100% Renewable Electric Power Systems

Technical Report Draft

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The purpose of this document is to describe my work and accomplishments, at OffGrid, for hiring managers. This document describes technical information about the algorithm and off-grid power system. I release all potential proprietary rights, pertaining to this system, into the public domain.

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I. INTRODUCTION

"It is not a dream, it is a simple feat of scientific electrical engineering, only expensive — blind, faint-hearted, doubting world!"—Nikola Tesla. Nikola Tesla is well-known for laying the foundation to the modern alternating current (AC) electric power system. When Tesla had the idea for an AC power system, he expressed his idea to his professor who called it a perpetual motion scheme—a theoretically impossible system. Today, the AC electric power system is the standard for transferring and delivering electric power from a wide range of renewable and non-renewable energy sources. The AC power system was an ambitious goal that Tesla achieved. His next ambitious goal was powering the world without fossil fuels which, unfortunately, he failed to achieve. In the quote above, Tesla was referring to the possibility of powering the world with 100% renewable energy. It is not a dream; It is not a perpetual motion scheme.

The electric power system is the network of power system components that delivers electricity to power televisions, refrigerators, computers, and every other device that plugs into an outlet. An electric power system can be divided into generation, transmission, and distribution. Generation (power plants) supply electric power. Transmission systems transfer the electric power, usually long distances, to distribution systems near the end consumer. Finally, the distribution system delivers the electric power to residential, commercial buildings, and industry.

A 100% renewable, electric power system—referred as off-grid system in this document—is a stand-alone renewable electric power system that can independently provide electric power to the end consumer year-round. The two main components of an off-grid system are renewable energy resources and energy storage systems (ESS). A major milestone for designing off-grid systems is determining how much renewable energy resources and how much energy storage capacity are required to provide reliable electric power year-round.

Any renewable energy resource can supply the power for off-grid systems. This document presents an approach to design off-grid systems using photovoltaic (PV) power systems. An algorithm was developed, that examines oversized PV systems, to determine the energy storage requirements for increasingly oversized PV. The result was a graph displaying how much energy storage vs. how much PV an off-grid system requires. The graph showed an inverse relationship between generation and storage. Since generation and storage have different costs, the algorithm computed the price of each off-grid system and determined the most cost-effective configuration. As an example, this document illustrates the result of an off-grid system for a residential building, assuming 90% efficient lithium-ion ESS.

The algorithm requires two parameters: expected time-series power supply of the PV and expected time-series power demand of the building. Future work could involve incorporating probability distributions of the power supply and power demand into the algorithm to improve the simulation and design off-grid systems that meet statistical requirements (e.g., there is an

80% chance that PV size X and storage capacity Y will reliably supply electric power year-round for this building for this year). Future work could also include mixing renewable energy resources and optimizing for the cheapest cost.

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 the performance of some power system components and appliances.

Renewable energy resources are technologies that supply power from renewable energy resources such as sunlight and wind. ESS are technologies that can either supply or consume power. ESS can consume power—store energy—and save for later use. The energy storage capacity describes the maximum amount of energy an ESS can store. The amount of stored energy in ESS can range from 0% capacity to 100% capacity.

Since a reliable electric power system requires balancing the supply and demand, ESS are crucial for reliability. When supply exceeds demand, ESS consume the power difference to balance the system. When demand exceeds supply, ESS supply the power difference to balance the system. An off-grid system design requires ESS to have enough stored energy to balance the system.

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

Another challenge of designing off-grid systems is the seasonal imbalance between supply and demand. A majority of PV generation occurs during the summer when the sun shines brighter and for longer periods of time. The standard PV size—the PV size with an expected annual generation equal to the expected annual consumption of the building— 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 depends on the correlation between the expected time-series power supply and power demand of the building. Two hypothetical scenarios are presented to validate this statement. 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. Table 1 summarizes the results.

Table 1: Hypothetical Scenario #1 Results

Annual consumption	10 MWh
Annual generation	10 MWh
Required storage capacity	None

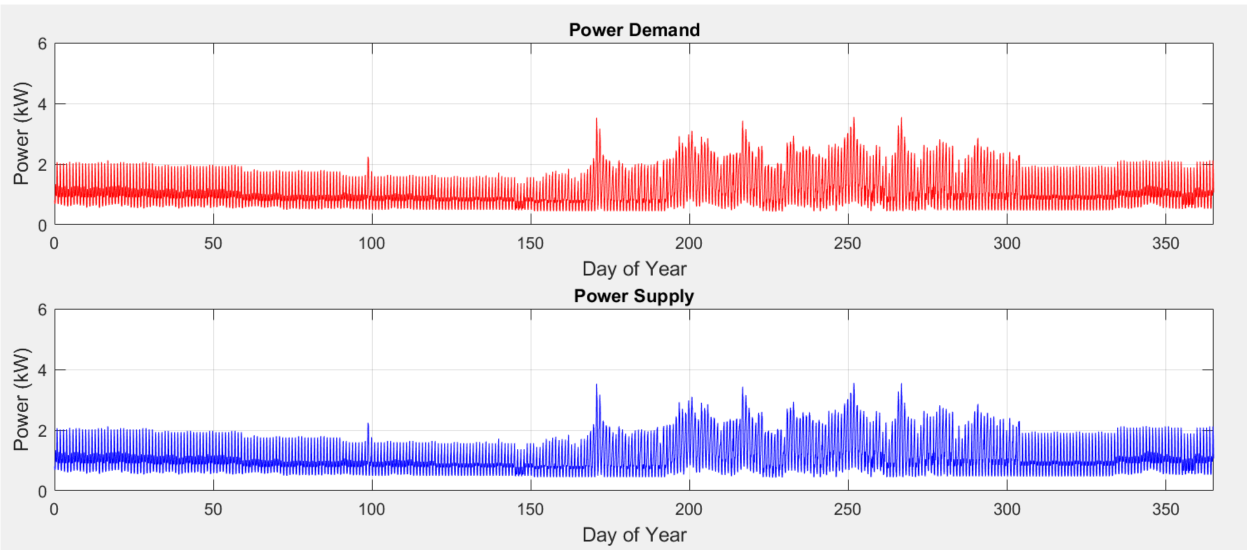

Figure 3.1: Power Supply and Demand of Hypothetical Scenario #1

For the second hypothetical scenario, which examines an opposite situation, let's assume the power supply and power demand are disjointed as in Figure 3.2. All the generation occurs during the first six months of the year while all the power demand occurs during the last six months; 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 a PV system with an annual generation of 11.11MWh. Generation must supply consumption and storage losses.

