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Renewing the Paradigm: Simulating the MISO Region Electrical Grid Using Renewable Energy Generation with Implementation of Long-term Hydrogen Storage

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Abstract

The current electrical grid regime is not optimized to include renewable sources of power generation such as wind and solar. Electrical storage, as of now, is primarily established through the short-term generation and demand-meeting consumption leaving much of the grid susceptible to inefficiencies and power loss during natural events that leave grids out of commission. Delineating a new type of long-term storage, a hydrogen fuel cell, would ensure a reliable source of power to the masses regardless of the physical and climatic geography. The MISO region provides a perfect case study to introduce the ideas of diverse energy generation and storage due to its wide-reaching services and its openness towards extreme weather situations. By conducting simulations using C++ over a three-year period, we investigated the possibilities of using a purely renewable energy portfolio (wind and solar), along with a mix of short-term battery storage and long-term hydrogen storage, to meet and exceed the hourly load requirements of the MISO region. The introduction of an arbitrary two-week polar vortex showed that using hydrogen as a storage conduit would allow uninterrupted power delivery during periods of intermittent/non-existent solar and wind. The diversity of short- and long-term storage and the capacity of renewable energy call for a new electrical grid paradigm to be developed in the coming years.

Keywords

grid optimization, hydrogen storage, renewable energy

Cover Page Footnote

I would like to acknowledge my advisor, James Doyle, for his esteemed assistance and guidance over the last four years. I would also like to thank Macalester College and the physics department for this opportunity to participate in research remotely.

Introduction

Almost all electrical power comes from some type of turbine generator. Through coal-fired power plants, natural gas steam plants, or even nuclear power plants, most of our electricity comes from the combustion of these nonrenewable resources. How is this electrical energy stored and thereby delivered to the masses? The current grid regime is load balancing, meaning that generation must nearly always match customer demand or "load". Through a hierarchy of generator types, load balancing is relatively cost-effective and reliable. However, this current grid layout does not allow for the inclusion of renewable energy sources such as wind and solar. To incorporate substantial amounts of solar and wind grid power, there needs to be critical change to the current method of power storage and delivery [1]. Source and geographical diversity and demand-side management, the idea of matching load to supply rather than supply to load, are keys to reducing the amount of storage needed to meet daily load requirements [2,3]. This research project focuses on the basic idea of overgeneration and storing energy at times of peak solar and wind availability such that this energy can be delivered at times of low availability [4].

By diversifying energy storage, it would allow us to rely more on wind and solar energy such that there would be a reduction in back-up power plants and an overall need for copious amounts of storage [1,3]. Storage is expensive, so creating a new regime that focuses on minimizing storage costs is beneficial [2]. A heavier utilization of solar and wind energy would also help in decarbonizing the electrical grid as we could finally work to relieve some of the environmental damage, mainly through anthropogenic climate change, that is exacerbated by traditional coal-fired plants and other nonrenewable sources of power [1,2,3]. Optimizing mixes of solar and wind generation lead the way to the distinction between short-term and long-term storage types. Investigating the relationship between short-term and long-term storage as well as delving more into the optimization of renewable energy generation are two main tenets of this research project.

To fully conceptualize the scope of the research project, time will be taken to delineate crucial terms and state variables that were used throughout the project.

- <u>Deficit Energy:</u> The amount of energy still required to meet the load requirement after the consumption of the generated energy i.e., wind and solar [4]. Example: If the load is 10 and the generated energy is only 7, this means that the deficit energy would be 3, meaning that another energy source would have to be used to cover that remaining 3 energy units.
- <u>Balance:</u> The difference between the generated energy and the load can be negative or positive. A negative balance implies that the generation exceeded the load while a positive balance implies a deficit energy [4].
- <u>Spillover Energy/Spill:</u> The “extra” energy that comes from overgeneration i.e. when inputs provide more energy than what is needed to equalize the load [4].
- <u>Gamma (γ):</u> The proportion of generation. If $\gamma > 1$, then we are over generating which means the wind and solar arrays are providing more energy than necessary to meet the demand. If $\gamma < 1$, this is a case of under generation, which means there would be a deficit energy present [4].
- <u>Equivalent Days of Storage:</u> All the values used in the program are unitless since everything is normalized. Thus, the values for storage that come as a result of the simulation must be converted to something that can be handled and interpreted.

The simulations ran for three years so simply multiplying the storage values by 3×365 gave the number of days that energy would be stored [4].

➔ <u>Efficiency:</u> The ratio of energy output in the desired form (i.e., electrical energy in this case) to the total energy output of the system. In this study, the efficiency of the battery storage is 80% while the efficiency of the hydrogen storage is 30% [3,4]. These efficiencies represent the working capability of these two isolated systems. In the simulations, there is no linkage between battery capacity or hydrogen capacity such that they are treated independently from another so any "wasted" energy simply goes to heat (a minor simplification).

Data [5,6,7,8,9]

The data was the most vital aspect of this project as the created programs were only as effective as the values that were imported into them. The geographical range of this study is the MISO region, which is comprised of 15 states that span a middle portion of the United States (see Figure 1).

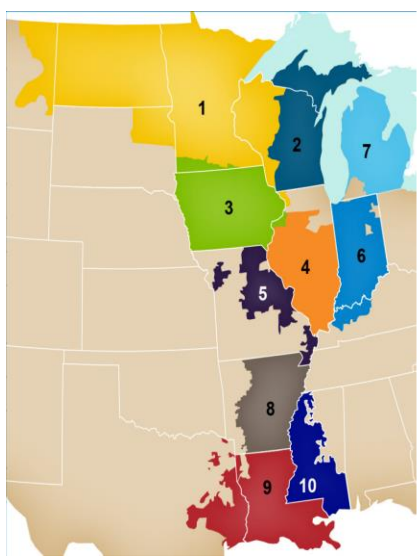

Figure 1: Map of the MISO Region.

The temporal range of the study was three years from 2016 to 2018, such that there were 26,280 data points from January 1st, 2016 to December 31st, 2018, with no missing values for any of the three variables: load, wind, and solar. The MISO database had complete values for the three years of load data from 2016 to 2018 [8]. Furthermore, MISO had the necessary wind data for 2016, 2017, and 2018. There are also archived datasets that show the daily distribution of fuel consumption. This “fuel mix” is broken down into several categories including wind, coal, nuclear, hydroelectric, gas, and “other” [6,7]. This “other” category includes power output due to solar, which proved difficult to extract in a manner that would seamlessly integrate into the load and wind datasets.

Solar data was collected from the National Renewable Energy Laboratory (NREL) for the target years (2016-2018) [9]. The NREL data was based on a geographic location’s value for its Global Horizontal Irradiance (GHI). GHI is the total amount of shortwave radiation received from above by a surface horizontal to the ground [9]. Using solar irradiance data as the solar dataset required further manipulation, since it is based on the spectral geography of a desired point location. To fully cover and convey the solar output of the MISO region, would require the use of hundreds of thousands of points. Instead of working through all that data, approximations were made of the solar irradiance (GHI) of the MISO region by selecting target cities from each of the fifteen states that MISO encapsulates. 15 cities in total were used in this approximation: St. Louis (MO), Springfield (IL), Sioux Falls (SD), New Orleans (LA), Milwaukee (WI), Louisville (KY), Little Rock (AR), Jackson (MS), Indianapolis (IN), Houston (TX), Fargo (ND), Detroit (MI), Davenport (IA), Billings (MT), and Minneapolis (MN). This “new” MISO region conveys all the solar output that was used in the simulations of this study.

