Renewable, Off-grid Power Systems

Technical Report Draft

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I. INTRODUCTION

The electric power system is the network of power system components that delivers electricity to power devices such as televisions, refrigerators, computers, and every other device that connects to an outlet. An electric power system can be divided into generation, transmission, and distribution. Generation supplies electric power; the transmission system the electric power usually long distances to distribution systems which deliver the electric power to homes, commercial buildings, and industry. A renewable, off-grid power system is a stand-alone electric power system that can provide electric power to the end consumer year-round. The two main components of an off-grid systems are renewable energy resources and energy storage systems. A major milestone for off-grid systems is determining how much renewable energy resources and how much energy storage capacity are required to provide the end consumer with electric power year-round.

This document presents an approach to design photovoltaic (PV), off-grid power systems by considering oversized PV systems. An algorithm was developed to determined how much energy storage capacity is required for various oversized PV systems. The result is a graph displaying how much energy storage vs. how much solar power are required for an off-grid system. Lastly, the price of each configuration was computed and most cost-effective configuration determined.

The algorithm requires two parameters: the expected time-series power supply of the PVs and expected time-series power demand of the building. Probability distributions of power supply and power demand were not part of this analysis; Incorporating probability distributions into the analysis could be used to design off-grid systems that meet statistical requirements.

II. BACKGROUND

One of the main challenges of an electric power system is balancing the power supply and power demand at all times. An imbalance could damage or affect some power system components and appliances.

The two main components for off-grid systems are renewable energy resources and energy storage systems. Renewable energy resources are technologies that produce energy from renewable resources such as sunlight and wind. Energy storage systems (ESS) are technologies that can store/save energy to supply electric power at a later time. A well-known ESS technology are batteries.

Since power supply and demand must be balanced at all times, ESSs are crucial to balancing the grid. When power supply exceeds power demand, ESS balance the grid by storing the power difference. When power demand exceeds power supply, ESS can balance the grid by supplying the necessary power to balance the grid.

One major challenge of designing off-grid systems is the daily imbalance between the power supply of the PVs and the power demand of the building. PVs generate power when the sun is shining. During the nighttime, PVs do not produce power while building typically consume power. PVs must generate extra power during the day to charge up the ESS to provide power during the nighttime.

Another major challenge of designing off-grid systems is the seasonal imbalance between power supply of the PVs and the power demand of the building. A majority of the PV generation occurs during the summer when the sun shines brighter and for longer periods of time. The standard PV size doesn't produce enough energy during winter days to power the building and charge up the ESS for the nighttime. Increasing the PV system size increases the power supply year-round.

III. CORRELATION BETWEEN POWER SUPPLY AND DEMAND

The required energy storage capacity and PV system size for an off-grid system depend on the correlation between the expected time-series power supply and power demand of the building.

To validate this statement, two extreme hypothetical scenarios will be analyzed. The top graph of Figure 3.1 shows the expected time-series power demand of a building with an annual consumption of 10 MWh; It forecasts the power demand for every hour of the year. Let's assume there exists a renewable energy resource with an identical time-series power supply as shown in the bottom graph of Figure 3.1. It forecasts the power supply for every hour of the year. Since the time-series data are identical, the annual generation is 10 MWh. The off-grid system for this hypothetical scenario would not require an ESS since the supply and demand are always balanced.

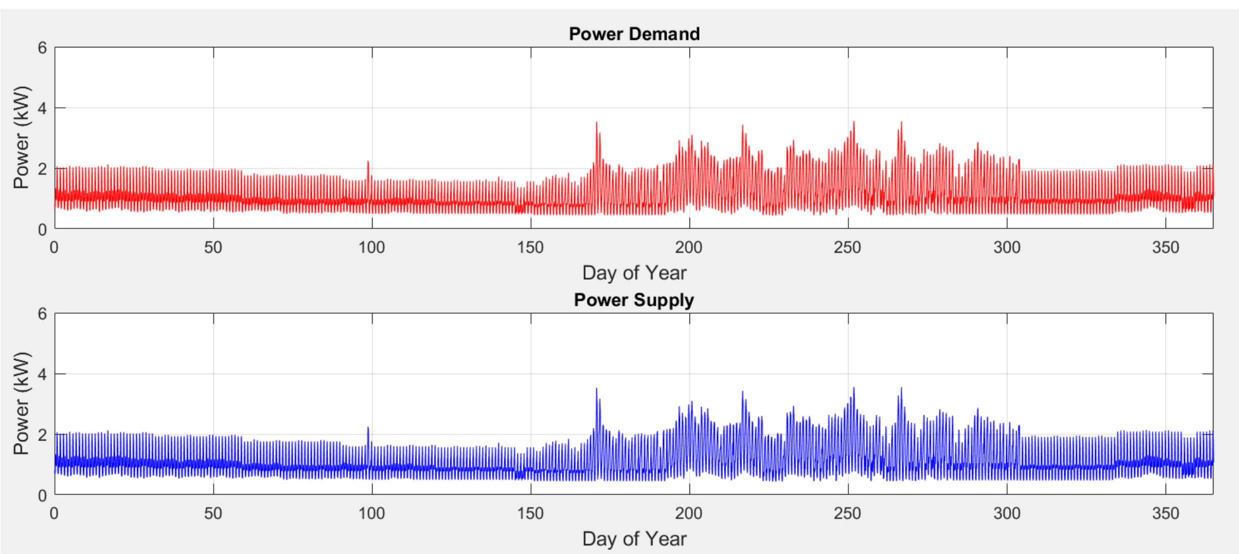

Figure 3.1: Power Supply and Demand of Hypothetical Scenario #1

For the second hypothetical scenario, which examines a completely opposite case, let's assume the power supply and power demand are disjointed as in Figure 3.2. All the power supply is generated during the first six months of the year while all the power demand occurs during the last six months of the year; the annual consumption is 10MWh. Assuming a 90% efficient ESS with no time-varying leakage, this hypothetical scenario would require an ESS capacity equal to the annual consumption—10MWh, and PV system size with an annual generation size of 11.11MWh. Generation must equal consumption plus energy storage losses.

