Network of Optimized Sustainable Energy Generation Systems

Technical Report Draft

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I. SUMMARY

The electric power system delivers electricity to homes and buildings to power televisions, refrigerators, computers, and every other device that plugs into an outlet. A Sustainable Energy Generation System (SEGS) is a stand-alone electric power system that independently provides power from renewable energy resources. The two main components for an SEGS are renewable energy resources and energy storage systems (ESSs). The main challenge for designing SEGSs is determining how much renewable energy resources and how much energy storage are required to reliably and independently supply power year-round.

By considering oversized generation, there are, theoretically, infinitely many possible configurations. An algorithm was pioneered to approximate all possible configurations of solar photovoltaic (PV) and energy storage for a SEGS, and an inverse relationship between oversized PV and energy storage was discovered as shown in Figure 1.1.

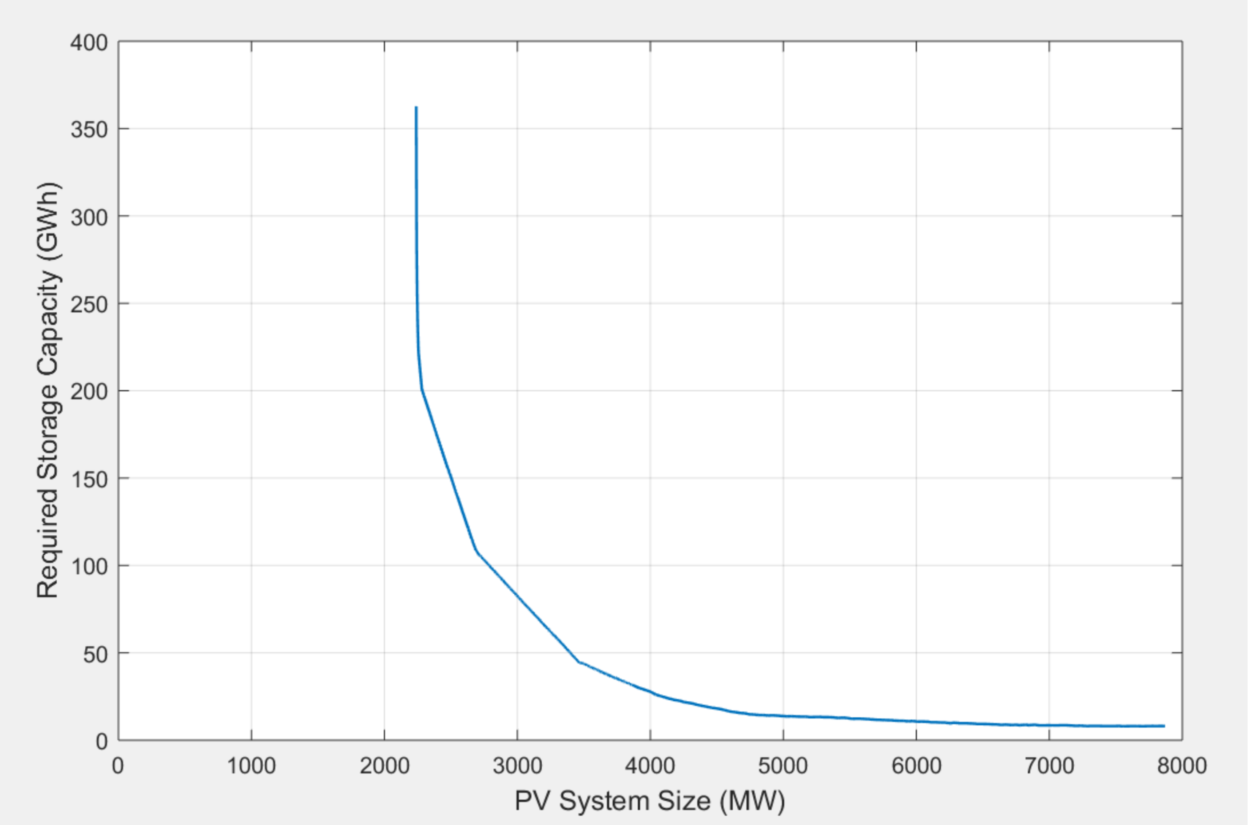

Figure 1.1: The inverse relationship between oversized PV and energy storage capacity

This relationship is important to optimize for the cheapest system. Since PV and energy storage have different costs, the algorithm calculates the cost of all possible configurations which is shown in Figure 1.2. The red “x” represents the most cost-effective system.

