Hybrid Micro-Grid for Adjuntas, Puerto Rico

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Abstract

In the aftermath of Hurricane Maria and other natural disasters, an environmental community organization, Casa Pueblo, in Adjuntas, Puerto Rico decided to increase their social and economic resilience to disasters through grid independent energy resources. This study looks to model different microgrid scenarios where solar power can be complemented with biomass resources and used to power commercial buildings in central Adjuntas. The project involves expansion of the existing 13 kW micro-grid that serves Casa Pueblo's load. HOMER and HelioScope softwares were used to model energy resources and identify the economically optimum solution, while fostering Casa Pueblo's goal of energy independence and resilience. Energy consumption for Casa Pueblo and 12 businesses, self-identified as interested, were considered to create a community electricity load. The study modeled four different scenarios. The first scenario modeled a microgrid with only photovoltaic generation. The high solar capacity required would be higher than the possible installation on the existing roofs and storage needs made the costs of Scenario 1 infeasible. Scenarios 2 and 3 included biomass gasification with 1 and 2, 15 kW generators in each model. These two models produced feasible solutions with LCOE below the current cost of electricity in Puerto Rico. Finally, Scenario 4 takes advantage of net energy metering with the Puerto Rico Electric Power Authority (PREPA). This scenario offered a solution with the lowest LCOE and NPC. However, the desire for energy resilience prioritizes grid independence, and therefore Scenario 3 was chosen as optimum, with a NPC of $605,377 over 25 years and an LCOE of $0.16/kWh.

Acknowledgments

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Introduction

This study looks to model different microgrid scenarios where solar and biomass resources could be used to power commercial buildings in central Adjuntas, to create an independent and resilient energy option to the central grid. In September 2017, Puerto Rico was hit by two category 5 hurricanes. The second, Hurricane Maria, destroyed 80% of the local grid and decimated the power system in the region leaving the community without power for almost a year [1]. This left 1.5 million people, nearly half the island, without electricity, the largest blackout in US history [2]. Full restoration of the transmission and distribution infrastructure was not achieved for 18 months [3]. Mountainous communities like Adjuntas in Puerto Rico were some of the last to be reconnected to the electricity grid.

During the year-long power outage, Puerto Rico did not have the infrastructure to power even the basic equipment at hospitals and pharmacies. This contributed to the overall death toll of Hurricane Maria. The only steady source of power in Adjuntas in the months following the hurricane was the solar microgrid installed on the roof of a non-governmental organization (NGO),Casa Pueblo [4].

Casa Pueblo is a community self-governance project started by Alexis Massol-González in 1980 to preserve the cultural, environmental and human resources of Puerto Rico. This project was established in response to the mining expeditions started by the government of Puerto Rico which would have destroyed 36,000 acres of land devastating the ecological landscape of the area. After its success against the mining efforts, the NGO purchased a house and converted it into an independent cultural community center. This community center was later expanded to include artisan store, library, antiquity room, historic photographs gallery, coffee roasting, and packaging machinery, plant nursery, laboratories for children science classes, a music school, an auditorium, a butterfly garden, a hydroponic system, a community radio station, and a solar energy system [5].

Major power disruptions have become common occurrences in Puerto Rico in recent years due to natural disasters including hurricanes and earthquakes. To increase the energy resilience of Adjuntas, Casa Pueblo, under the leadership of Arturo Massol-Daya has been successful in implementing several residential solar installations. They plan to increase their solar potential by 50% through implementation of solar panels on the roofs of more homes and businesses affected by Hurricane Maria.

The School for Environment and Sustainability has partnered with Casa Pueblo with the purpose of creating effective solutions for increased energy resilience and independence in Puerto Rico. The main objective was to model various scenarios in which Adjuntas could be electrified in a manner more economically competitive and resilient than the Puerto Rican grid, managed by the Puerto Rico Electric Power Authority (PREPA). Electricity sources modeled included PV generation, biogas generation, and the Puerto Rican grid. One of scenarios modeled in the study was to remain connected with the traditional grid, utilizing an agreement known as Net Energy Metering (NEM). This allows customers with behind-the-meter generation to offset or sell back their excess electricity. The economic benefits of NEM made it a valuable scenario to explore, however, the connection with the grid leads to energy insecurity issues.

One issue that comes up when trying to achieve energy resilience with solar power is variability. Generation can change instantaneously and must be replaced in order to balance generation and load. Of the available renewable resources in Puerto Rico, inland communities like Adjuntas must exploit what resources are available. The dense forests and coffee agriculture around Adjuntas allows for the possibility of a biomass energy resource. Plant biomass can be gasified into combustible syngas, which could be used to fuel a generator. Plant feedstocks were modeled from forest dead wood, but agricultural residues are also available from coffee agriculture, and have been widely used in this sort of application [6]. Dr. Jose Alfaro, a project advisor, works with biomass feedstocks for microgrids around the world, and founded a lab at the University of Michigan to do so, Micro-grids from Biomass Residues for Agricultural Circular Economy (MBRACE). Circular economies try to eliminate waste streams, and keep materials in use [7]. In the case of biogas microgrids, agricultural residues (waste) can be used for gasification and electricity generation. The leftover in the gasification process is known as biochar, which is high in carbon content and can be used for fertilizer. It seemed logical to incorporate this electricity generation component into this study.

Figure 01: (Left) Casa Pueblo Location (Right) Casa Pueblo Main Building

Moving Forward

The 2017 hurricanes are not the only natural disasters Puerto Ricans have recently faced. In January 2020, earthquakes again knockout out power infrastructure, including the main natural gas power plants on the island [8]. Since, Puerto Rico has been more reliant on backup power infrastructure and expensive diesel. These facts only further highlight the issues of having a highly centralized power system in Puerto Rico and necessitate solutions. In response, in 2019, the Governor of Puerto Rico signed a bill implementing a 100% renewable portfolio standard (RPS) by 2050, along with intermediate goals [9]. Large independent power producers (IPP) with damaged coal power plants stand at a crossroads, while groups like Casa Pueblo are jumping at the chance to build energy resilience and security through distributed energy resources.

In light of this increased interest in distributed generation, Casa Pueblo partnered with University of Michigan to study the possible benefits of adding a biomass component to the community energy supply in Adjuntas. Casa Pueblo has the desire to increase energy resilience and renewable electricity generation in Adjuntas, and recently they have been planning for a microgrid expansion, where Casa Pueblo could manage a microgrid with solar generation throughout Adjuntas. With the significant potential forest and agricultural biomass supplies, our research examines the feasibility of different microgrid scenarios with and without biomass gasification. Specifically, the main aim of this study is to determine the optimal configuration of a microgrid that can supply electricity for the modeled load.

Methods

For this project, we made the use of the following softwares and techniques:

HOMER Pro

HOMER Pro is a software tool originally developed at the National Renewable Energy Lab (NREL) for the optimization of microgrids with multiple renewable energy resources and power infrastructure [10]. HOMER optimizes energy resources along Net Present Cost and presents least cost options through a project lifetime, along with the Levelized Cost of Electricity (LCOE) and other parameters.

HOMER allows for sensitivity analyses to be performed along parameters that may be uncertain. Data input into HOMER includes load data, component costs and specifications, and resource data.