$$Generation(0.9) = Consumption$$

$$\Longrightarrow Generation = 11.11 \text{ MWh}$$

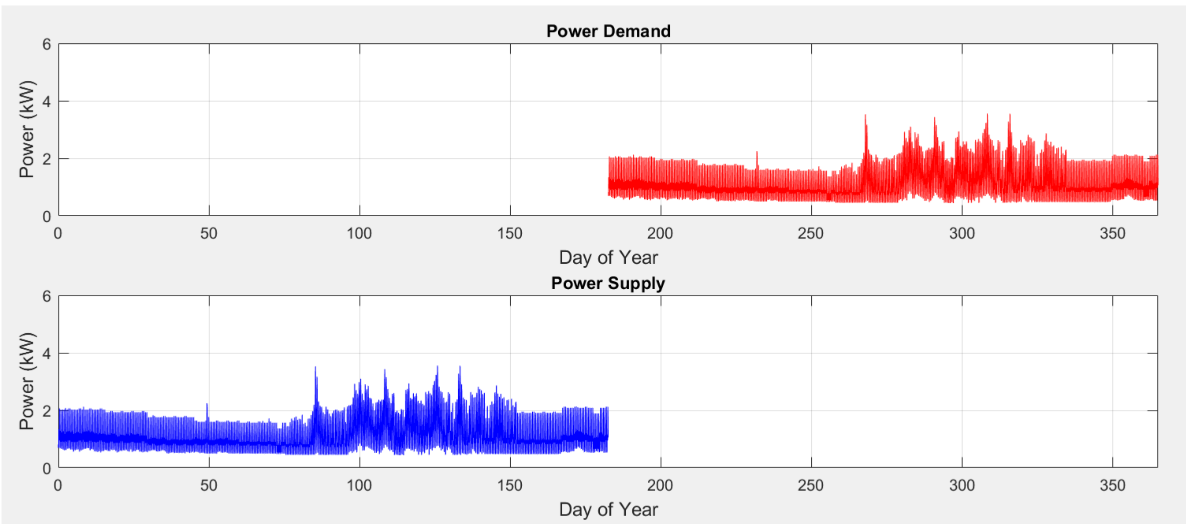

Figure 3.2: Power Supply and Demand of Hypothetical Scenario #2

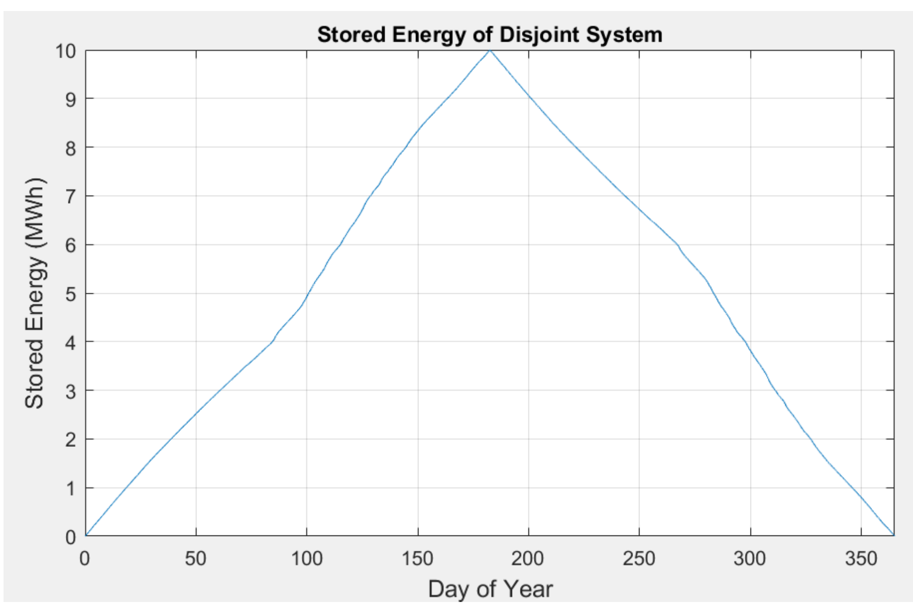

Figure 3.3: Stored Energy for Hypothetical Scenario #2

Figure 3.3 shows the amount of stored energy in the ESS over the year. The stored energy in the ESS is zero at the beginning of the year. During the first six months, since power supply is present while power demand is absent; all the power generated is stored in the ESS. During the first six months, the stored energy accumulates to 10 MWh; 11.11 MWh is generated, but 1.11 MWh is lost.

During the last six months, since power demand is present while power supply is absent, the 10MWh of stored energy is enough to independently supply the 10MWh consumption of the building. The stored energy is depleted at the end of the year, and this cycle starts over again.

These two hypothetical scenarios show the required storage capacity and PV system size for an off-grid system depends on the correlation (overlap) between supply and demand. Therefore, designing off-grid systems requires analyzing the correlation (overlap) of supply and demand for the entire year.

IV. OFF-GRID ALGORITHM

4.1 Parameters

An algorithm was written to simulate the expected time-series stored energy of the ESS. The algorithm requires two inputs: the expected annual time-series power demand of the building and the expected annual time-series power output of the solar panels. Time-series power demand data of a commercial building in San Diego, CA, with an annual consumption of 17.34 MWh, was obtained from OpenEI [1]. For this analysis, this power demand data was scaled such that the total consumption was 10 MWh. The top graph of Figure 4.1 shows the power demand data; It was the data used in section II.

The bottom of Figure 4.1 shows the expected annual time-series power output of solar panels in San Diego, CA with an annual generation of 10 MWh. This data was obtained from PVWatts, and it forecasts the power supply for every hour of the year [2].