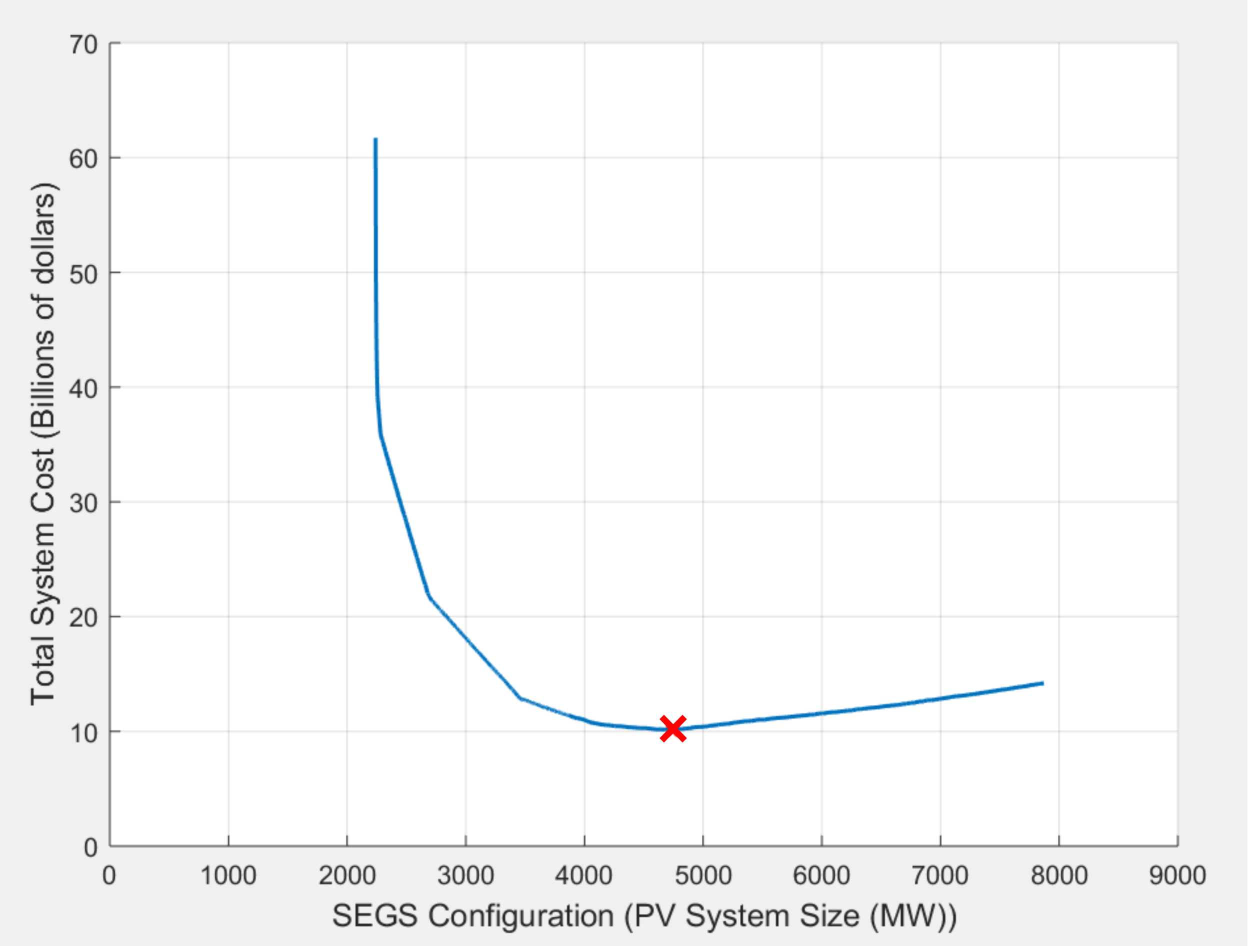

Figure 1.2: Total system cost for each SEGS configuration

II. INTRODUCTION

There are two main problems to achieve 100% renewable energy in the electric sector. The first problem is figuring out how to design SEGSs that incorporate all renewable energy resources (solar, wind, hydroelectric, etc.) and all ESSs (batteries, pumped hydro, etc.).

The second problem is figuring out how to replace the legacy electric generation resources with SEGSs. Currently, the consensus to this problem is to add more and more renewable energy as a whole until 100% is achieved. A better approach maybe isolating a section of the grid, building a SEGS for the isolated region, and then remove the carbon generating resources in those regions. By continuing this process, as more and more sections are upgraded with SEGSs, the number of required carbon generating resources decreases until 100% renewable energy is achieved.

This document presents a design for a SEGS using PVs, and this document also describes how SEGSs can be the building blocks to achieve 100% renewable energy in the electric sector. Section III presents useful background information. Section IV presents a network of optimized SEGSs to replace legacy electric generation resources. Section V presents the algorithm to design SEGSs using PV. Section VI presents optimized SEGSs. Lastly, section VII describes possible future work.

As an example, the algorithm was used to design a SEGS for Turlock Irrigation District (TID). TID is an electric utility that provides power to Turlock, CA and surrounding areas. TID has an annual consumption of about 2,006 GWh which is about 0.05% of the total US consumption.

III. BACKGROUND

Renewable energy resources are technologies that generate electricity from renewable resources such as sunlight, wind, biomass, nuclear, and hydroelectric. Renewable energy resources can be categorized into three groups: Renewable Power Technologies, Renewable Energy Technologies, and Renewable Fuel Technologies.

Renewable Power Technologies (RPTs) are technologies that generate real-time renewable power. Solar PV and wind turbines are two common examples of RPTs. The availability and the power output of RPTs are both intermittent; they depend on the renewable resource. For example, the availability of solar power depends if the sun is out, and the power output depends on the irradiance (the brightness of sunlight). The power output of RPTs must either be immediately utilized or stored, or else it’s wasted.

Renewable Energy Technologies (RETs) are technologies that accumulate renewable energy in stored form. The availability and the power output of RETs depends on the amount of stored energy. The only known RET is hydroelectric. In hydroelectric facilities, a dam stores energy in the form of water, and that energy can be released to generate electricity. The amount of stored energy is directly related to the volume of water. The stored energy of hydroelectric facilities increases when the water level increases via rainfall, stream, etc. Unlike RPTs, the accumulated energy of hydroelectric systems doesn’t need to be immediately utilized. The availability and the power output of RETs depends on the amount of stored energy. If stored energy is available, energy can be released to produce power on demand.

Renewable Fuel Technologies (RFTs) are technologies that generate power from renewable fuel. The availability and the power output depend on the presence of the fuel. Examples include biomass and nuclear. For example, the availability and the power output of nuclear power plants depend on the presence of nuclear fuel. If nuclear fuel is available, power from nuclear power plants can be generated on demand.

Energy Storage Systems (ESSs) are technologies that store energy. There are many types of ESSs that store energy in different forms (chemically, mechanically, thermally, etc). The most common ESS is batteries. Regardless of the ESS, they all serve a common purpose of storing and generating energy. The maximum amount of energy that can be stored is called the **capacity** of the ESS. The amount of stored energy increases by storing energy, or the amount of stored energy decreases by generating energy.

To give an analogy, imagine an ESS as a bucket that can hold 1 gallon of water. If the bucket is not full, water can be added to increase the volume of water, or water can be released to decrease the volume of water. Water can enter/exit the bucket slowly (i.e. 1 drop a second) or more quickly (i.e. 100 drops a second). In technical terms, stored energy is a measure of the water volume, and power is a measure of how that volume changes, or in other words, power is a measure of the rate water enters or exits the bucket.

The unit for energy is watt-hour (Wh).

$$1000\,Wh = 1\,kWh \qquad 1000\,kWh = 1\,MWh \qquad 1000\,MWh = 1\,GWh$$

The unit for power is watt (W).

$$1000\,W = 1\,kW \qquad 1000\,kW = 1\,MW \qquad 1000\,MW = 1\,GW$$

If the capacity of an ESS is 10 MWh, the maximum amount of storable energy is 10 MWh. Energy can be released to generate power which decreases the stored energy, or power can be stored which increases the amount of stored energy. The rate that energy enters or exits the system is the measurement of power.

ESSs inherently have energy losses. The **efficiency** of an ESS is the amount of retrievable energy. For example, if 10 kWh is stored in an 90% efficient ESS, only 90% of this energy (9 kWh) can be retrieved; the rest is lost. Some ESSs also have **efficiency degradation** effects which decreases the efficiency over time. For example, the efficiency of an 90% ESS may degrade to 85% after some time. Some ESSs also have state-of-charge and time-dependent **self-discharge** energy losses.

The **electric power system** is the network of power system components that delivers electricity to homes, commercial buildings, and industrial facilities. One major challenge of electric power systems is continuously balancing the power supply and power demand. The **power demand** of an electric power system is the amount of power being consumed by all the devices connected to this electric power system, and the **power supply** is the total amount of power being produced by all the generating resources of this electric power system. If power supply is considerably less than power demand, connected appliances/devices might not operate properly. If the power supply is considerably larger than power demand, the extra power could damage and/or affect power system components and/or devices.

The **annual expected consumption** of an electric power system is a measure of the total energy estimated to be consumed by all the devices/appliances connected to the electric power system.

The **annual expected generation** of a renewable energy resource is an estimation of the total energy production for a year.

Sustainable Energy Generation Systems (SEGS) are electric power systems that independently provide power with renewable energy resources. SEGSs connect directly to the end consumer, and they do not connect to other electric power systems which means they are stand-alone (off-grid) systems; however, SEGSs are connected to each other. The two main components for SEGSs are renewable energy resources and ESSs. Any type of renewable resource (RPTs, RETs, and RFTs) and any type of ESS can be utilized to design SEGSs.