- Load Data: Load data is the energy consumption data in time-series form. The steps taken to create a load are detailed in the section titled Load Curve.
- Capital cost, Replacement cost and O&M Cost: HOMER Pro provides a database of capital costs for different components. These values were complemented with literature review to include realistic values reflecting the location and size of the project.
- Resource data: HOMER Pro requires data on the available resources. As the microgrid in this case is a solar and biogas powered hybrid we used solar energy data from NREL and calculated biomass availability using literature review.
- Components: The components from the HOMER library were chosen to match an already established solar microgrid at Casa Pueblo.

HelioScope

HelioScope is a web-based PV design tool which is used to evaluate and design photovoltaic (PV) systems. It allows users to design arrays overlaid upon satellite imagery, for more accurate estimation of component sizing and placement [11]. HelioScope can detail how PV systems will generate electricity in the most realistic scenarios, accounting for electrical losses, weather, shading, and more. Users can select components including solar panels and inverters for use within designs. A detailed accounting of the HelioScope components used in modeling are in the methods and a description of the generation is in the results.

DJI Mavic Mini Pro

Resolution of the Google maps satellite imagery in the area was not sufficient for precise adjustment of solar panels and appropriate calculations. This study made use of DJI Mavic Mini Pro to take pictures of rooftops of the commercial buildings in Adjuntas. These pictures were then cropped and used as overlays for precise fitting of solar panels on top of buildings within the HelioScope model.

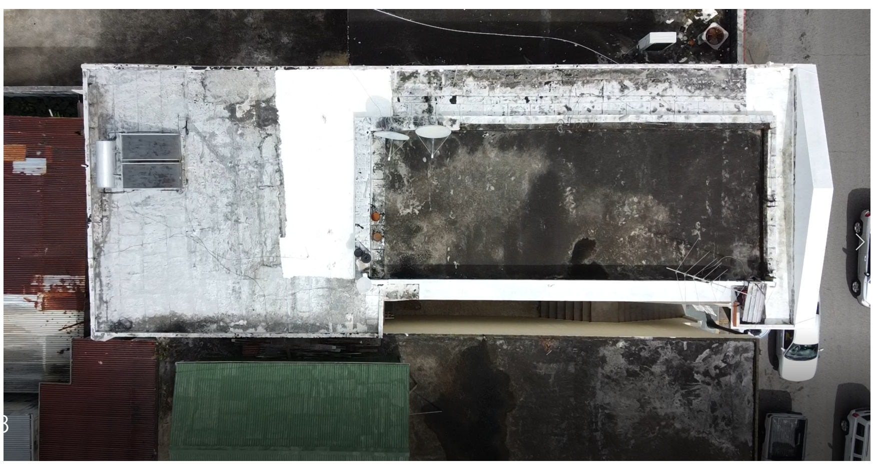


Figure 02. Example of drone aerial photo used as visual overlay in HelioScope

Scenarios Modeled

HOMER Pro was used to model four different scenarios

Scenario 1: is composed of only solar power sources without gasifiers. This system is composed of the expanded commercial solar grid and Casa Pueblo PV system. This model is a simple extension of an already existing PV microgrid on the roof of Casa Pueblo.

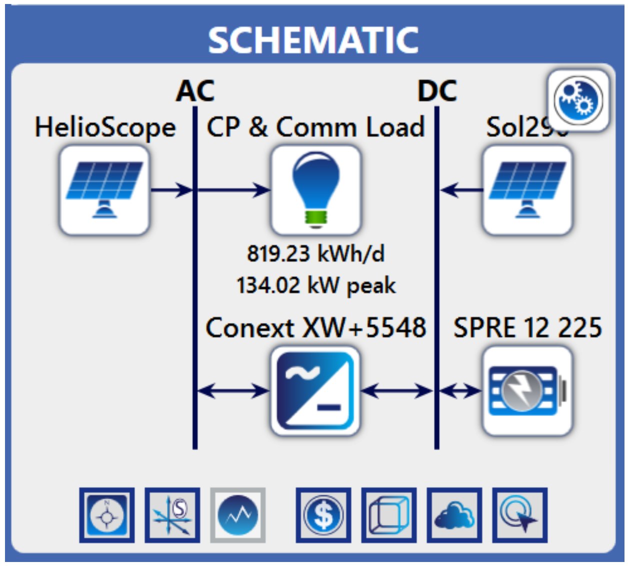


Figure 03: Scenario 1 Schematics

Scenario 2: is composed of the Helioscope model which represents the expanded solar grid, one full sized generator of 15 kW that runs on syngas and the existing Casa Pueblo solar array. The biogas fueled generator was added to the model to identify the impact of the gasifier on the overall system.

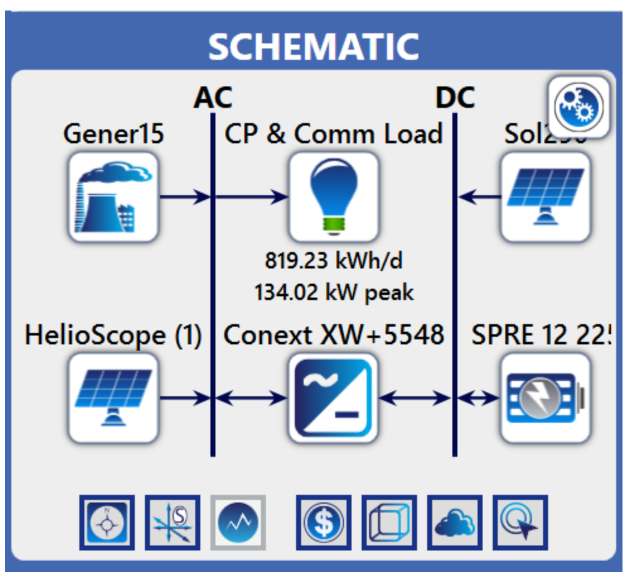


Figure 04: Scenario 2 Schematics

Scenario 3: is composed of scenario 1 with the addition of another full sized 15 kW generator running on syngas. This scenario was modeled to see the impact of two full sized gasifiers instead of one.

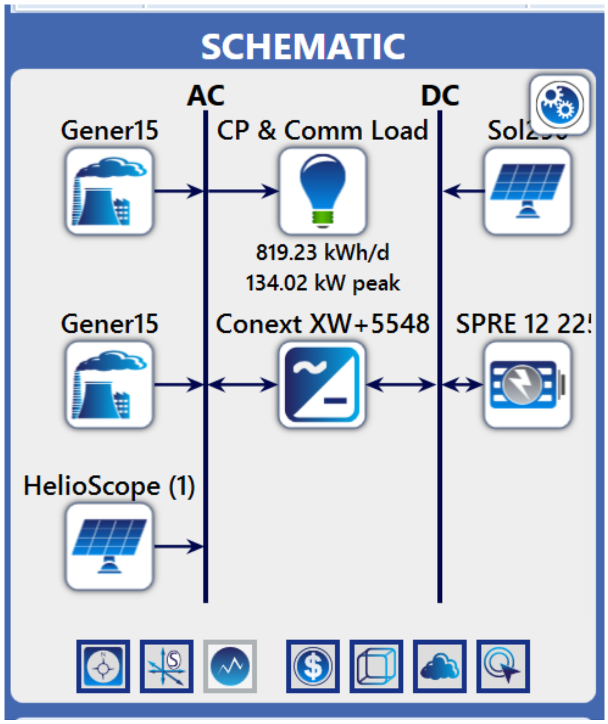


Figure 05: Scenario 3 Schematics

Scenario 4 is composed of scenario 1 connected to the main grid and utilizing net metering as a resource. This scenario was developed for cost comparison with and without net metering and grid help.

