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Large Scale Grid Integration of Wind and Solar Power with Storage

Abstract

The current energy grid in the United States is dominated by carbon intense energy generation methods that are based on production when and where it is required. However, solar and wind power have proved themselves as the most promising carbon free energy generation sources. Due to the unpredictable and uncontrollable nature of energy production from solar and wind, large scale integration of these resources into the electric grid will require robust storage capacity. In this project, we model the energy grid of the Midcontinent Independent System Operator (MISO) energy region with high concentrations of solar and wind power to analyze the impacts on storage, over-generation, base load and cost. Historical load data was taken from the MISO region, while solar and wind data was from the National Renewable Energy Laboratory Solar and Wind Integration Data Sets, all for the year 2007. Our findings show that the necessary storage capacity is significantly reduced when there is over-generation of energy, either from solar and wind or base load. Despite this, due to the falling price of solar, wind and storage technologies, the most cost efficient means of shifting to a carbon neutral energy grid is through the over-generation of wind, solar and storage, without base load.

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1 Introduction

Anthropogenic burning of fossil fuels is the number one cause of greenhouse gas emissions that contribute to climate change today [1]. Without rapid action to decarbonize the global energy grid, the impacts of climate change, many of which are already felt today, will continue to worsen [2]. The most recent Intergovernmental Panel on Climate Change (IPCC) special report on the effects of 1.5^o C of warming found that we have until 2030 to decrease greenhouse gas emissions by 45 percent, and until 2050 to become carbon neutral [3]. If these drastic reductions in emissions are not met, the consequences will be considerable. One of the most promising solutions to limit the amount of greenhouse gas emissions from fossil fuels is a transition to a clean energy grid. These renewable energy options include solar, wind, hydroelectric, bio-fuel and geothermal power. The two most promising of these options are solar power and wind power, since they can be scaled to replace the likes of coal and natural gas, which dominate our energy mix today. In 2009, the levelized cost of energy (LCOE) per MWh of solar power averaged a staggering $360, while wind power was sitting around $135. As of November 2019, these prices had dropped to around $40 and $41, respectively [4]. These prices are expected to continue dropping in the near future, as well as be propelled by any policy actions promoting clean energy such as subsidies or renewable energy credits.

The drawbacks of these renewable energy technologies means that their widespread use requires more than a simple replacement of fossil fuel plants with the clean energy alternatives. The unpredictability of these resources makes it difficult and expensive for their current integration. If the energy mix consisted of high concentrations of solar and wind, it would work great when the sun was shining and the wind was blowing, but there would be frequent blackouts when it was cloudy with no wind. These downfalls of solar and wind power mean that we would have to reshape the way the current energy grid is set up. In order to overcome these challenges, we must turn to storage as a means of capturing the excess energy production during ideal conditions to compensate for the times when there is a deficit. While the levelized cost of storage (LCOS) is expected to continue declining, the current price of these storage techniques remains very expensive [5]. For this reason, and to conserve materials, it is important to reduce the amount of storage required to meet energy demand as much as possible for a carbon-free grid.

There have been many previous studies related to the reduction of the required storage in an energy grid comprised of 100% solar and wind power that provide several means of achieving this goal. To start, drawing power from a large geographical area would reduce the amount of storage [6]. The larger the area of connected wind and solar farms there are to draw from, the more likely it is that there will be ideal conditions for energy generation at any given time period somewhere in this region. Additionally, it has been observed that wind and solar power compliment each other [7]. In other words, there is an ideal mix of wind and solar power that will result in the highest efficiency throughout a day. Over-generation, when the total combined production of wind and solar exceeds the overall requirement of energy for a given time period, has also been shown to effectively reduce storage requirements [8, 9]. Another option, rather than over-generation, is to add small amounts of balance energy, or on demand power (likely from fossil fuels), to meet some of the energy demand [10]. Beyond these methods, there are several other concepts that have the potential to reduce storage, including vehicle-2-grid storage and smart grid concepts.

