Strategic Energy Plan for a Net-Zero Field School in the Taboga Forest Reserve, Costa Rica

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Abstract

Sustainable development is increasingly necessary for businesses and institutions across the globe. University of Michigan Sustainability Without Borders students and Capuchins de Taboga researchers are laying the foundation for a biological research station and field school with net-zero greenhouse gas emissions in Costa Rica, a leading nation in sustainability. This study focuses on supplying the site and its expected operations with a sustainable energy supply. A bottom-up energy analysis was performed to project electricity consumption by students and researchers as the field school further develops. HOMER, a microgrid optimization software, was used to determine the microgrid architectures projected to have the lowest levelized cost of electricity. Models for both grid-connected and grid-isolated microgrids were developed to serve as a strategic energy plan and inform the site's continual development. In addition to installing a pilot solar + storage project to address researchers' energy security concerns, initial results provide evidence that the site's energy demand could be supplied economically with a combination of solar, battery storage, and rice and sugarcane biomass resources from surrounding agricultural operations. Upon completion, the net-zero Taboga Research and Education Exchange (T-Rex) will serve as a model for international sustainable research and schooling with a levelized cost of electricity of $0.16/kWh.

1. Introduction

Costa Rica is a lush and vibrant country with an incredible array of biodiversity. The country has risen to become a world leader in sustainability and conservation. Costa Rica had historically focused on agriculture and ranching, resulting in a steady loss of forest of about 55,000 hectares per year, leaving all but 21% of its forest cover (de Camino Velozo, 2016). Costa Rica's first national park, Poás Volcano National Park, was established on January 25th, 1971. The establishment of the national park system helped reduce deforestation, but it was not until 1992 that deforestation was made illegal. In addition to restrictions on deforestation, the Costa Rican government created an incentive program that rewarded people who planted trees with tax exemptions as well as financial compensation for the environmental services provided by their land (Wilson Center, 2015). The result of this program was a steady increase in forest cover, from 21% when the program first began to 51% based upon the most recent assessment. This is among the highest percent of forested land cover for developed nations. In 1994 Costa Rica amended its constitution to include the right to a healthy environment, further codifying its commitment to healthy environmental policies (Rubio, 2018).

The process of Costa Rica becoming a world leader in sustainability continued in 2007, when President Oscar Arias Sánchez announced that Costa Rica would be the world's first carbon neutral country by 2021 (Marshall, 2008). Since then Costa Rica has shown its commitment to a low-emission economy, achieving a record 300 days of electricity being generated by renewable resources in 2017 (Rubio, 2018). At that time Costa Rica's electrical grid operated with 93% of its energy being supplied from renewable sources (Kroposki, 2017). In January 2019, President Quesada declared, "Decarbonization is the great task of our generation and Costa Rica must be among the first countries to achieve it, if not the first." To achieve this goal the government released an official Decarbonization Plan.

For the years 2018-2050, the plan is organized into four main decarbonization themes: Transportation and Sustainable Mobility; Energy, Green Building, and Industry; Integrated

Waste Management; and Agriculture, Land Use Change and Nature-Based Solutions (Costa Rica Bicentennial Government, n.d.). Each of these themes are broken down into focus areas to direct decarbonization efforts. These changes are planned to be implemented through a series of strategies that are focused on addressing social, financial, environmental, and technological considerations. The country has already made significant progress toward these goals.

By 2019 99.62% of Costa Rica's electricity was supplied by renewable energy through a mix of hydro, wind, geothermal, and solar resources (Hanley, 2020). Greater microgrid development could further enhance Costa Rica's decarbonization efforts through a myriad of benefits. Microgrid consumers tend to have reduced electricity and heat costs, and overall system health is improved from greater peak shaving and deferred maintenance leading to an overall stronger system of a lesser environmental impact (Costa & Matos, 2009). Based on the goals and strategies of Costa Rica's Decarbonization Plan, establishing a net-zero biological station would prove as a strong case study for further microgrid development.

The Taboga Forest Reserve protects a tropical dry forest in the Guanacaste Province of Costa Rica. Established on May 23, 1978, the 297-hectare reserve is administered by Universidad Técnica Nacional (UTN) and their School of Forestry. The property was given to UTN administration 10 years ago from the Costa Rican Ministry of Agriculture (MAG) as part of the consolidation of technical universities and colleges in Costa Rica under the UTN umbrella. While UTN operates a commercial farm on the property, education programs within the Reserve ended roughly a decade ago, leaving the instructional campus in disrepair. Currently, UTN and the National System of Conservation Areas (SINAC) are on-site to administer the operations for surrounding rice and sugarcane agriculture, and provide general maintenance services to the Reserve.

The University of Michigan (UM) became involved with this site when faculty from the Psychology and Ecology and Evolutionary Biology Departments began studying White-Faced Capuchins that are native to the Reserve. The "Capuchins de Taboga" project launched in June

2017 as a long-term research project studying social cognition, communication, and hormone-behavior relationships in wild white-faced capuchins. To do this they are collecting long-term behavioral data, recording vocalizations, extracting hormones from fecal samples, and will run cognitive experiments from feeding platforms. The project is an international collaboration between UM, UTN, Georgia State University, and Michigan State University. The project operates out of a series of faculty houses and a small lab renovated for research operations.

2. Background

Two years ago, UTN offered UM full access to a set of buildings on the Northeast portion of the Taboga Forest Reserve. With this offer, UM faculty had the idea to expand their project into a leading net-zero education and research station. The ultimate goal of the biostation is for it to be a place where Costa Rican and international students, as well as researchers and scholars, can study, conduct research, and build demonstration projects in the fields of biology, ecology, ecotourism, agriculture, and sustainable systems. This learning is aided by the unique features the Reserve offers such as dry tropical forest, surrounding sugarcane and rice farms, and a small river that cuts through a portion of the Reserve. Dr. Jose Alfaro was asked to join the project based on his expertise in sustainable systems and experience from growing up and living in Costa Rica. The following report covers the first Master's Project to focus on supplying the biostation and field school with reliable, clean energy. Future Master's Projects and Sustainability Without Borders teams will continue this work and will focus on other areas of sustainability, such as the site's water supply, waste management strategies, and collaborative community engagement.

Capuchins de Taboga is currently headquartered in a series of small houses on the west side of the reserve. Each of the houses have four bedrooms, two bathrooms, two showers, a kitchen, and a common area. Currently, only two houses are used by the Capuchins project, and all lab work is carried out in an old UTN lab. Within the Reserve, researchers are moving to a different site that has three faculty houses and a dormitory complex. As all are in disrepair, they need to first be renovated before the entire project can officially be moved. The first faculty house was completed in June 2019. This house has four bedrooms, two bathrooms sharing a common sink area, a kitchen, living room, screened in porch, and a carport (Appendix A). The other two houses will have similar characteristics, except one of the houses will have only three bedrooms as the fourth will be converted into the project's lab space. The dormitory complex houses sixteen bedrooms with eight bathrooms shared between two bedrooms, two courtyards, and a cafeteria/kitchen.

Recently Drs. Beehner and Bergman started a foundation to develop the overall site as the Taboga Research and Education Exchange (T-Rex), emphasized in Figure 1.

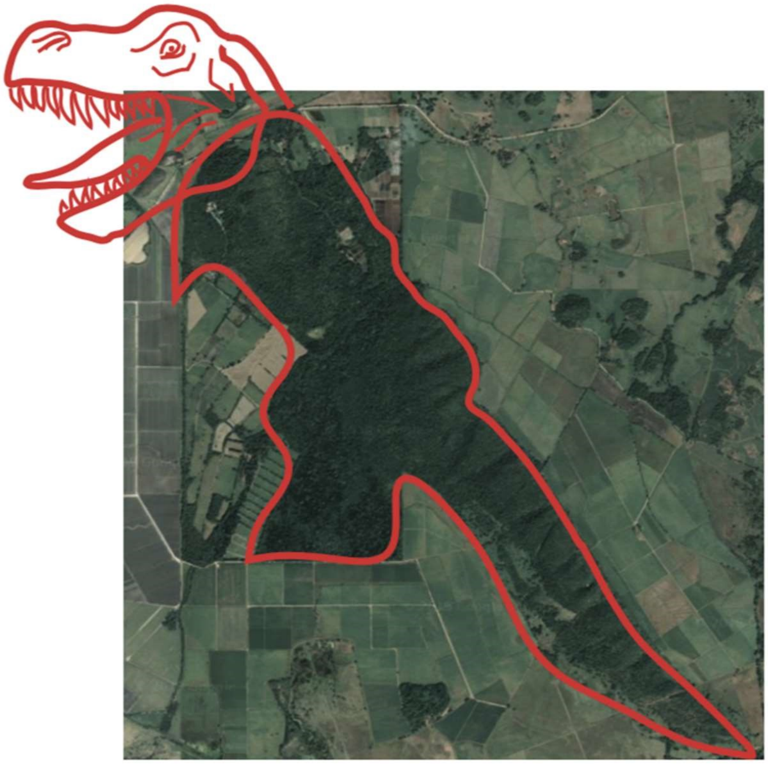

Figure 1. Satellite Image of the Taboga Forest Reserve.

As the vision for a net-zero field school has developed, the intended use of buildings has shifted. The team spent the last two weeks of May 2019 analyzing "House 4" and a separate laboratory space on the west side of the reserve, which currently houses visiting researchers. As of February 2020, Phase I of the development plan consists of renovating one of the faculty houses to house researchers (now completed). Phase II consists of renovating the other two faculty houses while moving the lab space to one of the second house's bedrooms. Expected completion for this phase was for Fall 2020; however, travel restrictions from the novel coronavirus pandemic have delayed Phases II and III. Phase III will involve renovating the abandoned 16-bedroom dormitory, to serve as sleeping and dining quarters for the field school.

The Instituto Costarricense de Electricidad (Grupo ICE) has a rule that residential distributed energy resources cannot be compensated for selling more than 49% of the electricity they generate to the grid, an important constraint to consider in the site's energy plan (Pinto, 2019).

3. Methods

A bottom-up energy model was constructed by surveying all devices and appliances used at the Taboga Forest Reserve by researchers on the Capuchins de Taboga team. By asking what equipment was being used and when, the data were aggregated into dry and wet season hourly load curves. This load was inputted into HOMER, a microgrid optimization software that balances load with different energy resources and system components to determine the microgrid architectures projected to have the lowest levelized cost of electricity.

HOMER optimizations were carried out for each of the three project phases, including models for an isolated microgrid, as well as a grid-connected system that would trade electricity with the Costa Rican Institute of Electricity (Grupo ICE). In the case of Phase III of the project, an additional biogas generator fueled by surrounding sugarcane and rice residues was modeled.

3.1 Phase I: One Faculty House (Green House)

To account for more intermittent power demands such as the cycling of the refrigerator-freezer and constant draws such as the Wi-Fi router, a base load electricity demand had to be measured. Access to the site's well pump was restricted during the team's visits, and was assumed to be included in base load power measurements.

The electric load for the facility was determined to be greatest in the hotter dry season of the year (November-April), when there is a greater need for fans. In addition to large overhead fans in the kitchen, living room, and three of the bedrooms, in the dry season it was assumed that each bed had a small fan directed at the occupant overnight. For all phases, the small fans and kitchen overhead fan were removed from the model to reflect decreased fan usage in the cooler wet season. Recently, there has been greater collaboration between Capuchins de Taboga researchers and UTN students, requiring workers to go into the field with students on weekends. Due to this, a load profile different than a standard residential shape was assumed to be the same for the facility during weekdays and weekends, as described below:

On a typical day, researchers wake-up at 5AM, prepare breakfast, and begin research work in the Reserve by 6AM. Research responsibilities and time-off rotate throughout the week, so typically one worker will stay at home for the morning before switching out with a worker in the field at noon. A slight electricity peak over the lunch hour is associated with these two workers cooking lunch. At 5PM, one worker will begin cooking dinner with the electric stove and/or oven for the whole team, with everyone returning to the building by 6PM. This coincides with the peak electricity demand for the day, as most of the lights and fans are on, people are taking showers, eating, and perhaps doing a load of laundry. From 8-10PM the team is lounging around the house, often watching a movie using a projector, and getting ready for bed. Lights are typically off by 10PM. Considering power draw, quantity of equipment, and time-of-use data, the following load data were aggregated to represent the team’s power demand across a day (Figure 2).

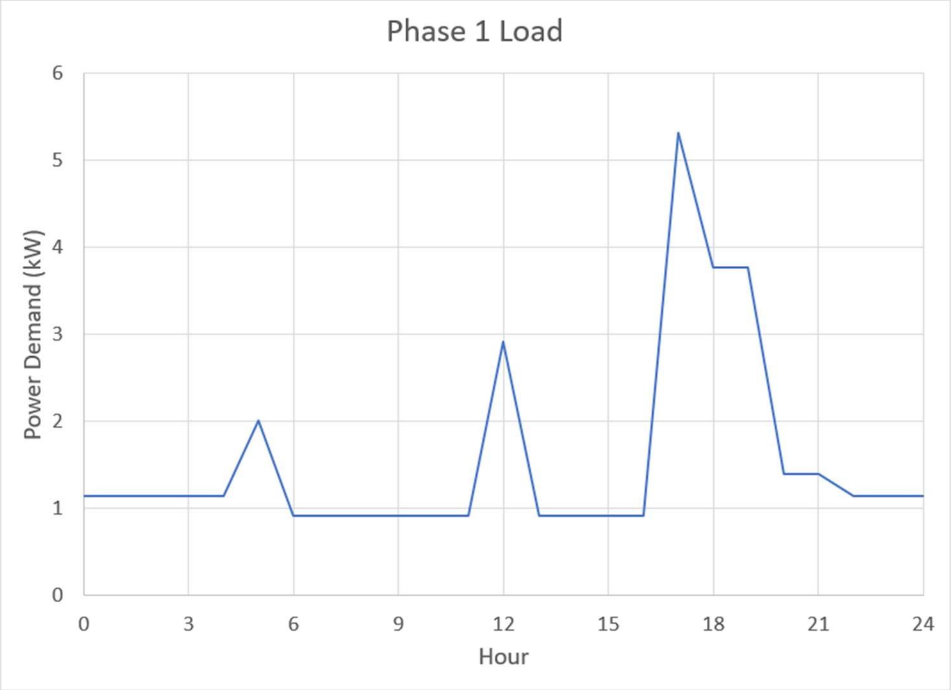

Figure 2. Load data for Phase I in the hotter dry season.

When importing time-series load data into HOMER, a 10% day-to-day variability and 20% timestep variability are assumed. The seasonal profile that was optimized in HOMER is included below in the box-and-whisker plots of Figure 3. Historical monthly averages of NASA Surface meteorology and Solar Energy data were used to model temperature and solar radiation resources for the duration of this analysis.

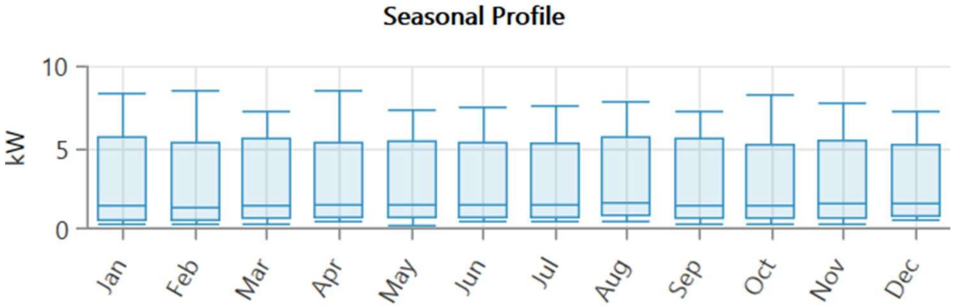

Figure 3. Seasonal Profile for Phase I across wet and dry seasons.

Costing information for the microgrid components to be modeled in HOMER came from personal communications with a local energy consultant and are listed in Table 1. Lifetime and efficiencies for system components were left at default values according to the generic HOMER library and are included in Appendix B.

Table 1. Cost Table for Solar/Storage Microgrid Components

Component	**Cost**	**Notes**
Photovoltaic Cells	$353/cell	0.39kW panels, includes associated inverter costs, racks, labor, electric materials
Batteries	$375/kWh	1 kWh Li-Ion, same cost as pilot project (Section 3.4)

Due to a constraint with Grupo ICE restricting net-metering, the search space in the HOMER optimization software had to be limited to a PV capacity range such that less than 49% of total solar generation in the microgrid was sold back to Grupo ICE.

3.2 Phase II: Three Faculty Houses and Lab

In Phase II of the project's development, all three faculty houses will be renovated, with a bedroom in House 2 serving as the dedicated lab space necessary for Capuchin research. These 11 field workers were assumed to follow the same daily schedule; however, there would be an additional electrical load from providing services to the lab. Due to the expected increased cycling of the water pump, three refrigerators, and the lab's sample-dedicated freezer, the measured baseload was assumed to double. A second washing machine is expected to be installed in this phase of the project, operating under the same assumption in Phase I of the project of 3 loads per week. The current team of researchers process lab samples once every other week, requiring the use of additional appliances on analysis days including a heat block, microplate reader and washer, plate shaker, analytical balance, vortexer and centrifuge. All these appliances would not be used simultaneously, so it was assumed that the two most energy-intensive appliances, the centrifuge and heat block, were used from 10-2PM on a typical lab analysis day.

Phase II of the project was subjected to the same isolated microgrid and grid-connected modeling as Phase I, and scaled to a greater average daily consumption to be determined from bottom-up energy modeling.

3.3 Phase III: Addition of 16-Bedroom Dorm

In addition to isolated and grid-connected PV microgrids, a hypothetical solar-biomass hybrid system was investigated for Phase III of the project, including the 16-bedroom dorm to house the field school's lodging and operations. It is unlikely that the gasifier-generator system would be run overnight due to noise concerns and residents sleeping, so the generator was forced off from 8pm to 5am daily before optimizing its scheduling in HOMER.

Maya Lapp, a fellow researcher in the Alfaro Lab, constructed a Biomass Harvesting and Gasification (BHAG) model during the summer of 2019. According to interviews with the surrounding farmers employed by UTN, the Taboga reserve is surrounded by rice and sugarcane fields shown in Table 2. The residue-to-product ratio (RPR) is useful for determining what proportion of total harvested biomass could be available to a gasifier to then supply a generator.

Table 2. Summary of residue yield parameters for Taboga fields.

Crop	Total Land (ha)	Number of Fields	Crop Yield (t/ha)	RPR
Rice	32	8	6,4,4	0.45
Sugarcane	100	25	60	0.14

The surrounding Taboga farming operation harvests 32 hectares of rice up to three times per year. The first harvest has the best soil quality, producing the greatest yield at six tons of rice per hectare (t/ha). The crop does not need to be replanted for the second harvest, which typically yields 4 t/ha. Finally, a third harvest is planted yielding an additional 4t/ha. Taboga currently collects the rice straw residue at an RPR of 0.45, which was assumed to be constant across the three harvests.

The reserve is also surrounded by 100 hectares of sugarcane, harvested once annually. These fields yield 60 t/ha sugarcane, and a literature RPR value of 0.14 for the sugarcane tops and leaves was assumed, since these residues are not currently collected (Crowe et al., 2009).