$$Generation(0.9) = Consumption$$

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

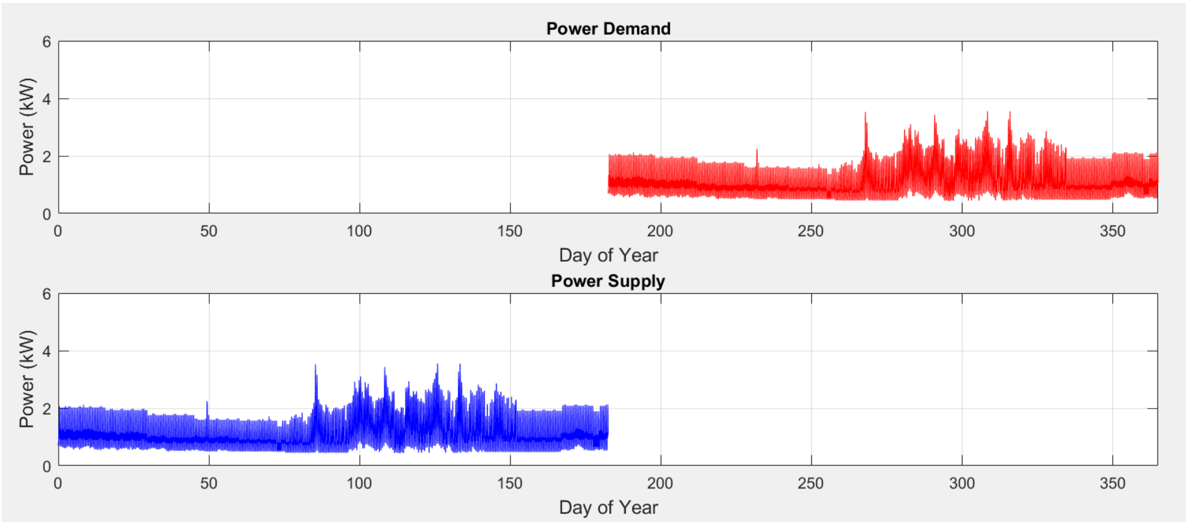

Figure 3.2: Power Supply and Demand of Hypothetical Scenario #2

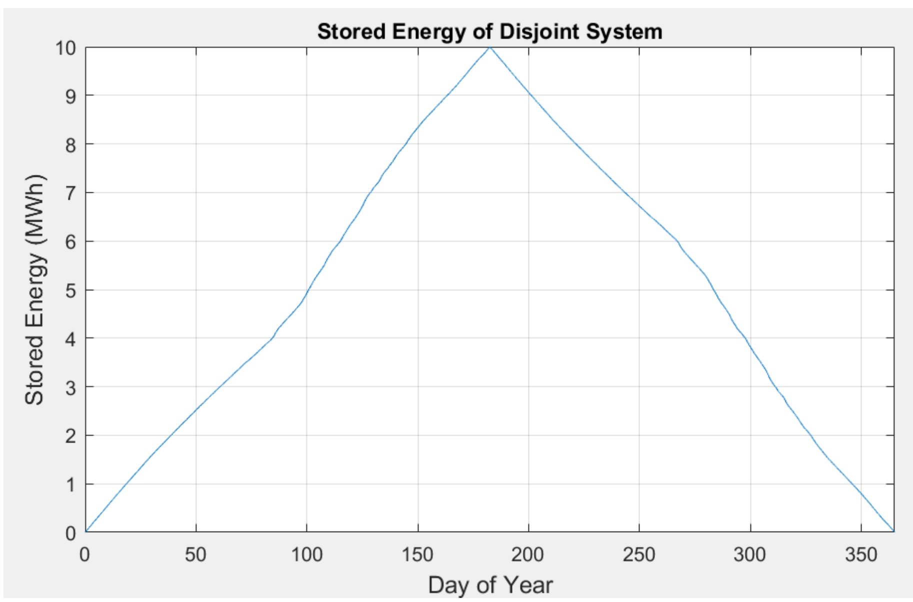

Figure 3.3: Stored Energy for Hypothetical Scenario #2

Figure 3.3 shows the amount of stored energy for 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; the EES stores all the generation, and the stored energy accumulates to 10 MWh.

During the last six months, since power demand is present while power supply is absent, the 10MWh of stored energy can independently supply the 10MWh consumption of the building.

The stored energy depletes at the end of the year, and this cycle starts over again. Table 2 summarizes the results for this hypothetical scenario.

Table 2: Hypothetical Scenario #2 Results

Annual consumption	10 MWh
Annual generation	11.11 MWh
Required storage capacity	10 MWh

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 required 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 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 III.

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].

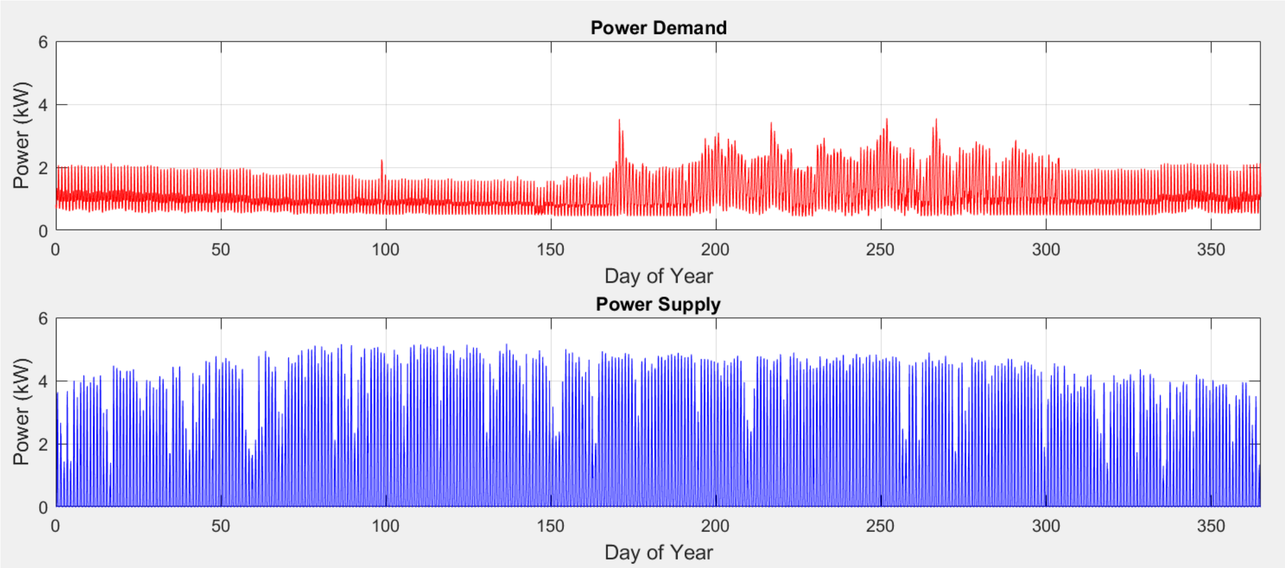

Figure 4.1: Power demand of building (top), Power supply of PVs (bottom)

4.2 Modeling Stored Energy

The algorithm iterated through the time-series power data to generate a running total of the stored energy. 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 energy storage losses.

