,033	6,033	2,886
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	6,331	44,316	21,200	772	5,405	2,586
5	0	0	0	0	0	0
6	176,541	21,891,059	10,472,257	14,687	1,821,145	871,200
7	0	0	0	0	0	0
8	173	36,322	17,376	0	0	0
	255,579	**22,044,231**	**10,545,532**	**21,491**	**1,832,582**	**876,672**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	78,567	37,585	8,812,316	8,771,334
2	0	0	0	0
3	0	0	0	0
4	49,721	23,785	1,313,072	1,287,137
5	0	0	0	0
6	23,712,204	11,343,458	35,392,430	23,023,684
7	0	0	0	0
8	36,322	17,376	36,322	17,376
	23,876,813	**11,422,204**	**45,554,140**	**33,099,531**

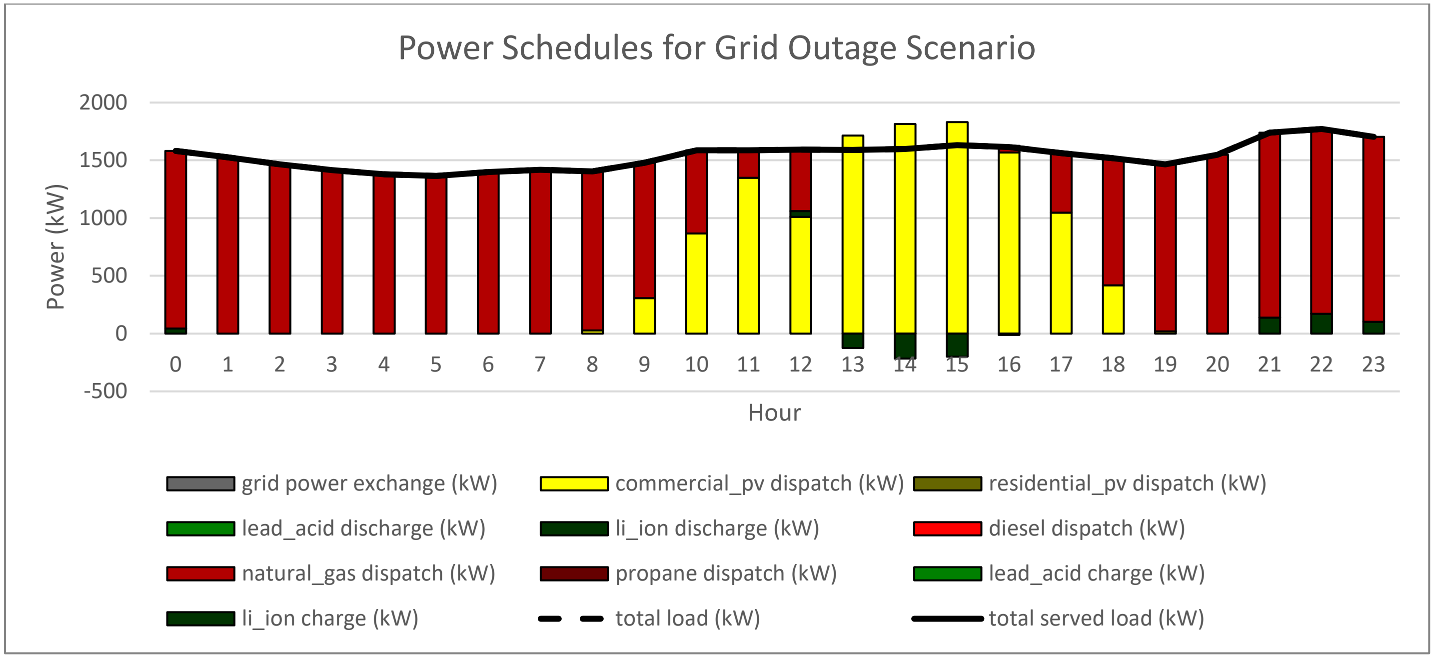


B.8.4. Yabucoa Microgrid 2901-03 CO2 Cost Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	2,500
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	217
5	diesel	generator	0
6	natural_gas	generator	1,600
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	80,729	80,729	38,619	6,707	6,707	3,209
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	7,128	49,896	23,869	592	4,146	1,983
5	0	0	0	0	0	0
6	168,552	22,788,270	10,901,465	14,004	1,893,387	905,760
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	256,409	**22,918,895**	**10,963,954**	**21,304**	**1,904,241**	**910,952**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	87,436	41,828	10,012,152	9,966,543
2	0	0	0	0
3	0	0	0	0
4	54,042	25,853	1,227,154	1,198,965
5	0	0	0	0
6	24,681,657	11,807,225	36,361,883	23,487,451
7	0	0	0	0
8	0	0	0	0
	24,823,135	**11,874,906**	**47,601,189**	**34,652,959**

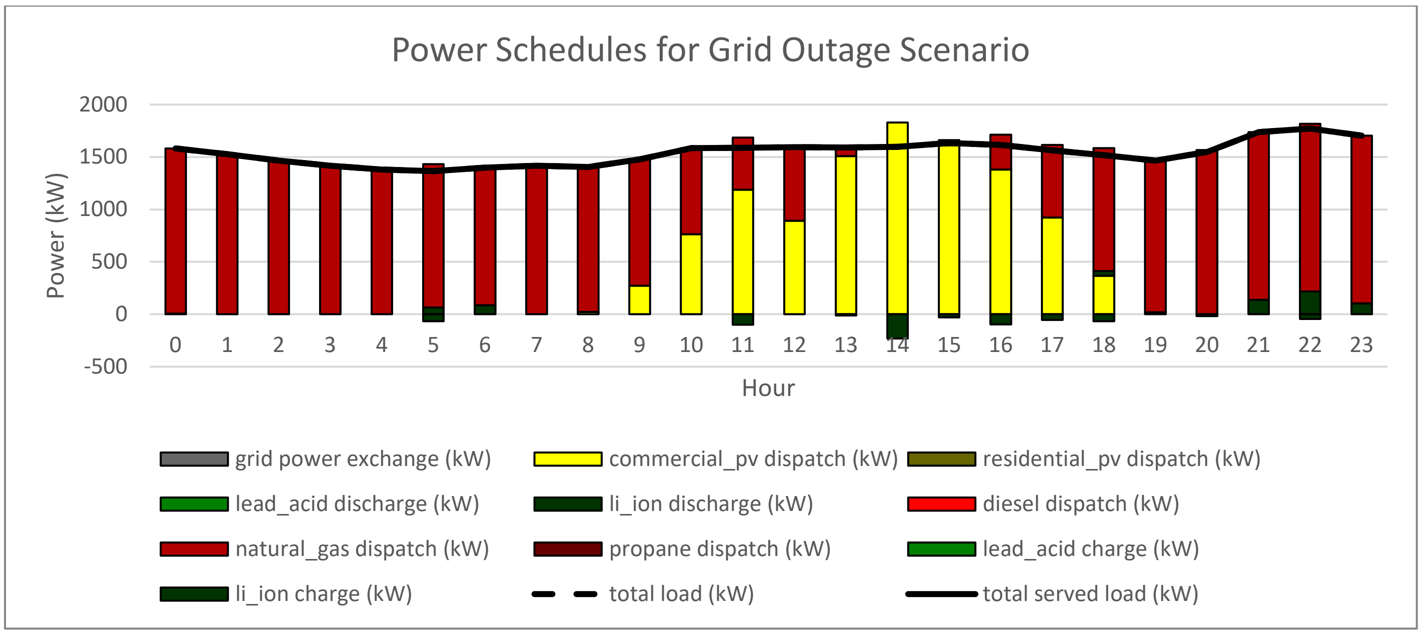


B.8.5. Yabucoa Microgrid 2901-03 Decreasing Demand Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	2,200
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	233
5	diesel	generator	0
6	natural_gas	generator	1,600
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			Grid Outage (Pr = 7.671%)		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	58,753	58,753	29,882	4,886	4,886	2,485
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	5,128	35,896	18,257	625	4,378	2,227
5	0	0	0	0	0	0
6	142,998	17,731,758	9,018,397	11,896	1,475,127	750,252
7	0	0	0	0	0	0
8	140	29,421	14,964	0	0	0
	207,019	**17,855,827**	**9,081,499**	**17,408**	**1,484,391**	**754,964**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	63,639	32,367	8,797,389	8,766,117
2	0	0	0	0
3	0	0	0	0
4	40,274	20,483	1,303,625	1,283,835
5	0	0	0	0
6	19,206,885	9,768,649	30,887,111	21,448,875
7	0	0	0	0
8	29,421	14,964	29,421	14,964
	19,340,219	**9,836,462**	**41,017,546**	**31,513,789**