ESSs are essential for SEGSs to balance power supply and demand. When supply exceeds demand, ESS can store the extra power to balance the system. When demand exceeds supply, ESS can generate the missing power to balance the system.

One major challenge of designing SEGSs with PVs is the daily imbalance between supply and demand. PV generate power, during the daytime, when the sun is shining while buildings typically consume power all day and night; therefore, the ESSs, must have enough stored energy to supply power during the nighttime.

Besides the daily imbalance between supply and demand there also exists a seasonal imbalance. A majority of PV generation occurs during 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 power system—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 provides the potential to generate more power year-round.

The **Generation-to-Consumption (G2C) ratio** of an SEGS is the ratio between the annual generation and the annual consumption. For example, if an SEGS has an annual generation of 15 GWh and an annual consumption is 10 GWh, then the G2C ratio is 1.5. The equation to compute the G2C ratio is shown below, and a few examples of G2C ratios are shown in Table 3.1.

$$G2C\ ratio = \frac{Annual\ Expected\ Generation}{Annual\ Expected\ Consumption}$$

Table 3.1: Generation-to-Consumption (G2C) Ratios

Generation (GWh)	Consumption (GWh)	G2C ratio
30	10	3.00
15	10	1.50
10	10	1.00
7.5	10	0.75

A SEGS is comparable to a person bouncing a basketball 3ft high continuously. In this analogy, the amount of energy the person applies to the ball on each bounce corresponds to the annual generation of the PV system while the amount of energy lost by friction on each bounce corresponds to the annual consumption. The amount of energy lost by air resistance is analogous to the annual energy loss of the ESS (e.g. efficiency, self-discharge, etc.). For the ball to bounce 3ft high continuously, the amount of energy the person delivers to the ball must be greater than the consumption plus total energy lost. Similarly, for an SEGS, the annual generation must be greater than the annual consumption plus energy losses. As a result, the G2C ratio for SEGSs will always be greater than 1 since storage losses always exist.

IV. NETWORK OF OPTIMIZED SUSTAINABLE ENERGY GENERATION SYSTEMS

The first electric power system in the United States was a coal-fired power plant in 1882 that provided residents of New York city with electricity. The electric grid, initially, consisted of many isolated electric power systems across the nation each providing power to its individual region.

Over the years as the electric industry grew and the population increased, power systems were developed across the nation and they grew to encompass larger regions. Eventually, neighboring electric power systems began connecting to increase reliability—if a power plant went down, power could be received from a different power system through the interconnected framework. The electric grid started as many isolated power systems, but it evolved into a large interconnected system.

There are two paths to achieve 100% renewable energy in the electric sector. The first approach is continuously adding more and more renewable energy as a whole until 100% is achieved. The second method is to upgrade sections of the electric grid one-by-one with SEGSs such that the SEGSs are electrically isolated from the original interconnected system. By continuing this process, as more and more sections are upgraded, the number of required carbon-based generating resources gets smaller and smaller until 100% renewable energy is reached. The result would be a decentralized system made of many SEGSs. Each SEGS is responsible for its own region but can ask for power from other SEGSs that have extra power or stored energy. Each SEGS has a centralized backbone, but as a whole, the connected SEGSs have a decentralized backbone.

Figure 4.1 through Figure 4.6 shows how upgrading the electric generation resources with SEGSs can be implemented. Figure 4.1 shows the existing electric grid. The first step is to design and develop a single SEGSs prototype to test as shown in Figure 4.2. The SEGS is an off-grid system so no electricity passes between the SEGS and the original electric grid.

Once the SEGS prototype is able to independently supply power year-round, the next step is to design and implement neighboring SEGSs and connect them as shown in Figure 4.3; the dotted lines represent the interconnection between SEGSs. If a SEGS receives less than expected power or experiences more than expected power demand, power can be received from a different SEGS through the decentralized backbone.

As more and more SEGSs are implemented, the number of required carbon generating resources gets smaller and smaller until 100% renewable energy is achieved. Figure 4.4 shows the electric grid at 66% SEGSs, and Figure 4.5 shows the electric grid at 100% SEGSs.

Figure 4.6 shows an example of the power flow through the network. The red SEGS requested power and the green SEGS accepted. Once an agreement is made, the two SEGSs connect through the decentralized backbone to transfer power.

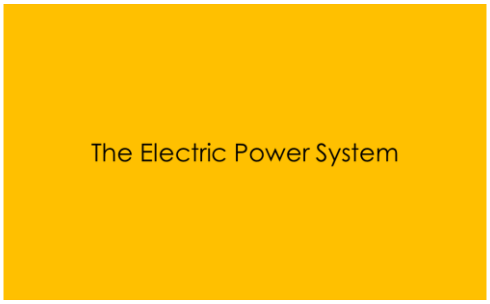

Figure 4.1: The Electric Power System

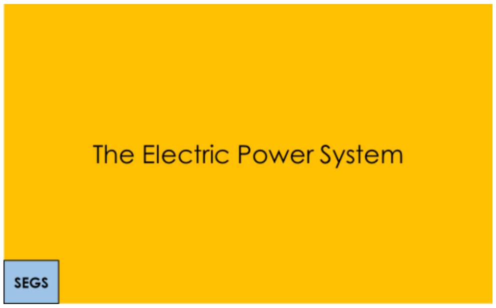

Figure 4.2: A SEGS prototype

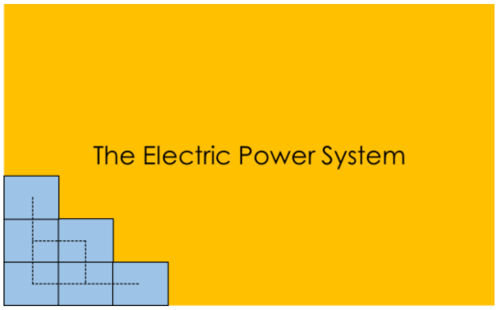

Figure 4.3: 10% SEGSs

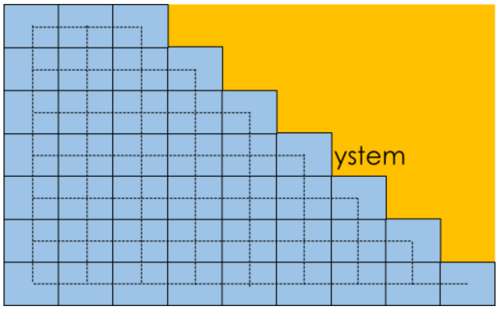

Figure 4.4: 66% SEGSs

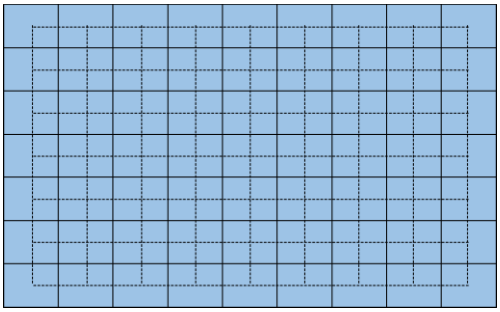

Figure 4.5: 100% SEGSs

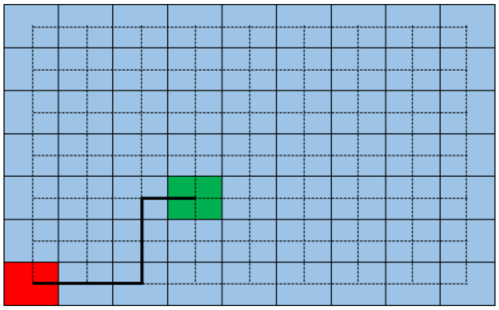

Figure 4.6: Power flow through the network

V. ALGORITHM

An algorithm was developed that approximates all possible configuration of PV and energy storage to design SEGSs. The two main parameters required are the expected time-series power output of the PVs and the expected time-series power demand of the power system.