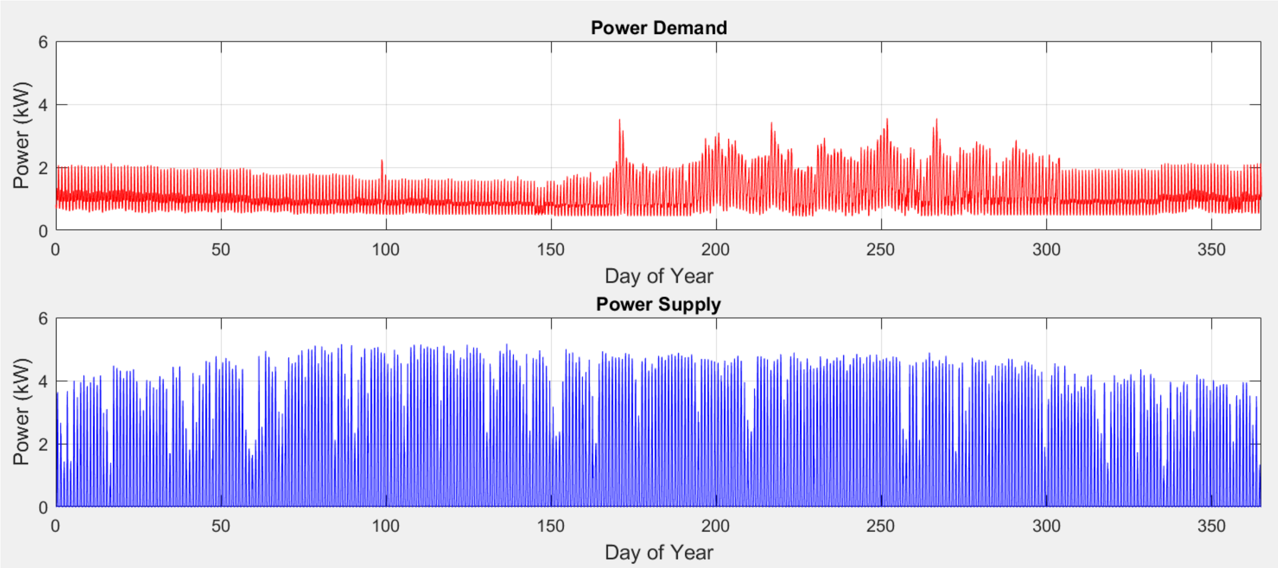

Figure 4.1: Power demand of building (top), Power supply of PVs (bottom)

4.2 Modeling Stored Energy

The algorithm iterated through the time-series power data to generate a running total of the stored energy in the ESS. The algorithm computed the total generation and consumption for each hourly interval. If generation exceeded consumption, the energy difference minus storage losses was added to the ESS. For example, if generation exceeded consumption by 1kWh, 0.9 kWh was added to storage since 0.1kWh was lost.

If consumption exceeded generation, the energy difference was subtracted from storage. For example, if consumption exceeded generation by 1kWh, 1kWh was subtracted from storage.

To illustrate, the top of Figure 4.2 shows the power supply and power demand data for three arbitrary days and the bottom graph shows the stored energy with initial storage of 100kWh.

The stored energy increased when generation exceeded consumption, and the stored energy decreased when consumption exceeded generation. The initial stored energy was 100kWh. After the first day, stored energy increased to 110kWh. After the second day, stored energy increased to 117 kWh. After the third day, stored energy decreased to 113 kWh.

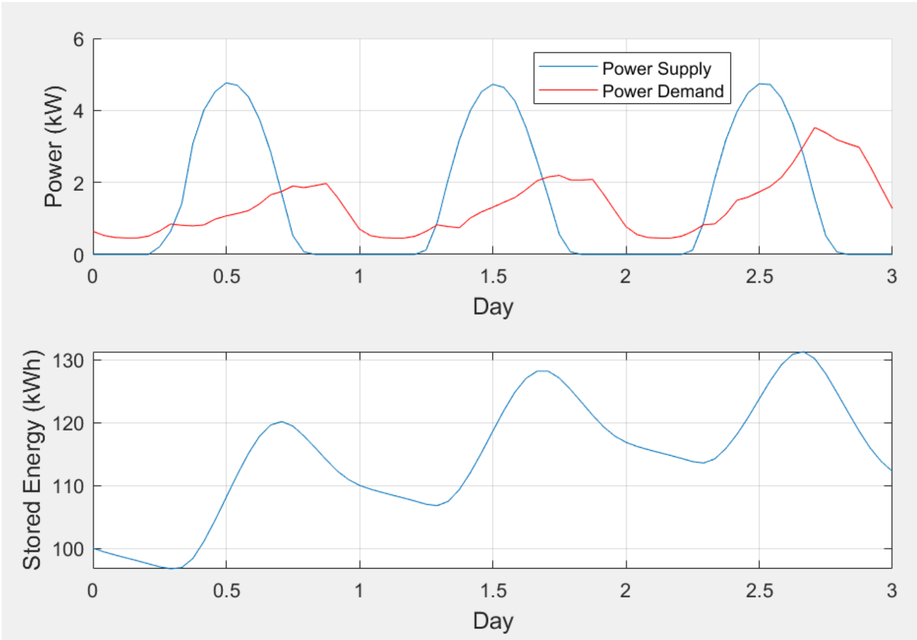

Figure 4.2: Power data for three days (top) Stored energy of ESS (bottom)

4.3 Initial Stored Energy and Shifting Property

Before the algorithm iterates through the time-series power data, the initial stored energy is selected. This value is arbitrary since the stored energy graph can be shifted up or down; Shifting the graph up or down is equivalent to incrementing or decrementing the initial stored energy value and repeating the iterative process. To illustrate the shifting property, Figure 4.3 shows the stored energy with an initial stored energy of 100kWh, 500kWh, and 0kWh. All three waveforms are identical except for a vertical shift.

After the initial stored energy is selected and the algorithm iterates through the power data, the stored energy data is shifted such that the lowest value was zero; the amount of stored energy must be positive since ESSs cannot contain negative energy.