The goals of this paper are threefold. First, we attempt to create a grid modeling algorithm for the MISO energy region that finds results consistent with previous publications. This would entail the creation of a successful algorithm that models the energy grid with varying amounts of solar and wind power to find the least amount of required storage. This model will specifically focus on the storage reduction techniques of over-generation and the complimentary behavior of wind and solar power. Second, we will evaluate the effects of base load power in addition to wind and solar power on the requirement for storage Base load is the energy requirement that is always needed, 24 hours per day and makes up a large amount of total energy demand. For this work, we will be considering this added base load supply to be nuclear, another valid carbon neutral energy fuel source. Lastly, using our data from the algorithm, we run a simple economic analysis to examine the most cost effective route to an emission free electrical grid. Our key interest in this analysis is whether or not base load power reduces the need for storage in a cost effective way. While our model will make many simplifications, such as ignoring grid stabilization and differences between storage types, it captures the main characteristics of the energy grid, providing a model that is robust enough to run the simple economic cost comparison.

2 Methods

2.1 Data

One of the limits on the accuracy of our model is the quality of the data we run through the algorithm. For this reason, it is imperative that we have both accurate data and a rather short time step between data points. The smaller this time step, the more reliable our data becomes and the more data points we have. One challenge of this data collection is that most recorded weather data for wind speed and solar radiation is only recorded every hour. In order to get around this constraint and find wind and solar data with a time step less than an hour, we must use simulated data that is based on these hourly totals. To assure a high quality of data consistent with the literature, we use the same data in this study as Johlas et al. [10]. There are three separate data sets needed for an energy grid model such as this: load data, solar data and wind data. For our analysis, we use data points gathered from the area covered by the MISO energy region, as seen in Figure 1.

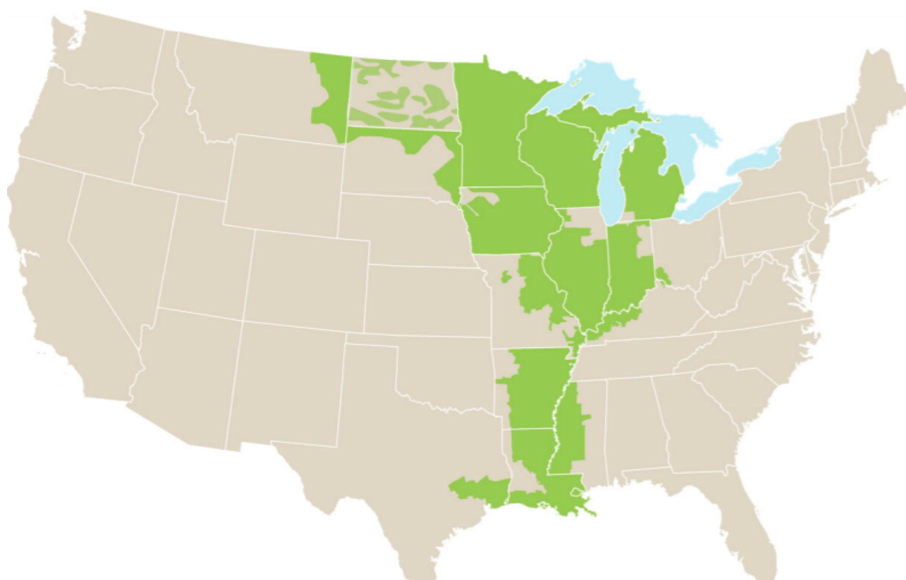

Figure 1: **MISO Energy Region-** Found in North America, MISO accounts for the highlighted region and they are in control of both monitoring the high-voltage transmission system and the energy market within this area. [11]

2.1.1 Load Data

The load energy is the amount of energy that is used by the population at a given time. The value of required load data can vary greatly throughout a single day, allowing us to characterize it into three different categories: base load, intermediate load and peak load.

