Sustainable Energy Generation Systems

Technical Report Draft

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I. INTRODUCTION

An 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 an electric power system that provides power independently with 100% renewable energy. An algorithm was developed to solve the root problem of designing SEGS which is figuring out how much renewable energy and how much storage is required for the system to be sustainable. As an analogy, let's compare SEGSs and airplanes. One fundamental engineering challenge for designing airplanes is figuring out how much thrust is required for the airplane to fly. Likewise, one fundamental challenge of designing SEGSs is figuring out how much energy and storage is required for the system to be self-sustainable.

By oversizing generation, there are various possible configurations, and the algorithm finds the relationship between renewable energy nameplate capacity and energy storage capacity. This relationship is important to optimize for the cheapest system. Since renewable energy and storage have different costs, the algorithm computes the cost of all possible configurations and finds the most cost-effective configuration. From my analysis the most cost-effective SEGS annually generates over twice as much energy than consumed. The extra energy can be used to power standby devices such as carbon dioxide scrubbers.

II. BACKGROUND

The major challenge of 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 (i.e. appliances, computers, industrial machinery, etc) connected to the electric power system. The **power supply** is the total amount of electricity produced by all the generating resources (power plants, renewable energy, etc). If power supply is considerably less than power demand, appliances/devices will not receive enough power to operate properly.

2.1 POWER DEMAND

The **expected time-series power demand** is a series of values that forecast power demand of an electric power system for every hour of the year. As an example, Figure 2.1 shows the expected time-series power demand of California that was obtained from EIA.gov database [1].

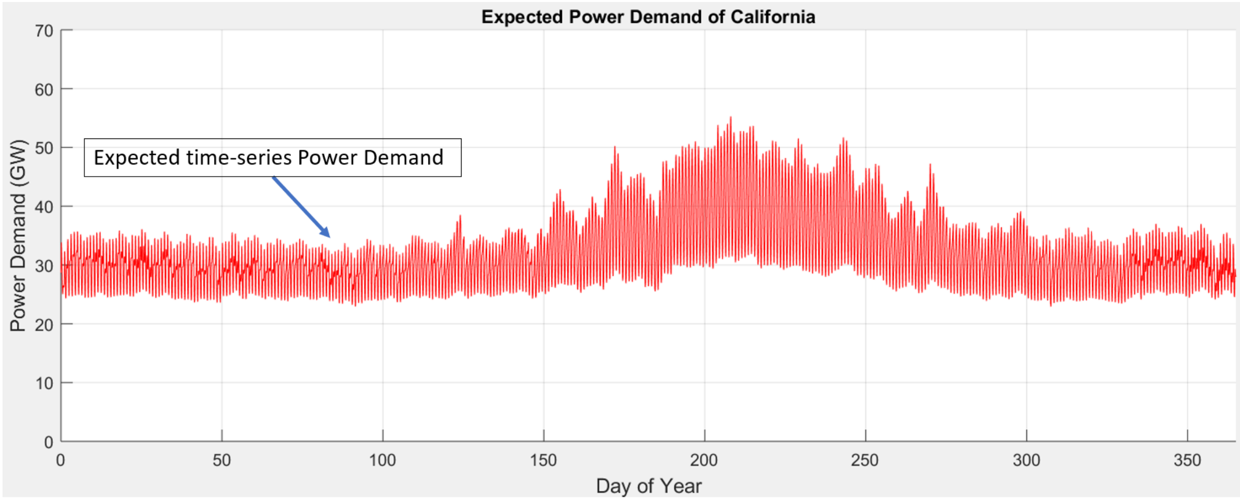

Figure 2.1: Expected time-series power demand of California

Projected peak power demand is the forecasted maximum power demand of the electric grid for the year. The expected maximum power demand of California is 55 GW. Figure 2.2 shows how the projected peak power demand is the maximum value of power demand.

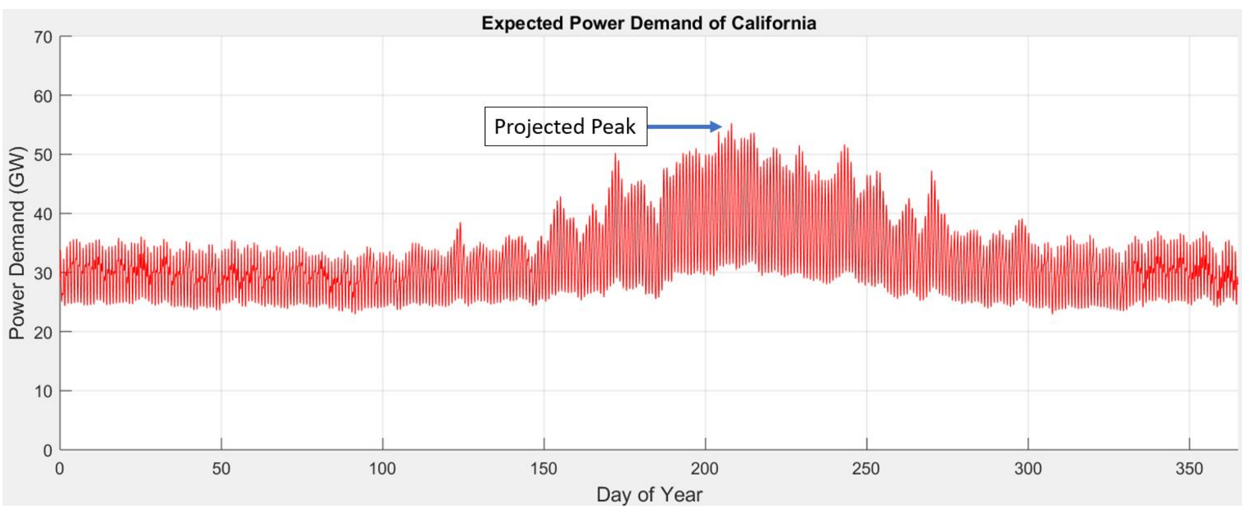

Figure 2.2: Projected peak power demand example

The **annual expected consumption** of an electric power system is a forecast of the total annual energy consumption from all the devices/appliances connected to the electric power system. For example, the California region has an annual expected consumption of 280,000 GWh*. The annual expected consumption is measured by the area underneath the expected time-series power demand as illustrated in Figure 2.3.

* The state of California has an energy consumption of 200,000 GWh. The California region as defined by the EIA.gov has a larger region since the data shows an annual generation of 280,000 GWh. In this paper, California will be defined as the region outlined by EIA.gov.

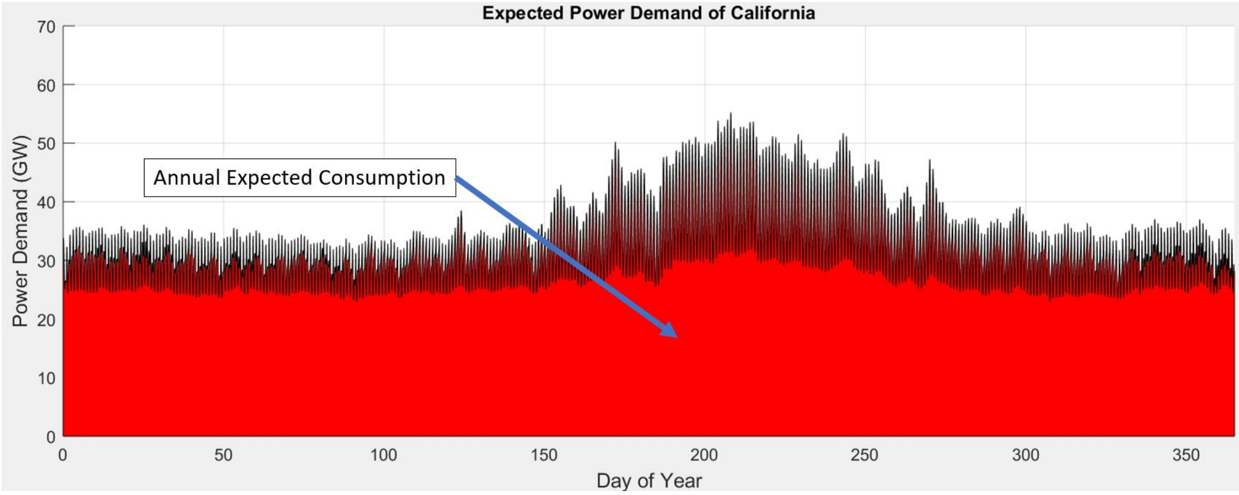

Figure 2.3: Annual expected consumption of 280,000 GWh

2.2 POWER SUPPLY

Renewable energy resources are technologies that generate electricity from renewable resources such as sunlight, wind, biomass, geothermal and hydroelectricity.

The **expected time-series power supply** of a renewable energy technology is a series of values that show the hourly estimate of power generation for the entire year. For example, Figure 2.4 shows the time-series power supply of a 1000 MW wind farm off the coast of California. The wind power supply data was simulated by using meteorological wind speed data from NREL's The Wind Prospector [2] along with the power-curve of a Vesta wind turbine (V164-7.0MW) [3].

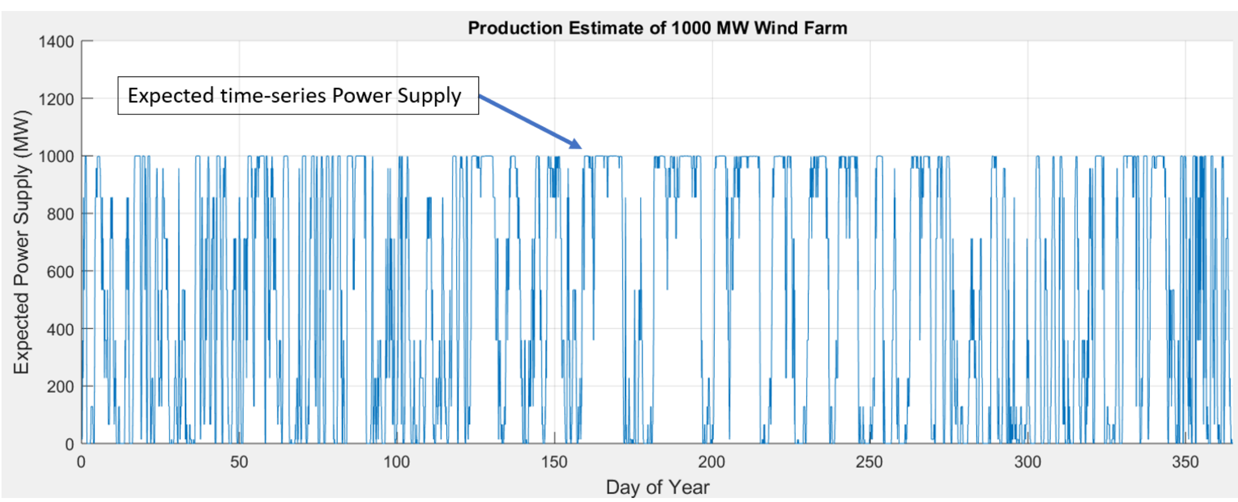

Figure 2.4: Expected time-series power supply of wind

Figure 2.5 shows the time-series power supply of a 1000 MW solar farm in California. The power supply data was obtained using NREL's PVWatts [4].

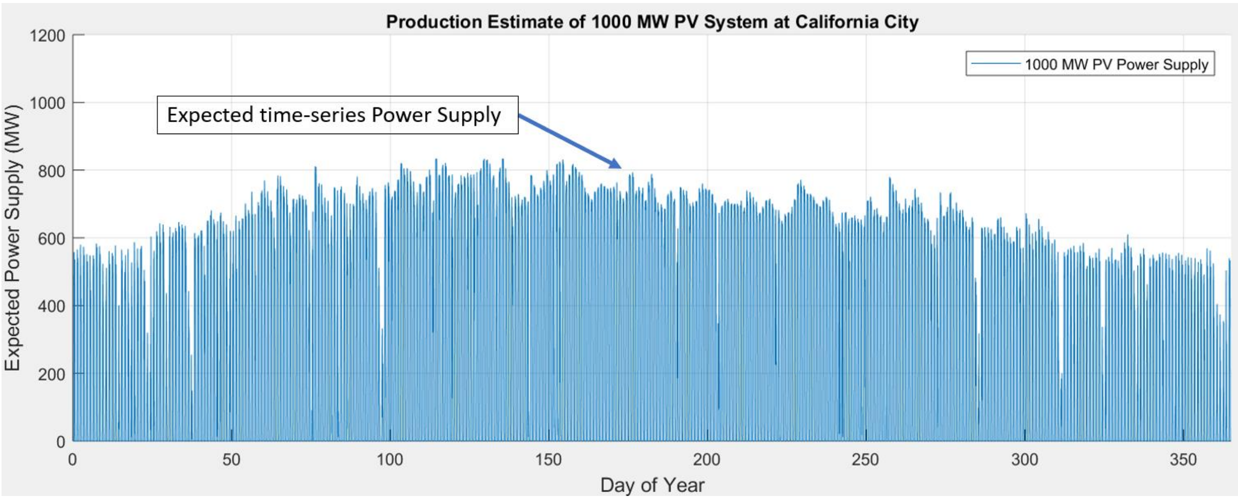

Figure 2.5: Expected time-series power supply of solar

The **annual expected generation** of a renewable energy resource is the estimated total energy production for a year. The annual expected generation is measured by the area underneath the expected time-series power supply. For example, the 1000 MW wind farm has an expected generation of 4500 GWh as shown in Figure 2.6, and the 1000 MW PV has an expected generation of 2,200 GWh as shown in Figure 2.7.

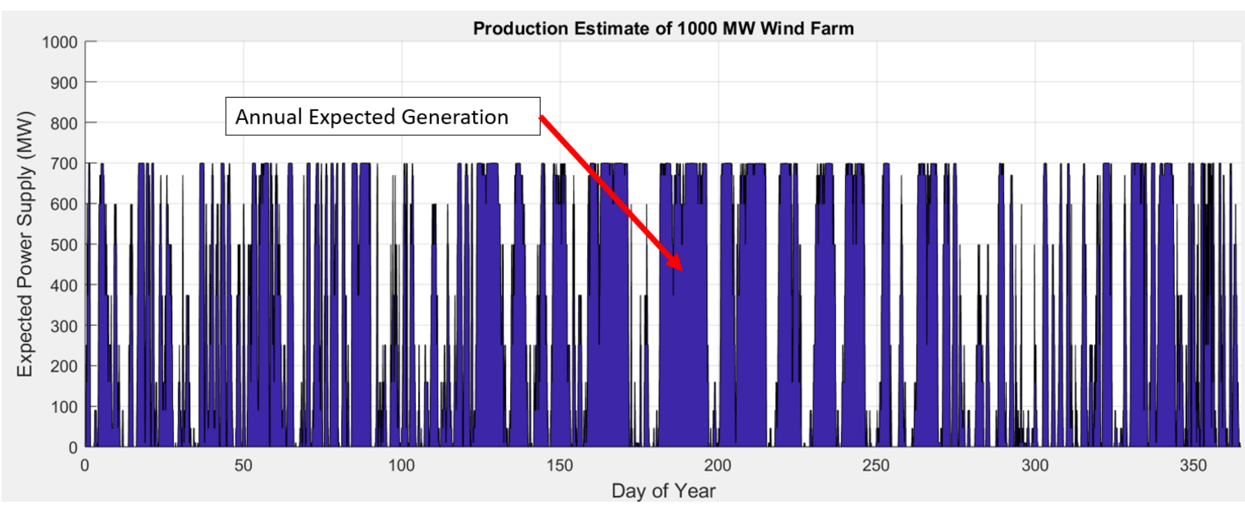

Figure 2.6: The annual expected generation of wind example

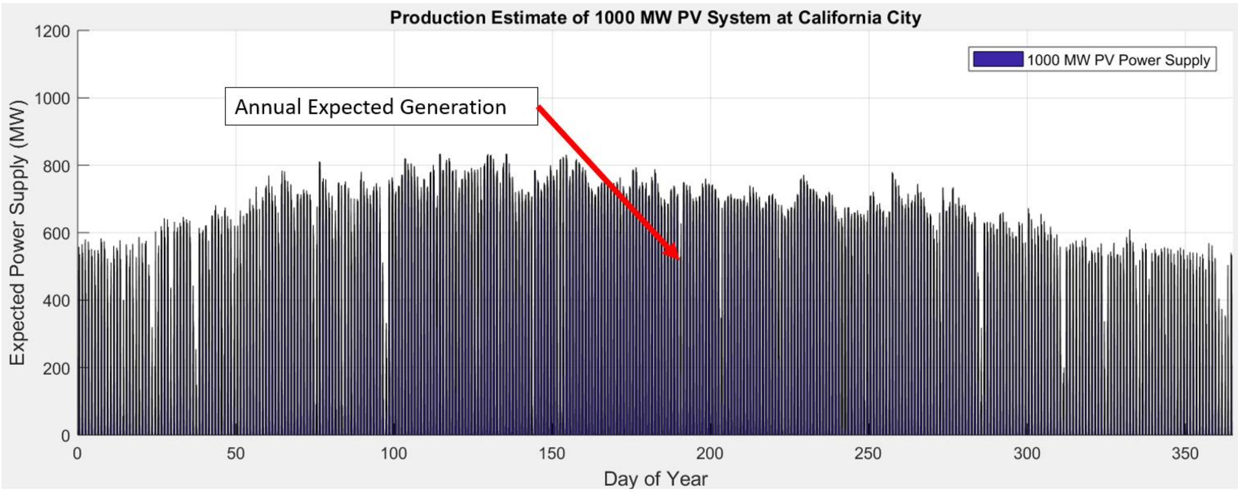

Figure 2.7: The annual expected generation of solar example

2.3 ENERGY STORAGE

Energy Storage Systems (ESSs) are technologies that store energy. There are many types of ESSs that store energy in different forms. The two ESSs studied were batteries and pumped hydro storage. Regardless of the ESS, they all serve a common function of storing energy to generate power at another time.