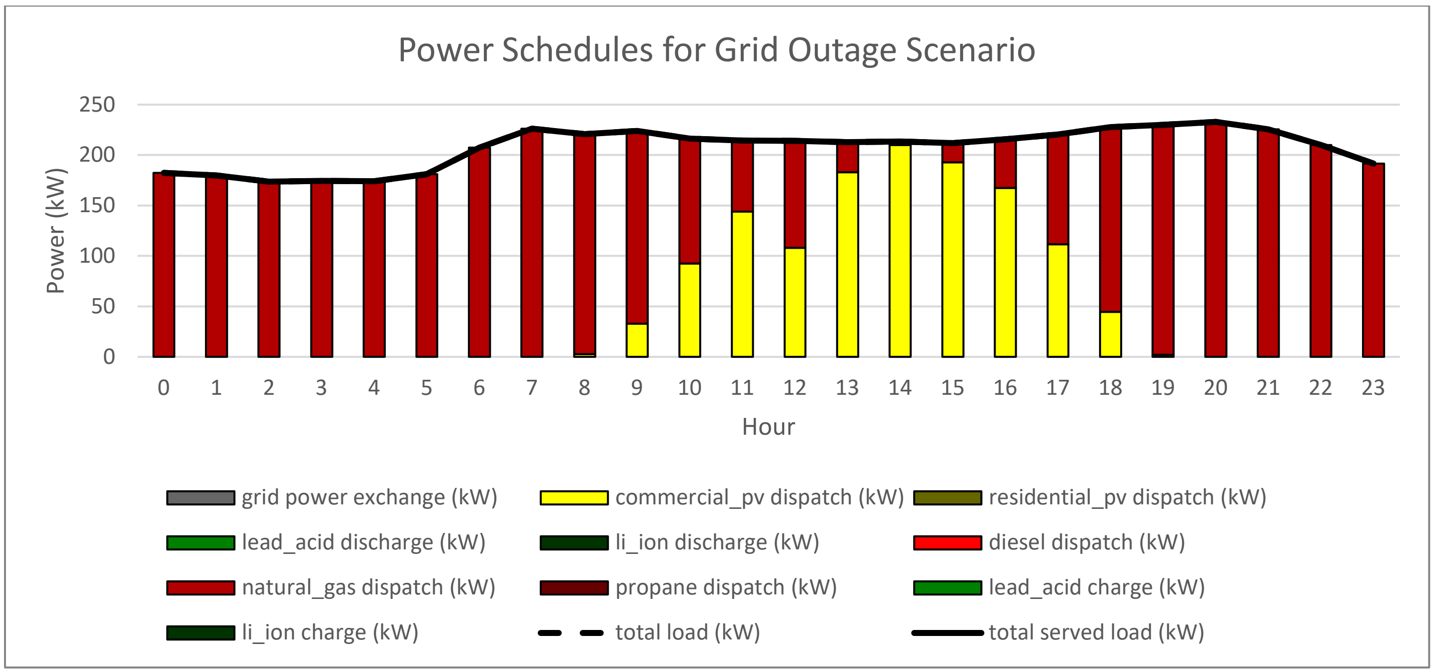


B.8.6. Yabucoa Microgrid 2901-03 High Priority Loads Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	267
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	0
5	diesel	generator	0
6	natural_gas	generator	300
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	8,704	8,704	4,164	723	723	346
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	24,869	3,083,751	1,475,207	2,066	256,217	122,569
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	33,573	**3,092,455**	**1,479,370**	**2,789**	**256,940**	**122,915**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	9,427	4,510	1,068,063	1,063,146
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	3,339,968	1,597,776	5,530,010	3,787,818
7	0	0	0	0
8	0	0	0	0
	3,349,395	**1,602,285**	**6,598,073**	**4,850,964**

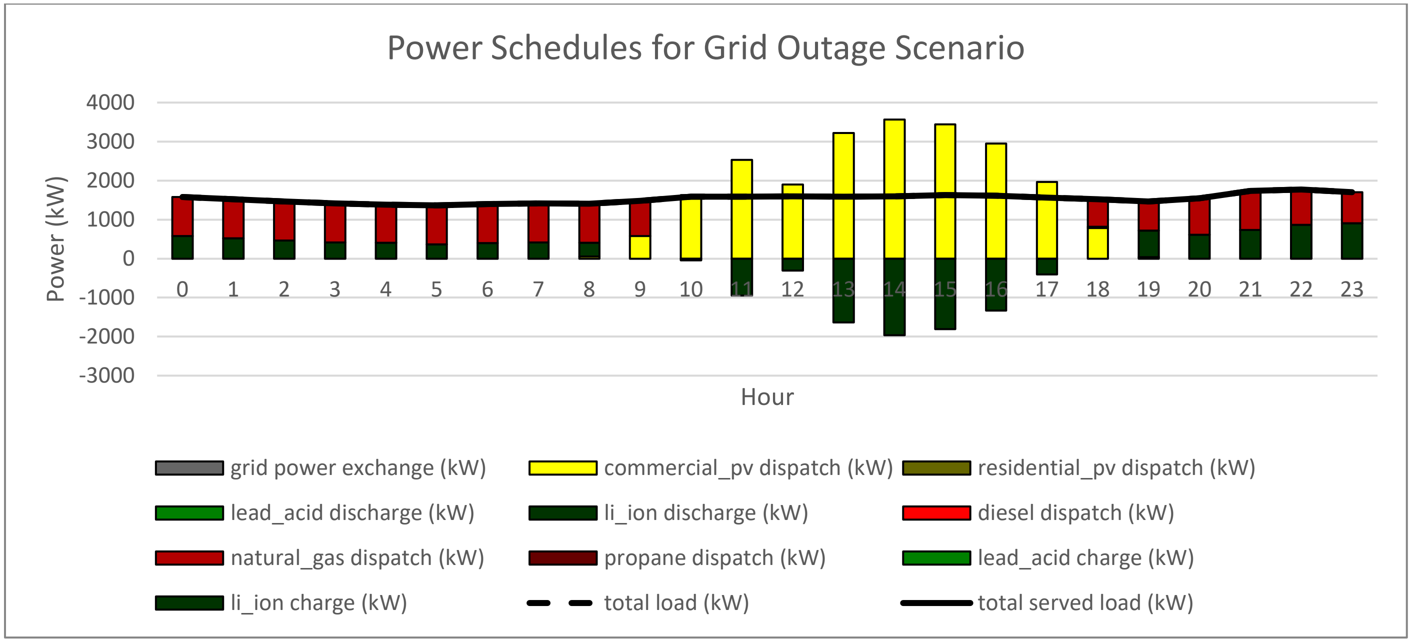


B.8.7. Yabucoa Microgrid 2901-03 Low Discount Rate Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	4,700
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	1,967
5	diesel	generator	0
6	natural_gas	generator	1,000
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			Grid Outage (Pr = 7.671%)		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	152,801	152,801	152,801	12,696	12,696	12,696
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	109,358	765,505	765,505	9,086	63,603	63,603
5	0	0	0	0	0	0
6	100,740	12,491,706	12,491,706	8,370	1,037,887	1,037,887
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	362,898	**13,410,011**	**13,410,011**	**30,152**	**1,114,185**	**1,114,185**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	165,497	165,497	9,706,497	9,706,497
2	0	0	0	0
3	0	0	0	0
4	829,107	829,107	6,048,641	6,048,641
5	0	0	0	0
6	13,529,592	13,529,592	17,649,592	17,649,592
7	0	0	0	0
8	0	0	0	0
	14,524,196	**14,524,196**	**33,404,730**	**33,404,730**

