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THESIS

DESIGN AND MODELING OF HYBRID MICROGRIDS IN ARCTIC ENVIRONMENTS

by

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**DESIGN AND MODELING OF HYBRID MICROGRIDS
IN ARCTIC ENVIRONMENTS**

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

As the U.S. military shifts its efforts from the Middle East to the Pacific and the Arctic, energy planners must also refocus methods of designing and modeling energy management to support such missions. This thesis develops a methodology to size the energy resources of a military hybrid microgrid and implements this methodology in a user-friendly tool that is easily accessible to engineers and energy managers at military facilities. The tool focuses on increasing the resilience specifically of military microgrids and on accurately sizing distributed energy resources (DERs) to account for climate. While complying with IEEE standard 1562-2007, the tool allows the user to specify environmental factors of the location and decide upon the total dependence of the system on solar power. Three experiments with a commercial off-the-shelf (COTS) microgrid validated the design tool and physics-based model. Then, this research tested the performance of 30 differently sized DERs to understand the parameters for the design of hybrid microgrids for military installations in a range of climates. Finally, the research provides the tool user with guidelines for designing the DERs for energy redundancy or flexibility and economy.

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LIST OF ACRONYMS AND ABBREVIATIONS

h_e	PV module efficiency
h_{inv}	inverter efficiency
h_g	generator efficiency
A:L	array to load
AEMRR	Annual Energy Management and Resilience Report
AMMPS	Advanced Medium Mobile Power Source
C_{T_B}	temperature correction factor of batteries
COTS	commercial off-the-shelf
D_{auto}	days of autonomy
D_{auto}^{99}	day of autonomy for 99% energy availability
D_{auto}^{95}	day of autonomy for 95% energy availability
D_Q^{NOC}	RUS for total load during NOC
$D_{Q_i}^{NOC}$	RUS for critical loads only
DERs	distributed energy resources
DM	design margin
DOD	depth of discharge
DOD	Department of Defense
DON	Department of the Navy
ECU	environmental control unit
ERA	Energy Resilience Analysis
F	fuel used
F_s	fuel storage
FOB	forward operating base
G_{hr}	fuel rate
HOMER	Hybrid Optimization Model for Electric Renewables
i_{bat}	battery current

i_{bus}	DC bus current
i_{gen}	generator current
I_l^{crit}	load in Ah/day of critical loads only
I_l^{NOC}	load in Ah/day of load during NOC
i_{load}	load current
I_{mpnew}	maximum power point current of PVs, accounting for temperature
i_{PV}	PV current
I_{PV}	PV current profile
KCL	Kirchhoff Current Law
L_{pr}	generic load profile
MDOD	maximum depth of discharge
MDT	Microgrid Design Toolkit
MIT-LL	Massachusetts Institute of Technology Lincoln Laboratory
MPPT	maximum power point tracker
N_B	number of total batteries
N_{Bp}	number of batteries in parallel
N_{Bp}^{crit}	number of batteries in parallel for critical loads only
N_g	number of generators
N_g^{max}	maximum allowable number of generators
N_g^{min}	minimum allowable number of generators
N_{Pp}	number of PV modules in parallel
N_{Ps}	number of PV modules in series when not using a MPPT
N_{Ps}^{MPPT}	number of PV modules in series when using a MPPT
NOC	normal operating conditions
NOCT	nominal operating cell temperature
NREL	National Renewable Energy Laboratory
OSD	Office of the Secretary of Defense

P_g	instantaneous power output of generator
$P_g^{\max}$	maximum allowable power output of generator
P_{gen}	rated generator power
$P_l^{\max}$	peak load power
$P_{l_{AC}}$	total daily AC power consumption
$P_{l_{DC}}$	total daily DC power consumption
$P_{l_{AC}}^{crit}$	total daily critical AC power consumption
$P_{l_{DC}}^{crit}$	total daily critical DC power consumption
P_{out}^{PV}	PV output of PV arrays
P_{out}^{PV}	power load profile
PI	proportional integral
PSH	peak sun hours
PV	photovoltaic
Q_b	nominal battery capacity
Q_t^{crit}	total storage capacity required during critical loads only
Q_{US}^{crit}	usable storage during critical loads only
Q_t^{NOC}	total storage capacity required during NOC
Q_{US}^{NOC}	usable storage during NOC
Q_l^{PV}	Ah to load from PV modules
Q_{out}^{PV}	output of PV modules in Ahs
$R_{A:L}$	array to load ratio
RUS	required usable storage
S_{pr}	solar arc profile
SAM	System Advisor Model
SF	solar fraction
STC	standard test conditions

T_{amb}	ambient temperature
T_{cell}	temperature of cell
TC_{I_A}	current temperature coefficient
$TC_{I\%}$	current temperature coefficient
$TC_{I_{ppm}}$	current temperature coefficient
TC_{V_v}	voltage temperature coefficient
$TC_{V\%}$	voltage temperature coefficient
$TC_{V_{ppm}}$	voltage temperature coefficient
$TC_{P\%}$	power temperature coefficient
TQG	tactical quiet generator
V_b	nominal battery voltage
V_{DC}	DC bus voltage
V_{DC}^*	reference DC bus voltage
V_{mpnew}	maximum power voltage of PV modules with temperature
V_{sys}	system voltage

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I. INTRODUCTION

A. BACKGROUND

The Department of Defense (DOD) is responsible for 80% of Federal Government energy consumption and of that, the Department of the Navy (DON) uses 28%. In 2009, the DON Energy Program set five goals to help achieve energy security and independence; one of these goals was to produce at least 50% of total DON energy requirements from alternative sources by 2020 [1]; there is no confirmation that the DON has reached this goal. With the advancements in Photovoltaic (PV) technology and the reduction in PV cost in recent years [2], solar power is a viable option as an alternative energy source. Specifically, solar power in conjunction with energy storage and diesel power in a hybrid microgrid is a possible answer to the DON goal.

While a substantial portion of U.S. Military operations have been in arid desert environments for the past twenty years, forces are preparing for future conflict in arctic climates [3]. With a change in environment comes change in the way leaders plan for energy management. The same consideration for the design of a microgrid in Afghanistan may not apply to the design of one at a higher latitude.

Effective use of solar power requires correct sizing of a hybrid microgrid according to the environment in which it operates. The power output of PV arrays is not only dependent on the solar irradiance the system receives, but also on the temperature of the environment. It is crucial that the specific location of the microgrid be used to size its batteries and PV arrays due to the great variability of both temperature and irradiance depending on the longitude and latitude of the microgrid. Figure 1 and Figure 2 show to what degree the solar irradiance and temperature differs throughout the country; moreover, the solar irradiance and temperature each vary to different degrees throughout the year, depending on the microgrid location.

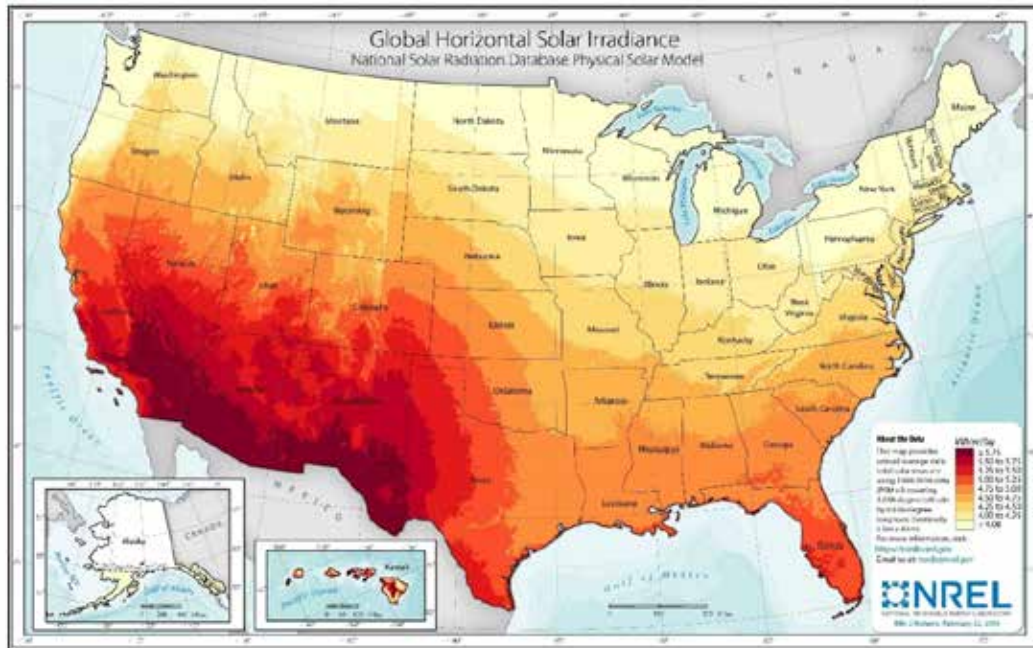


Figure 1. Map of the Annual Average Daily Solar Irradiance in kWh/m² of the Continental United States. Source: [4].

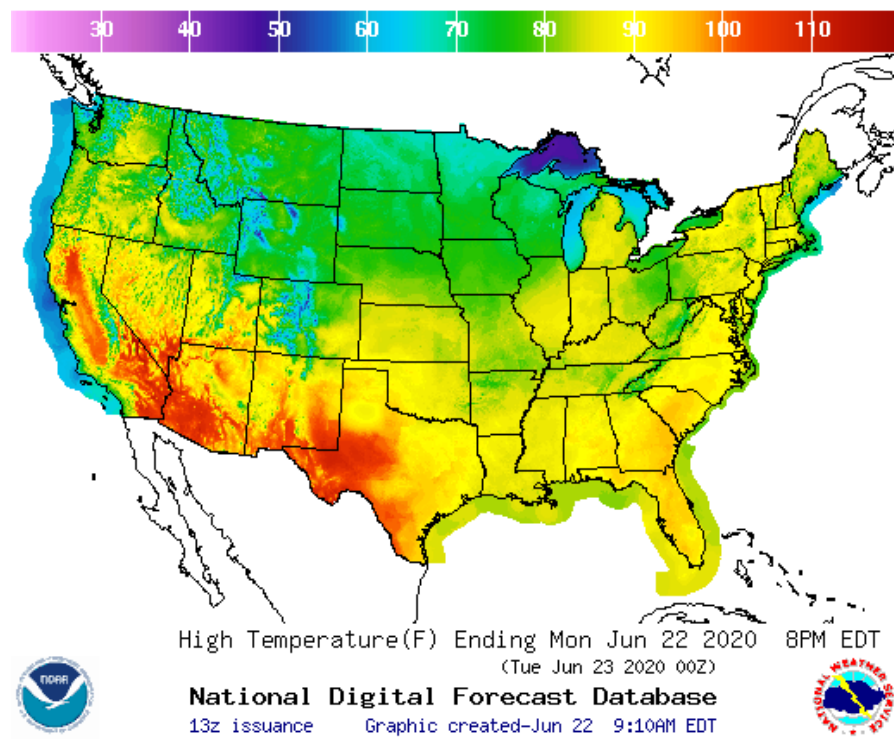


Figure 2. Map of Temperature in June of the Continental United States. Source: [5].

All of these factors play a role in the potential year-long production of solar power. A microgrid designed with correct sizing can ensure continued support for critical loads.

B. RELATED WORK

First, this research builds from a previous research conducted by Petros Siritoglou [6], who created a MATLAB tool intended for the sizing and modeling of stand-alone PV systems for military installations. The tool takes user inputs to a MATLAB graphical user interface, generates the number of PV arrays and batteries required to support the load and generates a one-day performance profile of the system in a MATLAB power flow system. The tool addresses temperature correction factors for battery capacity and adjusts the expected PV performance depending on model voltage and current temperature coefficients.

Current popular design tools are Hybrid Optimization Model for Electric Renewables (HOMER), Microgrid Design Toolkit (MDT) by Sandia National Laboratories, and System Advisor Model (SAM) by National Renewable Energy Laboratory (NREL). HOMER is a commercially-available design tool that can be used to design and evaluate renewable power systems and provides economic modeling of the systems. It is a popular tool that many academic papers use when sizing PV systems [7]. MDT is used by Marine Corps Systems Command and is a “decision support software tool” intended to be used in the early phase of the system design [8], [9]. SAM is a free software model, intended for use by project managers, policy analysts, technology developers, and researchers to evaluate residential and commercial projects. It can model photovoltaic systems, battery storage, wind power, solar water heating, geothermal power generation, and multiple other systems [10].

Energy Resilience Analysis (ERA) tool of Massachusetts Institute of Technology Lincoln Laboratory (MIT-LL) is funded by the Office of the Secretary of Defense (OSD). The tool is a MATLAB-based software, and it produces a performance and cost model for various system architectures for the user to evaluate and decide on. It uses installation mission requirements and data collected from operational military bases [11]. In 2019, the

OSD issued guidance that requires the use of the ERA tool for Energy Resilience and Conservation Investment Program investment decisions [12].

The research presented in [13] contains an exhaustive and thorough summary of all microgrid design tools and proposes an alternative design and evaluation tool from a system engineering perspective. It develops a resiliency metric and a method of system evaluation to be used by facility managers.

The work done in [14] reviews the use of PV technology in remote microgrids. Specifically, it examines the feasibility and performance of PVs in remote Alaskan microgrids that support small isolated communities. It considers the configuration of PVs, the effect of snow on surface albedo, and the cost data of installation.

The architecture and resilience of microgrids is further discussed in [15] from a systems engineering perspective. Some specific and relevant subjects covered in this research are the differences and similarities between military and civilian microgrids, and suggested improvement strategies for microgrid system resilience. One key difference between military and civilian microgrids is that civilian microgrids are often designed to minimize cost, while military microgrids must prioritize energy security. Additionally, identifying the critical loads of a military base is a complicated procedure that requires careful attention due to the sensitive nature of military critical loads with respect to national security. From a systems perspective, resilience of military microgrids can be improved “by incorporating redundancy into the system, automating switching between elements of the architecture, [and] hardening system elements” [15].

C. RESEARCH OBJECTIVES

The objective of this research is to develop a methodology to size the energy resources of a military hybrid microgrid and to implement this methodology in a user-friendly tool that is easily accessible to engineers and energy managers at military facilities. The tool includes design equations and a physics-based model to size energy resources and to simulate the functionality of the hybrid microgrid under various environmental and climatic conditions. The tool seeks to inform energy management planning for existing and future Navy and Marine Corps bases and forward operating bases; the end result is for

domestic and expeditionary forces to produce a smaller environmental impact and to expend fewer resources. While complying with IEEE standard 1562 [16], the tool allows the user to specify environmental factors of the location and decide upon the total dependence of the system on solar power. This research tests the performance of 30 differently sized distributed energy resources (DERs) to understand the parameters for the design of hybrid microgrid for military installations in a range of climates. The DERs include PV arrays, batteries, and generators.

D. ORGANIZATION

Chapter II explains the function of batteries, PVs, and generator in the overall hybrid microgrid, and describes the methodology of sizing each component. Next, in Chapter III, the physics-based model of the microgrid is presented and explained. Additionally, the control logic that manages the generator is explained and demonstrated. In Chapter IV, experimental validation of a PV system demonstrates the accuracy of the sizing tool for PVs and batteries located in Monterey, CA. In Chapter V, the results of several simulations are presented. A year-long simulation of various-sized systems is conducted for three different locations. Next, simulations of system recovery with generator failure are simulated. Finally, Chapter VI provides conclusions and recommendations for future work.

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II. SIZING METHODOLOGY OF THE HYBRID MICROGRID

In this chapter, the design methodology and its implementation in a user-friendly platform are presented. The purpose of this tool is to inform energy planners about the sizing of the batteries, PVs, the generator, and fuel storage in a hybrid microgrid for expeditionary naval facilities.

A. MICROGRID ARCHITECTURE

The microgrid architecture analyzed in this thesis is depicted in Figure 3 and it includes a battery bank, PV arrays, a generator, an inverter, and a controller.

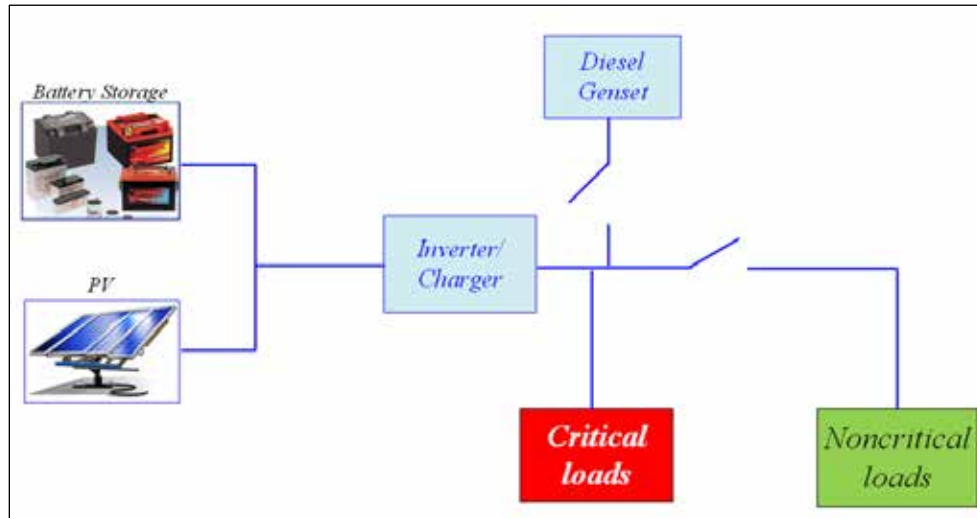


Figure 3. Architecture of Hybrid Microgrid Sized by Design Tool

The design tool presented in this thesis is comprised of three sections: the battery bank, the PV arrays, and the generator and fuel storage. The design equations were implemented in MS Excel because it is a software package available on most computers; therefore, the user does not need to acquire or install additional software to be able to design a microgrid with this tool.

Two options are available to the user: 1) a manual tool and, 2) an automatic tool – both are based on [6]. The automatic tool has preselected batteries and PVs, whereas the

manual tool requires users to research and select their own models of batteries, PVs, and generator. Finally, the tool accounts for the effects of temperature on PV performance, which enables this research to focus on the effects of external climate on system performance. Figure 4 and Figure 5 show the manual and automatic tools, respectively, with numbers based on the design for a 600 kWh/day microgrid located in San Diego, CA, in the “User Inputs.” The remainder of this chapter will discuss the individual sections of the tool, to include its inputs, calculations, and outputs.

Inputs		Outputs	
Battery Bank Design		Battery Bank Design	Outputs
System and Load Specifications		Batteries in series	10
1 Inverter efficiency	0.85	Batteries in parallel	28
2 Average Daily Power Consumption [kWh/day]	600	Total number of batteries	280
3 Average Daily Critical Power Consumption [kWh/day]	450	Minimum state of charge in NOC [%]	70
4 DC Bus Voltage [V]	480		
Battery Specifications		PV Design	Outputs
5 Battery Voltage [V]	48	Number of Modules in series	10
6 Capacity [Ah/battery]	200	Number of Modules in parallel	66
7 Efficiency (as a decimal)	0.98	Modules Total	660
8 MDOD (as a decimal)	1	PV output [Ah]	1967.8
9 Battery Type & Temperature Range [°C]	Li Temp≥5	PV output [kWh/day]	944.544
User Preferences		Generator Design	Outputs
10 Required Usable Storage for Total Load [days]	1	Number of generators	3
11 Required Usable Storage for Critical Load [days]	3	Maximum number of generators based on min charge time	6.4
PV Design		Fuel Storage Design	Outputs
Environmental Factors		Storage capacity needed [gal]	900
12 Insolation [kW/m ²]	0.8	Number of fuel containers needed	3
13 Peak Sun Hours [kWh/m ²]	5.7		
14 Ambient Temperature [°C]	20		
PV Specifications			
15 MPP Current [A]	6.09		
16 MPP Voltage [V]	59.1		
17 NOCT [°C]	47		
18 TCV	-0.1674		
19 TCV Units	V/C		
20 TCI	0.0029		
21 TCI Units	A/C		
User Preferences			
22 Solar fraction	1		
23 MPPT?	Yes		
24 Array to Load ratio	1.3		
Generator and Fuel Storage Design			
User Inputs			
25 Maximum load power [kW]	78		
26 Generator rated power [kW]	30		
27 Fuel storage container capacity [gal]	400		
28 Generator Fuel rate [gal/hr]	2.5		
29 Required Days of Autonomy	10		

Figure 4. Example of Inputs and Outputs of Manual Design Tool for Microgrid Sizing

Inputs		Outputs	
Battery Bank Design		Battery Bank Design	Outputs
System and Load Specifications		Batteries in series	10
1 Inverter efficiency	0.85	Batteries in parallel	28
2 Average Daily Power Consumption [kWh/day]	600	Total number of batteries	280
3 Average Daily Critical Power Consumption [kWh/day]	450	Minimum state of charge in NOC [%]	70
4 DC Bus Voltage [V]	480		
Battery Specifications		PV Design	Outputs
5 Battery Model	Relion RB48V200	Number of Modules in series	10
6 Battery Type & Temperature Range [°C]	Li Temp≥5	Number of Modules in parallel	66
User Preferences		Modules Total	660
7 Required Usable Storage for Total Load [days]	1	PV output [Ah]	1967.8006
8 Required Usable Storage for Critical Load [days]	3	PV output [kWh/day]	944.5443
PV Design	User Inputs	Generator Design	Outputs
Environmental Factors		Number of generators	3
9 Insolation [kW/m ²]	0.8	Maximum number of generators based on min charge time	6
10 Peak sun hours [kWh/m ²]	5.7		
11 Ambient Temperature [°C]	20		
PV Specifications		Fuel Storage Design	Outputs
12 PV Model	SunPower SPR-X22-360	Storage capacity needed [gal]	1173
User Preferences		Number of SIXCONs needed	2
13 Solar fraction	1	Number of other containers needed	#REF!
14 Array to Load ratio	1.3		
15 MPPT?	Yes		
Generator and Fuel Storage Design	User Inputs		
16 Maximum load power [kW]	78		
17 Generator Model and Rated Power	30kW AMMPS		
18 Fuel storage container type	SIXCON		
19 Other Fuel storage capacity [gal]	0		
20 Required Days of Autonomy	14		

Figure 5. Example of Inputs and Outputs of Automatic Design Tool for Microgrid Sizing

B. BATTERY DESCRIPTION AND SIZING

1. Battery Operation and Temperature

Batteries are adversely affected by a decrease in external temperature; specifically, lower temperatures degrade battery capacity and battery voltage. A low discharge temperature means a smaller capacity and steeper discharge rate which also causes a decrease in discharge voltage [17]. There are three primary causes of capacity degradation: 1) an increase of the electrolyte viscosity, 2) an increase of charge-transfer resistance, and

3) lithium plating [28]. As an example, Figure 6 is reproduced from the specification sheet of the Relion RB48V100 battery, one of the li-ion batteries pre-selected in the automatic tool. Figure 6 shows how the capacity and discharge voltage of this typical li-ion battery decreases as the temperature decreases.

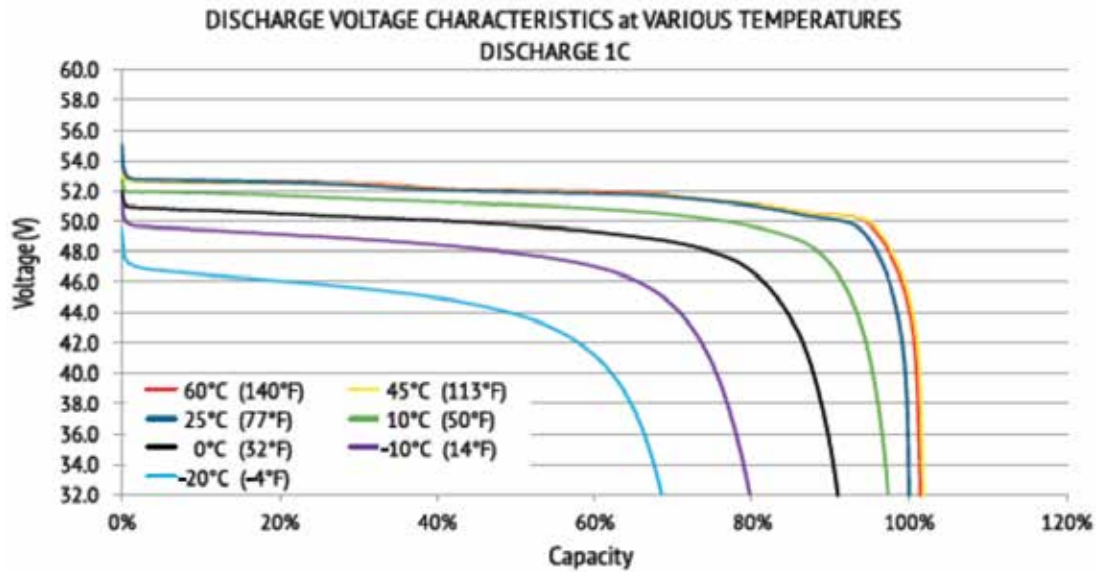


Figure 6. Discharge Voltage Characteristics of Relion RB48V100 Battery at Various Temperatures. Source: [19].

The cycle life of the battery decreases as the Depth of Discharge (DOD) increases. The design tool does not calculate battery degradation over time; it is a factor that the user must consider for system design. Figure 7 from the same specification sheet, shows how the life cycle increases at lower DODs.