According to the USDA Foreign Agriculture service, rice is harvested in Costa Rica from August to November (2017). Considering a one month offset for the processing of residues into usable biomass, for modeling purposes it was assumed the largest biomass harvest would be available in September, followed by two smaller harvests in October and December. Similarly, sugarcane is harvested from December to April, so it was assumed that biomass would be available in February (Crowe et al., 2009). Since some amount of biomass material would likely be available year-round, the yield of each harvest was stretched until the next supply of residues would be available. These yields were converted into month average available biomass data, and inputted into HOMER (Figure 4, Sample calculations in Appendix C).

Month	Available Biomass (tonnes/day)
Jan	0.660
Feb	3.510
Mar	3.510
Apr	3.510
May	3.510
Jun	3.510
Jul	3.510
Aug	3.510
Sep	1.980
Oct	0.660

Annual Average (t/d): 2.43

Average price ($/t): 0.00
Carbon content (%): 5.00
Gasification Ratio (kg/kg): 0.70
LHV of biogas (MJ/kg): 5.00

Figure 4. Available Biomass resource as a HOMER input.

Sugarcane biogas has been reported to have a lower heating value of 5MJ/kg, and rice biogas was assumed to be the same (Anukam et al., n.d.). Carbon content and gasification ratio were left at default HOMER values of 5% carbon and 0.7 kg biogas/kg biomass feedstock. Biochar, a product of the gasification process that can be applied to help with water retention and soil fertility, will be given to farmers in exchange for the harvest residues, so the biomass was assumed to be supplied to the hypothetical gasifier free of charge.

Upon adding the biogas resource into HOMER, the generator's efficiency needed to be modified to reflect the thermodynamic limits of the biomass resource. The same slope (1.8826 kg/hr/kW output) and intercept coefficient (0.083 kg/hr/kW rated) for the fuel curve was assumed as another University of Michigan's Sustainability Without Borders Project that had used coffee agricultural residues in Puerto Rico (Appendix C, Barr & Raheel, 2020). These values will need to be updated as Taboga's sugarcane and rice residues are further analyzed, and upon further specification for the on-site gasifier.

3.4 Off-grid Freezer Pilot Project

The research station experiences frequent power outages, which can jeopardize the state of frozen samples necessary for capuchin research. As a proof of concept for the site and to address the energy security issues of the freezer, 1.5 kW of solar was installed on the current laboratory's roof at the field station. This installation consisted of ten 150W-12V panels and eight, 1 kWh Li-Ion batteries. The schematic for the off-grid freezer project is included in Appendix D.

4. Results

4.1 Bottom-Up Energy Model Results

Although the electric load profiles had similar shapes throughout the day for each of the three phases, the scaled annual average consumption (kWh/day) was determined for each phase using a bottom-up energy modeling approach. A base load consumption of 0.8kW was measured with a time-of-use energy meter at the House 4 residency in May, which was included in the bottom-up energy model using data collected from various kilowatt-hour meters. This methodology is summarized below for five loads in Table 3. With respect to Phases I-III, the average consumptions were determined to be 28.7, 61.2, and 77.3 kWh/day, and were used to scale the load profile before optimizing in HOMER.

Table 3. Sample of bottom-up energy model for Phase III.

				Total consumption		
	Quantity	Power (W)	Usage	Monthly (Wh/month)	Annual (kWh/year)	Notes
Bedroom overhead fan	16	60	8 hrs/day	215040	2580.5	
Bathroom lights	6	8.5	1 hour/day	1428	17.1	
Bedroom face fan	32	40	8 hrs/day	286720	3440.6	*Only in hot dry season
Shower light	8	8.5	10 min/day	317.3	3.8	
Sink light	8	8.5	10 min/day	317.3	3.8	

Sankey diagrams were constructed for each of the phases to better understand electricity demands as the field school develops. The diagram for Phase I can be found below in Figure 5, with those for Phases II and III included in Appendix F.

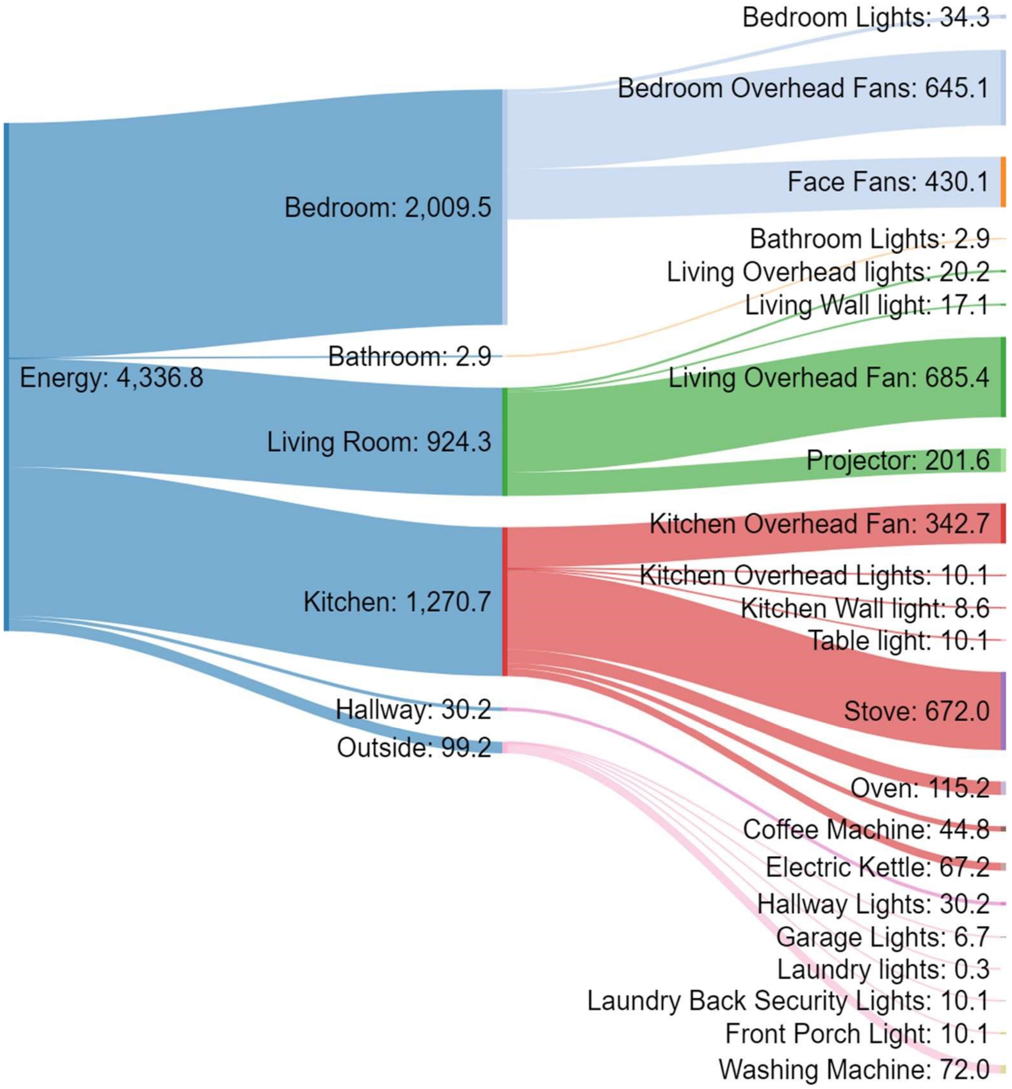

Figure 5. Sankey diagram for Phase I, values representing kWh/year.

4.2 Microgrid Optimization Results

Upon scaling daily consumption using the bottom-up energy model results, the most cost-effective microgrid architectures for each phase were optimized in HOMER. To determine grid-connected models compliant with Grupo ICE’s 49% rule, the PV Search Space in HOMER was iterated upon until no more than 49% of generated electricity was sold to the grid. Although biomass residues are exempt from Grupo ICE’s 49% rule, the biomass-supported microgrid was modeled without a grid connection as a 10-kW generator (Appendix B). Screenshots for the results of each model can be found in Appendices G-M. Optimized results such as net present costs (NPC) and levelized cost of electricity (LCOE) are summarized in the following Table 4.

Table 4. Results of HOMER Microgrid Optimizations.

	Phase I		Phase II		Phase III		
	grid-isolated	grid-connected	grid-isolated	grid-connected	grid-isolated	grid-connected	Biomass, grid-isolated
NPC ($)	35,804	9,465	77,943	22,232	94,557	24,289	58,365
LCOE ($/kWh)	0.265	0.0365	0.270	0.0406	0.259	0.0346	0.160
Excess Electricity (kWh/year)	11,640	0	27,149	0	31,429	0	0
Total PV Production (kWh/year)	23,458	13,620	52,420	27,948	63,192	37,322	298
PV Architecture (kW)	13.3	7.3	29.6	15.8	35.7	21.1	0.168
Li-Ion batteries (kWh)	62	0	127	0	163	0	63
Average Biomass feedstock (ton/day)	X	X	X	X	X	X	0.121

4.3 Off-grid Freezer Pilot Project Results

To address energy security concerns for the facility's lab freezer, the microgrid architecture of ten 150W PV panels and eight 1kWh lithium-ion batteries were procured and installed (Figure 6).

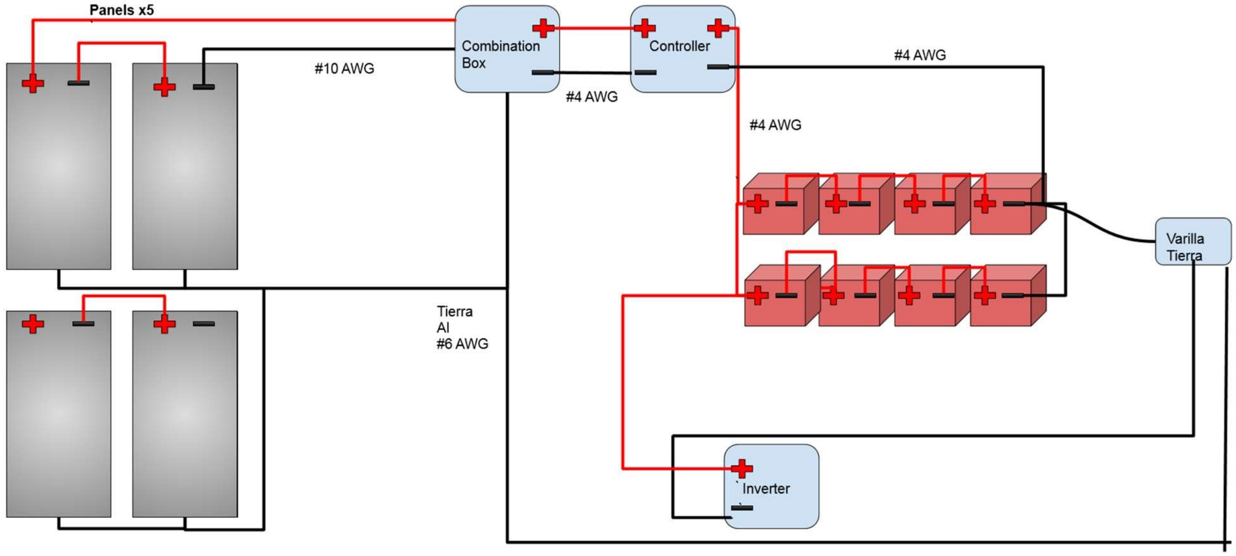

Figure 6. Wiring schematic for off-grid Lab freezer.

5. Discussion

In the energy models for each of the three Phases, the grid-connected microgrid resulted in the lowest net present cost and levelized cost of electricity compared to the grid-isolated model. It is clear that operations at the Taboga Forest Reserve could benefit from cheap electricity provided by photovoltaics; however, system adequacy issues concerning frequent blackouts experienced at Taboga encourages greater usage of distributed energy resources over which Taboga researchers have autonomy.

5.1 Microgrid Analysis

A common result for the state of charge of batteries in the grid-isolated models was deeper discharge projected to occur during the dry season (Figure 7). Likely due to the increased electricity demand in the dry season coinciding with a lesser solar resource, this is an important result to keep in mind. As the site's operations develop from the current research team to a fully occupied field school, it is likely that more students will visit the site over summer months, when more traditional university coursework is not in session.

These grid-isolated models also generated the greatest amount of excess electricity, primarily due to the afternoon hours between 12 and 6PM. The field school's operations and electric load should be shifted earlier from the end of the site's traditional workday, particularly during the dry season.

Figure 7. Simulated state of charge of batteries for Phase I operation, without grid connection.

An interesting result from the grid-connected models is that the most cost-effective architectures do not include battery storage. Batteries were one of the most expensive microgrid components, and are often cost prohibitive upon considering the Grupo ICE 49% rule described in the Background. According to Bloomberg New Energy Finance, lithium-ion battery pack storage is expected to drop roughly 20% annually, so these models should be revisited upon obtaining additional battery quotes (Goldie-Scot, 2019).

The biomass model constructed for Phase III of the project shows a more ideal state of charge simulation for the batteries. The batteries are nearly depleted at the beginning of the workday, and are fully charged from the solar and biomass resource by the end of the day (Figure 8). It also allows for a favorably consistent rate of fuel consumption of approximately 10kg/hr across the workday (Figure 9).

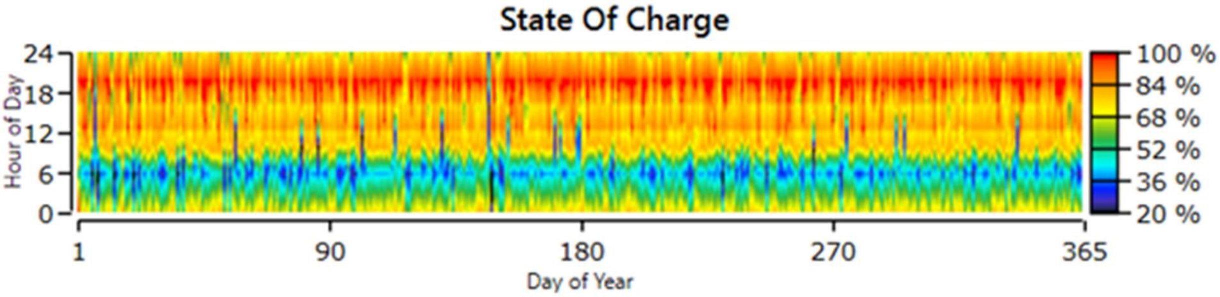

Figure 8. State of charge for batteries in Phase III biomass model.

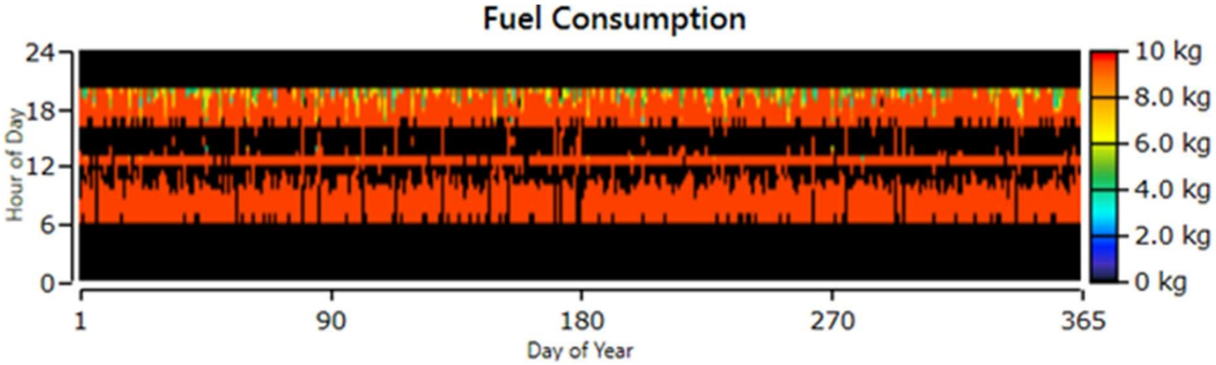

Figure 9. Biogas consumption for Phase III biomass model.

According to the results summarized in Table 4, the most significant increase in system costs comes from developing Phase I to Phase II. We expect Net Present Costs to more than double in this phase of development, compared to a price increase of up to 10% for the grid-connected models. Excess electricity generated steadily increases throughout the development of a grid-isolated facility, which is indicative that a fully self-sufficient facility is likely uneconomical until the two additional faculty houses and dormitory are renovated and equipped with time-of-use energy meters to better understand the site's load.

A sensitivity analysis was performed on the biomass resource, investigating the impact of the fuel's gasification ratio on the amount of biomass required. The search space spanned gasification ratios between 0.6 to 0.8 kg biogas/kg biomass feedstock to gasifier, with the lowest gasification ratio of 0.6 requiring 103 tons of residue per year. This is still within the projected yield of rice and sugarcane residues from the fields surrounding Taboga, and is a promising result that there may be enough surrounding biomass resources to realize an isolated microgrid.

5.2 Off-grid Freezer Pilot Analysis

This pilot project has provided the laboratory with enough power to sufficiently run the freezer that houses climate-sensitive research samples. As of April 2020, the off-grid system installed in May of 2019 has not experienced any significant complications, besides a small outage when the cables to the batteries got loose.

6. Conclusions and Next Steps

6.1 Conclusions from Energy Analysis

As a world leader in sustainability and conservation, Costa Rica is a prime location for the Taboga Research and Education Exchange to be constructed. It is feasible that the biological station and field school could be net-zero greenhouse gas emissions, and serve as an example for other research and schooling facilities across the globe of sustainable integration. To address sustainable energy at the Taboga Research and Education Exchange, a series of models were constructed to inform current and expected energy uses. These models provide insight into the cheapest and most efficient methods of providing the sight with sustainable energy. Although much work was done in the bottom-up energy accounting used to scale these microgrid optimization models, there are some aspects of this work that can be improved upon and that will need to be considered moving forward with this project.

Continuing to build on this Phase's work with biomass gasification will be a crucial part of the project in the future. Tecnológico de Costa Rica (Tech), joined the collaboration in early 2020, onboarding additional eager students with knowledge of biomass gasification to the Sustainability Without Borders team. Collaboration with UTN and Tech student teams will be a major part of this project. The experience in gasification technology that Tech has will be key in building and installing the gasifier. Furthermore, the opportunity for University of Michigan students to work in international teams will provide them with unique and challenging experiences. Work on the gasifier will also build on working relationships with the farms that surround the Reserve, furthering a project goal of greater involvement with the local community in biostation operations.

We also recommend greater collaboration between the energy modeling and Capuchins de Taboga teams, as it is imperative for designing a system that provides for the Capuchin de Taboga team's needs as they expand into the Taboga Research and Education Exchange. It is imperative that Capuchins de Taboga team monitors any changes the modeling team implements such as the off-grid freezer pilot project. Regular updates on the performance of the energy resources will be important for the energy modeling team to allow them to make necessary updates to the energy models or the sustainable energy plans. Monthly virtual meetings between the University of Michigan team and Capuchin Researchers would assure a smooth process in the creation of the Taboga Research and Education Exchange.

Furthermore, greater electrical submetering is needed between SINAC and the Capuchins de Taboga operations to further delineate utility bills and inform the expansion of the microgrid. Aligned with the mantra "you can't manage what you can't measure", it can be tricky to allocate resources shared between both parties, such as information and communication technologies and the water pump. Although it would take increased capital spending, greater time-of-use knowledge of the team's electricity consumption would enhance any optimization results and should be included in development plans throughout each phase—particularly once lab operations are moved to a newly renovated faculty house. The next team of Sustainability Without Borders students should compare utility bills and usage with the constructed energy models, and update them accordingly. Cost estimates for larger battery units should be obtained to more cost-effectively provide a greater storage resource. Upon installing greater time-of-use monitoring for the pilot project's batteries, specific loads should be shifted to that microgrid such as security lights and any additional refrigeration needs.