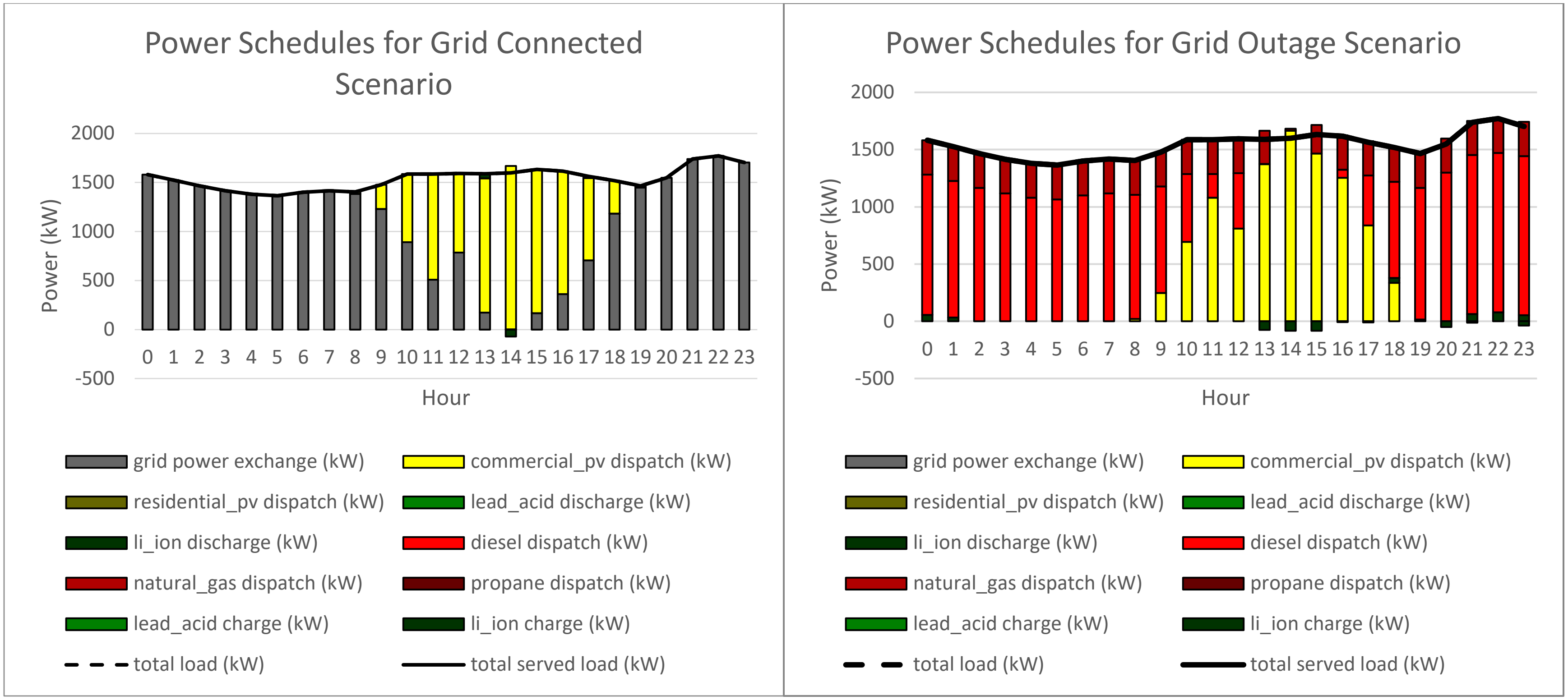


B.8.8. Yabucoa Microgrid 2901-03 Low Utility Electricity Price Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	2,000
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	83
5	diesel	generator	1,400
6	natural_gas	generator	300
7	propane	generator	0
8	grid power exchange	--	--

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	66,025	66,025	31,585	5,486	5,486	2,624
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	911	6,378	3,051	388	2,718	1,300
5	0	0	0	11,378	2,264,210	1,083,154
6	0	0	0	3,840	476,108	227,761
7	0	0	0	0	0	0
8	182,997	21,959,631	10,505,061	0	0	0
	249,933	**22,032,034**	**10,539,697**	**21,092**	**2,748,522**	**1,314,839**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	71,511	34,209	8,011,283	7,973,982
2	0	0	0	0
3	0	0	0	0
4	9,096	4,352	460,293	455,548
5	2,264,210	1,083,154	11,186,578	10,005,522
6	476,108	227,761	2,666,150	2,417,803
7	0	0	0	0
8	21,959,631	10,505,061	21,959,631	10,505,061
	24,780,556	**11,854,536**	**44,283,936**	**31,357,916**

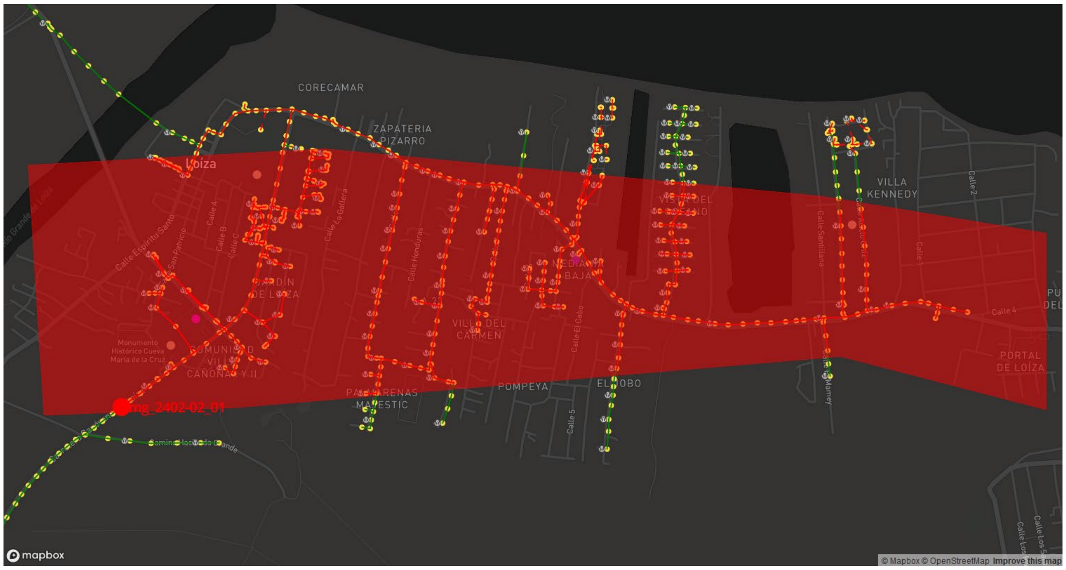

Power Schedules for Grid Connected Scenario
2000
1500
1000
500
0
-500
Power (kW)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour
grid power exchange (kW)
commercial_pv dispatch (kW)
residential_pv dispatch (kW)
lead_acid discharge (kW)
li_ion discharge (kW)
diesel dispatch (kW)
natural_gas dispatch (kW)
propane dispatch (kW)
lead_acid charge (kW)
li_ion charge (kW)
total load (kW)
total served load (kW)
Power Schedules for Grid Outage Scenario
2000
1500
1000
500
0
-500
Power (kW)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour
grid power exchange (kW)
commercial_pv dispatch (kW)
residential_pv dispatch (kW)
lead_acid discharge (kW)
li_ion discharge (kW)
diesel dispatch (kW)
natural_gas dispatch (kW)
propane dispatch (kW)
lead_acid charge (kW)
li_ion charge (kW)
total load (kW)
total served load (kW)