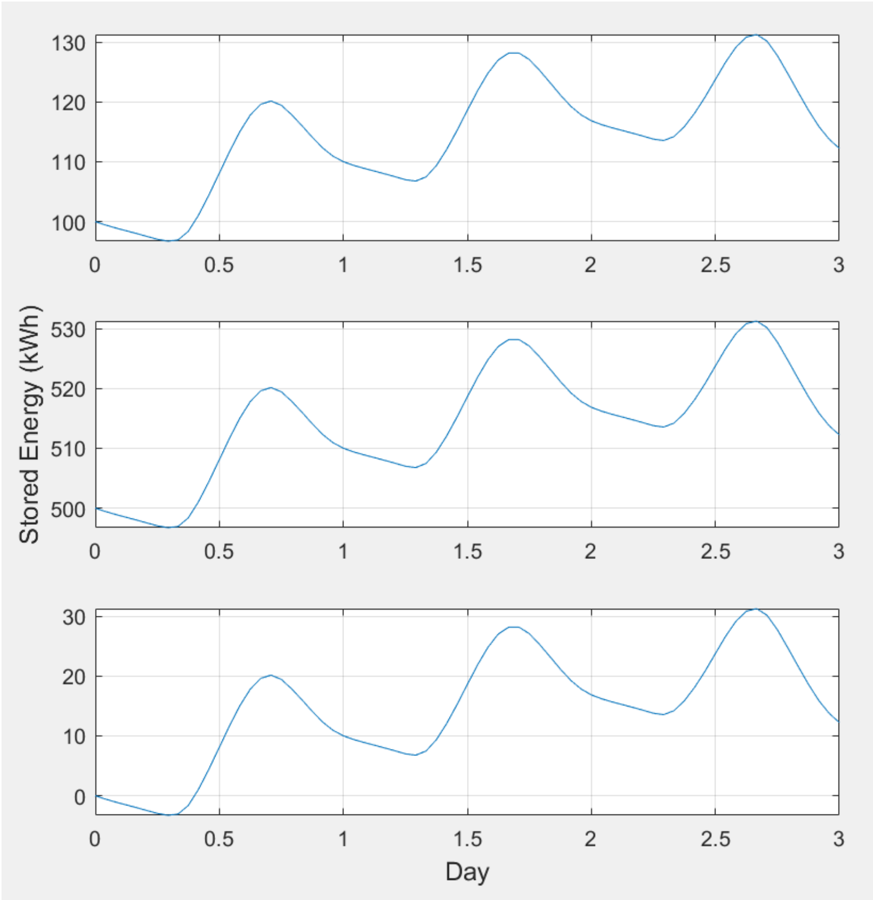

Figure 4.3: Stored Energy with initial storage of 100kWh, 500kWh, and 0kWh.

4.4 Five-year Analysis of Various Generation Sizes with a 100% efficient ESS

The power demand data was duplicated to represent five years as shown in Figure 4.4. The power supply data was scaled to represent five annual generation sizes of 9 MWh, 9.5 MWh, 10 MWh, 10.5 MWh, and 11 MWh. Figure 4.4 shows the power supply of the 10 MWh generation size.

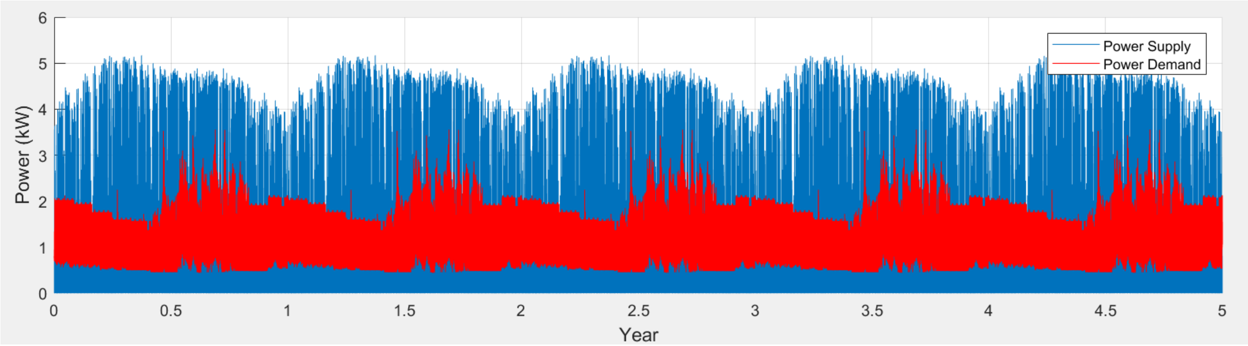

Figure 4.4: Power supply (blue) and power demand (red)

Using the five-year power supply and power demand data, the algorithm simulated the stored energy for each generation size with a 100% efficient ESS. Figure 4.5 shows the stored energy for each generation size. The initial storage was to set 8MWh.

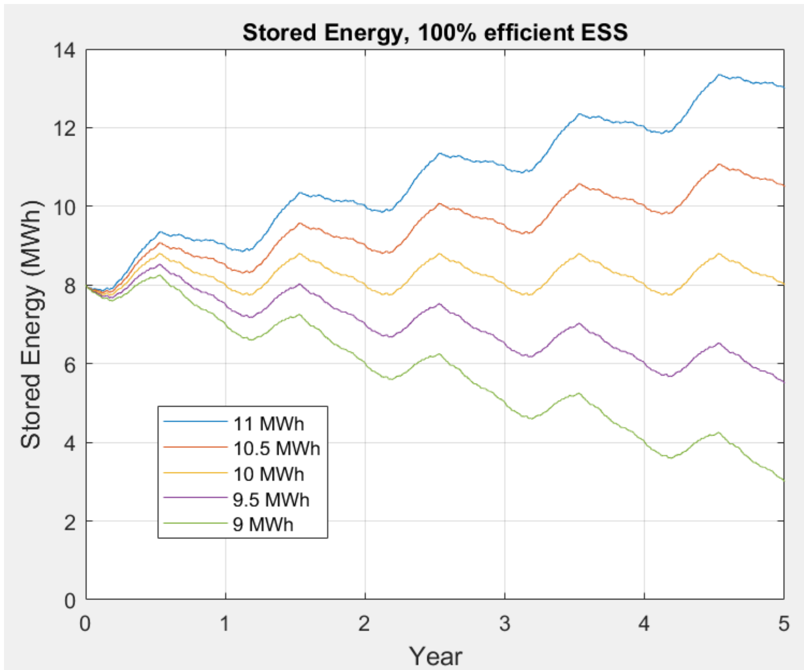

Figure 4.5: Stored Energy of various generation sizes

For the 9 MWh and 9.5 MWh generation sizes, since generation was less than consumption, the stored energy gradually decreased over the five-years. For the 10.5 MWh and 11 MWh generation sizes, since generation was greater than consumption, the stored energy gradually increased over the five-year time frame. For the generation size of 10.0 MWh, which equals the consumption of the building, the stored energy vs time resembled a sinusoidal with a period of one year. Even though, the stored energy fluctuated, it did not increase nor decrease over the five-years.

4.5 Five-year Analysis of Various Generation Sizes with a 90% Efficient ESS

The power supply and power demand data were analyzed with a 90% efficient ESS. Figure 4.6 shows the stored energy for each generation size.

The stored energy for the 9.0 MWh, 9.5 MWh, 10 MWh, and 10.5 MWh generation sizes gradually decreased over the five-years. Since ESS have energy losses, the generation must compensate for the energy losses. The 10 MWh, which previously balanced the system, was no longer able to balance the system. The 10.5 MWh generation size was also unable to balance the system. The stored energy for a generation size of 11 MWh gradually increased over the five-years. Therefore, the generation size that balances the system is between 10.5 MWh and 11 MWh.