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 an 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.

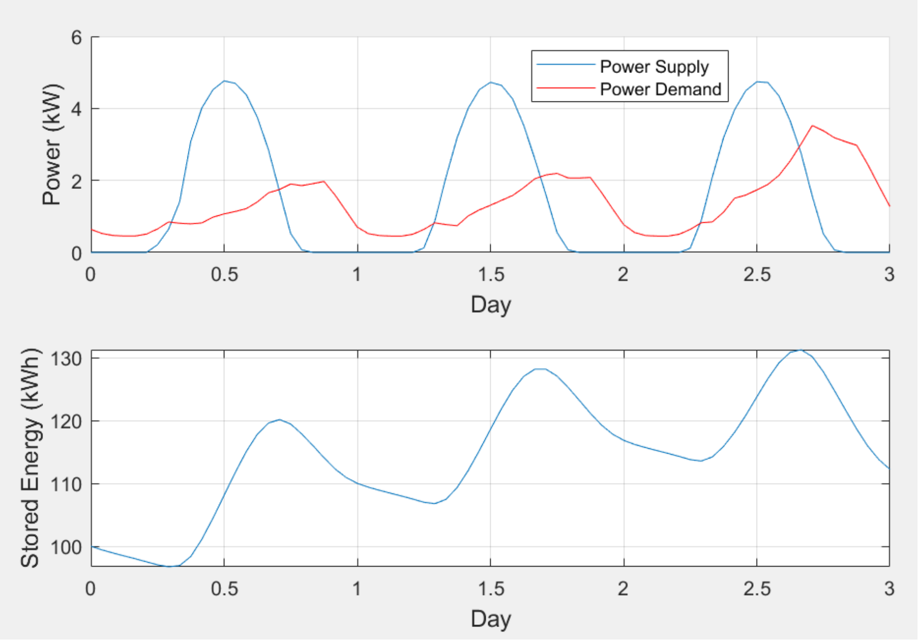

Figure 4.2: Power data for three days (top) Stored energy of ESS (bottom)

4.3 Initial Stored Energy and Shifting Property

Before the algorithm iterated through the time-series power data, the initial stored energy was selected. This value was arbitrary since the stored energy graph can be shifted up or down; Shifting the graph up or down was equivalent to incrementing or decrementing the initial stored energy value and repeating the iteration 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 were identical except for a vertical shift.

The algorithm used the initial amount of stored energy selected and iterated through the power data to generate a running total of the stored energy. Afterward, the stored energy data was shifted such that the lowest value was zero; the amount of stored energy must be non-negative since actual ESS cannot contain negative energy.

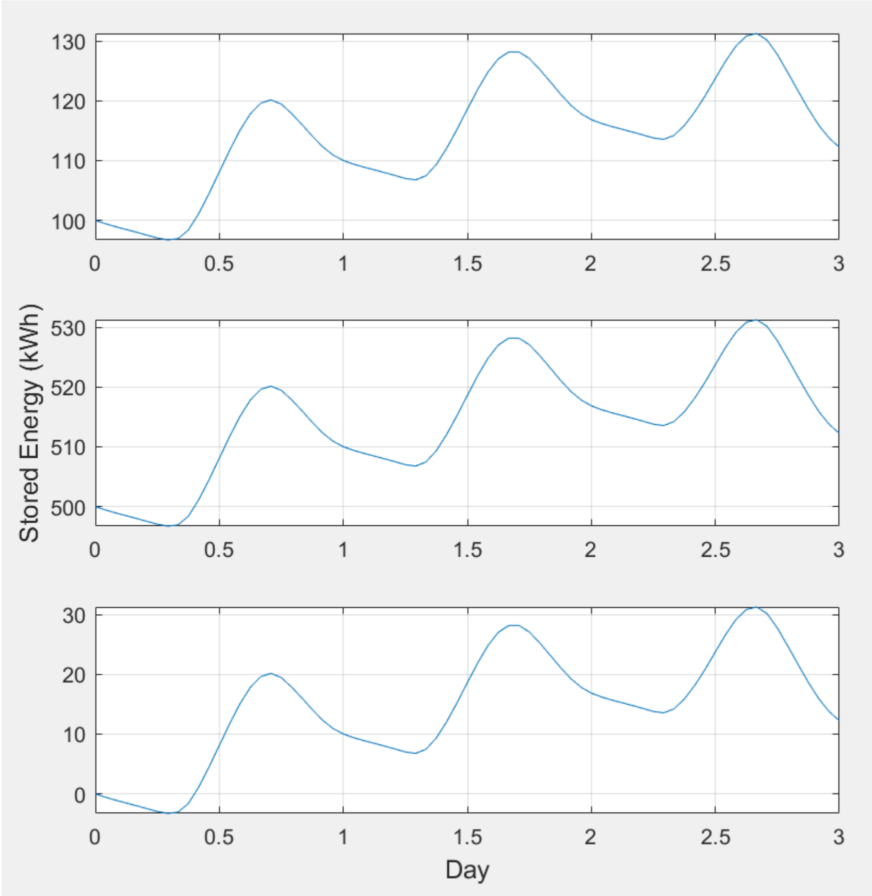

Figure 4.3: Stored Energy with initial storage of 100kWh, 500kWh, and 0kWh.

4.4 Five-year Analysis of Various Generation Sizes with 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. The PV was expressed in terms of annual generation size, instead of PV system size (kW), to compare the total generation and the total consumption.