B.9. Loiza Microgrid 2402-02 Results

B.9.1. Loiza Microgrid 2402-02 Case Data

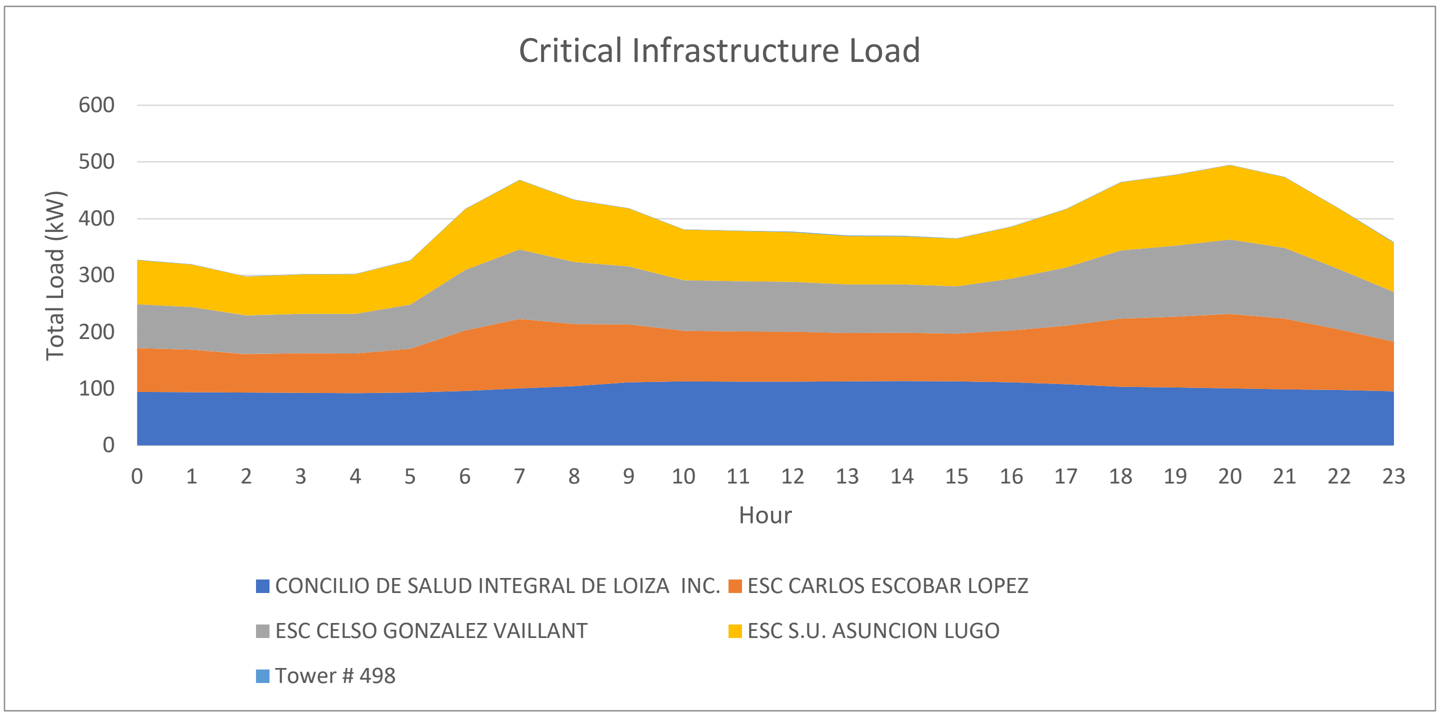
Microgrid Data	
Microgrid ID	mg_2402-02_01
Swing Node	18440991
Nominal Voltage (kV)	13.2
Number of Nodes	475
Number of OH Lines	318
Number of UG Lines	156
Number of Loads	158
Electrical Length (mi)	9.482
Total MW	3.101

Parent Feeder Data	
Feeder ID	2402-02
Swing Node	1000341872
Nominal Voltage (kV)	13.2
Number of Nodes	1711
Number of OH Lines	1401
Number of UG Lines	309
Number of Loads	482
Electrical Length (mi)	39.488
Total MW	8.273



B.9.2. Loiza Microgrid 2402-02 Critical Infrastructure Data

Critical Infrastructure Data					
Name	**Type**	**Power A (kW)**	**Power B (kW)**	**Power C (kW)**	**Priority Level**
CONCILIO DE SALUD INTEGRAL DE LOIZA INC.	clinic	37.802	37.802	37.802	100
ESC CARLOS ESCOBAR LOPEZ	shelter	43.748	43.748	43.748	75
ESC CELSO GONZALEZ VAILLANT	shelter	43.748	43.748	43.748	75
ESC S.U. ASUNCION LUGO	shelter	43.748	43.748	43.748	75
Tower # 498	telecom tower	0.216	0.216	0.216	50

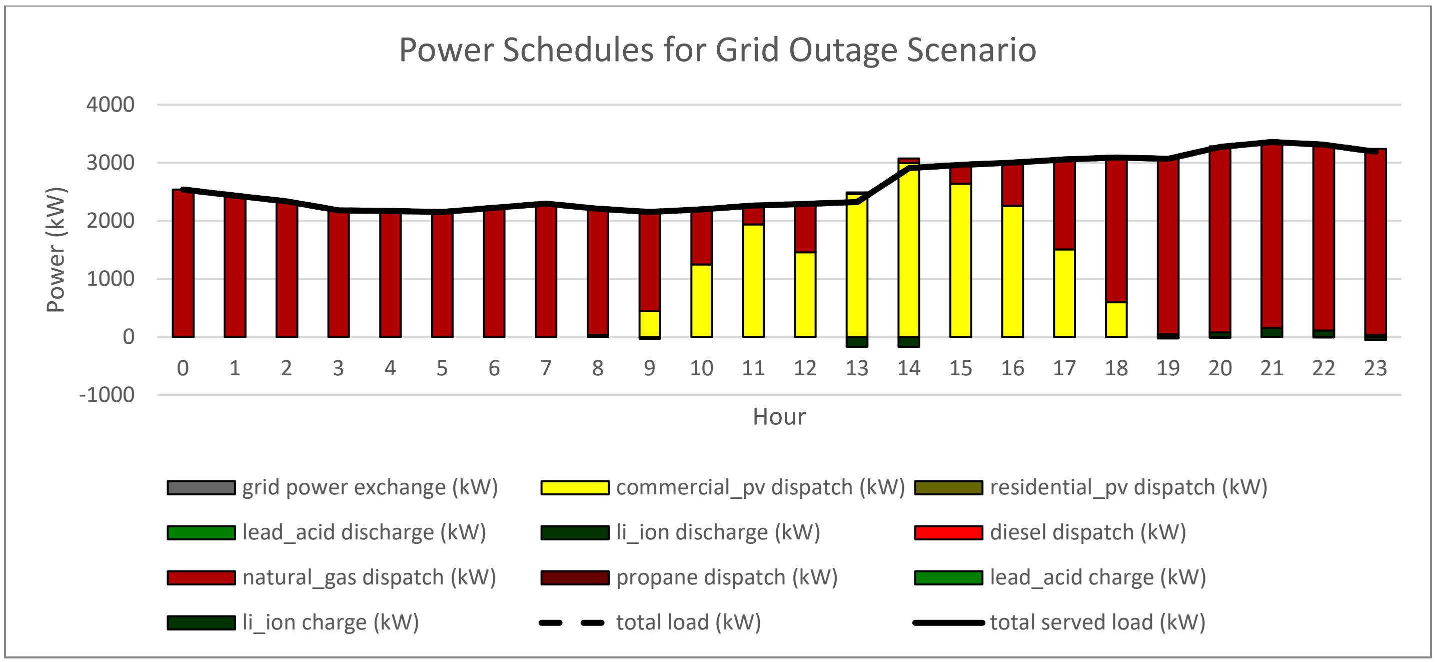


B.9.3. Loiza Microgrid 2402-02 Baseline Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	3,600
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	167
5	diesel	generator	0
6	natural_gas	generator	3,200
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			Grid Outage (Pr = 7.671%)		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	118,811	118,811	56,837	9,872	9,872	4,722
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	5,787	40,510	19,379	481	3,366	1,610
5	0	0	0	0	0	0
6	306,112	37,957,846	18,158,296	25,434	3,153,768	1,508,701
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	430,710	**38,117,168**	**18,234,512**	**35,786**	**3,167,005**	**1,515,034**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	128,683	61,559	14,420,273	14,353,150
2	0	0	0	0
3	0	0	0	0
4	43,876	20,990	946,270	923,383
5	0	0	0	0
6	41,111,614	19,666,997	64,472,066	43,027,449
7	0	0	0	0
8	0	0	0	0
	41,284,173	**19,749,546**	**79,838,609**	**58,303,982**

