Don’t Shed On Me: Optimal Microgrid Control Using Load Prioritization

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Abstract

Electricity is essential to daily life in the developed world, powering critical systems and services such as hospitals, water supply and wastewater treatment, and other functions. Power outages--such as those driven by increasingly large wildfires and Public Safety Power Shutoffs in California or the recent extreme weather-induced rolling blackouts in Texas--compromise functionality of these critical services. Microgrids that include storage and distributed generation resources can help alleviate some of these stresses, with the ability to isolate or ‘island’ from the main power grid and distribute power locally. However, microgrids have limited storage and generation available; therefore, the ability to prioritize loads and optimize discharge can help to maximize the benefit that these resources provide and minimize harm. This study creates an optimal storage dispatch schedule based on the priority of serving different loads, as well as storage and distributed generation resources available. Results showed that as expected, mean fraction of load served declines with outage duration, and increases with diesel generator fuel available. Additionally, the model tends to serve a large fraction of load for nodes with relatively low demand despite lower relative ranking, while providing less service to nodes with extremely high demand despite a higher relative ranking.

Introduction

Motivation & Background

The last few years have seen some of the most dangerous and destructive wildfires in California’s history. The 2018 Camp Fire created immense financial liability for Pacific Gas & Electric (PG&E), ultimately resulting in their bankruptcy. The 2020 California wildfire season has been billed as the most destructive in history, burning almost 5% of all California acreage.[1] The California Public Utilities Commission (CPUC) has given the investor-owned utilities (IOUs) the ability to conduct Public Safety Power Shutoffs (PSPSs) which allows for the de-energization of the electric grid in places deemed to be at risk of causing additional wildfires.[2] The CPUC does recognize, however, that “a PSPS can leave communities and essential facilities without power, which brings its own risks and hardships, particularly for vulnerable communities and individuals”. These risks are especially pronounced for Californians who require access to electricity to power lifesaving medical equipment.[3]

In the wake of these PSPS events, microgrids have emerged as one possible solution to managing the stress and impacts of prolonged power outages. The United States Department of Energy (DOE) defines microgrids as “a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode”.[4] A variety of challenges exist around the modeling and implementation of microgrids, but their potential benefits over the traditional power grid could outweigh the costs of doing so. In addition to their ability to isolate from broader electrical shutoffs, microgrids' incorporation of various distributed generation units can potentially alleviate concerns regarding the consistent supply of electricity and long-term energy security associated with the existing grid.[5]

Focus of this Study

This study aims to create a model for managing energy generation and storage resources and shedding loads in an optimized manner during an islanding event of a known time horizon. This is accomplished by using load and microgeneration forecasting combined with load prioritization of customer tiers to dispatch distributed resources optimally.

Relevant Literature

A variety of microgrid simulations and studies can be found in literature, examining topics ranging from grid reliability to smart loads.[6,7] Load prioritization schemes are present in many of these sources, since loads must be shed in a controlled and predictable manner as the power supply decreases. Often these are ordered as "tiers" which vary in customer importance. In [8], the first tier embodies all loads that are critical and not to be shed for any reason, including hospitals and 911 dispatch centers.[8] Discretionary loads that can be shed for short periods of time, such as HVAC equipment, are included in the second tier. Finally, the third tier contains loads that are only to be shed to sustain grid stability and prevent a blackout. It includes residential customers and commercial facilities with back-up generation. The literature appears to lack real world examples of how and when to prioritize loads within a microgrid. This study can fill this gap by connecting load prioritization to the real-world impacts of the PSPS events in California. Despite the literature containing some basic examples of load priority tiers, such prioritizations have lacked applicability. This work provides this by linking customer priority to discrete customer types and load profiles found in California.

In addition to managing how power is distributed to the loads connected across the microgrid, internal power generation from distributed generators must be accounted for to ensure adequate power distribution across the microgrid. As noted in [9], the interconnection of these distributed generators in a low-voltage system as proposed in this study may affect overall power system performance.[9] These microsources may be biomass, fuel cells, wind, or others, however, for the purpose of this study only solar and diesel generation will be analyzed. A description of how these generators will be modeled, controlled, and distributed is detailed in the *Mathematical Modeling & Implementation in Python* section below.

Technical Description

Load/Customer Categories & Ranking

When deciding which loads to shed, we have come up with a prioritization of different types of loads. These loads are classified and described in the table below. The guiding principle for assigning the priorities was ensuring that the most critical loads were directly connected to human life and broader social welfare. This led us to prioritizing medical baseline customers that need electricity to power life-maintaining devices, followed by critical infrastructure like fire stations, low-income residential customers, non-low-income residential customers, and then all other loads:

Table 1. Load Prioritization Categories and Ranks

Customer Category	**Rank**	**Load Source**	**Description & Justification**
Residential (Medical Baseline)	5	CARE Load Profile from CPUC + hourly medical baseline allowance (500 kWh/month or 0.694 kWh per hour)	Residential customers that are on medical baseline tariffs are among the most vulnerable groups with respect to intermittent electricity access. Because customers in this class rely on medical equipment for basic living functions, we prioritize their load needs first.[10]
Non-residential critical facility (e.g., hospital, fire station)	4	PG&E A10[11]	Some non-residential customers provide enormous social benefits to local groups. These include obvious facilities like hospitals and fire stations but could also include less obvious facilities like cell phone towers.[12] Thus, we prioritize this group second.[10]
Residential (CARE/FERA)	3	CARE Load Profile from CPUC	Residential customers that are not on medical baseline tariffs might be on California Alternate Rates for Energy (CARE) or Family Electric Rate Assistance Program (FERA) tariffs.[13] These are meant to assist low-income Californians and these customers might also be at greater risk of wildfire-related hardships (e.g., increased costs from replacing spoiled food are more burdensome on lower income households[14]). Thus, we prioritize this group third.
Residential (non-CARE/non-FERA)	2	PG&E E1[11]	Residential customers that are not on medical baseline or CARE/FERA tariffs are prioritized next. There might be low-income customers that are not enrolled in CARE/FERA. Regardless, during the COVID-19 pandemic a lot of office work has transitioned into working from home. By prioritizing the rest of residential customers 4th, we still allow for meaningful load shedding reduction for average working people. This could be useful for ensuring that heating/cooling remains constant depending on the time of the year, that customers are able to work from home, or that food remains unspoiled in residential refrigerators.
All other customers (e.g., commercial/industrial, agricultural)	1	ENERNOC Open Source Load information (Profile #14)[15]	Our final load priority group is a catch-all group for customers that don't fit into one of the four prior groups. This means all commercial and industrial loads, agricultural customers, streetlights, and even institutional or research loads (i.e., the University of California).