Base load is the power that is always being generated for 24 hours every day, or the energy that is always required by humans. This is currently produced mostly by large coal plants or nuclear facilities because these types of power generators are slow to react and take a while to ramp up or ramp down, so they are simply left on all the time to meet this base load. Intermediate load, or load following, is similar to base load in the fact that it does not need to ramp up or down all that quickly. Rather, it is the load that is constantly required throughout the daytime, largely determined by the workday. Intermediate load is also highly seasonal due to the additional energy from heating or cooling buildings during warm or cold seasons. The last category is peak load. Peak load is characterized as the highly variable load that changes drastically during the day and is needed to fulfill energy requirements at the maximum energy usage times. This is currently matched with smaller power plants that are quick to ramp up when they are needed. It is this component of load that is responsible for a large part of the needed storage with high concentrations of wind and solar since it is unlikely that wind and solar production will peak at the same time as the peak load every day. A generalized plot of load energy can be seen in Figure 2.

For our load data we use actual data for the year 2007 in the MISO energy region. This data is in time steps of 5 minutes for the entire year. The raw data is recorded in Megawatts and can be downloaded from the MISO website. In order to avoid discrepancies, such as units, between this load data and our wind and solar data, the load data is normalized such that the entire sum of load for the whole year is equal to one. This new data is now unit-less and simply shows the general pattern of load data during 2007, rather than actual Megawatt values.

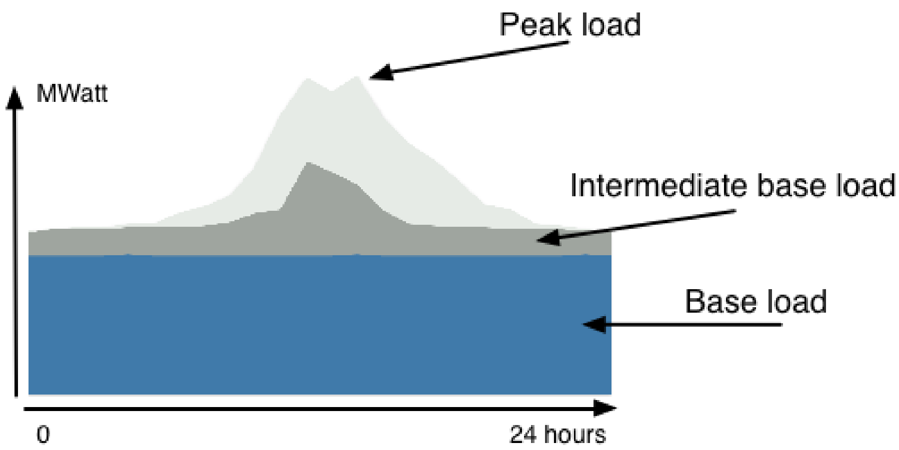

Figure 2: **Typical Load Curve-** A basic schematic showing the variation in base load, intermediate load and peak load throughout the course of a day. As is clear from the plot, load energy is highly invariable allowing for consistent generation techniques, while intermediate energy and peak energy require other means of power generation [12].

2.1.2 Solar Data

The solar data for this project is collected from the same region as our load data (MISO). However, there are some important distinctions between the two. Unlike our load data, the solar is not real time measurements of how much solar energy was being produced at a given time, rather it is how much solar energy potentially could have been harnessed at said time. This is important because theoretically, the entire region could be covered over by solar panels, which would generate way more energy than would be needed. Instead, the focus of the solar data is to get an idea of the actual trend of solar radiation and how it will align with our load data. Therefore, the solar data is based on real meteorologic weather patterns for the year 2007 in the region of interest. This real time meteorologic data, which was recorded hourly, was then used to simulate five minute data points by researchers at the National Renewable Energy Laboratory (NREL) [13]. This simulated data is open sourced through NREL's Solar Integration Data Set. This simulated data is unit-less and can not be completely accurate (because it is simulated), but since we are after higher resolution data and the more general pattern of solar fluctuation as a whole, the data set will suffice for good results.