The top of Figure 5.1 shows the time-series power demand data for the TID district in 2017. This data was obtained from the US Energy Information Administration (eia) open database, and it shows the power demand for every hour of the year [1].

The bottom of Figure 5.1 shows the expected annual time-series power output of solar panels in Turlock, CA for a G2C ratio of 1. This data was obtained from PVWatts, and it forecasts the power supply for every hour of the year [2].

Using the time-series data, the algorithm computes a running total of the stored energy. First, the algorithm sets a value for the initial stored energy of the ESS, then, for the first hour, the total generation of the PV and total consumption of the power system are compared. If generation exceeds consumption, the extra energy is stored which increases the stored energy; if consumption exceeds generation, the ESS provides the missing energy which decreases the stored energy. The algorithm repeats this process for the entire data considering efficiency, self-discharge losses, and efficiency degradation.

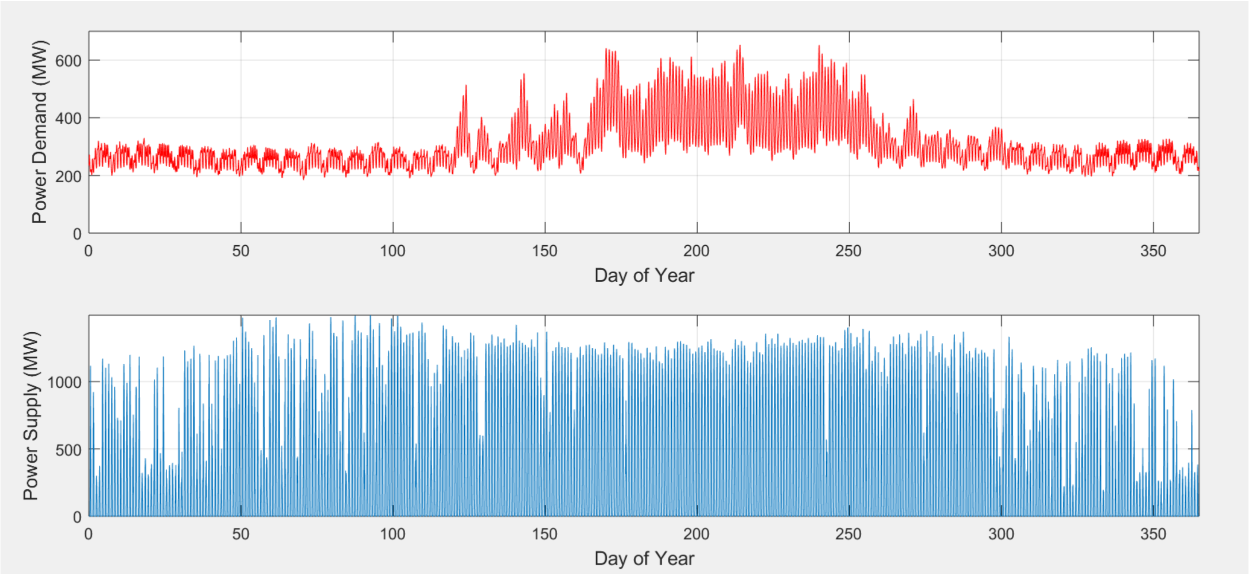

Figure 5.1: Power demand of TID 2017 (top), Power supply of PVs (bottom)

5.1 Algorithm Parameters

Table 5.1 shows a list of variables that can be modified in the algorithm. The default energy efficiency is 0.9 (90%), but can range between 0 and 1. The self-discharge rate specifies how much energy is lost over time due to time-varying leakage. The default self-discharge rate is 0.05 (5%) per month which corresponds to about 0.00007% per hour. The ESS efficiency degradation rate specifies the efficiency decrease over time. The algorithm uses a linear model for efficiency degradation, and the default efficiency degradation rate is 1% per year. For example, if the initial efficiency is 90%, after 5 years the efficiency decreases to 85%.

For the cost analysis, the algorithm assumes PVs cost $1.64 per watts installed which is the forecasted cost of PV for year 2025 [3], and the algorithm assumes ESSs cost $160 per kWh which is the forecasted cost of lithium-ion batteries for year 2025 [4].

Table 5.1: Algorithm Parameters

Variables	**Default Value**
Number of Years	20 years
G2C ratios	min G2C−4.500
ESS Efficiency	90%
ESS Self-discharge Rate (%/ month)	5% per month
ESS Efficiency Degradation Rate (%/year)	1% per year
PV System Cost ($/watt)	$1.64 per watt
ESS Cost ($/kWh)	$160 per kWh

Table 5.2 shows an example of the calculations when generation exceeds consumption. Suppose during hour interval (x), the generation is 10 kWh, the consumption is 9 kWh, the ESS efficiency is 88%, and the stored energy at the start of the interval is 100 kWh. Generation exceeds consumption by 1kWh which means 88% of 1 kWh is storable. The self-discharge loss is calculated by multiplying the stored energy with 0.007. The next stored energy value is computed by adding the stored energy and storable energy and subtracting the self-discharge losses.

Table 5.2: Example of Calculations when Generation exceeds Consumption

Parameter	**Value**	**Math Equations**
Hour_Interval	x	N/A
Stored_Energy(x)	100 kWh	N/A
Generation(x)	10 kWh	N/A
Consumption(x)	9 kWh	N/A
Energy_Difference(x)	1 kWh	Generation(x) − Consumption(x)
Efficiency(x)	88 %	N/A
Storable_Energy(x)	0.88 kWh	Energy_Difference(x) × Efficiency(x)
Self-discharge_Losses(x)	0.00616 kWh	Stored_Energy(x) × 0.007
Stored_Energy(x+1)	100.87384 kWh	Stored_Energy(x) + Storable_Energy(x) − Self-discharge_Losses(x)

Table 5.3 shows an example of the calculations when consumption exceeds generation. Suppose during hour interval (y), the generation is 9 kWh, the consumption is 10 kWh, the ESS efficiency is 88%, and the stored energy at the start of the interval is 100 kWh. Consumption exceeds generation by 1kWh, and to balance the system, the stored energy must supply the energy difference. The next stored energy value is computed by subtracting the energy difference and the self-discharge energy losses from the stored energy.