Microgrid Characteristics

The microgrid model created for the purposes of this study was inspired by a hypothetical grid of similar magnitude found in [16] that minimized the set of loads shed while maintaining grid stability.[16] The microgrid model presented below is connected to a medium voltage substation representing the external grid. In the event of this external grid's failure, it can be disconnected from the microgrid using a breaker at the point of common coupling. Local power generation consists of a single diesel generator and two photovoltaic (PV) generators, both of which are attached to a battery capable of storing excess power when power production exceeds demand. A variety of loads that may be encountered in a typical microgrid are included in this model, including residential households corresponding to ranks two, three, and five in Table 1 above, as well as a non-residential critical facility. Each element of the grid is detailed in Table 1 below, and a schematic can be seen in Figure 1.

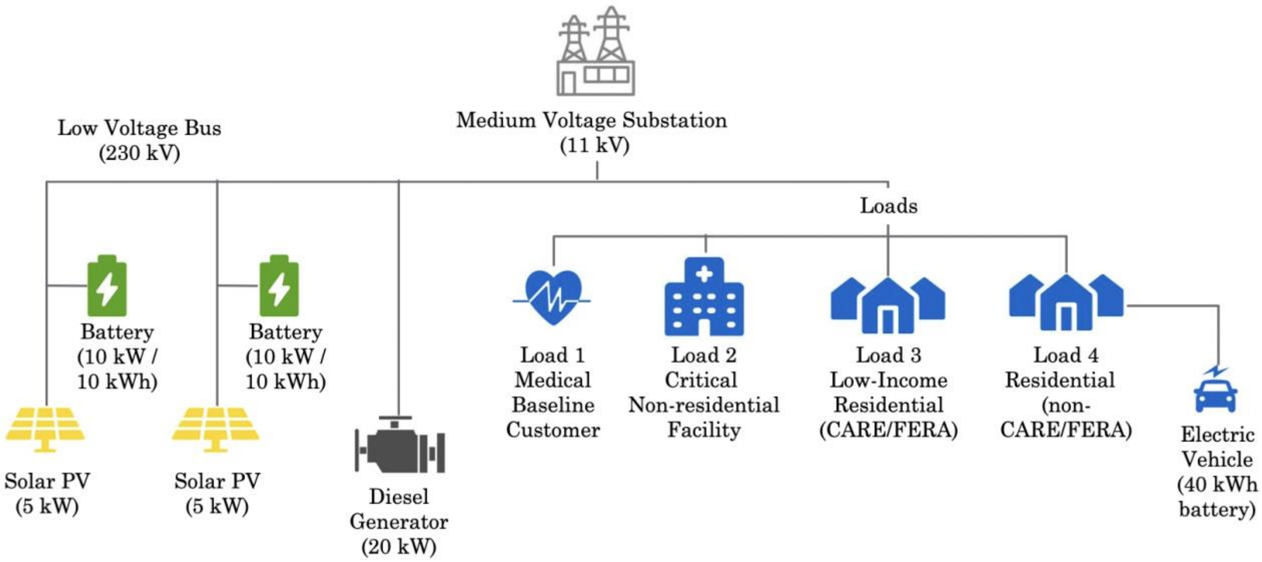

Figure 1. Microgrid diagram, adapted from D'Agostino et. al (2017).[16]

Each node is described in Table 2, including the elements that will be modeled in our optimization.

Table 2. Microgrid Node Descriptions

Characteristic	Description	Modeling	Nodes	Priority Rank
Batteries	2 batteries, 10 kWh each	-Battery state of charge -Battery capacity -Energy dispatched or stored at each time step	1,2	--
Solar generation	The PV capacity will be 5 kW capacity (actual generation varies by month and efficiency), and the generation is available to the whole grid.	-Apparent, active, and reactive power dispatched at each time step	1,2	--
Diesel generator	20 kW generator at central location serving the whole system	-Apparent, active, and reactive power dispatched at each time step -Fuel consumed at each time step -Maximum power allowed based on remaining fuel	3	--
Controllable Load 1- Residential Medical Baseline Customer	Load profiles as described in Tables 1 and 2.	Optimal fraction of load served at each time step	4	5

Characteristic	Description	Modeling	Nodes	Priority Rank
Controllable Load 2-critical non-residential facility	Load profiles as described in Tables 1 and 2.	Optimal fraction of load served at each time step	5	4
Controllable Load 3-Low Income Resident (CARE/FERA)	Load profiles as described in Tables 1 and 2.	Optimal fraction of load served at each time step	6	3
Controllable Load 4-Residential (non CARE/FARE)	Load profiles as described in Tables 1 and 2.	Optimal fraction of load served at each time step	7	2
Electric Vehicle Battery	Node 7 has a 100 kWh electric vehicle battery with vehicle to grid capabilities.	-Apparent, active, and reactive power dispatched -Battery state of charge -Battery capacity	7	2