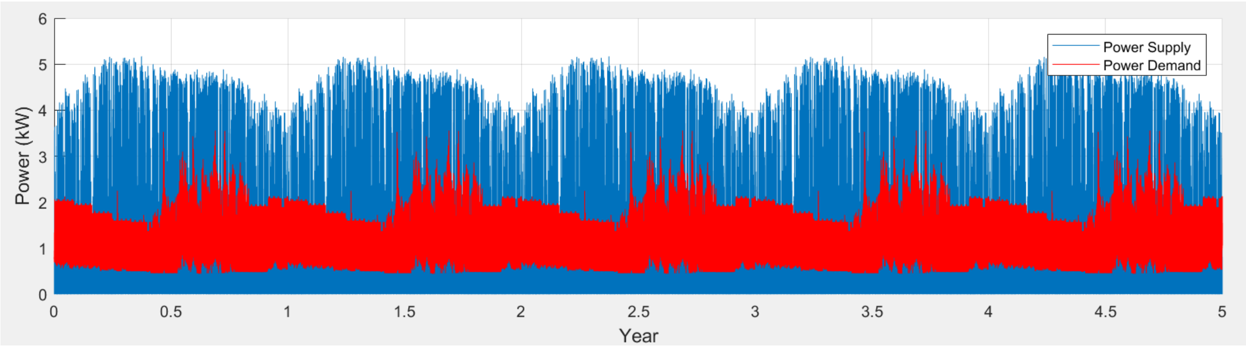

Figure 4.4: Power supply (blue) and power demand (red)

The five-year power supply and power demand data were used to simulate the stored energy for each generation size with a 100% efficient ESS (let's assume a 100% efficient ESS exists). Figure 4.5 shows the stored energy for each generation size. The initial storage was to set 8MWh.

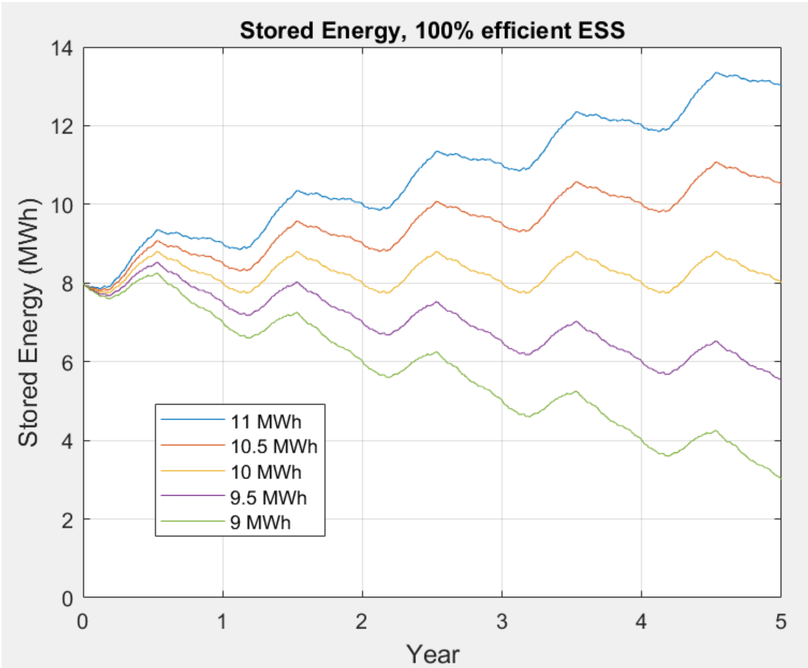

Figure 4.5: Stored Energy of various generation sizes

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 years. 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 neither increased nor decreased over the five years. Since there are no storage losses, generation equal to consumption balanced the system.

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

Next, the five-year power supply and power demand data were used to simulate the stored energy for each generation size 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 supply the consumption and storage 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 balanced the system was between 10.5 MWh and 11 MWh.

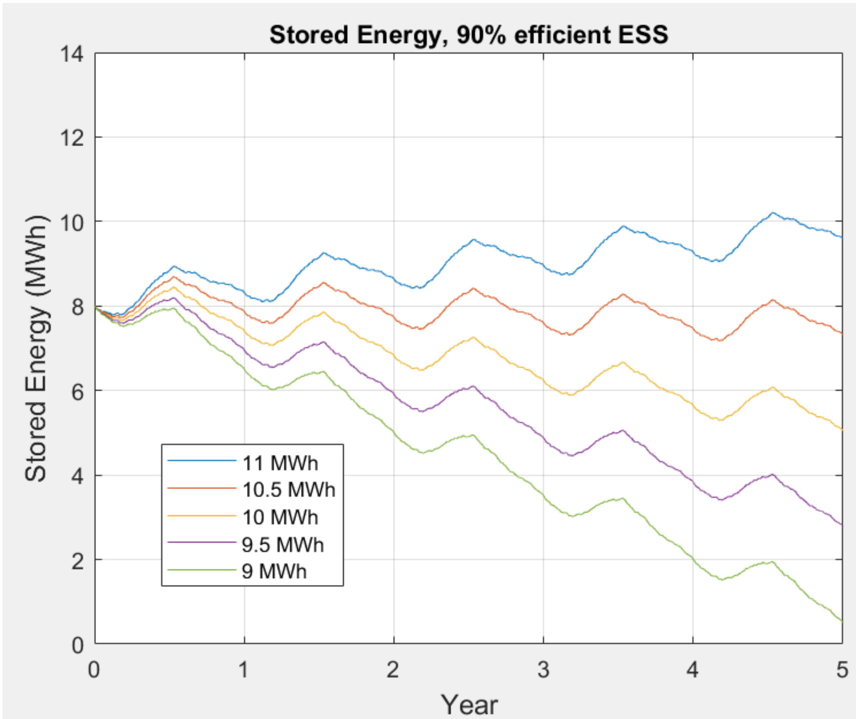

Figure 4.6: Stored Energy versus various generation sizes

V. RENEWABLE, OFF-GRID POWER SYSTEMS

5.1 The Balanced Off-Grid System

$$Generation = Consumption + Storage\ Losses$$

The algorithm found the generation size that balanced the off-grid system by continuously increasing the generation and checking if the system was balanced. The algorithm gradually increased the generation, starting with generation equal to consumption, and simulated 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 determined. For this example, a generation sizing of 10.65 MWh balanced the system. The stored energy was shifted such that the lowest value was zero. Figure 5.1 shows the stored energy with a generation sizing of 10.65 MWh for five years. Each annual cycle was identical.