Table 5.3: Example of Calculations when Consumption exceeds Generation

Parameter	**Value**	**Math Equations**
Hour_Interval	y	N/A
Stored_Energy(y)	100 kWh	N/A
Generation(y)	9 kWh	N/A
Consumption(y)	10 kWh	N/A
Energy_Difference(y)	1 kWh	Consumption (y) − Generation(y)
Self-discharge_Losses(y)	0.00616 kWh	Stored_Energy(y) × 0.007
Stored_Energy(y+1)	98.99384 kWh	Stored_Energy(y) − Energy_Difference(y) − Self-discharge_Losses(y)

As an example, the top of Figure 5.2 shows data of supply and demand data for three days. This data was processed using the algorithm, and the bottom of Figure 5.2 shows the result.

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

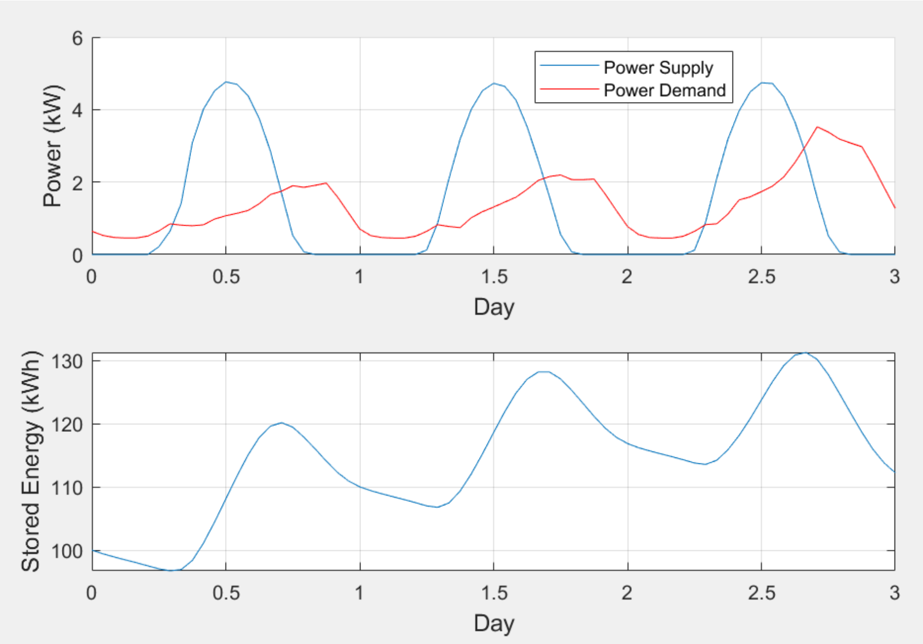

Figure 5.2: Power data for three days (top), stored energy of the ESS (bottom)

VI. OPTIMIZING SUSTAINABLE ENERGY GENERATION SYSTEMS

The power demand and the power supply data were duplicated to span twenty years. Figure 6.1 shows the power demand and the power supply for a G2C ratio of 1.00.

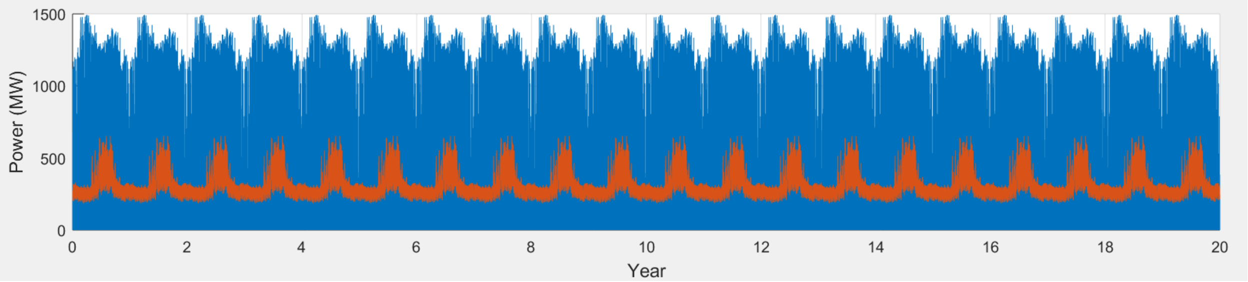

Figure 6.1: Power supply (blue) and power demand (red)

6.1 The Balanced Sustainable Energy Generation System

$$Generation = Consumption + Storage\ Losses$$

The algorithm used the time-series data to analyze a 90% efficient ESS with 1% per year efficiency degradation and 5% per month self-discharge losses. First, the algorithm found the minimum G2C ratio that balanced the system. Starting at a G2C ratio of 1. The algorithm simulated the stored energy waveform and determined if the system was balance. If the system was not balanced, the algorithm increased the G2C ratio and simulated the stored energy waveform again. This process continued until the G2C ratio that balanced the system was found.

The algorithm found 1.275 was the smallest G2C ratio for a balanced SEGS. Figure 6.2 shows the stored energy for G2C ratios of 1.8, 1.6, 1.4, 1.275, and 1.2. The G2C ratio of 1.275 was the smallest ratio with nonnegative stored energy data points. All G2C ratios less than 1.275 produced negative stored energy values while all G2C ratios greater than 1.275 produced non-negative stored energy values. Figure 6.3 shows the stored energy for the 1.275 G2C ratio.

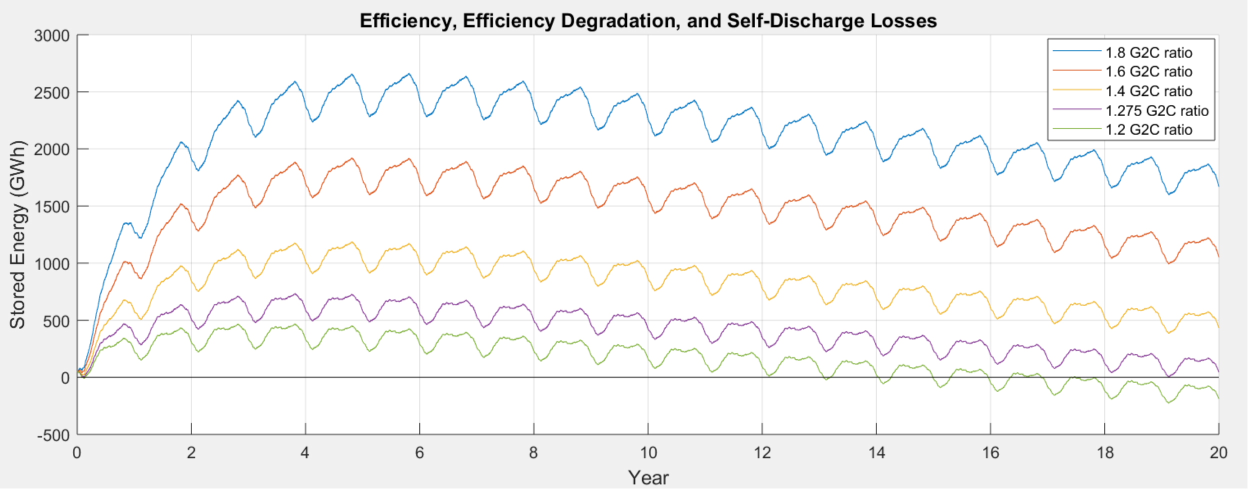

Figure 6.2: Stored energy assuming 90% ESS, 1%/year degradation, and 5%/month discharge