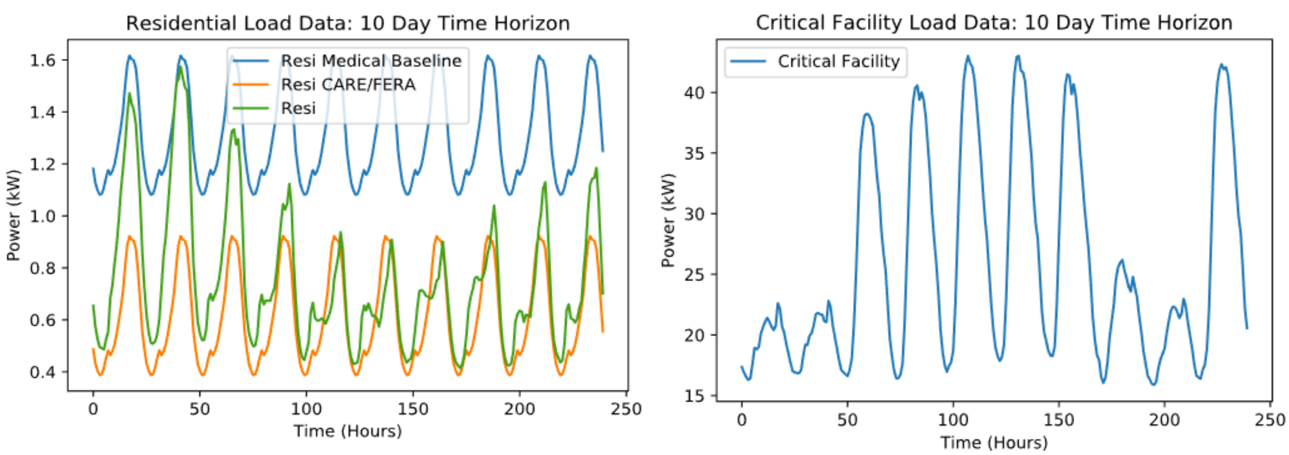

Figure 2. Load profile data for Residential Medical Baseline, CARE/FERA, residential non-CARE/FERA, and critical facility. (Sources: See Table 1)

Mathematical Modeling & Implementation in Python

We model the microgrid as a network with each node representing a single microgrid customer. All nodes (1-7) are connected directly to a central node (0), and no nodes are directly connected to another, as shown in Figure 1. Two nodes have a solar PV module and battery storage (nodes 1 and 2), one has a diesel generator (node 3), three exclusively draw power (nodes 4, 5, and 6), and one draws power and has an EV that can be used as a battery (node 7). We do not disaggregate storage, load, and generation of a single user to multiple nodes, paying attention to only power at the meter. Power flow on lines between nodes is governed by the DistFlow equations outlined in Baran & Wu.[17]

We simulate the microgrid only during its islanded state, over periods of time corresponding to PSPS events. We start with a period of 55 hours, corresponding to the average PG&E PSPS length in 2019.[18] To better understand the system's time flexibility, other outage lengths and diesel fuel availability are also tested (see Table 3). The simulation operates in one hour intervals, assuming constant power consumed or output by any battery, load, or generator over that hour.

In order to produce the apparent power solar generation parameter, average hourly generation profiles from the Global Solar Atlas for Berkeley were applied.[19] We considered the solar profiles for June (the month with the greatest solar output), December (the month with the lowest output), and September, a month that occurs in the middle of California's wildfire season. Figure 3 below depicts the hourly solar generation profile in Berkeley for each month. Because PSPS events are unlikely in December, and June's profile was nearly identical to September, we chose to only use September's profile in the model.

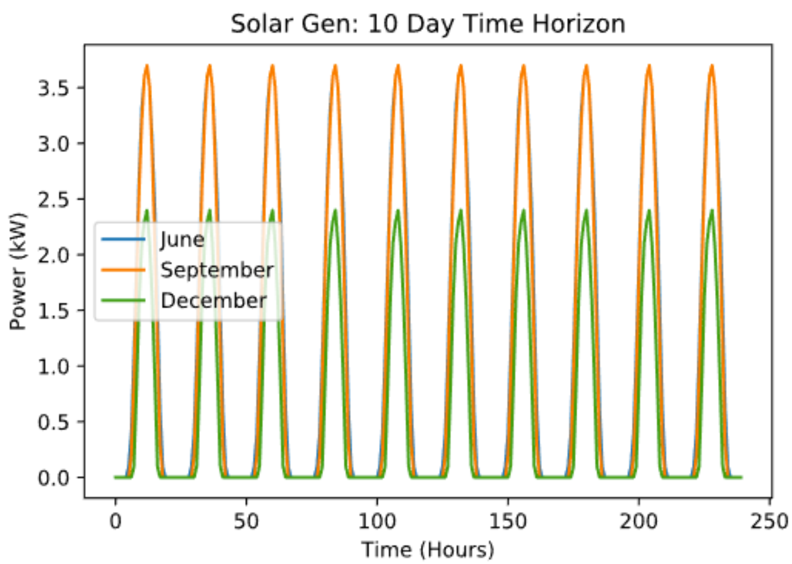

Figure 3. Hourly power output for 5 kW PV system installed in Berkeley, CA in June, September, and December[20]

The table below summarizes the various parameters that will be varied to produce different scenarios.

Table 3. Scenario Matrix

Scenario Number	**Outage Duration**	**Fuel Availability**	**Time of Year**
1	55 hours	6.4 gallons (4-hour supply for 20 kW at full output)	September
2	55 hours	25.6 gallons (16-hour supply for 20 kW at full output)	September
3	55 hours	Unlimited	September
4	5 days	6.4 gallons (4-hour supply for 20 kW at full output)	September
5	5 days	25.6 gallons (16-hour supply for 20 kW at full output)	September
6	5 days	Unlimited	September
7	10 days	6.4 gallons (4-hour supply for 20 kW at full output)	September
8	10 days	25.6 gallons (16-hour supply for 20 kW at full output)	September

Scenario Number	**Outage Duration**	**Fuel Availability**	**Time of Year**
9	10 days	Unlimited	September

Any charging or discharging of the batteries occurs when the model deems it optimal. Power throughput and energy storage limits which keep battery tied to realistic operation are defined by constraints. Appendix A describes the objective function, optimization variables, parameters, and constraints.