6.2 Future Sustainability Steps

Preliminary analysis was done to determine the viability of rain catchment as a sustainable water supply. Capuchins de Taboga researchers have been collecting monthly precipitation data for two years, and this data were aggregated to estimate a potential volume of collectable water. Roof areas were recorded for each building using Google Maps and Google Earth. With this information, the amount of water that could be collected by each building every month was calculated. Further calculations were made considering the possibility of including a first flush system on each roof. A first flush system diverts the first flow of water during a rainfall due to this first flow being contaminated with debris that has collected on the roof's surface since the last rainfall (Appendix E). Depending on what this water supply would be used for, a first flush system may need to be installed. It is recommended to divert two liters of water per square meter of roof. Calculations were repeated upon considering this added information.

As this was not the current focus of the project, this analysis is based solely on the amount of rain the campus could catch and does not include any information on how much water would be used by the campus. With this in mind, the data show that the campus could collect enough water in the wet season to be used for greywater purposes such as flushing toilets, minor garden irrigation, and other non-potable uses. Because it would be used for non-potable uses, it would be best to not install a first flush system in order to maximize the amount of water available to use for these purposes. With four months in the dry season producing no rainfall, other sustainable water solutions may have to be explored. It is currently uncertain if enough water from the wet season can be stored for use during the dry season. Future teams need to further the work started on sourcing a sustainable water supply for the campus including verifying rain catchment data, and investigating information on the water pumps being used on site.

On the next portion of the project there will be one or two students brought on from the University of Michigan Taubman School of Architecture. These students will be involved in the restoration and sustainable development of the dorm building, and possibly other buildings not currently scheduled as part of this project. This will ensure that when the campus is fully functional it will not only be running sustainably, but it will have been built sustainably as well.

Other aspects of the campus that need to be looked into for sustainable development are waste and transportation. Along with waste produced by normal everyday living, the Capuchins de Taboga team also produces waste from the processes they utilize in their research. Furthermore, the Capuchins de Taboga team currently gets around the reserve by using an aged truck. A more sustainable form of transportation and a plan to minimize waste are both issues future teams will investigate to insure the Taboga Research and Education Exchange is a world class, net zero biological station and field school.

Long term goals for the project include quality of life aspects. such as growing produce for the students and faculty on the reserve. By growing their own food, the biological station will reduce its dependence on the carbon-intensive distribution practices of major farms. Growing their own food would also add to the education of the students in ecology, botany, and sustainability. This would benefit from the compost practices created in the waste management stage and the greywater rain catchment from the sustainable water stage of the project.

Further involvement of local partners will be important to ensure the continued success of this project. Students and faculty from Costa Rican universities should be involved with each step of the project. These local partners will be able to provide expertise in various stages of the project. Community involvement, from working with farmers in biomass gasification, to community engagement and education programs, will help the station fill its role as an education center for the environment and sustainability. By participating in community engagement programs students and faculty will be able to learn the best techniques and strategies for teaching the public about complex topics of sustainability, and the public will become more engaged with the station and the work being done there.

By becoming net-zero through sustainable energy sources, water use, waste management, and community involvement the Taboga Research and Education Exchange will establish itself as a site that will be an example for other biological stations to become net-zero.

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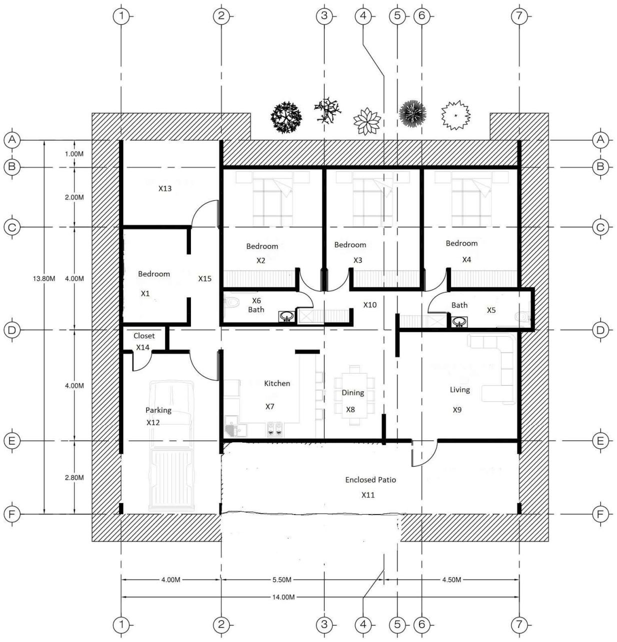
Appendices

Appendix A: Floor plan for Phase I “Green House” and various renovation photos



Appendix B: HOMER system component parameters tables used across models

Table 5. Generic flat PV parameter table.

Parameter:	Generic Flat Plate PV
Capacity (kW)	0.39
Capital Cost ($)	353
Replacement Cost ($)	353
O & M ($/yr)	0
Lifetime (yr)	25
Derating Factor (%)	80

Table 6. Generic 1kWh Li-Ion battery parameter table.

Parameter:	Generic 1kWh Li-Ion Battery
Capacity (kW)	0.39
Capital Cost ($)	375
Replacement Cost ($)	375
O & M ($/yr)	0
Lifetime (yr)	25
Throughput (kWh)	3000
Initial State of Charge (%)	100
Minimum State of Charge (%)	20
String Size	1
Voltage (V)	6

Table 7. Generic system converter parameter table

Parameter:	Generic System Converter
Capacity (kW)	1
Capital Cost ($)	0 (included in PV Pricing)
Replacement Cost ($)	0.01 (included in PV Pricing)
O & M ($/yr)	0
Lifetime (yr)	25
Inverter Efficiency (%)	95
Rectifier Efficiency (%)	95
Rectifier Relative Capacity (%)	100

Table 8. Generic 10 kW fixed generator parameter table.

Parameter:	Generic 10kW Fixed Generator
Capacity (kW)	10
Capital Cost ($)	6,000
Replacement Cost ($)	760
O & M ($/op. hour)	0.30
Lifetime (hrs)	15,000
Minimum Load Ratio(%)	25

Appendix C: Supplemental biomass information

Sample residue-to-product ratio (RPR) calculations:

$$1 - \frac{1}{0.45\,residue\ +\ 1\,crop} = 31.0\%\,mass\ rice$$

$$1 - \frac{1}{0.14\,residue\ +\ 1\,crop} = 12.3\%\,mass\ sugarcane\ residue$$

Sample rice harvest calculation for first harvest:

$$32\ \frac{ha\ \ rice\ harvest}{month} \times \frac{6\ t}{ha} \times 31\%\,residue \div 30\ days = 1.98\ t/day\ available\ biomass$$

Sample sugarcane harvest calculation:

$$100\ \frac{ha\ \ sugarcane\ harvest}{month} \times \frac{60\ t}{ha} \times 12.3\%\,residue \div 30\ days \\ \div 7\ months\ until\ first\ rice\ harvest = 3.51\ t/day\ available\ biomass$$

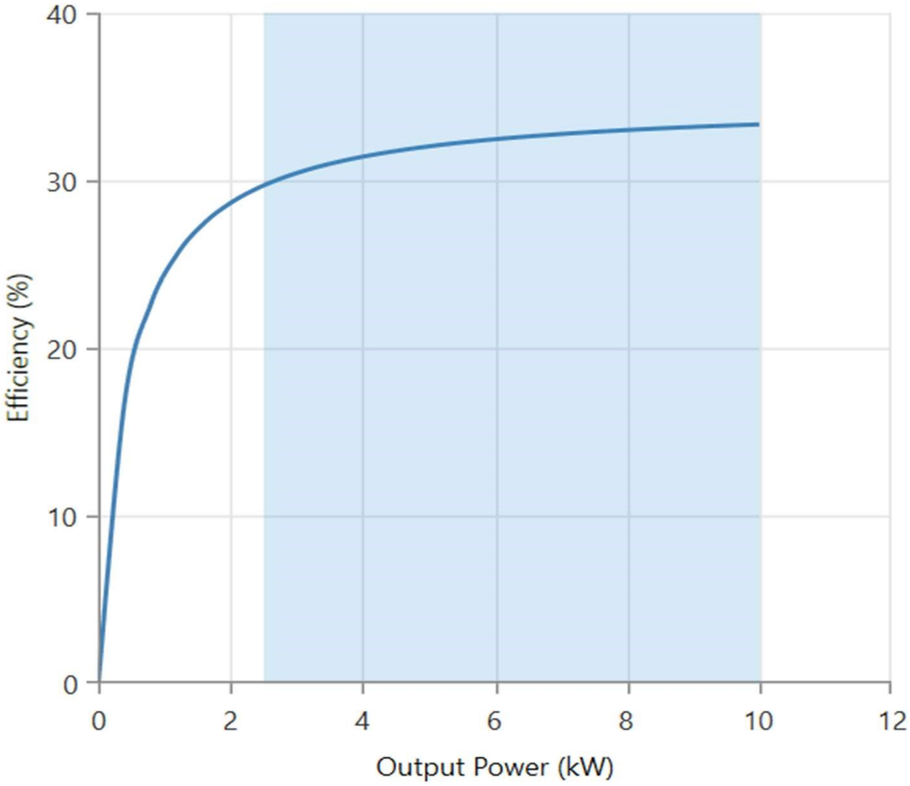
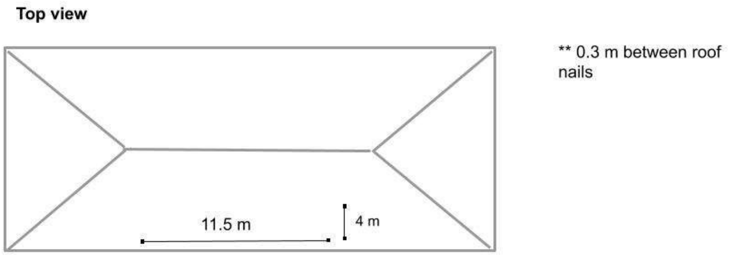
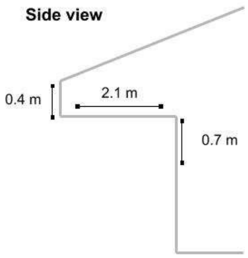
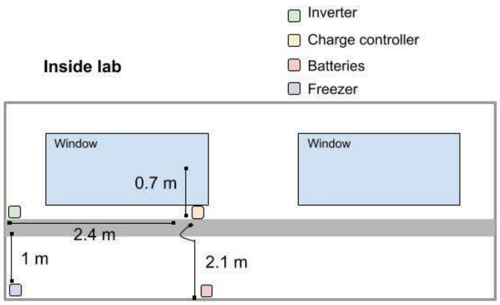


Figure 10. Generator efficiency curve used by Sustainability Without Borders-Puerto Rico.

Appendix D: Specifications of freezer pilot project microgrid







Appendix E: First flush system description

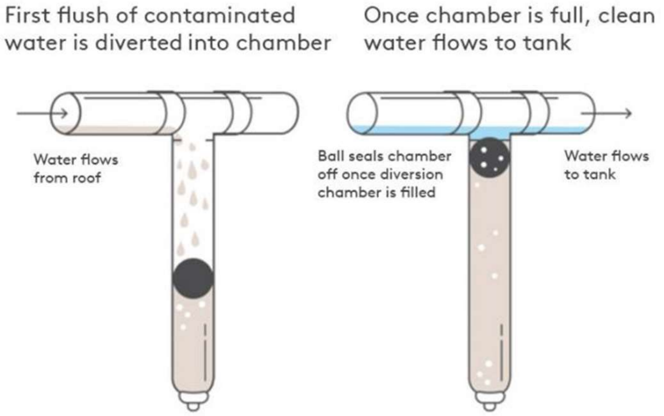


Figure 11. Rain harvesting first-flush diverter provided by Water Ionizer

Appendix F: Phase II and Phase III bottom-up Sankey Diagrams

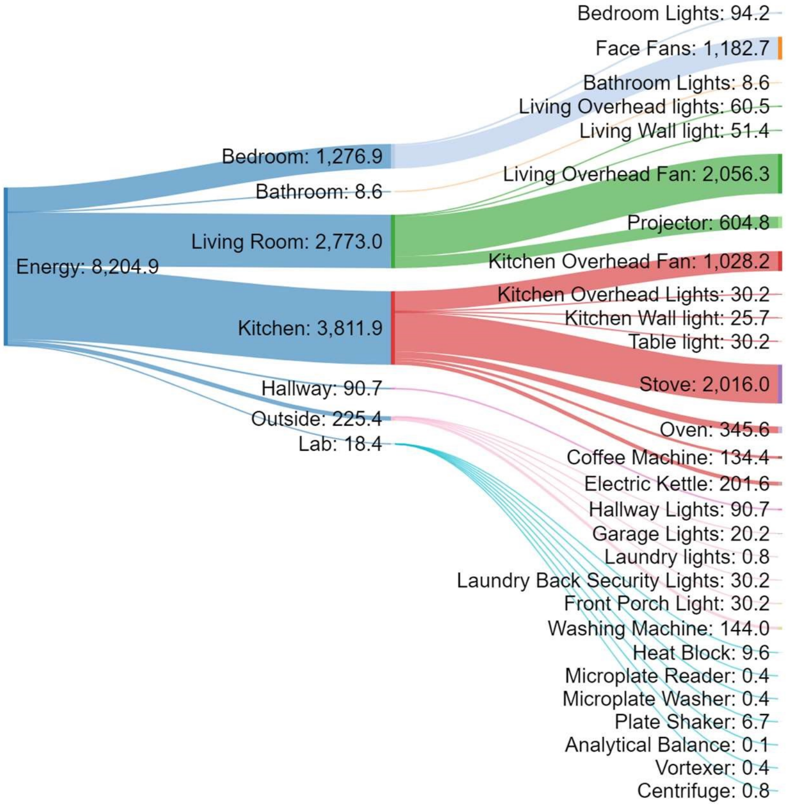


Figure 12. Phase II bottom-up Sankey diagram.

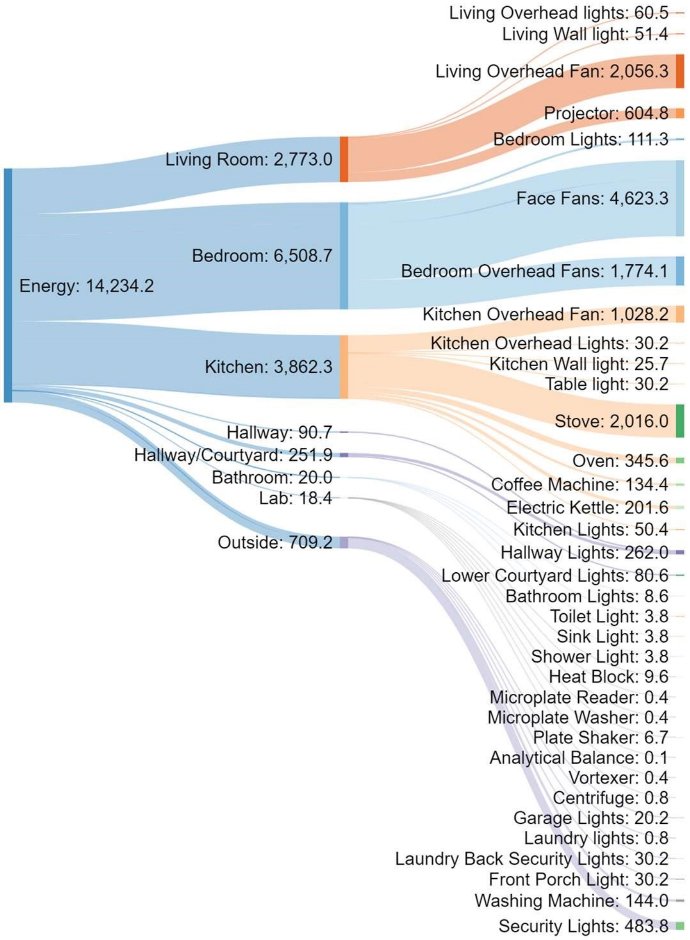


Figure 13. Phase III bottom-up Sankey diagram.

Appendix G: Phase I grid-isolated modeling results

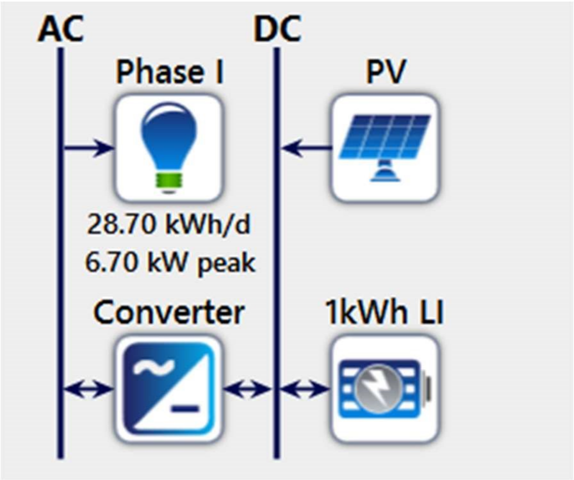
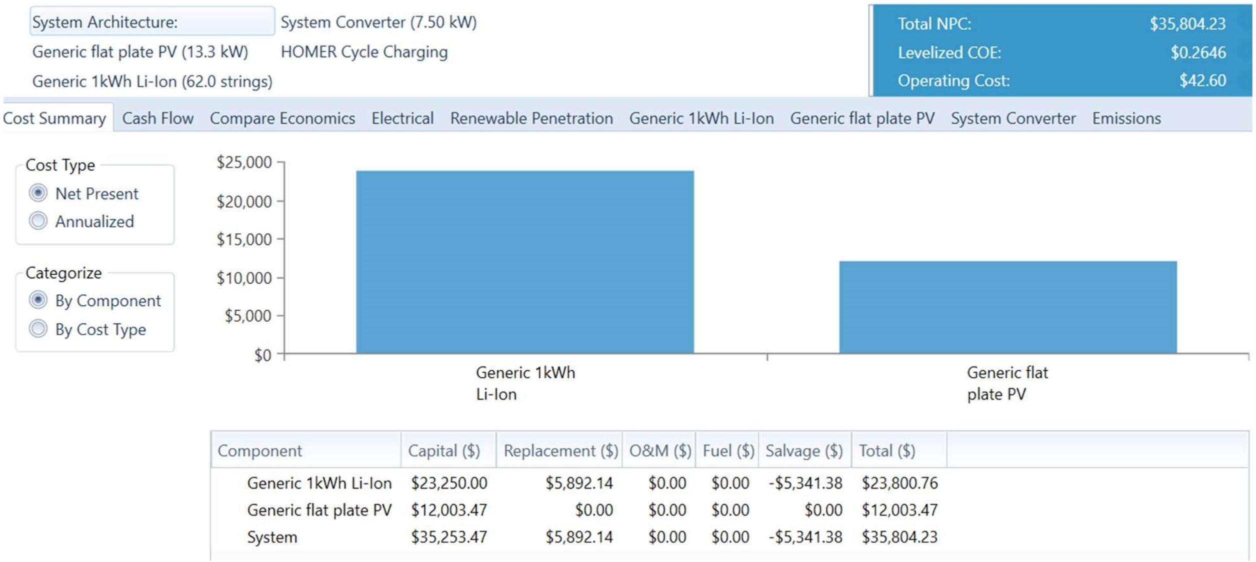


Figure 14. Phase I grid-isolated connection schematic.