The units of the load and wind datasets are watt-hours, and they come on the order of hundreds or thousands of watt-hours, while the approximated solar irradiance data has equivalent units to power flux density (i.e., watts per square meter). Now, it was perfectly feasible to complete the work by keeping the values unchanged and working in the normal SI units; however, normalizing these datasets provided ease of access for data visualization and analysis. Each three-year dataset (load, wind, and solar) was normalized, meaning the sum of each dataset is equal to a value of one with each data point now equaling some small-valued fraction. Normalization made it easier to conceptually understand the analysis without being caught in the crossfire of handling different units for our 26,280 hours (points) of data. Additionally, the process of normalization saves our understanding of γ as a type of proportion that assists in assigning generation factors to the wind and solar datasets.

Methods

The driving physical idea for this project was the principle of energy conservation. Whatever amount of energy that is generated must also be the same amount that is consumed. C++ was used to create programs that calculate remaining battery and hydrogen storage, track the running sums (spillover, deficit) and the value of balance, as well as give equivalent days of storage remaining after a simulation run. The coding itself was relatively straightforward as nested while/for loops were used for timekeeping and to set different initial values for the battery storage. Furthermore, the phase of the study that included working with hydrogen storage brought in the use of if/then statements such that the program knew to either pull from battery or hydrogen depending on the time value in the given three-year period, which is based on the imported datasets from MISO and NREL. Figure 2 shows a flowchart of our fundamental hydrogen storage program. This skeletal program is the foundation for this research and accentuates many fundamental concepts of physics such as the conservation of energy and the conservation of charge. Along with those conservation laws, the efficiencies of these storage systems were also considered to ensure that the simulations were the most pragmatic and realistic given the already approximated data being used to gather the results.

1. Declare arrays for load, solar, and wind data
2. Declare initial variables and set initial values:
   - Balance
   - Maxcap = .01 (10.95 days)
   - Currentcap = .001826 (~2 days)
   - Hydrocap
   - Def = 0
   - Spill = 0
   - Battery_eff = 0.8
   - Hydro_eff = 0.3
3. Input sol and wind fractions

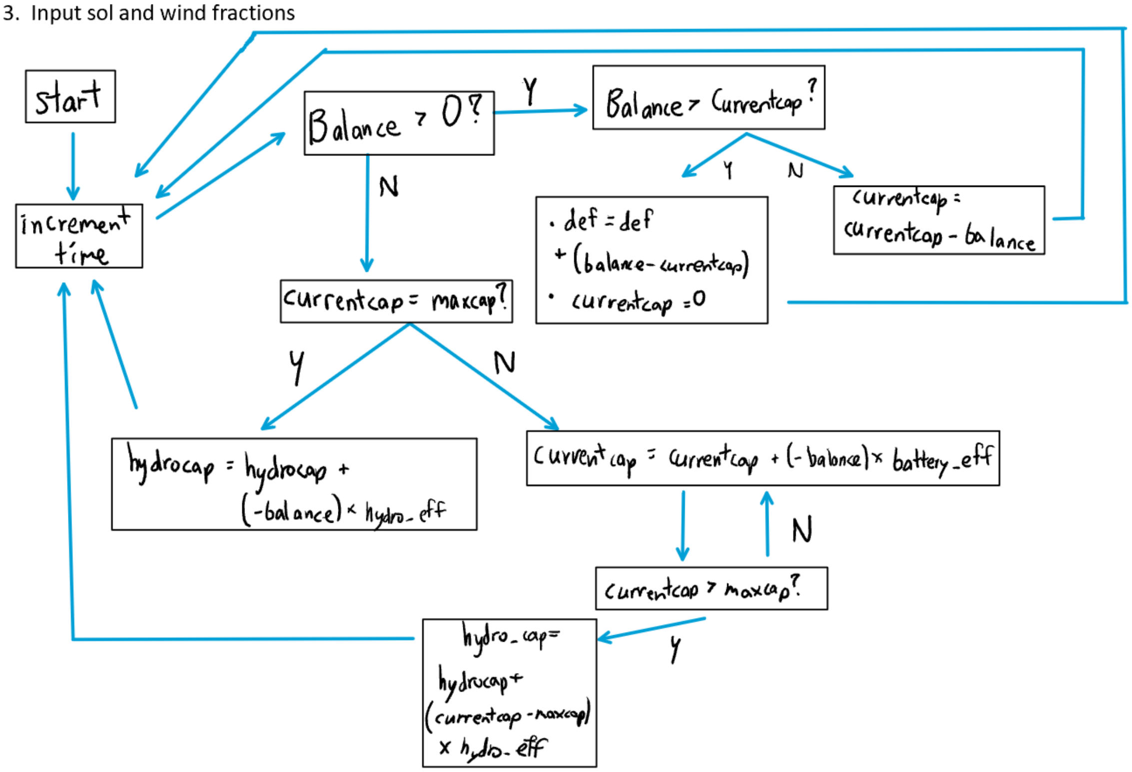

Figure 2: Flowchart of the foundational code used to track battery and hydrogen storage for the three-year period. The code is centered on calculating the balance at each time step and comparing it to the current battery capacity. Spill goes to hydrogen.

Figure 2 shows a basic code flow regarding how hydrogen storage is tracked and filled as well as how deficit is accumulated and how battery capacity is replenished or extinguished. Some unfamiliar terms come into existence in Figure 2, so they will be defined now to ensure optimal understanding of this foundational program. The variables, currentcap and maxcap, deal with how the battery storage is treated in the simulations; currentcap refers to the current storage value at a given time step, while maxcap simply refers to the maximum allowable storage capacity of the battery storage system. Having a set maxcap ensures that the other crucial variables such as deficit energy and spillover energy (energy that is added to the hydrogen storage component i.e., hydrocap) can be tracked. Other key elements of Figure 2 include the outputs and the way in which time is incremented. Each of the variables (i.e., currentcap, deficit, hydrocap) that appear because of the balance calculation are running sums which exemplifies the necessity of the "increment time" block. The simulation runs through the hourly datasets and tabs each increment or decrement to the variables' sums which is then read out and examined after the three years have been completed. It is from this program that we can alter the output details to see how certain gamma or how certain initial storages (currentcap) affect our end-of-year sums and overall results.

Throughout the research process, there was little deviation from this foundational code. Of course, things were changed or added to reflect a certain point in the research process such as changing the code to run over different initial parameters or different values of gamma. At times we wanted to manually input values of storage or have it loop over storage with incremental changes each run. Nevertheless, this so-called "skeletal" program is the foundation for all the work done regarding this study of storage optimization using renewable energy sources.

Results

Seasonal and Regional Variation Studies

Before we delved into the unknown of hydrogen storage and its relationship with battery storage and deficit energy, we needed a better understanding of the time-dependence on the balance energy and the spillover. For each year in the dataset, the balance energy and the spillover were charted for each month to get an average yearly layout of these two variables. To get monthly values, averages were calculated for each hour, such that there would be 24 values in a month. Then, the average hourly values were averaged together to acquire a single value for that given month. We employed this strategy for each of the three years, and the graphs of the results are below, which gave great insight into how these parameters work for a given year.