Modeling Results

Table 4, Figure 4, and Figure 5 present results from the modeling. As shown in Table 4, mean fraction of load served declines with outage duration, and increases with diesel generator fuel available. The model tends to serve a large fraction of load for nodes with relatively low demand (nodes 1, 4, and 5) even in nodes with lower relative ranking (nodes 6 and 7), while providing less service to nodes with extremely high demand despite a higher relative ranking (node 5). This is likely because the rankings of the nodes are relatively similar in magnitude (ranging from 2 to 5) while the demand of the nodes differ more substantially (demand for Nodes 4, 6, and 7 range from about 0.4 to 1.6 kW, while demand for Node 5 is one to two order of magnitudes higher, ranging from about 15 kW to 45 kW). As a result, in order to maximize the objective function (i.e., the sum of the product of node rank and fraction of load served) the model tends to fully or nearly fully serve Nodes 4, 6, and 7, while providing less service to Node 5, despite the fact that this node was assigned the second-highest rank. This pattern is also illustrated in Figure 4, which shows that the fraction of load served for Nodes 4 (blue), 6 (pink), and 7 (purple) typically remains greater than the fraction of load served for Node 5 (orange).

For scenarios where diesel fuel is constrained, power supplied closely tracks solar generation during the day, while the diesel generator and battery typically provide the bulk of their power when solar is unavailable. In the scenarios where diesel fuel is unlimited, the diesel generator and battery continue to provide more power when solar generation is unavailable, though the fraction of load met is much higher relative to the other scenarios. Notably, even in the unlimited diesel fuel scenarios, the load at Node 5 is not fully met, as power supply continues to be limited by the diesel generator's power output rating (20 kW).

Table 4. Mean fraction of load served across time steps and mean across nodes for each scenario

		Scenario								
	Outage Duration	**55 hrs**			**120 hrs (5 days)**			**240 (10 days)**		
	Diesel Fuel Available	**80 kWh**	**320 kWh**	**Unlimited**	**80 kWh**	**320 kWh**	**Unlimited**	**80 kWh**	**320 kWh**	**Unlimited**
Node	**Node 4**	1.00	1.00	1.00	1.00	1.00	1.00	0.76	1.00	1.00
	Node 5	0.11	0.37	0.95	0.04	0.14	0.80	0.04	0.05	0.77
	Node 6	1.00	1.00	1.00	1.00	1.00	1.00	0.85	1.00	1.00
	Node 7	1.00	1.00	1.00	0.69	1.00	1.00	0.55	1.00	1.00
	Mean	**0.78**	**0.84**	**0.99**	**0.68**	**0.79**	**0.95**	**0.55**	**0.76**	**0.94**

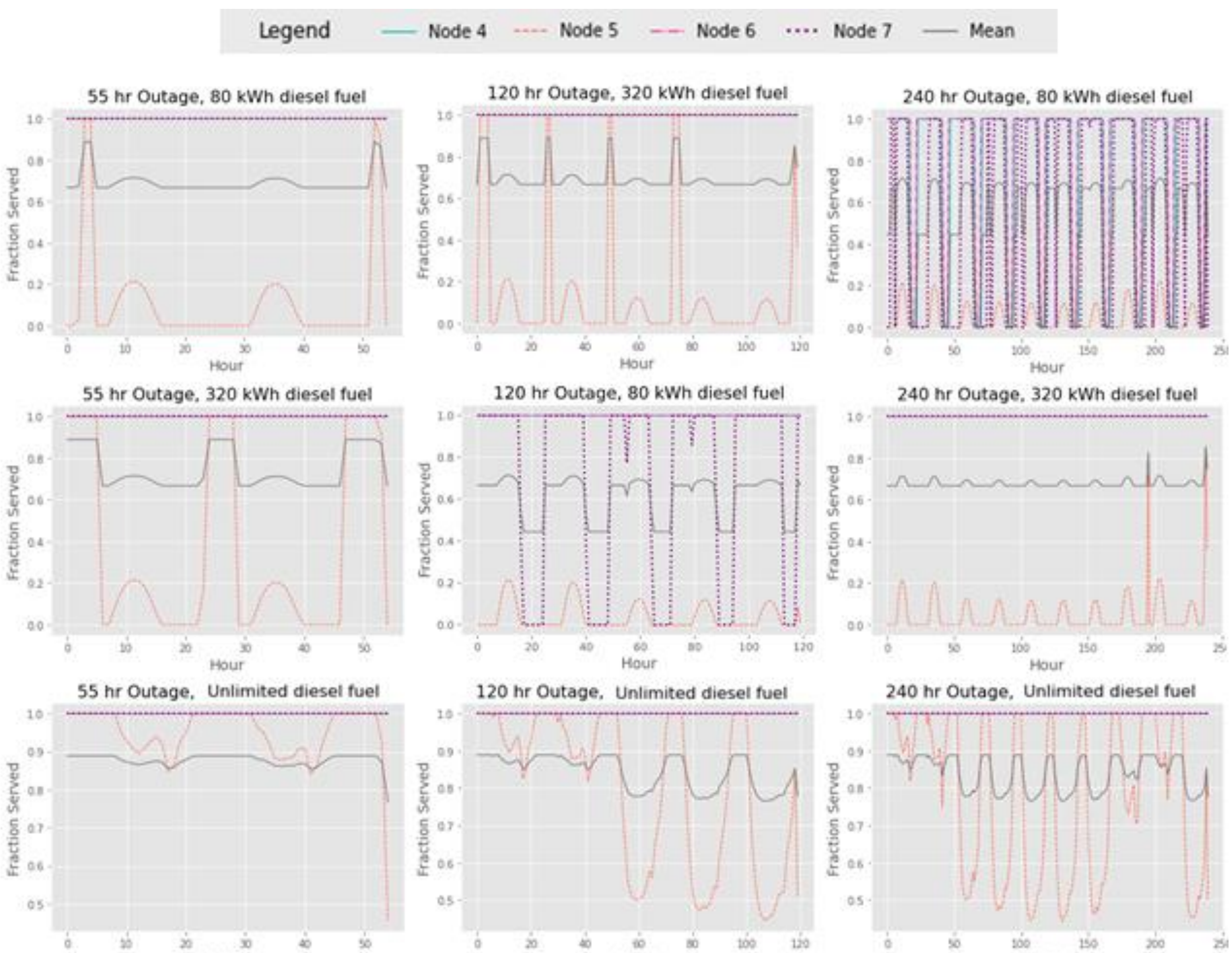

Figure 4. Fraction of load served per node (and mean of nodes) over time under each scenario