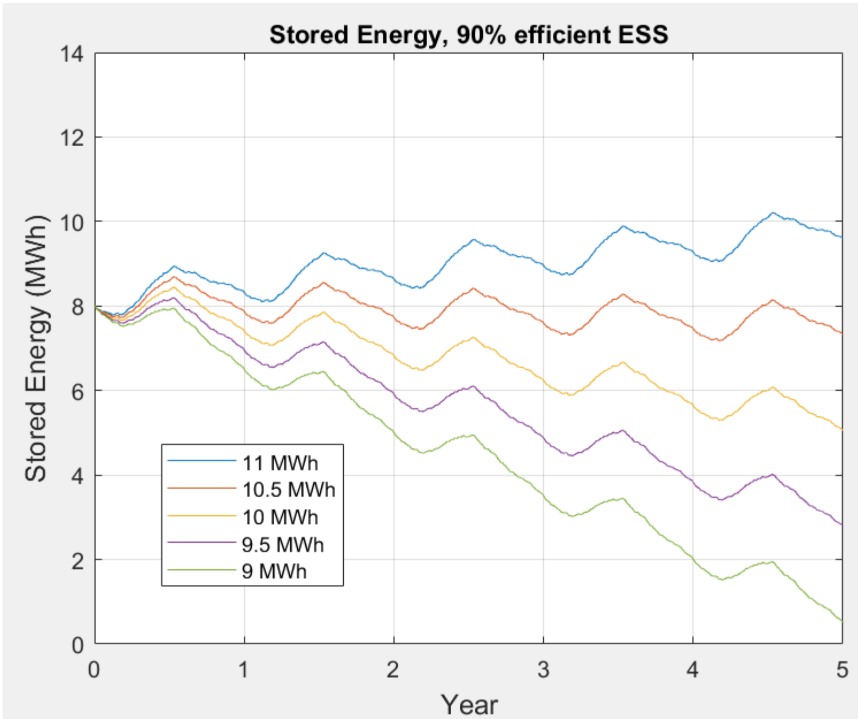

Figure 4.6: Stored Energy versus various generation sizes

V. RENEWABLE, OFF-GRID POWER SYSTEMS

5.1 The Balanced Off-Grid System

$$Generation = Consumption + Storage\ Losses$$

The algorithm finds the generation size that balances the off-grid system by continuously increasing the generation size and checking if the system is balanced. Starting with a generation size equal to consumption, the algorithm gradually increases the generation size and simulates the stored energy. If the system was unbalanced, the algorithm increased generation and analyzed the system again. This process continued until the generation size that balanced the off-grid system was found. For this example, a 10.65 MWh generation size balanced the system. Figure 5.1 shows the energy stored of the 10.65 MWh system for five years after the stored energy was shifted such that the lowest value was zero. Each annual cycle was identical.

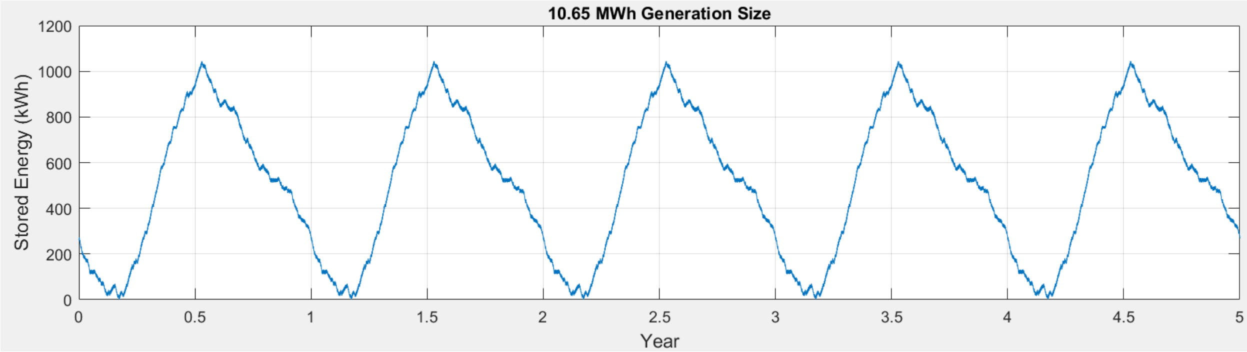

Figure 5.1: Stored Energy of 10.65 MWh Generation Size

Figure 5.2 shows the stored energy for a year. The initial stored energy was 266 kWh and gradually decreased to zero during the first sixty days. From day 60 through day 190, the stored energy gradually increased reaching a maximum of 1044 kWh. From day 190 through the end of the year, the stored energy gradually decreased to 266 kWh.

Over the year, the minimum stored energy was zero and the maximum stored energy was 1044 kWh. The amplitude of this graph represents the required energy storage capacity for this off-grid power system. A 10.65 MWh generation size requires a 1044 kWh storage capacity.

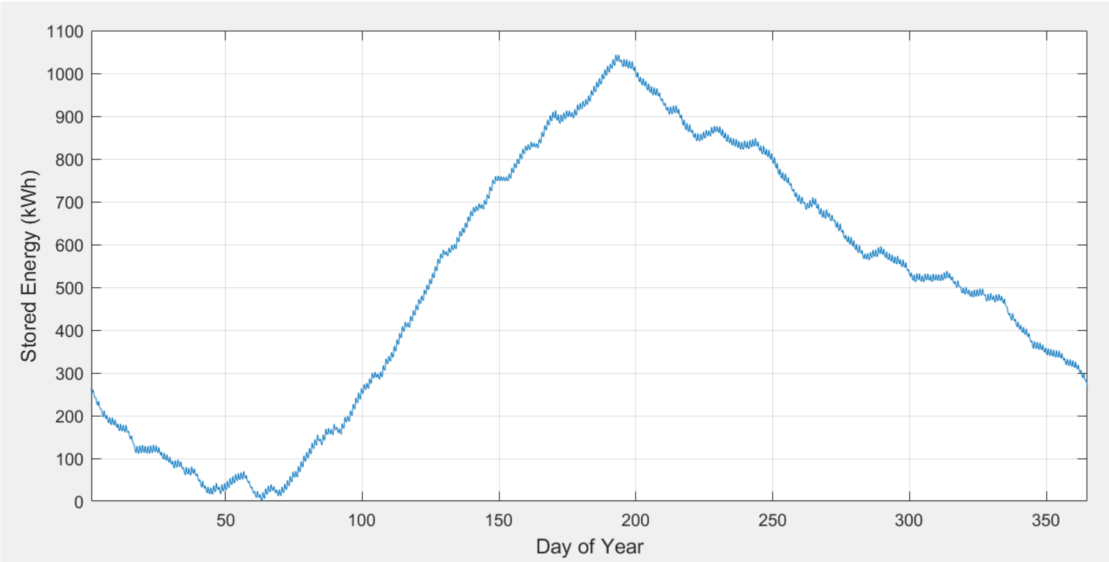

Figure 5.2: Stored Energy for a year with a 10.65 MWh

Figure 5.3 shows 90-day period of the stored energy. The stored energy, fluctuating every day, gradually increased to reach a maximum around day 190. Then, afterward, it gradually decreased.