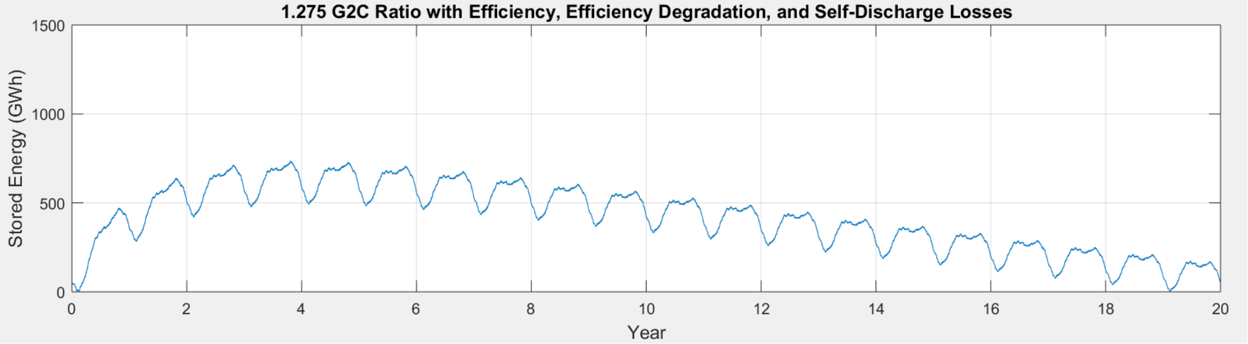

Figure 6.3: 1.275 G2C ratio with 90% ESS, 1%/year degradation, and 5%/month discharge

6.2 Oversizing Generation for Sustainable Energy Generation Systems

The algorithm found the minimum storage capacity for all viable G2C ratios (1.275 and above for this example). The minimum storage capacity was found by simulating the maximum possible energy storage capacity and gradually decreasing the capacity until the stored energy values became negative. The minimum storage capacity specified the required energy storage capacity for that G2C ratio.

For example, Figure 6.4 shows the stored energy for the 1.4 G2C ratio with the maximum storage capacity. The maximum storage capacity is the amplitude of the stored energy waveform. Starting at the maximum storage capacity of 1225 GWh for the 1.4 G2C ratio, the algorithm gradually decreased the storage capacity and simulated the stored energy. This process continued until the stored energy values became negative.

Figure 6.5 shows the stored energy with a storage capacity of 1000 GWh, and Figure 6.6 shows the stored energy with a storage capacity of 500 GWh.

For the G2C ratio of 1.4, the minimum storage limit was 160 GWh. Figure 6.7 shows the stored energy with a 160 GWh storage capacity. The minimum storage limit was 160 GWh; therefore, the required energy storage capacity for a G2C ratio of 1.4 was 160 GWh.