ESS share common characteristics. The maximum amount of energy that can be stored is called the **capacity** of the ESS. The **state of charge** is the percentage of energy currently stored (0%=empty; 100% = full). The **stored energy** of an ESS is the amount of energy currently stored within the ESS. The amount of stored energy increases by storing power, or the amount of stored energy decreases by generating power. The **efficiency** of an ESS is the amount of retrievable energy. If the efficiency is 90%, only 90% of the energy that enters the ESS can be retrieved; the rest is lost as waste.

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

$$1000\ Wh = 1\ kWh \quad 1000\ kWh = 1\ MWh \quad 1000\ MWh = 1\ GWh \quad 1000\ GWh = 1\ TWh$$

The unit for power is watt (W).

$$1000\ W = 1\ kW \quad 1000\ kW = 1\ MW \quad 1000\ MW = 1\ GW \quad 1000\ GW = 1\ TW$$

Pumped Hydro is an ESS that uses an upper reservoir and a lower reservoir to store energy. The capacity is determined by how much water the upper reservoir can hold. The amount of stored energy is measured by the volume of water in the upper reservoir. To generate power, water is released from the upper reservoir to the lower reservoir through a turbine to produce electricity. To store power, water is pumped from the lower reservoir to the higher reservoir. If the upper reservoir is full, the amount of stored energy is at maximum capacity (100%; full). If the upper reservoir is empty, the stored energy is zero (0%; empty). Water can be released/pumped rapidly (i.e. 9000 cubic feet per second) or slowly (i.e. 3000 cubic feet per second). The stored energy of pumped hydro is measured by the volume of water in the upper reservoir while the power is measured by the rate water is released/pumped.

Batteries are ESSs that store energy in chemical cells. Due to the nature of electrochemical cells, batteries suffer from additional energy losses. Batteries have **efficiency degradation** which decreases the efficiency over time. For example, the efficiency of a 90% battery ESS may degrade to 85% after a few years. In addition, batteries also have state-of-charge and time-dependent **self-discharge** losses.

2.4 EXPECTGED TIME-SERIES STORED ENERGY

The **expected time-series stored energy** is a series of values that forecasts the stored energy of an ESS. This data approximates how full/charged the ESS will be throughout the year. An algorithm was written to compute the expected time-series stored energy of SEGSs. The algorithm requires the expected time-series power demand of the electric grid and the expected time-series power supply of the renewable energy resources. Using an iterative process, the algorithm computes a running total of the stored energy. For each hourly interval, the algorithm compares the total generation and total consumption. If generation exceeds consumption, the extra energy is added to the ESS. If consumption exceeds generation, the missing energy is subtracted from the ESS. The algorithm repeats this process for the entire data considering all energy losses (i.e. efficiency, self-discharge losses, efficiency degradation, etc.). For example, Figure 2.8 shows the expected time-series stored energy of a possible SEGS for California.

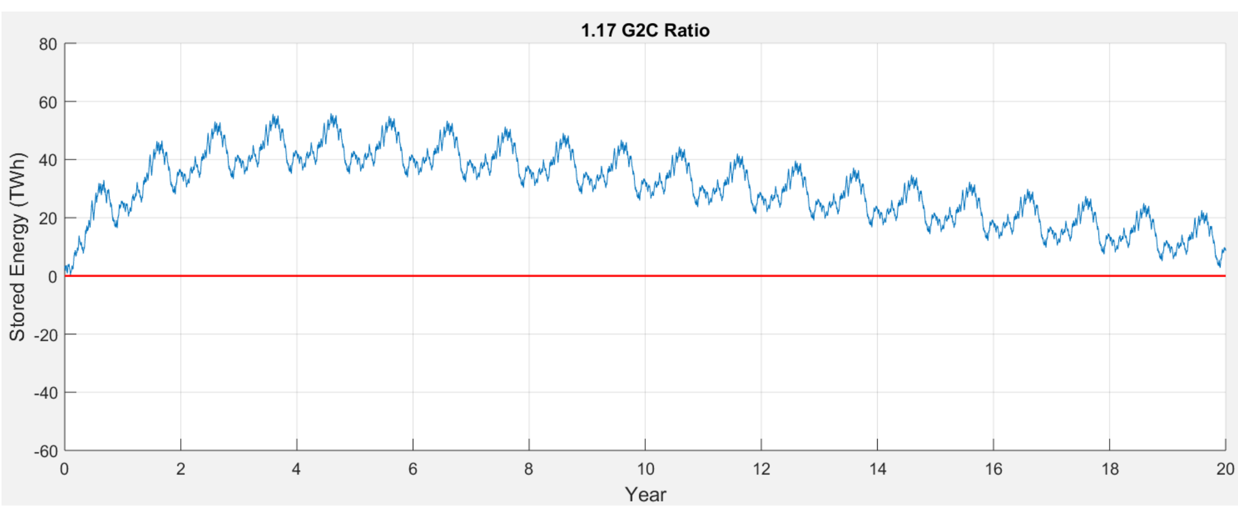

Figure 2.8: Expected time-series stored energy example

2.5 GENERATION-TO-CONSUMPTION RATIO

The **Generation-to-Consumption (G2C) ratio** of an SEGS is the ratio between the annual generation and the annual consumption. A G2C of 1 means the annual expected generation is equal to the expected consumption. A G2C of 1.5 means the expected annual generation is 1.5 times greater than consumption. Since California has an expected annual consumption of 280,000 GWh, a SEGS with G2C of 1.5 would have an annual expected generation of 420,000 GWh and at most 140,000 GWh of excess generation. A SEGS with G2C of 2 would have an annual expected generation of 560,000 GWh and at most 280,000 GWh of excess generation.

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

Table 1: California G2C Ratios

Generation (GWh)	Consumption (GWh)	G2C ratio
140,000	280,000	0.5
280,000	280,000	1.0
4200,00	280,000	1.5
560,000	280,000	2.0

The law of conservation of energy states the total energy of an isolated system remains constant; energy can neither be created nor destroyed. It can only be transformed or transferred from one form to another. An SEGS with energy storage will need to make up for the energy losses of the ESS since ESS have inefficiencies. As a result, ***the first law of Sustainable Energy Generation Systems is the G2C ratio must be greater than or equal to 1.***

One of the first challenges of designing SEGSs is finding the **minimum G2C ratio** which is the smallest G2C ratio such that the SEGS is sustainable. ***The second law of Sustainable Energy Generation Systems states a SEGS is sustainable if the expected time-series stored energy values are non-negative for the lifecycle.*** This law is derived from the law of conservation of energy. The energy is conserved if the expected time-series stored energy of the SEGS does not contain negative stored energy values. Negative stored energy values indicate the G2C ratio is insignificant to counterbalance the ESS's losses. It is impossible for energy to be expelled from storage at 0%.

Through trial and error, the minimum G2C ratio is found by using a recursive procedure of incrementing the G2C ratio and checking if the SEGS is sustainable. The algorithm gradually increases the G2C ratio starting at a G2C of 1 until the minimum G2C ratio that conserves energy is found.

2.6 CAPACITIES PLOT

The two major technologies for SEGSs are renewable energy resources and energy storage systems. The root problem of designing SEGS is figuring out how much of each technology is required. That is, how much renewable energy and how much storage is required. By considering overgeneration, there are theoretically infinitely many possible configurations. The **Capacities Plot** is a graph that shows the relationship between generation and storage and thus, illustrates all the possible combinations. ***The third law of Sustainable Energy Generation states the amount of storage required for a sustainable system in inversely related to the renewable energy capacity.*** Consider the idealized example in Figure 2.9. The x-axis represents the renewable energy capacity while the y-axis represents the energy storage capacity. All the points on, above, or to the right of the plot represent configurations for the SEGS that are sustainable.

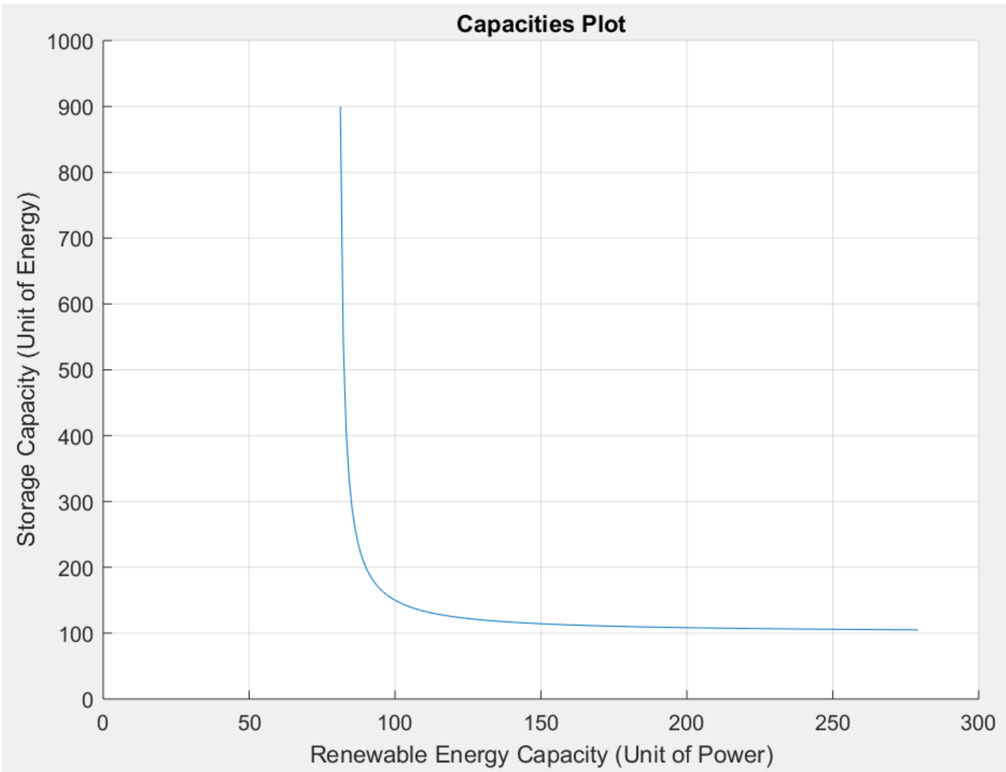

Figure 2.9: Capacities Plot Example

2.7 CONFIGURATIONS COST PLOT

The **Configurations Cost Plot** is a graph that shows the cost of each SEGS configuration. Since renewable energy and ESS have different cost, each sustainable SEGS system on the Capacities Plot has a different cost.

The **cost optimal SEGS configuration** is the SEGS configuration that results in the most cost-effective system. To give an example, the following plot shows the Configurations Cost Plot of an idealized system. The bottom point of the plot represents the configuration with the lowest cost.

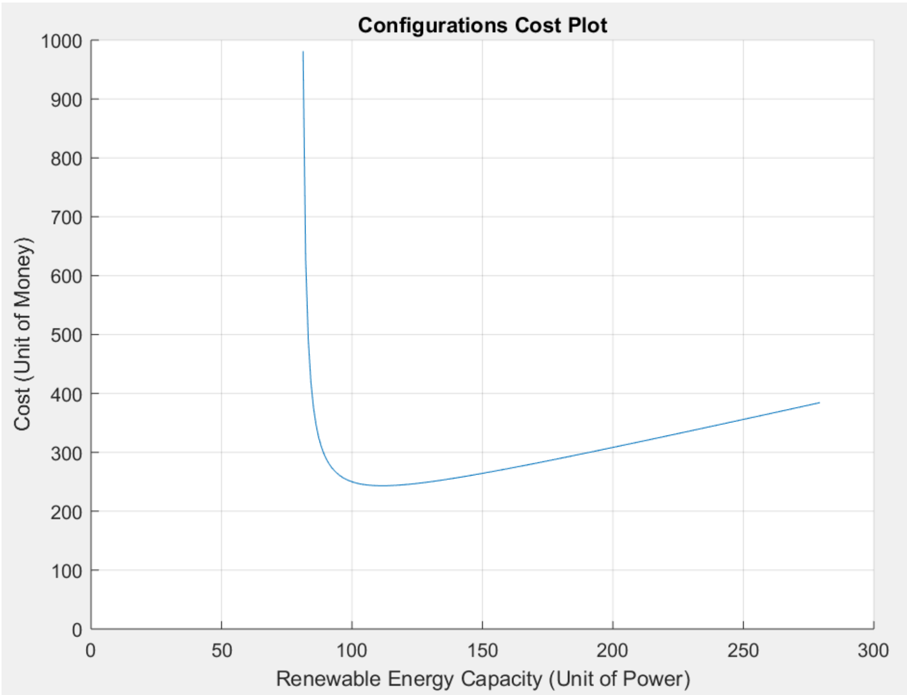

Figure 2.10: Configurations Cost Plot example

III. GEOTHERMAL

3.1 GEOTHERMAL – TRIVIAL SOLUTION

First, the algorithm was used to design SEGSs for California with Geothermal and pumped hydro storage. Geothermal is a renewable energy resource that generates a constant power supply year-round. As a result, there is a trivial solution for designing SEGS with geothermal. **The trivial solution is the net geothermal nameplate capacity must equal or be greater than the projected peak power demand.** The projected peak power demand is the expected maximum power demand of the electric grid. For California, the expected maximum power demand is 55 GW. Geothermal nameplate capacities greater than 55GW are also solutions. Figure 3.1 shows the power supply of the trivial solution and the power demand of California.