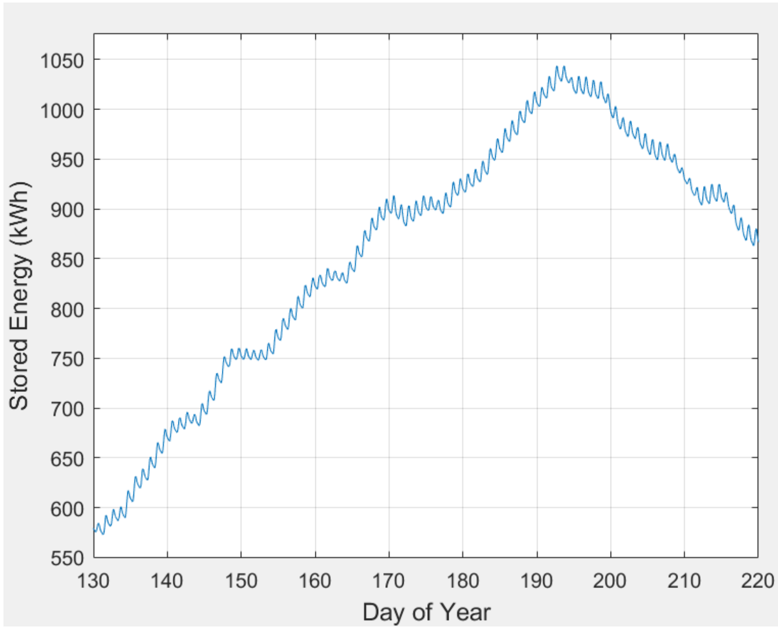

Figure 5.3: Stored Energy for the year with a 10.65 MWh

5.2 Oversizing Generation for Off-Grid Systems

$$Generation = Consumption + Storage\ Losses + Overgeneration$$

Larger generations sizes were considered by placing a limit on the energy storage capacity. The storage limit placed was the required energy storage capacity of the previous generation size. If the storage limit was reached, any overgeneration was discarded.

A 11 MWh generation size was analyzed with a 1044 kWh storage limit, and the stored energy of this system is shown in Figure 5.4. Since there was more generation, the amount of stored energy no longer reached zero. The clipping of the sinusoidal wave shows when the storage limit was reached. The amplitude of this waveform represents the required energy storage capacity for this system; therefore, a 11 MWh generation size requires 856 kWh of storage for an off-grid system.

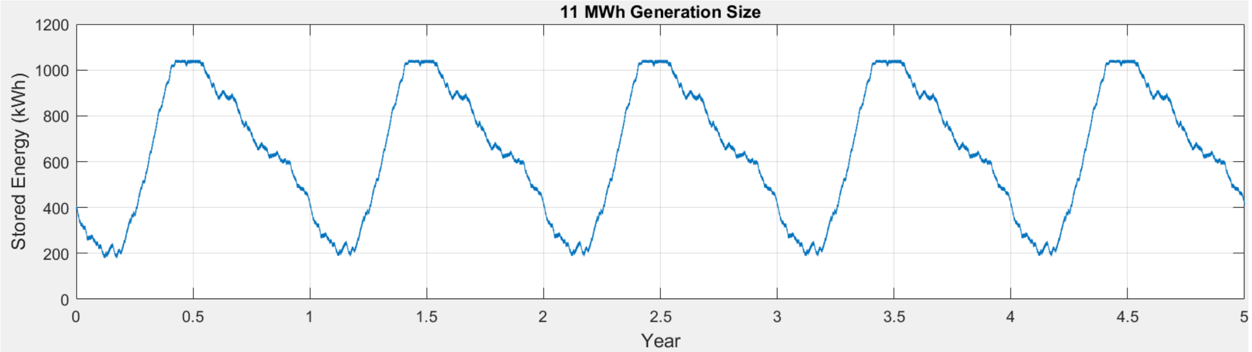

Figure 5.4: Stored Energy of 11 MWh Generation Size with 1044 kWh storage limit

Next, a 11.5 MWh generation size was analyzed with an energy storage limit of 856 kWh— the storage capacity requirement of the previous system. Figure 5.5 shows the stored energy with a 11.5 MWh generation size. The duration of the clipping was longer. The amplitude of this waveform was 608 kWh; therefore, a 11.5 MWh generation size requires 608 kWh of storage for an off-grid system.

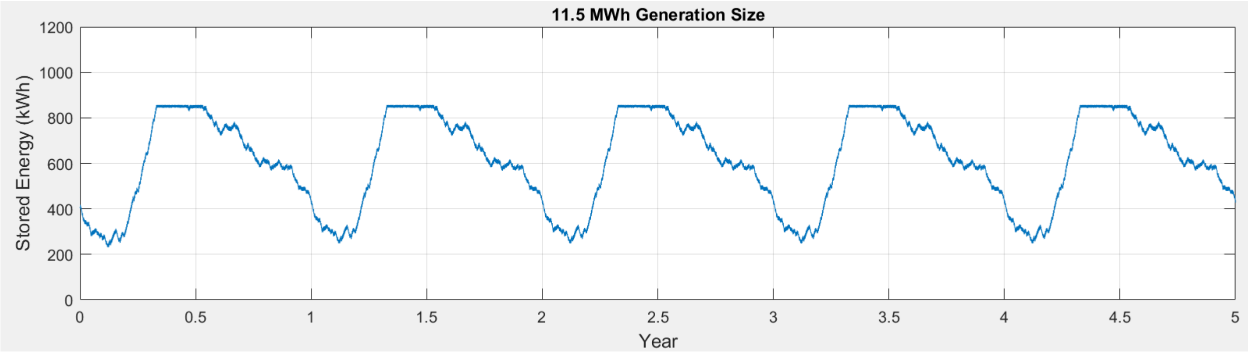

Figure 5.5: Stored Energy of 11.5 MWh Generation Size with 856 kWh storage limit

This process was repeated for generation size of 12 MWh, 13 MWh, and 15 MWh and Figure 5.6, 4.7, and 4.8 shows the stored energy, respectively. The required energy storage capacity of these were 365 kWh, 167 kWh, and 77 kWh, respectively.