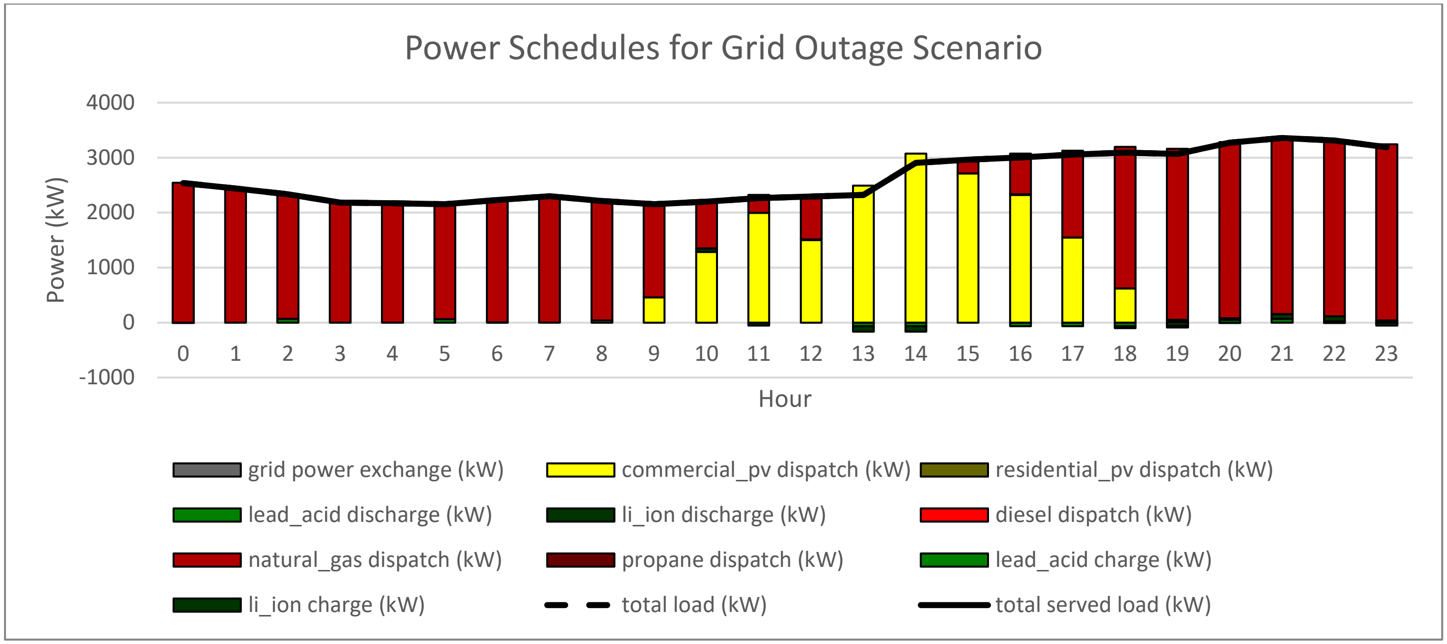


B.9.4. Loiza Microgrid 2402-02 CO2 Cost Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	3,700
2	residential_pv	pv	0
3	lead_acid	storage	67
4	li_ion	storage	100
5	diesel	generator	0
6	natural_gas	generator	3,200
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	121,779	121,779	58,257	10,118	10,118	4,840
2	0	0	0	0	0	0
3	2,264	15,848	7,581	362	2,537	1,213
4	3,155	22,084	10,565	434	3,036	1,452
5	0	0	0	0	0	0
6	303,110	40,980,483	19,604,267	25,249	3,413,666	1,633,031
7	0	0	0	0	0	0
8	324	67,951	32,507	0	0	0
	430,632	**41,208,145**	**19,713,176**	**36,163**	**3,429,356**	**1,640,537**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	131,897	63,097	14,820,476	14,751,676
2	0	0	0	0
3	18,384	8,795	433,727	424,137
4	25,120	12,017	566,556	553,453
5	0	0	0	0
6	44,394,149	21,237,298	67,754,601	44,597,750
7	0	0	0	0
8	67,951	32,507	67,951	32,507
	44,637,502	**21,353,713**	**83,643,312**	**60,359,524**

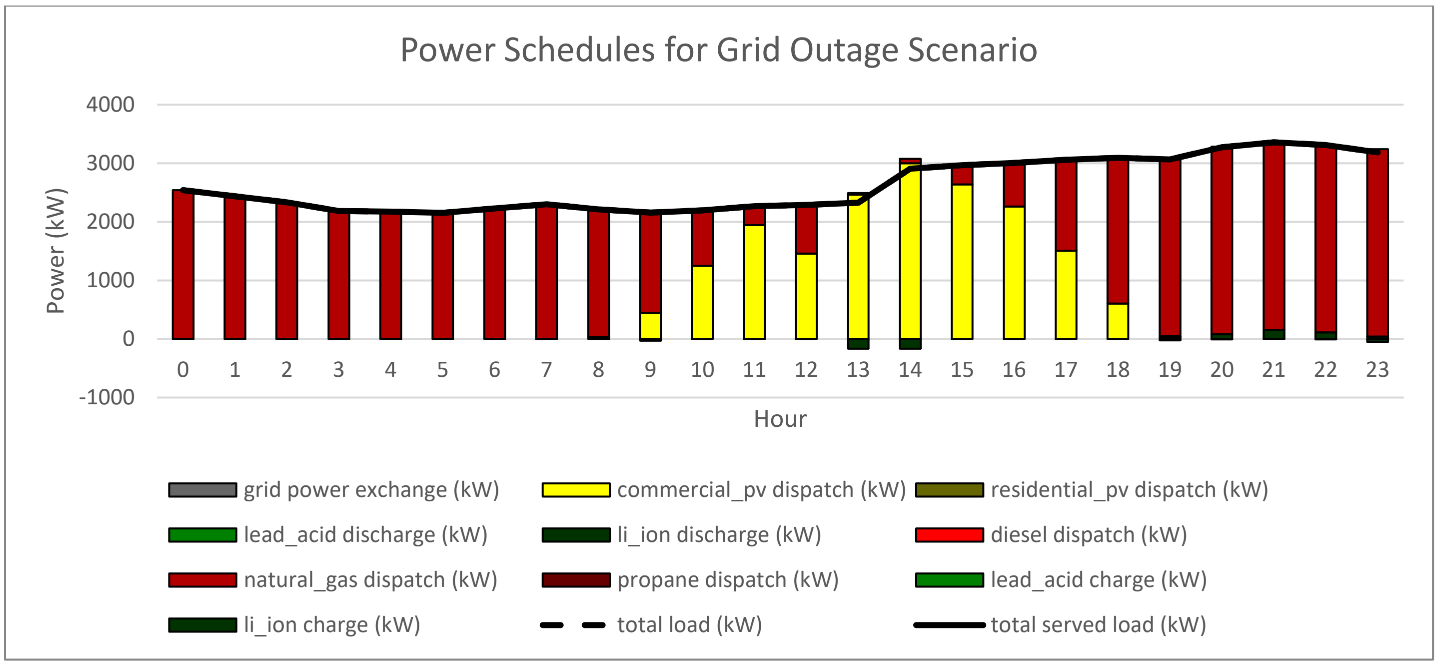


B.9.5. Loiza Microgrid 2402-02 Decreasing Demand Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	3,600
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	167
5	diesel	generator	0
6	natural_gas	generator	3,200
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	96,237	96,237	48,946	7,996	7,996	4,067
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	4,688	32,813	16,689	389	2,726	1,387
5	0	0	0	0	0	0
6	247,950	30,745,855	15,637,385	20,601	2,554,552	1,299,249
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	348,875	**30,874,906**	**15,703,020**	**28,987**	**2,565,274**	**1,304,702**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	104,233	53,013	14,395,823	14,344,603
2	0	0	0	0
3	0	0	0	0
4	35,540	18,076	937,934	920,469
5	0	0	0	0
6	33,300,407	16,936,633	56,660,859	40,297,086
7	0	0	0	0
8	0	0	0	0
	33,440,180	**17,007,722**	**71,994,616**	**55,562,158**