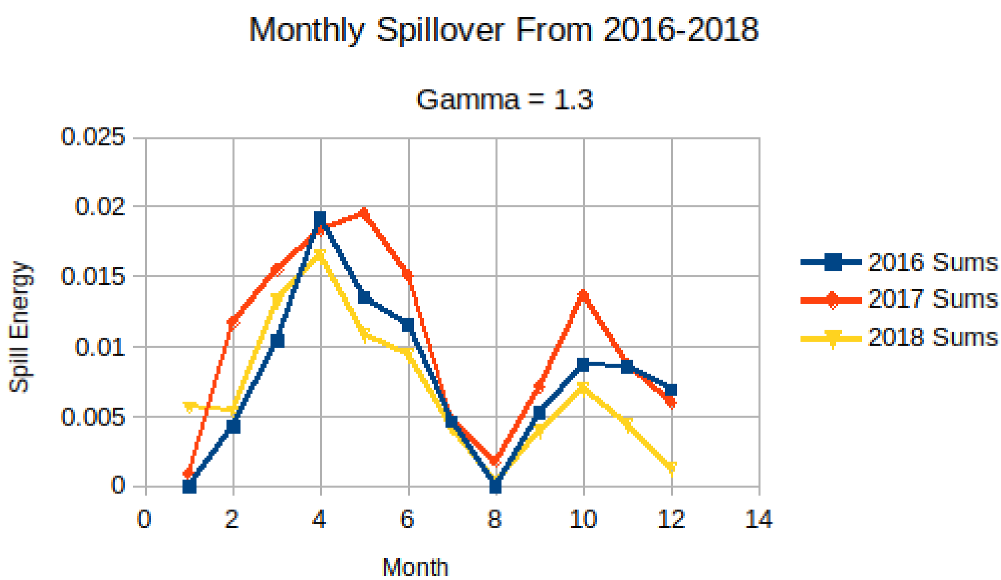

Figure 3: A plot depicting the average monthly spill energy for the three target years.

Figure 3 shows the average spillover for each month for the three years in question. As one can see, each year follows the same shape and trend, which offers a good consistency check with the collected data. The main takeaway from Figure 3 is that the most considerable spillover occurs during the spring and early summer (months 3, 4, 5) as well as during the fall (months 9-11). The presence of this bimodal shape shows that the ideal situation for generating hydrogen storage would be during these two peak times. Charging up long-term storage devices, like a hydrogen fuel cell, allows the possibility of using these kinds of renewable resources because we can constantly be saving energy to be used later when it is desperately needed (at relative minima per Figure 3). If a particular type of natural disaster, e.g., a blizzard, were to compromise any type of established power source (i.e., a power plant), people would be left with no power for days until the proper infrastructure is properly fixed. With this scheme for long-term hydrogen storage and renewable energy inputs, this would no longer be a problem as we simply would transition from traditional short-term battery storage to this new regime of long-term storage.

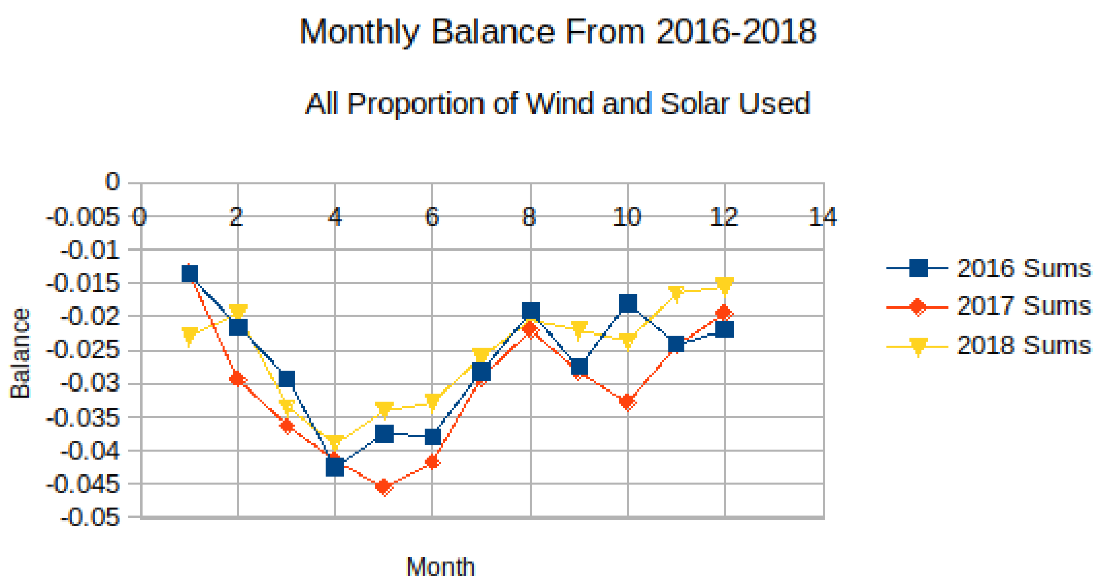

Figure 4: A plot depicting the average monthly balance for the three target years.

On the other hand, Figure 4 depicts the average monthly balance for each of the three target years. The monthly balance results correlate with the average monthly spill graph. The more negative the balance, the more spillover since a negative balance corresponds to the fundamental idea that the solar and the wind meet and exceed the load. This excess fills up the in-place battery storage capacity leaving a spillover.

Alongside this dependence on time, there is a geographical component present that directly affects the wind and solar generation for a given site, which alters the amount of storage required to achieve a given deficit energy (i.e., 0%, 3%, etc.). As aforementioned, the MISO region comprises 15 states, which can be broken down into three regions: North, Central, and South MISO. By creating these regionalized datasets, simulations were run to see the required storage that would leave us with zero deficit at the end of the three years. The results are below, and this graph allows us to make inferences regarding the energy mixes in these truncated MISO regions.

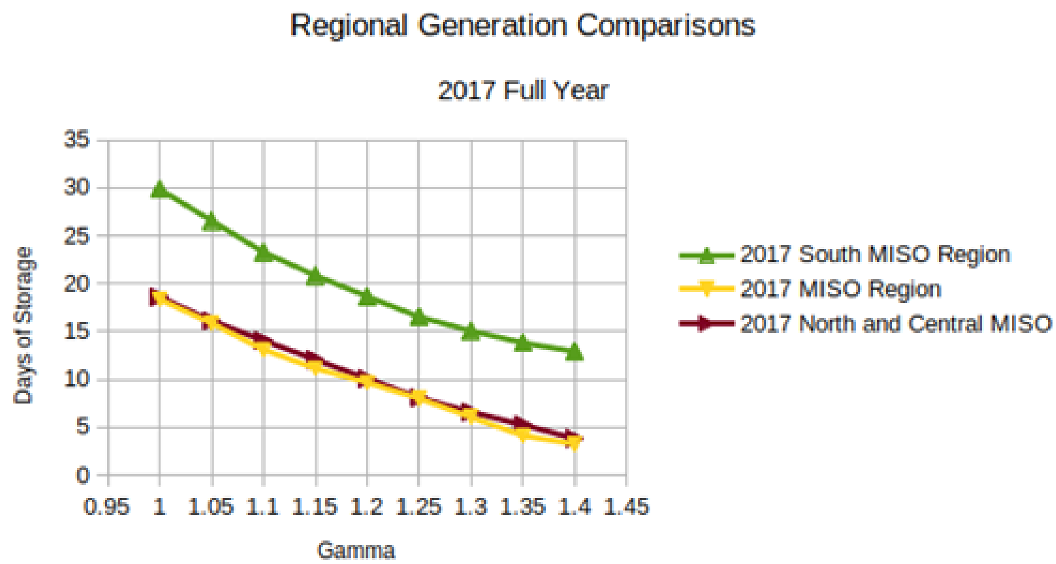

Figure 5: A plot depicting the regional breakdown of the MISO region. These days of storage correlate to a zero deficit energy. Generation based on data from NREL and MISO.

