ADDRESSING RESOURCE INTERMITTENCY THROUGH CO-LOCATING UTILITY-SCALE WIND AND PV SYSTEMS: STRATEGIES FOR MEETING REGIONAL ELECTRICAL DEMAND WITH RENEWABLE ENERGY

A Thesis
by
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Submitted to the Graduate School
Appalachian State University
in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE

May 2017
Department of Sustainable Technology & the Built Environment

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Abstract

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This thesis identifies and analyzes the benefits of co-locating wind and PV power production technologies. To analyze the benefits of co-locating wind and PV power production technologies, a novel empirically driven economic optimization model was developed. The optimization model determines the lowest possible cost system consisting of wind, PV, and storage capacity that meets the required load and energy reserve margin for any selected location. The optimization model also assumes a 100% renewable energy environment.

In a 100% renewable energy environment, the total sum of power a technology can produce is only one factor. A technology's consistency and variability of power production, the timing of its power production in comparison to peak loads, and its cost are also significant factors in determining a location's optimal combination mix of renewable energy technology capacities.

The main goal of this model is to always meet load demand for the least expensive cost. A mix of renewable energy technologies that can always satisfy load demand at exceedingly high probabilities, and do so at the lowest expense, should be preferred.

Acknowledgments

First, and foremost, I would like to thank God. Without God's support, not one word of this thesis would have been possible.

In addition, the never-ending support of my graduate adviser and thesis chairperson, Dr. Marie Hoepfl, has been truly invaluable. Marie, you are the Michael Jordan of editing—a true inspiration to writing clearly, thoughtfully, and accurately. Also, you have guided me with ingenuity, proficiency, and insurmountable hours of hard work throughout my entire graduate student experience. In summary, you have supported me in a countless multitude of ways. Thank you, Dr. Hoepfl. You truly are the glue.

Brent Summerville, thank you for being you. The world is a better place because of you, and I am fortunate to consider you my friend.

Last, but certainly never least, thank you Dr. Brian Raichle. Your unique perspectives and guidance on a myriad of complex renewable energy topics has allowed my thesis to excel beyond the reach of my own limitations. Brian, you have an incredible gift of being able to see complex systems from a variety of perspectives, all at the same time! It is almost magical. Our conversations have been extremely appreciated. Thank you!

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CHAPTER 1: INTRODUCTION

Introduction

Over the last six decades, our global environment has witnessed increases in temperature (National Centers for Environmental Information [NCEI], 2017) that many individuals attribute to the increase in fossil fuel carbon emissions (Boden, Marland, & Andres, 2010). One analysis attests that CO_2 levels have never been this high in the entire history of human civilization (Climate Central, 2013). It is widely believed that human activities associated with the Industrial Revolution are the cause for the increases in these bellwether environmental attributes (Intergovernmental Panel on Climate Change [IPCC], 2007).

Given that approximately 78% of the world's total energy generation comes from duration-limited sources such as coal, natural gas, and nuclear plants (International Energy Agency [IEA]), 2015), renewable energy technologies have been replacing fossil-fuel burning as means of energy generation since the 1960s (ProCon, 2013). Accentuating the trend of renewable energy technologies replacing their fossil-fuel counterparts, 41 of the United States' 50 states and five permanently inhabited territories have enacted binding renewable portfolio standards (RPS), or have adopted voluntary renewable energy targets (National Conference of State Legislatures [NCLS], 2017). Twenty-nine states have legally binding RPS laws that collectively apply to 55% of total U.S. retail electricity sales (Barbose, 2016). A RPS is a regulatory mandate to increase energy production to a specified level from renewable sources such as wind, solar, biomass, or other alternatives to fossil and nuclear generation (National Renewable Energy Laboratory [NREL], 2015). A legally binding RPS requires retail electric suppliers to supply a minimum percentage or specified amount of their retail load from eligible sources of renewable energy (Barbose, 2016).

The current most widely supported renewable energy sources are solar and wind. In 2016, the United States solar market nearly doubled its annual record by installing 14.6 GW of new solar photovoltaic (PV) power (Munsell, 2017). This newly installed 14.6 GW of solar PV equated to 39% of all new power brought online in the United States in 2016. Accompanying this massive arrival of new PV power was 8.2 GW of additional wind power (Hill, 2017), which equated to 29% of all new installed power in the United States in 2016 (Munsell, 2017). Combined, solar and wind development therefore represented 68% of new installed power, with coal, natural gas, hydro, and other renewables making up the remaining 32% of added power in 2016. Of the non-solar or non-wind renewable energy sources, only hydro added more than 1 GW of new power in 2016. Other renewable energy technologies (geothermal, biomass, biogass, waste-to-energy) did not add any new power greater than 1 GW due to the lack of long-term policy support (Bloomberg New Energy Finance [BNEF], 2017).