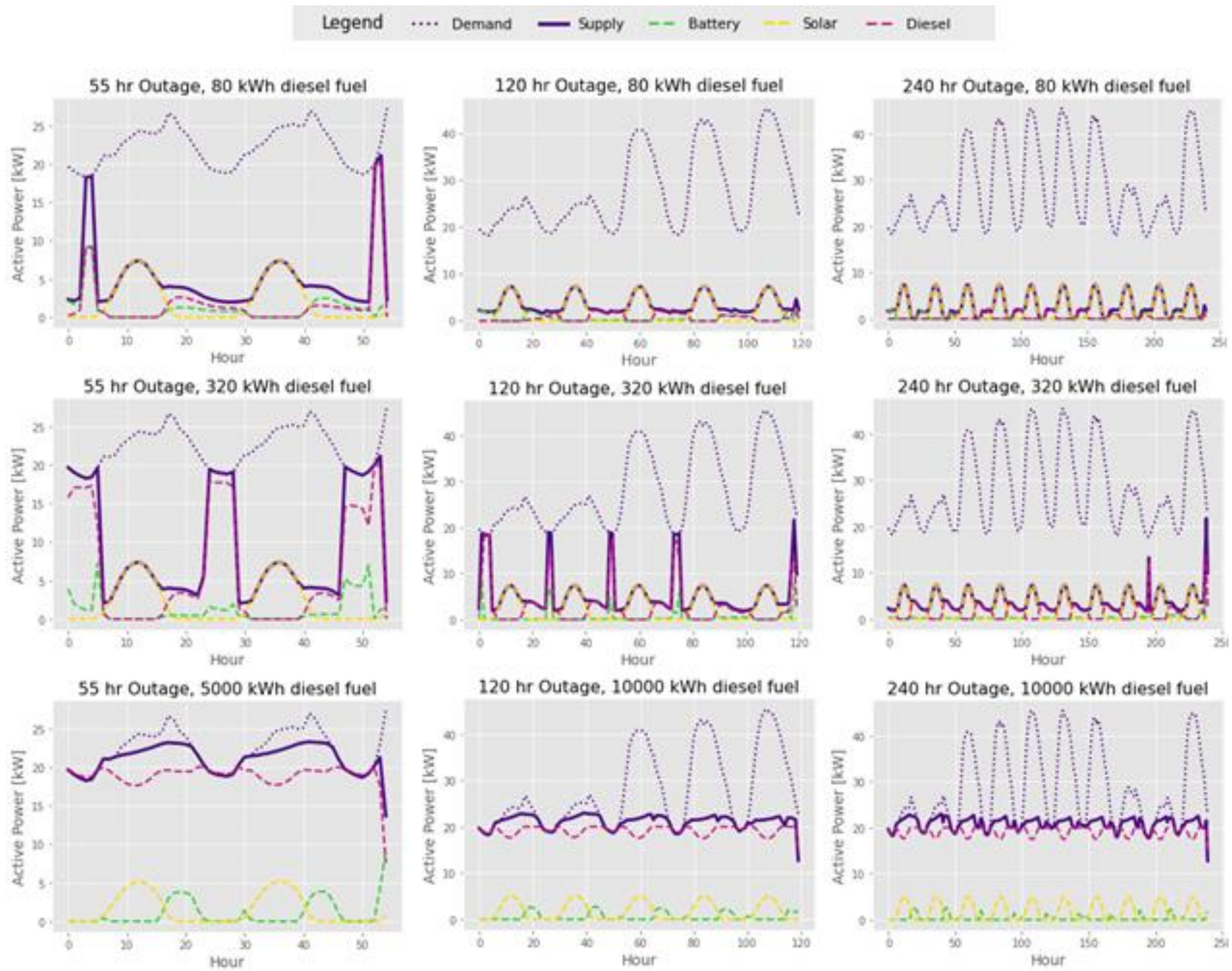

Figure 5. Total active power demand, supply, and generation over time for each scenario

Discussion

The results displayed in Table 4 and Figure 4 above indicate that the microgrid modeled in this analysis can satisfy the power demands of the majority of the loads, regardless of outage duration. One notable exception is Node 5, whose power demand is never fully met even when facing the shortest outage and unlimited diesel fuel is made available to Node 3. This may come across as strange given it is a higher priority than the two nodes that follow it, but the reason behind this becomes clear when examining the relative power demands of each node in detail. Node 5's power demand is significantly higher than other nodes as shown in Figure 2 above, thus the optimization algorithm is incentivized to meet all other load's demands before providing power to Node 5. Adjusting the relative values of the priority rankings could alleviate this issue. In fact, observing how the spacing between priority rank affects the program's choice to serve large, high-priority loads could be a useful method for tuning priority rank values. Specifically, modifying the value of priority rankings such that the difference in magnitude between the rankings exceeds the difference in magnitude between the nodal demands could drive the optimization to fully serve the higher-ranking nodes before fully serving lower ranking nodes. The results from applying the current ranking structure illustrates the tradeoff between serving loads an important but highly energy intensive load, versus serving those that are substantially less energy intensive yet possibly less critical.

Increasing the amount of diesel fuel available to Node 3 has enormous implications for achieving load power demands. The mean demand met is only 55% when the generator produces 80 kWh over a 240 hour outage, but increases by 39% when the generator is provided with unlimited fuel over that same timespan.