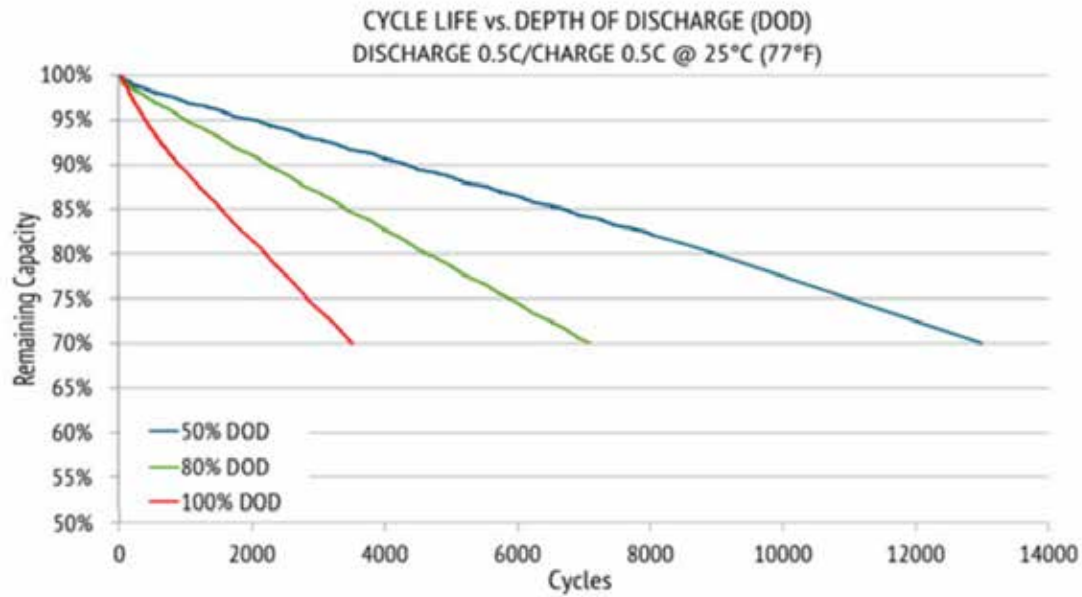


Figure 7. Life Cycle vs. Depth of Discharge of Relion RB48V100 Battery.
Source: [19].

Degradation occurs to different degrees based in part on the chemical make-up of the battery. Li-ion batteries are more resistant to the effects of temperature on capacity than lead-acid batteries [20]. Temperature affects lead-acid more adversely than li-ion because lead-acid batteries are more vulnerable to freezing at lower temperatures; thus lead-acid battery DOD must be lower to protect the battery. To illustrate this point, Figure 8 shows the discharge capacity of Li-Ion batteries and Lead-acid batteries, respectively.

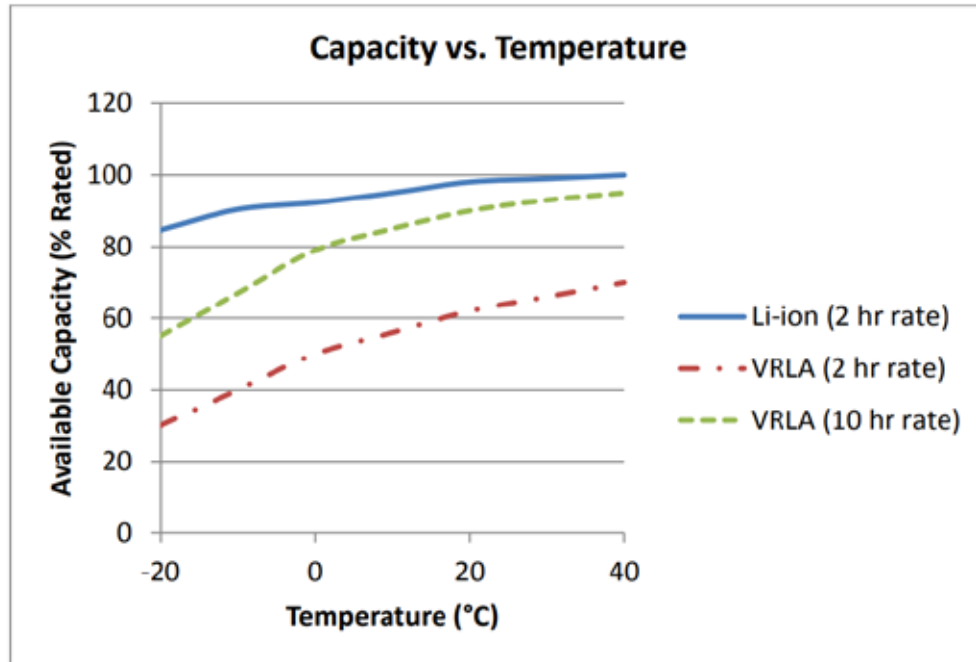


Figure 8. Comparison of Capacity of Li-Ion Batteries and Valve Regulated Lead-Acid Batteries Depending on Environmental Temperature.
Source: [20].

2. Battery Tool Inputs and Definitions

The battery portion of the tool sizes the number of batteries in parallel and series depending on the load and the operating environment requirements. There are three sections within the battery inputs of the tool in Figure 9 including: 1) system and load specifications, 2) battery specification, and 3) user preferences.

	Inputs	
	Battery Bank Design	User Inputs
	System and Load Specifications	
1	Inverter efficiency	
2	Average Daily Power Consumption [kWh/day]	
3	Average Daily Critical Power Consumption [kWh/day]	
4	DC Bus Voltage [V]	
	Battery Specifications	
5	Battery Voltage [V]	
6	Capacity [Ah/battery]	
7	Efficiency (as a decimal)	
8	MDOD (as a decimal)	
9	Battery Type & Temperature Range [°C]	
	User Preferences	
10	Required Usable Storage for Total Load [days]	
11	Required Usable Storage for Critical Load [days]	

Figure 9. Battery Inputs for Manual Tool

In the “System and Load Specifications” section, the user must know the inverter efficiency, the total daily power consumption in kWh/day, the daily critical power consumption in kWh/day, and the DC bus voltage. Next the user can either choose from the list of pre-selected batteries in the automatic tool or select a battery and input the battery specifications using the manual tool. The pre-selected batteries in the automatic tool are listed in Table 1.

Table 1. Models of Batteries is Automatic Tool

Model	Type	Voltage [V]	Capacity [Ah]	Efficiency [%]	MDOD [%]
Trojan SPRE 12 225 [21]	VRLA	12	203	98	80
Trojan 8D-AGM [22]	VRLA	12	230	98	80
SimpliPhi PHI 3.5 [23]	Li-ion	24	138	98	100
Relion RB48V100 [19]	Li-ion	48	100	98	100
Relion RB48V150 [24]	Li-ion	48	150	98	100
Relion RB48V200 [25]	Li-ion	48	200	98	100
Winston LFP400AHA [26]	Li-ion	48	400	98	80
Winston LFP7400AHA [27]	Li-ion	48	700	98	80
Winston LFP10400AHCA [28]	Li-ion	48	1000	98	80

In the “Battery Specifications” section, the user must know the voltage, capacity, efficiency, and maximum DOD (MDOD). Typical MDOD for li-ion batteries are close to 100%. Typical MDOD for deep charge lead-acid batteries are around 80%. Additionally, the user must select which type of battery (LA or Li, where “LA” is lead-acid and “Li” is Li-ion) and the lowest temperature range the microgrid could be operating in from a drop-down menu. The selection corresponds to a temperature correction factor based on the type of battery and the range of temperature which calculates the total storage capacity. It should be noted that there are many more ranges for lead-acid batteries because their capacity is more adversely affected by cold weather versus li-ion batteries. The lowest temperature this tool is designed to accommodate is -20 °C. The temperature correction factors are listed in Table 2.

Table 2. Temperature Correction Factors of Li-Ion and Lead-Acid Batteries.
Adapted from [6].

Temperature	TCF
LA Temp $\geq$ 25	1
LA 25>Temp $\geq$ 20	0.98
LA 20>Temp $\geq$ 15	0.95
LA 15>Temp $\geq$ 10	0.93
LA 10>Temp $\geq$ 5	0.9
LA 5>Temp $\geq$ 0	0.85
LA 0>Temp $\geq$ -5	0.8
LA -5>Temp $\geq$ -10	0.75
LA -10>Temp $\geq$ -15	0.7
LA -15>Temp $\geq$ -20	0.65
Li Temp $\geq$ 5	1
Li 5>Temp $\geq$ 0	0.98
Li 0>Temp $\geq$ -5	0.95
Li -5>Temp $\geq$ -10	0.92
Li -10>Temp $\geq$ -15	0.85
Li -15>Temp $\geq$ -20	0.77

The battery bank is sized for two categories of energy storage: storage for critical loads only and storage for normal operating conditions (NOC). The first category is used when the microgrid must shed its noncritical loads because the generator is inoperable, and there is an extended period of cloudy weather which causes the battery bank to fall below its calculated minimum SOC. In NOC, the microgrid is supporting both critical and noncritical loads and the battery SOC is above its calculated minimum SOC; the storage for NOC is sized to support all loads for the specified number of days. Because the generator is operable or the weather is not extensively cloudy during NOC, the storage for NOC does not need to be excessive. The required usable storage (RUS) days for both NOC and critical loads only will determine the minimum SOC of the battery bank during NOC.

In the “User Preferences” section, the user first determines the number of RUS days for NOC when the system is supporting the total load. If the load includes a critical load and the system will possess the ability to shed noncritical loads, then RUS for NOC can be close to or equal to 1. It is a decision point for the tool user on the desired level of

redundancy in terms of the generator and the battery storage; the research in [15] notes that redundancy improves system resilience.

The user also determines the number of RUS days for critical loads only. This will size the battery bank to support the critical loads when the weather is cloudy, the generator is inoperable, and the fuel tank is empty. The ratio of critical load RUS to total storage will determine the minimum state of charge of the batteries during NOC. The proper minimum state of charge ensures that battery energy will be available when needed.

When sizing the batteries for critical load only, there is no redundancy of energy storage and generator, so the user must be careful when deciding upon the RUS. To help judge the RUS for critical loads only, the user should consider the expected cloudiness of the environment, the expected failure rate of the generator, and the solar irradiance of the environment. Such information may be available from system analyses performed by systems engineers [13], [15]. To estimate the RUS for critical loads only based on local solar irradiance, the user can use the graph in Figure 10 [29]. The solar irradiance is also known as Peak Sun Hours (PSH). Figure 10 depicts the RUS as “Days of Usable Storage” dependent on the PSH to achieve a certain availability. In this case, availability refers to the percentage of the year that the battery bank will be available to support the load, independent from the generator.

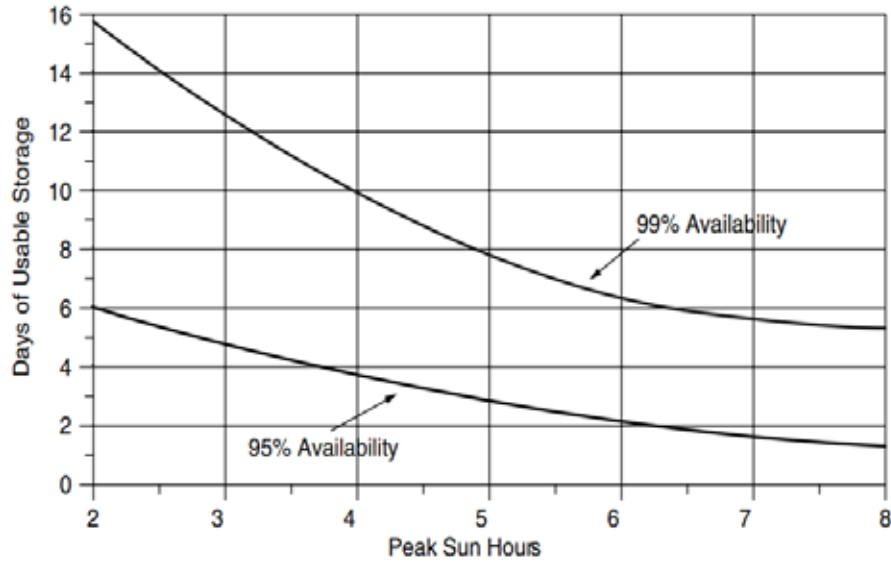


Figure 10. RUS for Critical Load Based on PSH for 99% Energy Storage Availability and 95% Energy Storage Availability without Generator. Source: [30].

Alternatively, Equations (1) and Equation (2) from [29] provide calculations to approximate how many days of RUS the microgrid needs to support the load with the battery bank, independent from the generator for 99% of the year D_{auto}^{99} and for 95% of the year D_{auto}^{95} , respectively.

$$D_{auto}^{99} [days] \gg 24.0 - 4.73 \times PSH + 0.3 \times PSH^2 \quad (1)$$

$$D_{auto}^{95} [days] \gg 9.43 - 1.9 \times PSH + 0.11 \times PSH^2 \quad (2)$$

The result from one of these equations, if applied to the design tool, should be used to compute the RUS for critical loads only. For example, if the PSH of the design month was 3.0, then the days of RUS for the critical load to be supported by the battery bank for 99% of the year and 95% of the year, independent from the generator is calculated as:

$$D_{auto}^{99} \gg 24.0 - 4.73 \times 3.0 + 0.3 \times 3.0^2 = 10.1 days \quad (3)$$

$$D_{auto}^{95} \gg 9.43 - 1.9 \times 3.0 + 0.11 \times 3.0^2 = 4.7 days . \quad (4)$$

In this example, if the user wishes energy from the battery bank to be available to the critical load 95% of the year, then the input to “Required Usable Storage for Critical Load” is 4.7.

It is important to note, however, that Figure 10 and Equation (1) and Equation (2) are estimates for storage for a stand-alone microgrid without a generator. The expected failure rate of the generator and the time expected to repair it should also be considered when selecting the RUS for critical loads only. As in the previous example, if Equation (2) suggests that 4.7 days of storage are required for 95% availability, but an inoperable generator can be fixed in less than 2 days, the additional 2.7 days of energy storage are redundant.

3. Battery Equations

Battery storage capacity is calculated in two different sections: sizing for NOC and sizing for critical loads only.

The following calculations size the batteries while in NOC for the design month. Equations (5) through (15) are adapted from [29]. The original equations in [29] do not distinguish between NOC and critical loads only because it does not discuss load shedding. Where $P_{l_{AC}}$ is the average daily power in Wh/day for the AC load and h_{inv} is the efficiency of the inverter, the power supplied by the batteries to the DC bus $P_{l_{DC}}$ is calculated by:

$$P_{l_{DC}} [Wh / day] = \frac{P_{l_{AC}}}{h_{inv}}. \quad (5)$$

The DC bus voltage V_{sys} is the voltage at the battery bank or the voltage of the PV arrays.

The total load I_l^{NOC} supplied by the battery bank is:

$$I_l^{NOC} [Ah / day] = \frac{P_{l_{DC}}}{V_{sys}}. \quad (6)$$

While I_l^{NOC} represents the DC bus current, the usable storage, Q_{US}^{NOC} represents the battery capacity in Ah required for the specified number of days D_Q^{NOC} needed during normal operation:

$$Q_{US}^{NOC} [Ah] = I_l^{NOC} \times D_Q^{NOC}. \quad (7)$$

The total storage capacity Q_t^{NOC} describes the usable storage capacity while accounting for the rated MDOD, temperature correction factor C_{T_B} , and design margin (DM) of 1.1:

$$Q_t^{NOC} [Ah] = \frac{Q_{US}^{NOC} \times DM}{MDOD \times C_{T_B}} \quad (8)$$

The nominal capacity of each battery is represented by Q_b and the number of batteries in parallel N_{Bp}^{NOC} is expressed by:

$$N_{Bp}^{NOC} = \text{Rounded up} \left(\frac{Q_t^{NOC}}{Q_b} \right) \quad (9)$$

The nominal voltage of each battery is represented by V_b and the number of batteries in series N_{Bs} is expressed as:

$$N_{Bs} = \text{Rounded up} \left(\frac{V_{sys}}{V_b} \right) \quad (10)$$

Next, the tool sizes the battery capacity required to support only the critical loads, which is required when the noncritical loads have shed due to low battery SOC and generator failure. This portion of the battery bank is sized similarly to the first portion. $P_{l_{AC}}^{crit}$ represents the average daily power required to the critical loads, while $P_{l_{DC}}^{crit}$ is the power required at the DC bus, accounting for the inverter losses. I_l^{crit} represents the critical load current in Ah/day.

$$P_{l_{DC}}^{crit} [Wh / day] = \frac{P_{l_{AC}}^{crit}}{h_{inv}} \quad (11)$$

$$I_l^{crit} [Ah / day] = \frac{P_{l_{DC}}^{crit}}{V_{sys}} \quad (12)$$

The usable critical battery storage Q_{US}^{crit} is calculated utilizing the required usable storage days for the number of days D_Q^{crit} :

$$Q_{US}^{crit} [Ah] = I_l^{crit} \times D_Q^{crit} . \quad (13)$$

The total critical storage capacity Q_t^{crit} and additional batteries in parallel N_{Bp}^{crit} , are calculated just as their counterparts are in Equation (8) and Equation (9).

$$Q_t^{crit} [Ah] = \frac{Q_{US}^{crit} \times DM}{MDOD \times C_{T_B}} \quad (14)$$

$$N_{Bp}^{crit} = \text{Rounded up} \frac{Q_t^{crit}}{Q_b} \quad (15)$$

The total batteries in parallel N_{Bp} are the sum of the NOC and critical batteries:

$$N_{Bp} = N_{Bp}^{NOC} + N_{Bp}^{crit} . \quad (16)$$

There are no additional batteries in series, as the increase in storage does not affect the DC bus voltage or battery voltage. The size of the battery bank N_B is:

$$N_B = N_{Bp} \times N_{Bs} . \quad (17)$$

To ensure that there is enough battery storage to support the critical loads during a crisis, the battery bank state of charge must not drop below a certain level during NOC. This required capacity equals the total critical storage capacity. The determined maximum depth of discharge during NOC $MDOD_{NOC}$ is expressed as:

$$MDOD_{NOC} = 1 - \frac{Q_t^{crit}}{Q_t^{NOC}} . \quad (18)$$

Similarly, the minimum SOC SOC_{min} is calculated as:

$$SOC_{min} = 100 \times \frac{Q_t^{crit}}{Q_t^{NOC}}. \quad (19)$$

C. PV DESCRIPTION AND SIZING

A current-voltage, or “I-V” curve characterizes the operation of a PV; a generic I-V curve and a power curve are shown in Figure 11. The maximum power that the PV can produce is the knee of the I-V curve since power is the product of voltage and current [29].

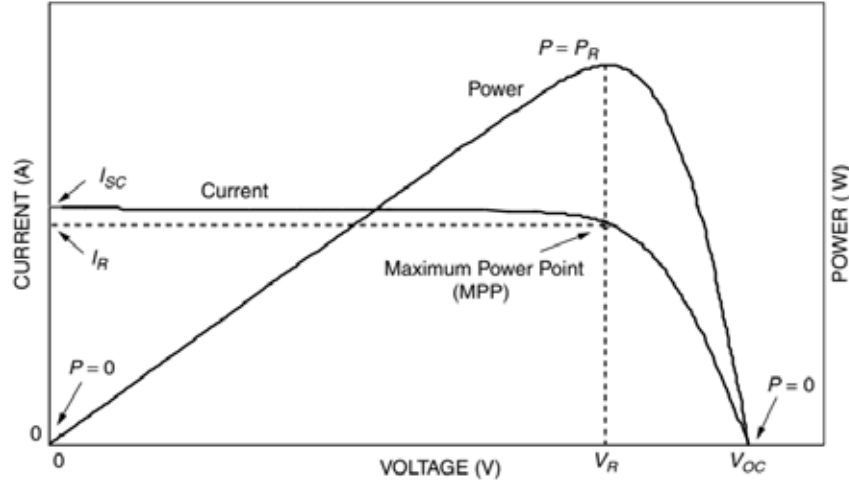


Figure 11. PV I-V Curve. Source: [29].

1. PV Tool Inputs and Definitions

The PV portion of the tool sizes the number of PVs in parallel and series depending on the required load and the operating environment. There are three sections within the PV inputs of the tool in Figure 12 including: 1) Environmental Factors, 2) PV Specification, and 3) User Preferences.

PV Design		User Inputs
	Environmental Factors	
12	Insolation [kW/m ²]	0.8
13	Peak Sun Hours [kWh/m ²]	5.7
14	Ambient Temperature [°C]	20
	PV Specifications	
15	MPP Current [A]	6.09
16	MPP Voltage [V]	59.1
17	NOCT [°C]	47
18	TCV	-0.1674
19	TCV Units	V/°C
20	TCI	0.0029
21	TCI Units	A/°C
	User Preferences	
22	Solar fraction	1
23	MPPT?	Yes
24	Array to Load ratio	1.3

Figure 12. PV Design User Inputs from Microgrid Design Tool

The required size of the PVs is largely dependent on the conditions of the environment because solar irradiance and temperature have a significant effect on the performance of PVs.

Higher temperatures slightly increase the short circuit current, but more drastically decrease the open circuit voltage. The short circuit current is proportional to the solar insolation if the operating voltage remains less than the open circuit voltage, which it usually does. Open circuit voltage is logarithmically related to insolation, so variations of insolation have little effect on the open circuit voltage. The ideal environment for PVs is cool and sunny [29]. To demonstrate these concepts, two sets of I-V curves were created from a series of 1-second simulation of a 1Soltech 1STH-215-P solar panel in MATLAB/Simulink using the following model in Figure 13.

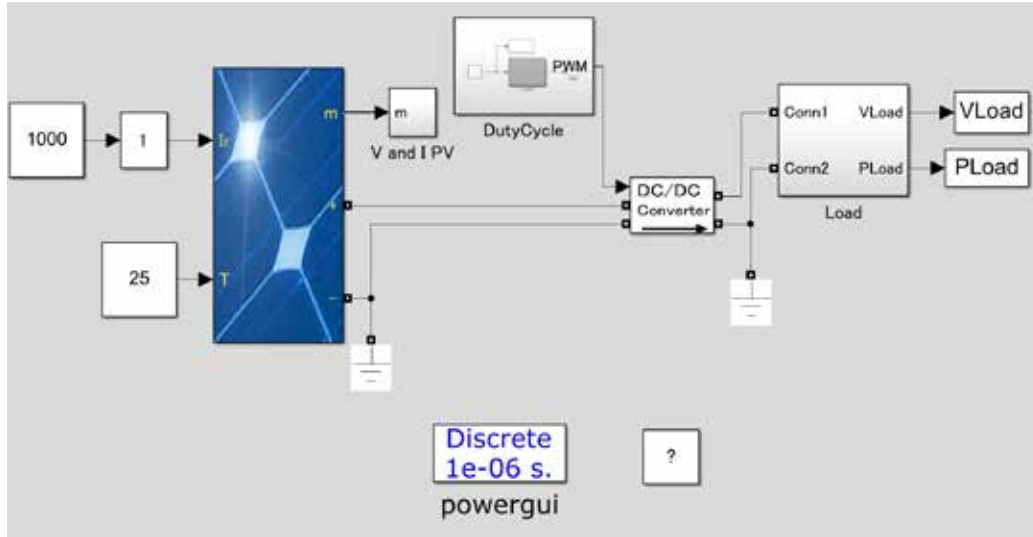


Figure 13. MATLAB Simulink PV Model

With the solar irradiance constant at 1 kWh/m^2 , three different cell temperatures were simulated as the duty cycle varied from 0 to 1. Next, with the cell temperature constant at $25 \text{ }^\circ\text{C}$, three different irradiances were simulated as the duty cycle varied from 0 to 1. The results shown in Figure 14 and Figure 15, illustrate the effect of irradiance on voltage and of temperature on current, respectively.

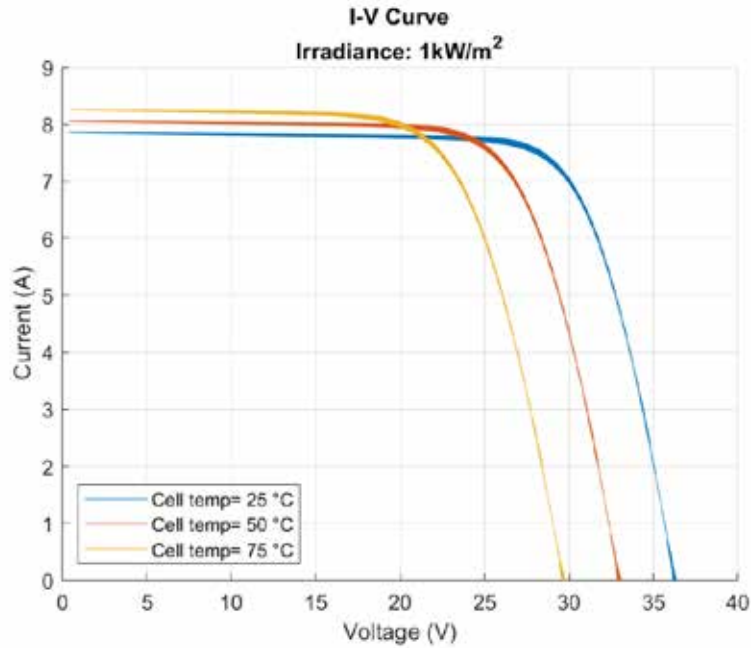


Figure 14. I-V Curve at Various Temperatures with Constant Irradiances

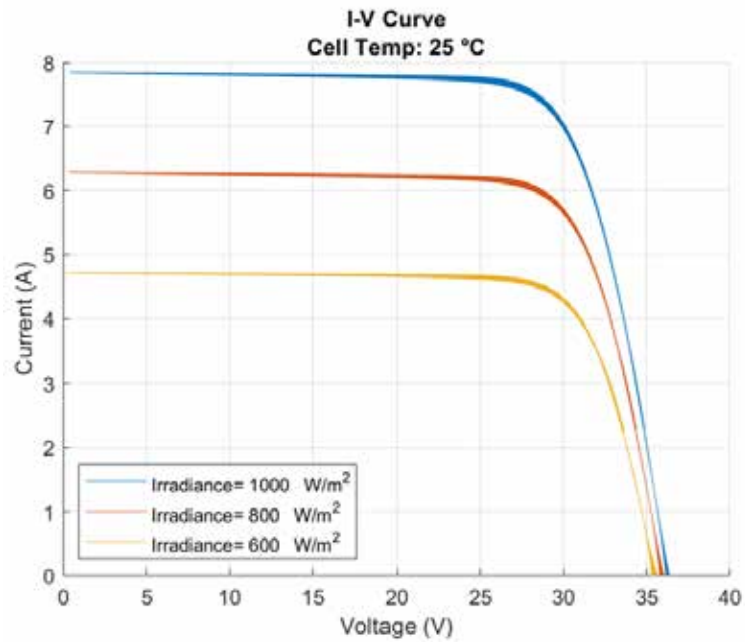


Figure 15. I-V Curve at Various Irradiances with Constant Temperature

In the “Environmental Factors” section, the user needs the solar insolation in kW/m^2 , the PSH in kWh/m^2 , and the ambient temperature in degree Celsius. The insolation (or

incident solar radiation) is the intensity of the sun at a certain latitude and it varies depending on the tilt angle of the PVs [29]. PSH is the measure of insolation over the entire day. Consideration of shading on the PVs was outside the scope of this thesis.