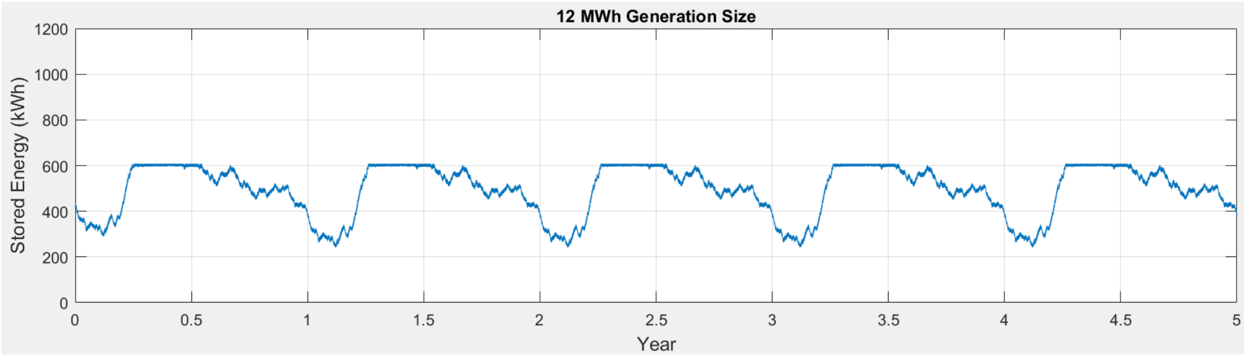

Figure 5.6: Stored Energy of 12 MWh Generation Size with 608 kWh storage limit

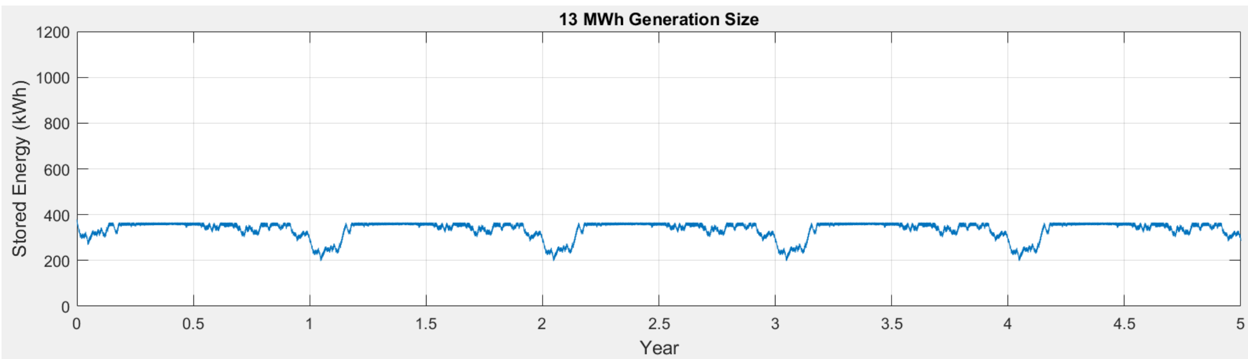

Figure 5.7: Stored Energy of 13 MWh Generation Size with 365 kWh storage limit

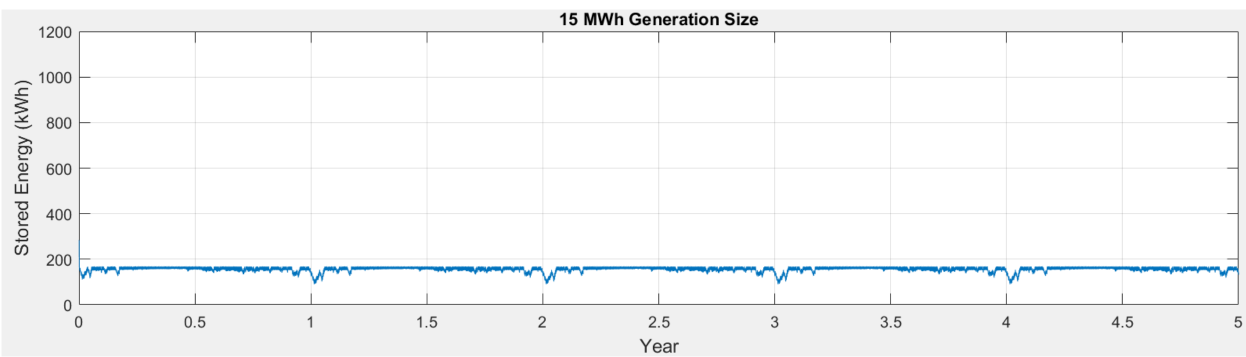

Figure 5.8: Stored Energy of 15 MWh Generation Size with 167 kWh storage limit

The algorithm performed this process but in smaller generation increments. Generation sizes from 10.65 MWh to 30 MWh in increments of 400 kWh were analyzed and storage capacity requirement was computed each time. Figure 5.8 shows the result of the data collected, the plot of required energy storage capacity vs generation size. The plot shows an inverse relationship between generation and storage. As generation increases the required energy storage capacity decreases.