Fueling new power momentum from solar and wind are a trio of governmental policy support mechanisms: Investment Tax Credits (ITC), Production Tax Credits (PTC), and state RPS policies. Federal ITCs and PTCs are primarily used as renewable energy project funding mechanisms, whereas individual states use RPS policies to provide a fundamental framework for future renewable energy goals. The RPS frameworks apportion targets for various types of renewable energy technologies, but their focus is mostly on wind and solar.

Statement of the Problem

Weather conditions and patterns, along with topography, are some of the most important factors in determining the reliability of power production from renewable energy technologies, especially PV and wind. Solar irradiance is more abundant in the summer and during the day. Conversely, solar irradiance is less available during the winter and is non-existent at night. This means PV panels only produce power between the hours of 8:00 a.m. and 8:00 p.m. at maximum during the summer, and 9:00 a.m. to 5:00 p.m. during the winter. Wind speeds are higher in the winter due to stronger convection patterns, and wind is more likely to be present at night. In summary, the two weather patterns complement each other and their respective power producing technologies can be co-located within a region to work in tandem to increase the reliability of renewable power production. Increasing the reliability of renewable power production decreases the intermittency of renewable power production. Decreasing the intermittency of renewable power production reduces the amount of negative net load hours. Reducing the amount of negative net load hours results in lower required capacities for renewable energy generating and storage technologies. Renewable energy systems that require less energy generation and storage capacity cost less money to implement and maintain, and thereby save resources.

Unfortunately, research indicates that state RPS target levels have been primarily influenced by an inter-state diffusion effect, the cost of electricity, and state government ideology (Helwig, 2014). According to Helwig (2014), a state's actual renewable energy potential capacity was only a minor influence on RPS targets. Although many of the states' RPS policies call for a diverse mix of renewable energy technologies, not a single state RPS cites a specific analysis that governs their renewable energy technology target mix (NCLS, 2017). Furthermore, no RPS sets goals for the magnitude or type of renewable energy storage capacity required to accompany the high penetration percentage of intermittent renewable energy stated in their RPS (NCLS, 2017). Confirming this lack of RPS analytical support, Mark Jacobson stated, "no set of consistently-developed roadmaps exist for every U.S. state" (Jacobson, 2015, p. 2094).

In summary, RPS legislators need a comprehensive optimization model to guide in the structuring of renewable energy technology (wind, solar, storage) target levels. A renewable energy optimization model applicable to any region's environment would help ensure all funds allocated to improving environmental energy generation are allocated appropriately based on sound scientific research.

Many previous studies (Yang, Lu, & Burnett, 2003; Saheb-Koussa, Koussa, Belhamel, & Haddadi, 2011), have discussed and modeled the feasibility and appropriate sizing to load of small off-grid hybrid PV/wind projects within a particular fixed area's weather conditions. However, full-year models that identify the optimal solar, wind, and storage mix for an entire region's load profile, while attributing cost parameters to each technology that vary according to the specified region, are far less prevalent.

Purpose of the Study

In recent years, due to increased capacity factors of renewable energy technologies and a significant drop in PV panel prices, the installed and annual maintenance cost of utility-scale PV and wind systems is close to parity (Lazard, 2015). Now that the two technologies' costs are more aligned, capitalizing on the complementary nature of solar and wind's diurnal and seasonal weather patterns to increase the reliability of power production makes more economic sense. The complementary nature of when PV and wind systems produce power can help energy utility companies mitigate the problems of intermittency that plague single-source renewable energy technologies — PV only producing power when it is sunny, wind turbines only producing power when it is windy. More reliable and continuous power production helps energy utility companies meet the steep peaks in their demand curves and reduces their reliance on energy storage (Supriya & Siddarthan, 2011). Pattison (2010) found that co-locating hybrid PV/wind systems dropped times of no energy production by 50% or more.

In addition, co-locating an optimal mix of utility-scale PV and wind projects within a region may be beneficial for state legislatures and energy consumers. State legislators would benefit two-fold: one, by being able to disclose to their constituents that the renewable energy targets in their RPS policies are drafted based on scientific research, and two, because the tax credits currently funding renewable energy projects would be properly allocated to ally with scientifically sound RPS technology target levels. Energy consumers would benefit from a healthier environment based on an optimized mix of renewable energy technologies that is produced at the lowest possible monetary cost.