The importance of the diesel generator to this particular model is reaffirmed by Figure 5, which shows consistent and relatively low levels of power being provided by both the solar and battery sources. The same cannot be said for power produced by the generator at Node 3, which shows much greater output and variability assuming that it is not limited to 80 kWh. Diesel fuel availability at this node was a key indicator of mean fraction shed; therefore, we recommend that microgrids utilizing a diesel generator have enough diesel fuel to last at least 55 hours, the average PSPS shut-off time. We hope this optimization model can contribute to the wealth of tools for making these microgrids more reliable, efficient, and effective, and even potentially extend their useful operational periods.

In future research, it would be helpful to further stratify the load prioritization. Despite having a 5-tiered system for general load prioritization, as smart homes become more common, there could be an opportunity for further control. Even within the highest ranked medical baseline category, it's reasonable to assume that there are some non-essential portions of that generalized load profile that are less important than the most important loads from the next tiered group. Practically, breaking up large high-priority loads like node 5 would mitigate the optimization's perverse incentive to avoid serving the large load despite its high priority.

Below we define a "microgrid baseline" which is meant to mirror California's medical baseline. The medical baseline program allows enrolled customers to have an extra baseline allowance of 500 kWh per month in recognition of their medical device needs. In a similar fashion, the microgrid baseline is meant to capture some portion of a customer's load that is "essential". From there, we prioritize the essential portions of each tier before prioritizing the non-essential loads. Table 5 below provides additional information on this framework for future consideration:

Table 5. Microgrid Baseline Prioritization

Customer Category	**Rank**	**Description & Justification**
Residential (Medical Baseline): Essential Microgrid Baseline Needs	10	Hourly Essential Microgrid Baseline Need = 0.649 kW + 0.20 + 0.05 kW = 0.944 kW 500 kWh per month (from Medical Baseline Allowance) / 30 days / 24 hours = 0.649 kW .20 kW (Refrigeration needs) .05 kW (other essential load allowance, e.g., heating/cooling/lighting)
Non-residential critical facility (e.g., hospital, fire station): Essential Microgrid Baseline Needs	9	Hourly Essential Microgrid Baseline Need = 5 kW 5 kW will be used as a generic number to represent the range of loads that could be deemed essential (communications technologies, medical equipment etc)
Residential (CARE/FERA): Essential Microgrid Baseline Needs	8	Hourly Essential Microgrid Baseline Need = 0.20 + 0.05 kW = 0.25 kW .20 kW (Refrigeration needs)

Customer Category	Rank	Description & Justification
		.05 kW (other essential load allowance, e.g., heating/cooling/lighting)
Residential (non-CARE/non-FERA): Essential Microgrid Baseline Needs	7	Hourly Essential Microgrid Baseline Need = 0.20 + 0.05 kW = 0.25 kW .20 kW (Refrigeration needs) .05 kW (other essential load allowance, e.g., heating/cooling/lighting)
All other customers (e.g., commercial/industrial, agricultural): Essential Microgrid Baseline Needs	6	Hourly Essential Microgrid Baseline Need = 1 kW Given that this tier is a catch-all for all other customers with varying levels of demand, there is no simple way to characterize the broad range of "essential" demands that could vary based on underlying characteristics (i.e., Agricultural customers would need energy for pumping which is likely not the case for retail or other commercial customers). For this group, we will use a 1 kW per hour baseline.
Residential (Medical Baseline): Non-essential loads	5	All other demand not covered by the Microgrid Baseline
Non-residential critical facility (e.g., hospital, fire station): Non-essential loads	4	All other demand not covered by the Microgrid Baseline
Residential (CARE/FERA): Non-essential loads	3	All other demand not covered by the Microgrid Baseline
Residential (non-CARE/non-FERA): Non-essential loads	2	All other demand not covered by the Microgrid Baseline
All other customers (e.g., commercial/industrial, agricultural): Non-essential loads	1	All other demand not covered by the Microgrid Baseline

Below we provide visuals of what these microgrid baselines would look like. Each graph contains the original load profile, the baseline amount, and the remaining amount of load (total net of the baseline):