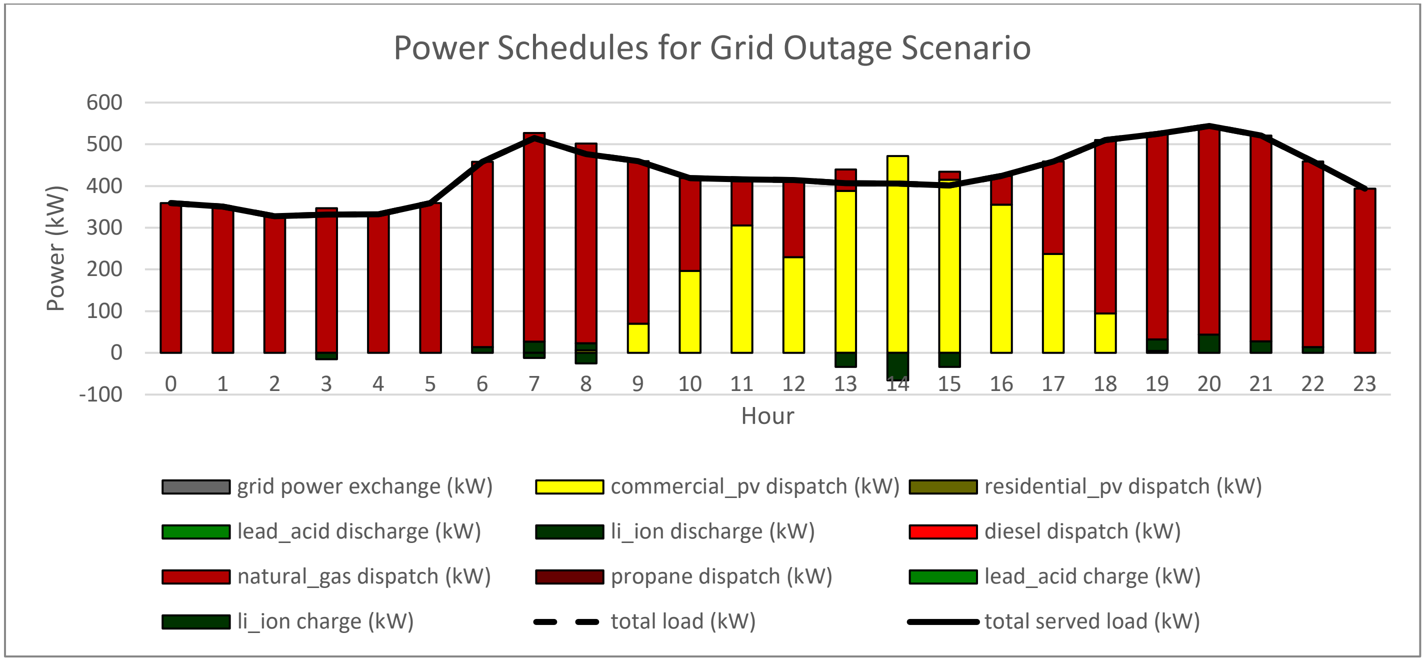


B.9.6. Loiza Microgrid 2402-02 High Priority Loads Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	567
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	67
5	diesel	generator	0
6	natural_gas	generator	500
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			**Grid Outage (Pr = 7.671%)**		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	18,707	18,707	8,949	1,554	1,554	744
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	2,397	16,778	8,026	199	1,394	667
5	0	0	0	0	0	0
6	50,586	6,272,702	3,000,739	4,203	521,174	249,320
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	71,690	**6,308,187**	**3,017,714**	**5,956**	**524,122**	**250,730**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	20,261	9,693	2,269,864	2,259,295
2	0	0	0	0
3	0	0	0	0
4	18,172	8,693	379,130	369,651
5	0	0	0	0
6	6,793,876	3,250,058	10,443,947	6,900,129
7	0	0	0	0
8	0	0	0	0
	6,832,309	**3,268,444**	**13,092,940**	**9,529,074**

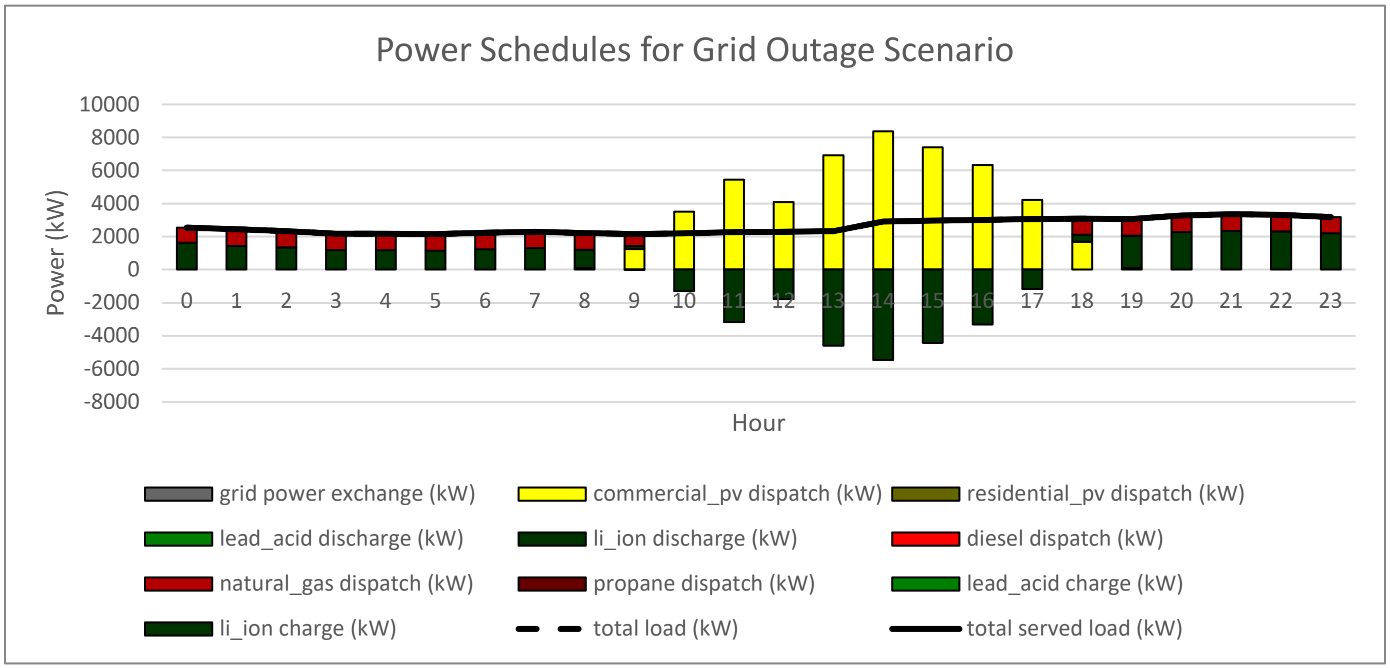


B.9.7. Loiza Microgrid 2402-02 Low Discount Rate Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	10,100
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	5,867
5	diesel	generator	0
6	natural_gas	generator	1,000
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			Grid Outage (Pr = 7.671%)		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	333,163	333,163	333,163	27,681	27,681	27,681
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	327,386	2,291,701	2,291,701	27,201	190,408	190,408
5	0	0	0	0	0	0
6	105,159	13,039,756	13,039,756	8,737	1,083,422	1,083,422
7	0	0	0	0	0	0
8	0	0	0	0	0	0
	765,709	**15,664,621**	**15,664,621**	**63,620**	**1,301,512**	**1,301,512**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	360,845	360,845	20,863,845	20,863,845
2	0	0	0	0
3	0	0	0	0
4	2,482,110	2,482,110	18,052,243	18,052,243
5	0	0	0	0
6	14,123,178	14,123,178	18,243,178	18,243,178
7	0	0	0	0
8	0	0	0	0
	16,966,132	**16,966,132**	**57,159,265**	**57,159,265**