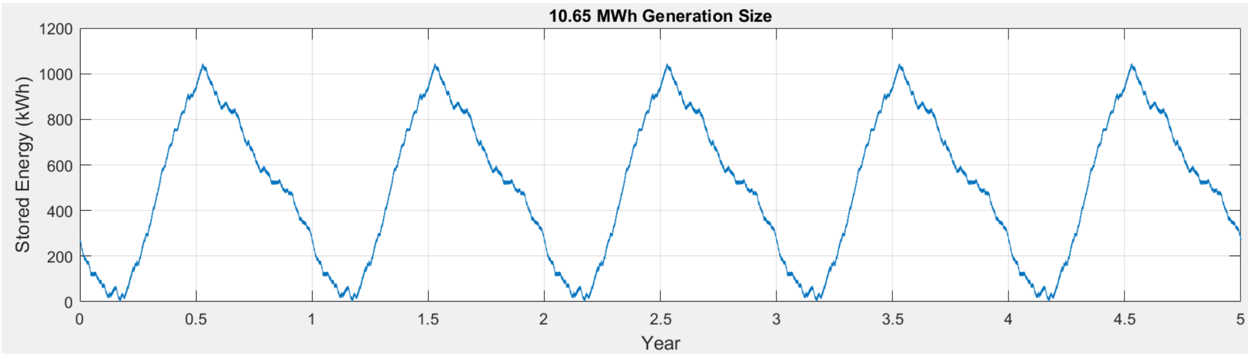

Figure 5.1: Stored Energy of 10.65 MWh Generation Size

Figure 5.2 shows the stored energy for a year. The initial stored energy was 266 kWh, and it gradually decreased to zero during the first sixty days. From day 60 to day 190, the stored energy gradually increased reaching a maximum of 1044 kWh. From day 190 to 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 represented the required energy storage capacity for this off-grid system. A 10.65 MWh generation size required a 1044 kWh storage capacity.

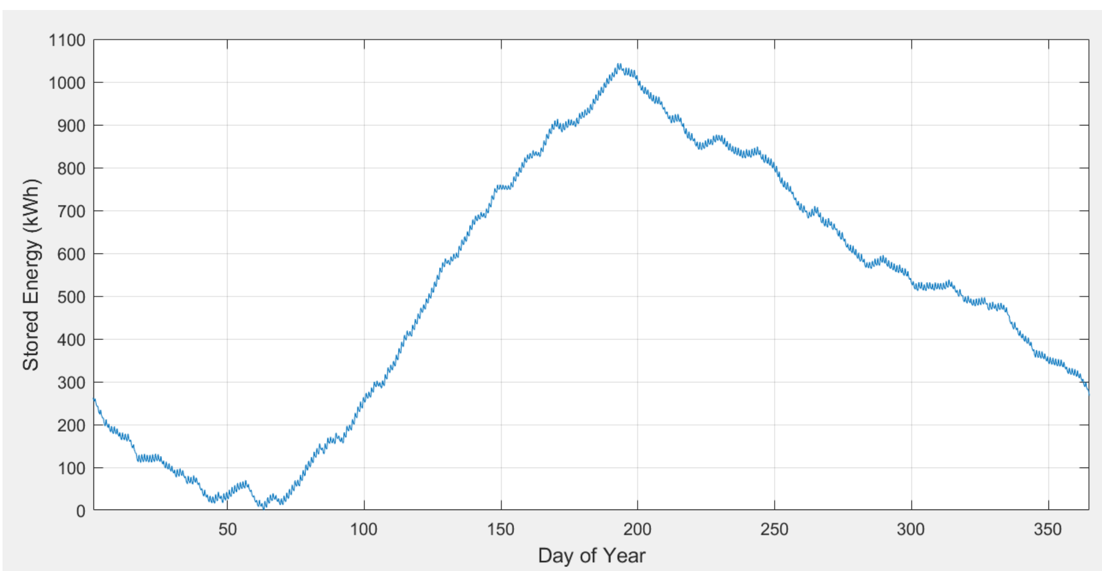

Figure 5.2: Stored Energy for a year with a 10.65 MWh

Figure 5.3 shows a 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.

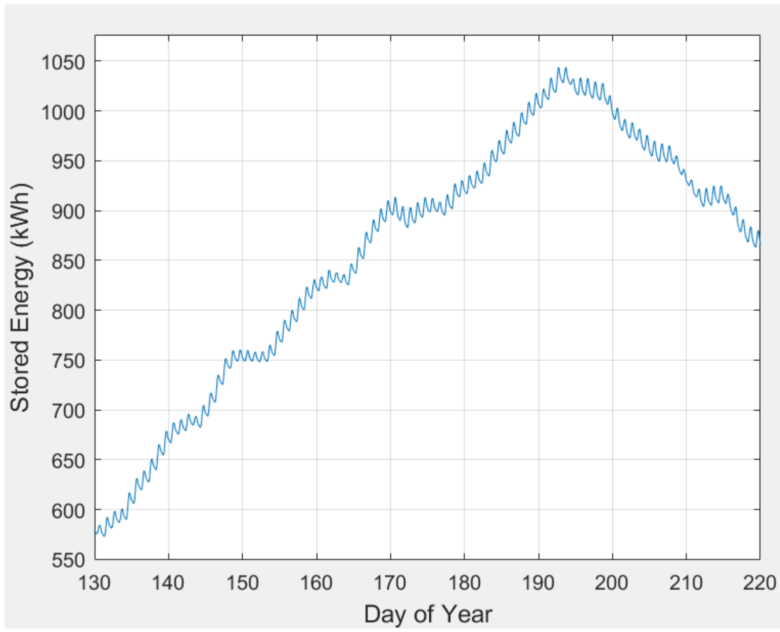

Figure 5.3: Stored Energy for the year with a generation sizing of 10.65 MWh

5.2 Oversizing Generation for Off-Grid Systems

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

Figure 4.6 shows that generation sizing larger than 10.65 MWh causes the stored energy data to gradually increases. 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. The stored energy was not allowed to exceed the limit, and overgeneration, the unstorable energy, was wasted.

Figure 5.4 shows the stored energy of a11 MWh generation size with a 1044 kWh storage limit. Since there is more power generated, the stored energy graph no longer reached zero. The clipping of the sinusoidal wave showed when the storage limit was reached. The amplitude of the stored energy graph represents the required energy storage capacity; therefore, an 11 MWh generation size requires an energy storage capacity of 856 kWh for this off-grid system.