The required inputs of the maximum power voltage, the maximum power current, the voltage temperature coefficient TC_V , the current temperature coefficient TC_I , and the nominal operating cell temperature (NOCT) of the PV array may be found in the specification sheet of the PV. This data is typically provided for standard test conditions (STC), which is an irradiance of 1 kW/m^2 , a cell temperature of 25°C , and an air mass ratio of 1.5. The TC_V is applied to the nominal voltage of the PV and the TC_I is applied to the nominal current of the PV to account for the effect of temperature on its performance. The TC_V will be expressed in terms of volts, percentage of open circuit voltage, or parts per million of open circuit voltage. The TC_I will be expressed in terms of Amperes, percentage of the short circuit current, or parts per million of the short circuit current. The tool accommodates for the variations in units across data sheets. Sometimes, no NOCT is provided, so an average value of 48°C can be used [30].

The user must decide on the use of a maximum power point tracker (MPPT) and the array to load (A:L) ratio. A MPPT is a device that keeps the operating point of the PV near the knee of the I-V curve, at its highest efficiency point. A simple summary of the operation of a MPPT is that it contains a buck-boost converter; it increases or decrease its duty cycle in order to increase or decrease its output voltage to achieve maximum power. The use of a MPPT may decrease the number of PVs in series required to support the load. From the dropdown menu of the MPPT option, if “yes” is selected, the tool will account for power conversion losses with a derating factor of .95. If “no” is selected, the tool will account for the system losses using a derating factor of .8.

According to IEEE standard 1562–2007 [16], the A:L is determined by the criticalness of the supported loads and intensity of the local solar irradiance. An A:L of 1:1 or 1:2 should be selected for noncritical loads when there is reliable solar irradiance. An A:L ratio of 1:3 or 1:4 should be selected for critical loads or when there is not reliable

solar irradiance [16]. The benefit of the higher A:L ratio is that the batteries will charge faster; the drawback is that it requires more solar modules, a thus higher cost and footprint.

As demonstrated in Figure 16, a higher A:L ratio is preferable when no generator maintenance or back-up generator is available. In the following simulation, a battery bank is depleted to 20% SOC and is operating with critical only critical loads. Over the course of four days, the system with an A:L ratio of 1:4 recovers to a 77% SOC, whereas the system with an A:L ratio of 1:1 recovers to only a 52% SOC.

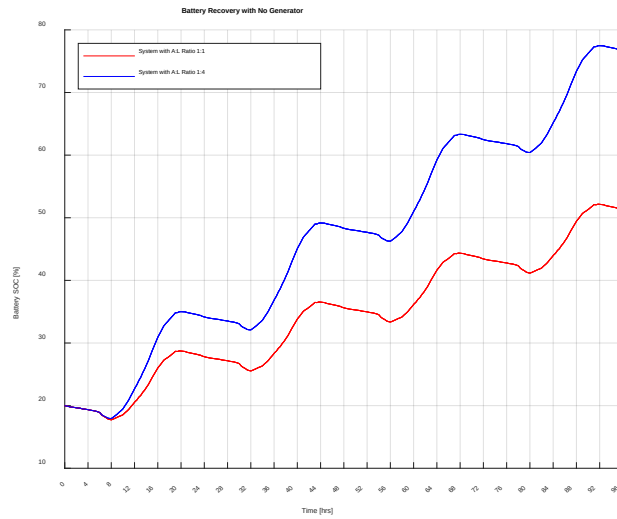


Figure 16. A:L Ratio Comparison

2. PV Equations

As previously stated, the ambient temperature must be considered when sizing the PV arrays because it so significantly impacts the performance of the PV. The design methodology presented in this thesis accounts for the highest temperatures; it sizes the number of PVs necessary when the PVs will be performing at their worst due to increased temperature. The solar fraction (SF) is a number between 0 and 1 which determines how much of the average daily AC power $P_{l_{AC}}$ will be provided by the PV arrays, using equations from [29]:

$$P_{l_{AC}}^{DM} = \frac{P_{l_{AC}} \times SF}{h_{inv}} \quad (20)$$

In Equation (20), $P_{l_{AC}}^{DM}$ represents the average daily power supplied during the design month for the AC load.

First, the temperature of the cell T_{cell} must be calculated, as is done in [29]. This is done by comparing the Nominal Operating Cell Temperature (NOCT) to 20 °C, and the solar insolation S to 0.8 kW/m², as in:

$$T_{cell} [^{\circ}C] = T_{amb} + \frac{NOCT - 20}{0.8} \times S \quad (21)$$

Next, the new voltage V_{mpnew} due to temperature must be calculated using adjustments from [16] for equations (22) through (24). The equation used for this calculation will depend upon the units of TC_V on the PV specification sheet. V_{mpnew} is calculated by comparing T_{cell} to its temperature under STC which is 25 °C. For TC_V in terms of volts TC_{V_v} [V/°C], percentage of maximum power voltage $TC_{V\%}$ [%/°C], and parts per million of maximum power voltage $TC_{V_{ppm}}$ [ppm/°C], the Equations (22) through (24) calculate V_{mpnew} , respectively.

$$V_{mpnew} [V] = V_{mp} + (TC_{V_v} \times (T_{cell} - 25)) \quad (22)$$

$$V_{mpnew} [V] = V_{mp} + \frac{V_{mp} \times TC_{V\%}}{100} \times (T_{cell} - 25) \quad (23)$$

$$V_{mpnew} [V] = V_{mp} + \frac{V_{mp} \times TC_{V_{ppm}}}{1000000} \times (T_{cell} - 25) \quad (24)$$

Similarly, a new current I_{mpnew} that accounts for the temperature of the cell must be calculated using the adjustments described in [16] for equations (25) through (27). Just as with the voltage calculation, this calculation depends on the unit of the TC_I , in terms of

Amps TC_{I_A} [A/°C], percentage of maximum power current $TC_{I\%}$ [%/°C], or parts per million of maximum power current $TC_{I_{ppm}}$ [ppm/°C] .

$$I_{mpnew} [A] = I_{mp} + (TC_{I_A} \times (T_{cell} - 25)) \quad (25)$$

$$I_{mpnew} [A] = I_{mp} + \frac{TC_{I\%}}{100} \times (T_{cell} - 25) \quad (26)$$

$$I_{mpnew} [A] = I_{mp} + \frac{TC_{I_{ppm}}}{1000000} \times (T_{cell} - 25) \quad (27)$$

Based on [16], the system losses to include battery efficiency and dirt on the arrays account for 10% to 20% of the total load. For this sizing methodology, 15% loss was used to account for dirt on the arrays l_d . Losses due to battery efficiency h_{bat} were inputted by the user in battery specifications. These two losses combined account for the system losses l_{sys} :

$$l_{sys} = l_d + (1 - h_{bat}) . \quad (28)$$

Using the $P_{l_{AC}}^{DM}$ calculated during the load analysis, the A:L ratio $R_{A:L}$ specified by the user, and the PSH, the modules in parallel N_{Pp} are sized using [16] by:

$$N_{Pp} = \text{Rounded up} \frac{P_{l_{AC}}^{DM} \times R_{A:L}}{(1 - l_{sys}) \times I_{mpnew} \times PSH} \quad (29)$$

To calculate the modules in series, the nominal module voltage must be calculated. Depending on the use of a maximum power point tracker, the module voltage will vary. The use of a MPPT has an estimated efficiency of 95.5%. By adjusting the equations from [16] to account for temperature, the required modules in series while using a MPPT N_{Ps}^{MPPT} is expressed as:

$$N_{Ps}^{MPPT} = \text{Rounded up} \frac{V_{sys}}{V_{mpnew} \times 0.955} \quad (30)$$

While not using a maximum power point tracker, the required modules in series

N_{Ps} is better calculated with a 0.8 derating factor for system losses as:

$$N_{Ps} = \text{Rounded up} \left\lceil \frac{V_{sys}}{V_{mpnew} \times 0.8} \right\rceil \quad (31)$$

In Equation (32), Q_{out}^{PV} represents the Ah produced by the PVs and is:

$$Q_{out}^{PV} = N_{Ps} \times I_{mpnew} \times PSH \times (1 - l_{sys}). \quad (32)$$

The total power produced by the PVs P_{out}^{PV} is:

$$P_{out}^{PV} = \frac{Q_{out}^{PV} \times V_{sys}}{1000}. \quad (33)$$

D. GENERATOR AND FUEL STORAGE DESCRIPTION AND SIZING

The tool calculates a minimum and a maximum number of generators to support the system. The generator is sized to support the load completely as a total back up to the PVs and batteries.

1. Considerations for Sizing

Maintaining efficiency must be considered when sizing a generator for a PV microgrid. The mechanical efficiency of a diesel generator decreases as the load decreases relative to the full-load capacity of the generator [31].

Running a generator at less than 50% rated capacity results in wet stacking which is inefficient and creates a maintenance burden [32]. Wet stacking occurs when a generator is operated at a light load for an extended period of time because the generator is not burning fuel efficiently; the unburned fuel in the exhaust condenses and mixes with soot which forms a dark sludge in the exhaust system of the generator.

To demonstrate how fuel efficiency increases as the load of a generator increases, Figure 17 is a graph of the fuel efficiency of a 10 kW generator.

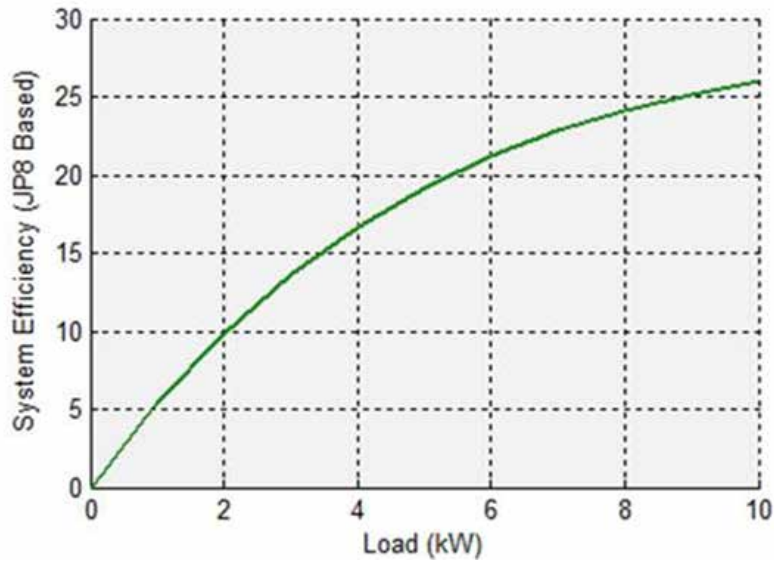


Figure 17. Fuel Efficiency of a 10 kW Generator vs. Load. Source: [33].

The tool assumes that the model and rated power of the generator is already selected. The tool uses the maximum load power and the rated generator power to calculate the minimum number of generators required. The user must consider the capabilities of the generator model on hand. Some generators such as the TQG do not operate in parallel so the use of a TQG means that only one generator may be used and therefore the load is quite small. Whereas, six AMMPS generators can operate in parallel, significantly increasing the power output.

The fuel storage required depends largely on how many days the user wishes the system to operate autonomously. For example, if the user wanted the system to support all loads without a fuel resupply for ten days, then the tool would calculate the gallons of fuel storage required to enable ten days of independence. One option is to size the fuel storage based on an organizational standard. For example, the Army standard for critical mission sustainment is 14 days [33]. It is the decision of the user whether that many days of fuel storage is required based on judgment of the likelihood of adverse weather and the size of the battery bank. The inputs to the generator and fuel design for the manual tool are in Figure 18.

Generator and Fuel Storage Design		User Inputs
25	Maximum load power [kW]	
26	Generator rated power [kW]	
27	Fuel storage container capacity [gal]	
28	Generator Fuel rate [gal/hr]	
29	Required Days of Autonomy	

Figure 18. Generator and Fuel Tool Inputs

2. Generator and Fuel Storage Equations

The minimum number of generators $N_g^{\min}$ is based on the rated generator power P_g and the requirement of the maximum load $P_l^{\max}$:

$$N_g^{\min} = \text{Rounded up} \left\lceil \frac{P_l^{\max}}{P_g \times 0.8} \right\rceil \quad (34)$$

To keep the generator from charging the batteries at a rate faster than C/5, the generator output $P_g^{\max}$ cannot be more than:

$$P_g^{\max} [W] = \frac{Q_t \times V_{\text{sys}}}{5 \times 0.8} \quad (35)$$

Therefore, the user can verify that the output will not exceed the maximum $P_g^{\max}$, by ensuring that the selected number of generators is less than:

$$N_g^{\max} = \text{Rounded down} \left\lfloor \frac{P_g^{\max}}{P_g \times 0.8} \right\rfloor \quad (36)$$

The fuel storage F_s is an estimate of the gallons of fuel required on site to achieve the desired duration of autonomy D_{auto} from fuel resupply. It is estimated from the fuel rate G_{hr} on the basis that the generator will not need to run more than 12 hours a day, since it will charge the batteries with any excess current while supporting the load:

$$F_s [\text{gal}] = N_g \times D_{\text{auto}} \times G_{\text{hr}} \times 2. \quad (37)$$

III. HYBRID MICROGRID MODELING

In this chapter the physics-based model of the hybrid microgrid is presented together with its implementation in Simulink/MATLAB.

A. POWER SYSTEM ARCHITECTURE

The hybrid microgrid model consists of the batteries, PV panels, generator, power converters and load. The architecture of this system is depicted in Figure 19 where a DC bus and an AC bus are highlighted; the former is regulated by the battery pack converter while the latter is regulated by either the generator, if it is on, or by the H-bridge inverter, when the generator is off.

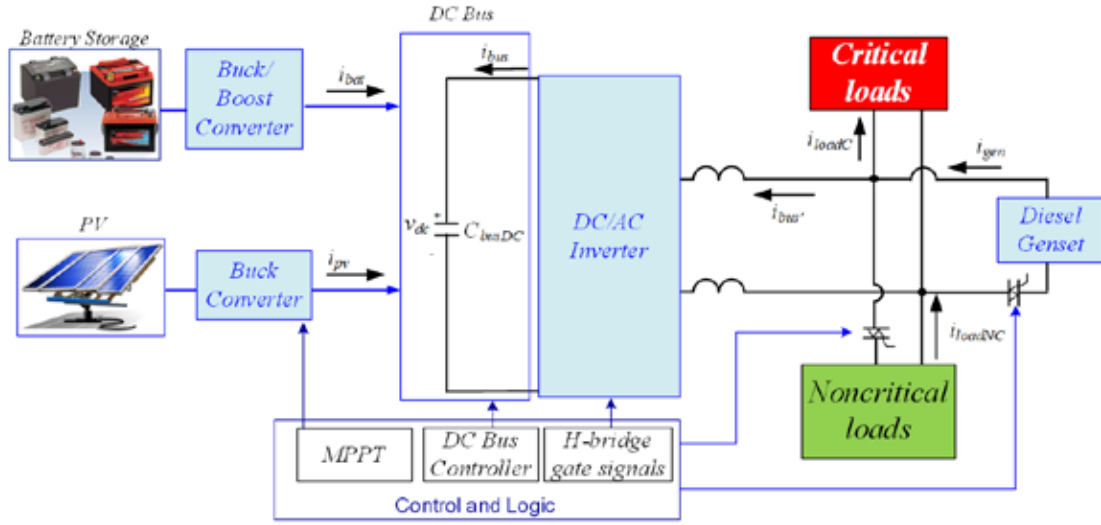


Figure 19. Hybrid Microgrid Power System Architecture

Three power converters are required for this architecture; two DC/DC converters to interface the PV panels and battery pack, and an H-bridge DC/AC inverter to interface the AC bus where the loads are connected. The PV panels are connected to the DC bus through a DC/DC converter with MPPT capabilities. The converter is necessary to interface the PV panels to the DC bus; it steps the voltage up or down depending on the PV voltage

1. Battery

The battery SOC is calculated:

$$SOC(t) = SOC(t-1) - \frac{i_{bat}}{h_{bat} \times N_{Bp} \times Q_b} dt \quad (38)$$

Capacity Q_b includes the temperature correction factor, and h_{bat} represents the efficiency of the battery. To prevent the PVs from overcharging the batteries, there is an overcharge controller, depicted in Figure 21. If the battery SOC is equal to the maximum battery SOC, then the PVs will cease to emit current.

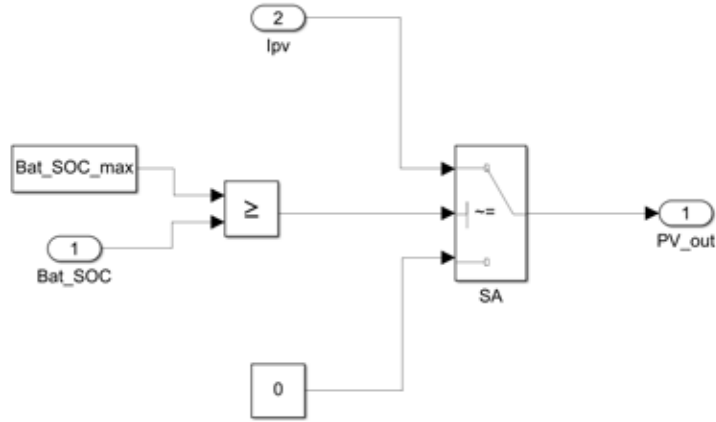


Figure 21. PV Controller

2. DC Bus

The parameters of the DC bus in the model are from [6] and listed in Table 3.

Table 3. DC Bus Parameters. Adapted from [6].

Parameter	Value
C_{busDC}	500 μ F
K_p	.022
K_i	.38

The capacitor labeled C_{busDC} in Figure 19 represents the DC bus, whose current i_{bus} and AC equivalent i_{bus}' are calculated using Kirchhoff Current Law (KCL) at the positive (top) DC bus node. The model is intended to study only the active power flow, therefore i_{bus} is effectively equal to i_{bus}' .

$$i_{bus} = -i_{PV} - i_{bat} \quad \hat{U} \quad i_{bus}' = i_{gen} - i_{loadC} - i_{loadNC} \quad (39)$$

$$i_{bus}' = i_{gen} + i_{PV} + i_{bat} - i_{loadC} - i_{loadNC} \quad (40)$$

The model calculates the DC bus voltage V_{DC} by:

$$V_{DC}(t) = \frac{1}{C_{busDC}} \int i_{bus} dt \quad (41)$$

The model regulates the DC bus to a fixed voltage using a proportional integral (PI) controller with the parameters listed in Table 3 adapted from [35]. With the reference DC bus voltage expressed as V_{DC}^* , the output of the PI is i_{bat} and is calculated:

$$i_{bat} = \frac{sK_p + K_i}{s} (V_{DC}^* - V_{DC}) \quad (42)$$

3. 24-Hour Profiles

There are three different profiles in this model: two load power profiles, and the PV output power profile. The two load profiles are shown in Figure 22 and Figure 23. The first

profile mimics the typical 24-hour power consumption on a forward operating base (FOB), while the second profile was created to mimic the profile in an environment with more extreme temperatures, where there would be a constant need for environmental control units (ECUs), and an increase in ECUs at night.

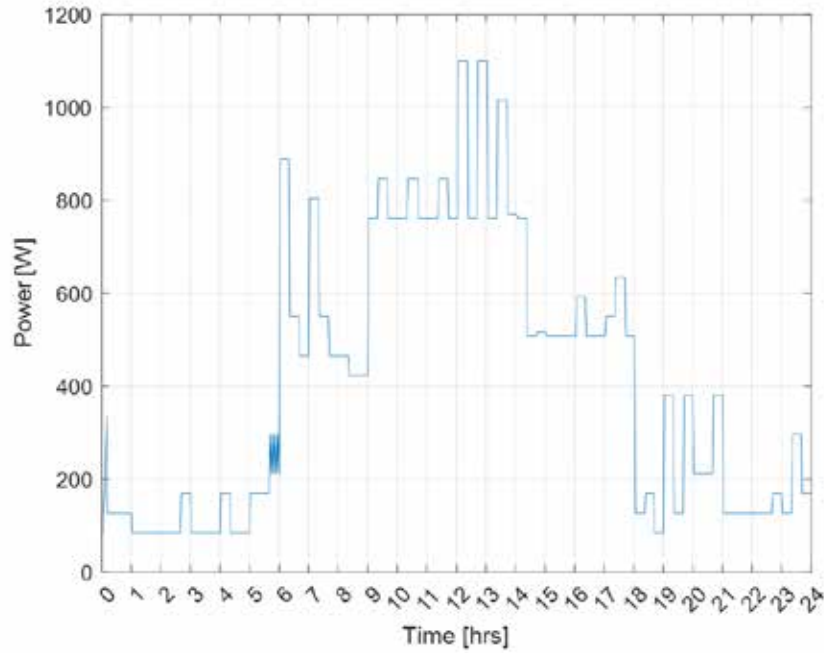


Figure 22. Load Power Profile 1. Adapted from [35].

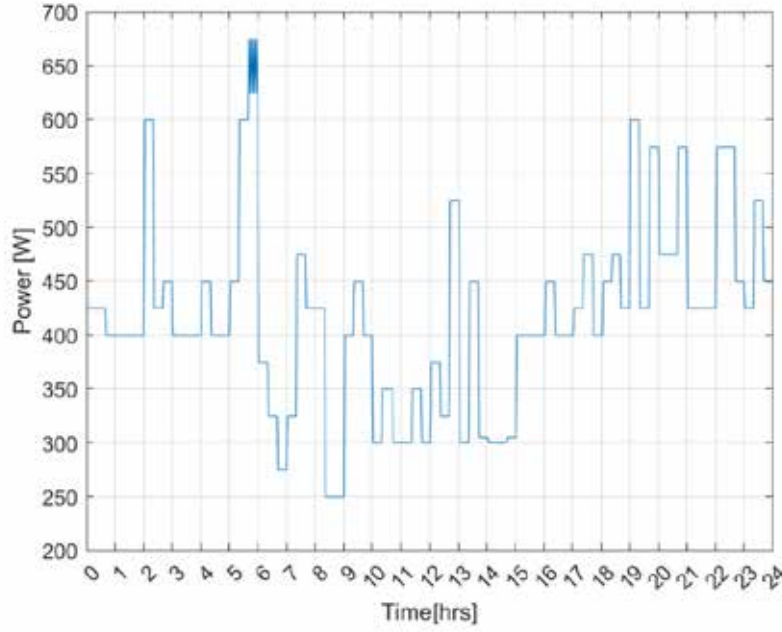


Figure 23. Load Power Profile 2

The user input labeled “DC load total” in the design tool is applied to a generic load profile L_{pr} in per unites, based on the typical requirements of a military microgrid. This creates a 24-hours profile P_l defined every 30 seconds, that represents the user-specified load:

$$P_l [W] = L_{pr} \times \frac{P_{l_{DC}}}{L_{pr} \times \frac{24}{720}}. \quad (43)$$

The same equation defines the load profile of the critical load.

The PV output I_{PV} is calculated in a similar fashion, where the tool calculation of I_{out}^{PV} in Ah is applied to a predefined arc of solar irradiance S_{pr} , as seen in Figure 24, with the following calculation:

$$I_{PV} [A] = S_{pr} \times \frac{I_{out}^{PV}}{S_{pr} \times \frac{24}{720}}. \quad (44)$$

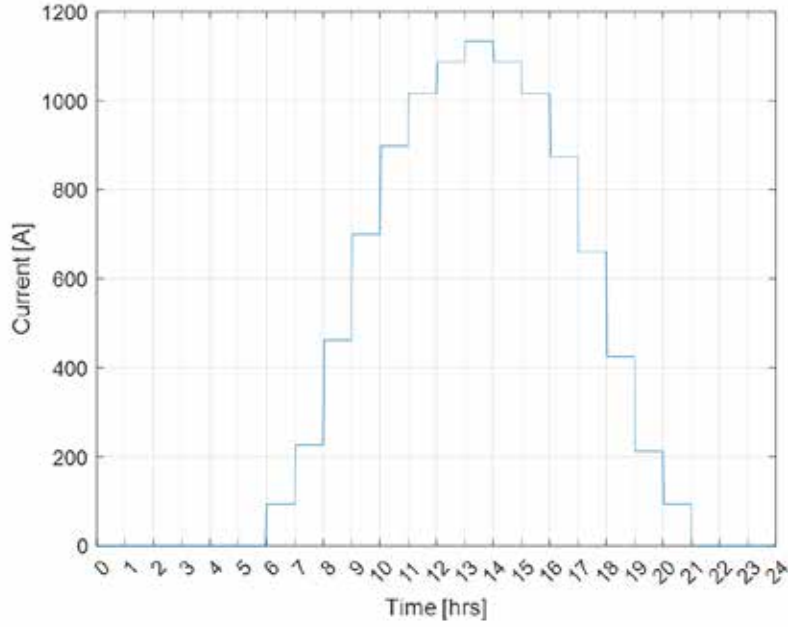


Figure 24. PV Current Profile

4. Generator

The use of a diesel generator as a power source makes the microgrid a hybrid stand-alone microgrid. As is suggested in [15] to improve system resilience, the microgrid in this research exercises automated switching between elements, based on the controller logic. The generator profile is a constant value that turns on and off by that automated switching. For simplicities sake, the generator runs at 80% of its total load. The generator output $P_{g_{out}}$ is calculated as:

$$P_{g_{out}} [W] = h_g \times P_g \times 0.8. \quad (45)$$

The logic of the generator controller is represented in the flow chart in Figure 25, where t is the present time, t_{ch} is the estimated time to charge the battery to 100% SOC, t_{end} is the time until the end of the day, t_c is the time the microgrid has kept the non-critical loads shed, and t_g is the time the generator has been on.