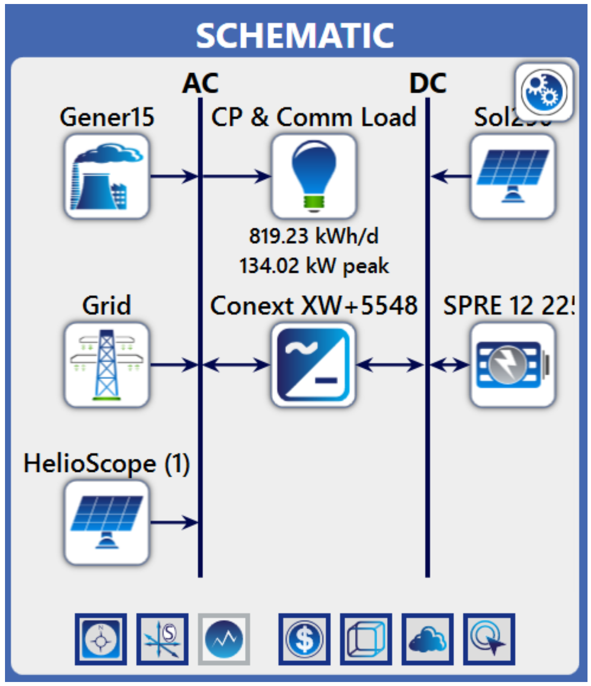


Figure 06: Scenario 4 Schematics

Load Curve

The load curve is the energy consumption data entered into the HOMER software. From there, HOMER will optimize the different generation sources in order to meet the electricity load in a way which minimizes the NPC. The load used in all scenarios came from combining the 2018 Casa Pueblo load with an estimated commercial load from the 12 businesses modeled.

- Casa Pueblo Load:
  The Casa Pueblo consumption data was retrieved from literature review [12] and from the employees working at Casa Pueblo.

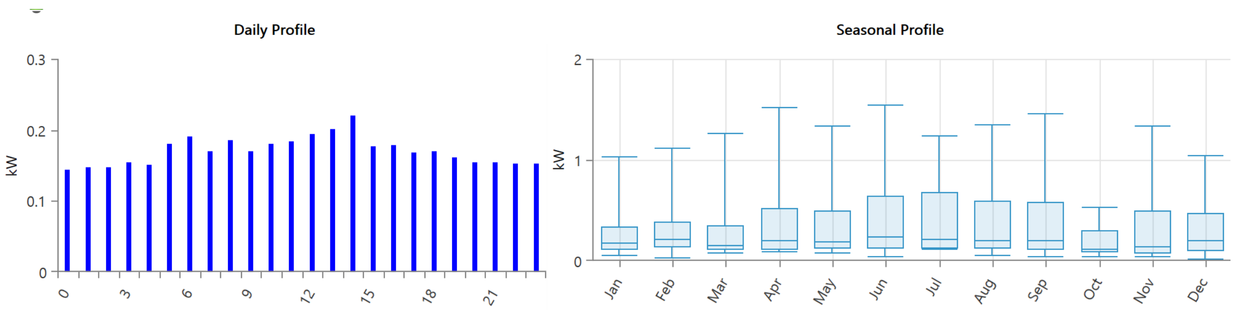


Figure 07: Casa Pueblo Load Curve

- Commercial Load Curve:
  The data needed to develop a load curve for businesses in Adjuntas came from a fellow researcher doing work with Casa Pueblo, Dr. Maximilian Ferrari. Through the course of his research, he had collected electricity usage data from 12 commercial establishments, self identified as interested, around the central business plaza in Adjuntas. Understanding the amount of electricity each business used daily allowed our team to combine the daily usage of all the businesses together to create a combined daily energy consumption of around 800 kWh/day. The commercial load was created by taking this energy consumption

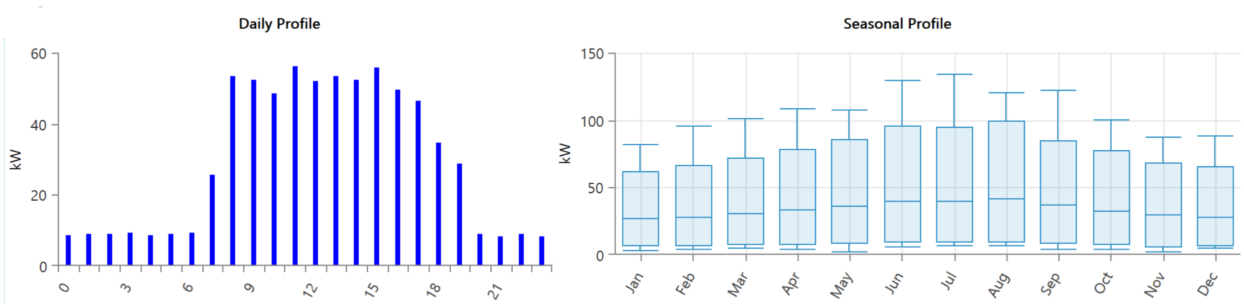


Figure 08: Commercial Load Curve

For the development of the complete load curve the Casa Pueblo Load Curve and the Commercial Load Curve were added together and loaded into HOMER.

Model Specifications

All the components used to model the different scenarios in HOMER are assumed to be bought, installed and maintained at market price.

Based on the model specifications obtained from Casa Pueblo on the components currently in use:

Table 01: Casa Pueblo System Components

Type	Brand	Model
Solar Panel	Solar World	290 SW Mono [13]
Battery	MK Power	8G8DLTP-DEKA 12-V 225-Ah Gel [13]
Converter	Schneider Electric	Conext XW + 5548 [13]

Table 02: Solar Panel Specifications Used in HOMER: Solar World 290 SW Mono

Base Panel from HOMER	Solar World 290 SW Mono [12]
Capacity (kW)	13.1 [14]
Capital Cost ($)	258.10 [12]
Replacement Cost ($)	206.48 [12]
Operations and Maintenance Cost (O&M) ($/yr)	6.38 [15]
Lifetime (yr)	25 [16]
Derating Factor (%)	85 [16]

Table 03: Battery Specifications Used in HOMER

Base Battery from HOMER	Trojan SPRE 12 225 [12]
Nominal Voltage (V)	12 [12]
Nominal Capacity (kWh)	2.71 [12]

Maximum Capacity (Ah)	226 [16]
Capital Cost ($)	399 [17]
Replacement Cost ($)	319.20 [18]
O&M ($/yr)	10.00 [19]
String Size	4 [16]
Minimum State of Charge (%)	20 [16]

Table 04: Converter Specifications Used in HOMER: Schneider Conext XW + 5548

Capacity (kW)	5.5 [12]
Capital Cost ($)	2,600.00 [12]
Replacement Cost ($)	3,100.00 [12]
O&M Costs ($/yr)	0.00 [12]

Table 05: Generator Specifications Used in HOMER: Generac 15kW Protector

Base Generator from HOMER	Generac 15kW Protector [12]
Capacity (kW)	15 [16]
Fuel	biogas
Lifetime (hours)	15,000 [16]
Minimum Load Ratio (%)	25 [16]
Capital Cost ($)	6,000.00 [1] [20]

[1] This is an overestimation for modeling purposes

Replacement Cost ($)	4800.00 [18]
O&M ($/yr)	0.30 [21]

Note: The costs for HelioScope are incorporated into HOMER under the Helioscope Component.