The purpose of this study was to develop a method for optimizing co-located solar, wind, and storage technology capacity levels that will result in a minimal total system cost for a specified region's weather pattern and load profile.

Research Questions

1. What is the optimal mix of utility-scale wind, PV, and energy storage capacities for a given regional weather pattern and load profile?
2. What are the generating and storage capacity differences between an economically optimized 100% renewable energy generating system and our current system?
3. What is the 30-year Levelized Cost of Energy (LCOE) of an optimized 100% renewable energy system?
4. Where are optimal candidate sites in the United States for co-located PV and wind systems of similar capacity?
5. Where are optimal candidate sites in the United States for renewable energy technology systems comprised of mostly PV?
6. Where are optimal candidate sites in the United States for renewable energy technology systems comprised of mostly wind?

7. Do the results of my optimization model reveal any unusual data or patterns that contradict any currently accepted industry norms regarding where to develop PV or wind systems, or the combination of both technologies?
8. What are the implications for optimal system size, storage size, and technology mix when assuming a no reserve margin requirement?

Definition of Terms

Co-located – a wind and PV project occupying the same specified geographical region.

Opposite phase generation – power being produced at a particular time by one technology while the other technology is dormant.

Productivity – reliability of power production and total energy generation.

Intermittency – the state of not producing continuous power.

Limitations of the Study

First, this study did not address the regulatory environment of every state. State renewable energy regulations vary widely and can have significant impacts on decisions about whether to develop a renewable energy project in a prospective area. This consideration was outside the scope of this study.

Second, the optimization model results are limited to weather and load data availability. The United States encompasses a wide range of weather patterns and regional load profiles. In particular cases, the available regional load profile dates do not match the weather data dates. In these cases, careful attention was paid to match the available load profile dates to weather data dates on a seasonal basis. For example, given a particular region, if the only available load profile dates ranged from July 1st, 2015 to June 30th, 2016, while the only available weather data dates ranged from January 1st, 2015 to December 31st, 2015, the load profile dates of January 1st, 2016 to June 30th, 2016 were conjoined with the July 1st, 2015 to December 31st, 2015 load profile dates and compared to the January 1st, 2015 to December 31st, 2015 weather data dates (see Figure 1).

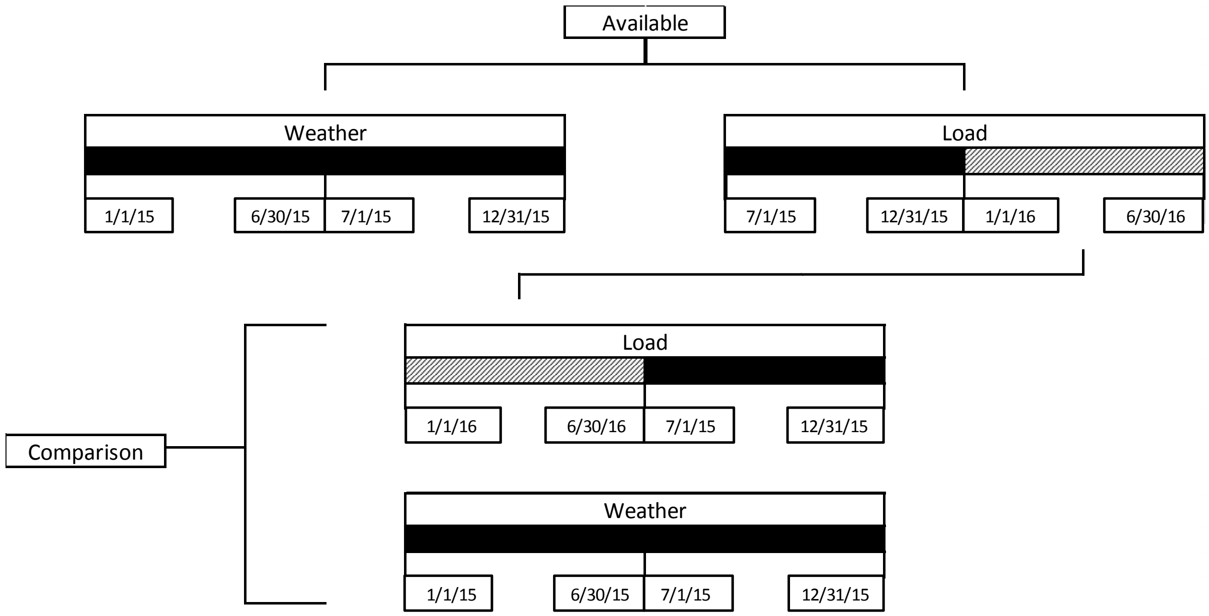


Figure 1. Example of conjoined load data dates to maintain seasonal weather comparison. The hashed areas indicate the first half of 2016's load data being substituted for the first half of 2015's load data.