Like the load data, the solar data is also normalized so that the entire data set for a year is equal to one. This provides several advantages when performing our analysis. First, this allows for the solar data to match the load data in overall scale, avoiding the issue that the initial data is based on how much solar potential there is rather than how much we could feasibly harness. The data remains unit-less and is now simply a model of the average pattern of solar potential in our region. Normalizing the data to one also allows us to introduce a generation factor, γ. The generation factor is rather straight forward, but is a key component to our algorithm and storage reduction analysis. If we have a γ of 1, then the combined wind and solar for the entire year will equal the entire load for the year. Therefore, over the entire year we will have solar + wind = load, but at any given time step, this will not necessarily be true. If the γ were 1.5, then we would be generating 1.5 times the load data with wind and solar, or, in other words, over-generating by 50%.

2.1.3 Wind Data

The wind data that was used for our model has similar characteristics to the solar data. Like the solar data, it is not a real time measurement of the amount of wind power produced, but how much wind potential there is in the region. Once again, the focus of this data is rather to observe a typical pattern of wind potential rather than the exact measurements. Our wind data comes from NREL's Wind Integration Data Toolkit that is open sourced. Like the solar, it is based on hourly data that was used to simulate five minute intervals, providing a unit-less yet high resolution data set that allows for high quality results. The wind data is then normalized in the same fashion as the solar data, so that it remains unit-less, is equal to one, and shows the general trend of wind potential throughout the year. This allows for the generation factor to fluctuate however we see fit between wind and solar. Since the total amount of wind + solar = 2 (both are normalized to 1), we can split the wind and solar up in any combination as long as they equal γ. So if we want to examine a γ of 1, with 40% coming from solar, the arithmetic is quite simple; 0.4(solar) + 0.6(wind) = 1.

2.2 Algorithm

The purpose of our algorithm is to recreate a model that is consistent with published literature accurately showing the complimentary nature between wind and solar power, as well as over-generation. In addition, our algorithm will study the impacts of base load power in the energy grid. All programming was completed in C++.

Before discussing the logical flow of the algorithm, we must define the key variables that are used. Our first variable is gamma, γ, which will be used to determine how much energy is being produced from wind and solar for a given sequence as well as signify if there is any over-generation from wind or solar. Another variable that has already been touched upon is solar percentage, P_s. This value determines how much of the generation factor is met using solar power. Solar percentage is also used to determine the wind percentage using Equation (1), where P_s is percent solar and P_w is percent wind.

$$P_w = 1 - P_s \tag{1}$$

The final key variable for the algorithm is beta, β. The variable β is power production that is set constant throughout the entire year in an attempt to mimic base load power as discussed in Section 2.1.1. For the purpose of our algorithm, it does not matter where we consider β to come from (i.e. coal, gas, hydroelectric, etc...), but for our economic model we will assume it is nuclear power since nuclear acts as a very good base load power generator and remains carbon free. We calculate β by simply setting it equal to a desired portion of the total load for the year; if we have a β of 0.5, then we are generating the equivalent of 50% of the load for the entire year from base load. It is important to note that γ can depend on β, so if we have a β of 0.5 and a γ of 1.0, 50% of our γ comes from β. The premise for the algorithm is quite simple, and is outlined in the steps below.

1. Input the desired values of the key variables for this sequence, including γ, P_s and β.
2. Update the solar and wind data based on γ and the corresponding P_s and P_w.
3. Compare the load, solar and wind data at each 5 minute time step, along with β.
    i. if β + (solar + wind) = load, move to next time step.
    ii. if β + (solar + wind) > load, move excess power to storage.
    iii. if β + (solar + wind) < load, draw from storage.
4. Record results for each time through the data after changing the variables.