System Architecture: System Converter (7.50 kW)
Generic flat plate PV (13.3 kW) HOMER Cycle Charging
Generic 1kWh Li-Ion (62.0 strings)

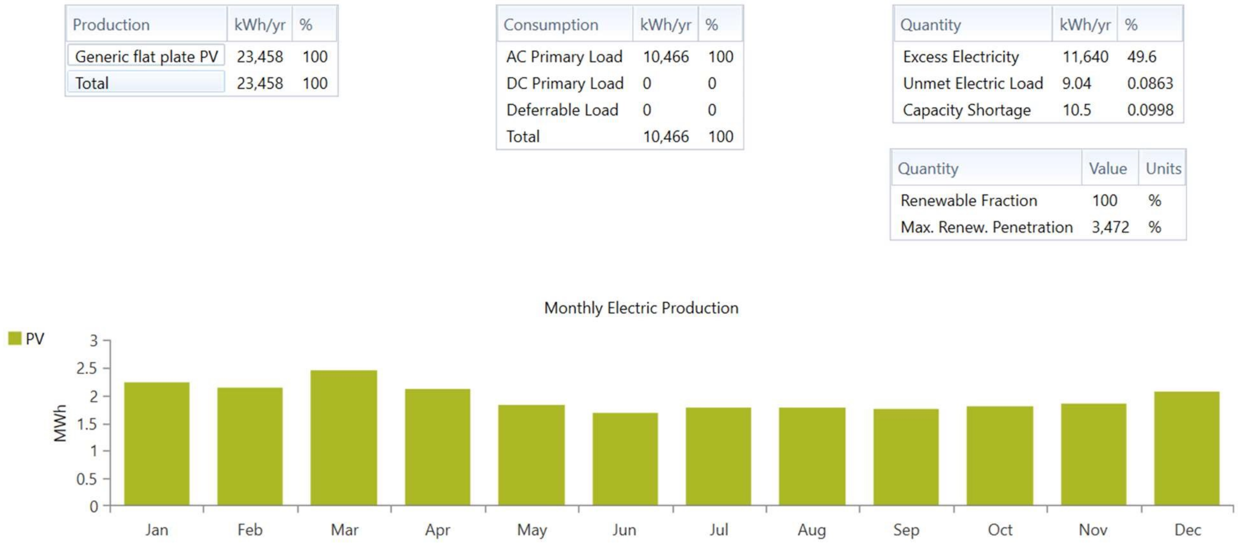
Total NPC: $35,804.23
Levelized COE: $0.2646
Operating Cost: $42.60

Cost Type
● Net Present
○ Annualized

Categorize
● By Component
○ By Cost Type

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Generic 1kWh Li-Ion	$23,250.00	$5,892.14	$0.00	$0.00	-$5,341.38	$23,800.76
Generic flat plate PV	$12,003.47	$0.00	$0.00	$0.00	$0.00	$12,003.47
System	$35,253.47	$5,892.14	$0.00	$0.00	-$5,341.38	$35,804.23

Figure 15. Phase I grid-isolated cost summary.



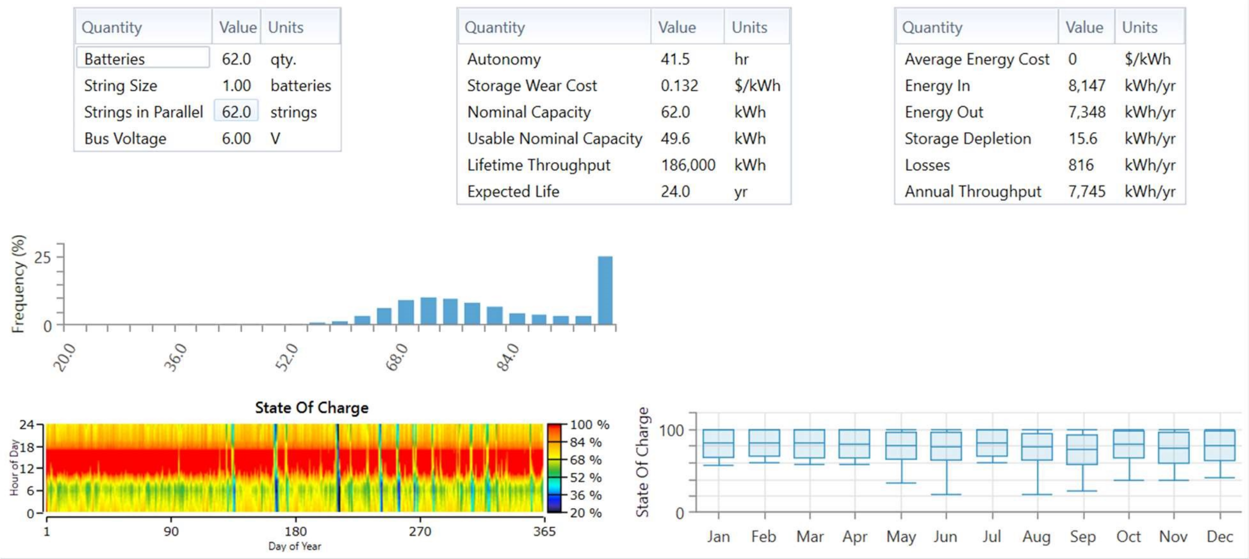
Production	kWh/yr	%
Generic flat plate PV	23,458	100
Total	23,458	100

Consumption	kWh/yr	%
AC Primary Load	10,466	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	10,466	100

Quantity	kWh/yr	%
Excess Electricity	11,640	49.6
Unmet Electric Load	9.04	0.0863
Capacity Shortage	10.5	0.0998

Quantity	Value	Units
Renewable Fraction	100	%
Max. Renew. Penetration	3,472	%

Figure 16. Phase I grid-isolated electrical summary.

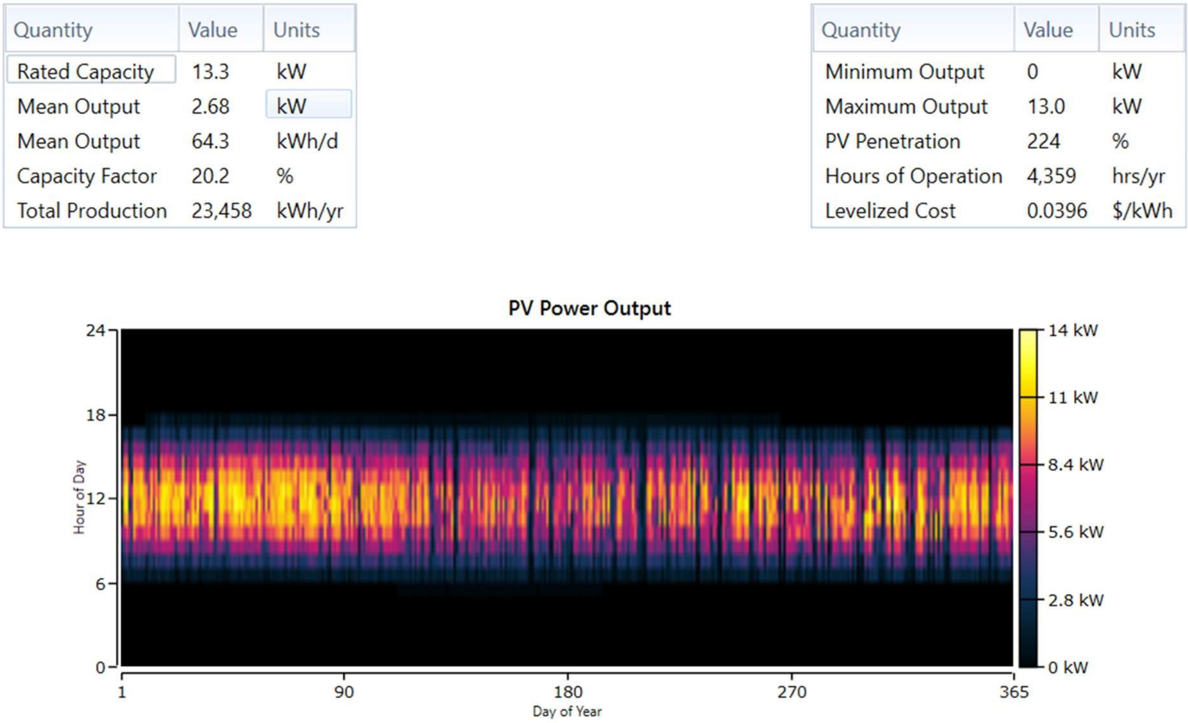


Quantity	Value	Units
Batteries	62.0	qty.
String Size	1.00	batteries
Strings in Parallel	62.0	strings
Bus Voltage	6.00	V

Quantity	Value	Units
Autonomy	41.5	hr
Storage Wear Cost	0.132	$/kWh
Nominal Capacity	62.0	kWh
Usable Nominal Capacity	49.6	kWh
Lifetime Throughput	186,000	kWh
Expected Life	24.0	yr

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	8,147	kWh/yr
Energy Out	7,348	kWh/yr
Storage Depletion	15.6	kWh/yr
Losses	816	kWh/yr
Annual Throughput	7,745	kWh/yr

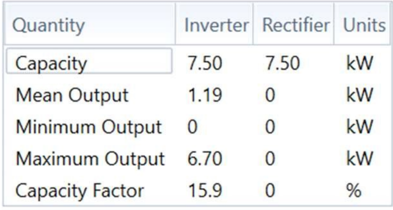
Figure 17. Phase I grid-isolated battery summary.



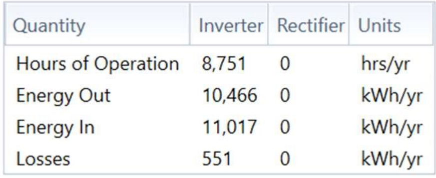
Quantity	Value	Units
Rated Capacity	13.3	kW
Mean Output	2.68	kW
Mean Output	64.3	kWh/d
Capacity Factor	20.2	%
Total Production	23,458	kWh/yr

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	13.0	kW
PV Penetration	224	%
Hours of Operation	4,359	hrs/yr
Levelized Cost	0.0396	$/kWh

Figure 18. Phase I grid-isolated PV summary.



Quantity	Inverter	Rectifier	Units
Capacity	7.50	7.50	kW
Mean Output	1.19	0	kW
Minimum Output	0	0	kW
Maximum Output	6.70	0	kW
Capacity Factor	15.9	0	%



Quantity	Inverter	Rectifier	Units
Hours of Operation	8,751	0	hrs/yr
Energy Out	10,466	0	kWh/yr
Energy In	11,017	0	kWh/yr
Losses	551	0	kWh/yr

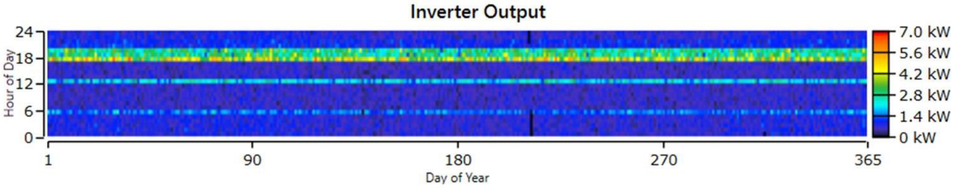


Figure 19. Phase I grid-isolated inverter summary.

Appendix H: Phase II grid-connected modeling results

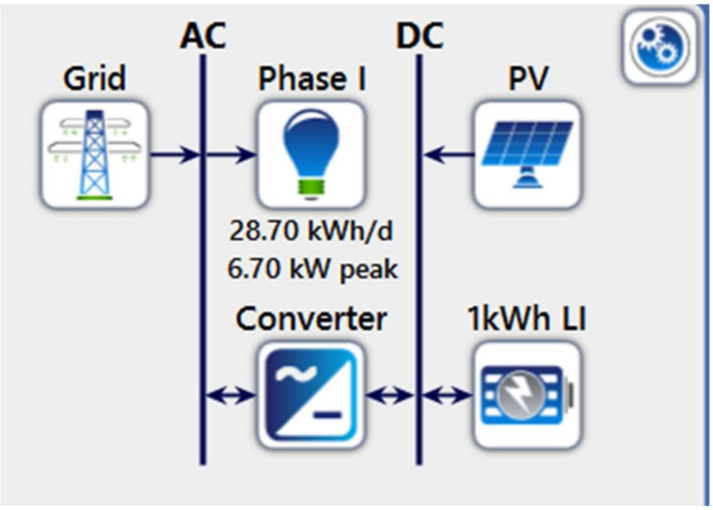
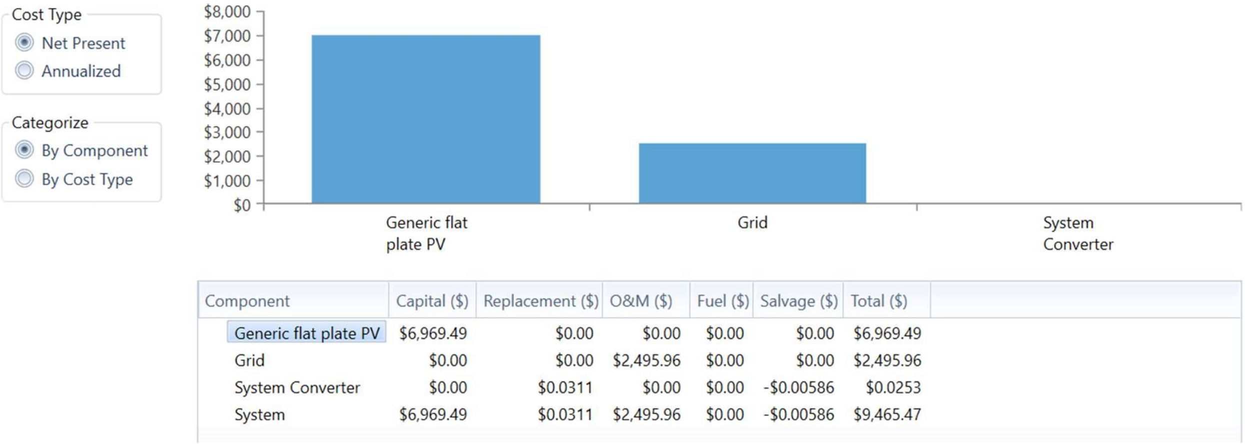


Figure 20. Phase I grid-connected connection schematic.

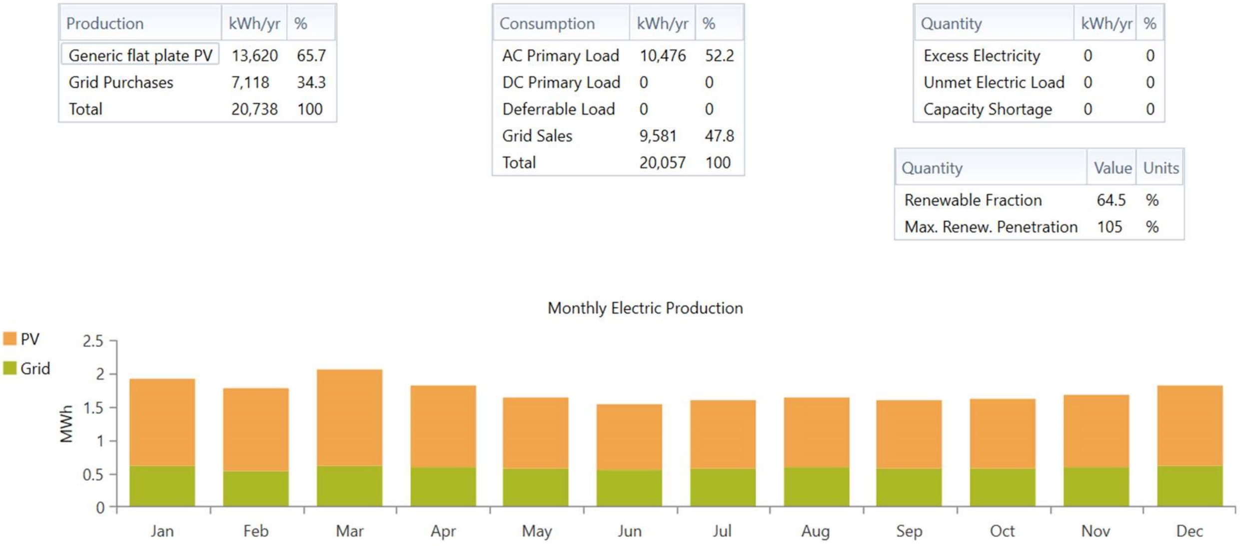


Cost Type
- ● Net Present
- ○ Annualized

Categorize
- ● By Component
- ○ By Cost Type

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Generic flat plate PV	$6,969.49	$0.00	$0.00	$0.00	$0.00	$6,969.49
Grid	$0.00	$0.00	$2,495.96	$0.00	$0.00	$2,495.96
System Converter	$0.00	$0.0311	$0.00	$0.00	-$0.00586	$0.0253
System	$6,969.49	$0.0311	$2,495.96	$0.00	-$0.00586	$9,465.47

Figure 21. Phase I grid-connected cost summary



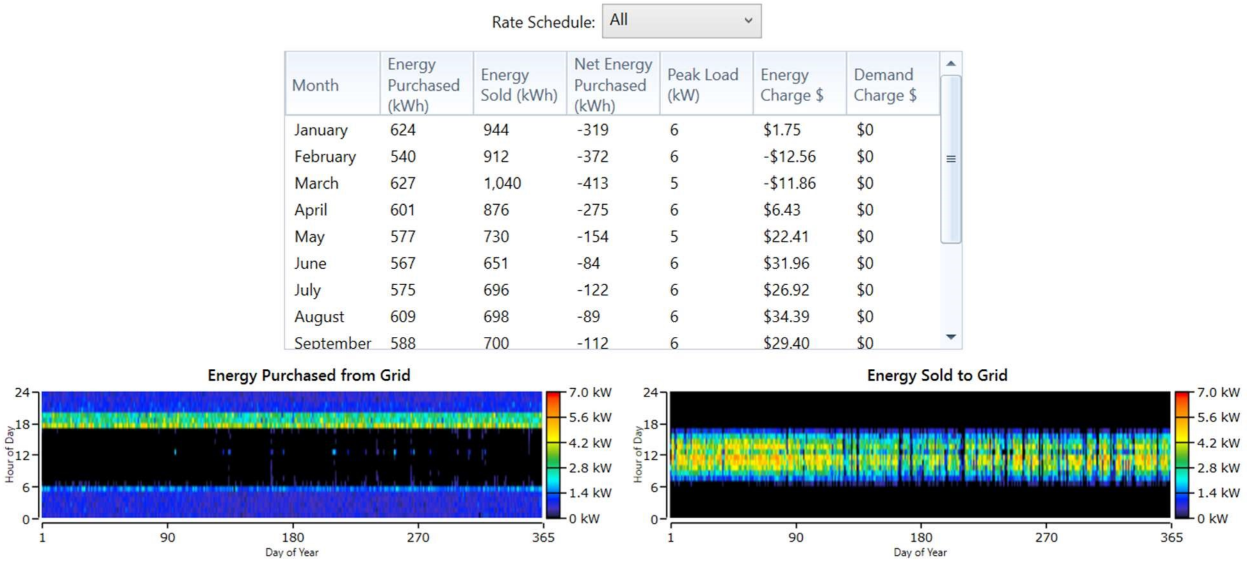
Production	kWh/yr	%
Generic flat plate PV	13,620	65.7
Grid Purchases	7,118	34.3
Total	20,738	100