Table 06: Grid Specifications Used in HOMER: Puerto Rico Electric Power Authority

Grid Power Price ($/kWh)	0.252 [22]
Grid Sellback Price ($/kWh)	0.100 [23]

Helioscope Specifications

Integration into HOMER:
Helioscope was integrated into HOMER software using the Helioscope wizard tool within HOMER. The capital cost of solar panels used for the model are the same as those used at Casa Pueblo, while inverter costs were taken from literature and input into HOMER manually. The Helioscope component in HOMER represents the electricity generation resulting from the 230 kW expanded community solar arrays and is considered one component in HOMER. This component is constrained to one in all but one scenario and is referred to as "HelioScope" throughout the paper.

Helioscope for Expanding Solar Generation Capacity:
Helioscope was used to fit solar panels on commercial buildings in adjuntas main square by expanding the solar microgrid that was previously restricted to Casa Pueblo. Ten field segments with solar arrays were created to cover ten buildings in the Helioscope model. Two of the buildings house more than one business. The string size was adjusted to cater to the large number of modules connected to each other. The Azimuth was set to face south, or in some cases in line with the south facing building edge and the default orientation of panels was set to landscape. Only one business has a tilted roof, which requires Flush Mounted Racking, the rest of the panels were designed for Fixed Tilt at Latitude (18^o). Certain keepout areas, areas unavailable for mounting solar panels, were input

into the model to represent AC units and satellite dishes taking up roof space. Three large trees present in the plaza area were also modeled into the Helioscope Scenario to account for shading losses[2].

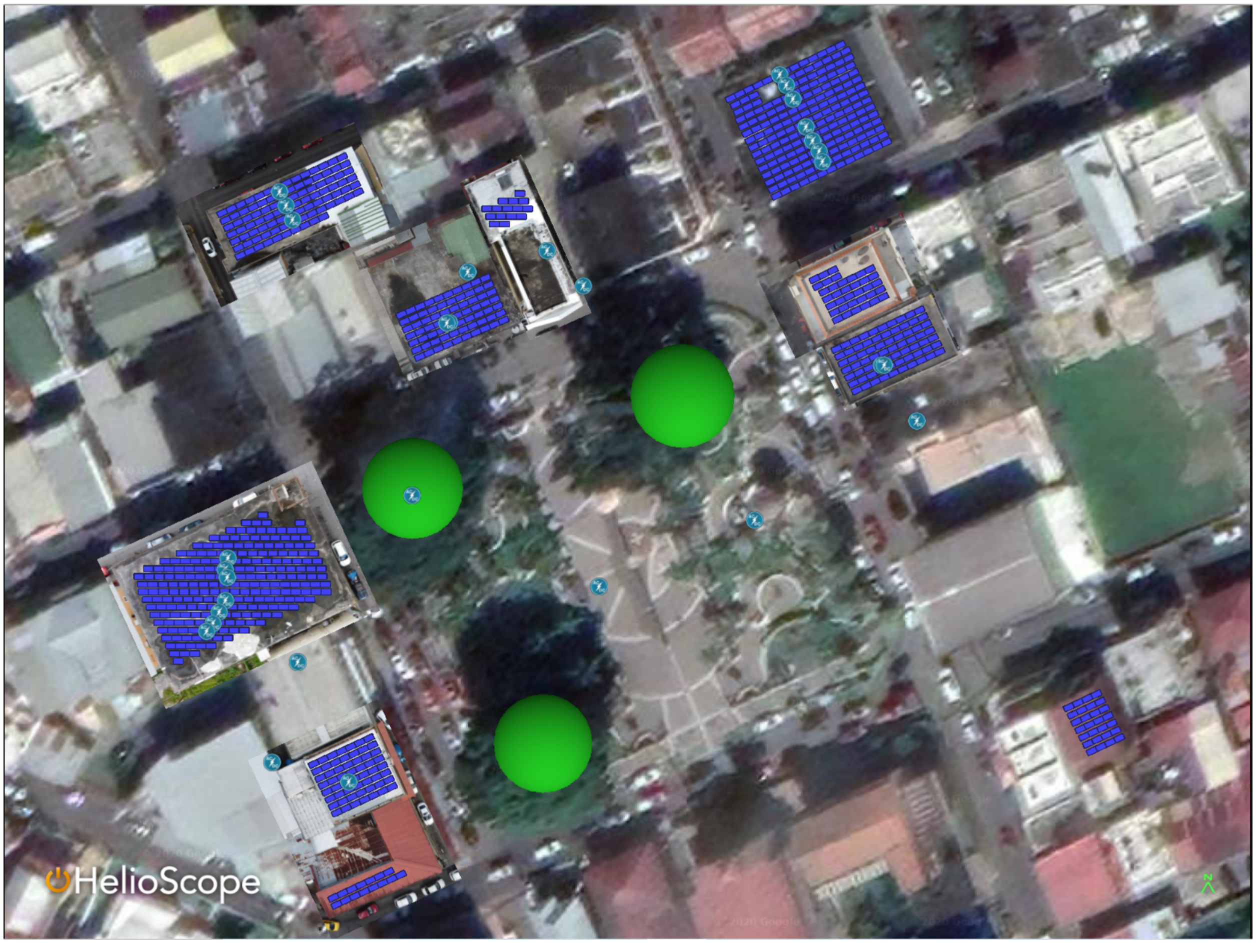


Figure 09: Detailed layout of the solar panels and the businesses covered by Helioscope

[2] Shading Losses: Energy Losses from the solar panels being shaded by the trees.

Field Segments

Description	Racking	Orientation	Tilt	Azimuth	Intrarow Spacing	Frame Size	Frames	Modules	Power
Hospice	Fixed Tilt	Landscape (Horizontal)	18°	154.86°	1.4 ft	1x1	28	28	8.12 kW
Freterria Gonzalez1	Fixed Tilt	Landscape (Horizontal)	18°	156.571°	1.1 ft	1x1	70	70	20.3 kW
LImar	Fixed Tilt	Landscape (Horizontal)	18°	180°	1.1 ft	1x1	15	15	4.35 kW
Jenny's Pharmacy	Fixed Tilt	Landscape (Horizontal)	18°	180°	1.1 ft	1x1	221	221	64.1 kW
Super Muebleria	Fixed Tilt	Landscape (Horizontal)	18°	154.113°	1.1 ft	1x1	191	191	55.4 kW
Panderia	Fixed Tilt	Landscape (Horizontal)	18°	153.976°	1.1 ft	1x1	36	36	10.4 kW
Digital Point	Fixed Tilt	Landscape (Horizontal)	18°	155.023°	1.1 ft	1x1	70	70	20.3 kW
Eve& coco's Pizza	Fixed Tilt	Landscape (Horizontal)	18°	155.023°	1.1 ft	1x1	56	56	16.2 kW
Lucy's Pizza	Flush Mount	Landscape (Horizontal)	18°	155.023°	1.1 ft	1x1	15	15	4.35 kW
Abreu	Flush Mount	Landscape (Horizontal)	18°	155.023°	1.1 ft	1x1	94	94	27.3 kW

Figure 10: Solar panel placement specifications and the names of the businesses

Figure 11: Overlay on Lucy's Pizza and the Flush Mountain Racking for its tilted roof.