Since our wind, solar and load data are unit-less, so too are the resulting storage values. For this reason, we compute it as days of storage where one day of storage is total load (or 1.0, since it is normalized) divided by 365 days, which is equivalent to 1/365 of the entire load for the year. This allows us to measure the storage as a fraction of total load. From running our data through this basic algorithm we will be able to gather many different variations on required storage, most important among them for our purposes are the combinations of P_s, P_w, β and γ that minimize the amount of storage that would be needed to have a fully carbon neutral energy grid.

3 Results

From the algorithm outlined above, we were able to evaluate many different solar, wind, base load and storage scenarios. Figure 3 shows the results for a γ of 1.0 with varying values of P_w, P_s and β. The plot shows the minimum values of storage for different mixes of wind plus solar percentage and base load percentage. It is clear that the overall storage requirement increases as the fraction of solar plus wind increases. The lowest required storage occurs when only 10% of power is produced from wind and solar and 90% of power is produced from base load. We speculate that this is because a modest amount of solar power is useful in meeting some of the daytime peak load. Despite this, the addition of base load power is clearly demonstrated to reduce the amount of storage required for a grid that has high concentrations of wind and solar power.

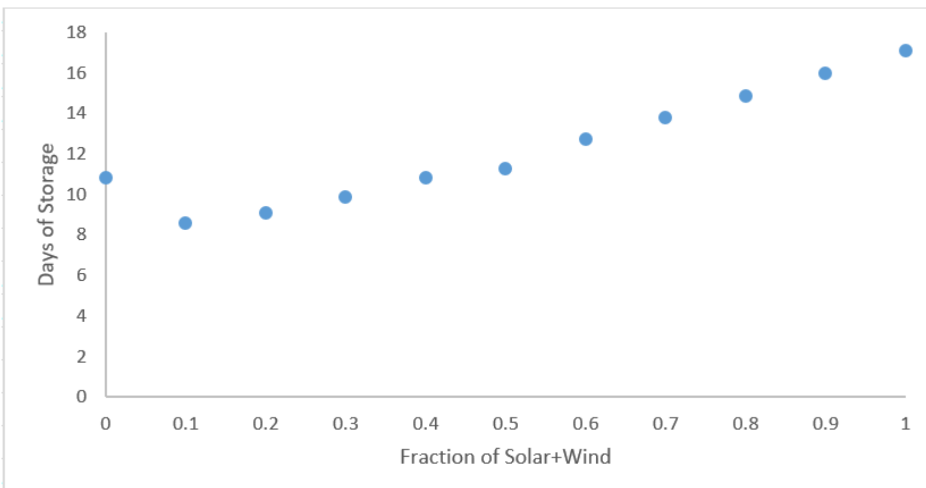

Figure 3: **Storage Capacity versus Solar Percentage for Varying Base Load Percentages-** The minimum storage capacity needed to make balance energy equal to zero for different fractions of solar plus wind and base load power. For example, when the fraction of wind plus solar equals 0, all power is produced from base load.

We were further able to reduce the amount of required storage by providing over-generation. This result is shown in Figure 4. Our results, which show that storage requirement is drastically reduced when there is over-generation, are consistent with prior literature. Since there is over-generation, some amount of energy throughout the year will be spilled, or wasted, so it is not the most energy efficient solution. We find that even at small amounts of over-generation, the equivalent days of storage drops considerably. For example, an over-generation of 30%, or $\gamma = 1.3$, drops the storage amount from roughly 17 days to below 3 days. From the figure, it is also clear that the storage requirement is less when over-generation comes from base load rather than wind and solar.