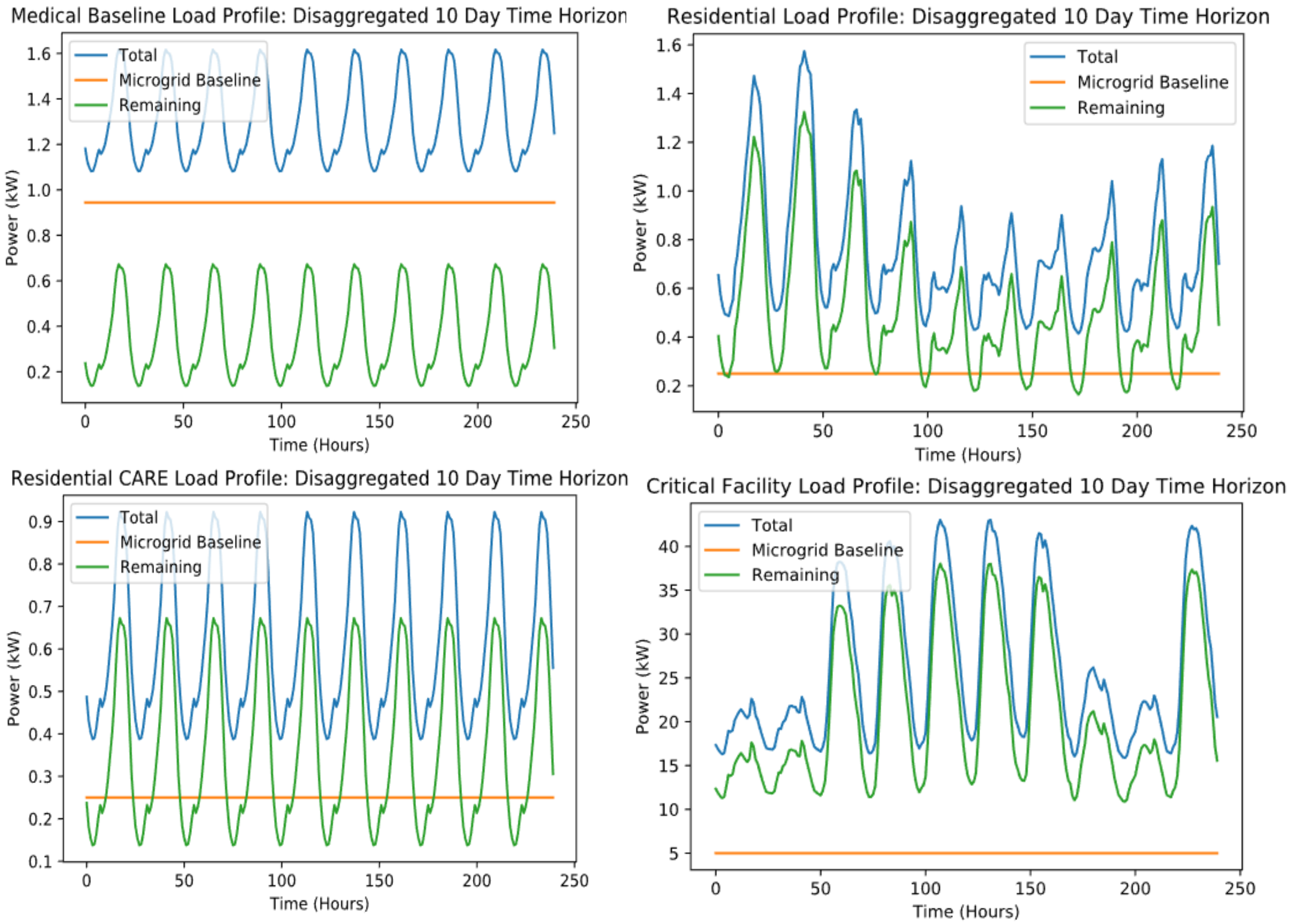

Figure 6. Microgrid Baseline Breakdown

Summary

This study optimized the dispatch schedule of microgrid energy storage resources, given known load priorities, operational characteristics, and system resource constraints. Microgrids may be able to provide continuous power service to critical facilities and homes during PSPS events, and other disturbances to the broader grid that prevent power delivery from outside the microgrid. However, when operating as an island (i.e., not receiving output from the broader grid), a microgrid must provide power using only local generation and storage. The model developed here instructed load scheduling in such an islanded microgrid where local storage resources are unable to meet total demand. While microgrids are not currently permitted to extend over property lines, demonstration projects like the Ecoblock project in Oakland have pushed the CPUC to consider amending the "Own Use" Exemption to accommodate microgrid communities moving forward.[20] As this occurs, it will be essential to create agreement amongst microgrid users to prioritize loads of the most vulnerable during islanding events. As extreme weather events become more frequent and intense due to climate change, and continue to compromise transmission resiliency in the coming years, more and more energy providers may seek to supplement or altogether replace risky transmission with microgrids that can remain self-sufficient for extended periods.[21] In future research, we recommend further stratifying the load prioritization and weighting the loads appropriately to make this model even more relevant to current and future needs.

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Appendices

Appendix A

This appendix describes the model objective function, optimization variables, parameters, and constraints.

Objective Function

Minimize $-R^T F$

Parameters

	Parameter	In code	Meaning	For every
1	R	R	Priority ranking of different customer categories	Node
2.1	D	D	Apparent power demand	Node
2.2	D_P	D_P	Active power demand	Node
2.3	D_Q	D_Q	Reactive power demand	Node
3	S_S	S_S	Power generated by solar PV (apparent)	Node
4.1	j_{max}	j_max	Maximum energy that battery can store	Node
4.2	j_{start}	j_start	Energy in battery at start of PSPS	Node
5	f_{start}	f_start	Diesel fuel available (in kWh) at start of PSPS	Node
6.1	b_{rating}	b_rating	Maximum power that battery can charge/discharge	Node
6.2	d_{rating}	d_rating	Maximum power generator can produce	Node
7	pf	pf	Power factor (converts active power demand to D)	Node
8.1	V_{min}	V_min	Minimum voltage allowed	Node
8.2	V_{max}	V_max	Maximum voltage allowed	Node
9.1	r	r	Resistance	Line
9.2	x	x	Reactance	Line
10	I_{max}	I_max	Maximum current	Line
11	A	A	Adjacency matrix: A[i, j]=1 if i is the parent of j	--
12	ρ	rho	Parent node index	Node
13	dt	dt	Length of time step (default 1 hour)	--
14.1	η_s	nu_s	Solar inverter efficiency	Node
14.2	η_b	nu_b	Battery inverter efficiency	Node

Optimization Variables

	Variable	In code	Meaning	For every
1	F	F	Fraction of real load served at each node	Node
2.1	l_S	l_S	Apparent power supplied	Node
2.2	l_P	l_P	Real power supplied	Node
2.3	l_Q	l_Q	Reactive power supplied	Node
3.1	b_S	b_S	Battery apparent power dispatched (+) or stored (-)	Node
3.2	b_P	b_P	Battery real power dispatched (+) or stored (-)	Node
3.3	b_Q	b_Q	Battery reactive power dispatched (+) or stored (-)	Node
4.1	d_S	d_S	Diesel power generated (apparent)	Node
4.2	d_P	d_P	Diesel power generated (real)	Node
4.3	d_Q	d_Q	Diesel power generated (reactive)	Node
5.1	S_P	S_P	Solar power generated (real)	Node
5.2	S_Q	S_Q	Solar power generated (reactive)	Node
6.1	s	s	Net apparent power consumed	Node
6.2	p	p	Net real power consumed	Node
6.3	q	q	Net reactive power consumed	Node
7	V	V	Bus voltage	Node
8.1	j	j	Battery state of charge (energy available)	Node
8.2	f	f	Diesel fuel (energy) available	Node
9	P	P	Active power flowing	Line
10	Q	Q	Reactive power flowing	Line
11	L	L	Squared magnitude of complex current	Line

Constraints

Notes on constraints:

- Within constraints, variables and parameters are indexed as [time, node/line].
- Unless otherwise specified, constraints are active and functionally equivalent at all time steps.