Consumption	kWh/yr	%
AC Primary Load	10,476	52.2
DC Primary Load	0	0
Deferrable Load	0	0
Grid Sales	9,581	47.8
Total	20,057	100

Quantity	kWh/yr	%
Excess Electricity	0	0
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value	Units
Renewable Fraction	64.5	%
Max. Renew. Penetration	105	%

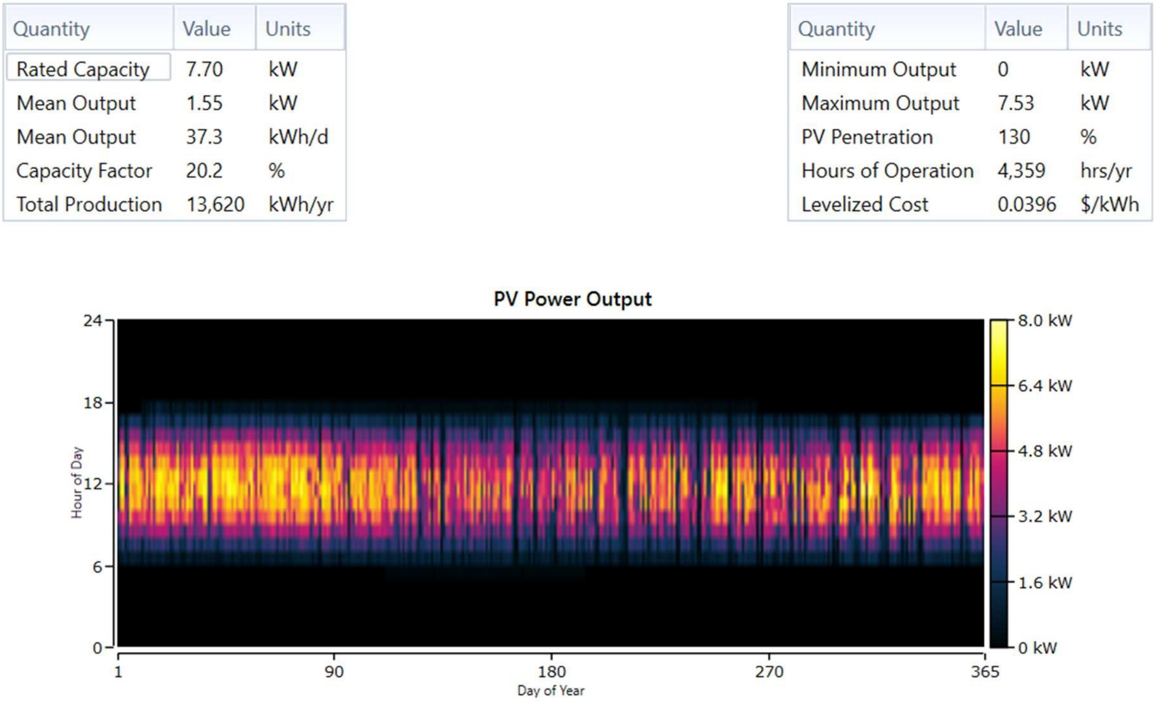
Figure 22. Phase I no-grid electrical summary.



Rate Schedule: All

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Load (kW)	Energy Charge $	Demand Charge $
January	624	944	-319	6	$1.75	$0
February	540	912	-372	6	-$12.56	$0
March	627	1,040	-413	5	-$11.86	$0
April	601	876	-275	6	$6.43	$0
May	577	730	-154	5	$22.41	$0
June	567	651	-84	6	$31.96	$0
July	575	696	-122	6	$26.92	$0
August	609	698	-89	6	$34.39	$0
September	588	700	-112	6	$29.40	$0

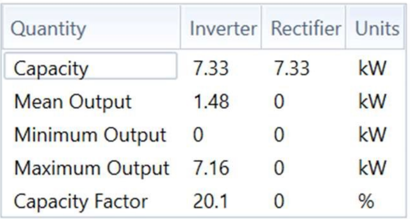
Figure 23. Phase I grid-connected grid summary.



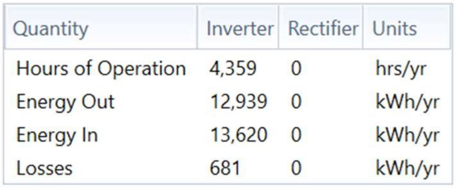
Quantity	Value	Units
Rated Capacity	7.70	kW
Mean Output	1.55	kW
Mean Output	37.3	kWh/d
Capacity Factor	20.2	%
Total Production	13,620	kWh/yr

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	7.53	kW
PV Penetration	130	%
Hours of Operation	4,359	hrs/yr
Levelized Cost	0.0396	$/kWh

Figure 24. Phase I grid-connected PV summary.



Quantity	Inverter	Rectifier	Units
Capacity	7.33	7.33	kW
Mean Output	1.48	0	kW
Minimum Output	0	0	kW
Maximum Output	7.16	0	kW
Capacity Factor	20.1	0	%



Quantity	Inverter	Rectifier	Units
Hours of Operation	4,359	0	hrs/yr
Energy Out	12,939	0	kWh/yr
Energy In	13,620	0	kWh/yr
Losses	681	0	kWh/yr

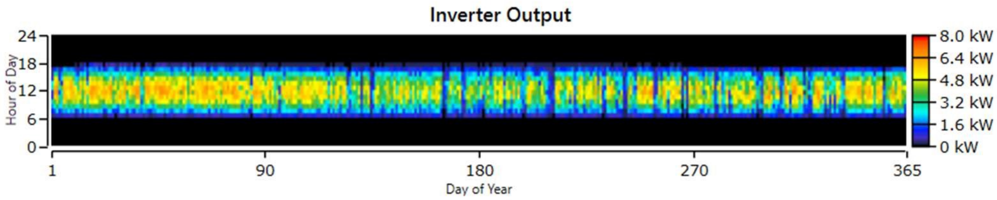


Figure 25. Phase I grid-connected inverter summary.

Appendix I: Phase II grid-isolated modeling results

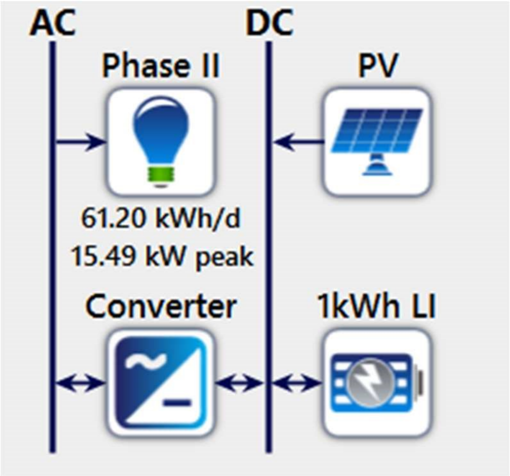
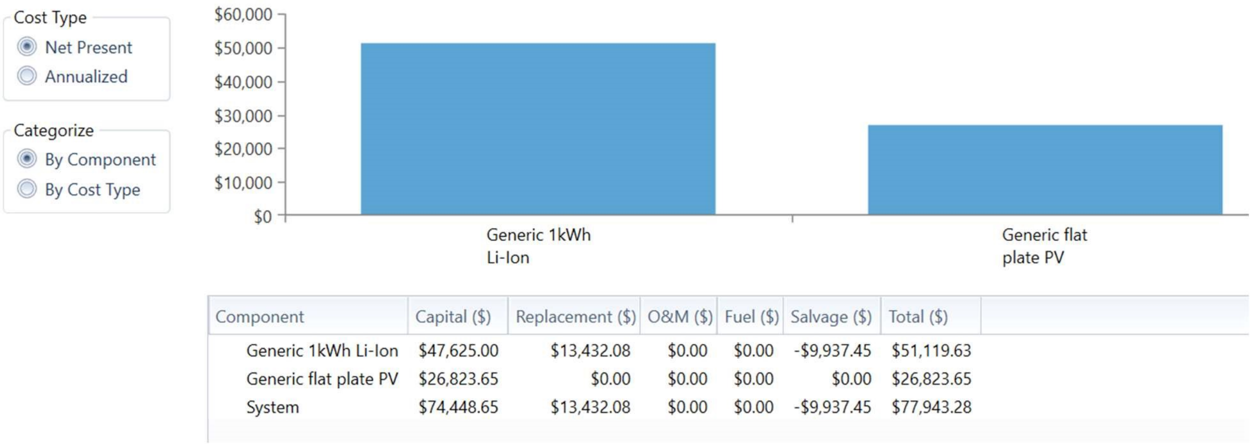


Figure 26. Phase II grid-isolated connection schematic.

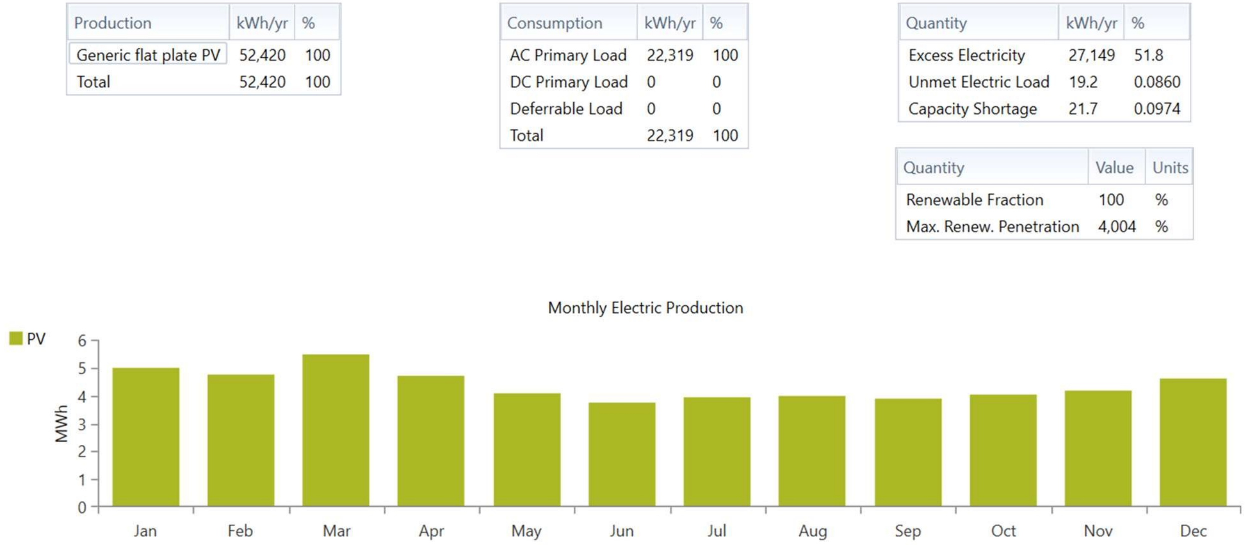


Cost Type
- ● Net Present
- ○ Annualized

Categorize
- ● By Component
- ○ By Cost Type

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Generic 1kWh Li-Ion	$47,625.00	$13,432.08	$0.00	$0.00	-$9,937.45	$51,119.63
Generic flat plate PV	$26,823.65	$0.00	$0.00	$0.00	$0.00	$26,823.65
System	$74,448.65	$13,432.08	$0.00	$0.00	-$9,937.45	$77,943.28

Figure 27. Phase II grid-isolated cost summary.



Production	kWh/yr	%
Generic flat plate PV	52,420	100
Total	52,420	100

Consumption	kWh/yr	%
AC Primary Load	22,319	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	22,319	100

Quantity	kWh/yr	%
Excess Electricity	27,149	51.8
Unmet Electric Load	19.2	0.0860
Capacity Shortage	21.7	0.0974

Quantity	Value	Units
Renewable Fraction	100	%
Max. Renew. Penetration	4,004	%

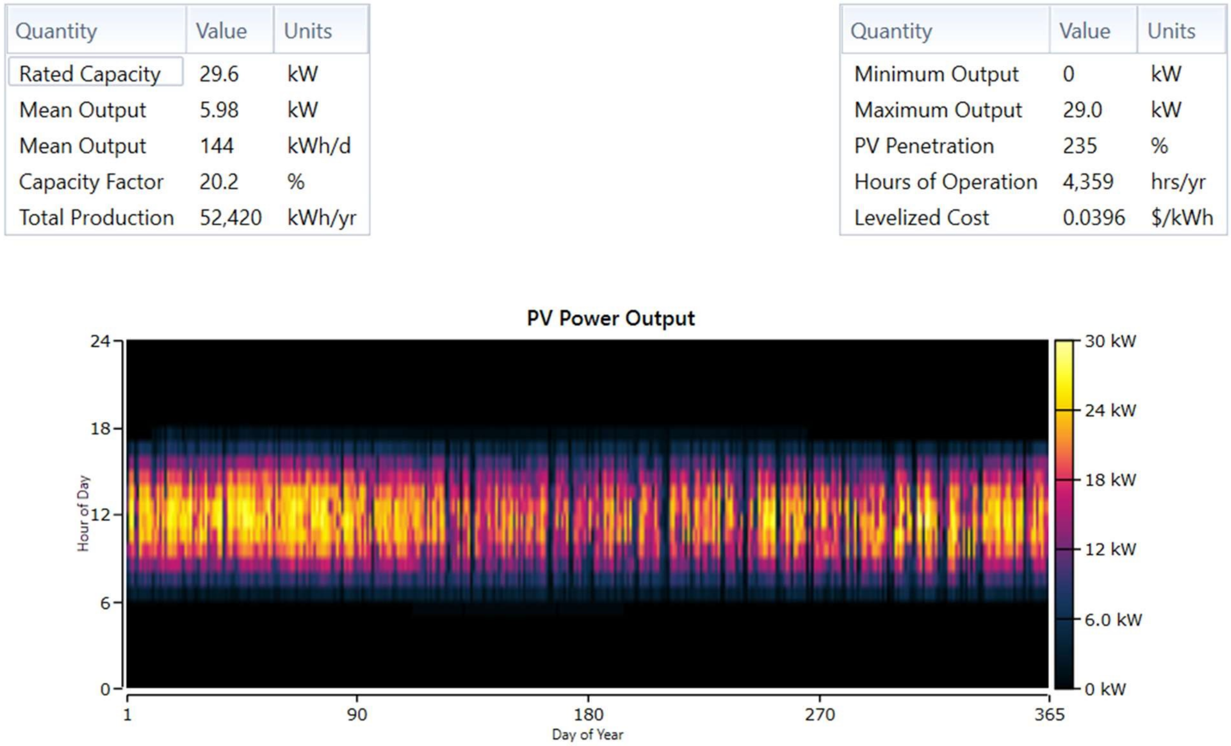
Figure 28. Phase II grid-isolated electrical summary.

Quantity	Value	Units
Batteries	127	qty.
String Size	1.00	batteries
Strings in Parallel	127	strings
Bus Voltage	6.00	V

Quantity	Value	Units
Autonomy	39.8	hr
Storage Wear Cost	0.132	$/kWh
Nominal Capacity	127	kWh
Usable Nominal Capacity	102	kWh
Lifetime Throughput	381,000	kWh
Expected Life	22.1	yr

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	18,099	kWh/yr
Energy Out	16,323	kWh/yr
Storage Depletion	35.0	kWh/yr
Losses	1,812	kWh/yr
Annual Throughput	17,206	kWh/yr

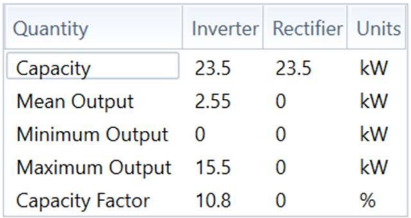
Figure 29. Phase II grid-isolated battery summary.



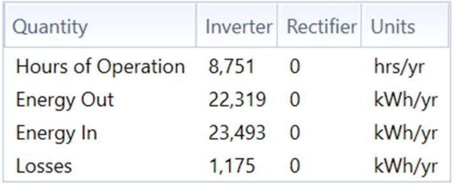
Quantity	Value	Units
Rated Capacity	29.6	kW
Mean Output	5.98	kW
Mean Output	144	kWh/d
Capacity Factor	20.2	%
Total Production	52,420	kWh/yr

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	29.0	kW
PV Penetration	235	%
Hours of Operation	4,359	hrs/yr
Levelized Cost	0.0396	$/kWh

Figure 30. Phase II grid-isolated PV summary.



Quantity	Inverter	Rectifier	Units
Capacity	23.5	23.5	kW
Mean Output	2.55	0	kW
Minimum Output	0	0	kW
Maximum Output	15.5	0	kW
Capacity Factor	10.8	0	%



Quantity	Inverter	Rectifier	Units
Hours of Operation	8,751	0	hrs/yr
Energy Out	22,319	0	kWh/yr
Energy In	23,493	0	kWh/yr
Losses	1,175	0	kWh/yr

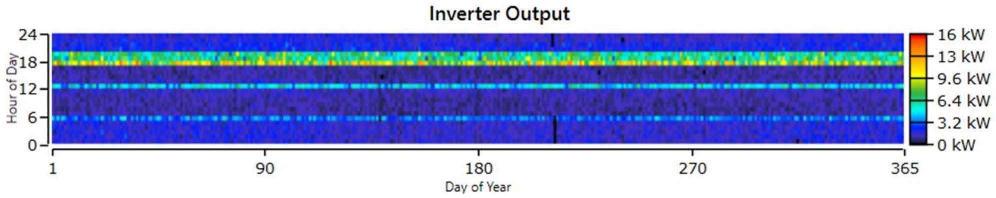


Figure 31. Phase II grid-isolated inverter summary.