Third, topography such as vicinity of transmission lines, roughness of terrain, and available land size for renewable energy project development was not considered in the optimization model. Further GIS analysis will be required to identify and determine optimal site locations that consider the viability and costs of these types of geological site parameters.

Fourth, pricing figures used in this model originate from the most recent project data available, and are in today's (1st quarter 2016; the most recent data available at time of this writing) dollars. Therefore, pricing data in this study are not forward looking, nor do I use any Net Present Value (NPV) techniques to discount future dollar values to today's dollar.

Fifth, this thesis only valuated a 100% renewable energy United States comprised of wind and PV. Other sources of renewable energy (hydro, bio, etc.) were not considered.

Significance of the Study

Determining the optimal percentage mix of wind and solar technology that matches a region's weather and load pattern is of utmost importance to ensure that renewable energy technology funds and resources are appropriately allocated. Optimizing the appropriation of renewable energy technology funds assures the target goal of a 100% renewable energy-sourced society is achieved at the lowest possible cost. Proper deployment of renewable energy technologies will save taxpayers' money because the generating renewable energy asset mix will have been implemented as an optimal minimum cost energy solution. To this end, it is important that state RPS policies aimed at renewable energy targets are based on sound data-driven research, and take into consideration the foundational attributes of a region's most abundant renewable energy sources.

The process of optimizing a region's renewable energy mix also safeguards resources that would be otherwise wasted via misallocation and misappropriation of technological funds. Government subsidies such as renewable energy tax credits and multipliers might incur unsubstantiated spending if budget decision makers are not properly educated on optimal renewable energy technology solutions. Essentially, misallocations of renewable energy tax credits could lead to misappropriated spending on non-optimized renewable energy projects.

In addition, the overall environment could suffer due to inadequate and inappropriate renewable energy technology solutions, whereas a thoroughly optimized renewable energy technology solution would solve the environment's deteriorating health problems faster and more reliably.

CHAPTER 2: REVIEW OF LITERATURE

A 100% Renewable Energy United States

The most prominent article in the literature regarding a 100% renewable energy United States was written by Stanford professor Mark Jacobson. Jacobson's study provided a roadmap for the United States' energy demand to become fully supported by renewable energy by the year 2050 (Jacobson, 2015). Jacobson's paper was a comprehensive analysis of all energy sectors, showing potential for a 100% renewable energy scenario based on each state's 39.3% reduction in end-use power demand and implementation of a renewable energy technology mix best supported by each state's renewable energy capacity factors.

In regard to reducing end-use power demand by 39.3%, Jacobson explained that 82.4% of the end-use power reduction could be gained from the efficiency of electrification of markets not currently sourced by electricity (e.g., residential and commercial heating, drying, and cooking; waterborne freight transport; rail and bus transport; heavy-duty truck transport; light-duty on-road transport). Essentially, for the Jacobson model to hold, all new stoves, washers, dryers, ships, trucks, and cars would need to be electric by the year 2030.

To determine a state's optimal renewable energy mix, Jacobson proposed a mix of renewable technology capacities that best matches the renewable energy resources available to that state to meet its particular projected gross annual energy demand. The renewable energy resources best available to each state were attributed based on Jacobson's GATOR-GCMOM modeling software (Jacobson, 2012).

In summary, the Jacobson study looked at annual energy demands, macro-level state weather conditions, and energy efficiency methods to produce a 100% renewable energy solution in the United States. My study took a more granular approach by utilizing an optimization model based on a given year's hourly weather and demand data.

State RPS Examples

As mentioned previously in the Introduction, 29 states have binding RPS policies. A binding RPS policy means that the primary electric utility companies in the state must, by law, source a specific percentage of their electrical output from qualified renewable energy sources. If utilities fail to meet the target renewable energy source percentage for their state through native production, or by purchasing renewable energy credits, they will be subject to monetary fines.