Figure 5 shows values of gamma with equivalent days of battery storage for different geographical datasets for the 2017 MISO dataset. To not much surprise, the South MISO region had the highest days of storage due to their probable lack of wind generation in comparison to the North and Central regions. Despite the higher presence of sun in these areas, the north and central MISO regions perform far better since they have a higher presence of wind which is crucial to the calculation of the balance, deficit, and the spill. Another thing to consider is the type of sunlight that these different regions are getting whether it is cloudless sky sun or overcast sun; perhaps the South MISO region has more overcast sun, which could explain why the South MISO region does not significantly influence the values of storage for the yellow curve, which combines all three regions. The maroon curve shows this case where only the North and Central MISO regions are considered in the simulation meaning that these two regions provide most of the power for the entire MISO region.

Preliminary Hydrogen Investigation

The end goal of this project was to implement a realistic weather event into a simulation that would replicate a period without short-term storage, meaning no access to our traditional power grid, during a high-level weather event. The uncertainty that follows any type of storm that knocks out the traditional power regime is warranted, but the introduction of long-term storage onto the energy scene eradicates the need for worry or uncertainty. If short-term, on-demand power is temporarily unavailable, the presence of long-term storage would seamlessly integrate into the grid, such that there would never be a lapse in power suppliance. Flipping the proverbial switch between short-term and long-term storage would allow customers to always have power even in the darkest of days. In order to investigate this matter of long-term storage integration, some basic calculations and simulations were conducted to get a better feel of how hydrogen storage interacted with our already existing programs of pure battery, short-term storage. Right away, these initial calculations gave insight into the relationship between battery storage and hydrogen storage and how adding hydrogen storage affects the deficit energy for a given value of gamma. Figures 6 and 7 show the preliminary results from these simulations that kickstarted the deeper exploration into our study of polar vortexes and their effects on power generation and storage.

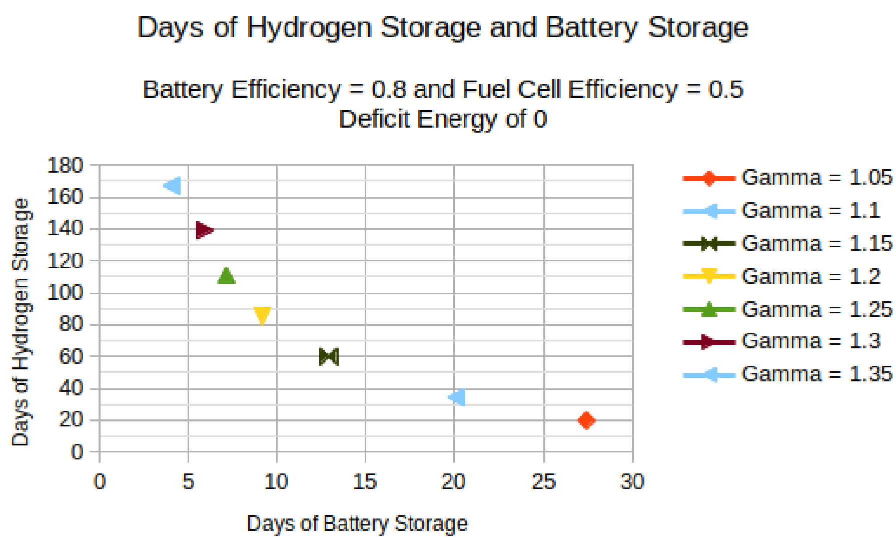

Figure 6: A plot depicting the days of available hydrogen storage against days of available battery storage. Greater gamma corresponds to more hydrogen storage and less battery storage.

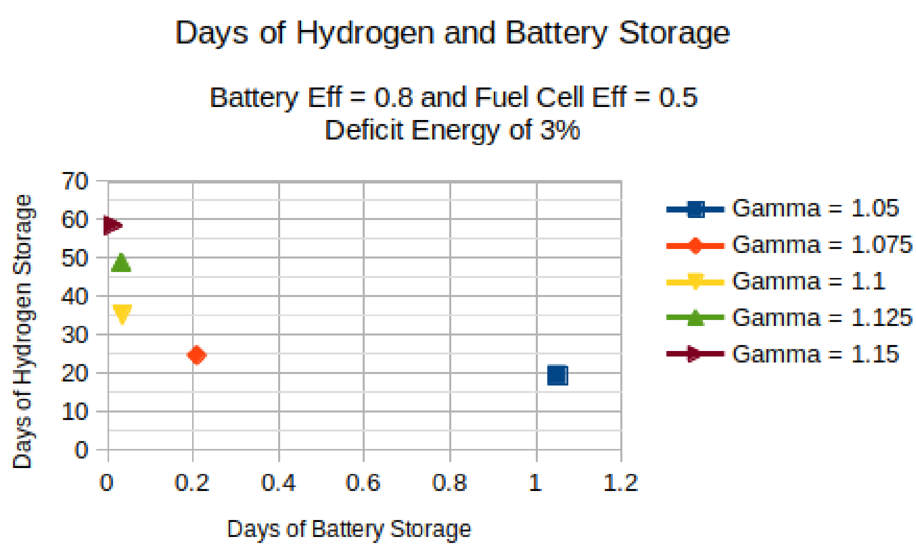

Figure 7: A plot that depicts days of hydrogen storage against days of battery storage. Here, the deficit energy cutoff for the simulation is 3%, instead of 0%. The same relationship holds as seen in Figure 6. Higher gamma means more available hydrogen. The maximum gamma value in this simulation was 1.15 which is lower than the maximum gamma in Figure 7: 1.35. This is because of the increase in deficit energy that characterizes these two different figures. With a deficit of 3%, it only takes up to 15% overgeneration to meet our deficit energy "requirement". It takes much more overgeneration to get to 0 deficit, which is illustrated in Figure 6.

The days of hydrogen were found by using the solar fraction that minimized the battery storage to calculate the hydrogen storage at each time step for the specific value of gamma. Then, the maximum value associated with the hydrogen storage array was taken off the master

26,280 element array (3 years) and multiplied by 365 for us to know the max number of days that we would have hydrogen for that given gamma and deficit threshold. The maximum days of hydrogen increase with increasing gamma meaning we have more storing capability the more we over generate. This all depends on what deficit energy we are trying to obtain. For example, we do not need to generate as much nearly over for a deficit energy of 3% versus a deficit energy of 0 (seen in Figure 6).