Appendix J: Phase II grid-connected modeling results

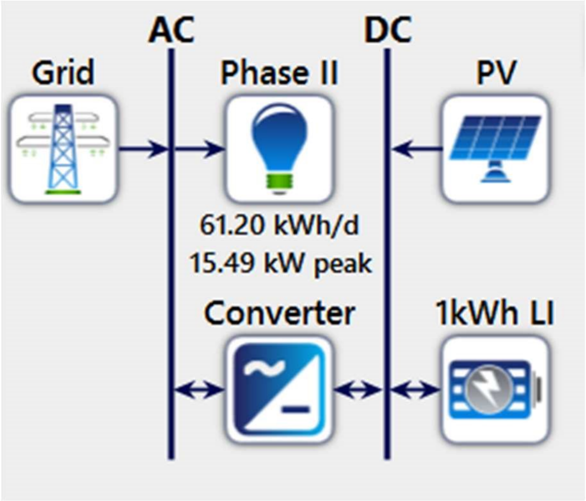
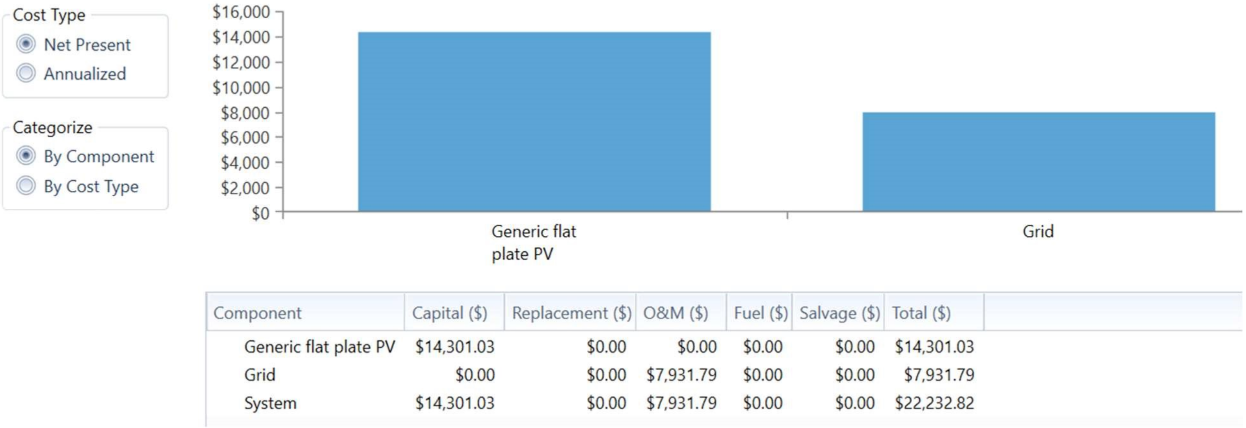


Figure 32. Phase II grid-connected connection schematic.

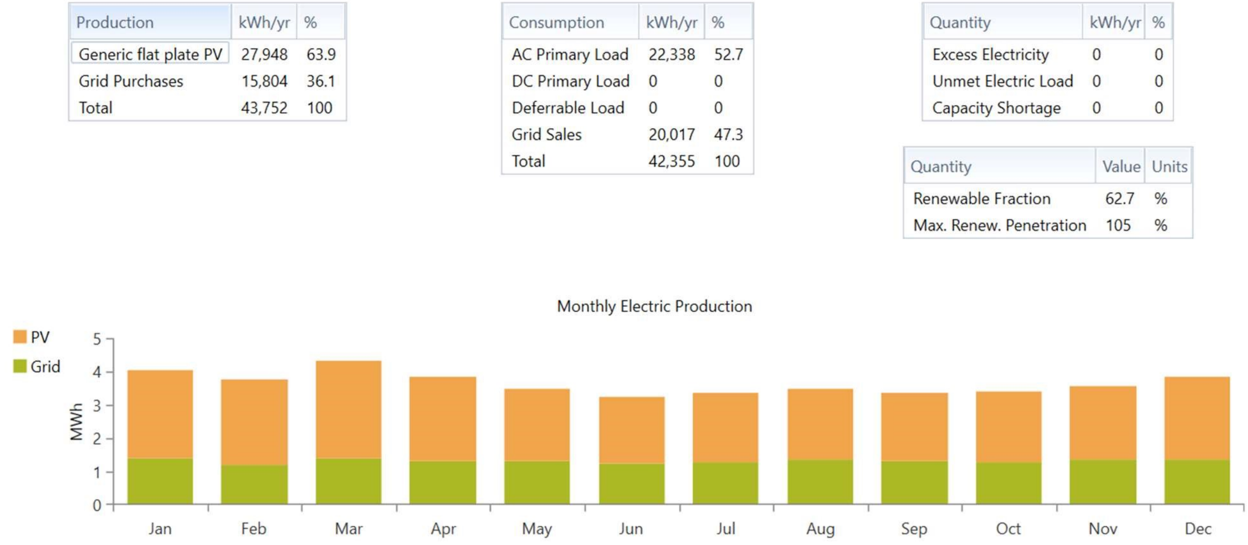


Cost Type
● Net Present
○ Annualized

Categorize
● By Component
○ By Cost Type

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Generic flat plate PV	$14,301.03	$0.00	$0.00	$0.00	$0.00	$14,301.03
Grid	$0.00	$0.00	$7,931.79	$0.00	$0.00	$7,931.79
System	$14,301.03	$0.00	$7,931.79	$0.00	$0.00	$22,232.82

Figure 33. Phase II grid-connected cost summary.



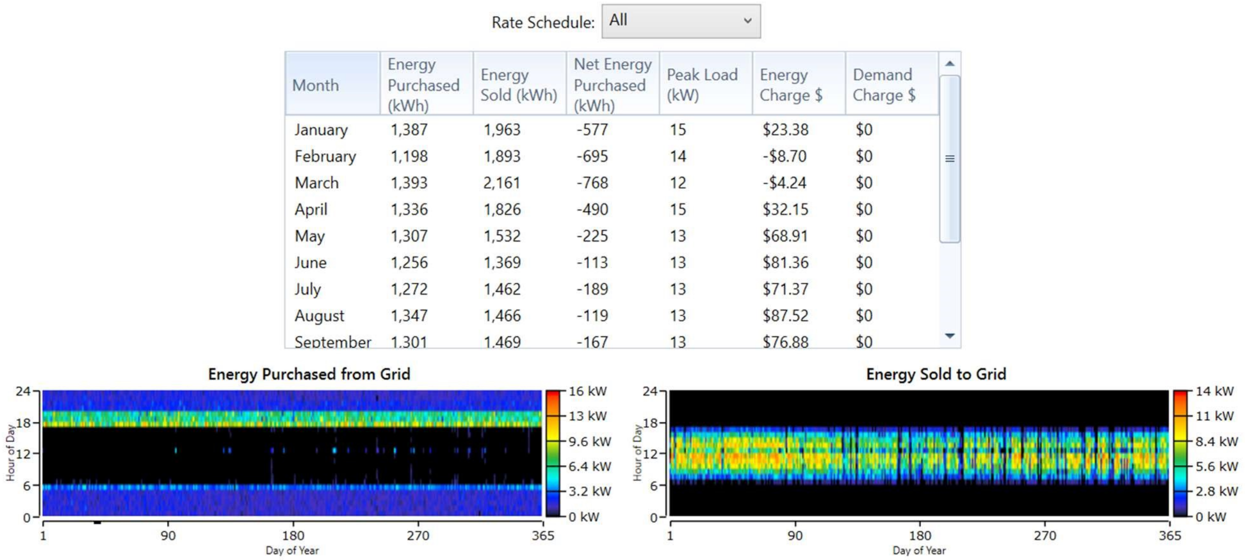
Production	kWh/yr	%
Generic flat plate PV	27,948	63.9
Grid Purchases	15,804	36.1
Total	43,752	100

Consumption	kWh/yr	%
AC Primary Load	22,338	52.7
DC Primary Load	0	0
Deferrable Load	0	0
Grid Sales	20,017	47.3
Total	42,355	100

Quantity	kWh/yr	%
Excess Electricity	0	0
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value	Units
Renewable Fraction	62.7	%
Max. Renew. Penetration	105	%

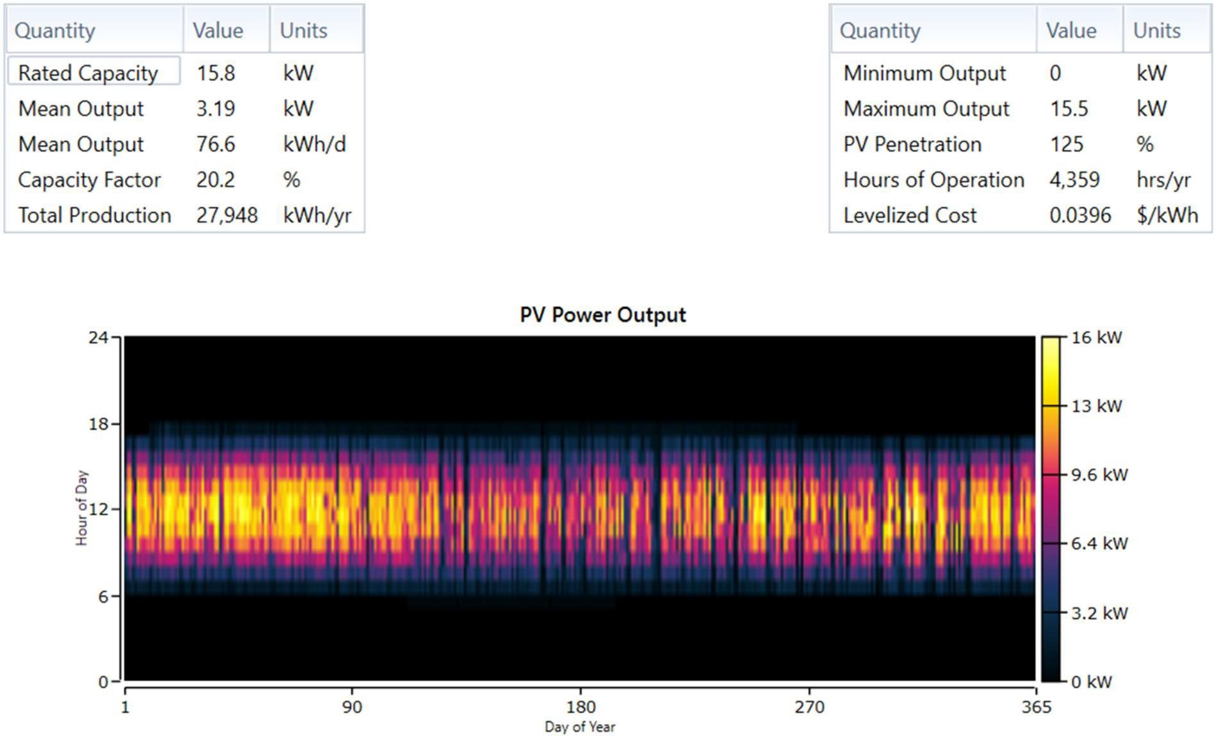
Figure 34. Phase II grid-connected electrical summary.



Rate Schedule: All

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Load (kW)	Energy Charge $	Demand Charge $
January	1,387	1,963	-577	15	$23.38	$0
February	1,198	1,893	-695	14	-$8.70	$0
March	1,393	2,161	-768	12	-$4.24	$0
April	1,336	1,826	-490	15	$32.15	$0
May	1,307	1,532	-225	13	$68.91	$0
June	1,256	1,369	-113	13	$81.36	$0
July	1,272	1,462	-189	13	$71.37	$0
August	1,347	1,466	-119	13	$87.52	$0
September	1,301	1,469	-167	13	$76.88	$0

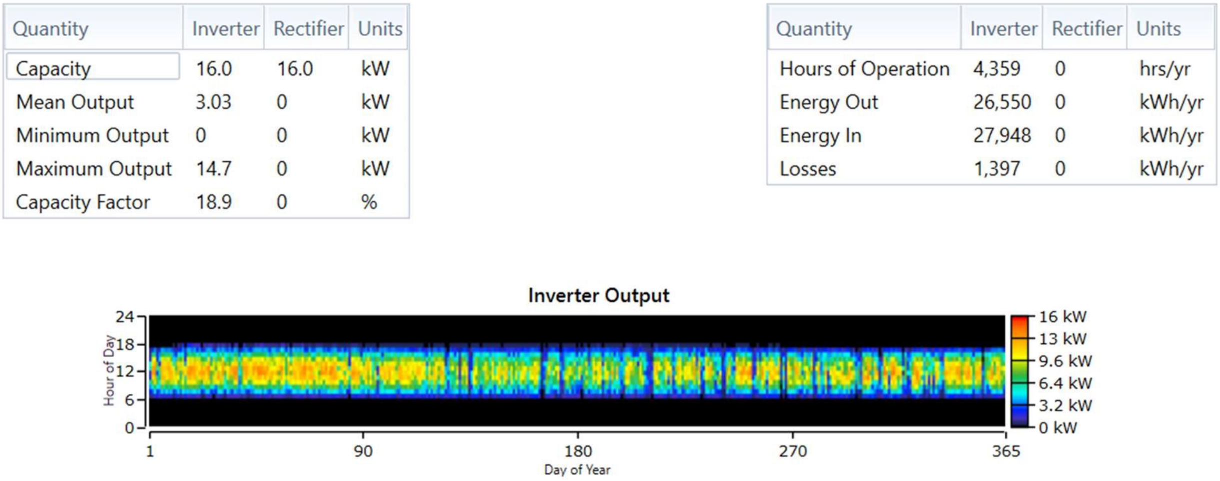
Figure 35. Phase II grid-connected grid summary.



Quantity	Value	Units
Rated Capacity	15.8	kW
Mean Output	3.19	kW
Mean Output	76.6	kWh/d
Capacity Factor	20.2	%
Total Production	27,948	kWh/yr

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	15.5	kW
PV Penetration	125	%
Hours of Operation	4,359	hrs/yr
Levelized Cost	0.0396	$/kWh

Figure 36. Phase II grid-connected PV summary.



Quantity	Inverter	Rectifier	Units
Capacity	16.0	16.0	kW
Mean Output	3.03	0	kW
Minimum Output	0	0	kW
Maximum Output	14.7	0	kW
Capacity Factor	18.9	0	%

Quantity	Inverter	Rectifier	Units
Hours of Operation	4,359	0	hrs/yr
Energy Out	26,550	0	kWh/yr
Energy In	27,948	0	kWh/yr
Losses	1,397	0	kWh/yr

Figure 37. Phase II grid-connected inverter summary.

Appendix K: Phase III grid-isolated modeling results

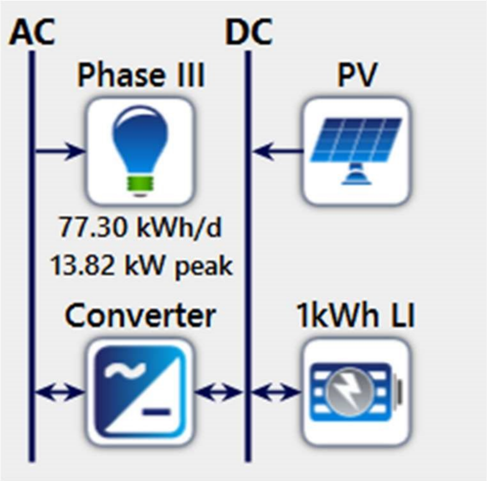
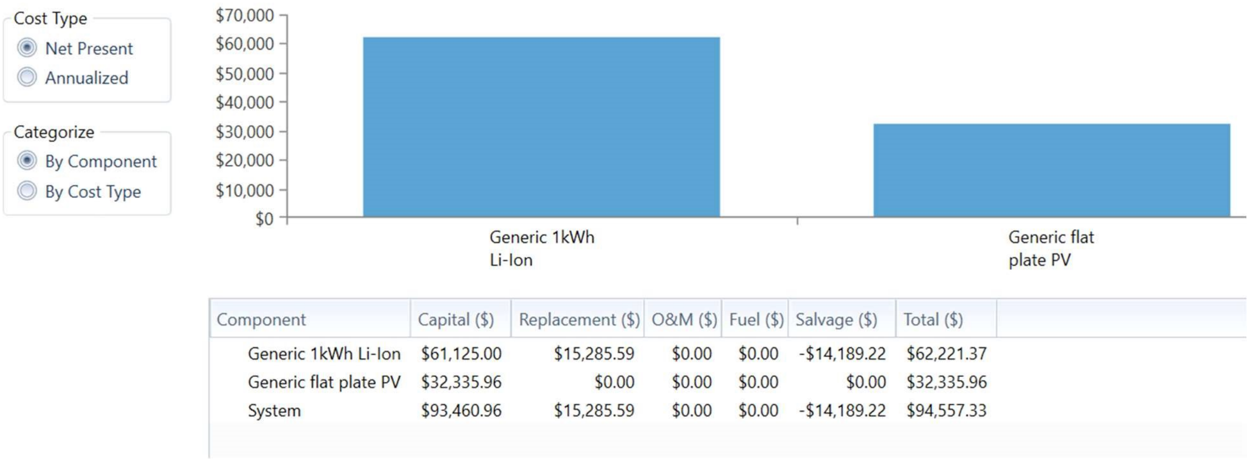


Figure 38. Phase III grid-isolated connection schematic.

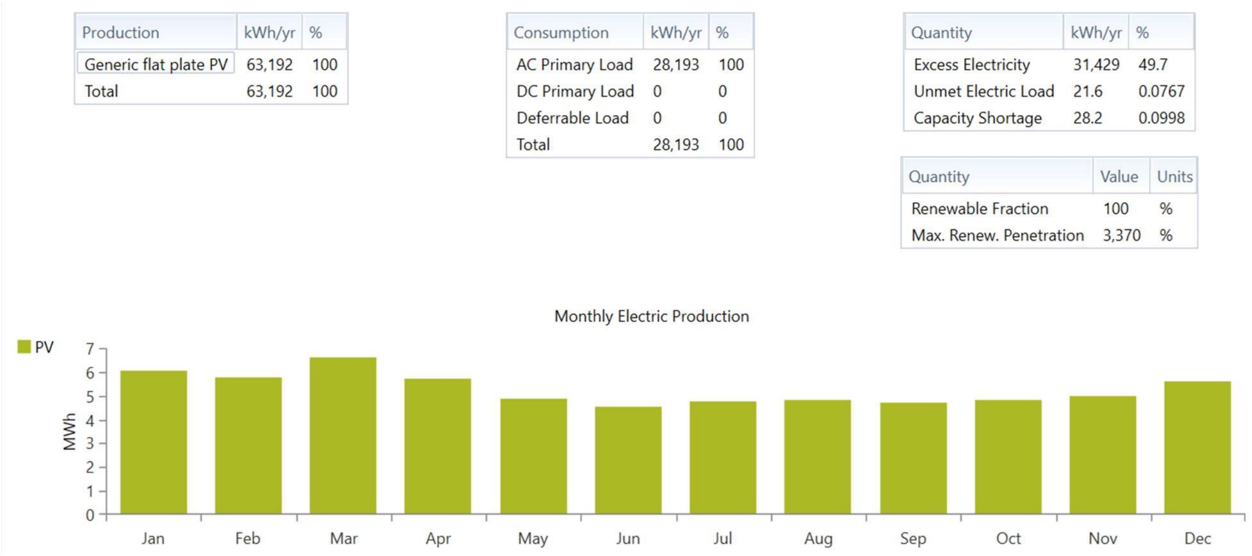


Cost Type
● Net Present
○ Annualized

Categorize
● By Component
○ By Cost Type

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Generic 1kWh Li-Ion	$61,125.00	$15,285.59	$0.00	$0.00	-$14,189.22	$62,221.37
Generic flat plate PV	$32,335.96	$0.00	$0.00	$0.00	$0.00	$32,335.96
System	$93,460.96	$15,285.59	$0.00	$0.00	-$14,189.22	$94,557.33

Figure 39. Phase III grid-isolated cost summary.