RPS Diversified Renewable Energy Portfolios

More relevant to my study is that many of the 29 binding RPS policies include language that references the importance of implementing an optimal mix of renewable energy technologies. For example, the State of California's SB350 RPS policy describes "a process that provides criteria for the rank ordering and selection of least-cost and best-fit eligible renewable energy resources to comply with the California Renewables Portfolio Standard Program obligations on a total cost and best-fit basis" (*Clean Energy and Pollution Reduction,* 2015, p. 22). It requires "an assessment of annual or multiyear portfolio supplies and demand to determine the optimal mix of eligible renewable energy resources with deliverability characteristics that may include peaking, dispatchable, baseload, firm, and as-available capacity" (p. 23). Connecticut's *Integrated Resources Plan* (Connecticut Department of Energy and Environmental Protection, 2014) specifies that several important metrics (customer costs, resource costs, state and regional emissions, employment, and other macroeconomic indicators) are used to evaluate the effects of its two base-case renewable energy scenarios. Hawaii's revised §269-96 statute (*Energy-efficiency* *portfolio standards,* 2013) states, "The public utilities commission shall establish energy-efficiency portfolio standards that will maximize cost-effective energy-efficiency programs and technologies" (para. 1). Illinois's Public Act 099-0906 concludes that a newly formed Illinois Power Agency is to "develop electricity procurement plans to ensure adequate, reliable, affordable, efficient, and environmentally sustainable electric service at the lowest total cost over time…", and further, that it must develop "a long-term renewable resources procurement plan…" (Public Act 099-0906, 2016, p. 21). New Mexico's *Renewable Energy Act* (2004) states, "the renewable portfolio shall be diversified as to the type of renewable energy resource, taking into consideration the overall reliability, availability, dispatch flexibility and cost of the various renewable energy resources made available by suppliers and generators" (Renewable Energy Act, 2004, Article 16, Section 4, para. A4). The state of New York has penned an energy plan (New York State Energy Planning Board, 2015) that provides a framework for new energy infrastructure, community engagement, and specific financing for funding renewable energy projects.

RPS Carve-Outs

Most states' RPS policies do not describe comprehensive plans, but do include specifically targeted renewable energy technology "carve-outs." Carve-outs are designated required amounts, or percentages of total energy, that must be sourced from a specified type of renewable energy. Carve-outs can be administered by attributing a higher renewable energy credit multiplier to one renewable energy technology versus another, or by specifically stating that a pre-determined percentage of total energy must be sourced by a specific type of renewable energy. Examples include:

- Colorado – 3x solar renewable energy credit multiplier[1]

[1] (*Concerning Measures*, 2013); Colo. S. B. 13-352, 2013

- Delaware – 3x solar multiplier, 1.5x wind multiplier, 3.5x offshore wind multiplier[2]
- Massachusetts – 1.63% solar carve-out for 2017, 1,600 MW of offshore wind by 2027[3,4]
- Maryland – 2.0% solar carve-out by 2022, 2.5% max off-shore wind by 2022[5]
- Minnesota – 7.2% wind, 1.5% solar carve-out by 2020[6]
- North Carolina – .2% solar carve-out for 2018 and every year after[7]
- New Jersey – 3% solar carve-out in 2017 and increasing every year after until 2028[8]
- New Mexico – of 20% by 2020 total RPS requirement – no less than 30% wind, no less than 20% solar, no less than 5% other renewable energy technology[9]
- Nevada – 6% solar carve-out for 2016 and every year after[10]
- Ohio – .15% solar carve-out in 2017 and increasing every year after until .5% solar carve-out in 2026, and then every year after[11]
- Pennsylvania – .2933% solar carve-out in 2017 and increasing every year after until .5% solar carve out in 2020, and then every year after[12]

A state's standard mechanism of administrating and enforcing their RPS laws is through issuing renewable energy credits (RECs) to the electric utility companies that are required to comply with the RPS laws. Typically, one megawatt hour (MWh) of renewable energy sourced by the electric utility company equates to it receiving one REC from the state (Lau & Aga, 2008).