Hydrogen and Polar Vortex Studies

Again, the prominent focus of this research was to not only implement the idea of utilizing hydrogen storage in the current electrical grid system but also to simulate a real-world issue to investigate the possibilities of utilizing hydrogen as well as distinguishing short-term and long-term storage. What came out of this query was the polar vortex simulations that allowed us to view the impact of a limited solar and wind generation for two weeks to model a national weather event that would leave the grid compromised to a certain degree. The polar vortex for each simulation occurs from February 1 to February 15 in 2018, an arbitrary selection. Still, it does guarantee that, for different over-generation percentages, the hydrogen storage will fill up in time to match the two-week deficiency in our renewable sources of power generation. We considered four cases for this application study: a standard three-year simulation with no polar vortex, a vortex that has no wind or solar, a vortex with 5% solar/wind generation during the two weeks, and a vortex that has 10% solar/wind during the two weeks. During this two-week vortex period, only the hydrogen storage is decremented, so therefore it is charged up through the spillover to account for this expected loss. The following figures below (Figures 7-9) exemplify our confidence that long-term hydrogen storage would be able to handle disastrous climate events that hinder power output, such as a polar vortex. With only solar and wind power generation, we would be able to withstand a two-week minimum vortex event in any of the following three scenarios (Figures 8-10).

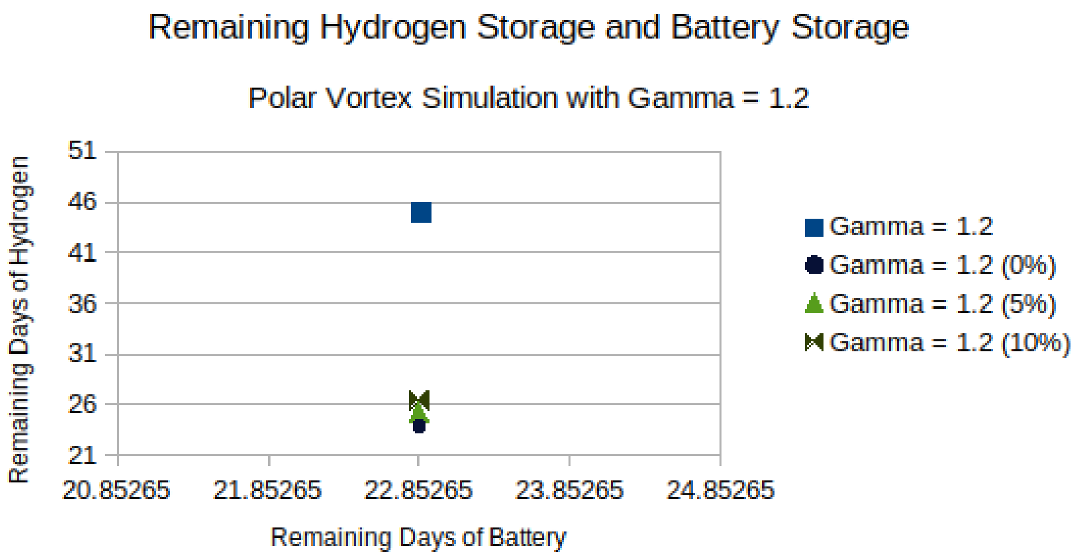

Figure 8: A plot showing the remaining days of hydrogen and the remaining days of battery storage after the 2-week polar vortex event given a gamma of 1.2. The “strongest” polar vortex (i.e., 0% generation) guarantees 26.5 days of hydrogen after the simulation’s end.

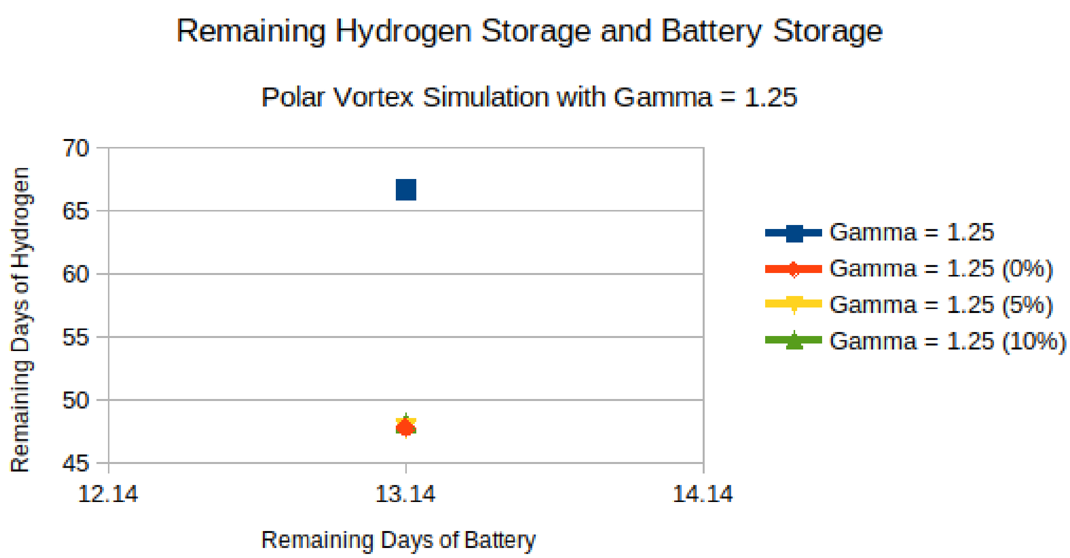

Figure 9: A plot showing the remaining days of hydrogen and the remaining days of battery storage after the 2-week polar vortex event given a gamma of 1.25. The “strongest” polar vortex (i.e., 0% generation) guarantees a minimum hydrogen storage of 48 days.

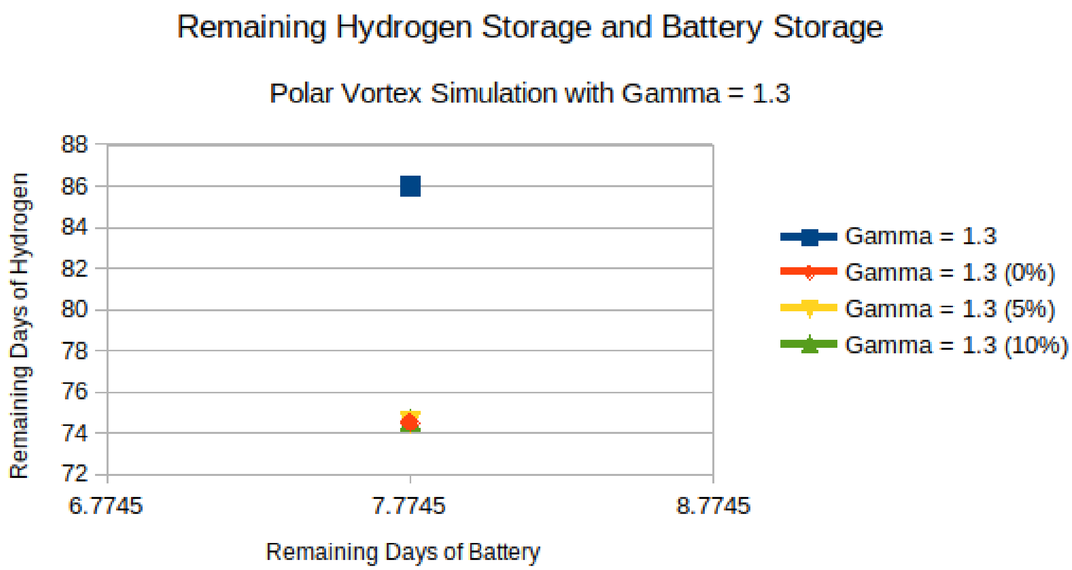

Figure 10 A plot showing the remaining days of hydrogen and the remaining days of battery storage after the 2-week polar vortex event given a gamma of 1.3. The "strongest" polar vortex (i.e., 0% generation) guarantees a minimum hydrogen storage of 74.5 days.