Table 07: Solar Panels in Helioscope:

Solar Panel Name	SolarWorld, SW 290 MONO (290W)
Total Number of Arrays (#)	796 [24]
Module DC Nameplate (kW)	230.8 [24]

Table 08: Inverter in Helioscope:

Inverter Name	Conext XW Pro NA (MPPT 60 150) (Schneider)
Total Number of Inverters (#)	31 [24]
Individual Inverter Capacity (kW)	186.0 [24]

Number of Strings (Feet)	113,574.2 [24]

Table 09: Economic Cost of Helioscope:

Capital Cost ($)	286047.6 [12,24]
Replacement Cost ($)	228,838.6 [12,18,24]
O&M ($/yr)	5078.48 [15]

Biomass Characterization

Puerto Rico has available biomass from dead wood in forests, which make up 56.3% of Puerto Rico by land area [25], and also from coffee farms. The dead wood numbers used in this study are pre-Hurricane Maria numbers. Properties of Inga Wood were used in HOMER to characterize available biomass. Inga Wood is the most abundant in Puerto Rican forests [26], and serves as a good indicator of a base biomass resource.

Table 10: Inga Wood Biomass Resource Specifications Used in HOMER

Lower Heating Value (MJ/kg)	20 [27]
Density of Biomass (kg/m^3)	720 [28]
Carbon Content (%)	51.2 [28]
Sulfur Content (%)	0
Average Price ($/tonne)	50 [29]
Gasification Ratio (kg/kg)	1.75 [30]

Biomass Availability

The amount of deadwood/acre [31] was used to estimate biomass availability using the percentage area representative of Adjuntas. A recovery rate of 50% was added to the calculation to meet the realistic expectations of the available biomass.

Adjuntas, Puerto Rico is a farming community that grows coffee and other crops. The agricultural residue from farms will put the biomass availability figure much more than is estimated here.

Price of Biomass

The price of biomass was estimated through literature review, and sensitivity cases were performed around this value.

Prices of biomass vary widely in literature depending on the type of feedstock, geography, and scale of generation, though reasonable estimates place the price of forest residues, wood waste, and agricultural residues in the order of 10-50 $/ton. The price of the biomass used for HOMER modeling was $40/ton, with sensitivity analyses being performed at $30/t and $50/t.

Adjusting the Fuel Curve

A fuel curve is required in HOMER to estimate the fuel consumption and the efficiency of the generator at different loads. In this modelheat content of the biomass and round trip efficiency of the gasifier and generator were used to estimate Data from a downdraft gasifier of similar design analyzed in Costa Rica was used [30].

Table 11: Fuel Curve specifications

Wood Thermal Content (MJ/kg)	20 [27]
Gasifier Efficiency (%)	0.15 [30]
Gasification Ratio	1.75 [30]

Biogas Characterization

Biomass is converted into syngas with a heating potential of approximately 7.4 MJ/kg. This was determined using the gas analyzer results of the syngas. For reference, the heating value of gasoline is approximately 43 MJ/kg [32]. The heating potential of the gas obtained from the biomass can also help in estimating the biomass expected to be consumed for the production of electricity.

Table 12: Syngas Resource Specifications Used in HOMER

LHV biogas (MJ/kg)	7.4 [33]
LHV gasoline (MJ/kg)	43.4 [32]
Density of gasoline (kg/L)	0.75 [34]
Density of biogas (kg/m3)	1.175 [35]

Results

Biomass Availability

The biomass availability was estimated to be 0.27 ton/day.

Table 13: Biomass Availability

Mass of Dry Deadwood Biomass in PR forests (t)	1260000 [36]
Forested Area of Puerto Rico (ha)	479400 [31]
Forested Area of Puerto Rico (km2)	4794 [31]
Dry Dead Biomass per km2 of forest ($t/km^2/yr$)	262.8 [31]
Collection area (km^2)	0.75 [3] [37]
Fraction of available biomass that can be recovered	50%
Amount of biomass recovered annually (t/yr)	98.56
Amount of biomass recovered monthly (t/month)	8.213

[3] This area is about half of the size of the city of Adjuntas, and represents the land from which biomass can be retrieved

Amount of biomass available daily (t/day)	0.270

Table 14: Syngas Production (Fuel Curve Adjustment)

Output Desired (kW)	Biomass FeedRate kg/hr)	Syngas Production
1	1.2	2.1
2	2.4	4.2
3	3.6	6.3
5	6	10.5
7.5	9	15.75

Fuel Curve Graphs

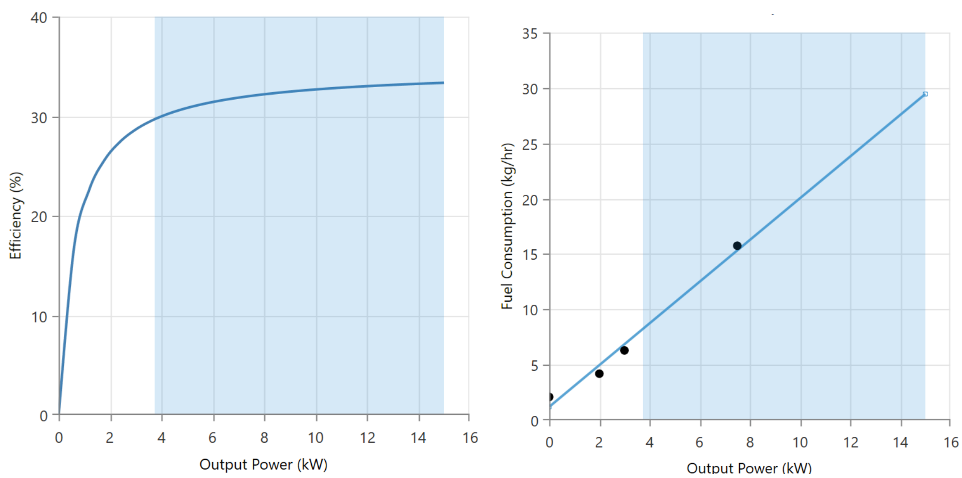


Figure 12: Efficiency of the generator (left) Fuel consumption graph (right)

Helioscope

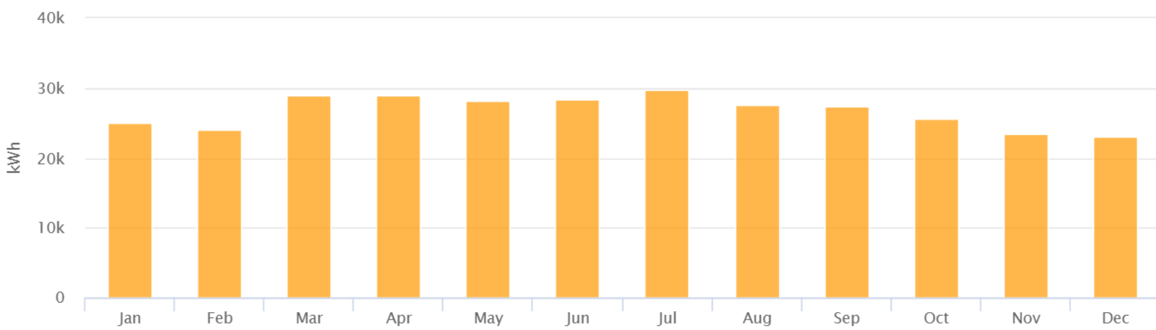
Table 15: General

Base Model in HOMER	Helioscope
Annual Production (MWh)	320.4
Performance Ratio (%)	77.1
Lifetime (Years)	20