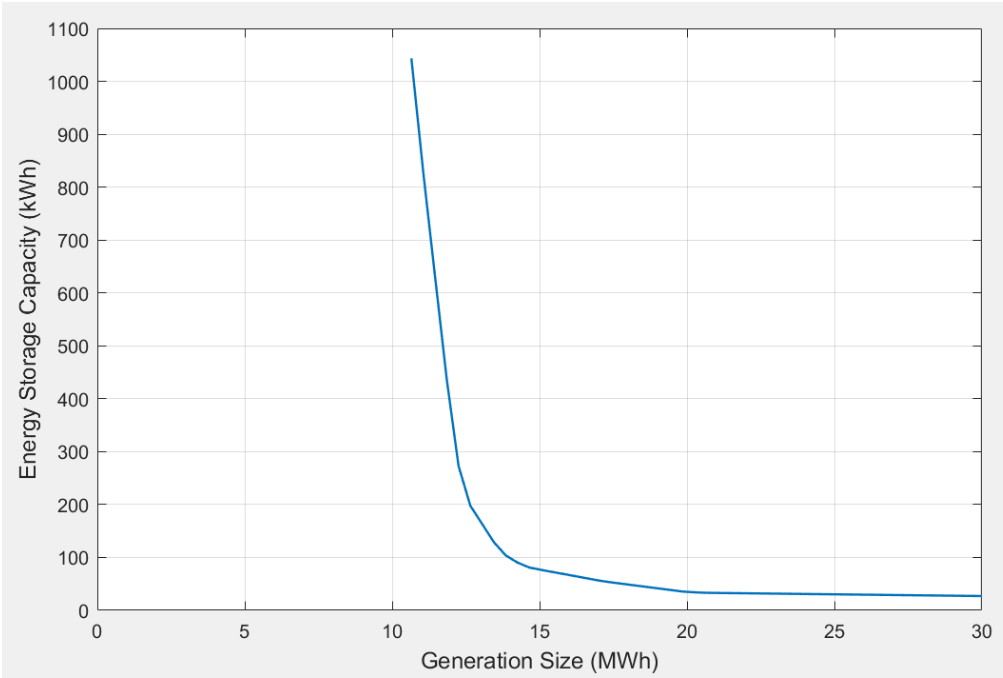

Figure 5.8: Required energy storage capacity vs. generation size

5.3 Cost Analysis

The relationship between generation and storage in Figure 5.8 is valuable for determining the most cost-effective system. Since PVs and ESS have different costs, the algorithm computed the total system cost of each configuration. Assuming PVs cost $4 per watt installed and lithium-ion battery ESS cost $400 per kWh, Figure 5.9 shows the total system cost for each off-grid configuration. The lowest point in this plot represents the cheapest off-grid configuration.

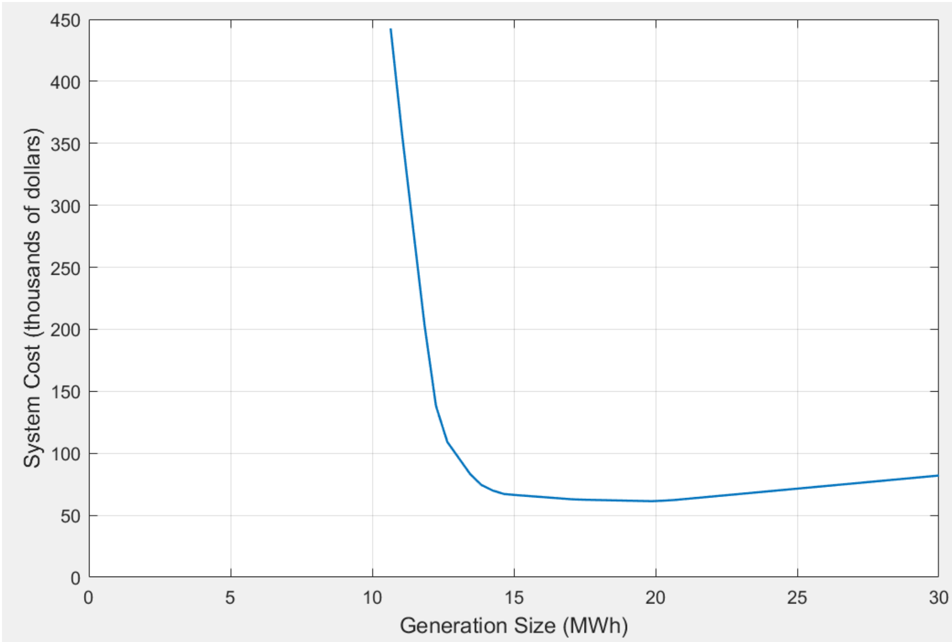

Figure 5.9: Total System Cost vs PV system size (off-grid configuration)

5.4 Energy Losses

One disadvantage of the off-grid method described is the energy losses due to overgeneration. Since off-grid systems are not connected to the grid, energy losses from overgeneration cannot be sold to the grid. Figure 5.10 shows energy losses due to overgeneration.

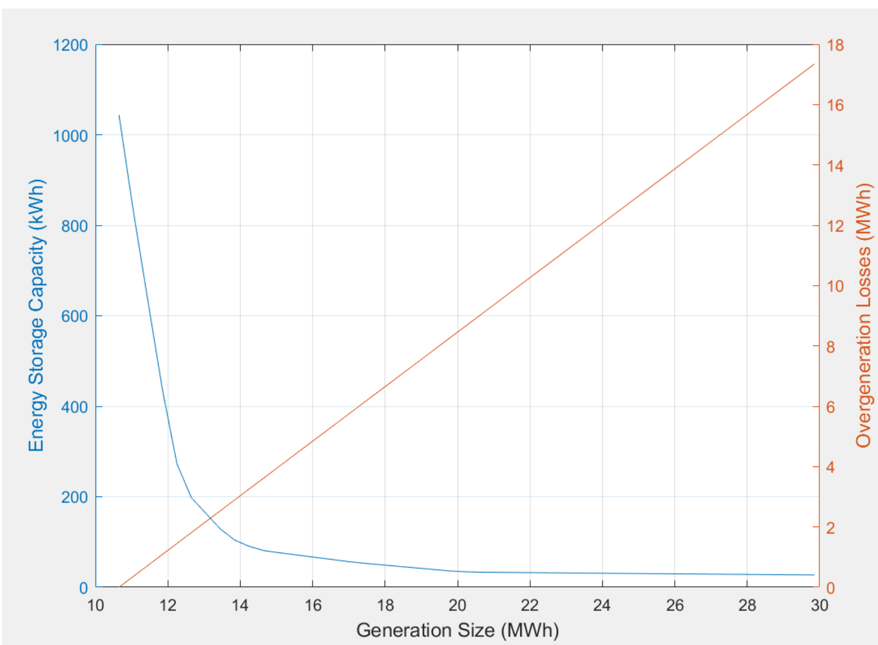

Figure 5.10: Energy Losses due to Overgeneration