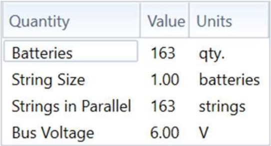
Production	kWh/yr	%
Generic flat plate PV	63,192	100
Total	63,192	100

Consumption	kWh/yr	%
AC Primary Load	28,193	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	28,193	100

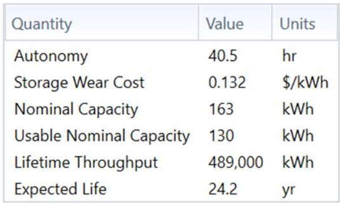
Quantity	kWh/yr	%
Excess Electricity	31,429	49.7
Unmet Electric Load	21.6	0.0767
Capacity Shortage	28.2	0.0998

Quantity	Value	Units
Renewable Fraction	100	%
Max. Renew. Penetration	3,370	%

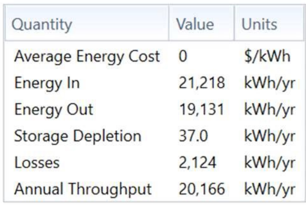
Figure 40. Phase III grid-isolated electrical summary.



Quantity	Value	Units
Batteries	163	qty.
String Size	1.00	batteries
Strings in Parallel	163	strings
Bus Voltage	6.00	V



Quantity	Value	Units
Autonomy	40.5	hr
Storage Wear Cost	0.132	$/kWh
Nominal Capacity	163	kWh
Usable Nominal Capacity	130	kWh
Lifetime Throughput	489,000	kWh
Expected Life	24.2	yr



Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	21,218	kWh/yr
Energy Out	19,131	kWh/yr
Storage Depletion	37.0	kWh/yr
Losses	2,124	kWh/yr
Annual Throughput	20,166	kWh/yr

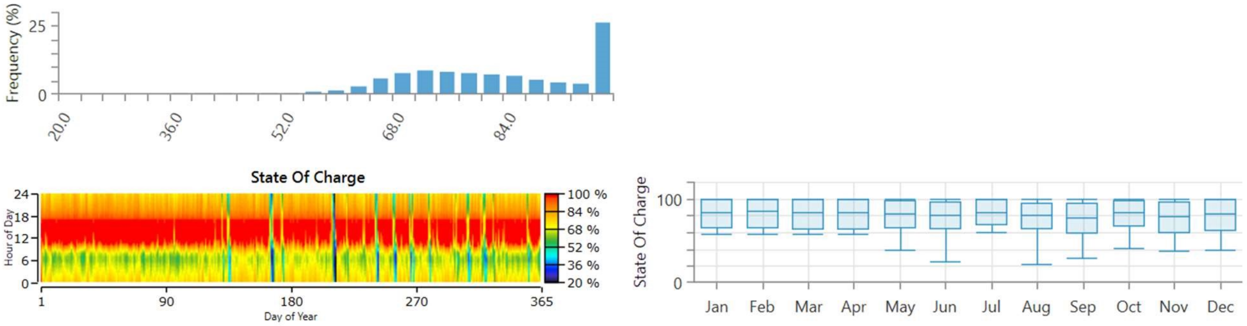
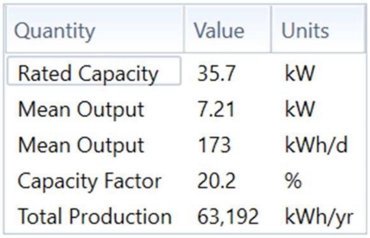
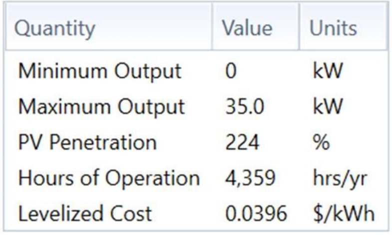


Figure 41. Phase III grid-isolated battery summary.



Quantity	Value	Units
Rated Capacity	35.7	kW
Mean Output	7.21	kW
Mean Output	173	kWh/d
Capacity Factor	20.2	%
Total Production	63,192	kWh/yr



Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	35.0	kW
PV Penetration	224	%
Hours of Operation	4,359	hrs/yr
Levelized Cost	0.0396	$/kWh

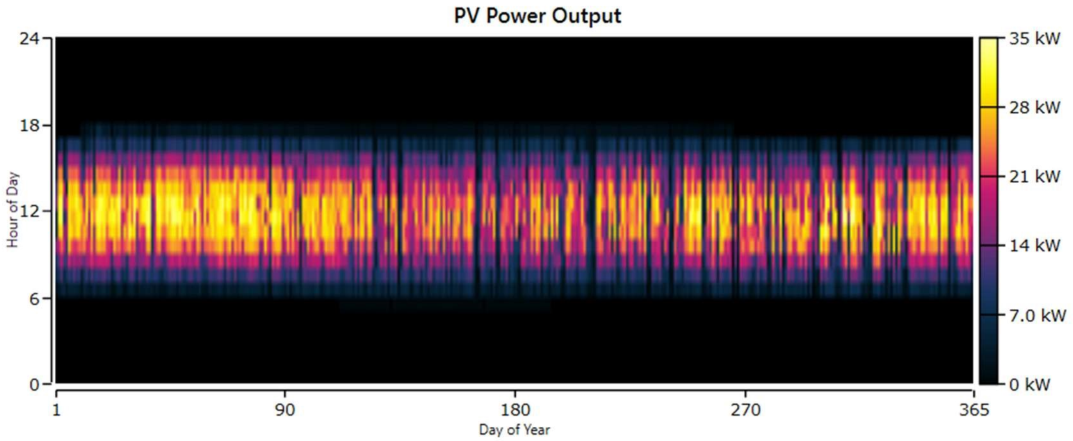
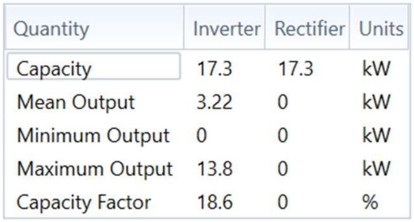
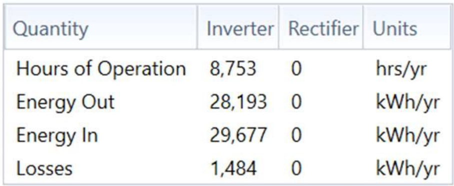


Figure 42. Phase III grid-isolated PV summary.



Quantity	Inverter	Rectifier	Units
Capacity	17.3	17.3	kW
Mean Output	3.22	0	kW
Minimum Output	0	0	kW
Maximum Output	13.8	0	kW
Capacity Factor	18.6	0	%



Quantity	Inverter	Rectifier	Units
Hours of Operation	8,753	0	hrs/yr
Energy Out	28,193	0	kWh/yr
Energy In	29,677	0	kWh/yr
Losses	1,484	0	kWh/yr

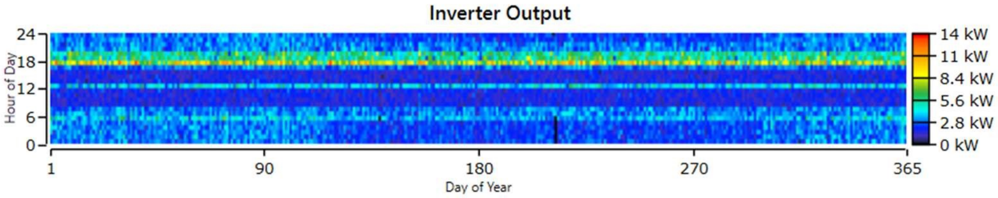


Figure 43. Phase III grid-isolated inverter summary.

Appendix L: Phase III grid-connected modeling results

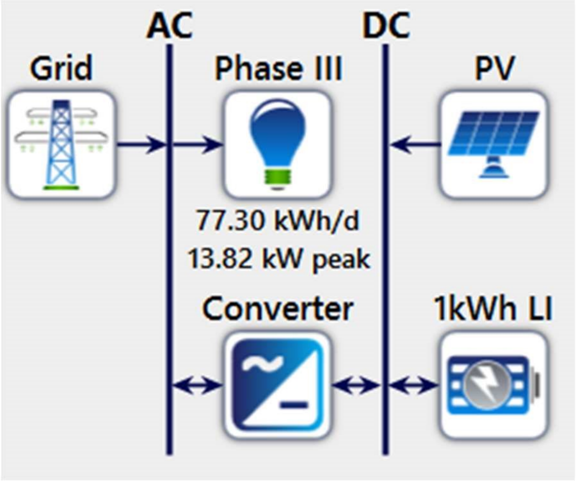
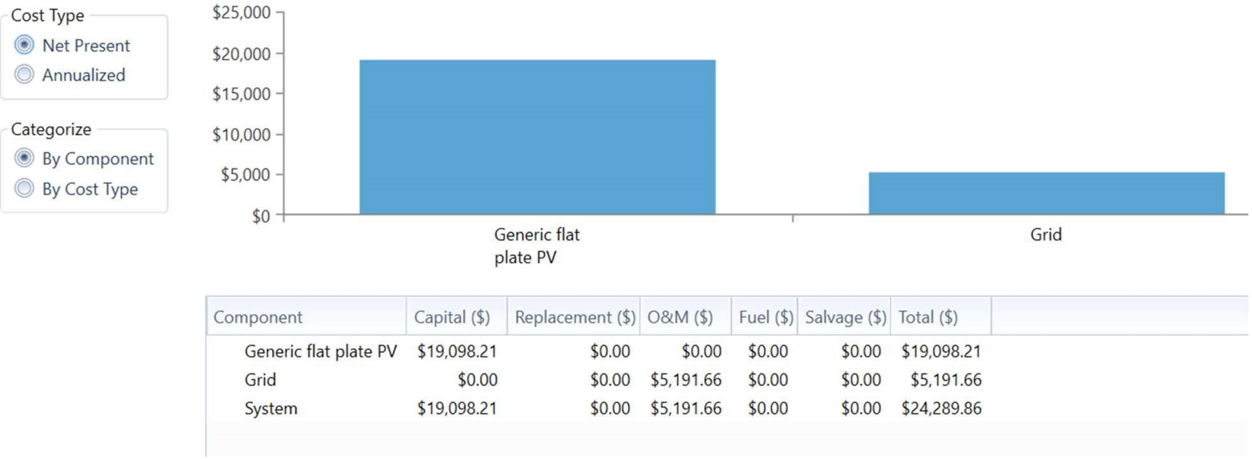


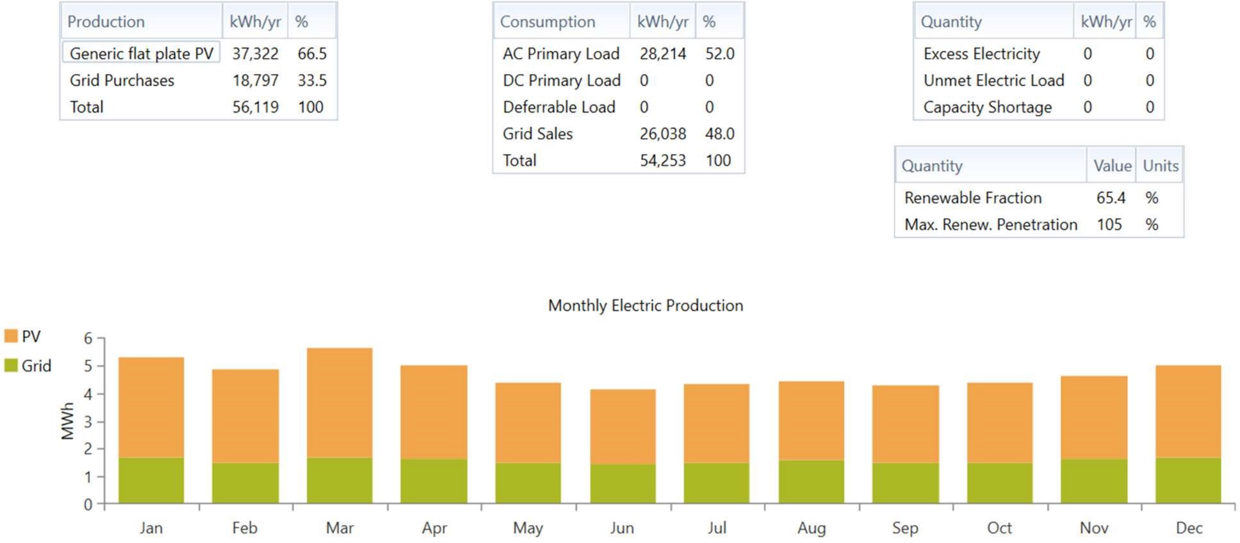
Figure 44. Phase III grid-connected connection schematic.


Cost Type
● Net Present
○ Annualized

Categorize
● By Component
○ By Cost Type

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Generic flat plate PV	$19,098.21	$0.00	$0.00	$0.00	$0.00	$19,098.21
Grid	$0.00	$0.00	$5,191.66	$0.00	$0.00	$5,191.66
System	$19,098.21	$0.00	$5,191.66	$0.00	$0.00	$24,289.86

Figure 45. Phase III grid-connected cost summary.

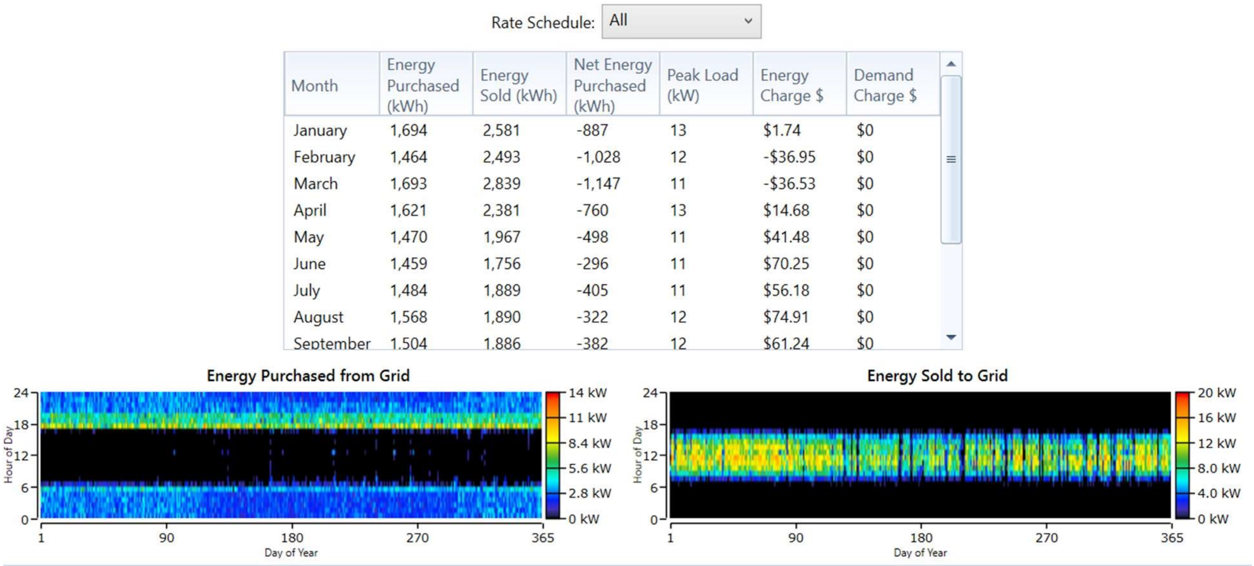

Production	kWh/yr	%
Generic flat plate PV	37,322	66.5
Grid Purchases	18,797	33.5
Total	56,119	100

Consumption	kWh/yr	%
AC Primary Load	28,214	52.0
DC Primary Load	0	0
Deferrable Load	0	0
Grid Sales	26,038	48.0
Total	54,253	100

Quantity	kWh/yr	%
Excess Electricity	0	0
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value	Units
Renewable Fraction	65.4	%
Max. Renew. Penetration	105	%

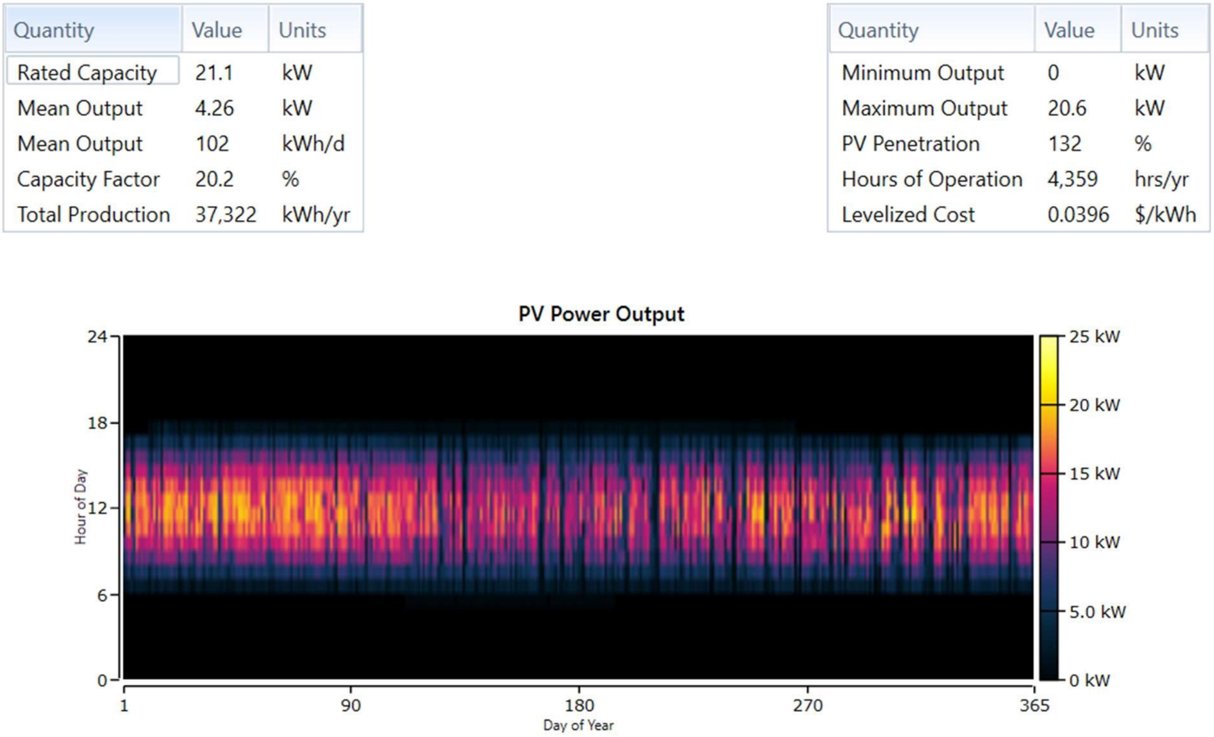
Figure 46. Phase III grid-connected electrical summary.