Derating Factor (%)	100

Monthly Production

Monthly Production



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Month	GHI (kWh/m^2)	POA (kWh/m^2)	Shaded (kWh/m^2)	Nameplate (kWh)	Grid (kWh)
January	121.2	142.0	134.0	29,794.7	24,990.1
February	121.0	134.3	128.9	28,597.9	24,129.5
March	154.1	162.2	157.4	34,966.4	28,996.7
April	162.1	161.0	156.8	34,742.6	28,973.4
May	165.8	157.2	153.1	33,830.8	28,160.4
June	170.7	158.7	154.7	34,182.3	28,455.8
July	176.3	166.0	161.7	35,796.7	29,796.0
August	157.4	154.3	150.4	33,350.7	27,538.4
September	149.2	154.6	150.2	33,334.2	27,440.0
October	133.8	144.8	139.8	31,011.2	25,608.0
November	115.9	132.9	126.2	28,038.1	23,379.3
December	111.5	132.4	123.3	27,364.3	22,963.9

Figure 13: The monthly production of electricity by the collective grid

System Losses

There is a 26.2% loss of power throughout the entire system. The division of the sources of loss is outlined below:

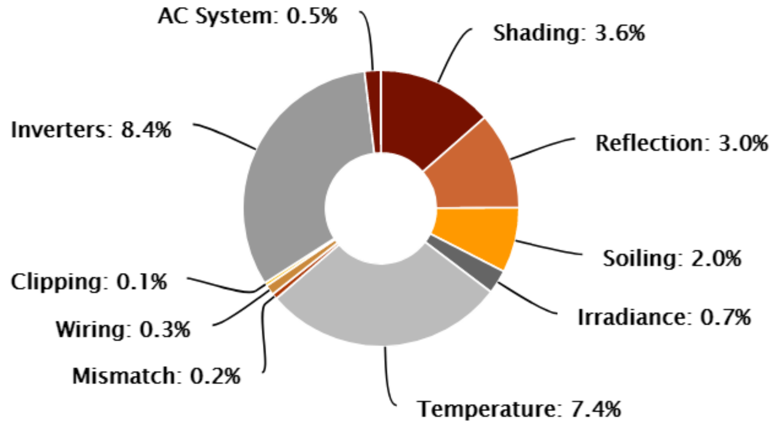


Figure 14: Sources of power loss

Table 16: Summary of Results

Scenario	#1 - Only solar generation, no biogas	#2 - Scenario 1 + 15 kW Generator	#3 - Scenario 2 + 15 kW Generator	#4 - Scenario 2 + Net Metering
Net Present Cost (NPC) ($)	1,482,078	648,350	605,377	324,278
LCOE ($/kWh)	.392	.171	.160	.0536
Operating Cost ($/yr)	38,801	18,313	16,616	1,313
Excess Electricity (kWh/yr)	666,902	105,424	128,488	489
Excess Electricity (%)	67.2	25.5	29.9	.103
Total PV Production (kWh/yr)	992,627	343,474	343,474	343,474
Total	0	70,398	86,647	86,653

Generator Production (kWh/yr)				
Biomass Resource Needed (tonne/day)	0	.219	.269	.27
Renewable Fraction (%)	100	100	100	90.4
Cost Recovery Time (years)	25	25	25	25
Helioscope Component (#)	3.02	1	1	1

Scenario 1

Scenario 1 has the largest overall electricity production, NPC, LCOE and excess electricity.
The electricity production for scenario 1 is 82.7 MWh/month and the excess electricity is 55.6 MWh/month. This means 67.2% of the electricity produced is curtailed.
HelioScope is the only contributor to electricity production while the solar PV system in comparison has negligible production.
The NPC for Scenario 1 is $1,482,078 and the LCOE is $.392/kWh.

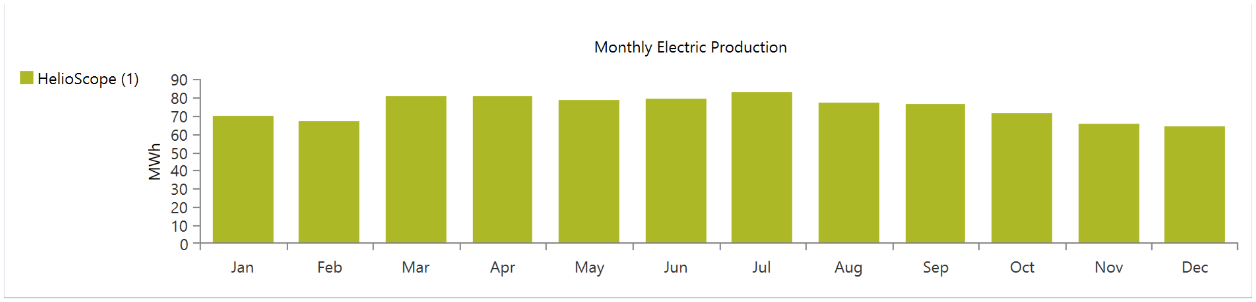


Figure 15: Monthly production of electricity in Scenario 1

Scenario 2

Scenario 2 has a monthly production of 34.4 MWh/month and an excess production of 8.8 MWh/month (25.5%). The major contributor to the electricity production is HelioScope as seen in Figure 14 and Sol 290 solar panels have the smallest production.
The NPC of Scenario 2 is $648,350 and LCOE of $0.171/kWh.
Generator production accounted for over 70,000 kWh of generation annually, this required biomass inputs of .22 t/day/.

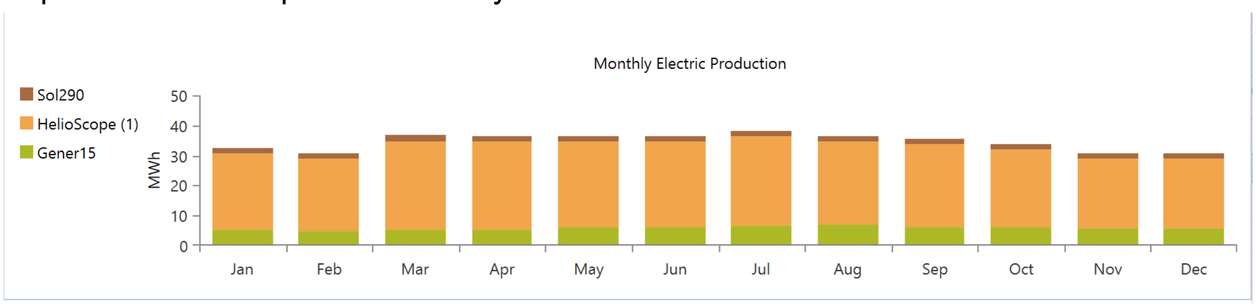


Figure 16: Monthly production of electricity in Scenario 2

Scenario 3

Scenario 3 has a monthly production of 35.84 MWh/month and an excess electricity of 10.7 MWh/month (29.9%). Similar to scenario 2 majority production in scenario 3 is by HelioScope while Sol290 solar panels and the second generator are the minimum contributors to the electricity production.
The NPC of scenario 3 is $605,377 and LCOE of $0.160/kWh
Generator production accounted for over 86,000 kWh of generation annually, this required biomass inputs of .27 t/day/.