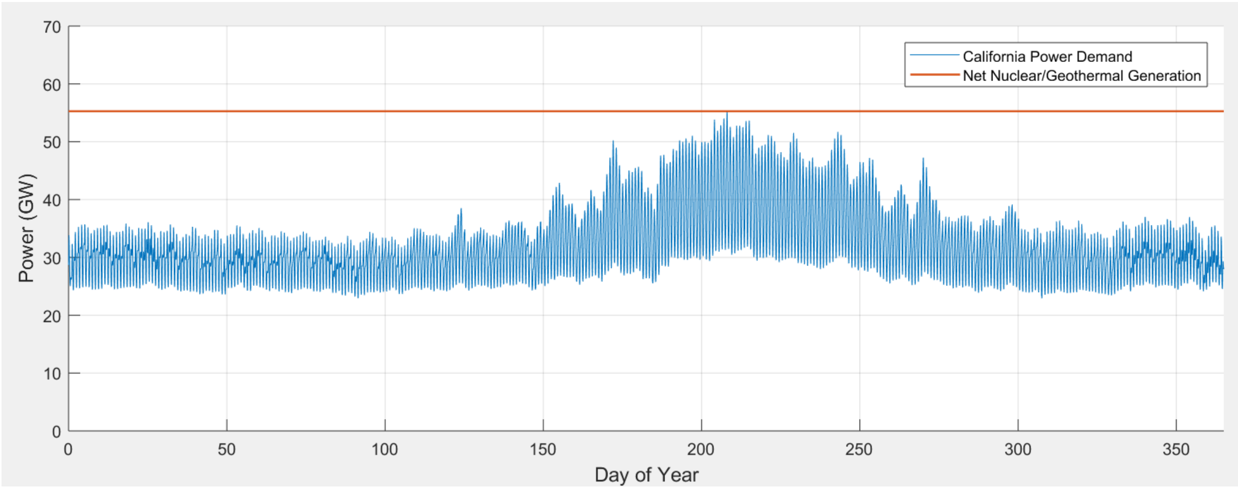

Figure 3.1: Trivial Solution for Geothermal

As previously discussed, the main challenge of electric power systems is supplying enough power all year round. The trivial solution solves this problem by incorporating a geothermal nameplate capacity that exceeds all possible power demand quantities. Since the trivial solution can always meet the power demand, the trivial solution does not require an ESS. The extra power will need to be disconnected or redirected to balance the electric grid. The extra power can be disconnected by turning off geothermal power plants, or the extra power can be redirected by powering stand-by devices such as carbon scrubbers. For California, the geothermal trivial solution has a G2C ratio of 1.72 which means there will be at most 200,000 GWh of excess generation. The green area in Figure 3.2 represents the extra energy.

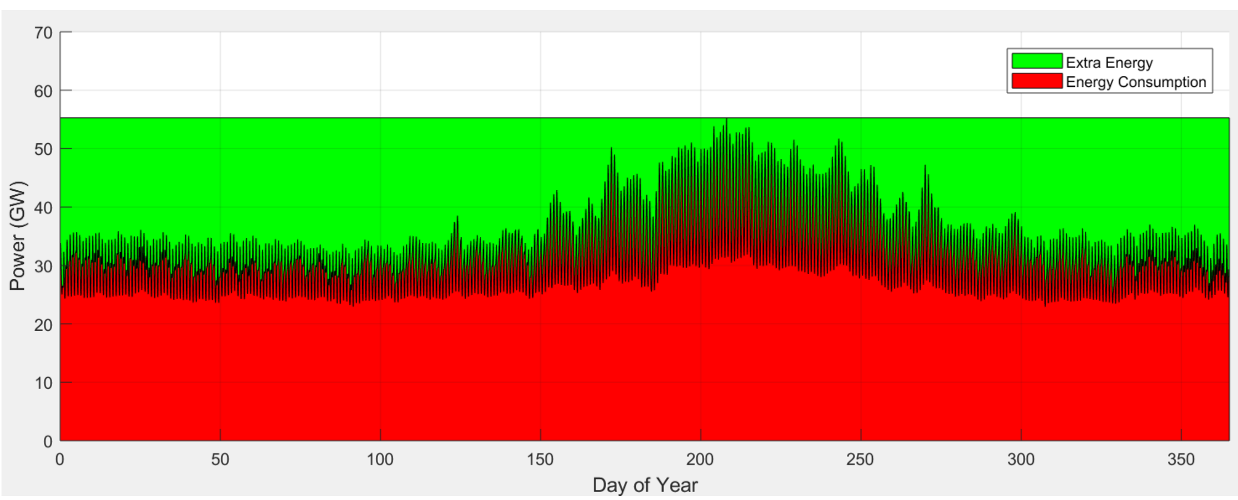

Figure 3.2: Extra Energy of the Trivial Solution

3.2 GEOTHERMAL AND PUMPED STORAGE

Reducing the net geothermal nameplate capacity from the trivial solution of 55GW will require ESS to meet the power demand. For example, consider a 40GW net geothermal nameplate capacity as shown in Figure 3.3. The graph shows the 40GW geothermal capacity doesn't meet the power demand for a period of months in the middle of the year.

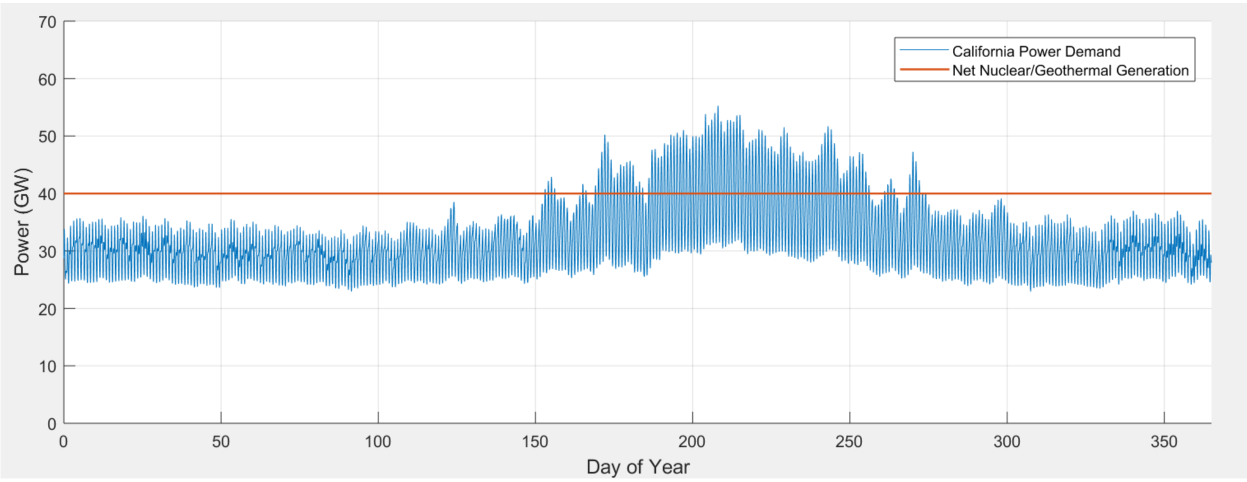

Figure 3.3: 40GW Geothermal Nameplate Capacity for California

The algorithm was used to design a SEGS with pumped hydro storage and a 40GW net geothermal nameplate capacity. Using a brute force approach and trial and error analysis, the algorithm simulated increasingly larger and larger storage capacities until the system became sustainable. The second law states a SEGS is sustainable if the expected time-series stored energy values are non-negative. Figure 3.4 shows the expected time-series stored energy of the 40GW geothermal plant with 300GWh. A storage capacity of 300GWh is insignificant to sustain a 40GW geothermal plant since Figure 3.4 shows the expected time-series stored energy contains negative stored energy values.

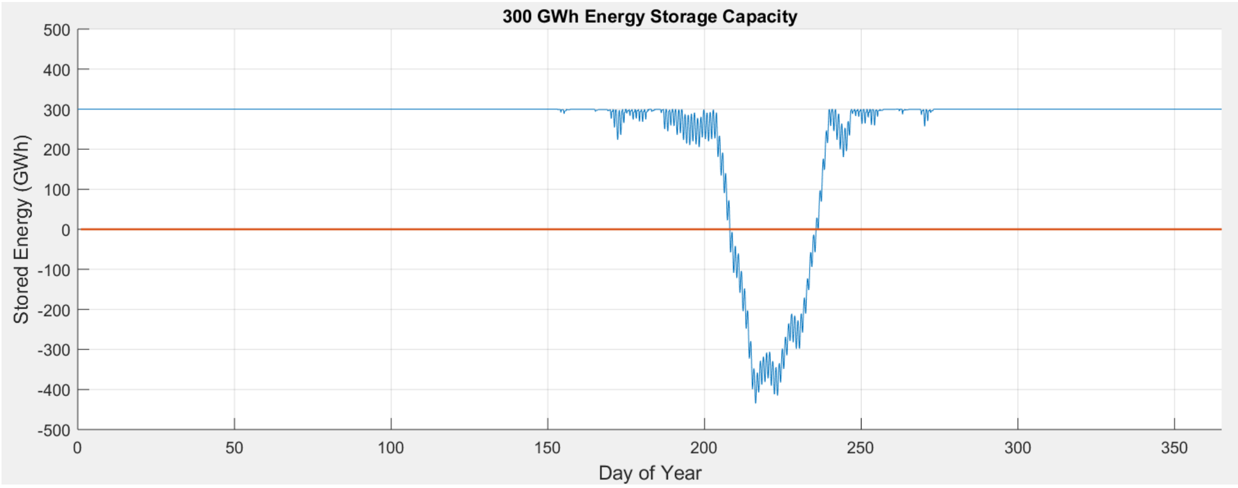

Figure 3.4: Expected time-series stored energy of 40GW Geothermal SEGS

Using a brute force approach, the algorithm found the minimum required energy storage capacity was 735 GWh and would require 15GW of power capacity. Since the energy storage technology is pumped hydro the required storage capacity (735 GWh) represents the volume of the reservoir while the power capacity (15GW) represents how fast the water must flow between the reservoirs.

Figure 3.5 shows the expected time-series stored energy of the ESS for the 40GW geothermal SEGS with 15GW/735GWh ESS. The ESS is at full capacity for a majority of the year expected during the period of excessive demand in the middle of the year. After this period, the stored energy begins to increase and reaches full capacity. Since the stored energy of pumped hydro is measured in terms of the upper reservoir's water volume, the graph also describes the amount of water in the upper reservoir for the year (0% means empty; 100% means full). The upper reservoir is full for a majority of the year and begins to deplete in the middle of the year. Afterwards, the amount of water in the upper reservoir increases from empty to full.

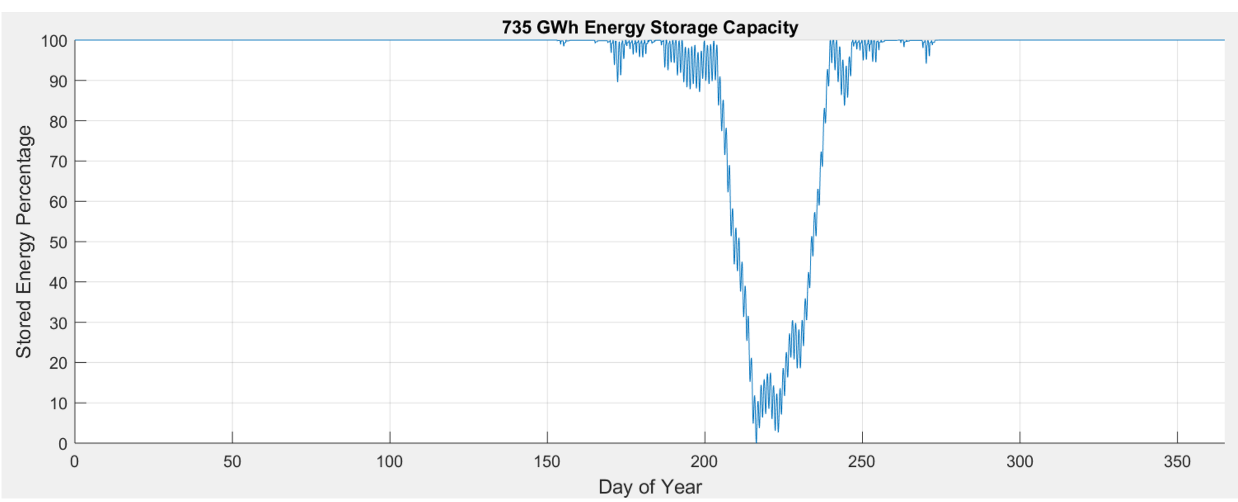

Figure 3.5: Expected time-series stored energy of 40GW Geothermal SEGS

Figure 3.6 shows the total power supply of the SEGS. This includes the power supply of the 40 GW geothermal system and ESS. By overlaying the total power supply with the power demand, it was verified that the power supply matched the power demand for the period of excessive demand.

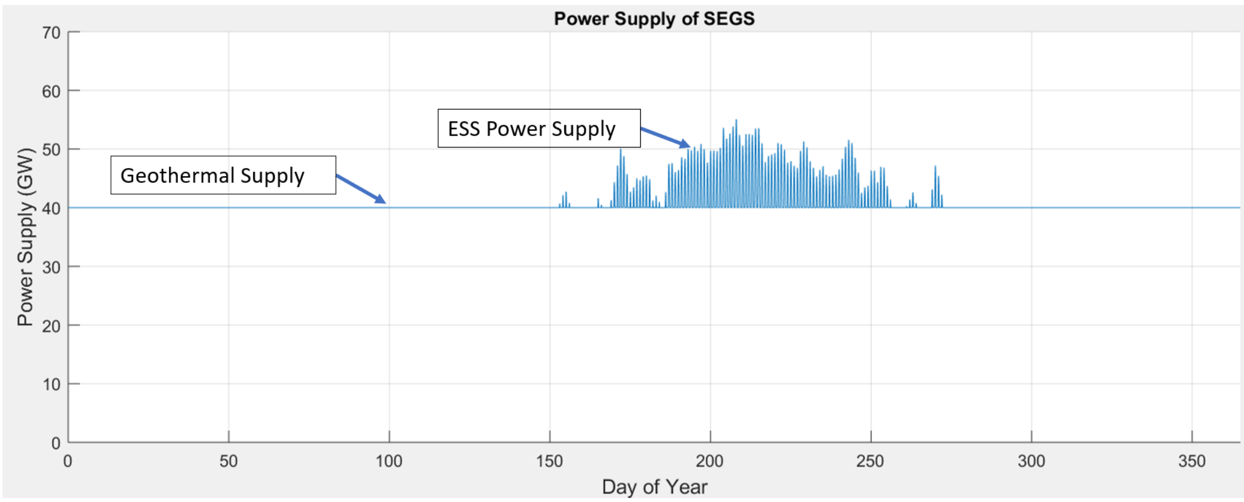

Figure 3.6: Total power supply of 40GW Geothermal SEGS

Figure 3.7 shows on a single graph the trivial solution and the 40GW solution for geothermal and pumped storage SEGSs. The x-axis represents the geothermal nameplate capacity and the y-axis represents the pumped storage capacity. For example, the red "x" is located at (55,0) and represents the trivial solution. The first number (55) represents the geothermal nameplate capacity of 55GW while the second value (0) represents the required ESS capacity of 0 GWh. Likewise, the blue "x" located at (40,735) represents the 40GW geothermal solution. The first value is the nameplate of the geothermal system and the second value is the required capacity of the ESS.