Discussion

Regarding the seasonal variation study, the connection between balance and spill is apparent and crucial to understanding the idea of gamma and overgeneration. The more a powerplant over generates, the quicker our hydrogen fuel cell can store the necessary energy needed to power the MISO region during our forced polar vortex. We see that overgeneration by 30% (Figure 10) leaves us with a minimum of 74 remaining days of hydrogen and ~8 days of battery at the end of the three-year simulation. Based on Figure 8 and Figure 9, when we over generate at less than 30%, the number of remaining days of hydrogen decreases (less comparable spill to a gamma of 1.3), and the number of battery days increases. This seemingly inverse relationship between our long-term and short-term regimes is intriguing but is not that all surprising. The balance is inherently connected to the amount of spill, rather than the amount that goes into hydrogen, so the greater gamma means more hydrogen at the expense of the short-term battery storage since the amount of electrical energy available must always be conserved and equal. What goes into our storage must be consumed either through actual consumption, the hourly load, or as a type of exhaust, i.e., heat, due to the efficiencies of our two storage systems.

An important property of energy is that it is a conserved quantity meaning what goes in must equal what is coming out/being consumed. In preparing the polar vortex studies, setting the initial conditions of the program was perhaps the most crucial step, since the data collected at the beginning of the study never changed; the only true varying components of the simulations were the initial value of storage, the maximum capacity of the battery storage, the efficiencies of the battery and hydrogen storage systems, and the value of gamma and the corresponding proportions of wind and solar generation. Choosing an appropriate, realistic starting value for battery storage was challenging as it required meticulous trial and error to ensure that the battery storage never went to zero or negative as that would collapse the whole reality of the simulation. Deciding to have the initial storage as half of a given maximum capacity allowed the simulations to be more streamlined as now, we can base an entire run based on maximum days of storage i.e., maximum capacity and get storage output for any kind of conditions we wanted to investigate whether it be the desired deficit, storage capacity value, or hydrogen storage value. The beauty of our program is that it can be run for any arbitrary value of any of our defined state variables and output values that pertain to remaining days of storage that can be graphed, analyzed appropriately, and understood in the greater context of this study.

The flexibility of the skeletal program (Figure 2) allowed for the plethora of applications that were covered in this analysis: seasonal variation, regional variation, the relationship between hydrogen storage and battery storage, and most importantly, the hydrogen storage and polar vortex studies. Of course, many approximations were made in the data collection such that the results shown in this paper are not exactly true to precision, but they are still rigorous and show the need for a type of long-term storage to combat the current deficiencies of the current gird regime.

Conclusions and Future Work

Based on the simulations that were done, a complete transition to renewable sources of energy generation is possible on the contingency of developing and integrating long-term storage infrastructure. The process of over generating wind and solar energy allows for storage to be minimized since any spillover energy from the short-term batteries goes immediately into the long-term hydrogen storage. Given the results for the polar vortex scenarios, it is also evident that hydrogen storage and subsequent discharging can handle a 2-week weather crisis when there is no/limited wind or solar availability in the short-term. The more overgeneration there is, the greater opportunity there is for having enough hydrogen to sustain the grid for days, weeks, and even months at any point in time. Higher gamma values mean quicker hydrogen charging which means consumption of hydrogen can be used at a more rapid rate if needed depending on the weather.

There are still several challenges pertaining to this field of grid optimization and renewable energy generation, and it is evident that all the viable solutions and perspectives were not covered in this preliminary report. The cost of storage still needs to significantly decrease such that this delineation of battery and hydrogen storage can be made a reality [1,2]. Further exploration into economics would give a better understanding of the true realism of this conjecture which would allow future simulations to include energy costs which could then be minimized like deficit energy in this research. Another consideration is how hydrogen storage is being charged up; this analysis assumes that all spillover goes directly into the long-term storage designation, but there are most likely other ways this can be done to make the process even more streamlined and efficient. For example, any value of spillover energy could be proportioned such that it is split between the battery and hydrogen storage types to fill both simultaneously. A rising issue that must also be addressed is the rising electrification not only in the United States but also across the globe; there will only be an increase in power demand as products and services require access and service from the grid, and it only makes sense to progressively include renewable generation sources into the grid so that the current plant hierarchy can be eventually phased out [3]. Continuing to rely on antiquated means of power such as coal and other fossil fuels is only a short-term solution. The future of power and electrical storage needs a diverse, renewable portfolio to ensure that electrical grids around the world can become clean and efficient and can keep the lights on during any climatic scenario [3].

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Appendix

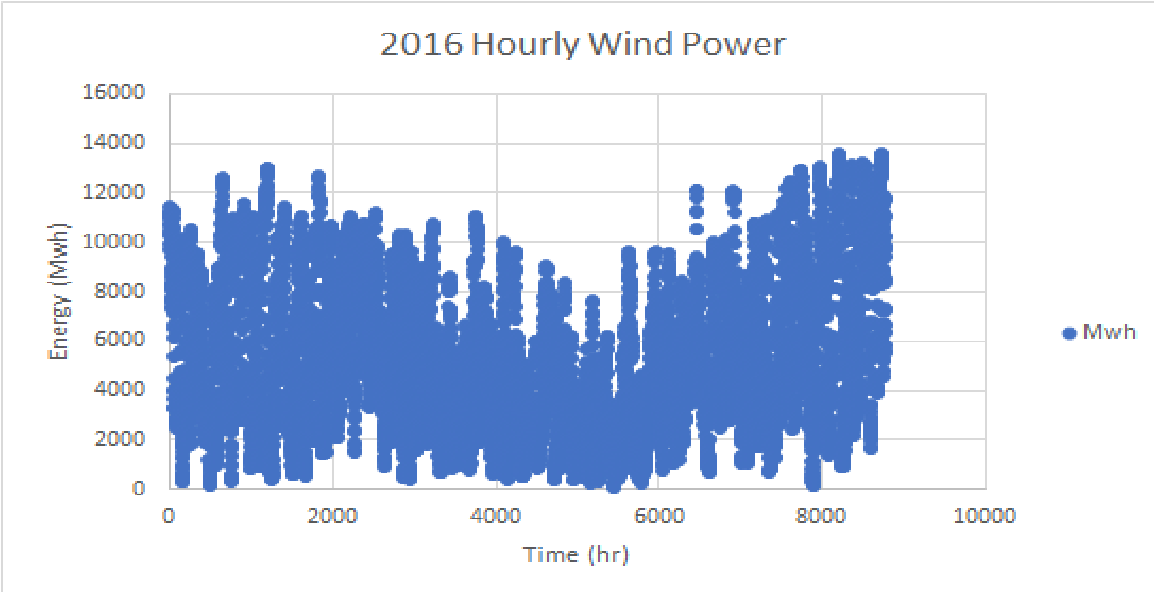

Figure 11: A plot of the hourly wind power generation for 2016. From the MISO database.