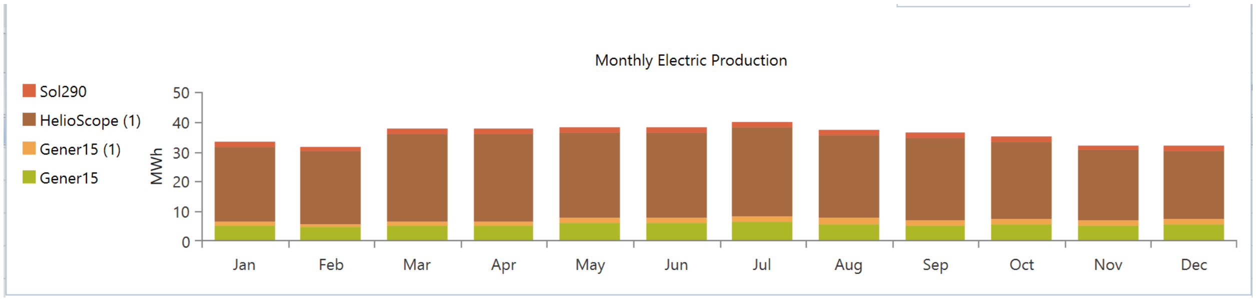


Figure 17: monthly production of electricity in Scenario 3

Scenario 4

This scenario is connected to the grid (PREPA), while utilizing Net Energy Metering. Scenario 4 has a monthly production of 35.8 MWh/month and has no excess electricity.

Similar to the other scenarios the majority production of electricity is by HelioScope while the biogasifier and the grid contribute significantly to the electricity production. Sol 290 solar panels similar to previous scenarios have the minimum contribution to the overall production.

Scenario 4 has an NPC of $324,278 and LCOE of $0.0536/kWh.

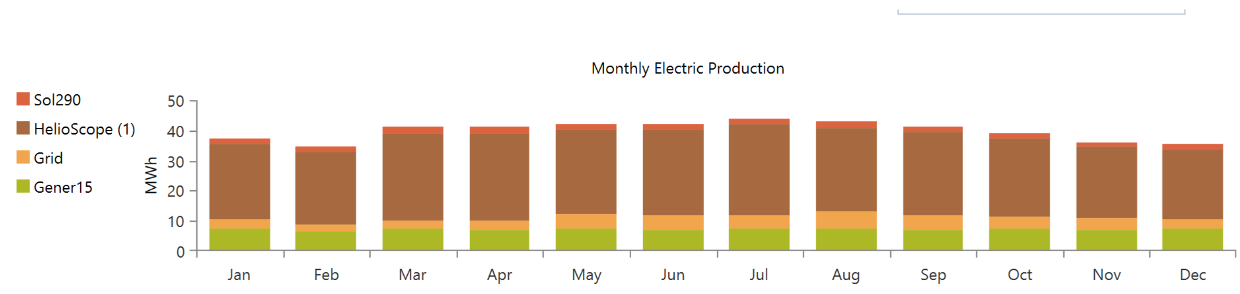


Figure 18: Monthly production of electricity in Scenario 4

Sensitivity Analysis

The baseline price of $40/t was used for the price of biomass, with sensitivity analyses being performed with prices of $30/t and $50/t. The results of these analyses can be seen in Table 16. Changing the price of biomass between these two values did relatively little to the overall results of the analysis. The change of biomass price has no effect on the results of Scenario 1, as solar generation is the only electricity source. This range of biomass prices could add $22,609 and $14,413 to the NPCs of Scenarios 2 and 3, respectively. Finally, the different prices could cause a range of $1,649 around the true NPC.

Table 17. Sensitivity Results

Scenario	Biomass Price ($/t)	#1 - Only solar generation, no biogas	#2 - Scenario 1 + 15 kW Generator	#3 - Scenario 2 + 15 kW Generator	#4 - Scenario 2 + Net Metering
Net Present Cost (NPC) ($)	30	1,482,078	637,182	594,676	320,674
	50	1,482,078	659,791	609,089	322,323
LCOE ($/kWh)	30	.392	.169	.157	.0528
	50	.392	.174	.161	.0567
Operating Cost ($/yr)	30	36,680	17,450	15,655	1,031
	50	36,680	19,040	17,625	1,629

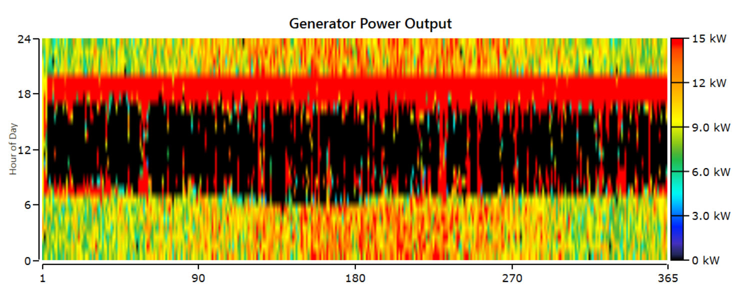
Discussion

It was natural to structure our models as additive, building onto the current PV infrastructure in place at Casa Pueblo piece by piece. Scenario 1 models a case in which over 200 kW of solar capacity are installed around buildings in Adjuntas to provide electricity for the combined load in conjunction with the current 13 kW array at Casa Pueblo. This expanded solar design was not able to provide for the given community load. There are ways in which the output can be increased, but the major barrier to such a solution is cost. Microgrids that rely solely on variable renewable resources like wind and solar need to rely on storage to provide energy when needed throughout diurnal and seasonal cycles. Energy storage, in this case battery storage, is expensive and causes the cost to expand significantly. Results were produced in HOMER from Scenario 1 by releasing the constraint on community solar generation. The community load can only be met by increasing the roof space for the placement of solar panels. Renting or buying more roof space for solar panels would contribute to the overall cost of the system and would further increase the NPC and LCOE.

The high cost of electricity storage is one driver which pushes the solution to include more generation, causing the expansion of the community solar array. The capital costs of the solar arrays contribute almost 60% to the NPV in Scenario 1, and the system ends up overgenerating significantly. Having the ability to generate electricity instantaneously to supply changes in demand could provide greater flexibility in meeting demand. This led to the addition of biomass gasification to Scenario 2.

Scenario 2 models out how solar generation in Adjuntas could be expanded into a generation network in the downtown plaza and includes the addition of a 15 kW generator powered by biogas. Model results showed an LCOE of .171 $/kWh, significantly lower than the average price in Puerto Rico that is greater than .2 $/kWh [39]. The economic feasibility of this solution shows promise for the ability to power Adjuntas from sustainable energy sources. In addition, Scenario 2 has Net Present Cost of about $650,000 over 25 years.

The results of Scenario 2 showed the biogas generator running at full capacity during peak electricity demand in the evening throughout the entire year. Daily biomass availability was not a limiting factor, so a second generator was added to the model to create Scenario 3. The results from Scenario 3 show that the



LCOE could be lowered to

Figure 19: Generator Power Output - Scenario 2

.160 $/kWh from .171 $/kWh in Scenario 2, along with a reduction of over $40,000 from the NPC. This decrease in LCOE and NPC can be attributed in part to less need for energy storage in the system. When more power can be generated on-site instantaneously, as with the gasifier/generator system, the high costs of energy storage can be avoided, lowering total system costs. In this case, the biomass was not a limiting factor, with daily consumption at .269 t/day. In under 10 years the initial capital investment of Scenario 3 would break even with simply purchasing electricity from the PREPA grid.