Rate Schedule: All

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Load (kW)	Energy Charge $	Demand Charge $
January	1,694	2,581	-887	13	$1.74	$0
February	1,464	2,493	-1,028	12	-$36.95	$0
March	1,693	2,839	-1,147	11	-$36.53	$0
April	1,621	2,381	-760	13	$14.68	$0
May	1,470	1,967	-498	11	$41.48	$0
June	1,459	1,756	-296	11	$70.25	$0
July	1,484	1,889	-405	11	$56.18	$0
August	1,568	1,890	-322	12	$74.91	$0
September	1,504	1,886	-382	12	$61.24	$0

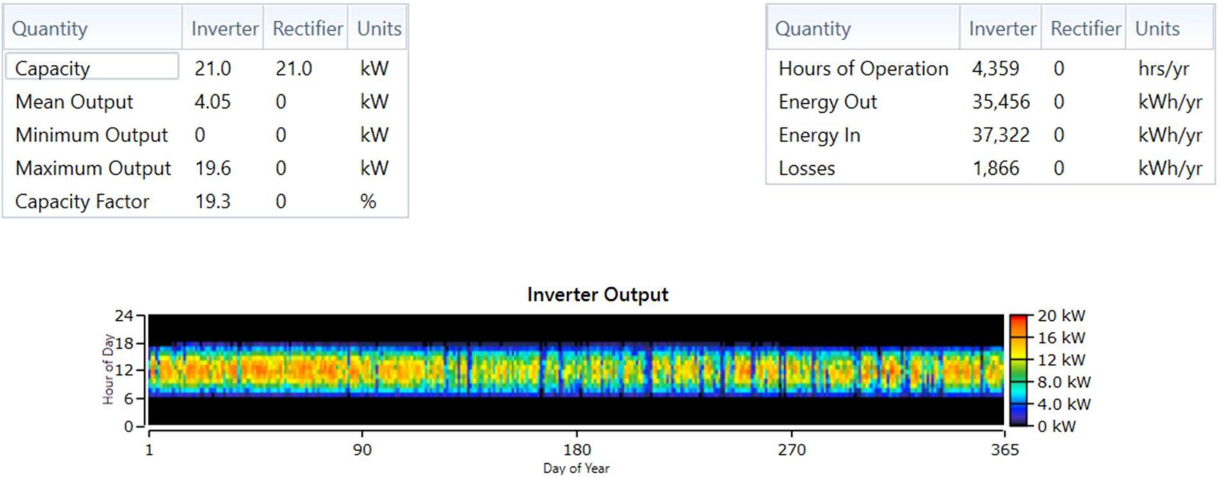
Figure 47. Phase III grid-connected grid summary.



Quantity	Value	Units
Rated Capacity	21.1	kW
Mean Output	4.26	kW
Mean Output	102	kWh/d
Capacity Factor	20.2	%
Total Production	37,322	kWh/yr

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	20.6	kW
PV Penetration	132	%
Hours of Operation	4,359	hrs/yr
Levelized Cost	0.0396	$/kWh

Figure 48. Phase III grid-connected PV summary.



Quantity	Inverter	Rectifier	Units
Capacity	21.0	21.0	kW
Mean Output	4.05	0	kW
Minimum Output	0	0	kW
Maximum Output	19.6	0	kW
Capacity Factor	19.3	0	%

Quantity	Inverter	Rectifier	Units
Hours of Operation	4,359	0	hrs/yr
Energy Out	35,456	0	kWh/yr
Energy In	37,322	0	kWh/yr
Losses	1,866	0	kWh/yr

Figure 49. Phase III grid-connected inverter summary.

Appendix M: Phase III grid-isolated biomass modeling results

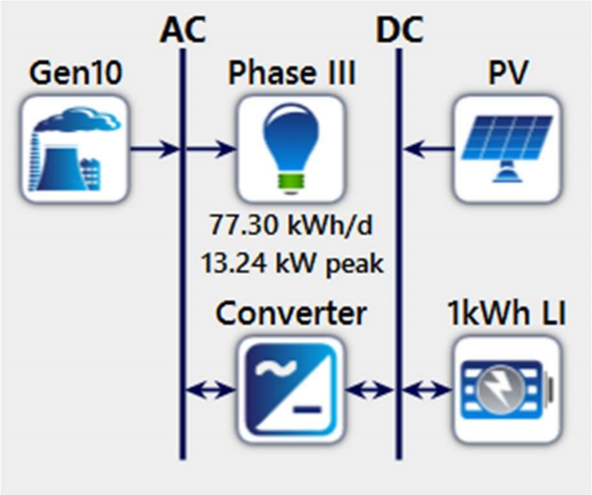
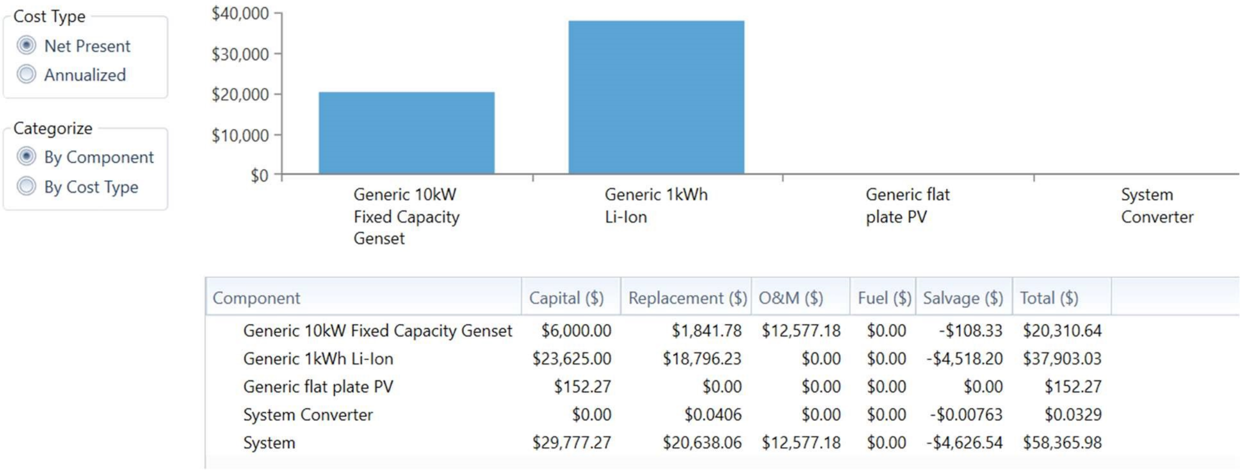


Figure 50. Phase III grid-isolated biomass connection schematic.

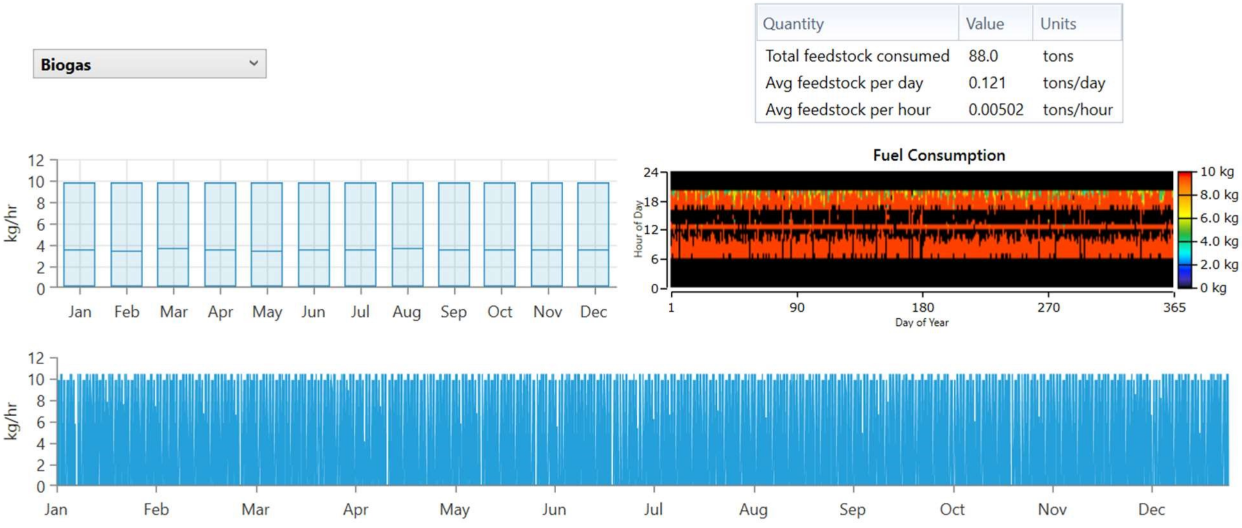


Cost Type
● Net Present
○ Annualized

Categorize
● By Component
○ By Cost Type

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Generic 10kW Fixed Capacity Genset	$6,000.00	$1,841.78	$12,577.18	$0.00	-$108.33	$20,310.64
Generic 1kWh Li-Ion	$23,625.00	$18,796.23	$0.00	$0.00	-$4,518.20	$37,903.03
Generic flat plate PV	$152.27	$0.00	$0.00	$0.00	$0.00	$152.27
System Converter	$0.00	$0.0406	$0.00	$0.00	-$0.00763	$0.0329
System	$29,777.27	$20,638.06	$12,577.18	$0.00	-$4,626.54	$58,365.98

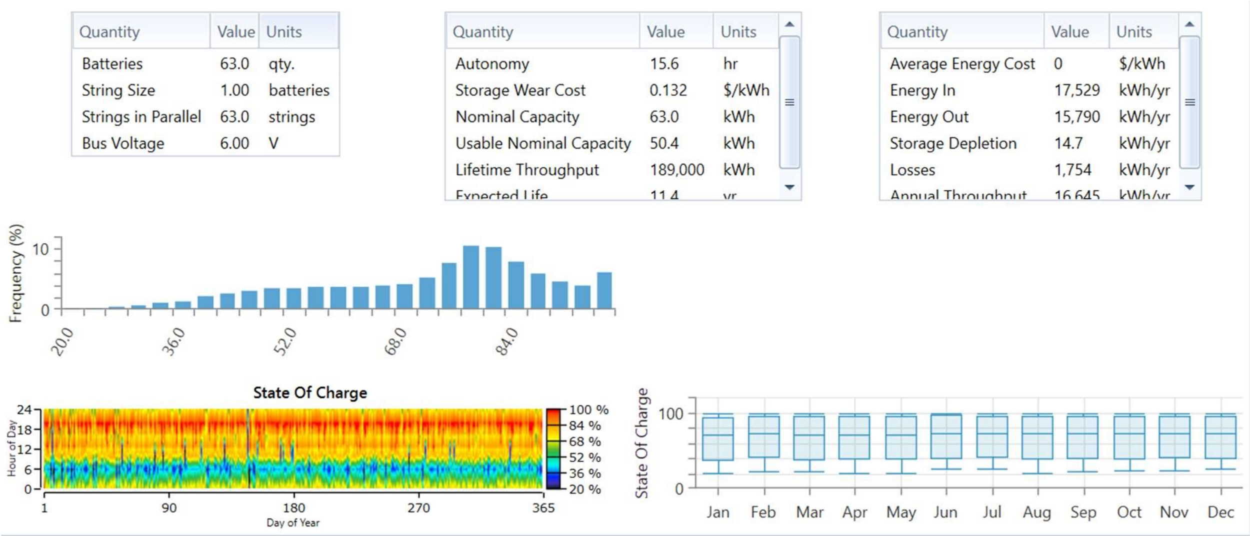
Figure 51. Phase III grid-isolated biomass cost summary.



Biogas

Quantity	Value	Units
Total feedstock consumed	88.0	tons
Avg feedstock per day	0.121	tons/day
Avg feedstock per hour	0.00502	tons/hour

Figure 52. Phase III grid-isolated biogas summary.

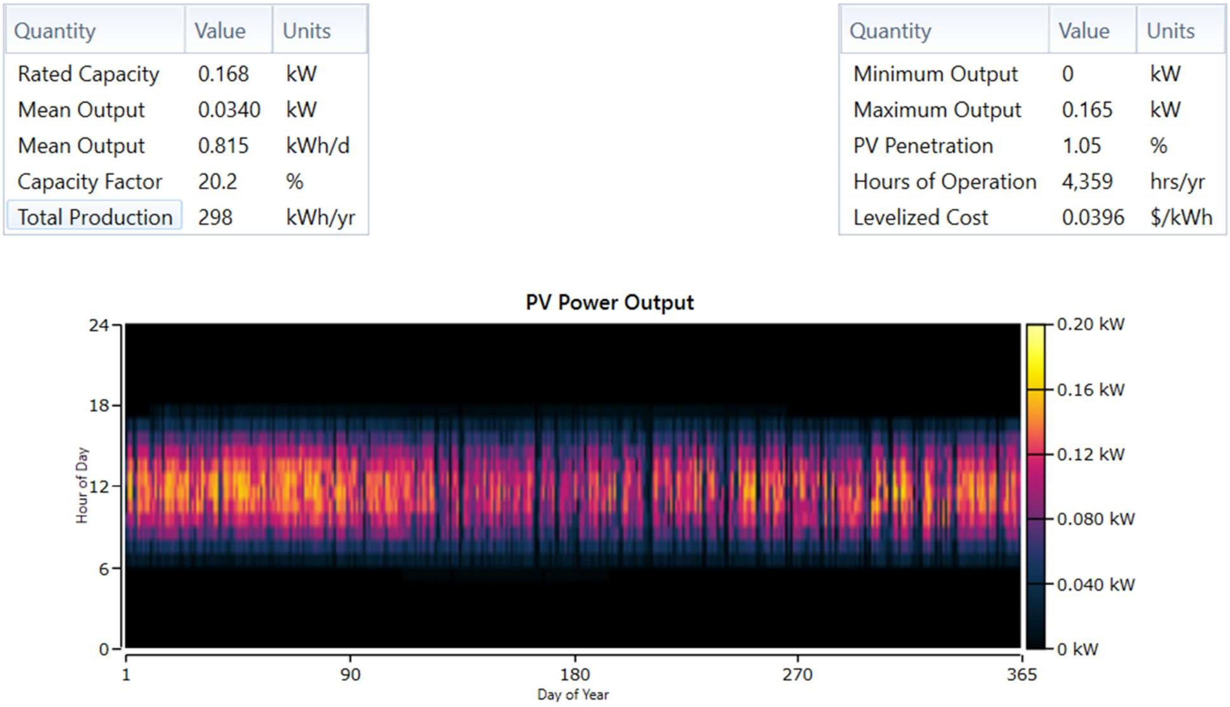


Quantity	Value	Units
Batteries	63.0	qty.
String Size	1.00	batteries
Strings in Parallel	63.0	strings
Bus Voltage	6.00	V

Quantity	Value	Units
Autonomy	15.6	hr
Storage Wear Cost	0.132	$/kWh
Nominal Capacity	63.0	kWh
Usable Nominal Capacity	50.4	kWh
Lifetime Throughput	189,000	kWh
Expected Life	11.4	yr

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	17,529	kWh/yr
Energy Out	15,790	kWh/yr
Storage Depletion	14.7	kWh/yr
Losses	1,754	kWh/yr
Annual Throughput	16,645	kWh/yr

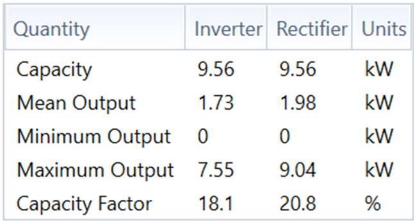
Figure 53. Phase III grid-isolated biomass battery summary.



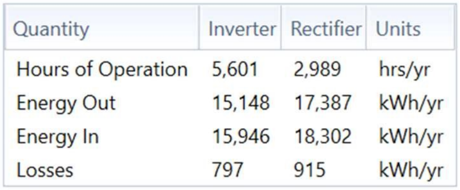
Quantity	Value	Units
Rated Capacity	0.168	kW
Mean Output	0.0340	kW
Mean Output	0.815	kWh/d
Capacity Factor	20.2	%
Total Production	298	kWh/yr

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	0.165	kW
PV Penetration	1.05	%
Hours of Operation	4,359	hrs/yr
Levelized Cost	0.0396	$/kWh

Figure 54. Phase III grid-isolated biomass PV summary.



Quantity	Inverter	Rectifier	Units
Capacity	9.56	9.56	kW
Mean Output	1.73	1.98	kW
Minimum Output	0	0	kW
Maximum Output	7.55	9.04	kW
Capacity Factor	18.1	20.8	%



Quantity	Inverter	Rectifier	Units
Hours of Operation	5,601	2,989	hrs/yr
Energy Out	15,148	17,387	kWh/yr
Energy In	15,946	18,302	kWh/yr
Losses	797	915	kWh/yr

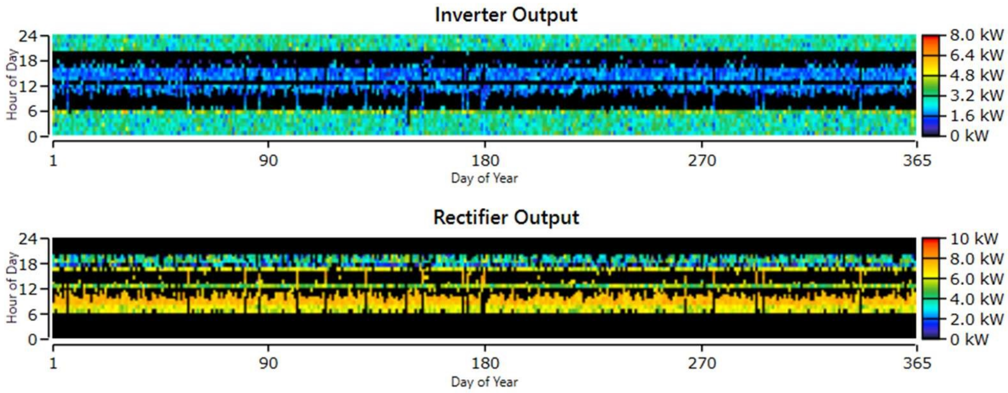
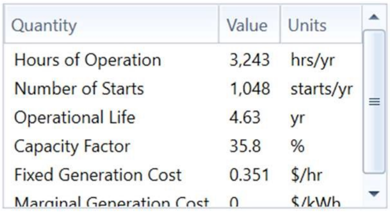
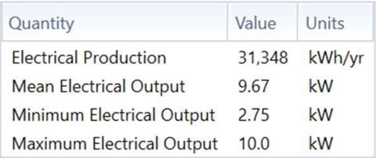


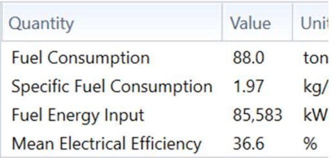
Figure 55. Phase III grid-isolated biomass inverter summary.



Quantity	Value	Units
Hours of Operation	3,243	hrs/yr
Number of Starts	1,048	starts/yr
Operational Life	4.63	yr
Capacity Factor	35.8	%
Fixed Generation Cost	0.351	$/hr
Marginal Generation Cost	0	$/kWh



Quantity	Value	Units
Electrical Production	31,348	kWh/yr
Mean Electrical Output	9.67	kW
Minimum Electrical Output	2.75	kW
Maximum Electrical Output	10.0	kW



Quantity	Value	Unit
Fuel Consumption	88.0	ton
Specific Fuel Consumption	1.97	kg/
Fuel Energy Input	85,583	kW
Mean Electrical Efficiency	36.6	%

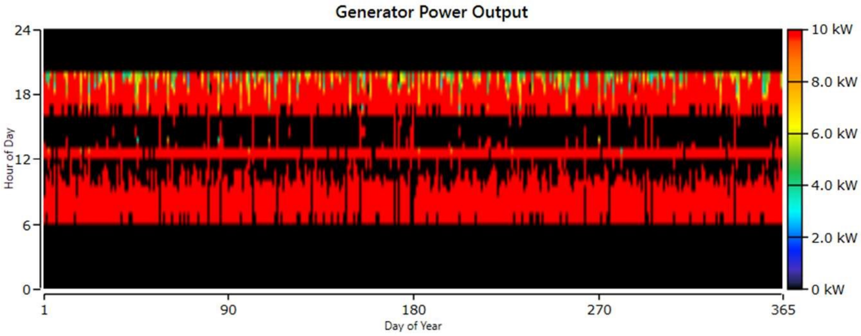


Figure 56. Phase III grid-isolated biomass generator summary.