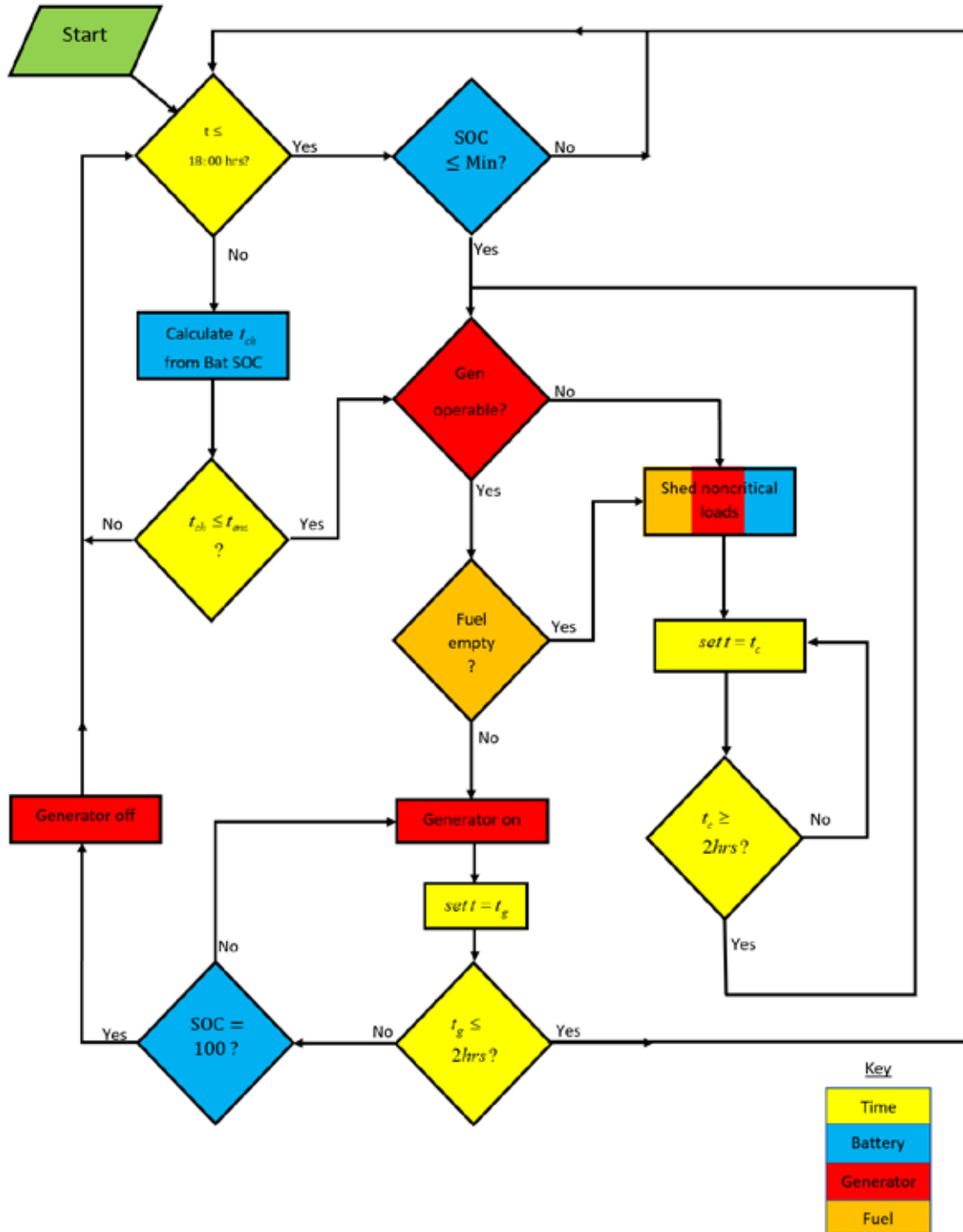


Figure 25. Generator Energy Management Algorithm

The Simulink model controls the generator using logic functions in the following subsystems. The generator remains off if the battery SOC is above the minimum used in

the design tool. If the battery falls below this minimum SOC, the generator will turn on for 2 hours, shown in Figure 26.

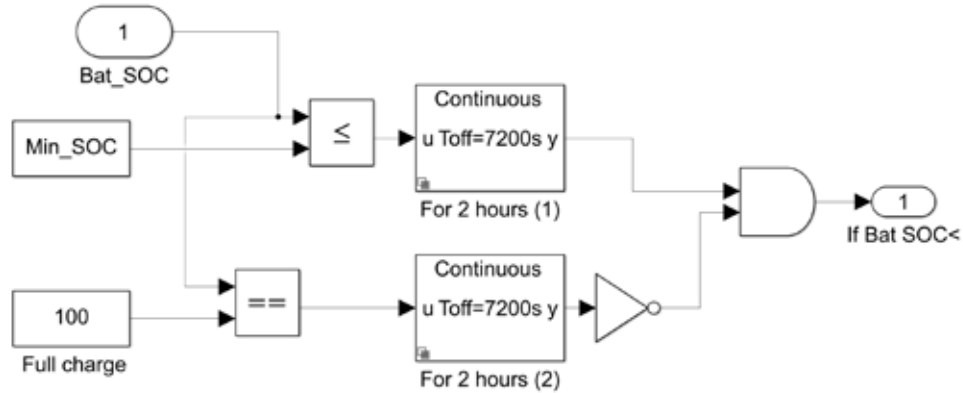


Figure 26. Check if SOC<Min

If the load is less than the generator output, the generator will simultaneously support the load and charge the batteries. The generator will turn off if within the two hours, the battery SOC returns to 100% or if after two hours, the battery SOC is above the minimum. When the level of fuel reaches zero, the generator turns off and remains off.

If the generator is unavailable and the battery falls below the minimum SOC, it will shed the noncritical or intermittent loads, shown in Figure 27. Those loads will remain disconnected for 2 hours; after two hours, if the system has returned to NOC, support of the noncritical loads will resume.

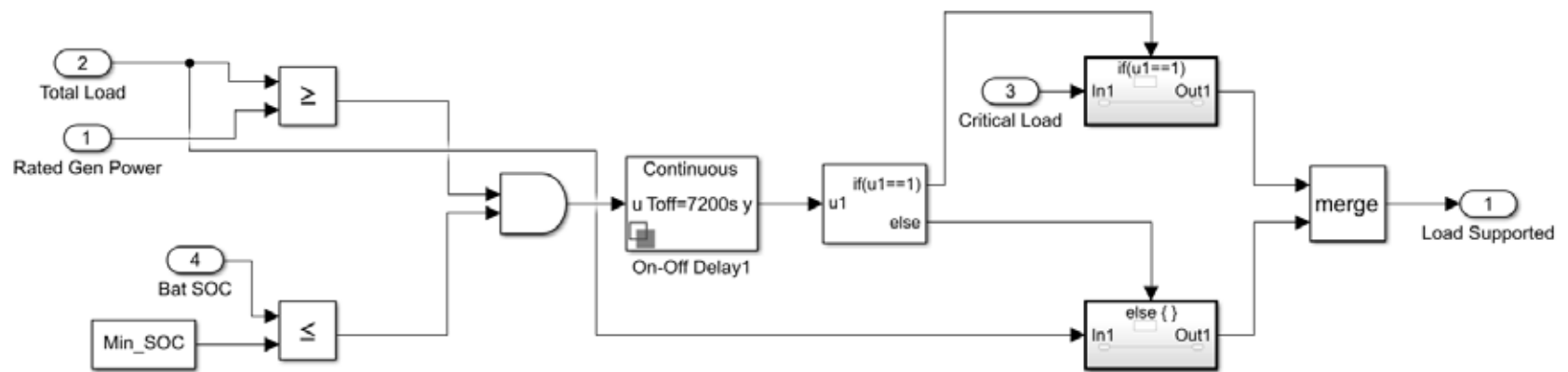


Figure 27. Load Shedding Logic

The microgrid ends each day with a battery SOC of 100 to maximize the energy storage available in case of sudden malicious attack, adverse weather conditions, or equipment failure. To end each 24-hour period with a battery SOC of 100, the logic in Figure 28 is in place after 18:00 hrs. If the estimated time to charge the battery is greater than or equal to the remaining time before 23:59 hrs, the generator will turn on. The estimate of the time to charge the battery is based on the assumptions that the solar output will remain low and continue to decrease every hour, and there will be no significant peaks in load during that time. That estimate is calculated by the algorithm in Figure 28.

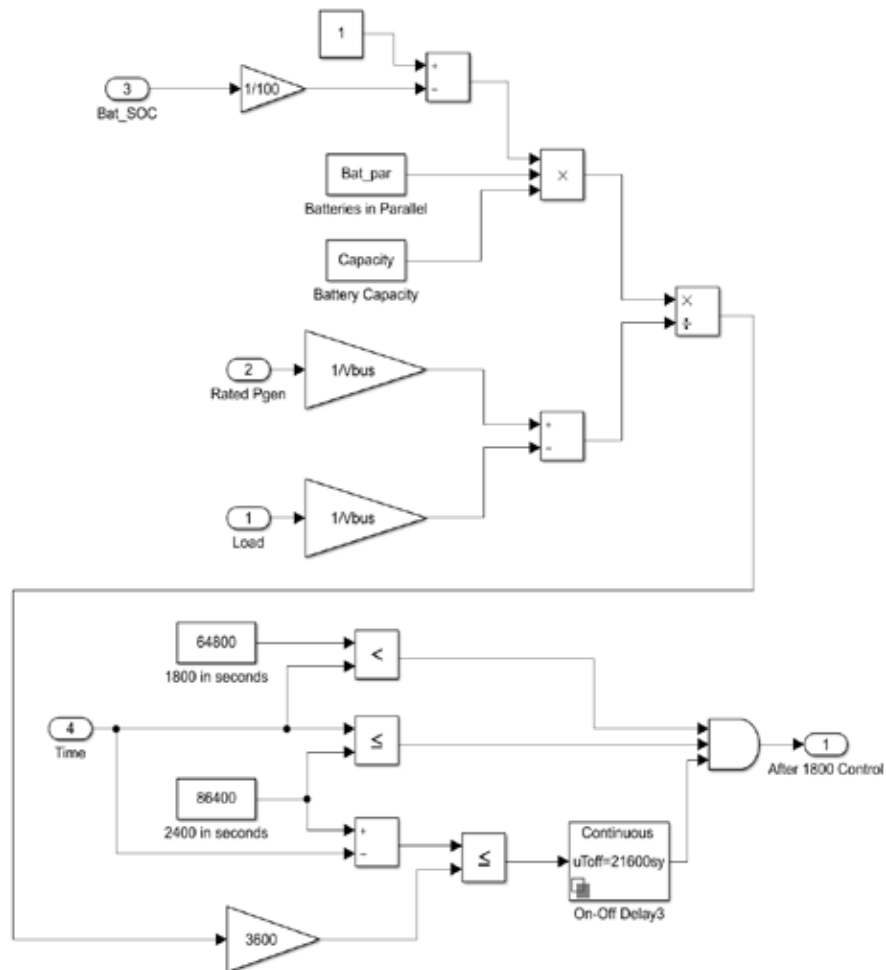


Figure 28. Energy Management System to Restore the Battery SOC to 100% by Midnight

The level of fuel F used is calculated in (46) and tracked in Figure 29 where P_{gen} is the instantaneous output of the generator in W.

$$F = \dot{a} \frac{P_{gen} \times G_{hr}}{18000 \times P_g \times N_g} \quad (46)$$

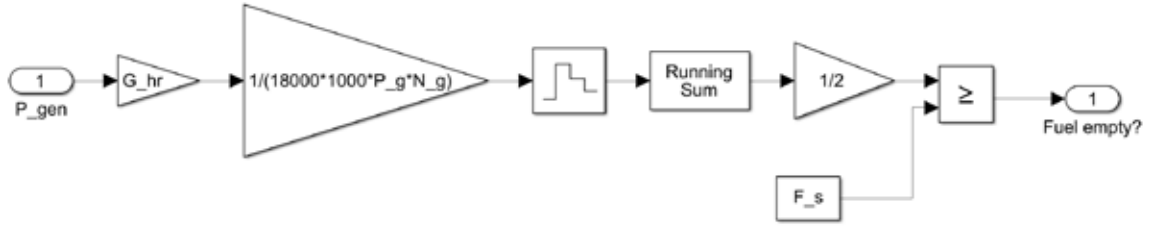


Figure 29. Fuel Comparison Algorithm

P_{gen} is divided by 18000 to account for the time step of the algorithm. The fuel consumed is totaled using a running sum in MATLAB. Then this amount of fuel used is compared to the initial fuel level to check if the fuel storage is empty.

The logic depicted in Figure 30 turns the generator off if the fuel storage is empty. There is a delay within the logic before the generator output to prevent an endless loop.

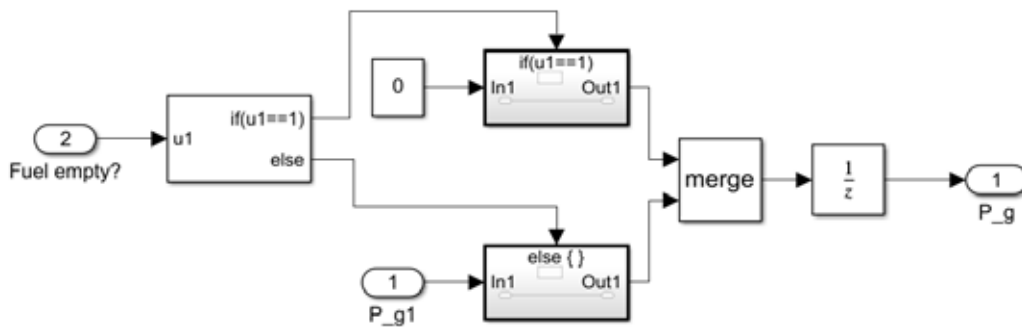


Figure 30. Check if Fuel Storage is Empty

IV. EXPERIMENTAL VALIDATION

The following calculations and experimentation were done to verify the accuracy of the design tool and the effectiveness of the physics-based model. In Part A, we will calculate the capabilities and parameters of the experimental microgrid. In parts B, C, and D we will provide experimental results that validate the calculations of the design tool as well as the power flow model.

A. EQUIPMENT AND CALCULATIONS

The experimental validation was conducted with a stand-alone microgrid that was assembled with commercial off-the-shelf (COTS) components, depicted in Figure 31. Photographs of the microgrid are shown in Figure 32 and Figure 33.

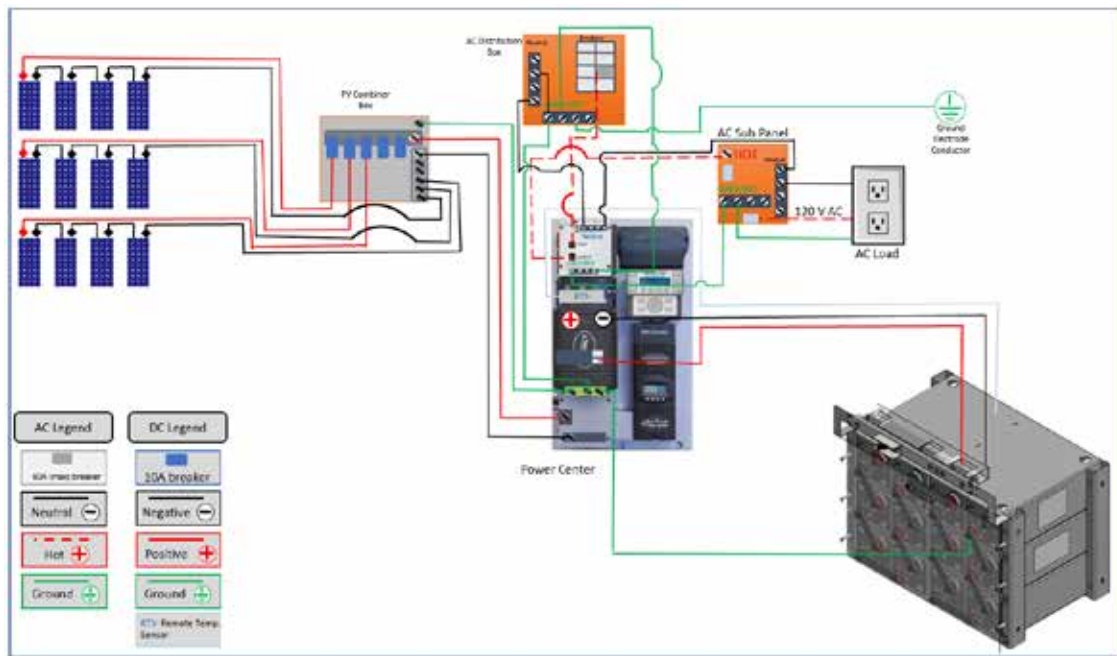


Figure 31. Experimental Microgrid Architecture. Adapted from [36].

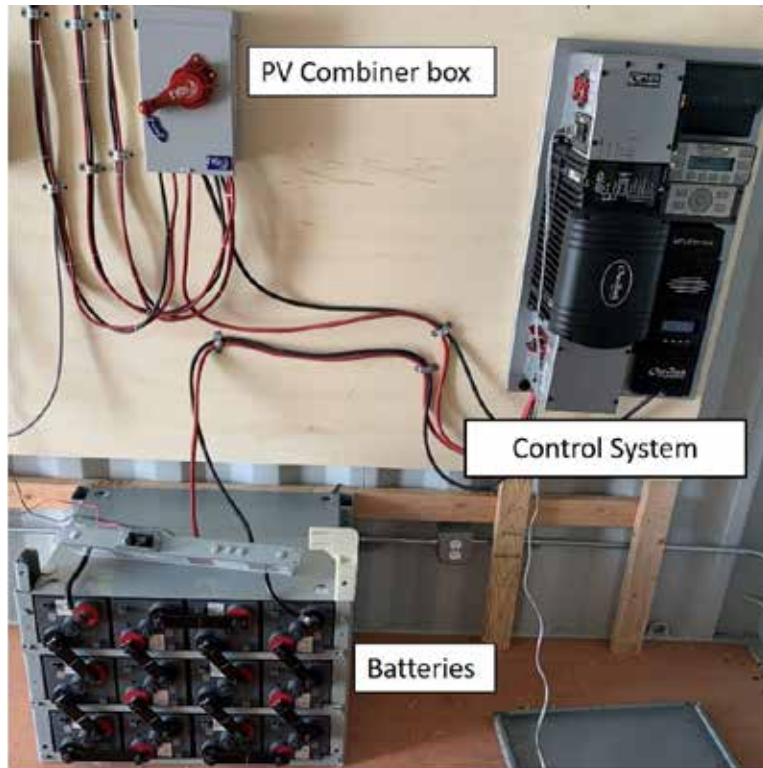


Figure 32. Control System, Batteries, and PV Combiner Box of Experiment Microgrid



Figure 33. PVs of Experiment Microgrid

1. Control System

The energy management system of the microgrid, shown in Figure 34 is the Outback FLEXpower system. It is a power electronics system that consists of the FLEXnet DC battery monitor, the FLEXmax charge controller, the inverter and charger, and the MATE3 system display and control panel.



Figure 34. Microgrid Control System

a. Battery Monitor

The FLEXnet DC battery monitor collects the battery pack measurements listed in Table 4 and Table 5. This data is used to evaluate the performance of the microgrid.

Table 4. FLEXnet DC Battery Monitor Data. Adapted from [37].

Shunt A [A]	Shunt B [A]	Shunt C [A]	Battery Voltage [V]	SOC
-------------	-------------	-------------	---------------------	-----

Table 5. FLEXnet DC Battery Monitor Additional Data. Adapted from [37].

Accumu- lated Ah Shunt A	Accumu- lated kWh Shunt A	Accumu- lated Ah Shunt B	Accumu- lated kWh Shunt B	Accumu- lated Ah Shunt C	Accumu- lated kWh Shunt C
Days since full	Today's minimum SOC	Today's net input [Ah]	Today's net output [Ah]	Today's net input [kWh]	Today's net output [kWh]

The overall power center is wired with Shunts A, B, and C as in Figure 35, which measure the current from the power source, the current from the inverter and charger, and the current from the charge controller, respectively.

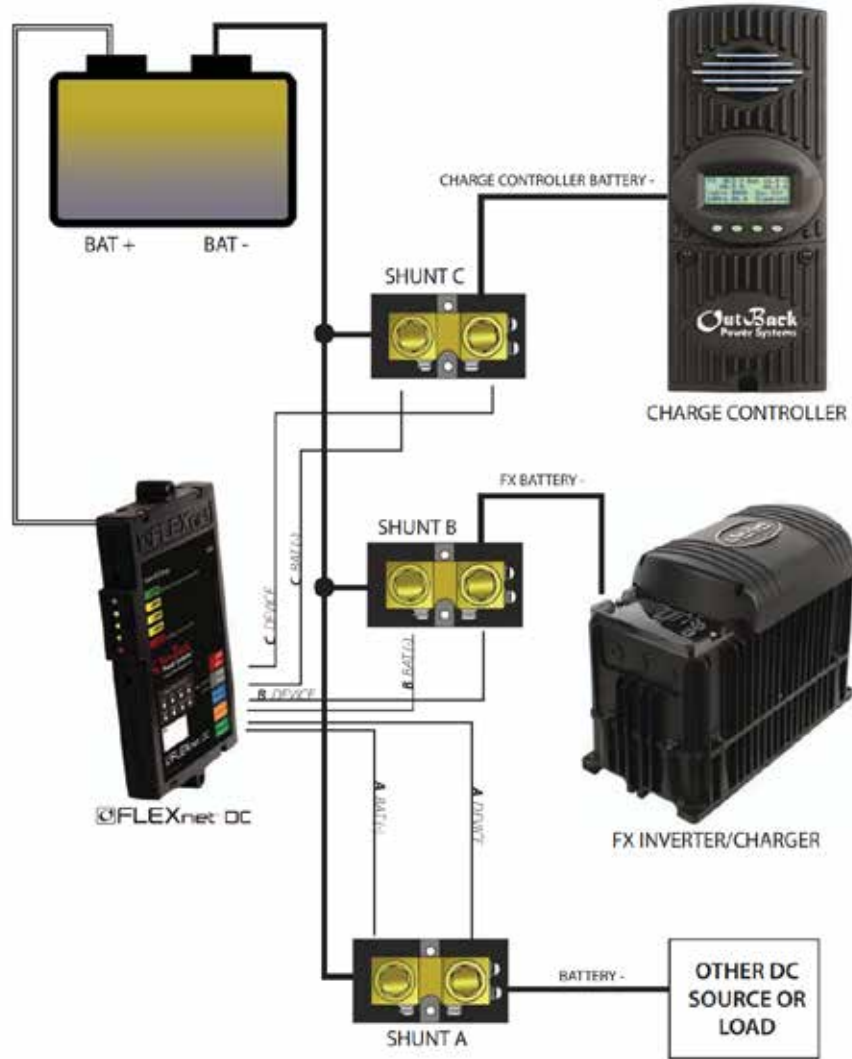


Figure 35. Configuration of Shunts for Current Measurement by Battery Monitor. Source: [38].

b. FLEXmax charge controller data

The charger controller uses a MPPT so the output power of the PV arrays is maximized at all times. The charge controller contains a buck converter which converts PV voltages into lower voltages to charge the batteries; thus, the current to the batteries is higher than the current from the PVs. This will be illustrated in the experiments later in this chapter; additionally, Figure 36 depicts this concept by showing an example of the PV voltage profile and the lower voltage of the batteries.

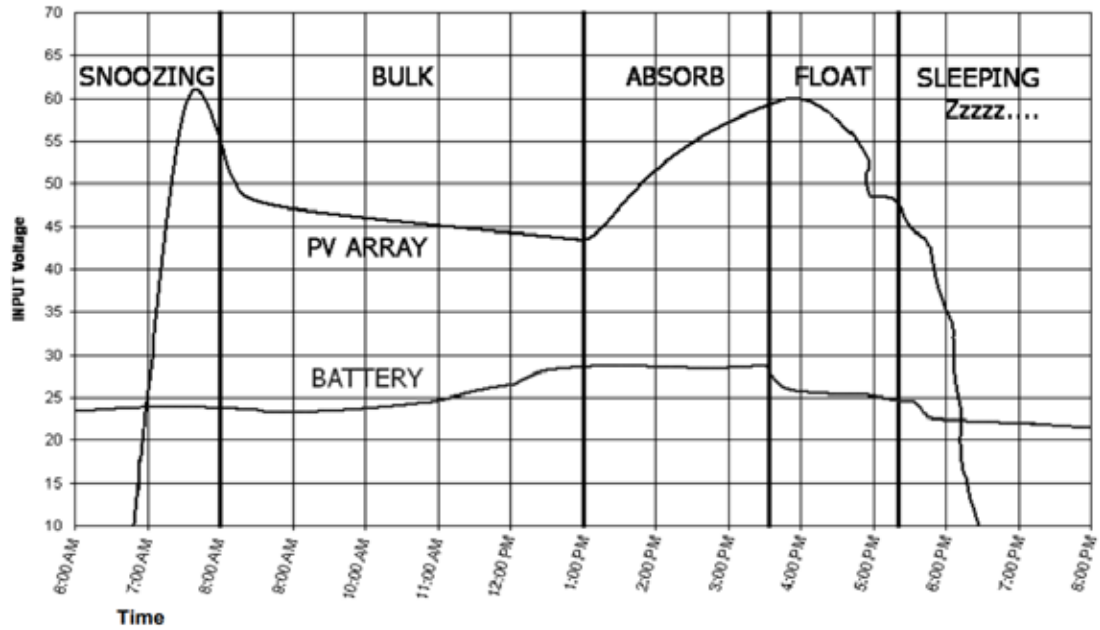


Figure 36. Example of PV and Battery Voltage Controlled by Charge Controller. Source: [39].