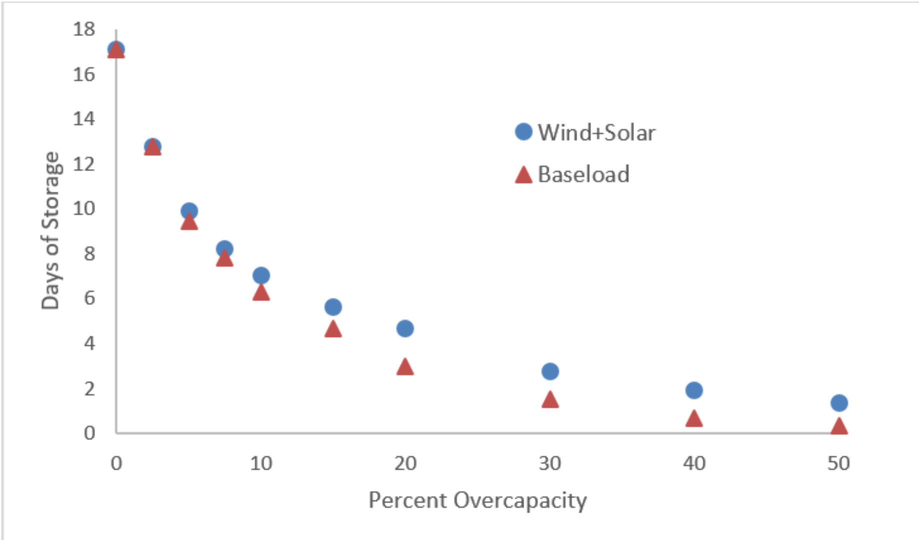

Figure 4: **Storage Capacity for Over Generation from both Base Load and Wind plus Solar-** The minimum storage requirements when there is over-generation from either wind plus solar or base load.

As our results from Figures 3 and 4 show, the addition of base load power to the energy mix reduces the amount of storage. However, an important consideration is the overall cost of the combinations. For the cost comparison, we use nuclear power as the energy source since it is a viable, emission free source of power. The prices used are found in Lazard's LCOE and LCOS reports [4, 5]. In Figure 5 we show the cost of energy where γ is equal to 1.0 with differing percentages of power from solar plus wind and base load. Due to the high LCOE for nuclear, the cheapest option is when there is no base load power in the energy mix. The difference in price for no base load power versus 100% base load power is extreme; it is roughly 3 times cheaper to have no base load power from nuclear in your energy mix. This is most likely because, even at the highest amounts of storage we found (about 17 days), that is a mere 5% of the year so it is really not all that much. In contrast, most of our comparisons for nuclear used a percentage far above this. All told, we would simply need much more nuclear than we would storage, so the price gets driven up.

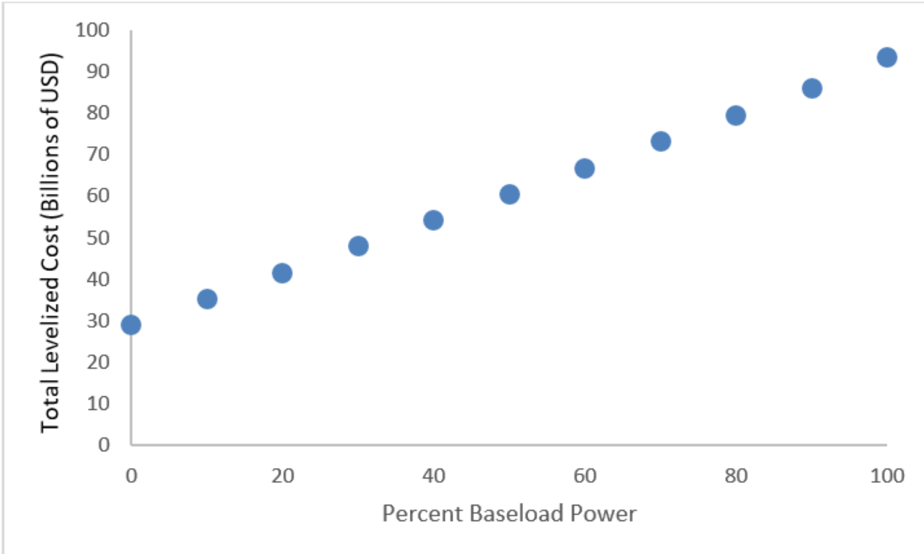

Figure 5: **Levelized Cost of Energy plus Storage as a Function of Base Load Power Percentage-** The estimated LCOE plus LCOS with varying percentage of power coming from base load, or nuclear. Each data point includes both the LCOE and LCOS associated with it added together for total levelized cost. The results show that the price increases linearly as the amount of base load is increased.