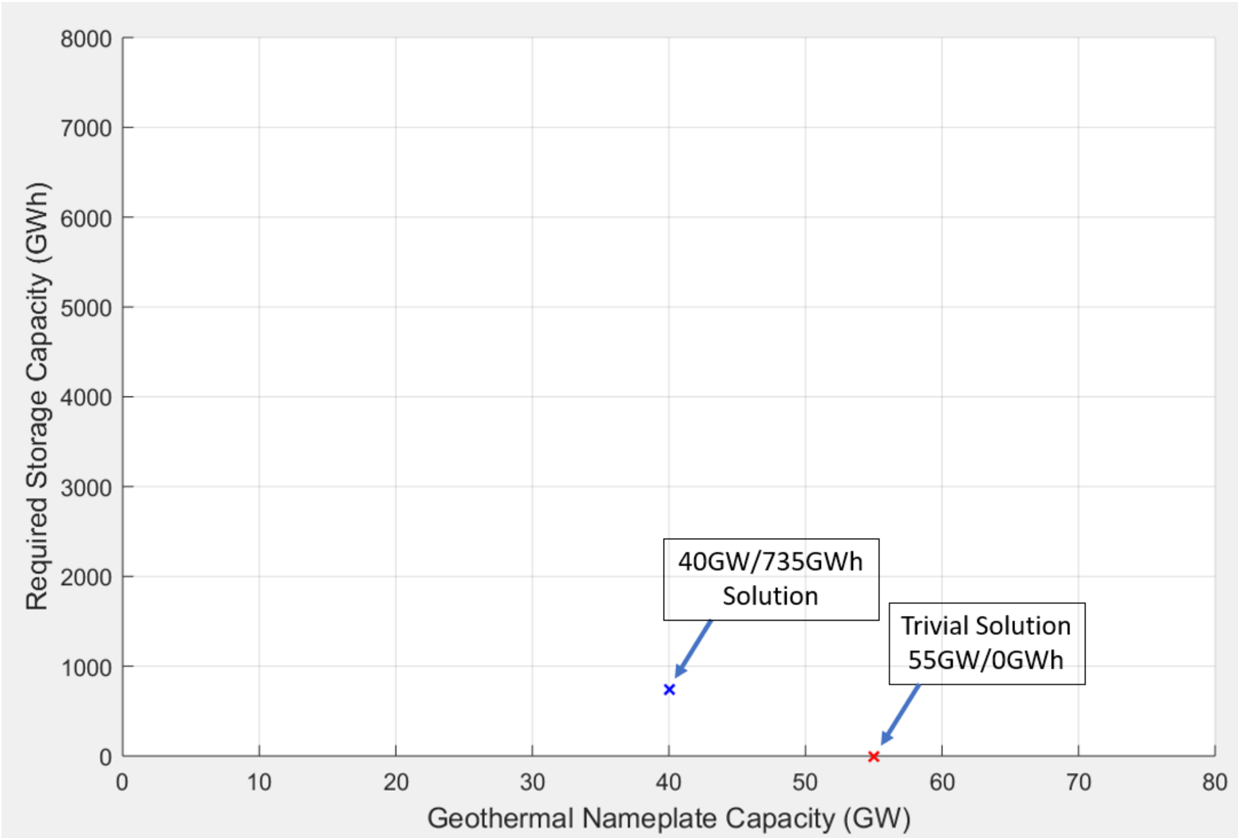

Figure 3.7: Trivial Solution and 40GW Geothermal Solution

The trivial solution of 55GW requires no storage since the power supply is always greater than the power demand. The power supply of geothermal capacities less than 55GW are not always greater than the power demand; therefore, geothermal solutions less than 55GW require energy storage.

Starting at the trivial solution, the algorithm was modified to gradually decreased the geothermal size and find all the storage requirements for geothermal capacities less than 55GW. Figure 3.8 shows the Capacities Plot for geothermal and pumped storage. The minimum possible geothermal nameplate capacity was 35GW. There are no solutions with a total geothermal nameplate capacity less than 35GW. Figure 3.9 shows the sustainable regions for SEGSs with geothermal and pumped storage. Every point in the green region represents a SEGS configuration that is sustainable while every point in the red region represents a SEGS configuration that is unsustainable.

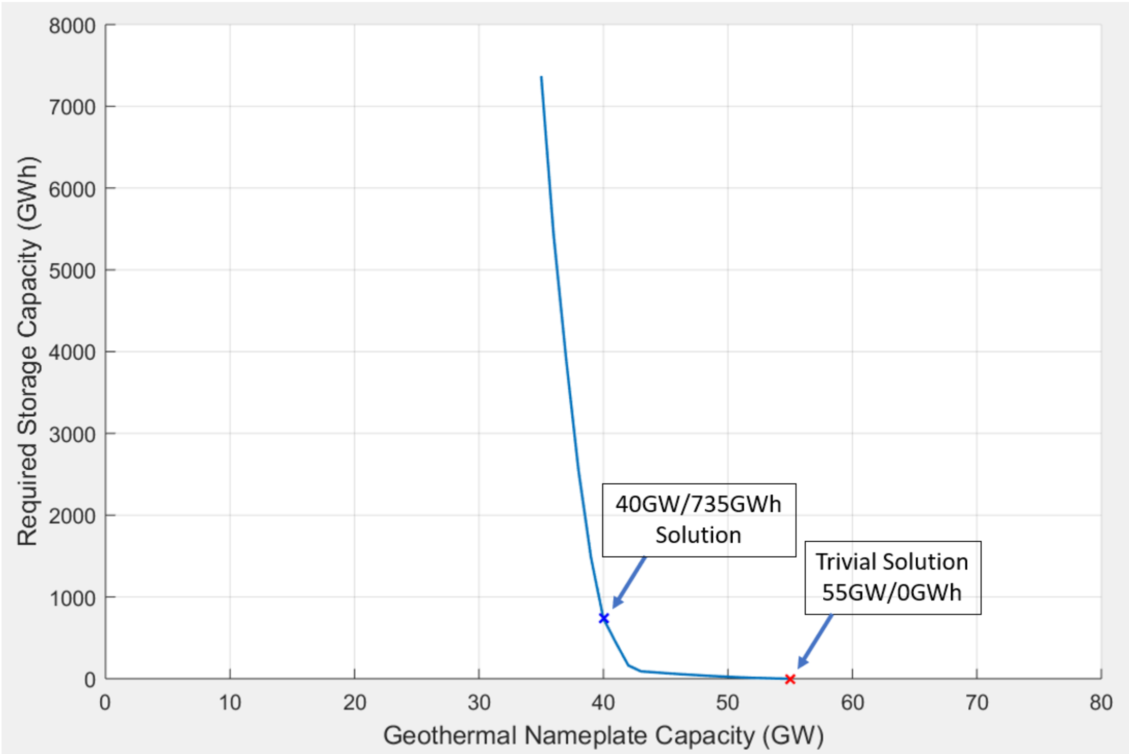

Figure 3.8: Capacities Plot for Geothermal and Pumped Storage

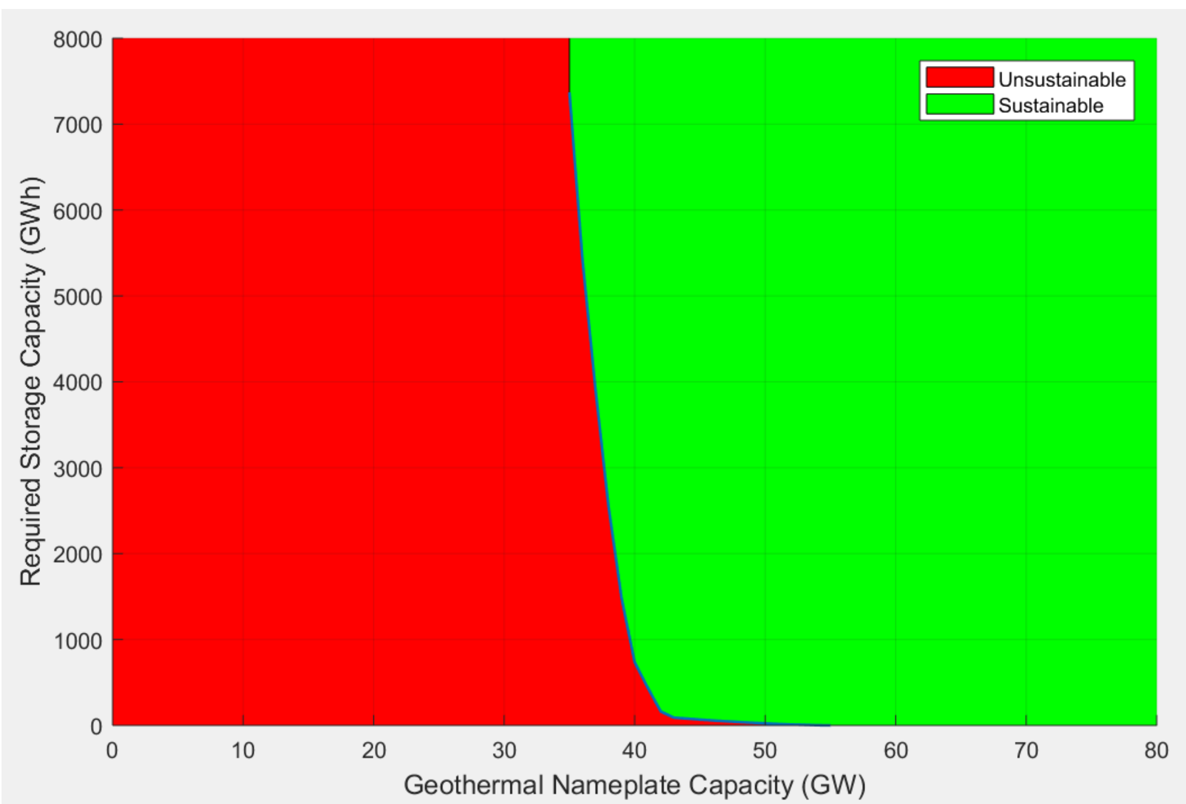

Figure 3.9: Sustainable Regions for Geothermal

The trivial solution approach can only be applied to renewable energy resources that are non-intermittent such as geothermal, nuclear and biomass. Intermittent renewable energy resources such as wind and solar do not have a trivial solution. In the next section, the algorithm is used to find the solutions for wind energy which is an intermittent renewable energy resources.

IV. WIND AND LITHIUM-ION ENERGY STORAGE

The algorithm was used to design SEGSs with wind and lithium-ion battery storage. There is no trivial solution for designing an SEGS with wind energy since the power output of wind is intermittent. The first law of designing SEGSs states the G2C ratio must be greater than or equal to 1; therefore, the algorithm first scaled the renewable energy resources for a G2C ratio of 1. Since the California region has an annual consumption of 280,000 GWh, the first law states the expect annual generation of the wind farm must be greater than or equal to 280,000 GWh.

The wind power supply data was scaled for a G2C ratio of 1 which corresponds to a wind farm with a nameplate capacity of 62GW. Figure 4.1 shows the power supply of the wind farm compared to the power demand of California. The area underneath the two plots are equal to 280,000 GWh.

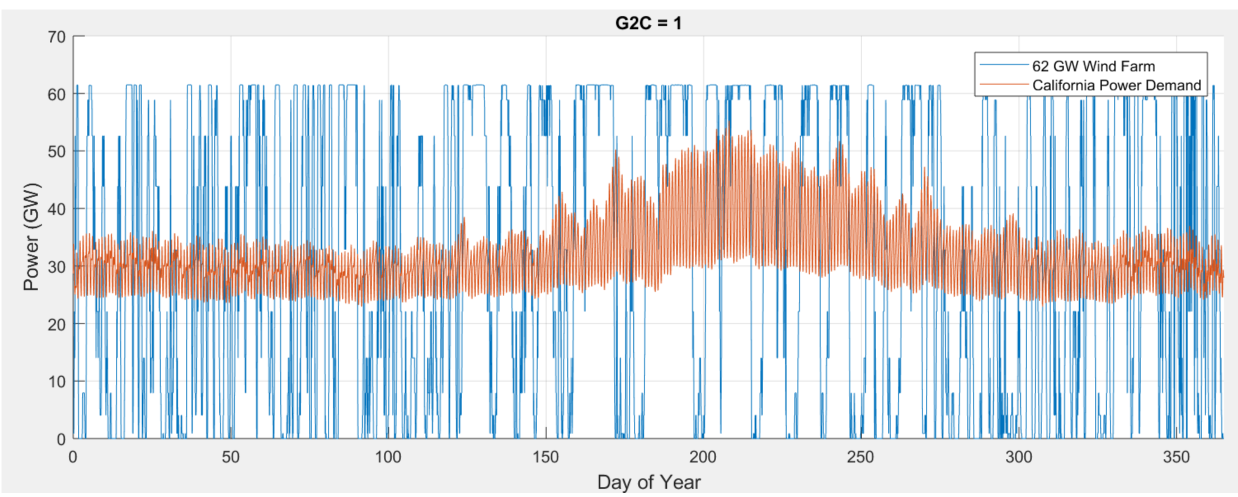

Figure 4.1: Power Demand of California and Power Supply of Wind Farm with G2C of 1

4.1 MINIMUM G2C RATIO

Starting at a G2C ratio of 1, the minimum G2C ratio was found by using a recursive procedure of incrementing the G2C ratio and checking if the stored energy contained negative values. The minimum G2C ratio is the smallest G2C ratio such the expected stored energy values are positive. If there were negative energy values, the G2C ratio does not produce enough energy to meet the demand. The algorithm gradually increased the G2C ratio until the minimum G2C ratio that did not result in negative stored energy values was found. For this example, the minimum G2C ratio was 1.17. The following figures show the expected time-series stored energy for G2C ratios of 1.00, 1.05, 1.10, 1.15 and 1.17.

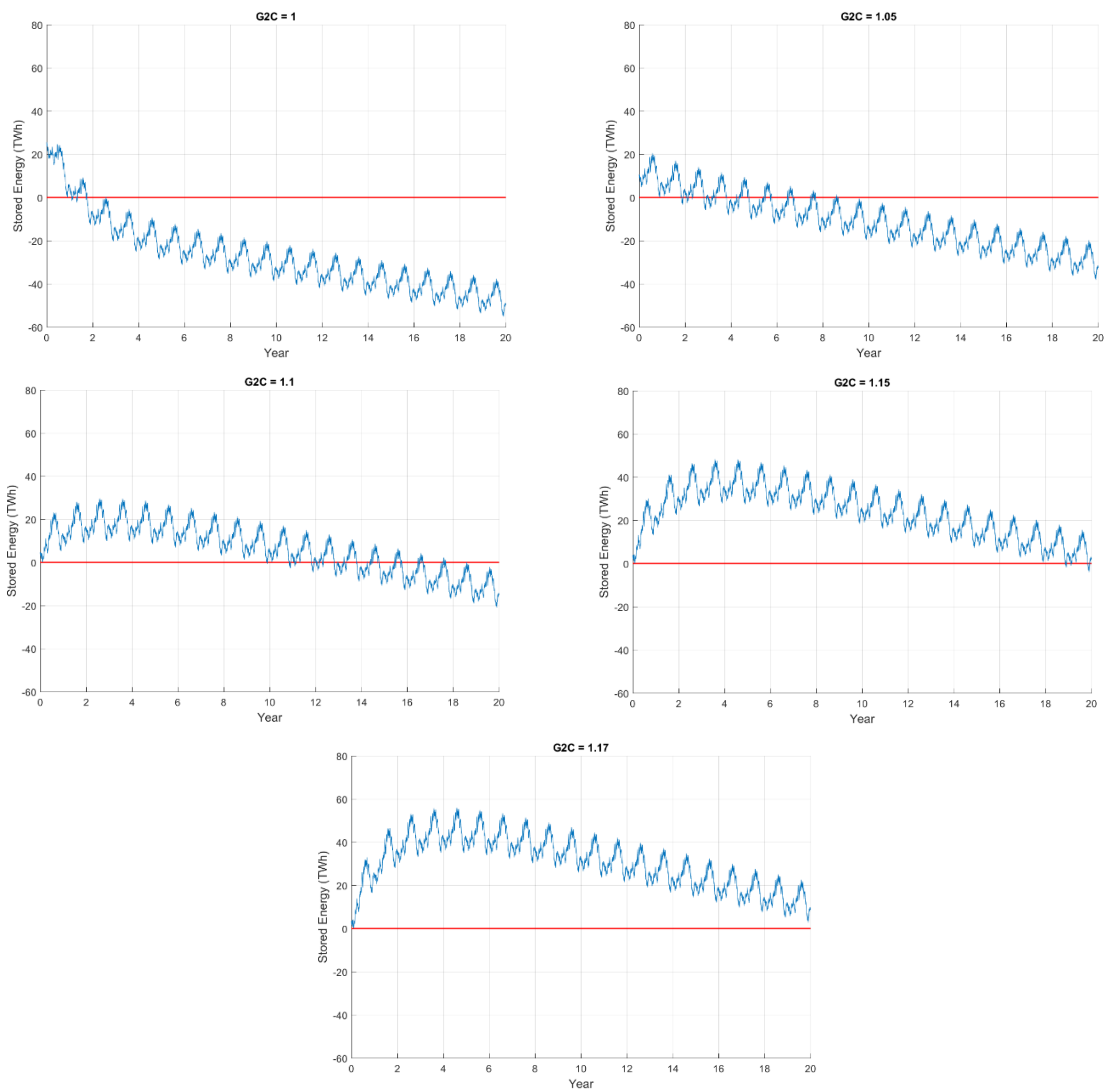

Figure 4.2: Expected time-series stored energy for G2C ratios of 1.00, 1.05, 1.10, 1.15 and 1.17

The second law of designing SEGSs states the expected time-series stored energy values must not be negative. All G2C ratios below 1.17 have stored energy values that are negative and are therefore unsustainable. The minimum G2C ratio was 1.17 since it was the lowest G2C such that the stored energy values were all positive.