The data from the charge controller that is used to evaluate the microgrid is listed in Table 6.

Table 6. FLEXmax Charge Controller Data. Adapted from [37].

Charger Current [A]	PV Current [A]	PV Voltage [A]	Daily Energy [kWh]	Battery Voltage [V]	Daily [Ah]

c. Inverter/charge and MATE3 Display

The efficiency of the inverter is 90% [40]. The MATE3 display is the user interface, by which data is collected.

2. Battery Characteristics and Calculations

The microgrid energy storage includes 12 batteries in series, as seen in Figure 37. Table 7 lists the characteristics of the batteries.



Figure 37. Battery Bank of Experiment

Table 7. Characteristics of Experiment Battery. Adapted from [41].

SLR500-2	
Type	Lead-Acid Deep Cycle
Voltage	2 V
Capacity (10 hr)	500 Ah
MDOD	.7

Before any experimentation, the total daily power consumption the batteries can support in kWh/day is calculated. Working backwards from the tool calculations, total power available to the AC load is determined from the following calculations:

$$V_{sys} = N_B \times V_b \hat{=} 12 \times 2 = 24 \text{ volts} \quad (47)$$

$$Q_t = N_{Bp} \times Q_b \hat{=} 1 \times 500 = 500 \text{ Ah} \quad (48)$$

$$Q_{US} = \frac{Q_t \times C_{T_B} \times MDOD}{DM} \hat{=} \frac{500 \times 1 \times 0.7}{1.1} = 318 \text{ Ah} \quad (49)$$

$$I_l = \frac{Q_{US}}{D_Q} \hat{=} \frac{318}{1} = 318 \frac{\text{Ah}}{\text{day}} \quad (50)$$

$$P_{l_{DC}} = I_l \times V_{sys} \hat{=} 318 \times 24 = 7.63 \frac{\text{kWh}}{\text{day}} \quad (51)$$

Finally, the batteries can support an AC load of:

$$P_{l_{AC}} = P_{l_{DC}} \times \eta_{inv} \hat{=} 7.63 \times 0.9 = 6.87 \frac{\text{kWh}}{\text{day}} \quad (52)$$

3. PV Characteristics and Calculations

Sole power source of the microgrid is solar, with four PV modules in series and three in parallel, for a total of 12 PV modules. Table 8 lists the characteristics of each PV array.

Table 8. Characteristics of PV Module. Adapted from [42].

HQST-100D-S	
P_m	100 W
V_{SC}	20 V
V_{mpp}	16 V
I_{mpp}	6.25 A
I_{oc}	6.45 A
$TC_{P\%}$	-.44 %/°C
$TC_{V\%}$	-0.30 %/°C
$TC_{I\%}$	0.04 %/°C

As with the battery calculations, the capabilities of the PVs must be calculated to determine the AC load the PVs could support. The solar irradiance for the operating month is 6.3 and the solar insolation is estimated to be 0.8. Starting with the size of the PVs and working in the opposite direction as the design tool, we calculate the daily average power consumption that the PVs can support:

$$T_{cell} = T_{amb} + \frac{NOCT - 20}{0.8} \times 0.8 \quad T_{cell} [^{\circ}C] = 19 + \frac{45 - 20}{0.8} \times 0.8 = 44^{\circ}C \quad (53)$$

$$I_{mpnew} = I_{mp} + \frac{I_{SC} \times TC_{I\%}}{100} \times (T_{cell} - 25) \\ \hat{=} 6.25 + \frac{6.45 \times 0.04}{100} \times (44 - 25) = 6.30 A \quad (54)$$

$$V_{mpnew} = V_{mp} + \frac{V_{OC} \times TC_{V\%}}{100} \times (T_{cell} - 25) \quad (55)$$

$$16 - \frac{20 \times 0.30}{100} \times (44 - 25) = 14.86V$$

$$V_p = V_{mp} \times DF \quad 14.86 \times 0.955 = 14.14V \quad (56)$$

$$V_{sys} = N_{ps} \times V_p \quad 4 \times 14.14 = 56.56V \quad (57)$$

$$I_{sys} = I_d + (1 - h_{bat}) \quad 0.15 + (1 - 0.98) = 0.17 \quad (58)$$

The I_{out}^{PV} produced by the PVs in one day is given by

$$I_{out}^{PV} = \frac{N_{pp} \times (1 - I_{sys}) \times I_{mp} \times PSK}{R_{A:L}} \quad \hat{=} \quad \frac{3 \times 0.83 \times 6.3 \times 6.3}{1.3} = 76.02 \frac{Ah}{day} \quad (59)$$

The $P_{l_{DC}}$ produced by the PVs in one day is given by

$$P_{l_{DC}} = I_{out}^{PV} \times V_{sys} \quad \hat{=} \quad 76.02 \times 56.56 = 4.24 \frac{kWh}{day} \quad (60)$$

The PVs can support an AC load with daily average power consumption

$$P_{l_{AC}} = P_{l_{DC}} \times \eta_{inv} \quad \hat{=} \quad 4.24 \times 0.9 = 3.82 \frac{kWh}{day} \quad (61)$$

The difference between these calculations and those done in the sizing tool is that these calculations must account for the charge controller. The buck converter in the charge controller steps down the voltage of the PVs for the batteries, thus the Ah of the charger is higher than that of the PVs. Therefore, the charger output in Ah is greater from the PV output, and must be calculated to reflect the charge that reaches the battery. On a clear day, at a temperature of approximately 64 °C, the average power that reaches the batteries, produced by the PVs is:

$$I_{ch} = \frac{E_{l_{DC}}}{V_b \times N_{Bs}} \quad \hat{=} \quad \frac{4240}{24} = 176.67 \frac{Ah}{day} \quad (62)$$

B. LABORATORY EXPERIMENT A: PARTIALLY CLOUDY MORNING

The first experiment lasted for 12 hours during a partially cloudy morning. The load profile and sequence of events is depicted in Figure 38. Note that the previous load is turned off before the following one turns on.

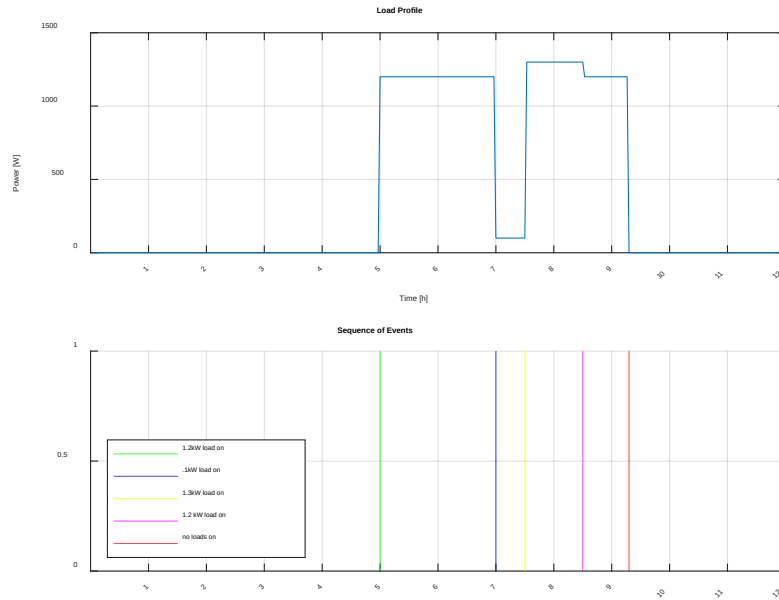


Figure 38. Load Profile and Changes in Load During Experiment A

1. Experiment A Results

Figure 39 shows the SOC of the battery bank measured during experiment A.

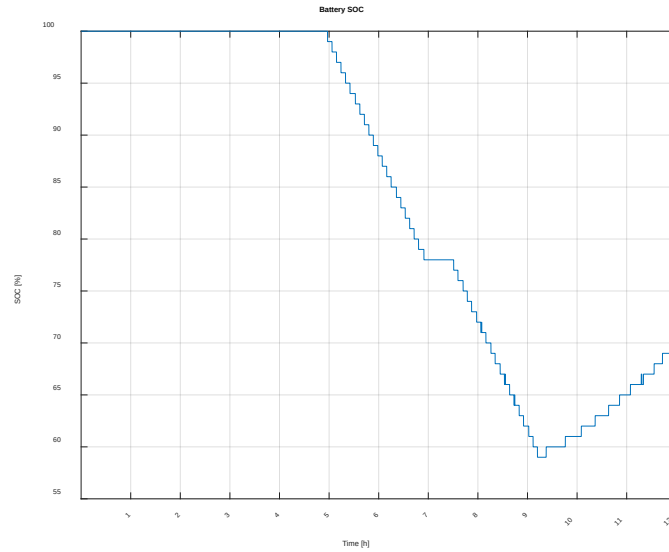


Figure 39. Battery SOC of Experiment A

The battery monitor measured the current to the load across shunt A and the current to the charger across shunt B, both shown in Figure 40.

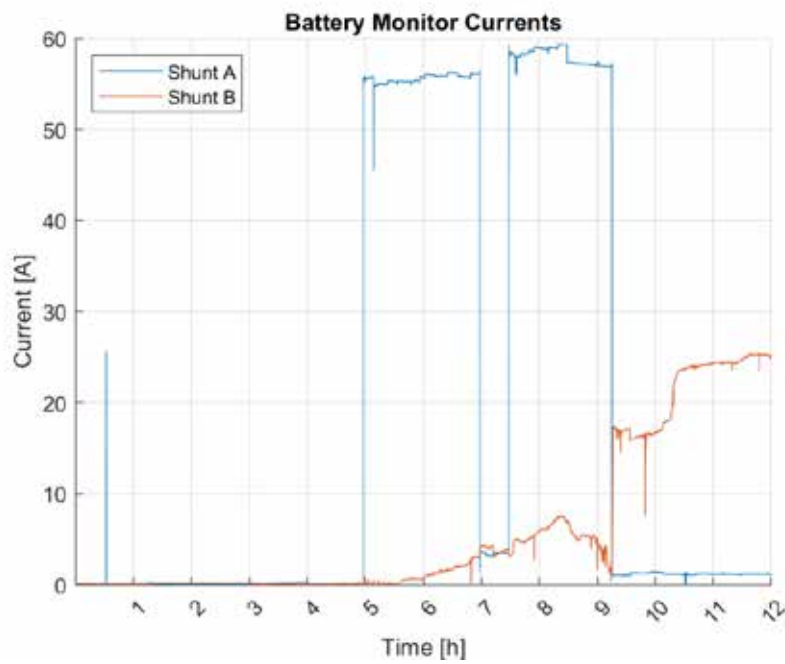


Figure 40. Currents Measured by Battery Monitor in Experiment A

The shunt B current represents the current from the PVs after it has been increased by the charge controller; Figure 41 compares three currents measured by the system. It shows the shunt B current of the battery monitor is equivalent to the charger current of the charge controller, and the PV current of the charge current is lower.

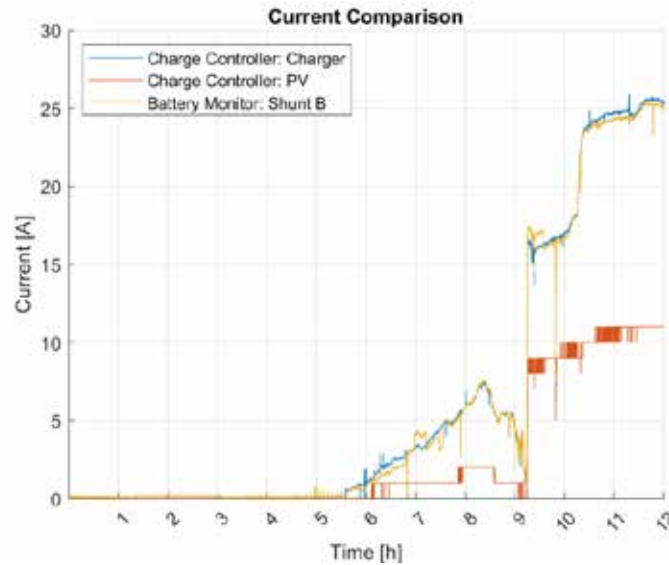


Figure 41. Comparison of Charger, PV, and Shunt B Currents in Experiment A

The PV voltage in Figure 42 varies throughout the day due to the variations of solar irradiance as the MPPT finds the operating voltage and current of the PVs. The operating voltage is above its V_{mp} , and closer to its V_{OC} before 09:10 h, at which point the operating voltage falls below V_{mp} and the PV output increases, which can be seen in Figure 41 by the jump from about 2 A to 8 A of PV current.

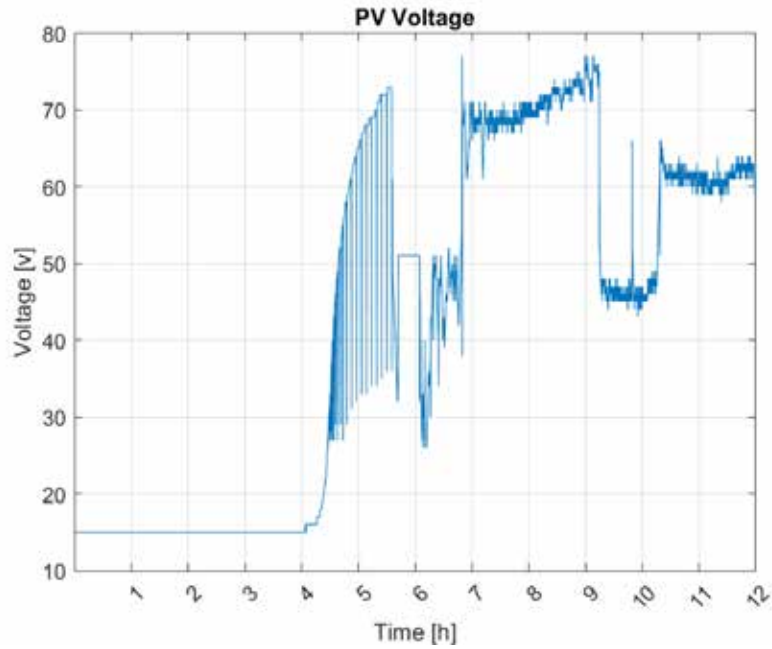


Figure 42. Operating Voltage of PVs in Experiment A

The power output of the charger and PVs in Figure 43 is comparable.

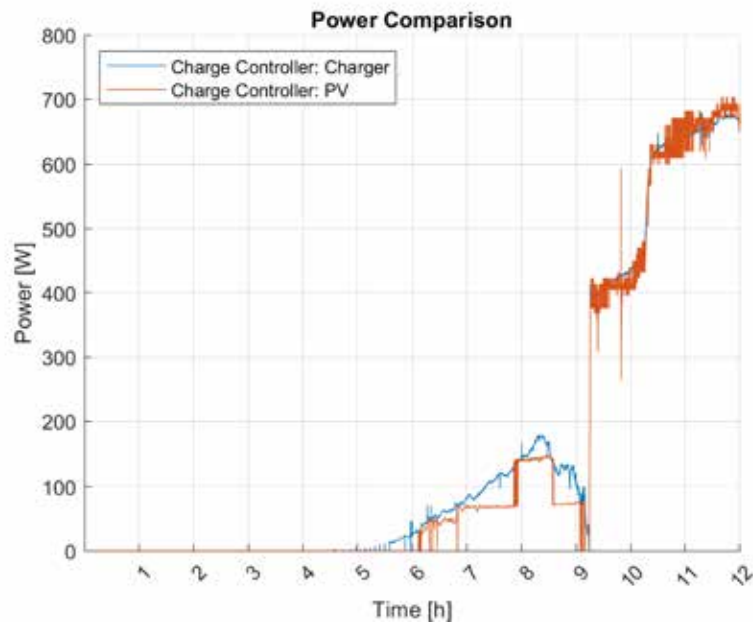


Figure 43. Comparison of Charger and PV Power Output in Experiment A

2. Simulation Equivalent

To verify that the physics-based model presented in Chapter III can predict the experimental measurement on the COTS microgrid, shunt A current and shunt B current were inputs to a 12-hour simulation using the power flow model. Shunt A current corresponded to the load and shunt B current corresponded to the PV output. For the sake of the power flow model, the charger current and the PV output are the same since the model does not simulate a charge controller.

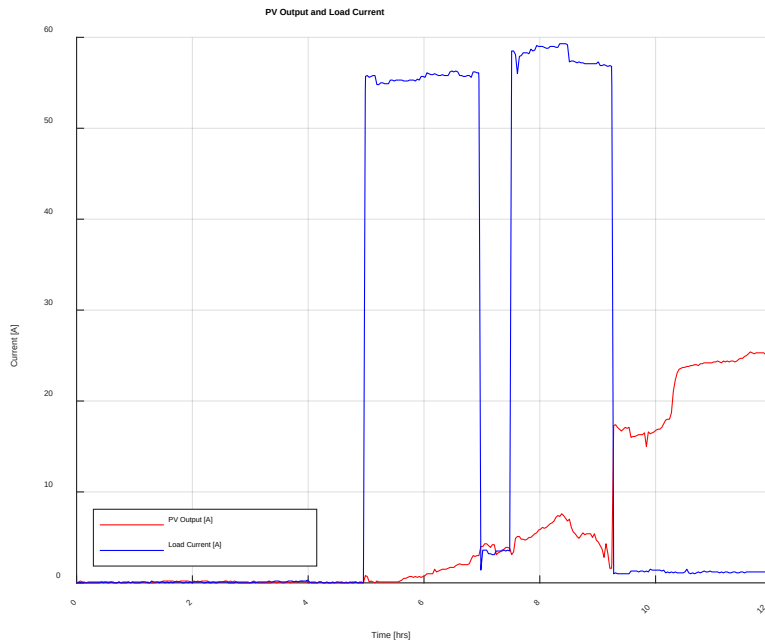


Figure 44. PV Output and Load Current for Simulation of Experiment A

The results were strikingly similar; the SOC of both the experimental and simulated batteries in Figure 45 are within .5% SOC during the 12 hours. This results validates the physics-based model used for the simulations reported in Chapter III.

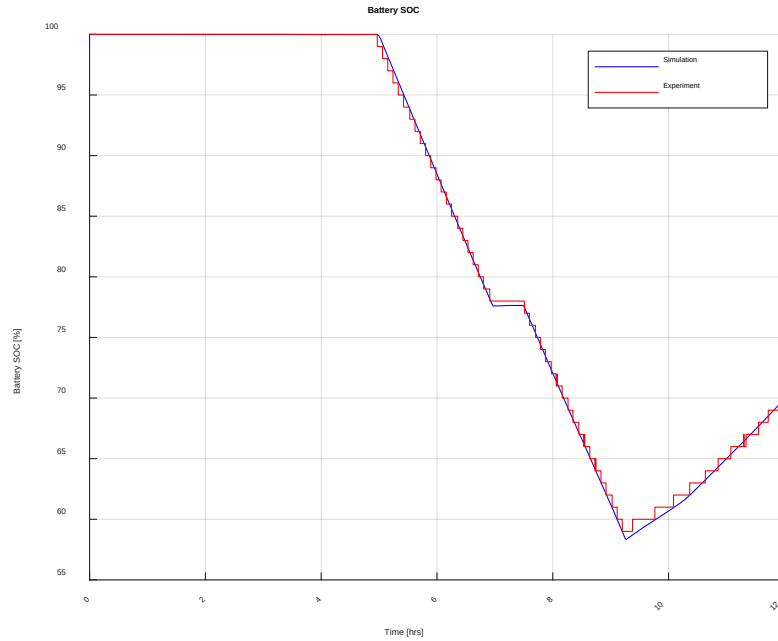


Figure 45. Experimental and Simulated Battery SOC of Experiment A

C. LABORATORY EXPERIMENT B: ONE DAY OF BATTERY CHARGING WITH NO LOAD

Experiment B lasted for 24 hours from 13:00 hrs on one day to 13:00 hrs on the next with no load and a relatively low level of clouds. The purpose of Experiment B is to verify how the model simulates the battery charging with no load.

1. Experiment B Results

During the 24 hours experiment, the battery charges from 72% to 99%, depicted in Figure 46.

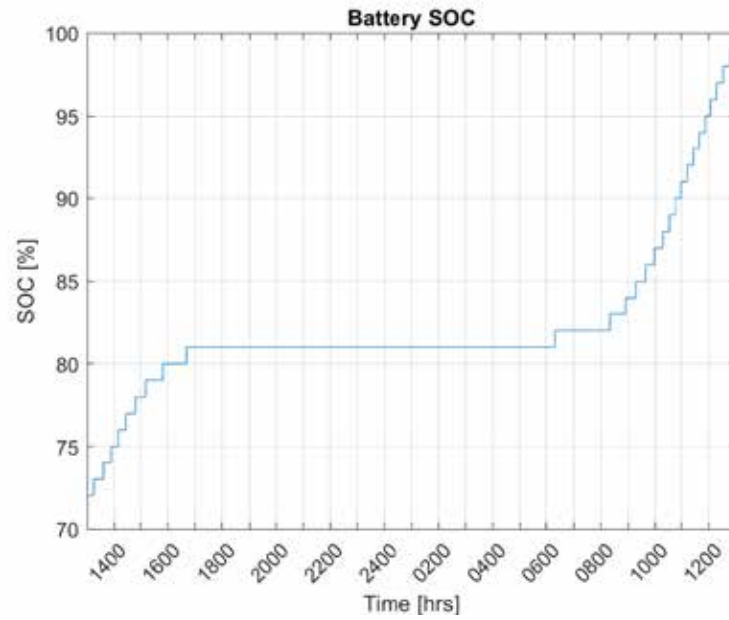


Figure 46. Battery SOC in Experiment B

The voltage of the PVs is captured in Figure 47. Just as in experiment A, it varies throughout the day due to the MPPT.

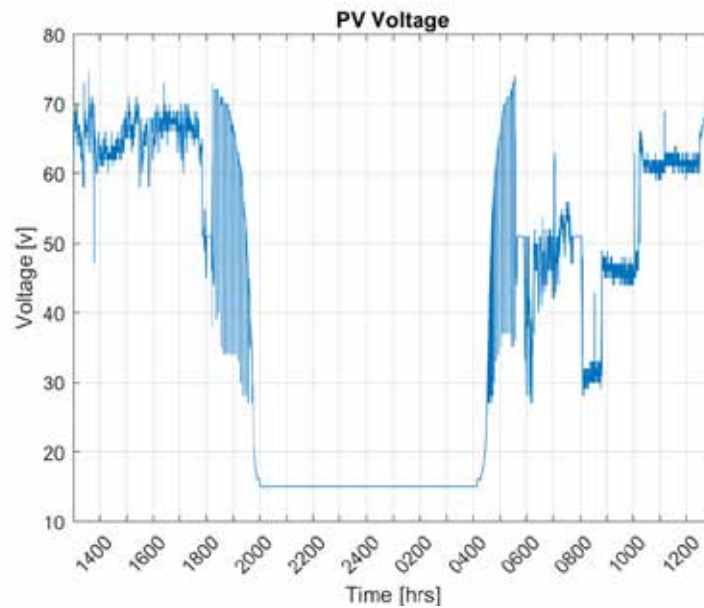


Figure 47. Operating Voltage of PVs in Experiment B

Again, the current from the PVs is lower than the current of the charger, shown in Figure 48. The power output of the PVs is equal to the power of the charger, shown in Figure 49.

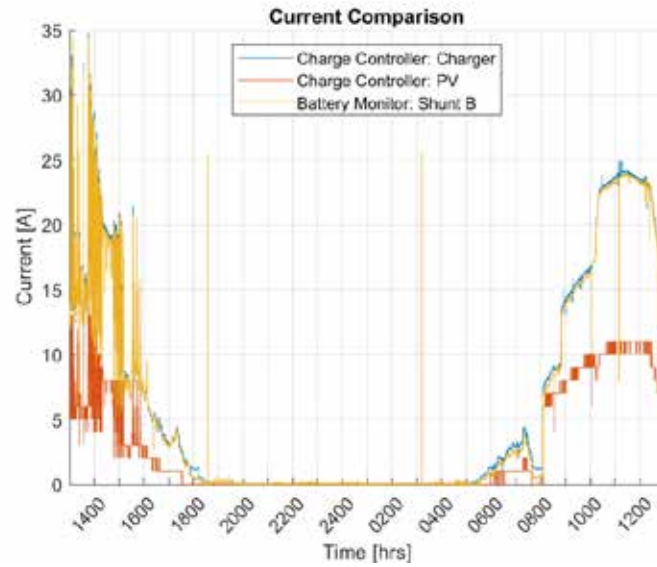


Figure 48. Comparison of Charger, PV, and Shunt B Currents in Experiment B

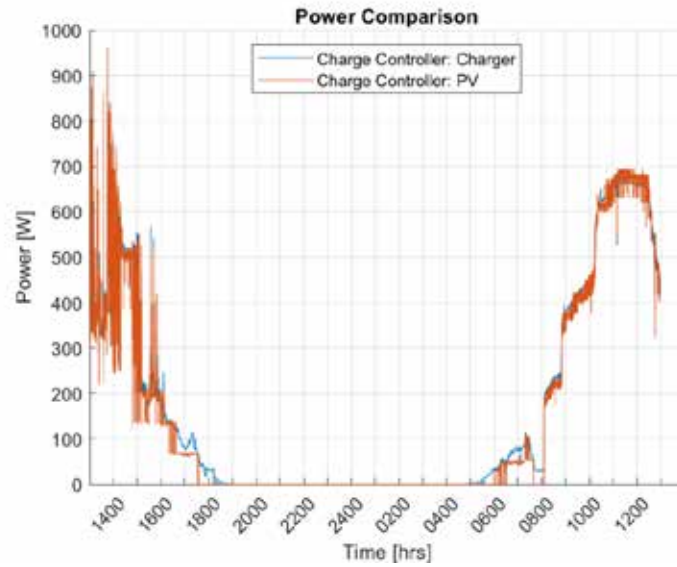


Figure 49. Comparison of Charger and PV Power Output in Experiment B

2. Simulation Equivalent

To verify the model, shunt A current and shunt B current seen in Figure 50 were inputted as the load current and PV output respectively, and the model was run for 24 hours.