Figure 6 shows similar results as Figure 5. We find that it is more expensive to rely on nuclear rather than wind plus solar and storage when using over-generation. From Figure 4, we know that as we increase over-generation, from either wind plus solar or base load, the storage requirement decreases drastically. We then find that over-generating with nuclear power would more than double the cost, whereas over-generation from wind plus solar and storage would would actually the reduce the cost.

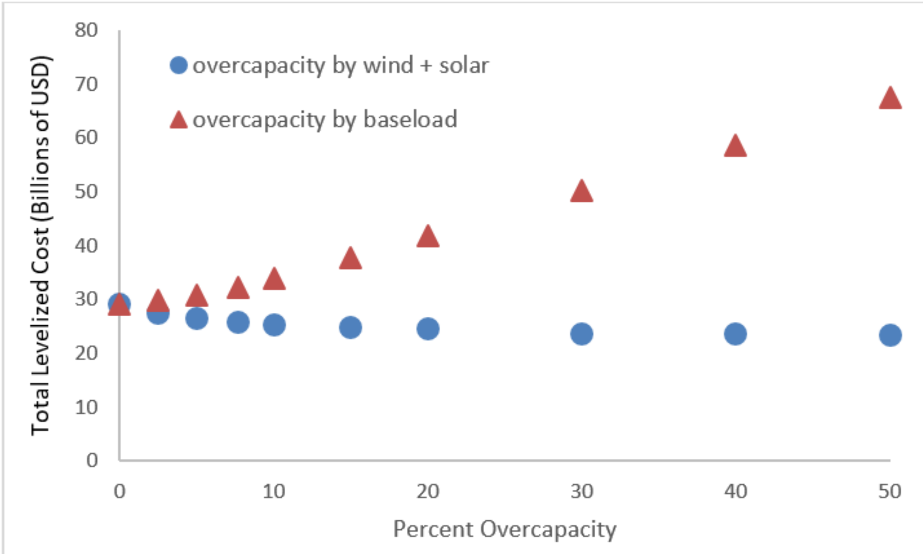

Figure 6: **Levelized Cost of Energy and Storage with Over Generation-** The estimated LCOE plus LCOS with over-generation. Like 5, the data points show total levelized cost and include both LCOE and LCOS. It is clear that over-generating from nuclear increases the overall cost of energy, whereas over-generating from wind plus solar and storage decreases the overall cost of energy.

4 Conclusion

In conclusion, the three aforementioned goals of the project were met successfully. We were able to recreate an algorithm that was consistent with previous studies, showing the trend of storage with differing values of wind and solar as well as over-generation. Additionally, the effects of base load power either as over-generation or as a part of our γ factor were studied. It was shown that the addition of base load power reduces the required storage for almost every combination of the energy mix. Lastly, a simple economic model based on the LCOE and LCOS was completed. The economic analysis found that, due to the high cost of nuclear power, the most cost effective route to a carbon free energy grid is when there is no power generation from nuclear; or when $\gamma = 1.5$ and all the power is met using wind and solar. Future work on this project could include an in depth analysis on the more specific type of storage utilized in an energy grid comprised of high wind and solar (i.e. fuel cells, batteries or super-capacitors), and their most efficient combinations for use in large scale grid storage. Additionally, it is important to consider whether decentralized storage (storage capacity at individual wind and solar farms) or centralized storage (large storage facilities used by many wind and solar farms) would work best. The limitations of this project include the data used. While this data gave a very good typical trend of wind, solar and load, it comes from the year 2007 and there is a high chance that our energy consumption and weather patterns have shifted since then. There are also several simplifications made in our algorithm, such as ignoring grid stability or any grid inefficiencies (such as transmission).

5 Acknowledgments

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