Once the minimum G2C ratio was found, the algorithm found the minimum required storage capacity for the minimum G2C ratio. The minimum storage capacity was found by gradually decreasing the storage capacity until the stored energy values became negative.

Starting at the minimum G2C ratio of 1.17, the algorithm started with the maximum storage capacity of 56 TWh and gradually decreased the capacity. The minimum storage capacity without negative stored energy values was 19.3 TWh. The following graphs show the expected time-series stored energy of the 1.17 G2C ratio with 56TWh, 40 TWh and 19.3 TWh storage capacities.

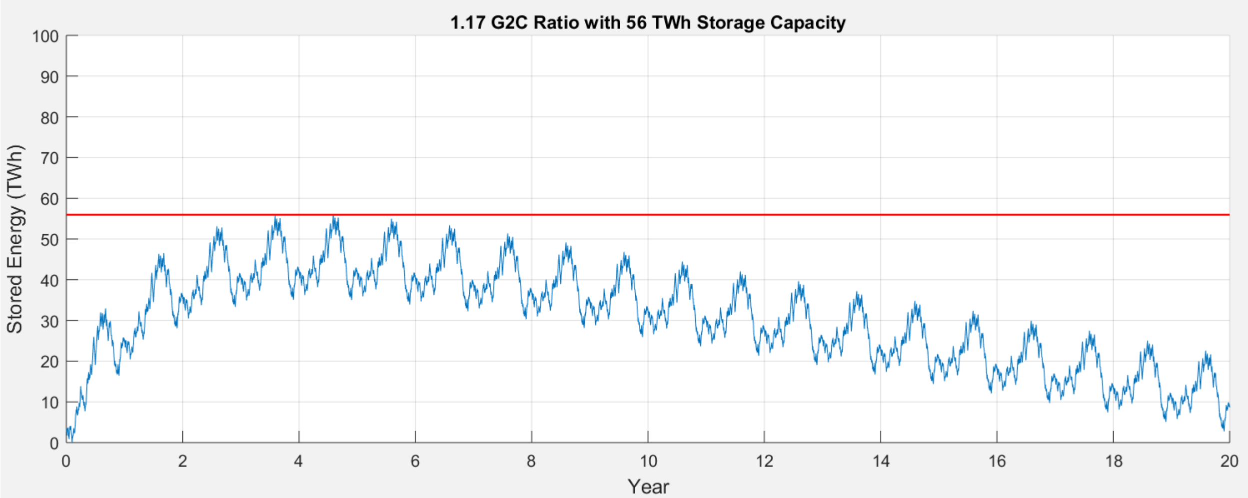

Figure 4.3: Expected time-series stored energy of 1.17 G2C ratio with 56 TWh Storage Capacity

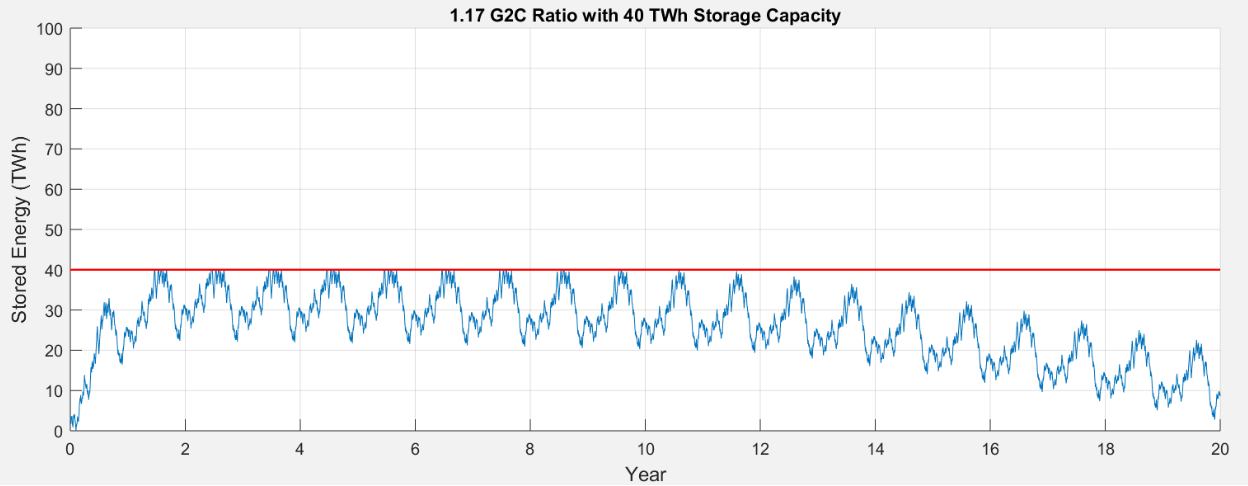

Figure 4.4: Expected time-series stored energy of 1.17 G2C ratio with 40 TWh Storage Capacity

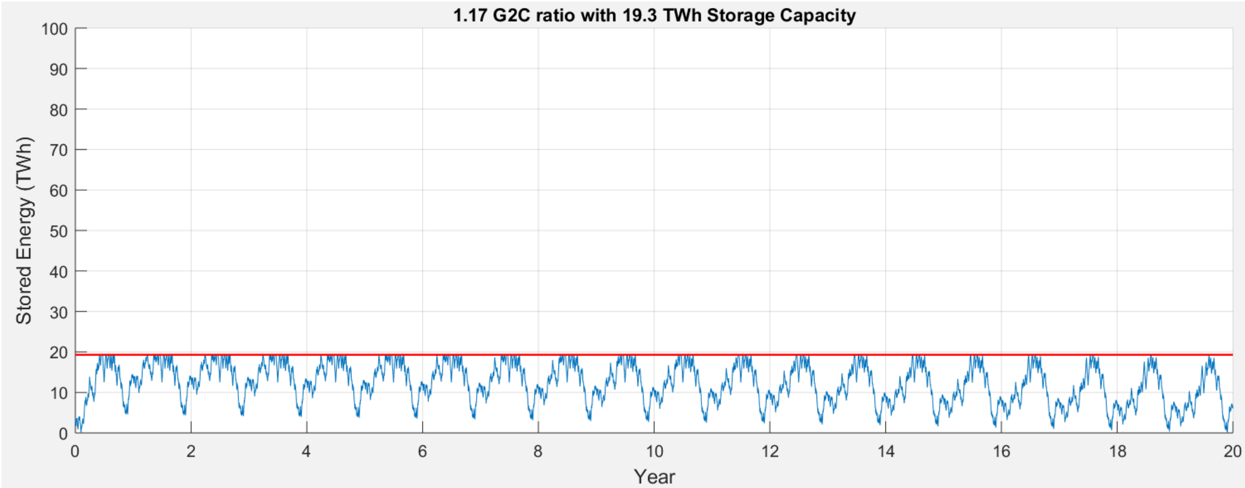

Figure 4.5: Expected time-series stored energy of 1.17 G2C ratio with 19.3 TWh Storage Capacity

As the storage capacity decreased, the time-series stored energy approached zero and obtained negative stored values for storage capacities less than 19.3 TWh.

A G2C ratio of 1.17 corresponds to a 73 GW wind farm and would require 19.3 TWh of energy storage. Figure 4.6 shows the configuration of the minimum G2C ratio. The x-axis represents the G2C ratio of the wind farm and the y-axis represents the required energy storage capacity. The blue "x" located at (1.17, 19.3) is the minimum G2C ratio solution. The x coordinate is 1.17 and the y coordinate is 19.3. The red area shows the unsustainable region. Every point in the red region represents an unsustainable SEGS configuration.

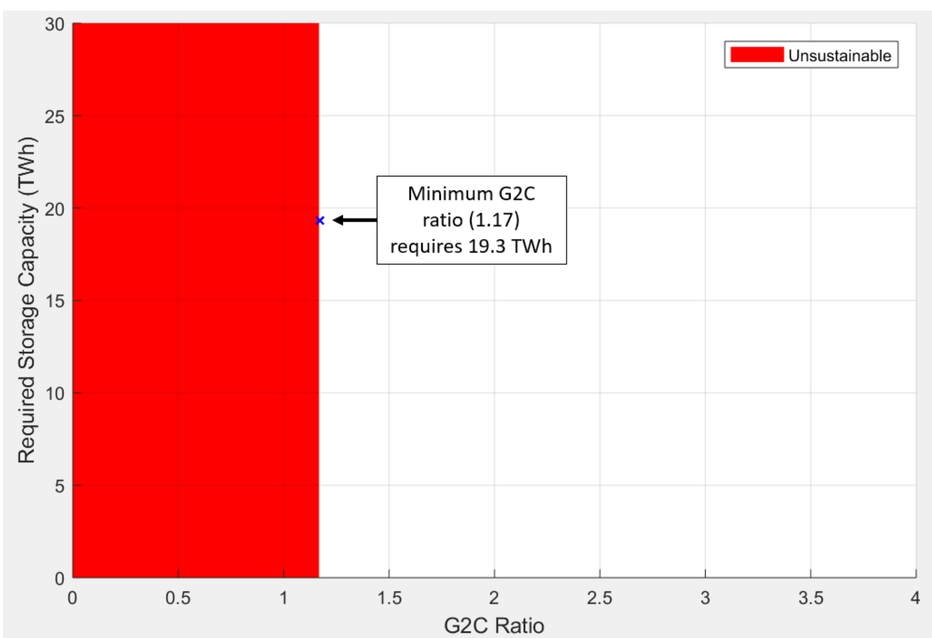

Figure 4.6: G2C Ratios Below the Minimum are Unsustainable

Next, the algorithm found the minimum storage capacity for all G2C ratios greater than 1.17 (the minimum G2C ratio). The algorithm used a similar approach to find the configuration of the other solutions. As another example, the solution for a 1.4 G2C ratio is elaborated. Figure 4.7 shows the time-series stored energy values for the 1.4 G2C ratio with maximum storage capacity.

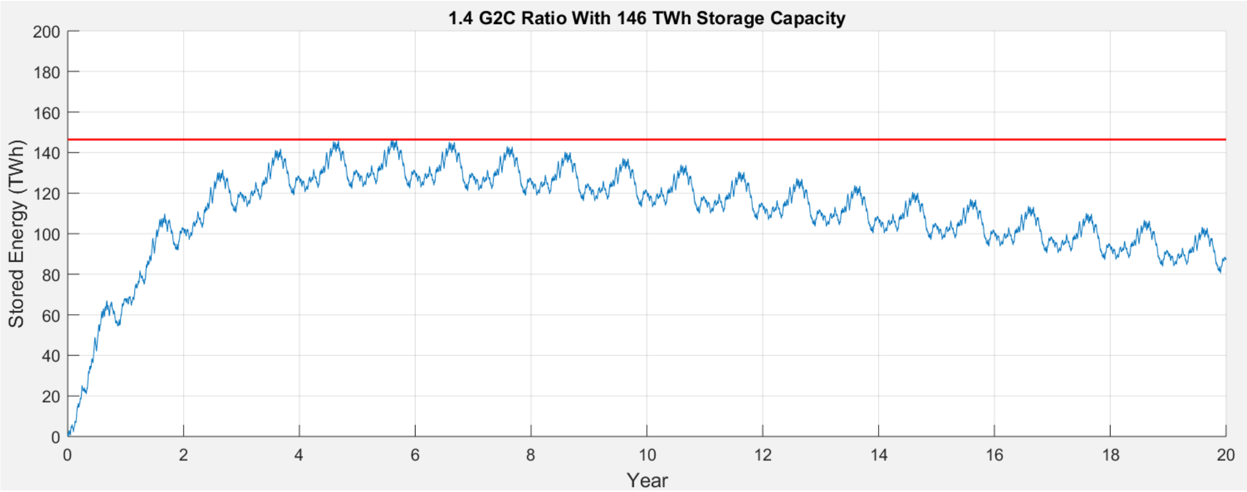

Figure 4.7: Expected time-series stored energy of 1.4 G2C ratio with 146 TWh Storage Capacity

Starting at the maximum storage capacity of 146 TWh 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. For the 1.4 G2C ratio, the minimum storage capacity without negative stored energy values was 10.9 TWh. The following graphs show the stored energy with storage capacities of 60 TWh, 30 TWh and 10.9 TWh.