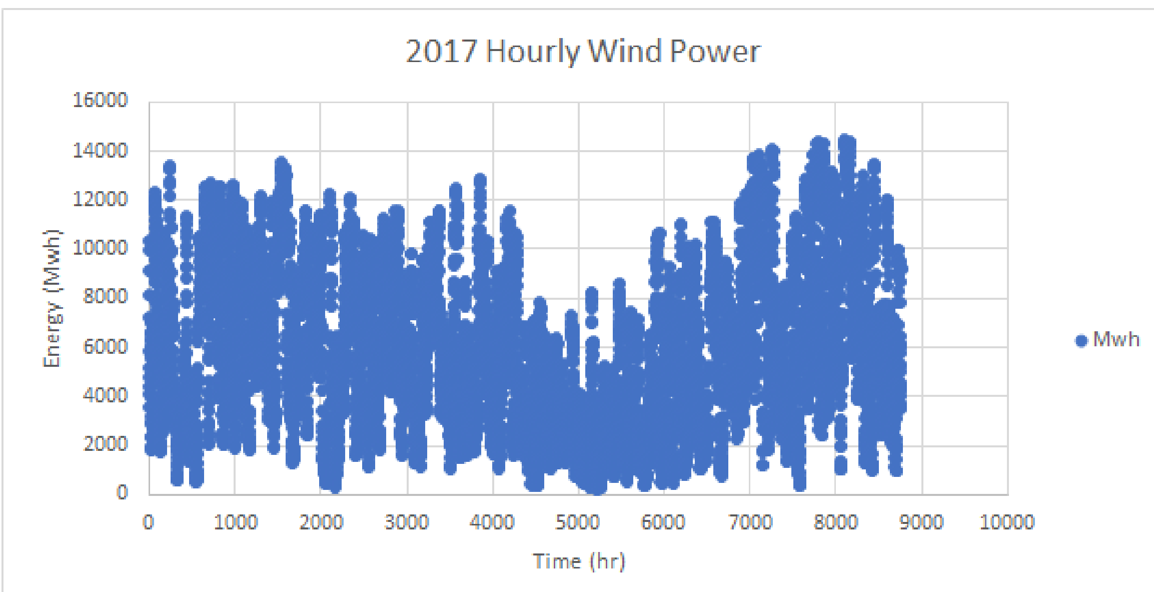

Figure 12: A plot of the hourly wind power generation for 2017. From the MISO database.

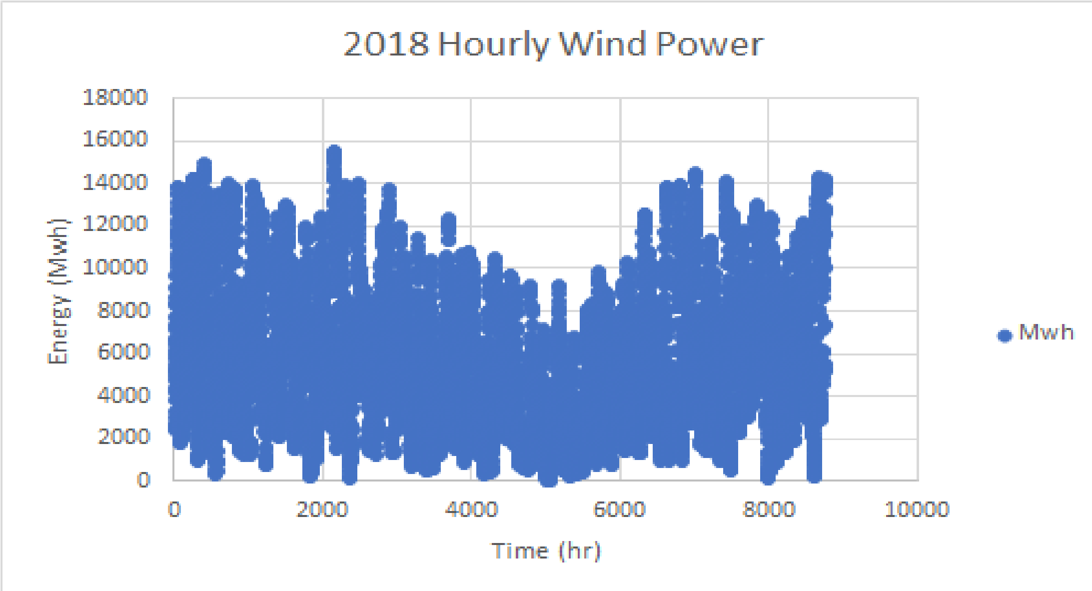

Figure 13: A plot of the hourly wind power generation for 2018. From the MISO database.

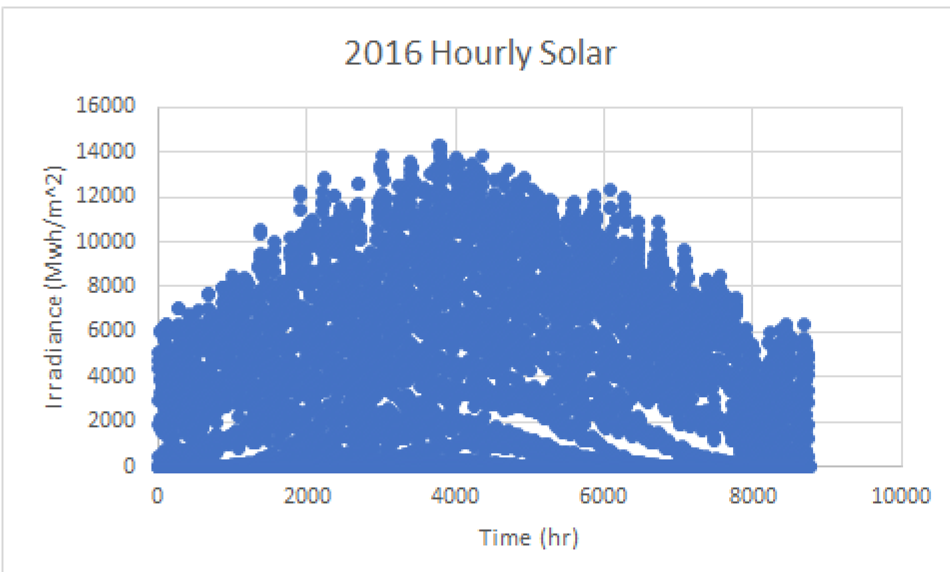

Figure 14: A plot of the hourly solar irradiance for 2016. From NREL.

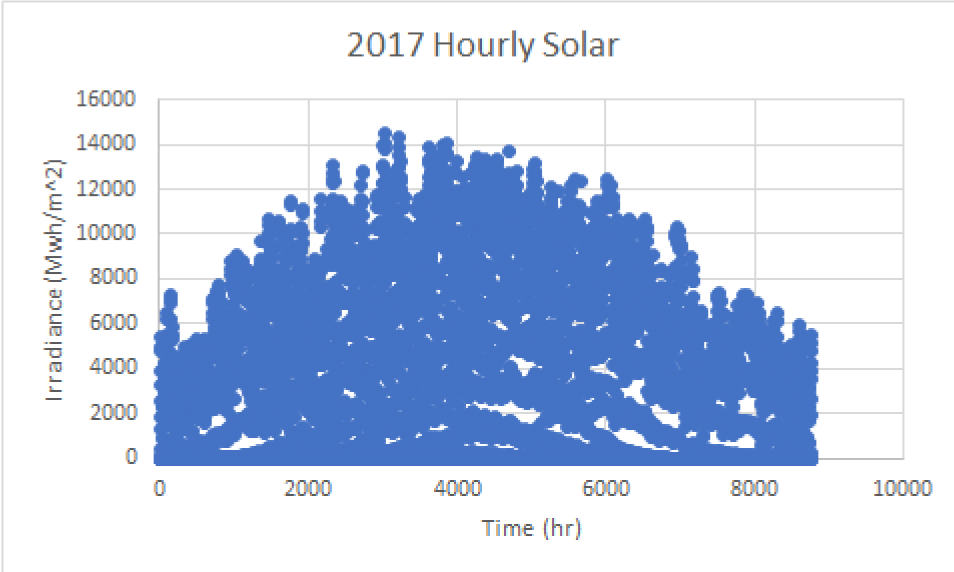

Figure 15: A plot showing the hourly solar irradiance for 2017. From NREL.