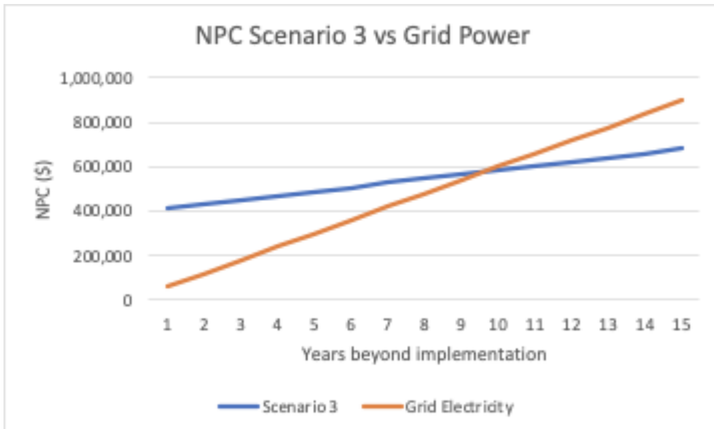


Figure 20: Net Present Cost of Scenario 3 and Grid Electricity

Scenarios 2 and 3 rely heavily on biomass for generation, in both cases fulfilling around 20% of the total load with biomass-derived electricity. Scenario 1 illustrates a case in which electricity generation from biomass is not feasible. A system of collecting, purchasing, and processing biomass from many sources around a rural community such as Adjuntas does not come about immediately, and it is likely that there may be disruptions to this supply chain that make our estimate of .27 t biomass/day infeasible. In this case, it is important to understand the reaction of our model when electricity is not being generated in this manner. Scenario 1 serves this purpose and consists of only solar electricity generation and battery storage. This Scenario is not feasible unless the solar generation constraint of one (~200 kW) is removed. The result of this optimization is a community solar expansion around 3 times larger than the one designed for in HelioScope.

Scenario 4 was meant to examine a net energy metering scenario, where the community can offset their electricity usage with onsite PV generation. Generators are paid by PREPA $.1/kWh for electricity generated beyond their load needs [23]. Economic results in this case were very favorable, with the lowest NPC of all scenarios at $324,278 over 25 years. This also represents a significant decrease in LCOE. However, Scenario 4 relies on PREPA for generation and transmission, reducing the energy resilience and renewable penetration.

Scenarios 2, 3, and 4 do produce excess electricity beyond what is needed to meet the given load. Scenarios 2 and 3 produce 25.5% and 29.9% excess electricity each year. The high cost of battery storage in the model is one cause of this excess. As electricity is cheaper to store, less will be wasted without meeting a load. Scenario 4 has very little excess annual energy, as anytime the solar generation exceeds the load, NEM provides this electricity back to the grid for consumption.

There are recent and unfortunate examples of why energy resilience is so important, especially in rural Puerto Rico, and reliance on the grid can limit a microgrid from functioning independently. Though in a world of perfect infrastructure, it may be cost effective to pursue only this method, in this case, it may be a viable transition strategy to a fully independent microgrid. Adjuntas presents an opportunity to mix strategies along the path to 100% renewables. Casa Pueblo could pursue the strategies laid out in Scenarios 1 and 2, to create a fully independent micro grid around downtown Adjuntas, while other areas can use NEM or microgrids for their own economic or energy resilience benefits.

Scenarios 2 and 3 present illustrate realities in which 12 businesses in downtown Adjuntas could be outfitted with solar arrays, connected with PV and biomass electricity generating resources at Casa Pueblo, to create an independant and completely renewable microgrid with an LCOE that is below current rates in Puerto Rico. The lower NPC and LCOE in Scenario 3 make it the optimal microgrid solution of the scenarios modeled.

The additional generation of one or two biogas generators is able to take pressure off of the solar generation and storage components. Modeling constraints dictated that there would be less than a 1% energy shortage. This need for reliable power can make 100% solar systems less feasible because of the variability of the resource and the cost of energy storage. A generator can ramp quickly to supplement solar power during periods of high load, and can act as a backup to batteries overnight. With a robust system of biomass collection, processing, and gasification, biogas generators can be a tool for achieving sustainable and resilient microgrids.

These results show the feasibility of supplying a commercial load in Adjuntas with 100% renewable energy, independant from PREPA systems. Additionally, the conservative nature of the cost estimates explored likely makes all the modeled scenarios overestimates in terms of NPC and LCOE. This decision was made in the modeling process so that the feasibility of scenarios would be more applicable to other microgrid scenarios that must invest capital in more components. Though this scenario is likely feasible from a cost perspective, further questions need to be answered before such a solution should be implemented.

The electrical generation of the solar components can likely be increased. Electrical losses such as inverter loading could be further eliminated to increase output from those components. Biomass availability was assumed constant through all modeling scenarios, but this supply chain has various complexities which make it a source for further research. Collecting agricultural residues for gasification in rural areas like Adjuntas can be difficult. Considerations to manage include the cyclical agricultural patterns that will affect supply, optimization of collection methods, and spikes in biomass supply associated with hurricanes.

The gasification process is another source of uncertainty that should be studied. The assumptions regarding the gasification efficiency were not based on data from the gasifier at Casa Pueblo. Rather, these parameters came from similar research performed in Costa Rica [30]. With the installation of the biogasifier at Casa Pueblo, gasification trials can be performed to determine how the feedstocks available perform, both in terms of heating value and gasification ratio. With the installed gasifier and generator, we can understand more precisely how a certain mass of organic material translates to an energy output, and the energy models of community microgrids can be improved.

Conclusion

This study was focused on finding a cost effective method to generate electricity for businesses in Adjuntas, in order to ensure stronger energy resilience to the community in the face of natural disasters like hurricanes and earthquakes. Four scenarios were developed to understand potential microgrid solutions in Adjuntas, with electrical generation systems including PV, biogas, and the PREPA grid. All scenarios also included expanded solar generation to over 230 kW, separated into field segments located on different commercial buildings in Adjuntas. The optimum solution examined involved supplying the electricity load with the expanded solar generation, along with two biogas fueled generators. The total biomass needed in this scenario was almost .27 t/yr. The NPC and

LCOE were found to be about $605,000 over 25 years and $.16/kWh, respectively.

Biomass gasification may have potential for use in microgrids looking to supplement variable renewable resources with something more controllable. Achieving 100% solar electricity for a community is difficult, as that electricity is often being used at times when sunlight is not available. By adding a deployable component to such a biogas generator, electricity can be dispatched when required, taking pressure off storage systems and PV generation. We found that by adding a 15 kW biogas generator to the baseline scenario, feasibility was attained, along with an LCOE competitive with PREPA rates.

Future work can be spent increasing the accuracy of certain aspects of modeling, including gasifier and generator efficiencies. In many ways, these components were outside of the scope of our modeling. The availability of in situ data on gasification and generation was sparse, as the gasifier was not in use during scenario modeling. The reasonable assumptions and estimates we developed could be improved on, by incorporating performance data from the installed equipment.

Another area for improvement is in the understanding of biomass resources for gasification. If biomass is to be a significant contributor to the energy resources for Adjuntas, it must be well understood where it comes from and how it performs in gasification. Our assumptions were based on forest deadwood, but agricultural coffee residues are available from farmers as well. Understanding how much of this agricultural biomass is available, and how it could be collected in an energy and cost efficient manner would be vital to developing a sustainable system of biomass energy feedstock.

Overall, Casa Pueblo is in a very good position to move forward in trying to create an expanded community microgrid with hybrid generation from both solar and biomass. They have expertise, offset capital costs, and significant community support. In addition, our modeling, using a conservative costing approach still supplied electricity which is cheaper than Puerto Rican grid electricity. Perhaps more importantly is the fact that this can further bring energy security and resilience to a vulnerable community.

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