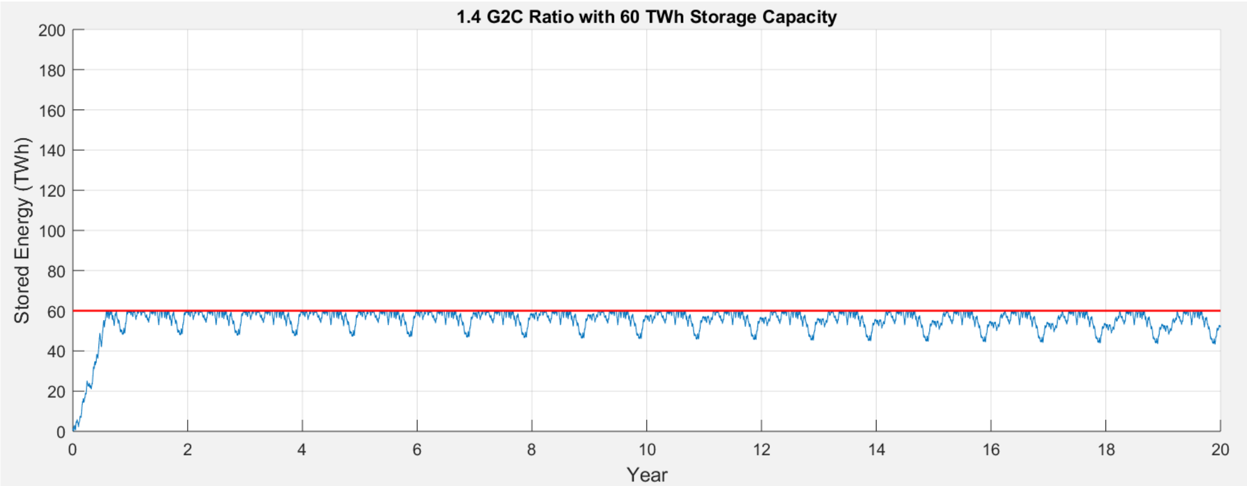

Figure 4.8: Expected time-series stored energy of 1.4 G2C ratio with 60 TWh Storage Capacity

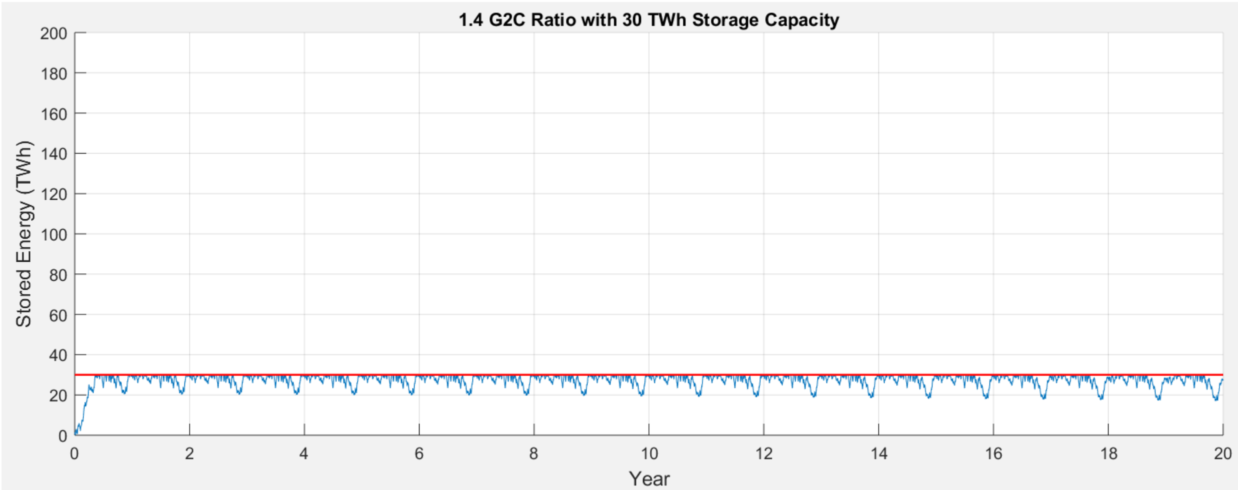

Figure 4.9: Expected time-series stored energy of 1.4 G2C ratio with 30 TWh Storage Capacity

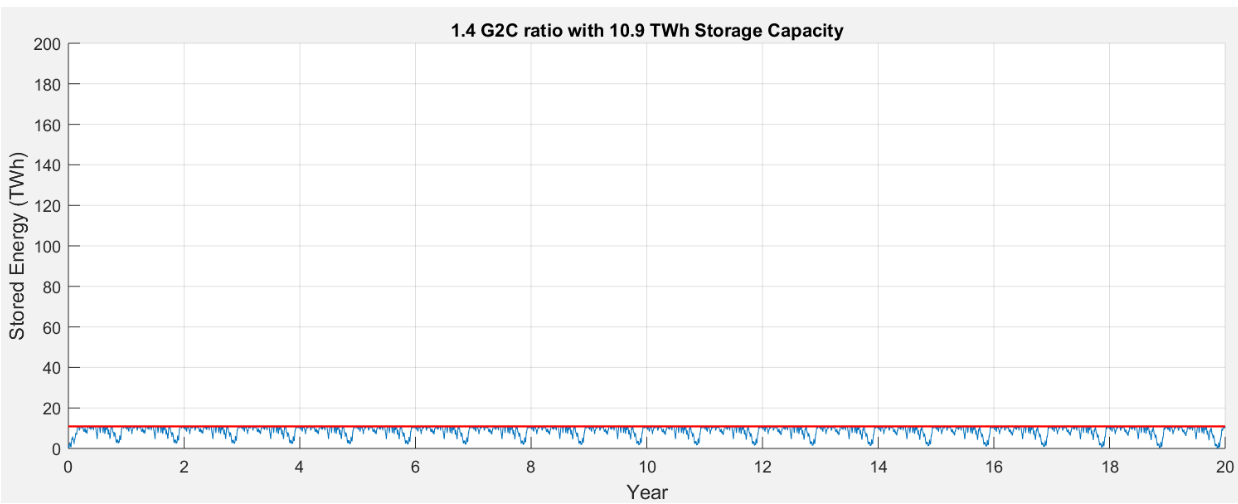

Figure 4.10: Expected time-series stored energy of 1.4 G2C ratio with 10.9 TWh Storage Capacity

For the G2C ratio of 1.4, the minimum sustainable energy storage was 10.9 TWh. Increasing the G2C ratio from 1.17 to 1.4, decreased the required storage capacity from 19.3 TWh to 10.9 TWh. These two solutions are plotted on Figure 4.11.

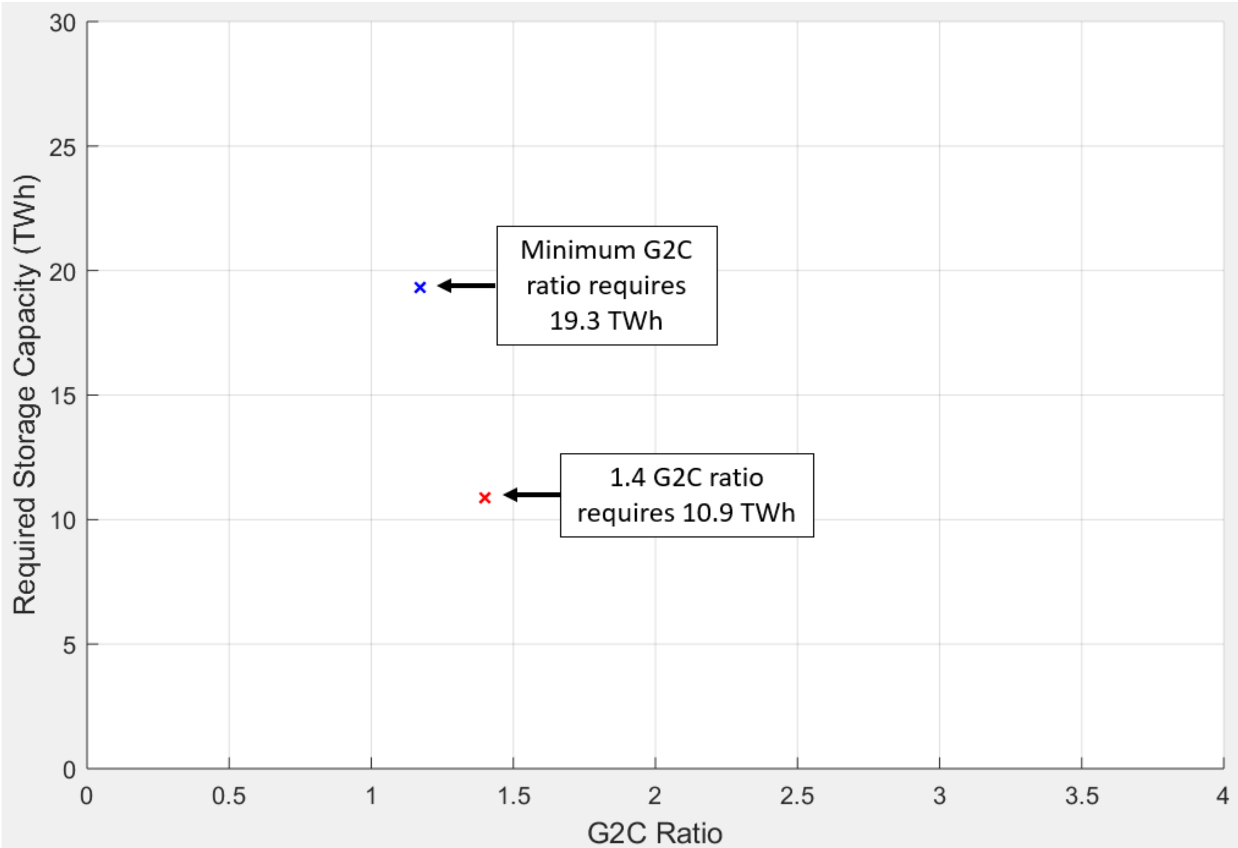

Figure 4.11: The minimum G2C ratio solution and the 1.4 G2C ratio solution

The algorithm found the required storage capacities for each sustainable G2C ratio to derive the Capacities Plot of the SEGS which shows the required energy storage capacity vs. G2C ratio. Figure 4.12 shows the Capacities Plot of 100% wind SEGS. The plot shows an inverse relationship between required storage capacity and G2C ratio. Figure 4.13 shows the sustainable and unsustainable regions.

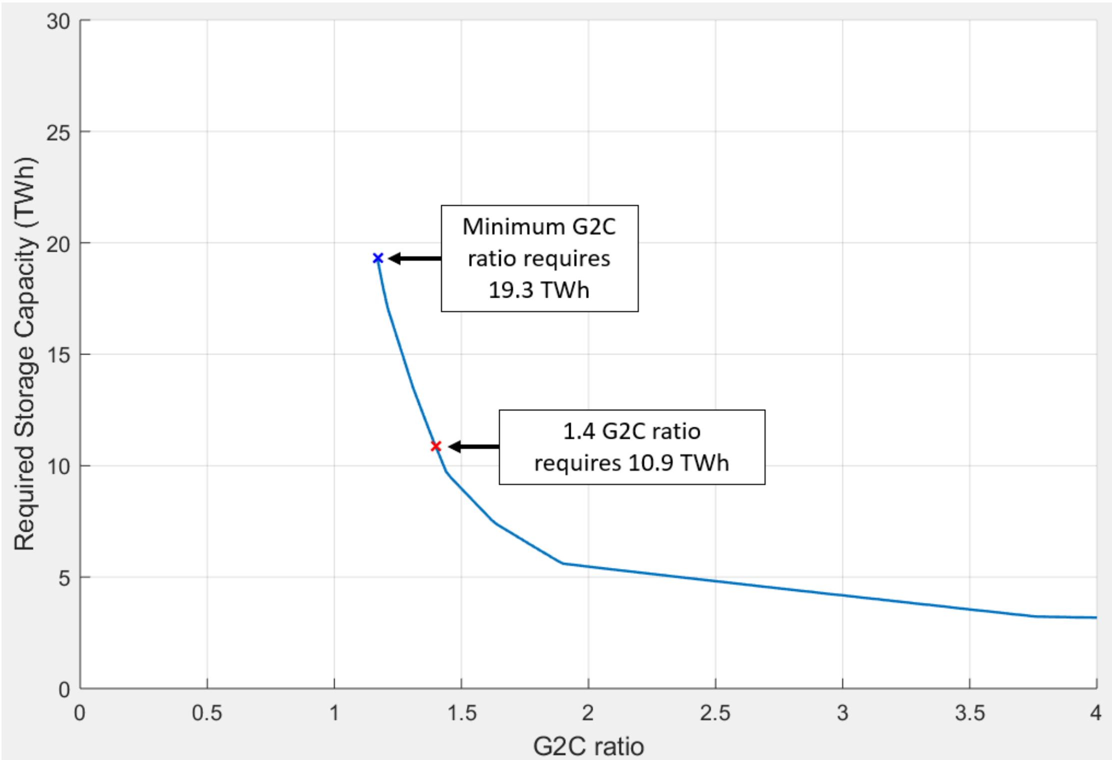

Figure 4.12: The Capacities Plot for Wind and battery ESS

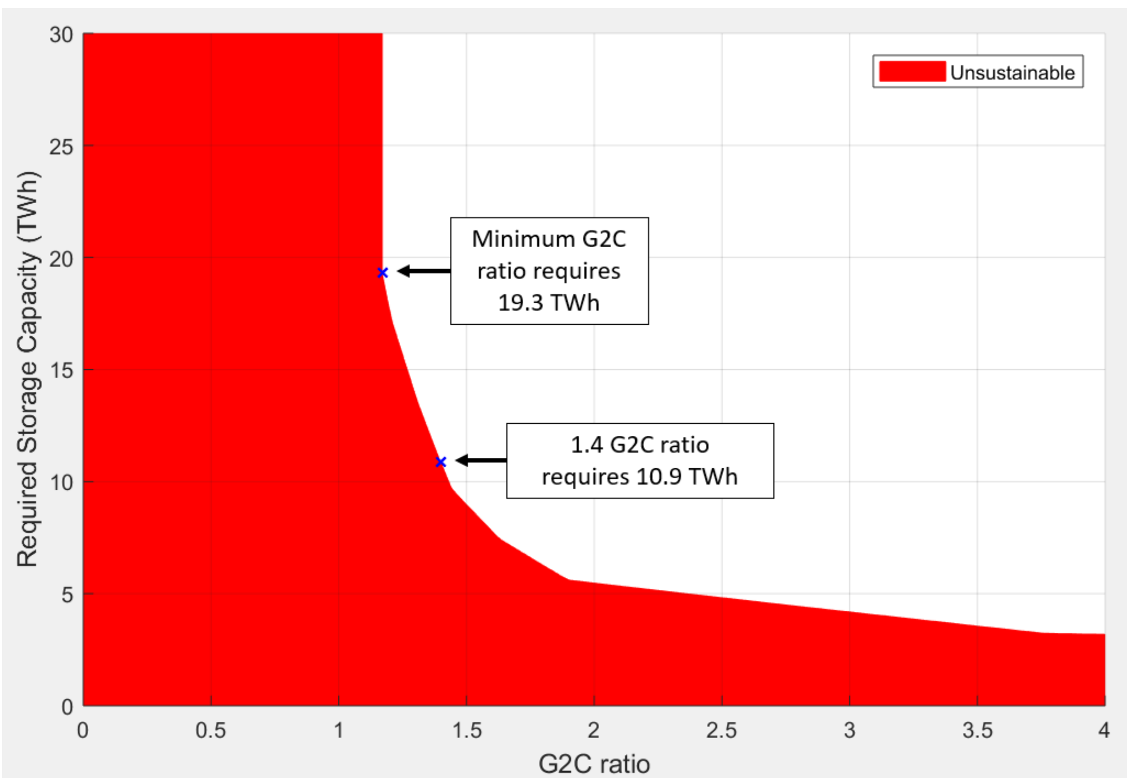

Figure 4.13: Unsustainable Region

4.2 COST

The Capacities Plot shows the relationship between G2C ratio and storage capacity which is important to determine the cost optimal SEGS configuration. Since wind turbines and ESSs have different costs, the algorithm computes the total cost of each SEGS. The algorithm assumed the cost of wind was $1.5 million per MW [5] and the cost of ESSs was $100 per kWh [6].

The minimum G2C ratio of 1.17 has a wind power nameplate capacity of 73 GW and would require 19.3 TWh of storage. The wind power would cost 108 billion dollars and the ESS would cost 1927 billion dollars. The total cost for the SEGS with 1.17 G2C ratio would be 2035 billion dollars. Of the total cost, 95% of the cost was for the ESS.

The 1.4 G2C ratio solution has a power nameplate capacity of 88 GW and would require 10.9 TWh of energy storage. The wind power would cost 129 billion dollars and the energy storage would cost 1083 billion dollars. The total cost for the SEGS with 1.4 G2C ratio would be 1212 billion dollars.

Increasing the G2C ratio from 1.17 to 1.4 increased the annual expected generation by 20%, but it also decreased the storage capacity by 56% from 19.3 TWh to 10.9 TWh. To summarize, increasing the generation by 20% decreased the required storage by 56% and it decreased the total cost by 60%. Figure 4.14 summarizes the cost of these two solutions.