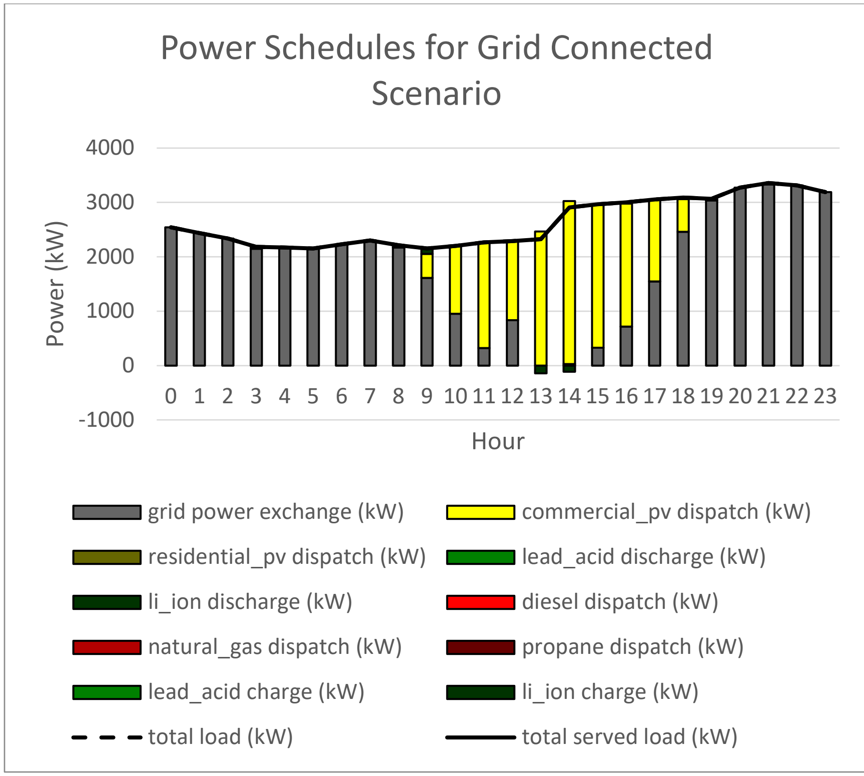


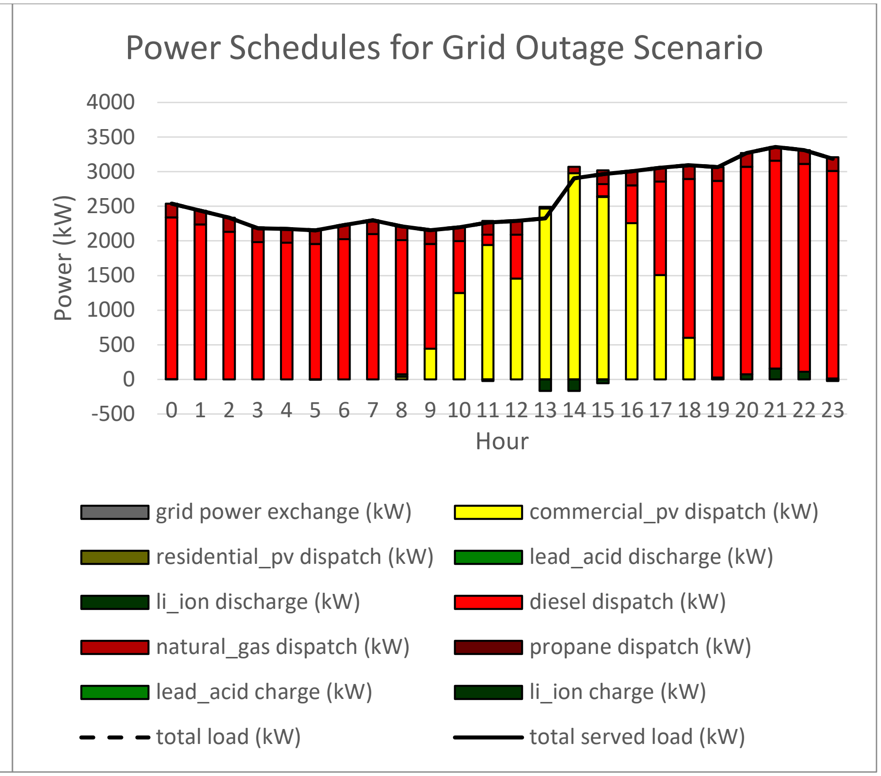
B.9.8. Loiza Microgrid 2402-02 Low Utility Electricity Price Sensitivity Results

Optimal Selected Capacity by DER Option			
DER Asset #	**DER Option**	**DER Type**	**Optimal Selected Capacity (kW)**
1	commercial_pv	pv	3,600
2	residential_pv	pv	0
3	lead_acid	storage	0
4	li_ion	storage	167
5	diesel	generator	3,000
6	natural_gas	generator	200
7	propane	generator	0

	Grid Connected (Pr = 92.329%)			Grid Outage (Pr = 7.671%)		
DER Asset #	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**	**Lifetime Energy Throughput (MWh)**	**Lifetime Operating Cost ($)**	**Lifetime Operating Cost (NPV$)**
1	118,845	118,845	56,853	9,864	9,864	4,719
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	3,372	23,606	11,293	473	3,311	1,584
5	0	0	0	22,912	4,559,476	2,181,165
6	0	0	0	2,529	313,597	150,019
7	0	0	0	0	0	0
8	305,977	36,717,260	17,564,824	0	0	0
	428,195	**36,859,711**	**17,632,969**	**35,778**	**4,886,247**	**2,337,486**

DER Asset #	Total Lifetime Operating Cost ($)	Total Lifetime Operating Cost (NPV$)	Total Capital and Operating Cost ($)	Total Capital and Operating Cost (NPV$)
1	128,709	61,572	14,420,299	14,353,162
2	0	0	0	0
3	0	0	0	0
4	26,916	12,876	929,310	915,270
5	4,559,476	2,181,165	23,678,837	21,300,525
6	313,597	150,019	1,773,625	1,610,047
7	0	0	0	0
8	36,717,260	17,564,824	36,717,260	17,564,824
	41,745,958	**19,970,455**	**77,519,331**	**55,743,828**


Power Schedules for Grid Connected Scenario
4000
3000
2000
1000
0
-1000
Power (kW)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour
grid power exchange (kW)
commercial_pv dispatch (kW)
residential_pv dispatch (kW)
lead_acid discharge (kW)
li_ion discharge (kW)
diesel dispatch (kW)
natural_gas dispatch (kW)
propane dispatch (kW)
lead_acid charge (kW)
li_ion charge (kW)
total load (kW)
total served load (kW)


Power Schedules for Grid Outage Scenario
4000
3500
3000
2500
2000
1500
1000
500
0
-500
Power (kW)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour
grid power exchange (kW)
commercial_pv dispatch (kW)
residential_pv dispatch (kW)
lead_acid discharge (kW)
li_ion discharge (kW)
diesel dispatch (kW)
natural_gas dispatch (kW)
propane dispatch (kW)
lead_acid charge (kW)
li_ion charge (kW)
total load (kW)
total served load (kW)

This page left blank.

References

3.0: LNG Distributed Production and Virtual Pipeline. (2017, October 30). Retrieved from https://www.youtube.com/watch?v=Pfs2zMxm9gk.

Abedi, M., & Kwang, Y. (2015). Smart Energy Storage System for Integration of PMSG-based Wind Power Plant. *IEEE Power & Energy Society General Meeting.*

Agency, I. R. (2017). *Electricity Storage and Renewables: Costs and Markets to 2030.* Abu Dhabi: International Renewable Energy Agency.

Agile Alliance. (n.d.). *Agile Manifesto.* Retrieved from https://www.agilealliance.org/agile101/12-principles-behind-the-agile-manifesto/

Anchal, L., & Kulkarni, R. (2017). Stationary Electrical Energy Storage Technology for Global Energy Sustainability: A Review. *International Conference on Nascent Technologies in Engineering* .

Aneke, M., & Meihong, W. (2016). Energy storage technologies and real life applications–A state of the art review. *Applied Energy* (179), 350-377.

Atanasoae, P. (2017). Integration of Thermal Energy Storage Systems for Improved Efficiency and Flexibility of the Combined Heat and Power Plants of Medium and Small Power. *International Conference on Electromechanical and Power Systems.*

Bruce, D., Kamath, H., & Jean-Marie, T. (2011). Electrical energy storage for the grid: a battery of choices. *Science, 334*(6058), 928-935.