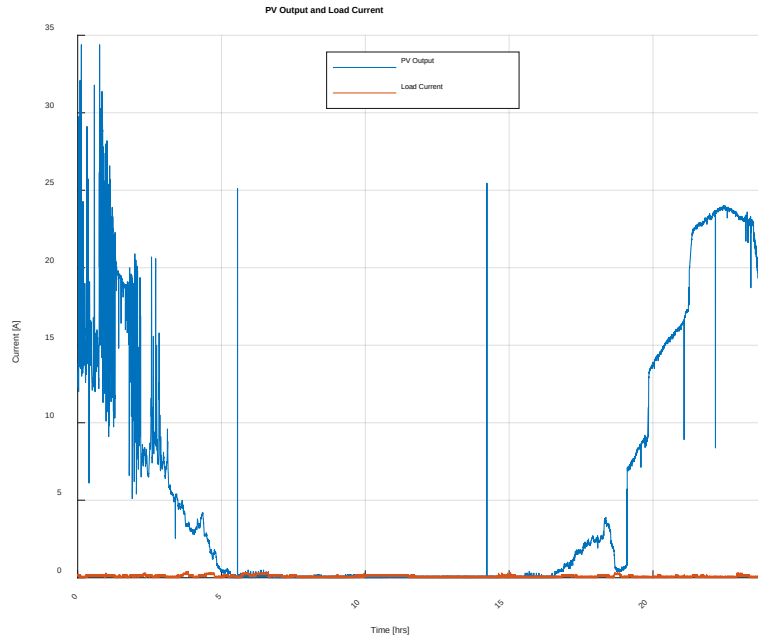


Figure 50. PV Output and Load Current for Simulation of Experiment A

The results show that the simulated battery SOC remained within 2% of the experimental battery SOC. This helps to validate the physics-based model.

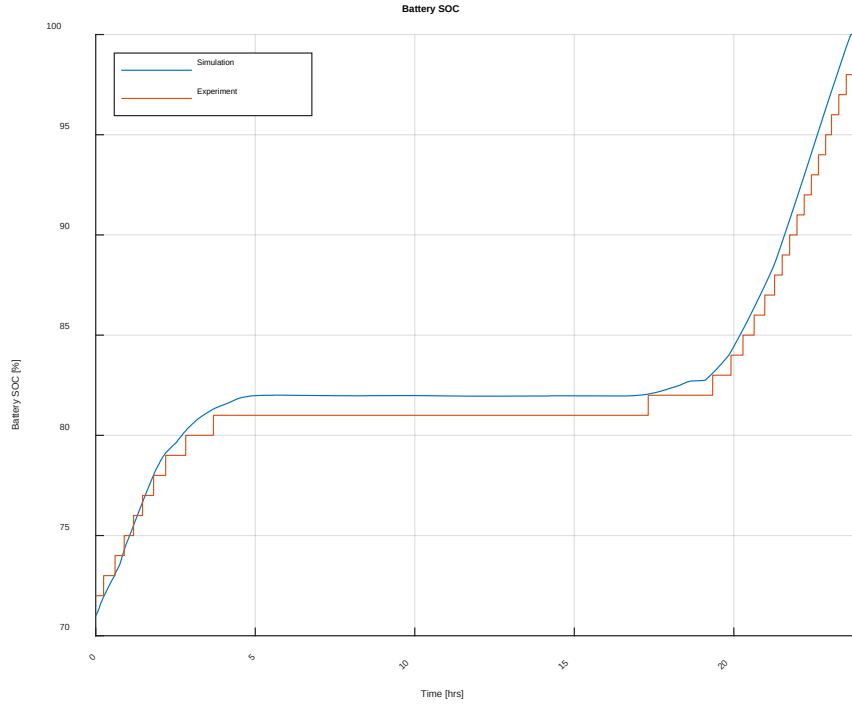


Figure 51. PV Output and Load Current for Simulation of Experiment B

D. LABORATORY EXPERIMENT C: DEPLETION OF BATTERY ON A CLEAR DAY

The purpose of Experiment C is to verify the accuracy of the sizing tool by comparing the capacity of the batteries in the experiment with what was calculated in Part A of this Chapter. Experiment C lasted for approximately 11 hours, starting at 08:10 h on a completely clear day with a varying load until the battery was discharged to its MDOD. The load profile is depicted in Figure 52.

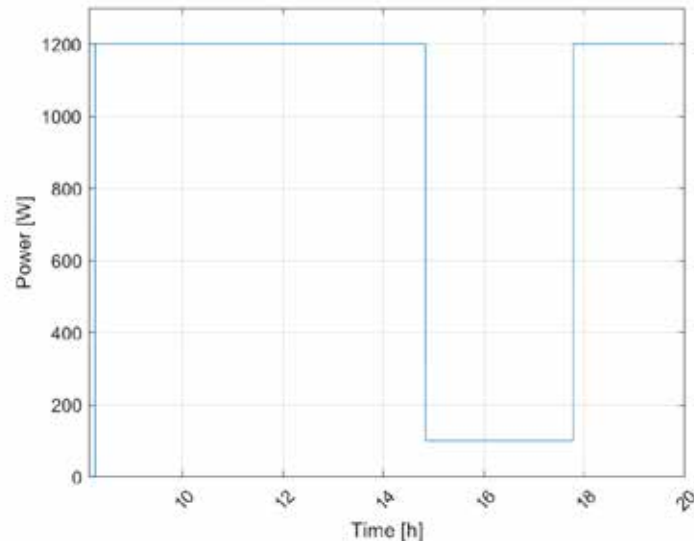


Figure 52. Load Profile for Experiment C

1. Experiment C Results

Figure 53 shows the performance of the battery bank over the course of the day as it discharges to its MDOD 70%. In Figure 54 , shunts A and B measure the current to the load and the current from the charge controller, respectively.

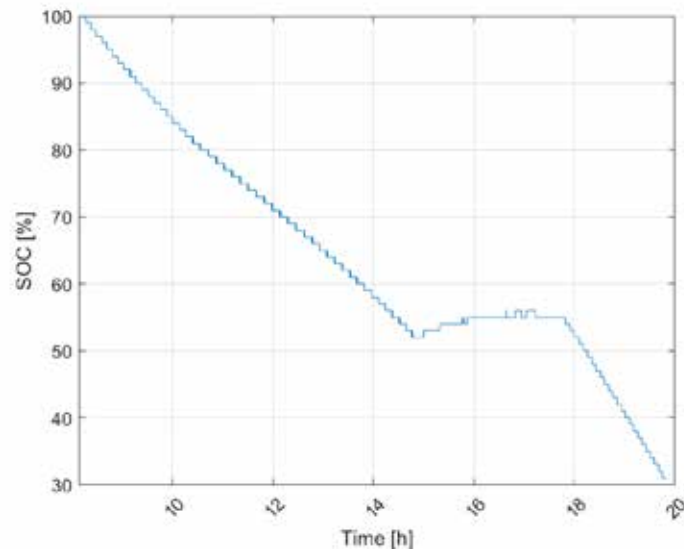


Figure 53. Battery SOC in Experiment C

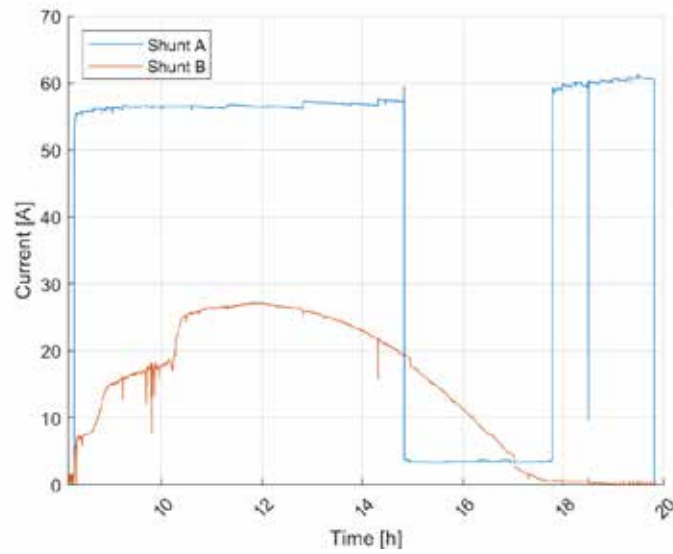


Figure 54. Battery Monitor Currents in Experiment C

The battery voltage in Figure 55 slowly decreases as the SOC decreases, with an increase in voltage when the load decreased around 15:00 hrs.

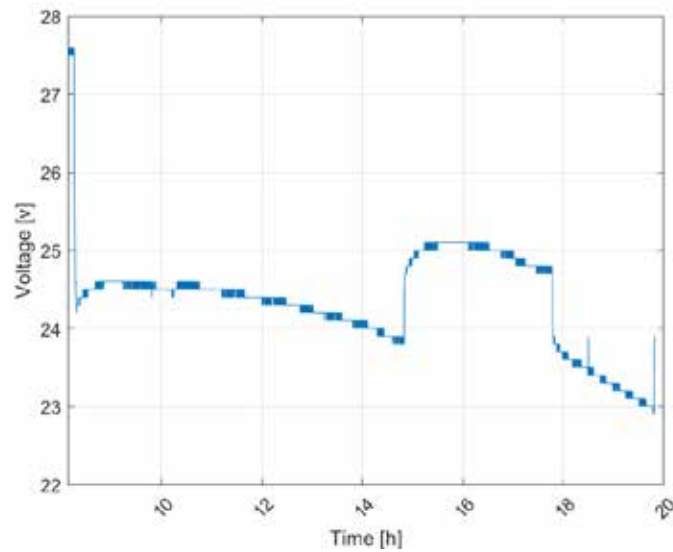


Figure 55. Battery Voltage in Experiment C

The PV voltage in Figure 56 dramatically rises just after 10:00 hrs, when the charger current in Figure 54 also increases from about 18 amps to 25 amps. The PVs are operating quite close to their V_{mp} of 64 volts from about 10:00 hrs to 17:30 hrs when the insolation is highest and the PV current is above 0.

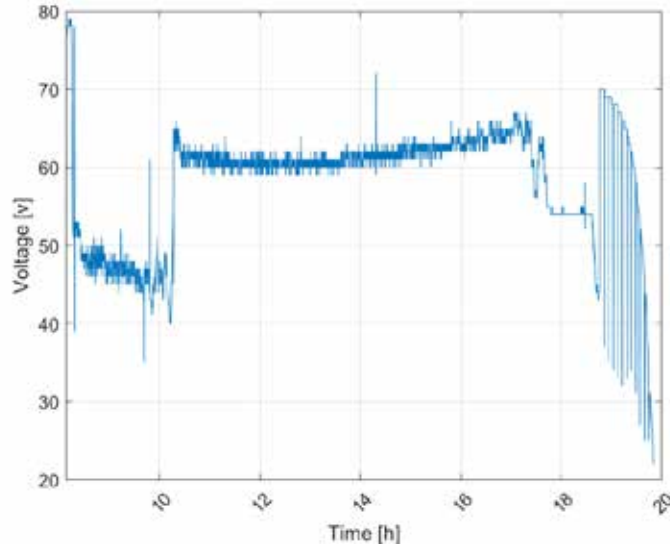


Figure 56. Operating PV Voltage of Experiment C

The charger, PV, and shunt B currents are compared in Figure 57, and it is clear that the currents through shunt B and the charge controller are equal, while the PV current is lower.

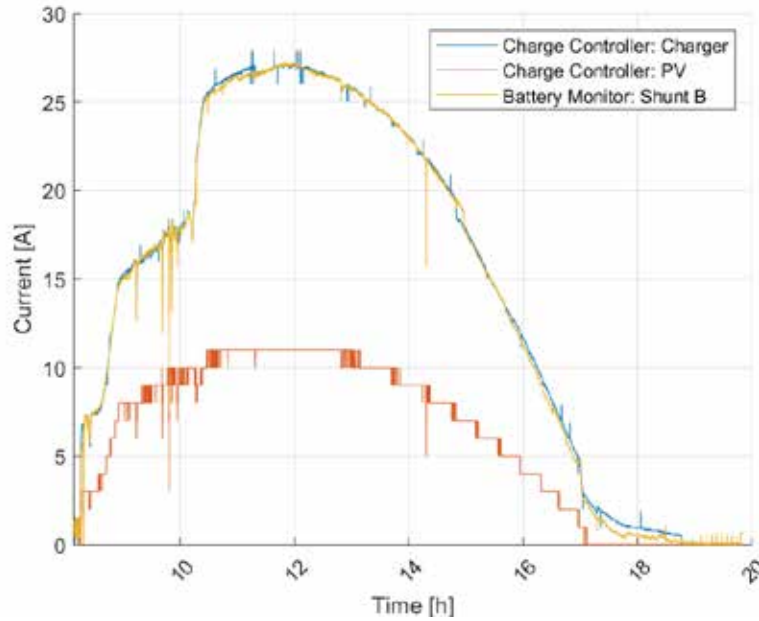


Figure 57. Comparison of Charger, PV, and Shunt B Currents in Experiment C

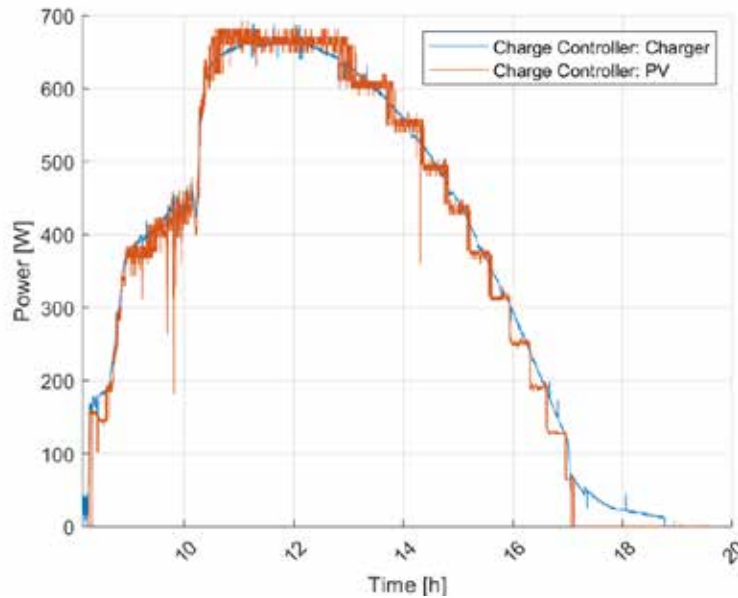


Figure 58. Comparison of Charger and PV Power Output in Experiment C

2. Experiment C Simulation Equivalent and Tool Validation

Again, the simulated results obtained with the physics-based model are validated by the experimental results. Shunt A current was used as the load profile and shunt B

current was used as the PV output of the physics-based model, as shown in Figure 59. The battery SOC of the simulation and Experiment C are almost identical, as shown in Figure 60.

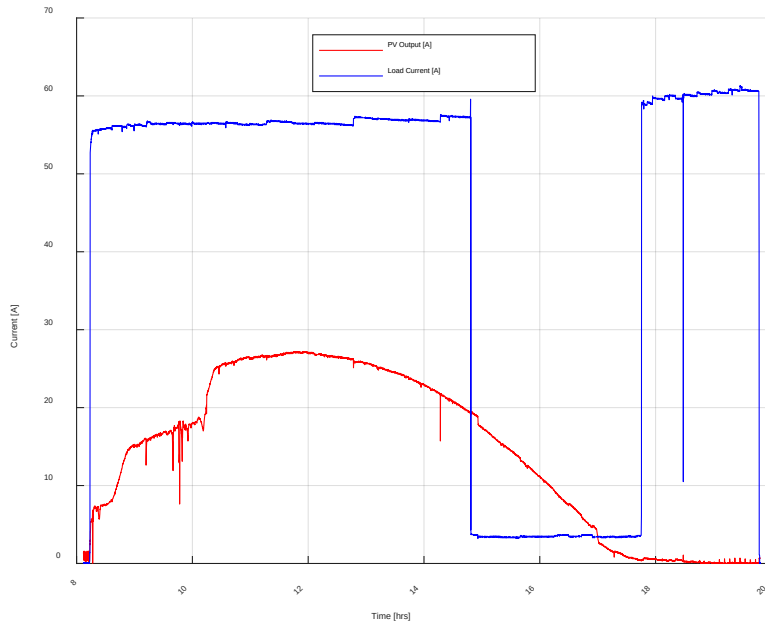


Figure 59. PV Output and Load Current for Experiment C Simulation

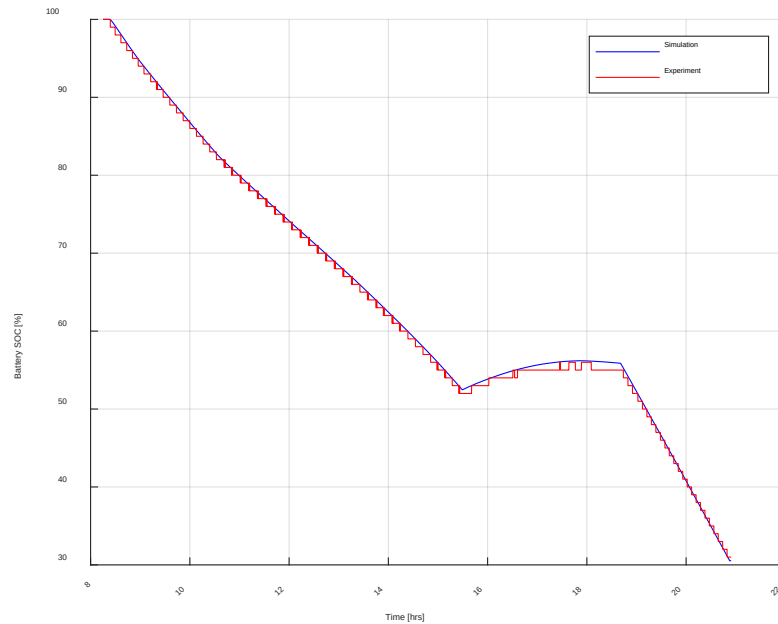


Figure 60. Battery SOC Comparisons between Simulation and Experiment C

From the calculations, the battery should be able to support a daily DC load of 7.63 kWh with 318 Ah of charge. The PVs should produce 4.2kWh per day and charge the batteries with 176.67 Ah on one clear day. From Figure 61, the cumulative net output in Ah of the batteries was 333 Ah, slightly exceeding the expected capability, and the cumulative net output in Ah of the PVs was 170, just under the expected capability. Figure 62 shows the daily power provided by the batteries was 7.99 kWh, which, again, is just higher than the calculation. The daily power provided by the PVs was 4.16 kWh, slightly lower than expected. A hypothesis as to why there was slightly lower than expected power from the PVs is there was shading from a building on two of the 12 PV modules during the morning hours of operation.

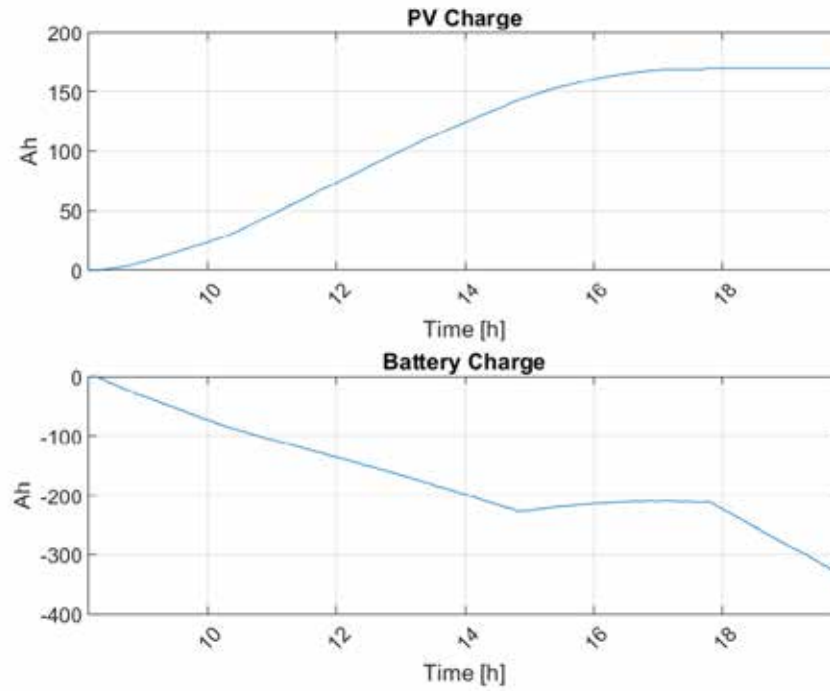


Figure 61. PV and Net Battery Ah from Experiment C

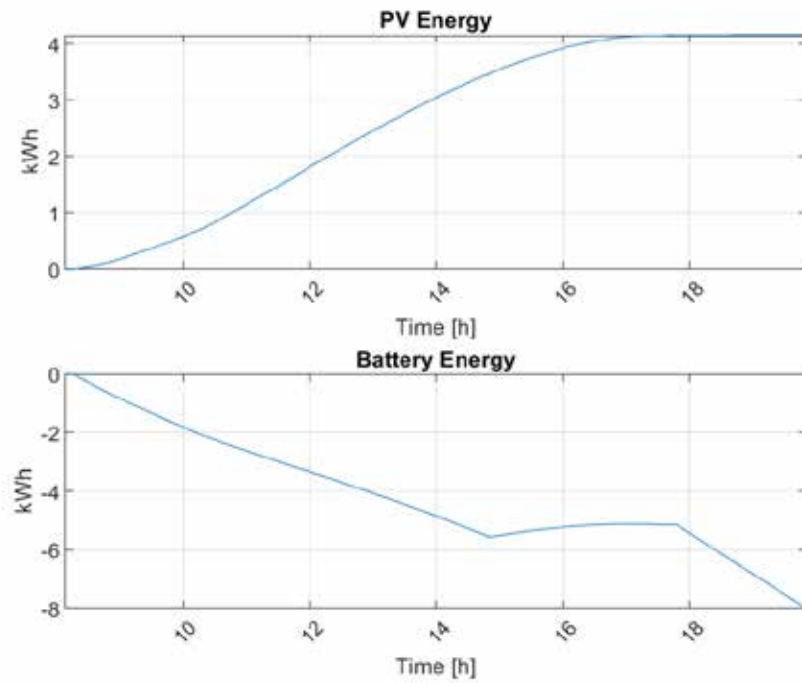


Figure 62. PV and Net Battery kWh from Experiment C

A summary of the experimental results is in Table 9. This validates the ability of the sizing methodology to size the battery bank and PV arrays to support the load.

Table 9. Summary of Calculations and Experiment Comparison

	Calculation	Experimental Value
PV Output [Ah/day]	176.67	170
PV Output [kWh/day]	4.2	4.16
Battery Output [Ah/day]	318	333
Battery Output [kWh/day]	7.63	7.99

V. DESIGN FOR DIFFERENT SOLAR FRACTIONS

The following chapter examines hybrid PV microgrids with different solar fractions and uses two case studies to understand the impact of the designs on the microgrids' performance.

A. OBJECTIVE OF CASE STUDIES

The simulation results presented in this section strive to answer the question: how much can a hybrid PV microgrid rely on solar power and what are considerations for design when selecting the SF?

For environments where there is great variability in the amount of available sunlight the year, it may be difficult to determine how much the system should depend on PV sources for energy and how much the system should utilize the generator and battery bank. For example, it is easy to understand from Figure 63 and Figure 64 that the same microgrid, in which the PV arrays are designed using the typical irradiation available in the month of January, will produce well over what is required by the loads in the month of June; what is not clear, however, is by how much and how this should influence the design.