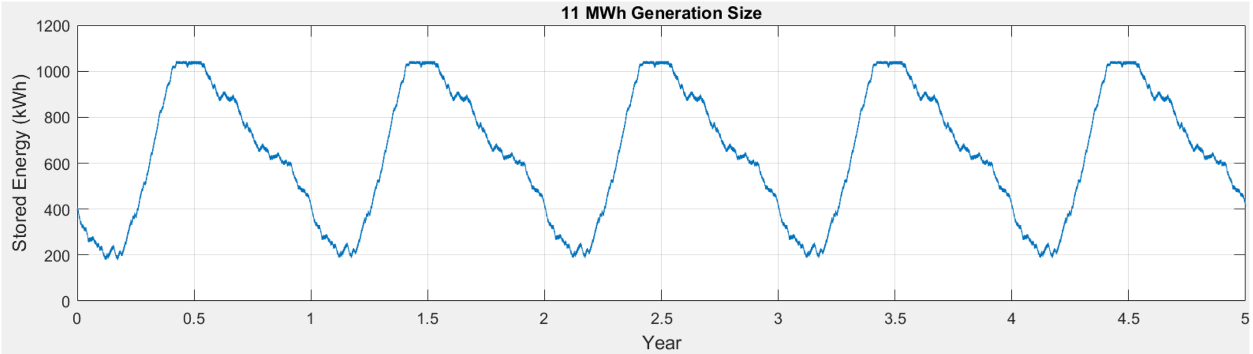

Figure 5.4: Stored Energy of 11 MWh Generation Size with 1044 kWh storage limit

Next, an 11.5 MWh generation 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 11.5 MWh generation. The duration of the clipping was longer. The amplitude of this waveform was 608 kWh; therefore, 11.5 MWh generation requires an energy storage capacity of 608 kWh for an off-grid system.

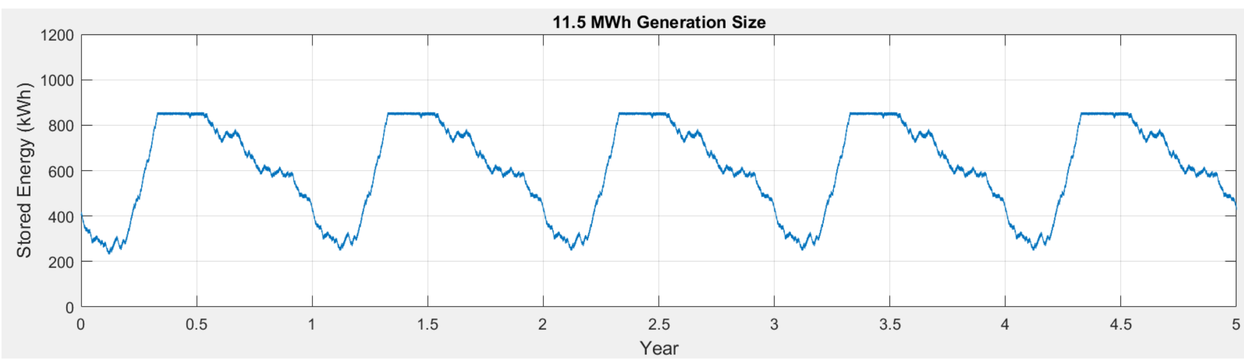

Figure 5.5: Stored Energy of 11.5 MWh Generation Size with 856 kWh storage limit

This process was repeated for generation sizes 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 capacities of these generation sizes were 365 kWh, 167 kWh, and 77 kWh, respectively.

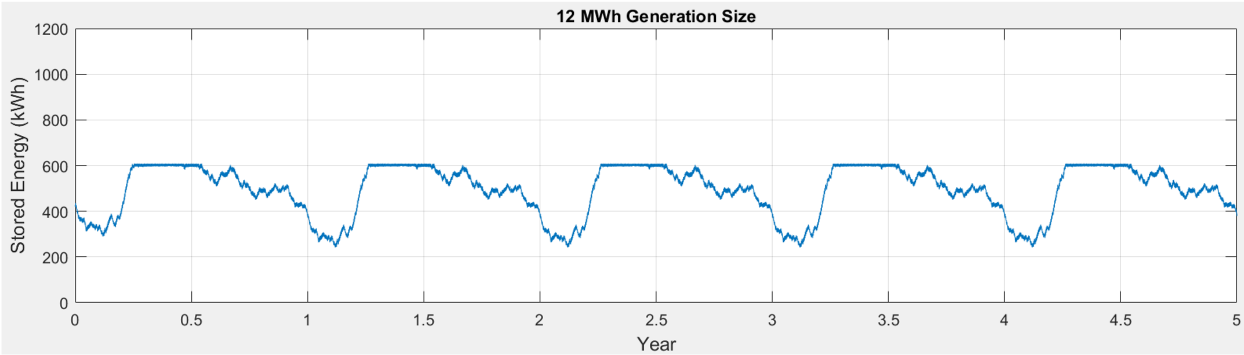

Figure 5.6: Stored Energy of 12 MWh Generation Size with 608 kWh storage limit

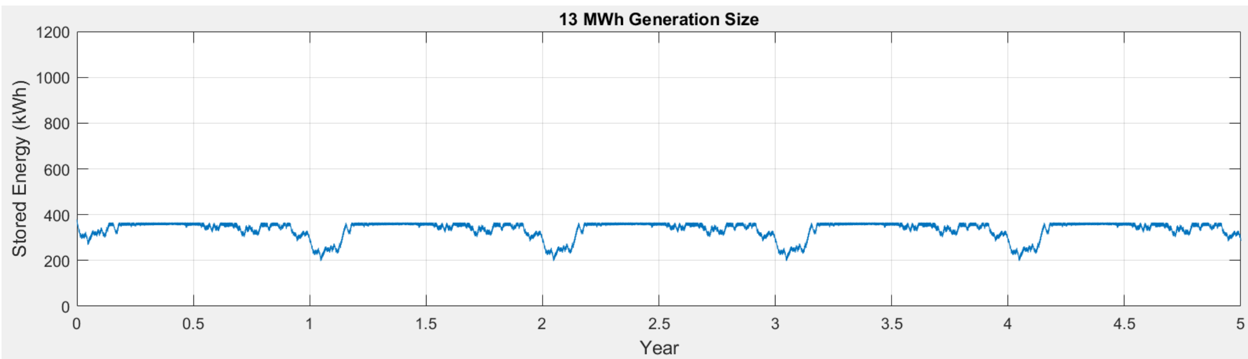

Figure 5.7: Stored Energy of 13 MWh Generation Size with 365 kWh storage limit

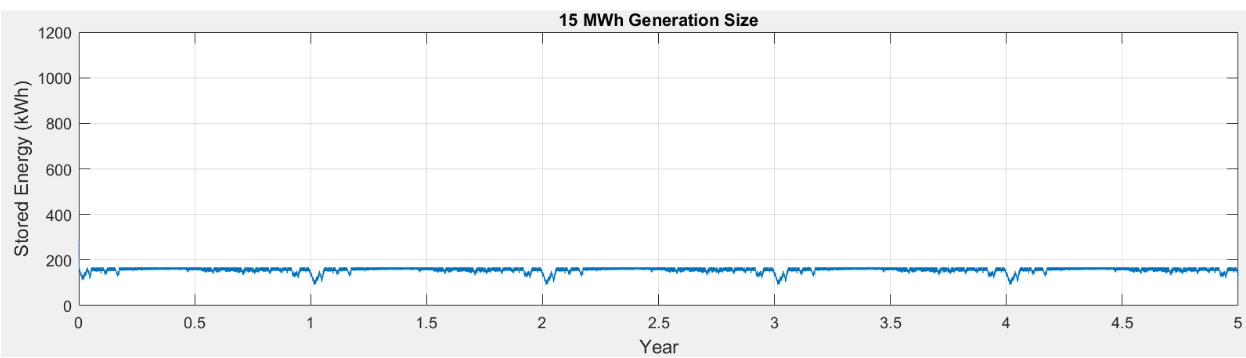

Figure 5.8: Stored Energy of 15 MWh Generation Size with 167 kWh storage limit

The algorithm performed this process but in smaller 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, 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.