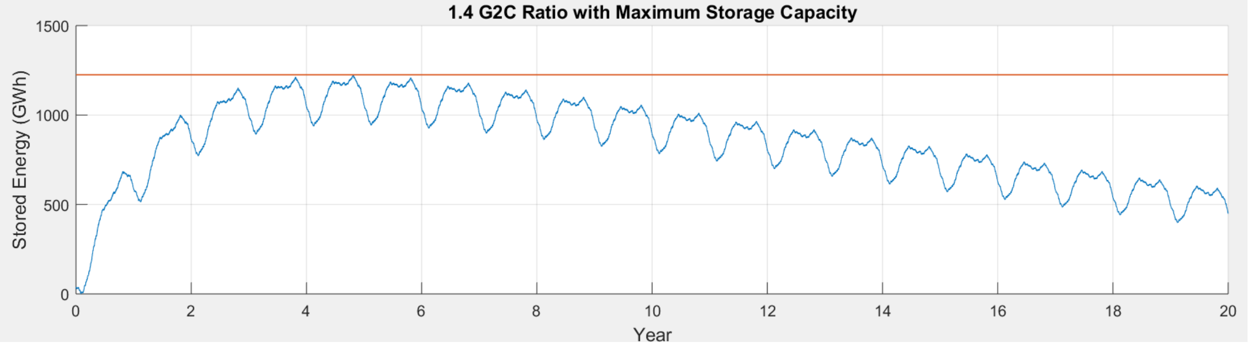

Figure 6.4: Stored Energy of 1.4 G2C Ratio with Maximum Storage Capacity

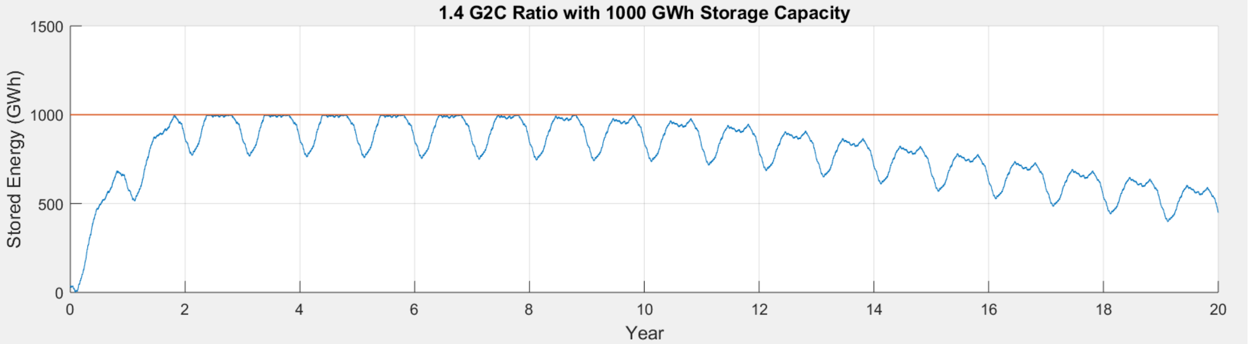

Figure 6.5: Stored Energy of 1.4 G2C Ratio with 1000 GWh Storage Capacity

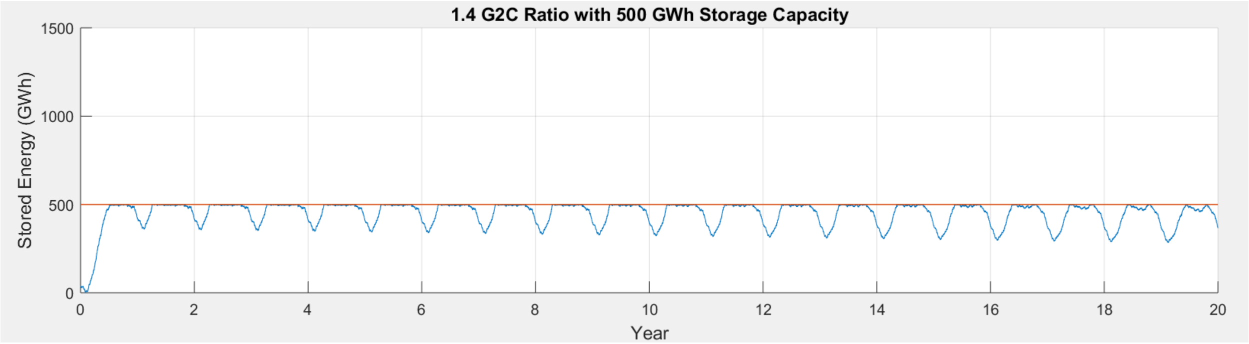

Figure 6.6: Stored Energy of 1.4 G2C Ratio with 500 GWh Storage Capacity

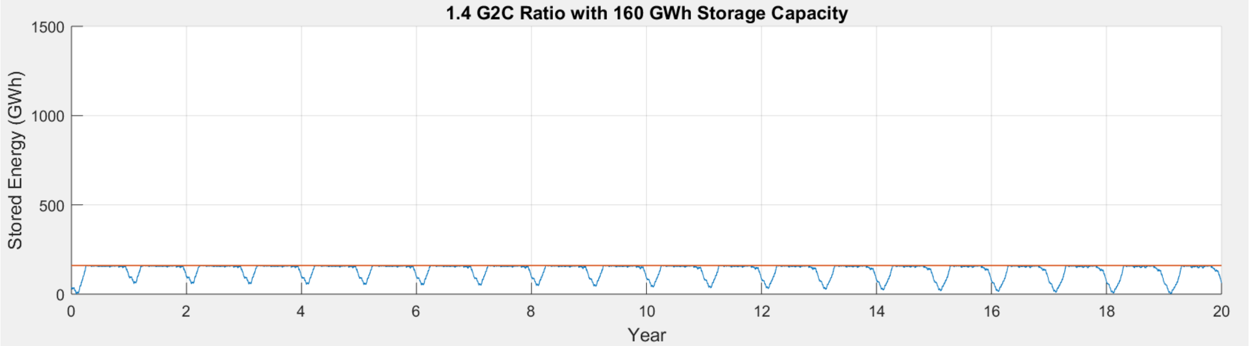

Figure 6.7: Stored Energy of 1.4 G2C Ratio with 160 GWh Storage Capacity

The algorithm performed this process for each viable G2C ratio. Figure 6.8 shows the result: the plot of required energy storage capacity vs. G2C ratio. The plot shows an inverse relationship between required storage capacity and G2C ratio.

6.3 Determining Most Cost-effective Configuration

The relationship between G2C ratio and storage capacity in Figure 6.8 is valuable for determining the most cost-effective system. Since PVs and ESSs have different costs, the algorithm computed the total system cost of each configuration. The algorithm assumed the cost of PVs was $1.64 per watts which is the forecasted cost of PVs for year 2025, and the algorithm assumed the cost of ESSs was $160 per kWh which is the forecasted cost of lithium-ion batteries for year 2025. Figure 6.9 shows the total system cost for each SEGS configuration. The lowest point in this plot shown by the red "x" represents the cheapest SEGS configuration of about 10.1 billion dollars. The most cost-effective configuration was a G2C ratio of 2.702 which corresponds to a PV system size of 4,745 MW and an ESS capacity of 14,781 MWh.