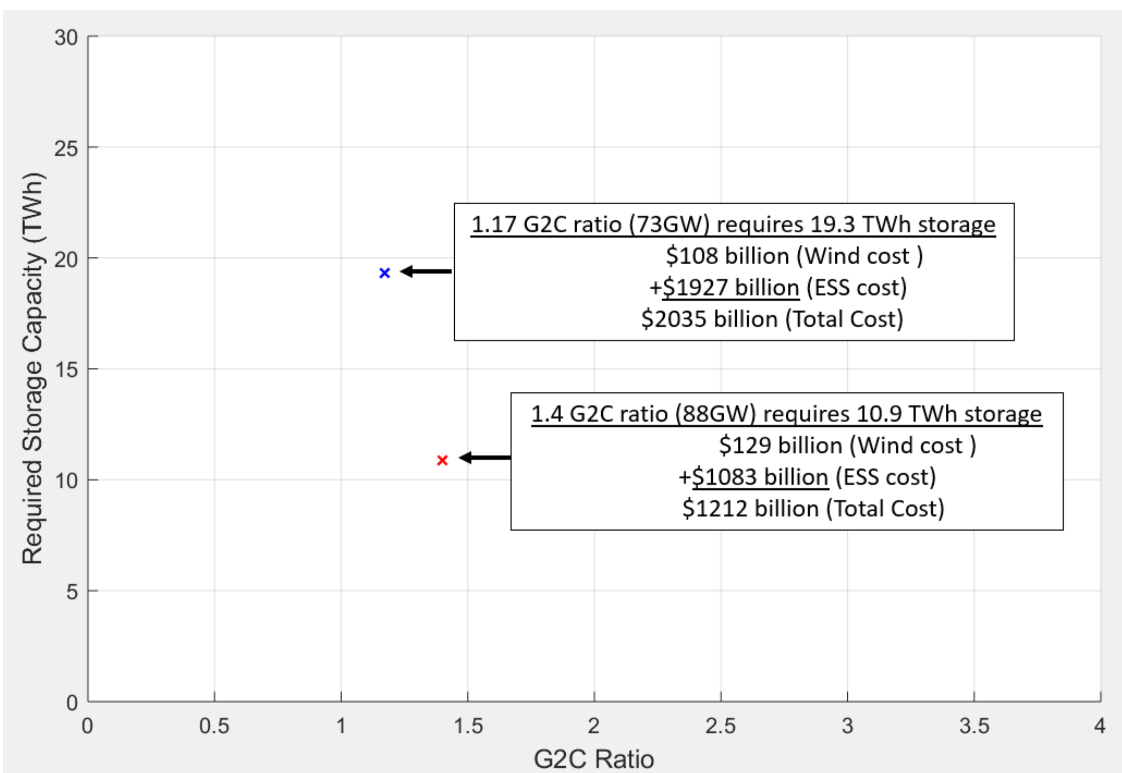

Figure 4.14: The 1.17 G2C ratio and 1.4 G2C ratio solutions

The algorithm computed the cost of each sustainable G2C ratio, and Figure 4.15 shows the result. The lowest point in this plot shown by the red "x" is the cost optimal SEGS configuration of about 670 billion dollars. A G2C ratio of 3.76 was the most cost-effective configuration which corresponds to a wind nameplate capacity of 230GW and an ESS capacity of 3.2 TWh.

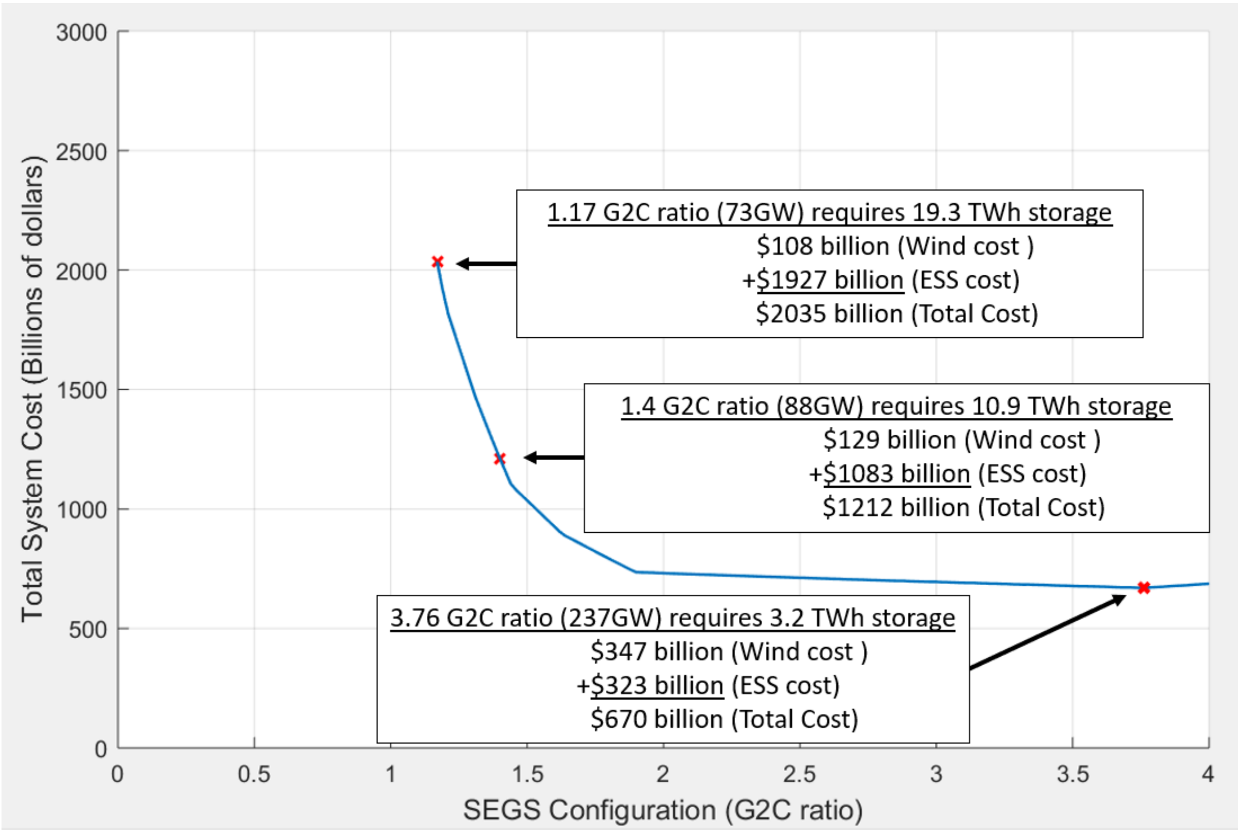

Figure 4.15: Configurations Cost Plot for Wind and Battery ESS

V. WIND, SOLAR AND STORAGE

Next, the algorithm was modified to design SEGS with wind, solar, and battery storage. The challenge with incorporating two different renewable energy technologies (wind and solar) is figuring out the optimal nameplate capacity of each technology, i.e. 40% solar/60% wind or 70% solar/30% wind, etc.

5.1 50% WIND AND 50% SOLAR

At first, the annual expected generation of each technology was equally split. An annual expected generation of 50% solar energy and 50% wind energy was arbitrarily chosen to design SEGS. The SEGS with G2C of 1 has an expected annual generation of 280,000 GWh. Half of the energy is generated from wind and the other half is generated from solar. For solar, the system will require a net solar nameplate capacity of 64,100 GW to generate 140,000 GWh per year. For wind, the system requires a net wind nameplate capacity of 30,800 GW to generate 140,000 GWh per year. Figure 5.1 shows the time-series power demand of California and the power supply of wind and solar.

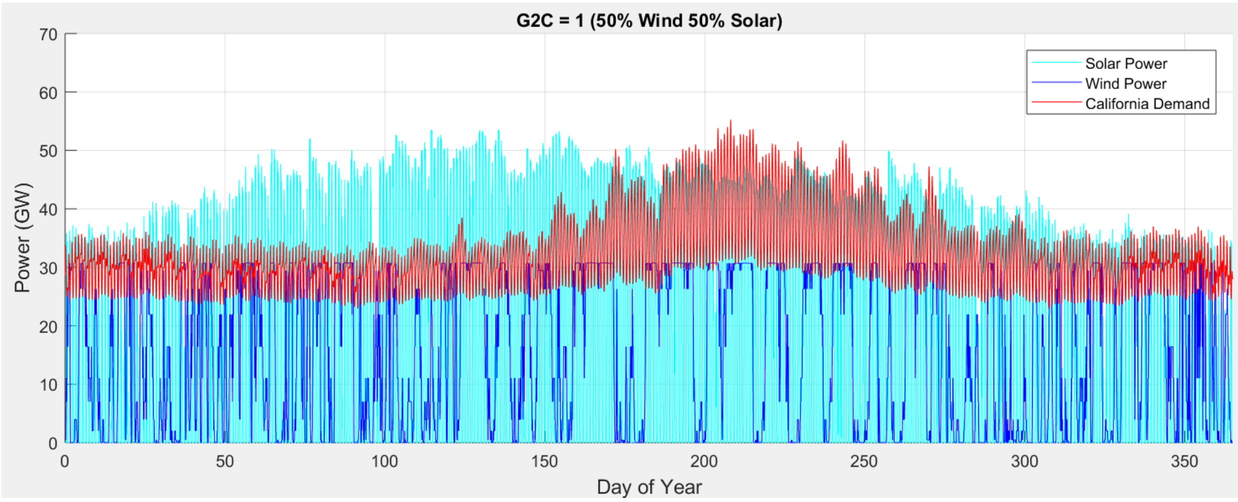

Figure 5.1: Power Demand and Power Supply of Wind and Solar

Using the same procedure described in Section IV, the algorithm iterated through the data and found the minimum required storage capacity for each G2C ratio. Figure 5.2 shows the Capacities Plot 50% Wind and 50% Solar, and Figure 5.3 shows the Cost Configurations plot of 50% Wind and 50% Solar.

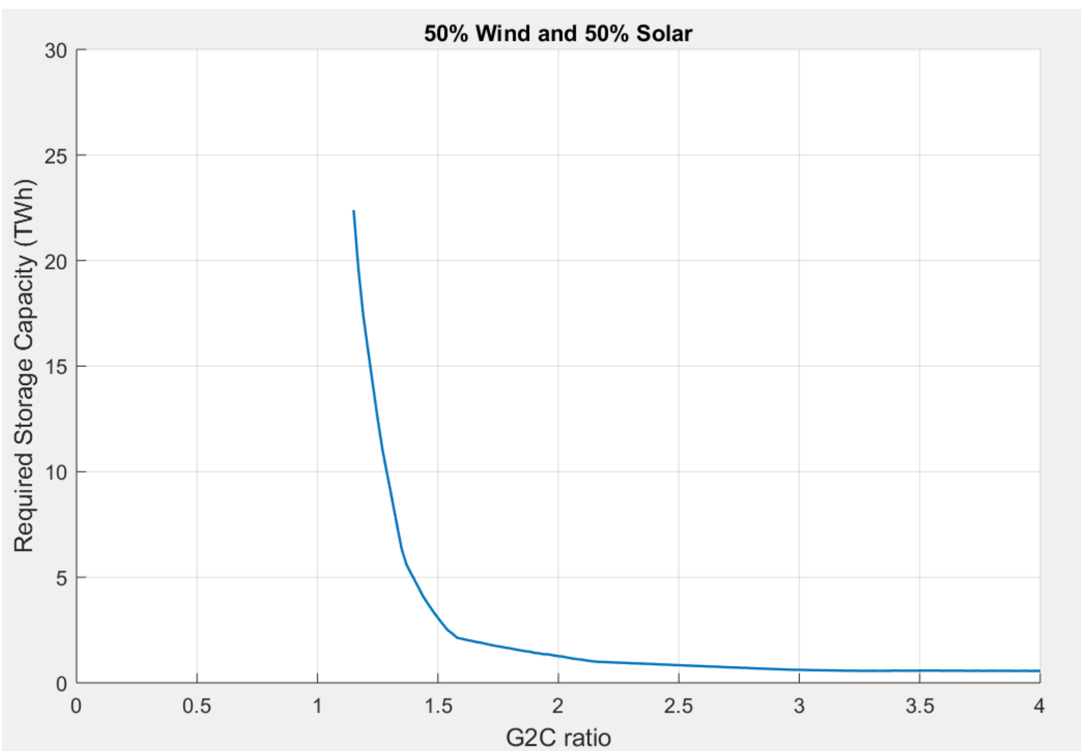

Figure 5.2: Capacities Plot of 50% Wind and 50% Solar

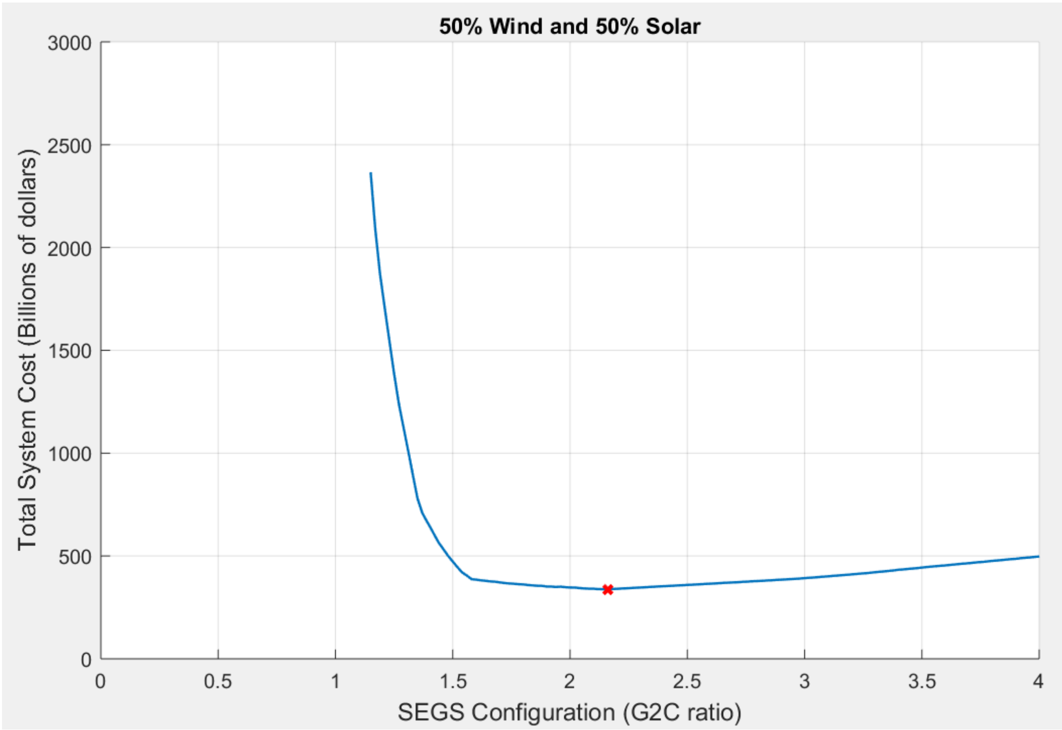

Figure 5.3: Configurations Cost Plot of 50% Wind and 50% Solar

From Figure 5.3, the most cost-effective configuration of 50% wind and 50% solar was a 2.16 G2C ratio and would require a storage capacity of 1 TWh and cost 340 billion dollars.

5.2 OPTIMAL SIZING OF WIND AND SOLAR

Figure 5.4 shows the Capacities Plot of the 100% Wind SEGS from Section IV and the Capacities Plot of the 50% Wind/50% Solar SEGS. From this figure, the 50% Wind and 50% Solar SEGS system requires much less storage capacity than the 100% wind SEGS.

Figure 5.5 shows the Cost Configurations Plot of the 100% wind SEGS and the Cost Configurations Plot of the 50% Wind/50% Solar SEGS. Since the 50% Wind/50% Solar SEGS requires much less storage, it had an effect on the total cost of the system. The 50% Wind/50% Solar SEGS is considerably more cost-effective than the 100% Wind SEGS.