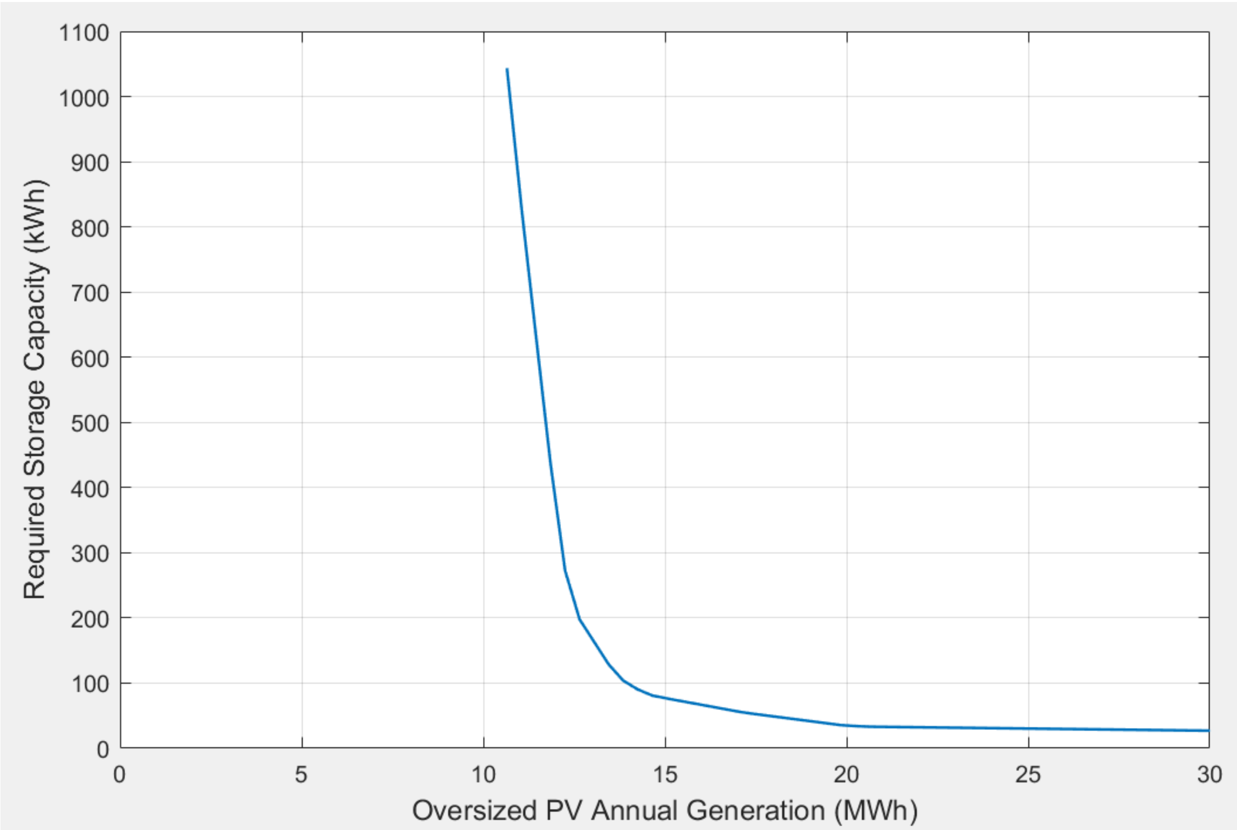

Figure 5.8: Required storage capacity vs. Oversized PV annual generation

5.3 Cost Analysis

The relationship between generation and storage in Figure 5.8 is valuable for determining the most cost-effective system. Since PV and ESS have different costs, the algorithm computed the total system cost of each configuration, assuming PV cost $4 per watt installed and lithium-ion ESS cost $400 per kWh. Figure 5.9 shows the total system cost for each off-grid configuration. The lowest point in this plot shown by the red “x” represents the cheapest off-grid configuration of about 62k dollars. The most cost-effective configuration was a generation sizing of 19.85 MWh. By referencing back to Figure 5.8, this generation size requires a 35.6 kWh energy storage capacity. The generation sizing of 19.85 MWh corresponds to an 11.78 kW PV system size.