	Constraint	Meaning	For nodes/lines
1	$F = \frac{l_P}{D_P}$	Definition: Fraction of load served	All
2.1	$P[:,0] = 0$	No real power flow between node 0 and itself	0
2.2	$Q[:,0] = 0$	No reactive power flow between node 0 and itself	
2.3	$L[:,0] = 0$	No current flowing between node 0 and itself	
2.4	$V[:,0] = 1$	Node 0 voltage is reference voltage, thus 1 p.u.	
3.1	$s = l_S - b_S - d_S - S_S$	Definition of net apparent power consumed	All
3.2	$p = l_P - b_P - d_P - S_P$	Definition of net real power consumed	All
3.3	$q = l_Q - b_Q - d_Q - S_Q$	Definition of net reactive power consumed	All
4.1	$b_S[:,[0,3,4,5,6]] = 0$	No battery (dis)charge at nodes w/out batteries	0,3,4,5,6
4.2	$b_P[:,[0,3,4,5,6]] = 0$		
4.3	$b_Q[:,[0,3,4,5,6]] = 0$		

4.4	$d_S[:, [0:2,4:7]] = 0$	No generator power output at nodes w/out generators	All except 3
4.5	$d_P[:, [0:2,4:7]] = 0$		
4.6	$d_Q[:, [0:2,4:7]] = 0$		
4.7	$S_P[:, [0,3:7]] = 0$	No solar PV power output at nodes w/out solar	0,3,4,5,6,7
4.8	$S_Q[:, [0,3:7]] = 0$		
5	$l_P \leq D_P$	Power delivered cannot exceed demand	All
6.1	$j[0] = j_{start}$	Batteries start with stored energy of j_{start}	All
6.2	$j[t] = j[t-1] - b_S[t-1]dt$	Energy available in battery at any time is the previous hours' energy minus energy dispatched in that hour	All
6.3	$0 \leq j$	Battery cannot have negative energy stored	All
6.4	$j \leq j_{max}$	Battery cannot store more energy than its capacity	All
7.1	$f[0] = f_{start}$	Generators start with fuel supply specified in f_{start}	All
7.2	$f[t] = f[t-1] - d_S[t-1]dt$	Diesel fuel supply is fuel supply at previous hour minus fuel burned in that hour	All
7.3	$0 \leq f$	Generator cannot have negative fuel supply	All
8.1	$b_S[0]dt \leq j_{start}$	Battery does not discharge more energy at any time than available in previous time step	All
8.2	$b_S[t]dt \leq j[t-1]$		All
8.3	$d_S[0]dt \leq f_{start}$	Generator does not use more fuel than available at any time than available in previous time step	All
3.4	$d_S[t]dt \leq f[t-1]$		All
9.1	$-b_{rating} \leq b_S$	Battery cannot charge above power rating	All
9.2	$b_S \leq b_{rating}$	Battery cannot discharge above power rating	All
10	$d_S \leq d_{rating}$	Generator cannot generate above power rating	All
11.1	$P_{ij} = p_j + r_{ij}L_{ij} + \sum_{k=0}^{N} A_{jk}P_{jk}$	DistFlow equation describing real power flow on lines	All
11.2	$Q_{ij} = q_j + x_{ij}L_{ij} + \sum_{k=0}^{N} A_{jk}Q_{jk}$	DistFlow equation describing reactive power flow on lines	All
12	$V_j - V_i = (r_{ij}^2 + x_{ij}^2)L_{ij} - 2(r_{ij}P_{ij} + x_{ij}Q_{ij})$	Voltage drop between two nodes explained by impedance losses along the lines	All
13	$L_{ij} \geq \frac{P_{ij}^2 + Q_{ij}^2}{V_j}$	Definition of squared magnitude of complex current, relaxed to make convex	All
14.1	$\sqrt{l_P^2 + l_Q^2} \leq l_S^2$	Definition of apparent power demand	All
14.2	$\sqrt{b_P^2 + b_Q^2} \leq b_S^2$	Definition of apparent power (dis)charged by battery	All
14.3	$\sqrt{d_P^2 + d_Q^2} \leq d_S^2$	Definition of apparent power output by diesel generator	All

14.4	$\sqrt{S_P^2 + S_Q^2} \leq S_S^2$	Definition of apparent power generated by solar	All
16.1	$\sum_i l_S[t,i] \leq \sum_i b_S[t,i] + d_S[t,i] + S_S[t,i]$	Apparent power supplied cannot exceed apparent power generated at any time	All
16.2	$\sum_i l_P[t,i] \leq \sum_i b_P[t,i] + d_P[t,i] + S_P[t,i]$	Real power supplied cannot exceed real power generated at any time	All
16.3	$\sum_i l_Q[t,i] \leq \sum_i b_Q[t,i] + d_Q[t,i] + S_Q[t,i]$	Reactive power supplied cannot exceed reactive power generated at any time	All
17.1	$v_{min}^2 \leq V_j$	Voltage cannot slip under allowed minimum	All
17.2	$V_j \leq v_{max}^2$	Voltage cannot exceed allowed maximum	All
18	$L_{ij} \leq I_{ij,max}^2$	Current cannot exceed line capacity	All
19.1	$d_S \geq 0$	Generator cannot output negative real power	All
19.2	$d_P \geq 0$	Generator cannot output negative apparent power	All
19.3	$l_S \geq 0$	Apparent power consumed cannot be negative	All
19.4	$l_P \geq 0$	Real power consumed cannot be negative	All
19.5	$S_P \geq 0$	Solar cannot generate negative real power	All

Appendix B

View project GitHub repository for more details.