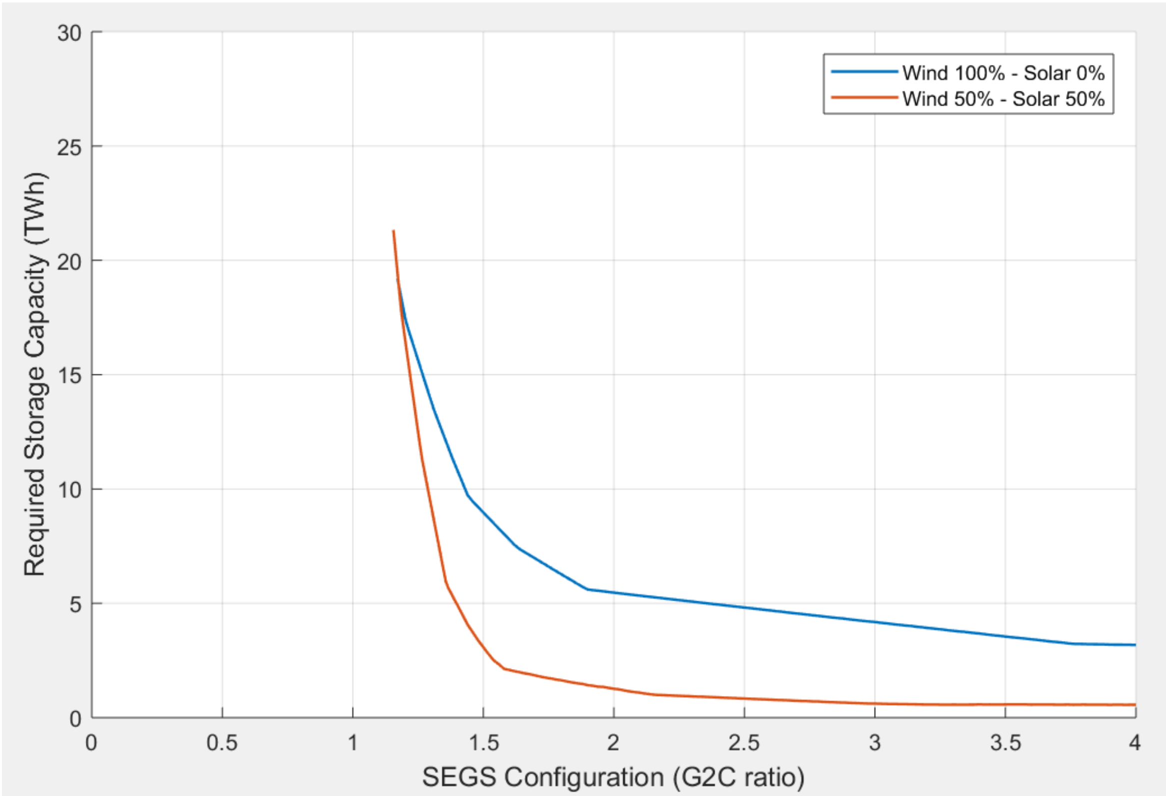

Figure 5.4: Capacities Plot of 100% Wind and 50% Wind/50% Solar SEGS

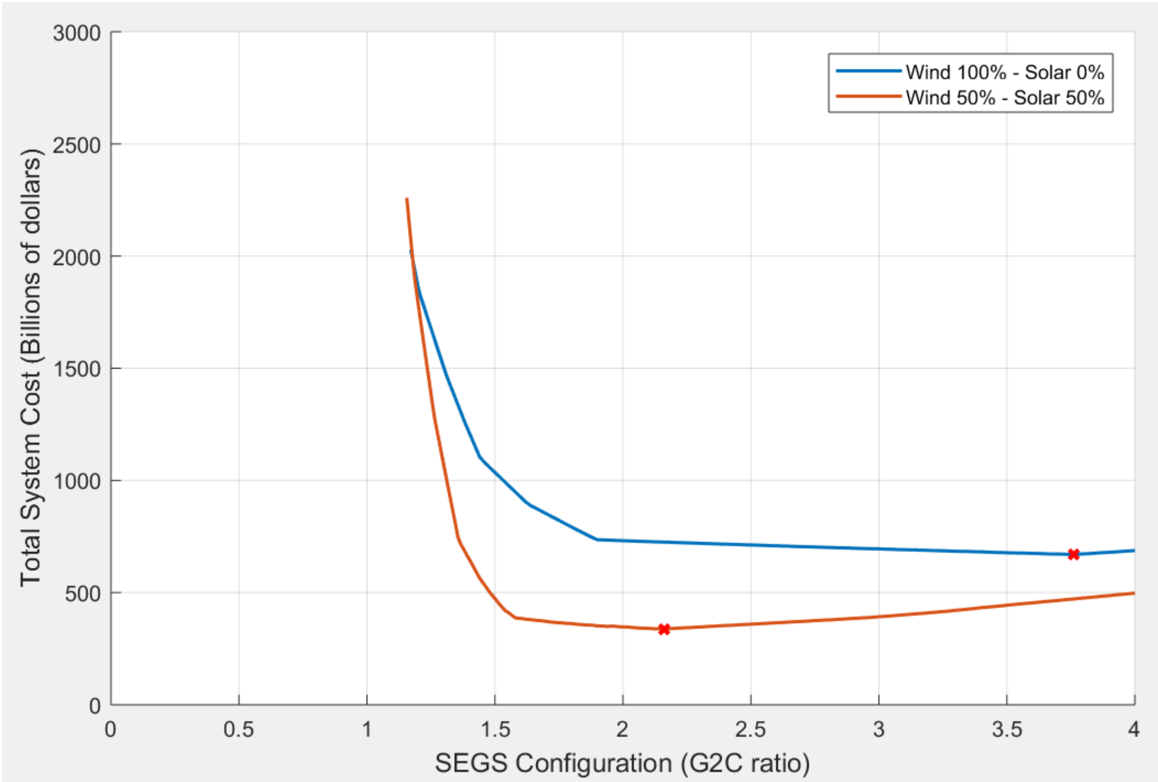

Figure 5.5: Configurations Cost Plot of 100% Wind and 50% Wind/50% Solar SEGS

A hundred different simulations were compiled to design SEGSs with different percentages of wind and solar. The first simulation designed an SEGS with 100% wind. The second simulation designed an SEGS with 99% wind and 1% solar. The fifth simulation designed an SEGS with 95% wind and 5% solar. The twentieth simulation designed an SEGS with 80% wind and 20% solar. The eightieth simulation designed an SEGS with 20% wind and 80% solar. The one hundredth simulation designed an SEGS with 0% wind and 100% solar.

Figure 5.6 shows the Configuration plots of seven different distributions. Figure 5.7 shows the Configurations Cost Plot of the seven different distributions.

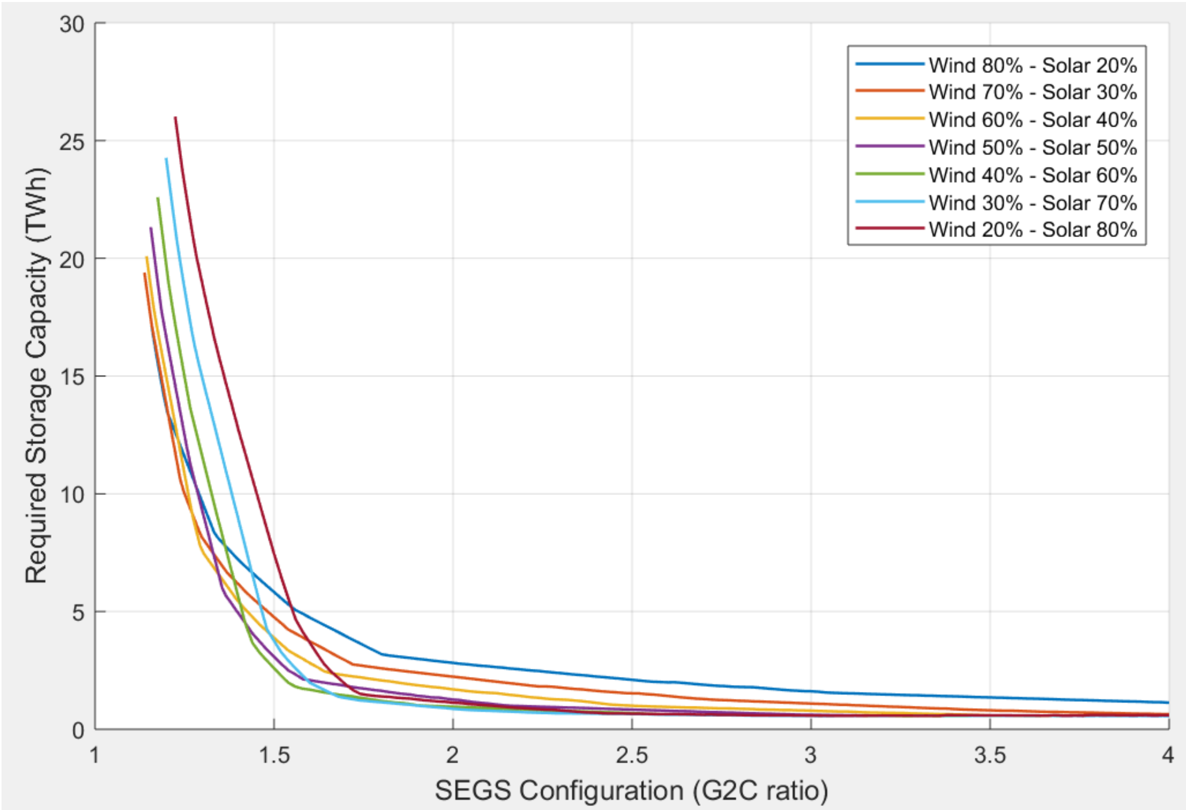

Figure 5.6: Capacity Plots of various Wind/Solar distributions

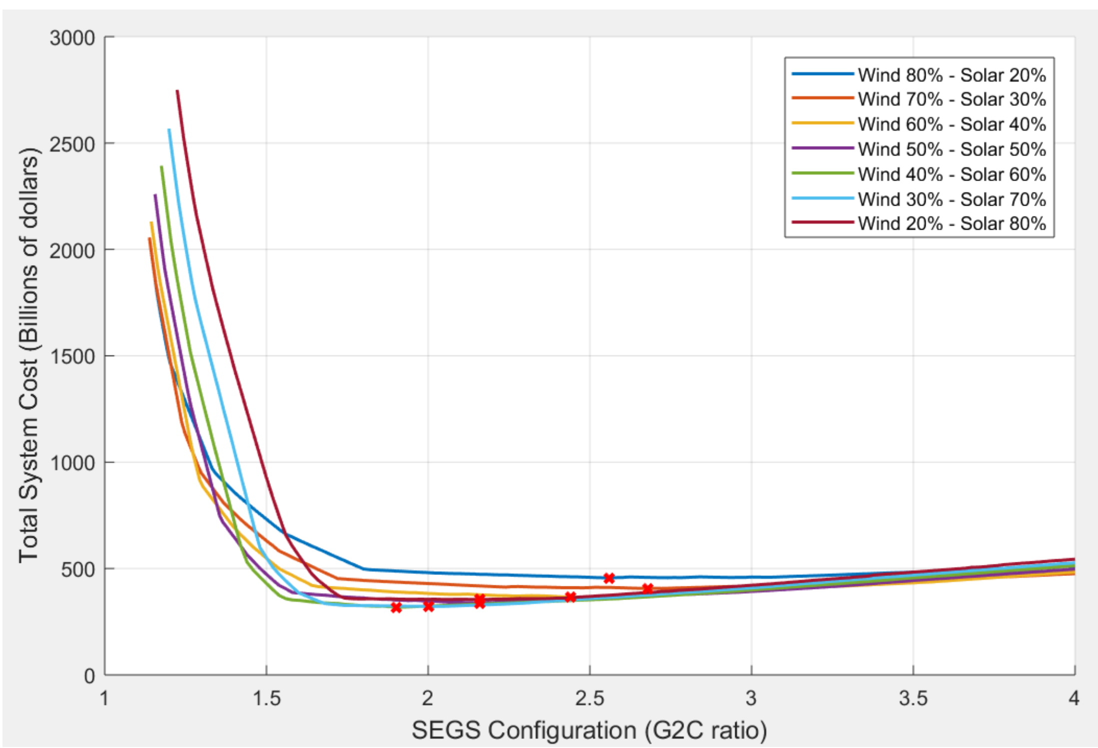

Figure 5.7: Configurations Cost Plot of various Wind/Solar distributions

The most cost-effective configuration of each distribution was compiled and plotted. Figure 5.8 shows the cost of the optimal configuration for each distribution. The optimal system is a 1.82 G2C SEGS with 65% Solar and 35% Wind and would cost 310 billion dollars.

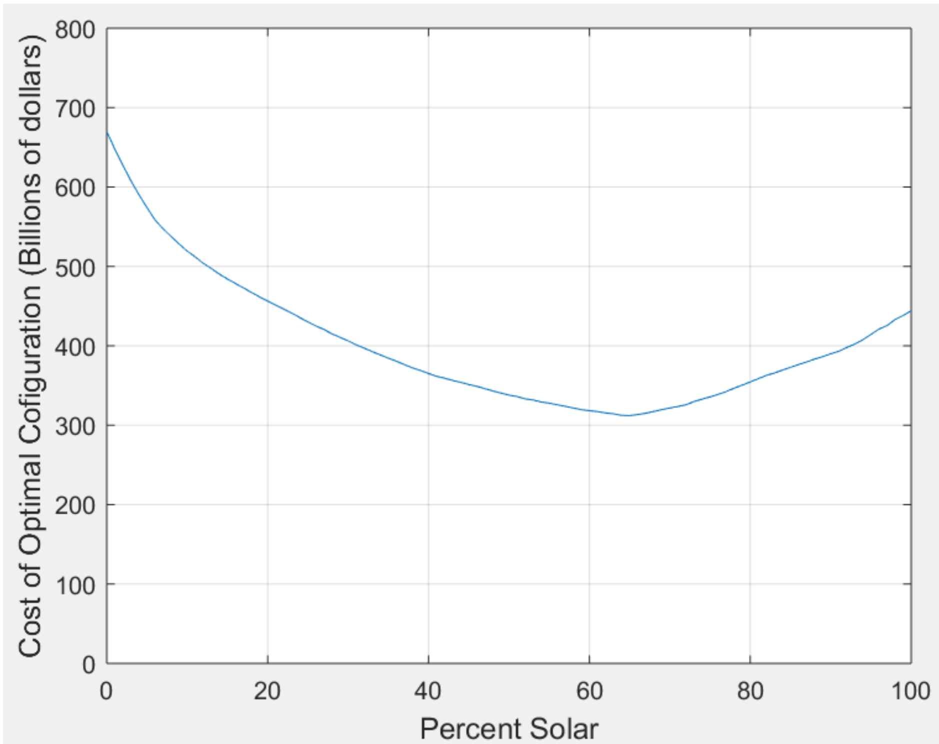

Figure 5.8: Total System Cost vs. Percent Solar

VI. UTILIZING OVERGENERATION TO SCRUB CARBON DIOXIDE FROM THE ATMOSPHERE

The most cost-effective wind and solar SEGS requires a 1.82 G2C ratio which means the SEGS system produces 1.82 times more energy than consumed. The energy generated will either be consumed, lost due to energy losses, or overgeneration. The algorithm was used to determine the energy losses and overgeneration. Twenty-four percent of the total generation (122,000 GWh) is not utilized and is considered overgeneration. Twenty-one percent of the total generation (108,000 GWh) is lost by the energy losses of the SEGS. Fifty-five percent of the total generation is for consumption.

It's possible to utilize the unused energy to power stand-by devices such as atmospheric carbon dioxide scrubbers. Research shows the primary energy required to capture CO_2 from ambient air is between 800 and 1200 kJ/mol of CO_2 [7]. Therefore, if carbon scrubbers are connected to the SEGS and all the excess energy (122,000 GWh) is used to power carbon scrubbers. The system would be able to extract 16 million metric tons of CO_2 per year.

VII. REFERENCES

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