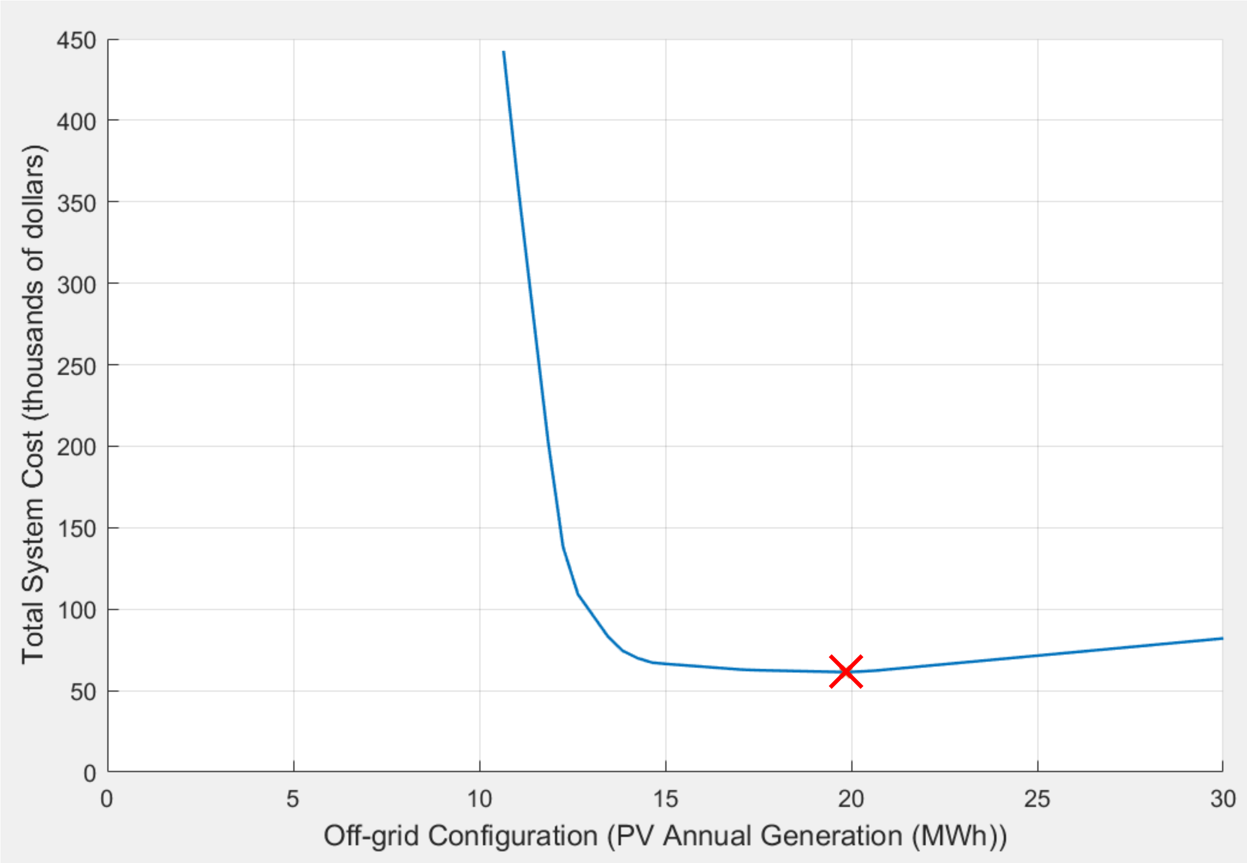

Figure 5.9: Total System Cost vs. PV/storage configuration

5.4 Inverter Size

The inverter size, for the most cost-effective configuration, was obtained by finding the maximum power input/output of the ESS. For this example, the algorithm computed 7.4kW was the maximum power input/output of the ESS. Therefore, the most cost-effective configuration would require an 11.78 kW PV system (generation sizing of 19.85 MWh) and a 7.4kW/35.6kWh ESS.

5.5 Energy Losses

A disadvantage of the off-grid method is the energy losses due to overgeneration. Since off-grid systems are disconnected from the grid, energy from overgeneration cannot be sold on the grid. Figure 5.10 shows the annual energy losses due to overgeneration for each PV/storage configuration.

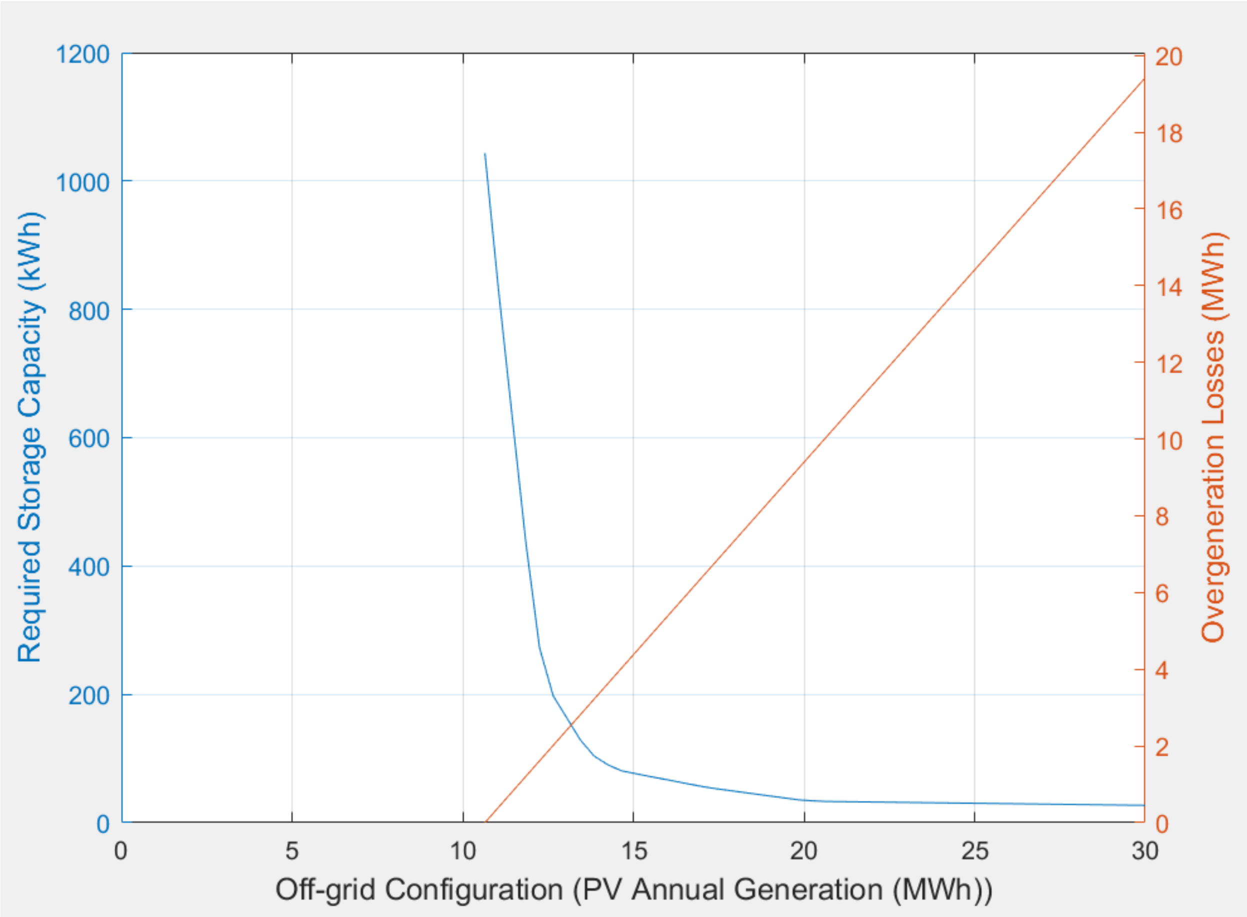

Figure 5.10: Energy Losses due to Overgeneration

VI. REFERENCES

1. https://en.openei.org/datasets/dataset/commercial-and-residential-hourly-load-profiles-for-all-tmy3-locations-in-the-united-states

2. http://pvwatts.nrel.gov/