Cambridge Economic Policy Associates. (2018). *Study on the Value of Lost Load of Electricity Suppy in Europe.*

Carnegie, R. (n.d.). *Utility Scale Energy Storage Systems* . Retrieved 01 2020, from www.purdue.edu/discoverypark/energy/assets/pdfs/SUFG/publications/SUFG%20Energy%20Storage%20Report.pdf

Castro-Sitiriche, M., Burgos-Rivera, A., & Burgos-Citron, A. (2019). Localization of the Communities Reconnected Lst to PREPA After Hurricane Maria: Implications FOr Hazard Mitigation. *PRYSIG CoHemis.*

CHP Association. (2017, October 11). *Harvey, Irma, and Maria: How Hurricanes in 2017 Remind Us of the Need for CHP.* Retrieved from https://resilienceguide.dg.industrialenergytools.com/caseStudies

Cole, W. (2016). Utility-Scale Lithium-Ion Storage Cost Projections for Use in Capacity Expansion Models. *2016 North American Power Symposium (NAPS).*

Colthorpe, A. (2017, Nov. 23). *Tesla Makes Good on '100 Day' Battery Promise, Sells Boring Hats*. (Energy Storage News, Solar Media Ltd.) Retrieved from www.energy-storage.news/news/tesla-makes-good-on-100-day-battery-promise-sells-boring-hats

Crowley. (2018, June). *Crowley Adds 40 ISO Tanks to Meet Growing Customer Demand.* Retrieved from http://www.crowley.com/News-and-Media/Press-Releases/Crowley-Adds-40-ISO-Tanks-to-Meet-Growing-Customer-Demand

CYME. (2018). *CymeDist Reference.* CYME.

Diorio , N. (2015). Economic Analysis Case Studies of Battery Energy Storage with SAM. *doi:10.2172/1226239.*

EPRI. (2018). *Open DSS.* Retrieved from https://www.epri.com/#/pages/sa/opendss?lang=en

ERCOT. (2018). *Analysis of the Impacts of the Clean Power Plan: Final Rule Update.*

European Commission. (2017). . *Regulation of the European Parliament and of the Council on the Internal Market for Electricity.*

(n.d.). *European Union Value of Lost Load (VoLL).*

Farhadi, M., & Osama, M. (2016). Energy Storage Technologies for High-Power Applications. *IEEE Transactions on Industry Applications, 3*(52), 1953–1961.

Generac. (n.d.). *Generac Diesel Generators.* Retrieved from https://www.electricgeneratorsdirect.com/power/generac-diesel-generators.html?gclid=EAIaIQobChMI3Yzp-Kyb3wIVkLjACh2rzA68EAAYASAAEgI6U_D_BwE

Gonen, T. (2008). *Electric Power Distribution System Engineering.* Boca Raton: CRC PRess.

Intergovernmental Panel on Climate Change. (2018). *Global Warming of 1.5 °C. an IPCC special report.*

IPCC. (n.d.). *Pull the Emergency Brake on Global CO2 Emissions.* . Retrieved from https://www.statista.com/chart/15737/global-co2-emissions-ipcc-targets/

Kersting, W. (2007). *Distribution System Modeling and Analysis.* Boca Raton: CRC Press.

Kintner-Meyer, M. (2013). National Assessment of Energy Storage for Grid Balancing and Arbitrage: Phase. *doi:10.2172/1131386.*

Laurence Berkeley National Laboratory. (2018). *Estimate Interruption Cost Calculator*. Retrieved from https://icecalculator.com/interruption-cost

Lazard. (n.d.). *Levelized Cost of Storage v3.0.*

LG Chem, Energy Solutions Company ESS Battery Division. . (n.d.). *Advanced Batteries for Energy Storage. Global Catalog.*

London Economics. . (n.d.). *Estimating the Value of Lost Load: Briefing paper prepared for the Electric Reliability Council of Texas, Inc.*

Lugo-Alvarez, M., Broderick, R., & Ortiz-Rivera, E. (2020). Strategic Placement and Design of Microgrids using Nighttime Imagery. *47th IEEE Photovoltaic Specialists Conference (PVSC).*

Merchant, E. (2017, Sept. 20). *Lithium-Ion Battery Production Is Surging, but at What Cost?* (Gtm, Greentech Media) Retrieved from www.greentechmedia.com/articles/read/lithium-ion-battery-production-is-surging-but-at-what-cost?utm_source=Storage&utm_medium=Newsletter&utm_campaign=GTMStorage#gs.td6BDkU

NREL. (2018). *2018 Annual Technology Baseline (ATB).* NREL.

NREL. (2018). *A Comparison of Fuel Choice for Backup Generators.*

NY Times. (2017, October 7). *Minus Electrical Grid, Puerto Rico Becomes Generator Island.* Retrieved from https://www.nytimes.com/2017/10/07/us/puerto-rico-power-generators.html.

NYISO. (n.d.). *Carbon Pricing Draft Recommendations.*

Peppanen, J., Reno, M., & Broderick, R. (2016). Distribution System Low-Voltage Circuit Topology Estimation using Smart Metering Data. *IEEE PES T&D Conference and Exposition.* Dallas, TX.

Poonpun, P., & Jewell, W. (2008). Analysis of the Cost per Kilowatt Hour to Store Electricity. *IEEE Transactions on Energy Conversion, 23*(2), 529–534.

(n.d.). *Regulation of the European Parliament and of the Council on the Internal Market for Electricity.*

(2018). *Regulation on Microgrid Development- 9028.* San Juan: Puerto Rico Energy Bureau.

Reno, M., Ellis, A., Quiroz, J., & Grijalva, S. (2012). Modeling Distribution System Impacts of Solar Variability and Interconnection Location. *World Renewable Energy Forum.*

Romm, J. (2017, Jan.). *Chart of the Month: Driven by Tesla, Battery Prices Cut in Half since 2014.* (ThinkProgress) Retrieved from thinkprogress.org/chart-of-the-month-driven-by-tesla-battery-prices-cut-in-half-since-2014-718752a30a42/.

Sandoval, M., & Grijalva, S. (2019). *PR Grid Redesign Report.* ProsumerGrid.

Siemens. (2018). *IRP Value of Loss Load.*

Silva, P. (2018). *Grenhouse Gas Regulatory Update.*

Singh, U., & E., B. (2010). Load Estimation for Distribution Feeder Monitoring and Management. *IEEE PES General Meeting.*

(n.d.). *Social Cost of Carbon Pricing of Power Sector CO2.*

Stam, C. (2018). *EU carbon prices expected to rise quickly and accelerate energy transition.*

Superintendencia de Electricidad Republica Dominicana. (2017). *Resolucion SIE-009-2017 MEM: Fijacion Costo Marginal Tope de Energia de Corto Plazo en el Mercado Spot y Costo de Desabastecimiento.*

The Brattle Group. (2013). *Resource Adequacy Requirements: Reliability and Economic Implications.* .

Vera Rosado, I. (2018). *Incrementa el precio del gas en la Isla.* Retrieved from https://www.elvocero.com/economia/incrementa-el-precio-del-gas-en-la-isla/article_a645f872-6d79-11e8-a149-bfb3a1886a42.html.

Zakeri, B., & Sanna, S. (2015). Electrical energy storage systems: A comparative life cycle cost analysis. *Renewable and sustainable energy reviews*(42), 569-596.

DISTRIBUTION

Email—Internal

Name	Org.	Sandia Email Address
Robert Broderick	8812	rbroder@sandia.gov
Summer Ferreira	8812	srferre@sandia.gov
Technical Library	01977	sanddocs@sandia.gov

Email—External

Name	Company Email Address	Company Name
Dan Ton	dan.ton@hq.doe.gov	U.S. Department of Energy
Merrill Smith	merrill.smith@hq.doe.gov	U.S. Department of Energy
Marisol Bonnet Acosta	marisol.bonnet@hq.doe.gov	U.S. Department of Energy
Eric Britton	eric.britton@hq.doe.gov	U.S. Department of Energy
Marcelo Sandoval	msandoval@prosumergrid.com	Prosumer Grid
Efrain O'Neill Carrillo	efrain.oneill@upr.edu	University of Puerto Rico - Mayagüez

This page left blank

Sandia National Laboratories
is a multimission laboratory
managed and operated by
National Technology &
Engineering Solutions of
Sandia LLC, a wholly owned
subsidiary of Honeywell
International Inc. for the U.S.
Department of Energy's
National Nuclear Security
Administration under contract
DE-NA0003525.