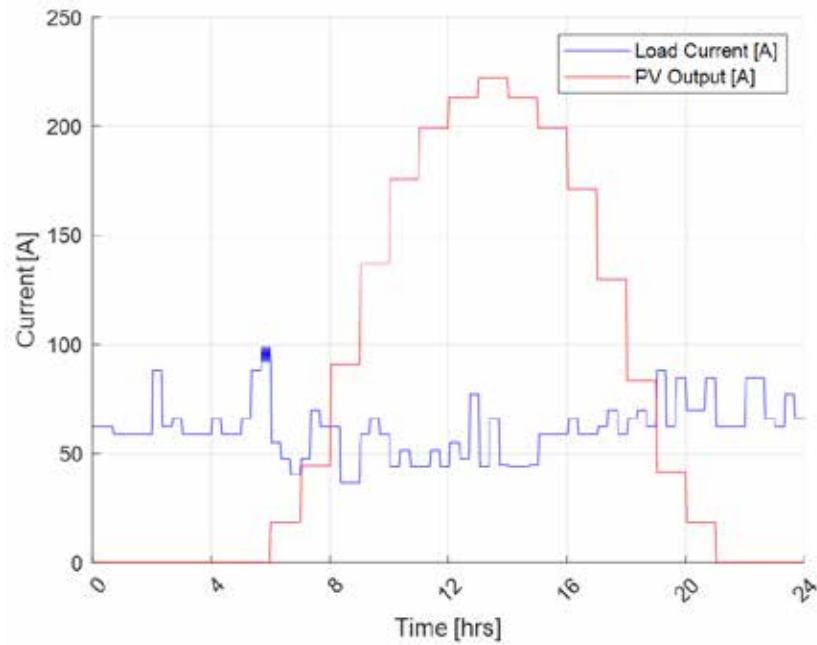


Figure 63. Simulation results for the Month of January with PV Arrays Sized for January Irradiance

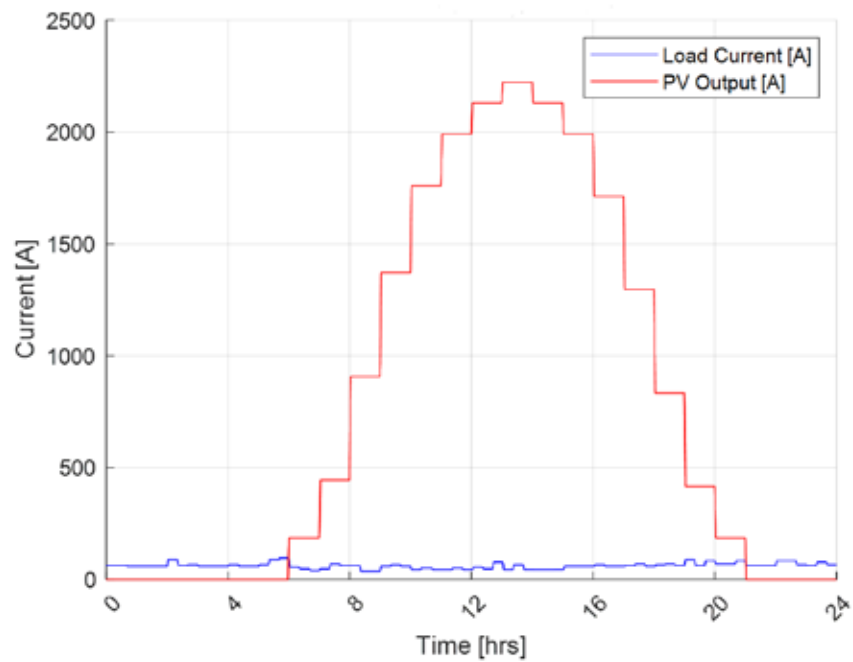


Figure 64. Simulation Results for the Month of June with PV Arrays Sized for January Irradiance

As discussed in Chapter II, the user has the option in the design tool to select a SF from 0.1 to 1. For example, if the SF is 0.1, the PVs will be sized to support 10% of the total load. The remainder of the load must be supported by another power source, such as a generator. Sizing the PVs to a smaller SF in the design month can help prevent an overdesign during the months with more sun. The simulation results presented in this chapter will explore implications, benefits, and drawbacks of utilizing different SFs in different environments.

Two case studies are presented in the following sections, each supported by several simulations obtained using the physics-based model presented in Chapter III and experimentally validated in Chapter IV. The first case study is a year-long simulation during NOC, when there is assumed to be no adverse weather or generator outages. The second case study includes an inoperable generator and the microgrid recovering from successive days of cloudiness. From these two case studies, the microgrid power flow was simulated and its performance evaluated by comparing its fuel usage, the minimum SOC of the batteries in normal operation, and the charge rate of the batteries with an inoperable generator.

B. ENVIRONMENT AND SYSTEM REQUIREMENTS

Each case study includes simulation results for three different locations; Fairbanks, Alaska; San Diego, California; and Rota, Spain. Analyzing different locations will help compare the feasibility of microgrids in different climates, as well as the variation in monthly solar irradiance in different locations. The solar and temperature profiles of each are depicted in Figure 65 and Figure 66 .

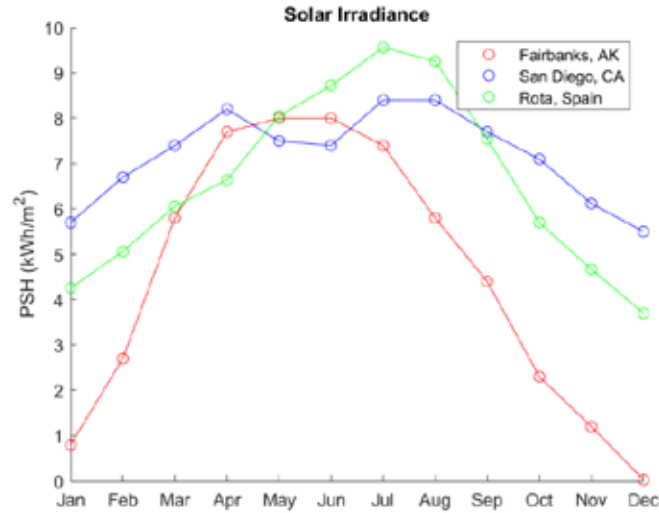


Figure 65. Annual Solar Irradiance of Three Locations. Adapted from [29], [43].

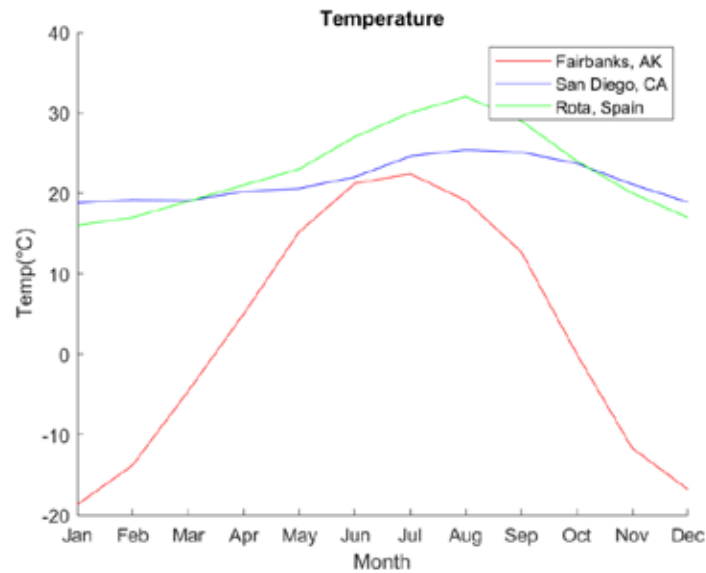


Figure 66. Temperature of Three Locations. Adapted from [29], [44].

The system and load specifications, battery model, required usable storage days, PV model, A:L ratio, use of MPPT, and generator design were the same for each of the three locations. As a result, the size of each microgrid PV array was different in each location, but all three were designed to support the same load in their respective locations.

The inputs and outputs of the design tool for Fairbanks, AK for this simulation are shown in Figure 67.

Inputs		Outputs	
Battery Bank Design	User Inputs	Battery Bank Design	Outputs
System and Load Specifications		Batteries in series	10
Inverter efficiency	0.85	Batteries in parallel	43
AC Load total (kWh/day)	600	Total number of batteries	430
AC Load critical (kWh/day)	600	Minimum state of charge in NOC (%)	75
System Voltage (v)	480		
Battery Specifications		PV Design	Outputs
Battery Model	Relion RB48V200	Number of Modules in series	9
Battery Type & Temperature Range (°C)	Li-15>Temp2-20	Number of Modules in parallel	48
User Preferences		Modules Total	432
Required Usable Storage for Total Load (days)	1	PV output (Ah)	198,7776
Required Usable Storage for Critical Load (days)	3	PV output (kWh/day)	95,413248
PV Design	User Inputs	Generator Design	Outputs
Environmental Factors		Number of generators	3
Peak sun hours (kWh/m²)	0.8	Maximum number of generators based on min charge time	8
PV Specifications			
PV Model	SunPower SPR-X22-360	Fuel Storage Design	Outputs
User Preferences		Storage capacity needed (gal)	1173
Solar fraction	0.1	Number of SIXCONs needed	2
Array to Load ratio	1.3	Number of other containers needed	#REF!
MPPT?	Yes		
Generator and Fuel Storage Design	User Inputs		
Maximum load power (kW)	78		
Generator Model and Rated Power	30kW AMMPS		
Fuel storage container type	SIXCON		
Other Fuel storage capacity (gallons)	0		
Required Days of Autonomy	14		

Figure 67. Tool Inputs and Outputs for Fairbanks, AK, Design

The progression in PV size at each location is linear from 0.1 to 1 SF. Figure 68 shows the size of each of the 10 systems. The generator of each microgrid is the same, but the battery bank size of each is different based on the required storage capacity at different temperatures. The effect of the battery size is not examined in this research because each battery bank has the same capabilities when adjusted with the temperature correction factor.

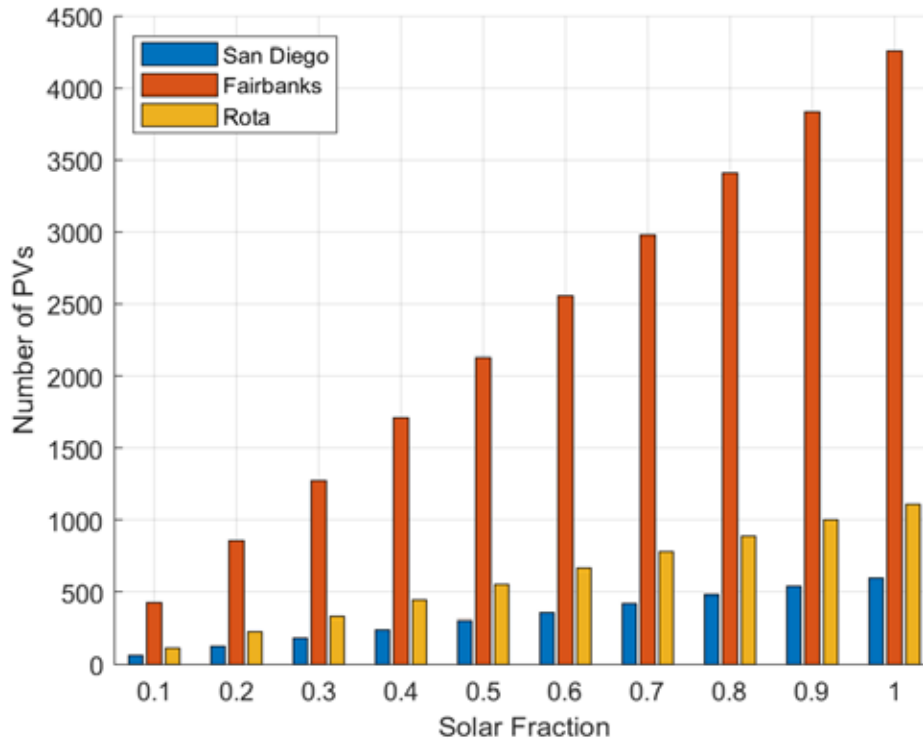


Figure 68. Size of PV systems as a Function of the SF, for the Three Locations.

C. CASE STUDY 1: ONE YEAR OF NORMAL OPERATING CONDITIONS

The first case study includes simulations to compare 30 different systems (10 systems each for 3 different environments) with regards to fuel consumption and minimum SOC over the course of one year. The PV systems were designed for the month of January with values of SF from 0.1 to 1. January was the second-to-worst month in terms of available sunlight in Fairbanks; the worst month, December, was not selected because the amount of sunlight was so minimal. The simulation covered one year in each of the three locations, with the following assumptions: there were no cloudy days, every month had 30 days, the load each day was the same. As a result of the assumption that there were no cloudy days during this scenario, the estimates of fuel usage are lower than is realistic; however, this assumption was true for all designs at each location. As discussed during the explanation of generator control, the generator turns on at some time after 18:00 hr every day to return battery charge to 100%.

1. Select Monthly Performances

Table 10 summarizes the figures of six of the 120 simulations obtained for the microgrid located in Fairbanks. The purpose of these figures is to compare 0.1, 0.5, and 1.0 SF designs within the month of January, and then to compare the performance of each design between two extreme months: January and June. The designs will be compared based on the amount of curtailed PV energy, the batteries minimum SOC, and the fuel consumption.

Table 10. Microgrid Simulation Results in Fairbanks, AK

	Month of Operation	Design SF in January	Load, PV Currents and Battery SOC	Currents to Load, from DG and PV+Battery
Figure 69	January	0.1	a)	b)
		0.5	c)	d)
		1.0	e)	f)
Figure 70	June	0.1	a)	b)
		0.5	c)	d)
		1.0	e)	f)

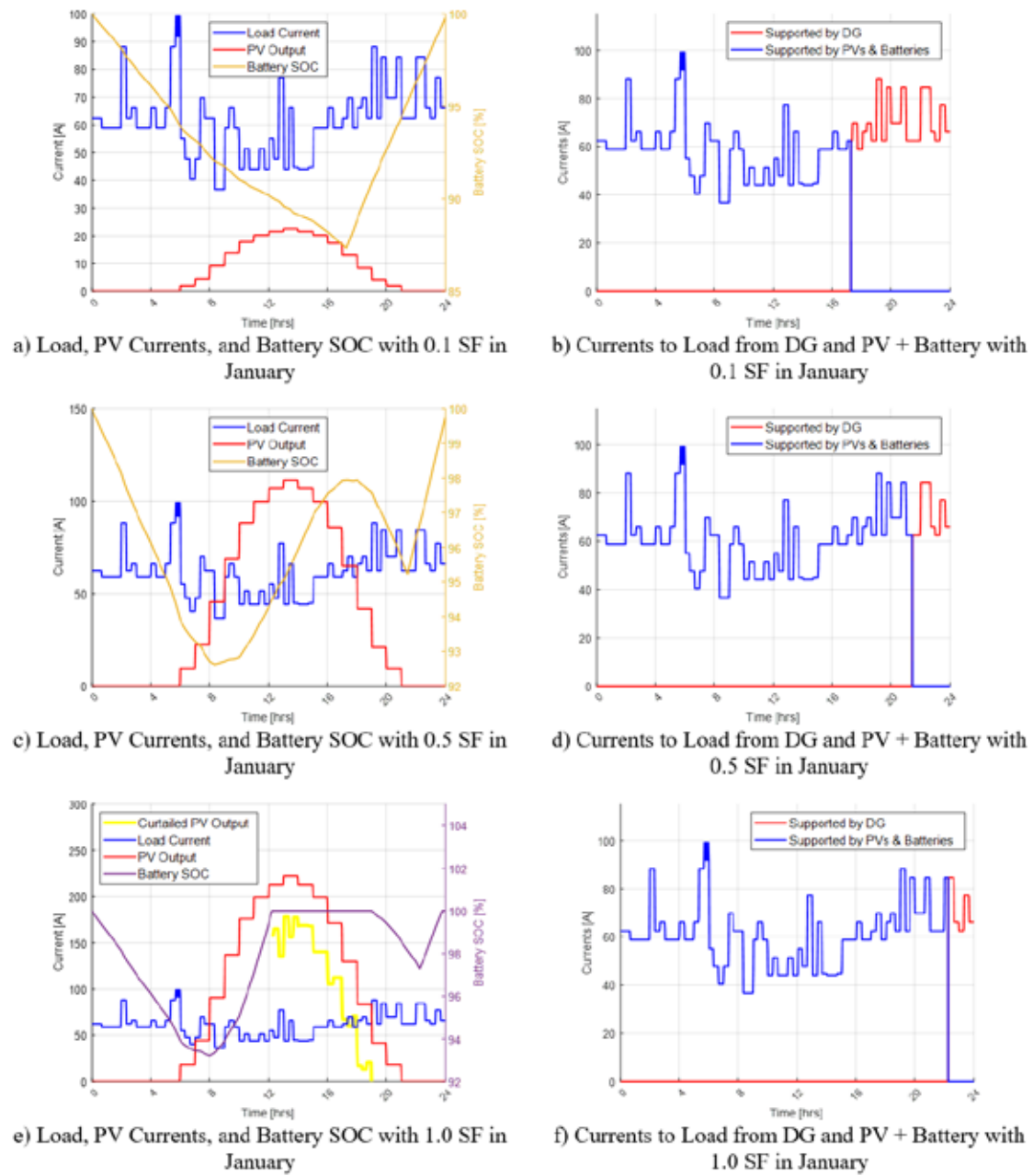
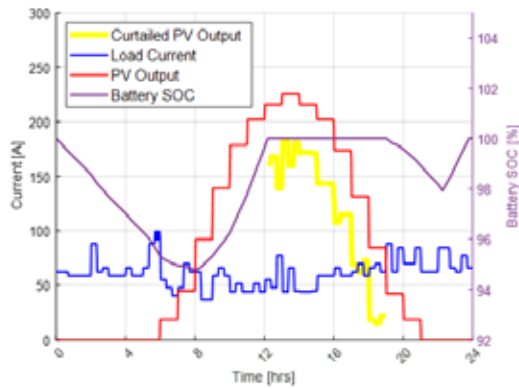
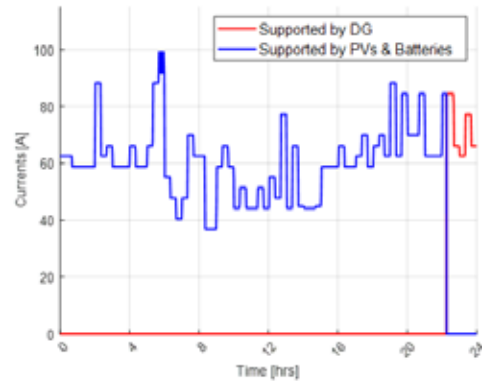


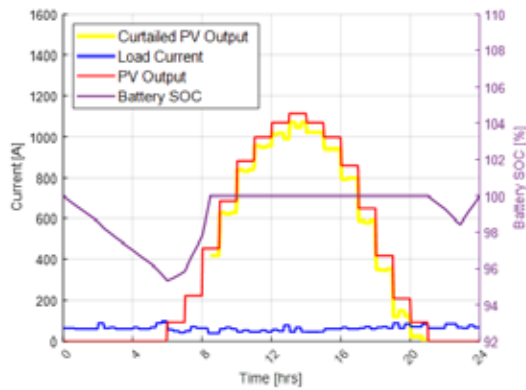
Figure 69. Selected Results from Case Study I of One-Day Simulation in January with Various SFs



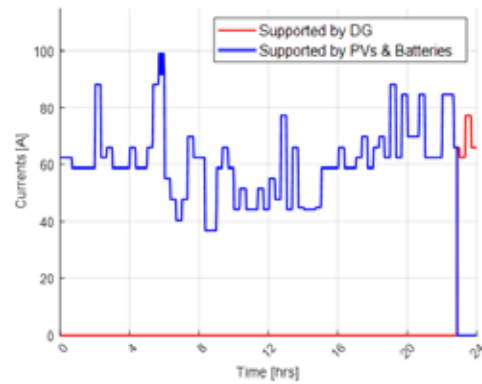
a) Load, PV Currents, and Battery SOC with 0.1 SF in June



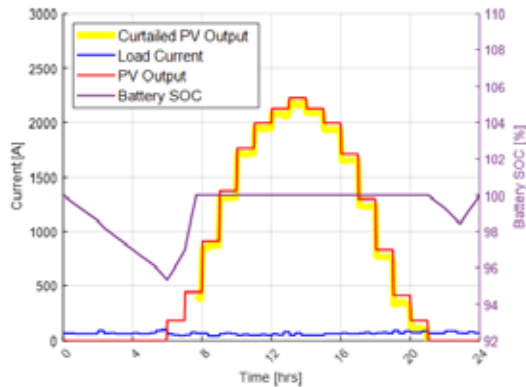
b) Currents to Load from DG and PV + Battery with 0.1 SF in June



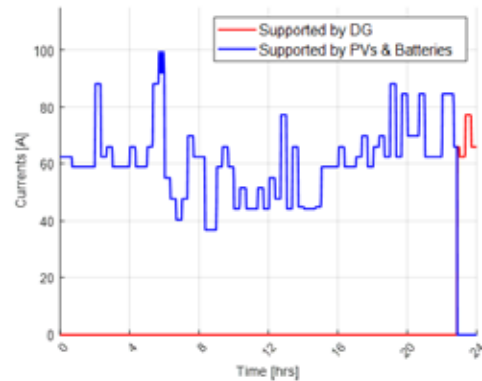
c) Load, PV Currents, and Battery SOC with 0.5 SF in June



d) Currents to Load from DG and PV + Battery with 0.5 SF in June



e) Load, PV Currents, and Battery SOC with 1.0 SF in June



f) Currents to Load from DG and PV + Battery with 1.0 SF in June

Figure 70. Selected Results from Case Study I of One-Day Simulation in June with Various SFs

Figure 69 a) and Figure 70 e) show extremes of under-designed and overdesigned systems in months of exceptionally low and exceptionally high solar irradiance. In January, with an SF of 0.1, the system relies heavily on the battery storage and the generator. Conversely, in June with an SF of 1.0, the battery SOC does not drop below 95%, the microgrid barely uses the generator for less than 1 hour in the evening and the PV must be curtailed in the center hours of the day.

The difference in performance of the three systems in January is much more pronounced than the difference between the three systems in June. Both the 0.5 and 1.0 SF systems' battery banks remain at 100% SOC from approximately 08:00 hrs to 20:00 hrs during the month of June. The 0.1 SF systems battery bank remain at 100% from approximately 12:00 hrs to 19:00 hrs during the month of June. Whereas, in January, the 0.1 and 0.5 SF system battery bank does not return to 100% SOC until 23:59 h, and the 1.0 SF design maintains a 100% SOC from approximately 12:00 hrs to 19:00 hrs. On the other hand, the January designs have little or no curtailment of the PV energy created, seen in Table 11, while the January designs create an enormous amount, seen in Table 12.

Table 11. Results of PV Curtailment in January with January Designs

SF	Charge Curtailed [Ah]	Energy Curtailed [kWh]
0.1	0	0
0.5	0	0
1.0	789	379

Table 12. Results of PV Curtailment in June with January Designs

SF	Charge Curtailed [Ah]	Energy Curtailed [kWh]
0.1	816	392
0.5	8,552	4105
1.0	18,325	8796

2. Fuel Usage

The annual and monthly fuel usage of each system can help judge its design. Figure 71 documents the annual fuel usage across the 10 SF designs between the three systems. Over the course of one year, the fuel usage in gallons remains relatively constant as the SF decreases, until approximately 0.5 SF, when it spikes up. In fact, the increase in fuel usage of the 0.6 SF system from the 0.9 SF system in Fairbanks is just 96 gallons or 7.3% of the 0.9 SF system fuel usage; while the difference in size between the 0.6 SF and the 0.9 SF systems is 855 PVs, or a 25% decrease. The increase of fuel usage of the 0.4 SF system from the 0.6 SF system is 298 gallons or 21.2% of the 0.6 system fuel usage; while the difference in size between the 0.4 SF and 0.6 SF system is 846 PVs, or a 33% decrease. This suggests that the percentage of fuel saved by increasing the number of PVs decreases as the size gets closer to that of the 1.0 SF system.

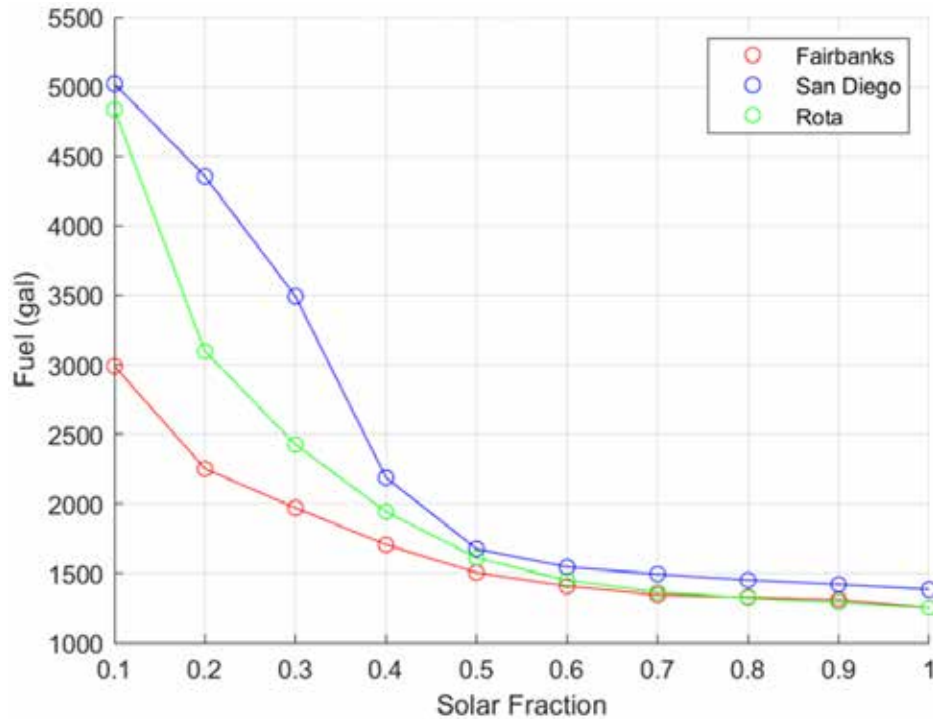


Figure 71. Annual Fuel Usage with January Design System

The monthly fuel consumption of four of the systems in each location is depicted in Figure 72, Figure 73, and Figure 74. Again, the systems at each location are different, but they are designed to support the same load. It is irrelevant to compare the fuel usage between the three locations, but significant to compare the differences between the monthly fuel usages depending on the SF in each location.

The fuel usage of the San Diego and the Rota systems are constant when the 1 and the 0.7 SF designs are implemented. The fuel usage of the Fairbanks systems, as well, are constant with the 1 and 0.7 designs, except for the month of December when the usage increases to account for the nonexistent sunlight. In Fairbanks, the fuel usage is below 150 gallons per month from March until September for all the designs, but outside of those months, the fuel usage spikes. Alternatively, the fuel usage in San Diego is constant at approximately 120 gallons per month for the 1 and 0.7 designs, but then rises, during the year to between 250 and 350 gallons of fuel for 0.3 and between 430 and 480 gallons of fuel for 0.1. This suggests that in environments where there is a significant difference between winter and summer solar irradiance, the fuel usage does not increase significantly

during the spring, summer, and fall months as the size of the system decreases; but during the winter months, the fuel usage spikes as the size of the system decreases.