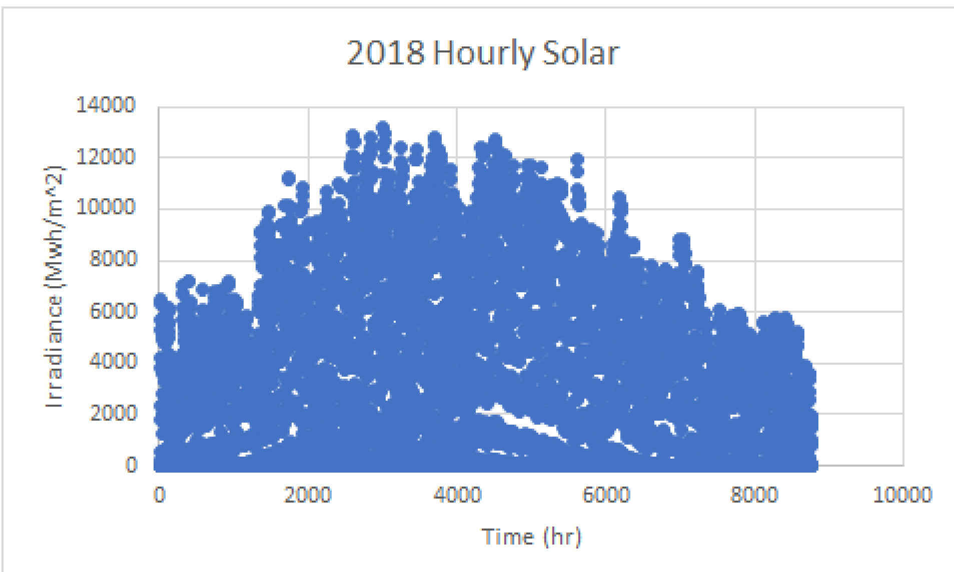

Figure 16: A plot showing the hourly solar irradiance for 2018. From NREL.

Example Program: hydrogen_2_weeks.cpp

```
#include <iostream>
#include <fstream>
#include <stdlib.h>
#include <time.h>
#include <math.h>
```

```
using namespace std;

void InputLoad(double[]); //declares functions for reading in load, solar,
and wind data
void InputSolar(double[]);
void InputWind(double[]);

int main(){

double load[26280];  //declare arrays for load, solar, wind data
double solar[26280];
double wind[26280];
double hydro[26280];

double balance;
double maxcap;
double currentcap; // battery storage
double hydrocap = 0;  // hydrogen storage previously spillover
double def = 0;  // initialize deficit energy sum
double spill = 0; // initialize spill energy sum

InputLoad(load);//reads in load, solar, and wind data
InputSolar(solar);
InputWind(wind);

double battery_eff = 0.8; // charging efficiency for the battery storage
double hydro_eff = 0.3; // charging efficiiency for the hydrogen storage

double totalGen = 0; // initialize running total of generated energy for
the simulation
double totalConsumed = 0; // initialize running total of consumed energy
for the simulation
double heat;

double sol_frac;  // proportion of available wind used
double wind_frac; // proportion of available solar used

cout << "Input solar fraction: " << endl;
cin >> sol_frac;

cout << "Input wind fraction: " << endl;
cin >> wind_frac;

maxcap = .01;
currentcap = .001826;

for (int t = 0; t < 26280; t++)//begin time loop
{
      balance = load[t] - (sol_frac*solar[t] + wind_frac*wind[t]); //
calculates the balance for each time step i.e. one hour
      if (balance > currentcap && balance > 0)  // load exceeds generation
and balance larger than current storage
      {
```

```
            def = def + (balance - currentcap);   // deficit is
continually added for a total after loop
            currentcap = 0;  // storage is drained to 0

      }
      else if (balance <= currentcap && balance > 0)  // load exceeds
generation but balance less than current      storage
      {
            currentcap = currentcap - balance;  // decrease current
storage by value of balance
      }
      else if (balance < 0)  // generation exceeds load thus we get
spillover
      {
            if (currentcap == maxcap)
            {
                  spill = spill + (-balance); // if storage full, excess is
spilled and keep a running total of spill
                  hydrocap = hydrocap + (hydro_eff*(-balance));
                  hydro[t] = hydrocap;
                  if (hydrocap >= .012785)
                  {
                        break;
                  }
            }
            else
            {
                  currentcap = currentcap + (battery_eff*(-balance));
//increase current storage until max
                  if (currentcap > maxcap)
                  {
                        spill = spill + (currentcap - maxcap);//spill if
storage > max
                        hydrocap = hydrocap + (hydro_eff*(-balance));
                        hydro[t] = hydrocap;
                        currentcap = maxcap;  // set current storage to max
storage value after spillover
                        if (hydrocap >= .012785)
                        {
                              break;
                        }
                  }
            }
      }
      else if (balance == 0)  // load equals generation
      {
            currentcap = currentcap;  // all values stay the same for that
time step
            hydrocap = hydrocap;
            def = def;
      }
      else
      {
      cout << "error" << endl;
```

```
      }
} //time loop

for (int i = 0; i < 26280; i++) // time loop for cons. of energy
{
      totalGen = totalGen + sol_frac*solar[i] + wind_frac*wind[i];
      totalConsumed = totalConsumed + load[i];
} // end of energy time loop

totalGen = totalGen + def + maxcap ;// calculates final value for total
generated energy for our system
totalConsumed = totalConsumed + hydrocap + currentcap; // calculates final
value for total consumed energy for our system
heat = totalGen - totalConsumed;

ofstream F1("2_week_hydro.txt");

for (int t = 0; t< 26280; t++){

F1 << hydro[t] << endl;
}

F1.close();

return 0;

}  // main ends

// Setting the real data into arrays

void InputLoad(double load[])
{

std::ifstream infile1("3_year_load.txt");//option to input data from
external text file
double a;
int index1= 0;

    while(infile1 >> a)
    {
        load[index1] = a;

            index1++;
      }
}

void InputSolar(double solar[])
{

std::ifstream infile2("3_year_solar_bysolar.txt");
double b;
int index2= 0;

    while(infile2 >> b)
```

```
    {
        solar[index2] = b;

            index2++;
      }
}

void InputWind(double wind[])
{

std::ifstream infile3("3_year_wind_bywind.txt");
double c;
int index3= 0;

    while(infile3 >> c)
    {
        wind[index3] = c;

            index3++;
      }
}
```