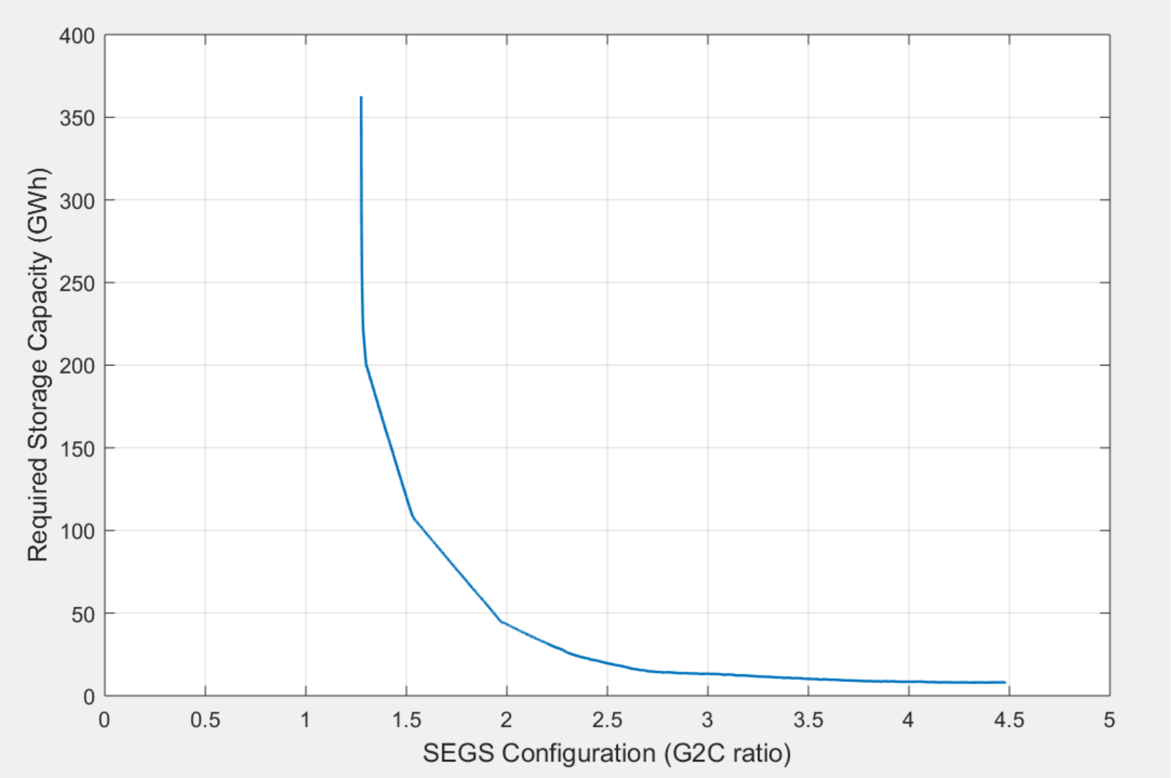

Figure 6.8: Required storage capacity vs. oversized PV annual generation

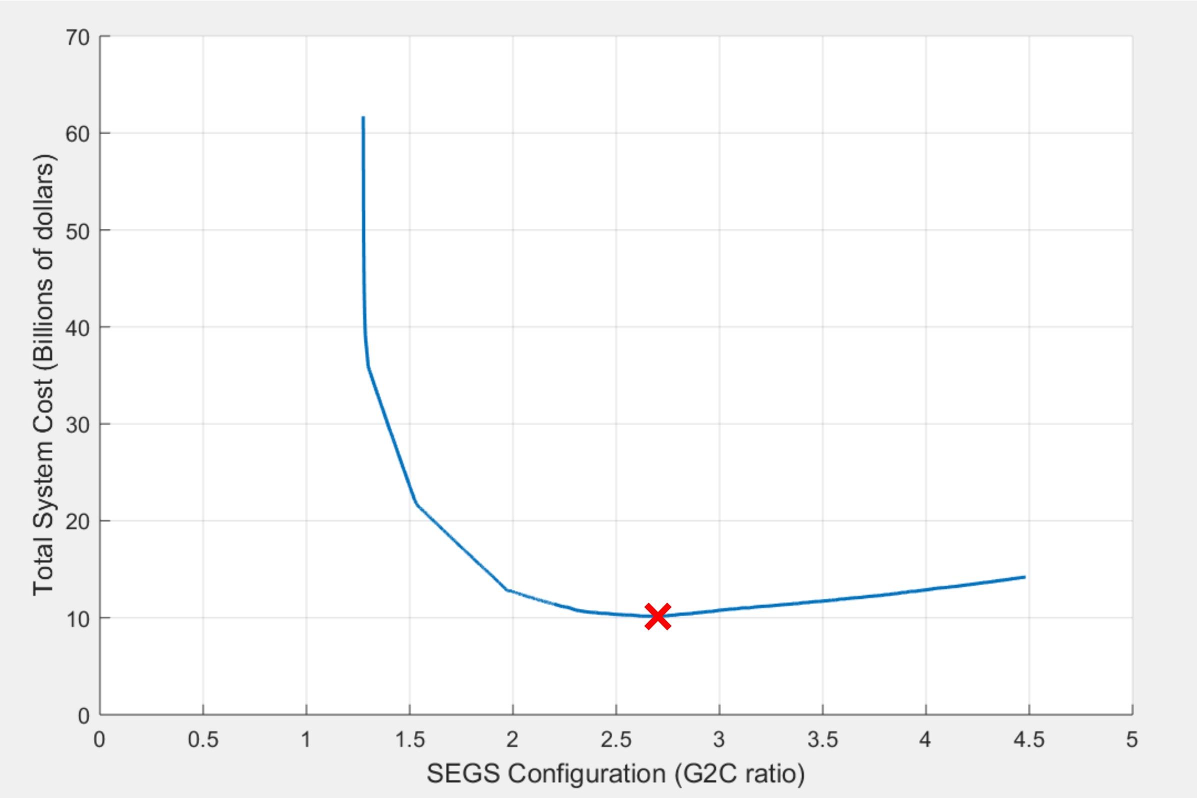

Figure 6.9: Total System Cost vs. PV/storage configuration

6.4 Inverter Size

For the most cost-effective configuration, the inverter size was determined by finding the maximum power input/output to the ESS. For this example, the maximum power input/output to the ESS was 2629 MW. Therefore, the most cost-effective configuration would require an 4745 MW PV system and a 2629 MW/14781 MWh ESS.

6.5 Overgeneration Usage

The most cost-effective SEGS requires a 2.702 G2C ratio which means the PV system produces 2.702 times more energy than required by the power system. The annual consumption of TID is 2,006 GWh, and on average, each year the PV system will produce about 7252 GWh. Thirty-six percent of this energy will be used for consumption. Seventeen percent of this energy will be lost due to storage losses, and the remaining forty-seven percent of this energy (3000 GWh) is unused which is lost. It’s possible to utilize the unused energy to power stand-by devices such as atmospheric carbon dioxide extraction systems. Figure 6.10 shows a graph of the power available from overgeneration for the first year.

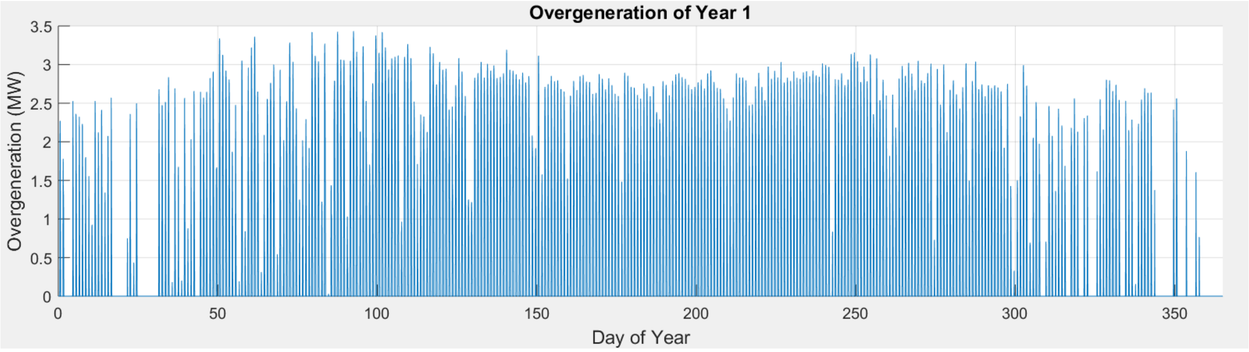

Figure 6.10: Overgeneration for the first year

VII. FUTURE WORK

Future work includes incorporating probability distributions to design SEGSs that meet statistical requirements (e.g., there is an 80% chance that PV size X and storage capacity Y will reliably supply electric power for the year), mixing renewable energy resources and energy storage systems to optimize for the cheapest cost (e.g., PV size X, wind energy size Y, and energy storage Z is the optimal system), and improving the accuracy of the ESS model.

7.1 Optimal Location of Renewable Energy Mix

In addition to optimizing the renewable energy mix, it’s also possible to optimize the location of the renewable energy resources. For example, suppose the diagram in Figure 7.1 shows all locations where wind and solar energy can be harvested within the state of California. By including irradiance and wind models into the algorithm, it’s possible to optimize based on location as shown in Figure 7.2.

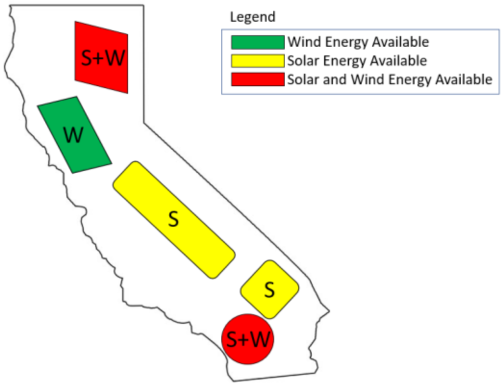

Figure 7.1: Energy availability illustration

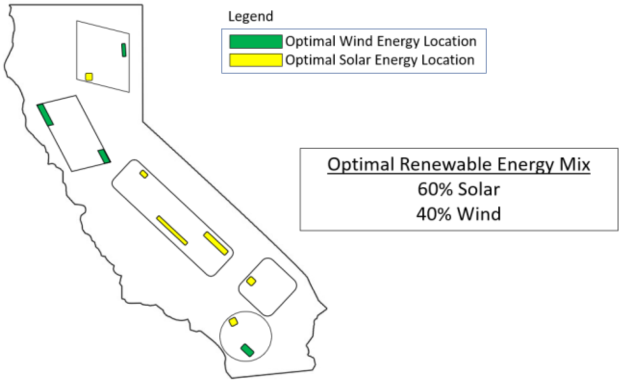

Figure 7.2: Optimal location illustration

VIII. REFERENCES

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