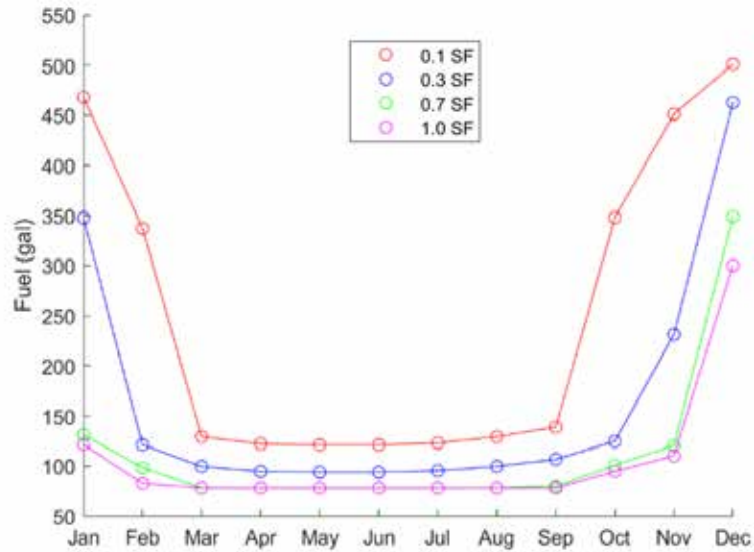


Figure 72. Monthly Fuel Usage by Fairbanks System

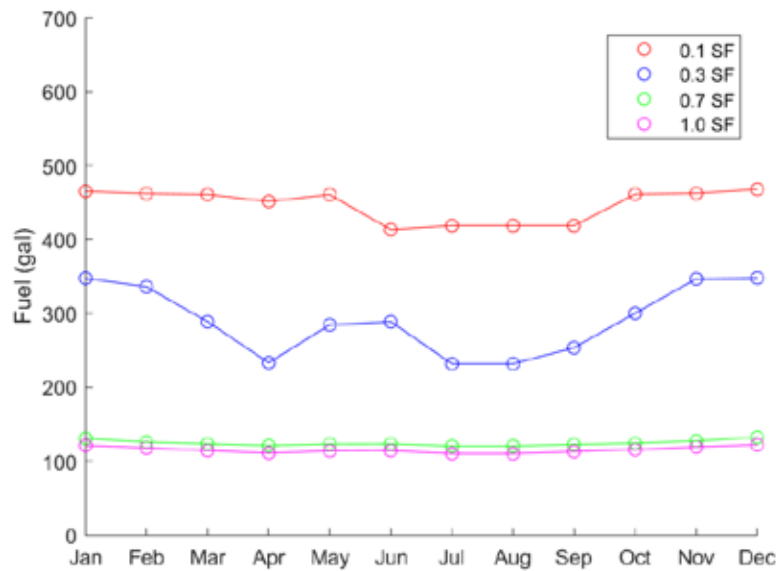


Figure 73. Monthly Fuel Usage by San Diego System

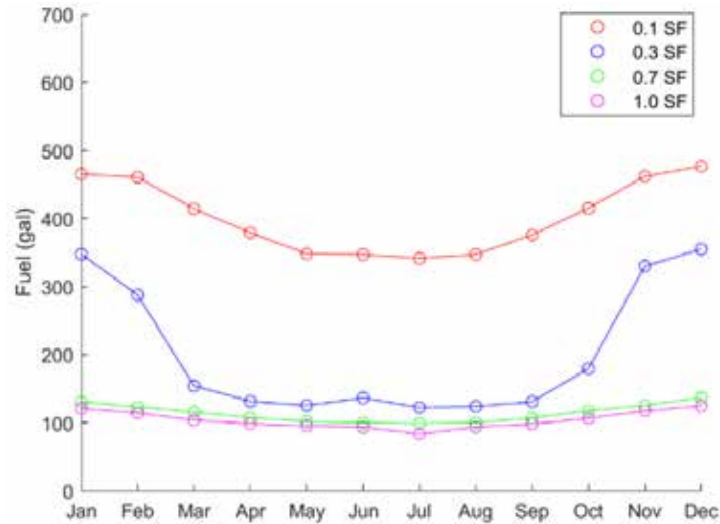


Figure 74. Monthly Fuel Usage by Rota System

3. Minimum SOC

The minimum SOC of the batteries indicates the available storage, and thus the availability of the batteries to support the load. While the microgrid designed for Fairbanks, Alaska has more batteries to compensate for the cold temperatures, the actual capacity of each of these systems was the same. Actual capacity is the capacity of the entire battery bank when the MDOD and temperature derating factor are accounted for. Table 13 shows the size and usable storage of the three microgrids.

Table 13. Size and Actual Capacity of Battery Bank in Microgrid at Three Locations

Location	Number of Batteries	Actual Capacity [Ah]
Fairbanks, AK	430	66,220
San Diego, CA	340	68,000
Rota, Spain	340	68,000

In Fairbanks, the SOC remains relatively high across all systems from February to October; at the tail ends of the year when utilizing a lower SF of 0.1 or 0.3, the SOC dips. The battery bank is substantially depleted for three months with the 0.1 SF design, requiring heavy use of the generator, or a larger battery bank. The SOC of the 1.0, 0.7, and 0.3 SF Fairbanks systems is identical in the months of April through July, suggesting that there is no benefit in a microgrid designed with 1.0 SF during those months.

In both Rota and San Diego, the difference in SOC between the 1.0 SF system and the 0.7 SF system is less than 0.5%, indicating that the 1.0 SF system does not provide a significantly higher storage availability than the 0.7 SF system, even with its considerably larger PV array.

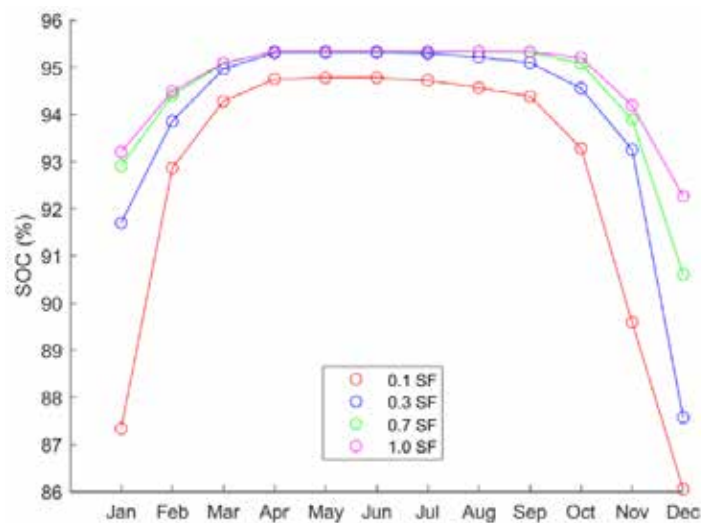


Figure 75. Minimum SOC of Fairbanks Battery

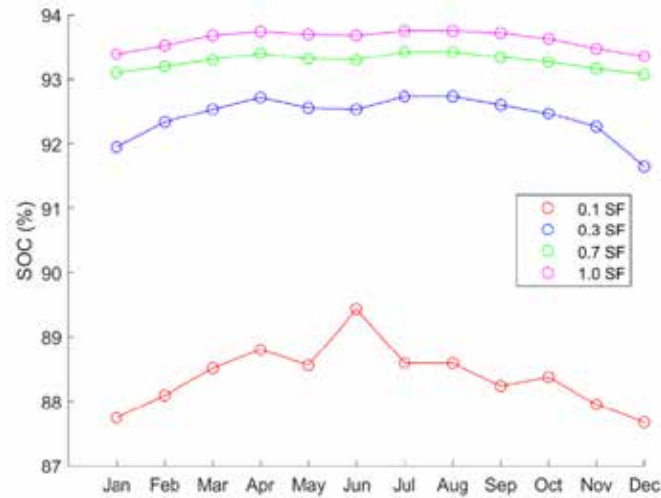


Figure 76. Minimum SOC of San Diego Battery

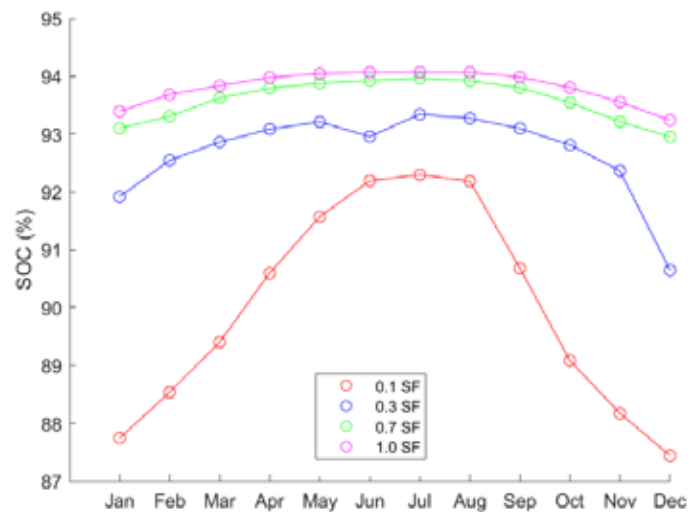


Figure 77. Minimum SOC of Rota Battery

D. CASE STUDY II: RECOVERY FROM DEPLETED BATTERIES WITH INOPERABLE GENERATOR

In the second scenario, the generator of each of the systems is assumed inoperable, and the batteries begin the simulation partially depleted, with SOC of 30%. Therefore, each system designed in part A must operate on PV power and battery alone. The purpose of these simulations is to evaluate each microgrid design to determine if it could operate without DG throughout the year, or if it would require generator supplementation.

1. Select Monthly Performance

Table 14 summarizes the figures of eight of the 120 simulations in Fairbanks. The purpose of these figures is to compare the recovery rates of one system in four different months, and then to compare the recovery rates in one month of two systems.

Table 14. Microgrid Simulation Results of Battery Recovery in Fairbanks, AK

Figure		SF of January	Month of Operation
Figure 78	a)	0.1	January
	b)		March
	c)		July
	d)		September
Figure 79	a)	0.5	January
	b)		March
	c)		July
	d)		September

Figure 78 and Figure 79 show results from these specific 8 scenarios. Figure 78 a) and Figure 79 c) show extremes of under-designed and overdesigned systems in months of exceptionally low and exceptionally high solar irradiance. In January, with an SF of 0.1, the system has a negative charge rate, and the battery bank is further depleted to almost 10% SOC of the course of the day. Conversely, in July with an SF of 0.5, the battery bank returns to 100% SOC and ends the day at 97% SOC.

The 0.1 SF system can only charge to above 30% SOC in the month of July, demonstrating this system could not standalone from the generator for over half the year. On the other hand, the 0.5 SF system can charge to well above 30% SOC in three of the four months, reaching 97%, 98%, and 75% in March, July, and September, respectively. The 0.5 SF system obviously charges the batteries to a higher SOC than the 0.1 SF system, and the 1.0 SF system obviously charges the batteries to a higher SOC than the 0.5 SF system.

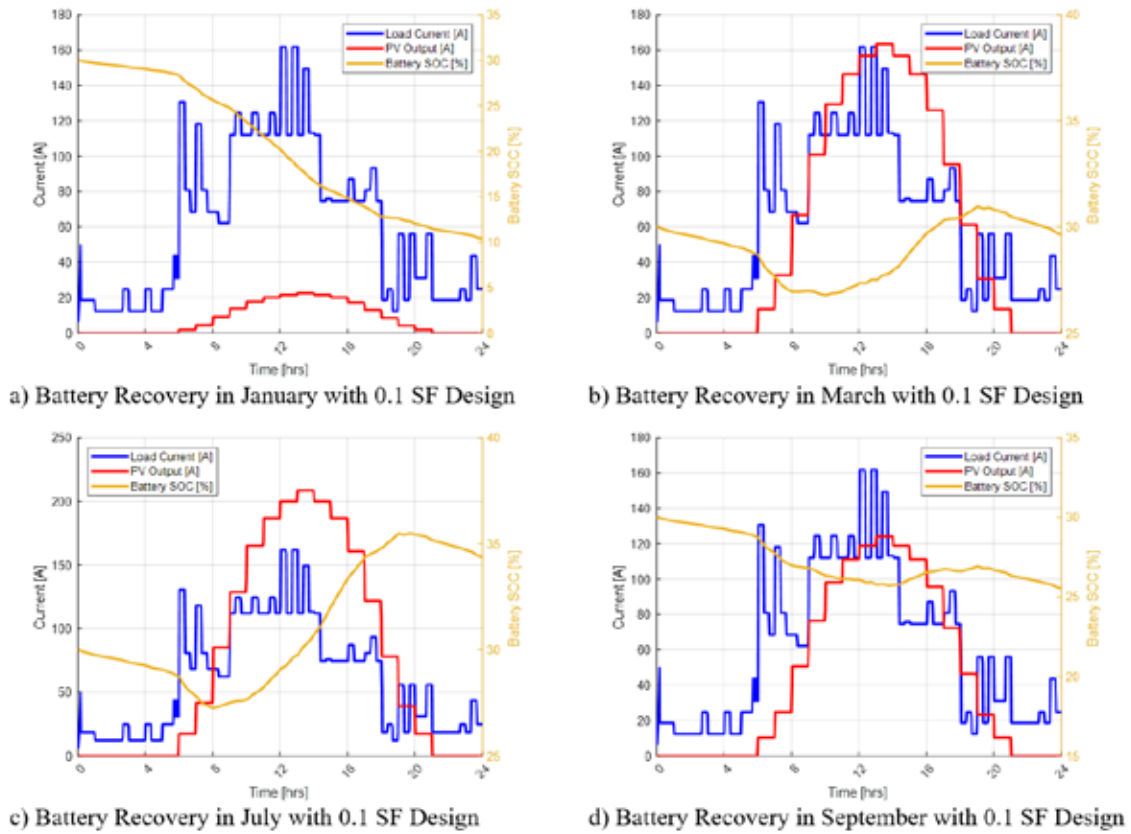


Figure 78. Selected Results from Case Study II of Battery Recovery with 0.1 SF Design in Various Months

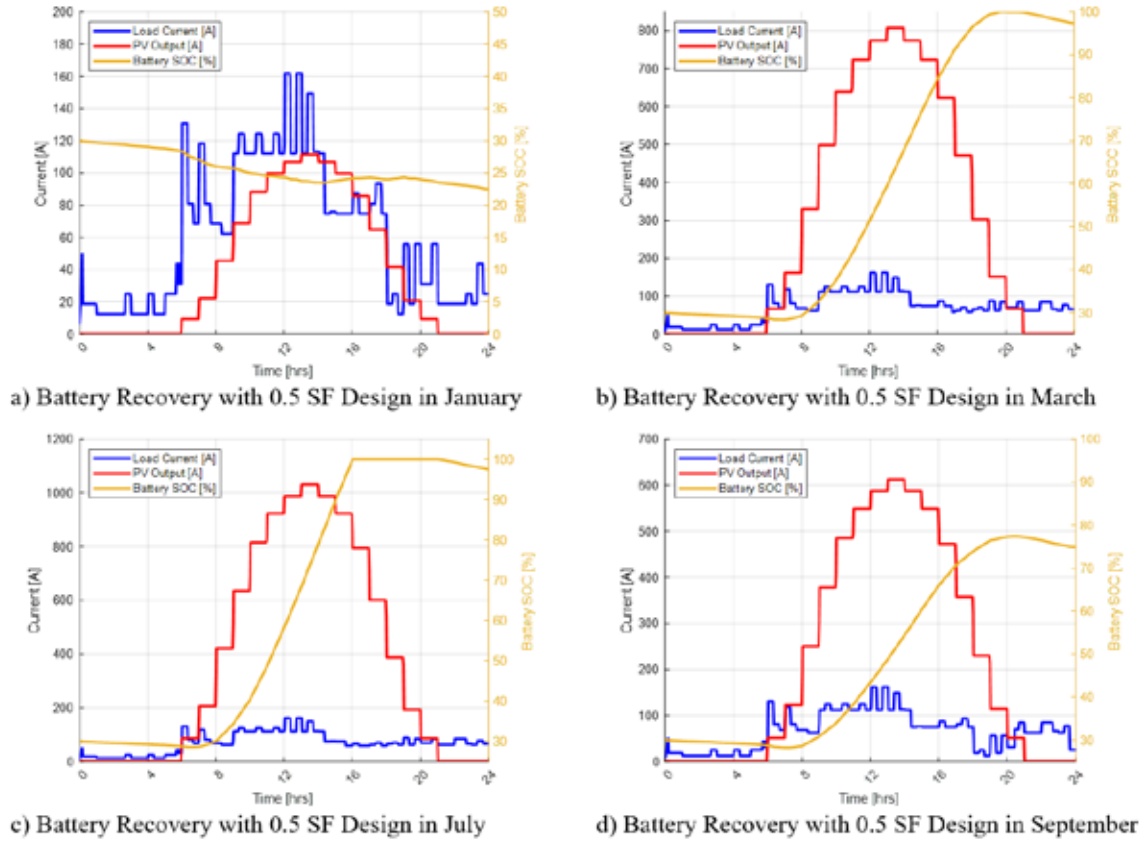


Figure 79. Selected Results from Case Study II of Battery Recovery with 0.5 SF Design in Various Months

2. Charge Rate

The final characteristic of the systems that this research looks at is their rate of recovery. The rate of recovery is defined as the rate which the battery charges while supporting the load, without a generator on a sunny day. While battery charge rate is usually expressed as the time it would take to fully charge the battery (for example a charge rate of C20 means the battery would charge in 20 hours), the charge rates of these simulations are slow in comparison, so it is easier to express the charge rate as the percent of charge increase in 24 hours.

While a smaller SF means a lower initial cost, the average rate of recovery is negative below a certain SF. With a small enough SF, the system cannot stand alone from the generator throughout the entire year. The average annual charge rate is depicted in

Figure 80 and the monthly performance at each of the locations is examined in Figure 81, Figure 82, and Figure 83. In San Diego, most monthly charge rates are negative for the systems of 0.1 through 0.5 SFs. The use of one of these systems would require heavy use of the generator. In Alaska, because there is such a dramatic difference in solar irradiance between the design month and the summer months, the majority of monthly charge rates for the systems of 0.3 to 1.0 are positive.

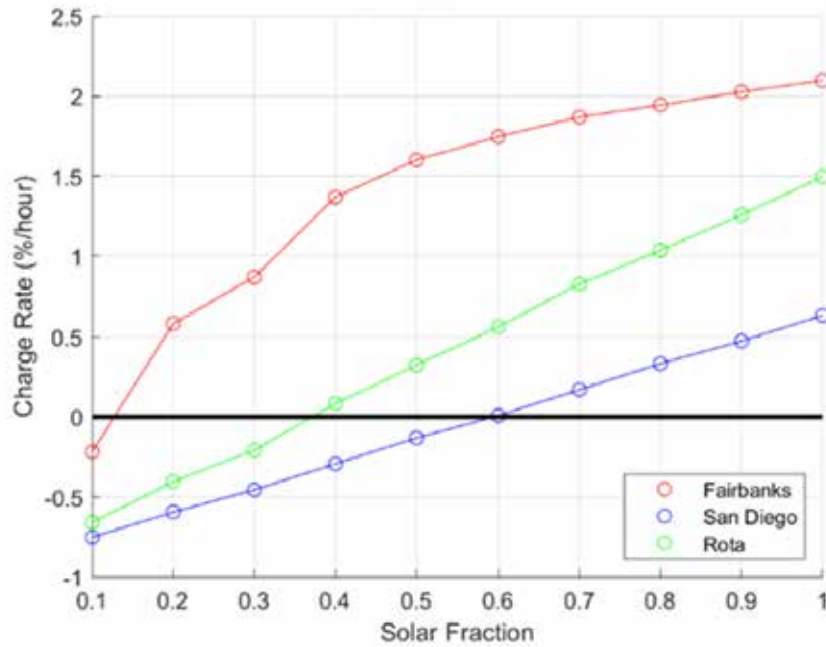


Figure 80. Average Annual Battery Charge Rate Without a Generator with 10 SFs of Various Locations

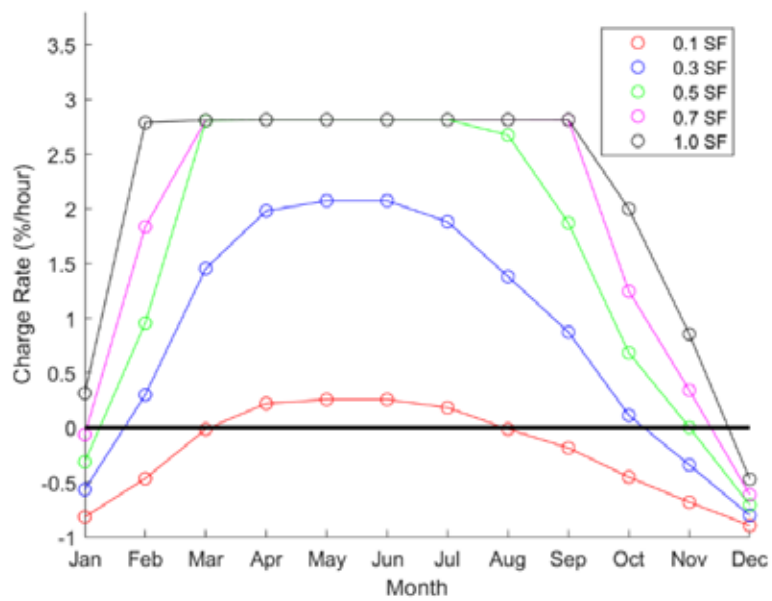


Figure 81. Battery Charge Rate by Month in Fairbanks with Designs of Various SF

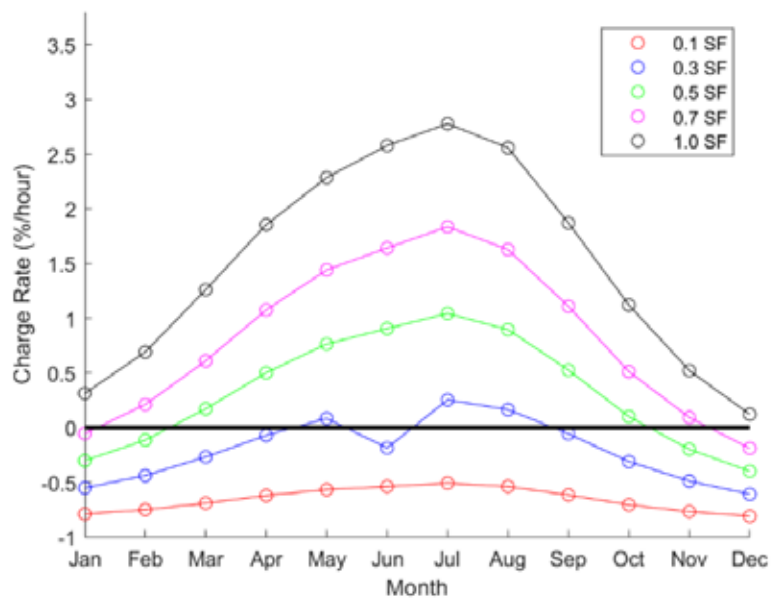


Figure 82. Battery Charge Rate by Month in San Diego with Designs of Various SF

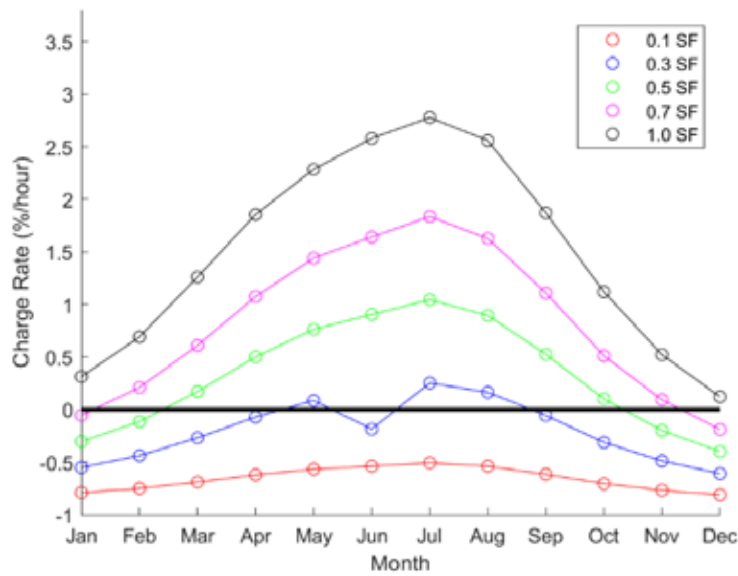


Figure 83. Battery Charge Rate by Month in Rota with Designs of Various SF

The following conclusions are drawn from Case Study II. The less variation there is in solar irradiance throughout the year for an environment, the higher the SF of the hybrid PV microgrid must be to operate on solar power and battery storage alone for the majority of the year. Conversely, the greater variation there is in solar irradiance throughout the year for an environment, the more reasonable it is to use a lower SF, while still supporting the load with primarily solar power and conserving initial cost.

VI. CONCLUSION

This thesis develops a design tool to investigate the constraints of sizing hybrid microgrids based on the environment, to include annual variations of both temperature and solar irradiance. Ultimately, the tool user must make key design decisions including how much the system should rely on solar and to what degree the generator is for redundancy or flexibility. With redundancy at one end of the spectrum and flexibility at the other end in terms of the size requirement for PV arrays, the correct answer depends upon the location of the system and the user-perceived need of energy security. The following observations were made during this research that can support the decision of system SF.

If the generator is entirely for redundancy, then the system must have a positive charge rate throughout the year; this would mean sizing the system for the month with the lowest solar irradiance at 1.0 SF. In a location like Fairbanks, Alaska, this is all but unfeasible due to the sheer size of the system and negligible insolation in the winter months.

If the generator is for flexibility and economy, then the user should compare the fuel conserved as the SF increases. In Fairbanks, where there is a dramatic difference between solar irradiance in the design month and the summer months, a 1.0 SF is not required to operate independently of the generator for over half the year. In fact, a 1.0 SF system in Fairbanks is not significantly less dependent on the generator than a system with a lower SF of 0.6 or 0.7.

Future work by systems engineers to quantify the merits of redundancy, flexibility, and economy would provide the tool user with a more obvious answer for how to design the system to ensure energy security and resilience. Other future work could include a more refined generator simulation and a battery life-cycle expectancy calculation. An idea for future work is to construct a way to estimate the average battery lifetime based on the system and have that factor into the design of the system from the start.

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