[2] (*Renewable Energy Portfolio*, 2011); Del. Code Ann. 26 § 356 et seq., 2011
[3] (*Commercial Property*, 2016); Mass. H. B. 4568, Chap. 23L, 2016
[4] *(Renewable Energy Portfolio standard—Class I)*; Mass. 225 CMR 14.00: M.G.L c. 25A, § 11F, 2014
[5] (*Clean Energy Jobs*, 2016); Md. H. B. 1106, 2016
[6] (*Renewable Energy Objectives*, 2016); Minn. Stat. § 216B.1691, 2016
[7] (*Renewable Energy and Energy Efficiency*, 2007); N.C. G.S. § 62-133.8, 2007
[8] (*Renewable Energy and Energy Efficiency – Amount*, 2016); N.J. A.C. § 14:8-2.3, 2016
[9] (*Renewable Energy for Electric*, 2013); N.M Stat. § 17.9.572.7, 2013
[10] (*Establishment of portfolio*, 2013); Nev. Rev Stat § 704.7821, 2013
[11] (*Electric distribution*, 2009); Ohio Rev Code § 4928.64, 2009
[12] (*Alternative Energy*, 2004); Pa. Code § 75.61, 2004

By these means the state determines if the electric utility company has met its mandated amount of sourced renewable energy by totaling all of the RECs the electric utility company earned that year. Any company that fails to earn enough RECs can purchase them from other companies, or pay a fine according to the law.

In an effort to provide more support for one renewable technology over another, the states use a REC multiplier. The multiplier increases the amount each MWh of sourced renewable energy is worth in the amount of renewable energy credits. For example, Colorado has enacted a three times (3x) multiplier for solar PV. For every MWh of solar energy sourced by a Coloradan electric utility company, it receives three RECs, instead of the standard one REC.

In summary, multipliers are the state's method of encouraging desired types of renewable energy technologies. If a state wishes to deploy more solar, the legislative body enacts a law that increases the multiplier for solar. The same mechanism can be used with wind, biomass, or any other type of renewable energy.

Co-locating PV/Wind Systems

Based on my literature search, previous studies involving the co-location of PV/wind systems seem to fall into three categories: (a) small autonomous off-grid hybrid PV/Wind systems, (b) small hybrid PV/wind grid-tied systems, and (c) hybrid PV/wind system power production modeling.

The energy generation data in the studies I found was almost always linked to a small, distinct geographically-limited weather pattern location. This is fundamentally different from the varying weather patterns and multi-site analysis conducted in this study.

Supporting my analysis is that almost every hybrid PV/wind system study I found highlighted the complementary nature of solar and wind that leads to a reduction in power production intermittency. This key factor underpins my analysis.

Small Autonomous Off-Grid Hybrid PV/Wind Systems

Stand-alone hybrid PV/wind off-grid systems that include a single turbine and a small PV array are traditionally used to mitigate the power production intermittency that plagues single source renewable energy technologies (Arribas, Cano, Cruz, Mata, & Llobet, 2010). These types of systems also typically have battery storage to ensure the load requirements are always met. A study by Kellogg, Nehrir, Venkataramanan, and Gerez (1996) focused on meeting the load demands of a small hypothetical home in central Montana. Yang, Lu, and Burnett (2003) studied weather data in Hong Kong to determine a "utilization factor" of hybrid PV/wind systems versus single technology systems. Even though these studies were off-grid in nature, they underscore the importance of the use of storage in a 100% renewable scenario.

Small Grid-Tied Hybrid PV/Wind Systems

I was able to find studies that analyzed grid-connected hybrid PV/wind systems where the researchers modeled energy generation data for a distinct location such as Easter Island, Chile (Caballero, Sauma, & Yanine, 2013), central Catalonia in Spain (González, Riba, Rius, & Puig, 2015), and Adrar, Algeria (Saheb-Koussa, Koussa, Belhamel, & Haddadi, 2011). Each study was slightly different. For example, Saheb-Koussa et al. (2011) reviewed the economic and environmental impacts of a small grid-tied system and González et al. (2015) utilized sensitivity analysis of small hybrid system variables, but all of their input data came from a single geographic location. I could not find any study that was cross-regional or that took into consideration the climatic variation between different regions.

Power Production Modeling

I was fortunate to find many studies that created their own algorithms, programming methods, and probabilistic models that helped me develop my own optimization model and its parameters. In addition, I found studies that put forth models for maximizing power production for hybrid renewable energy systems (Bhandari, Lee, Lee, Cho, & Ahn, 2015; Karemore & Kamdi, 2013; Luna-Rubio, Trejo-Perea, Vargas-Vázquez, & Ríos-Moreno, 2010; Perera, Attalage, Perera, & Dassanayake, 2013). Each of these models provided helpful elements in shaping my analytical model, but none addressed all of the parameters I wanted to include. Specific elements taken from these models are described in more detail below.

The Bhandari et al. (2015) study was quite helpful and actually listed various optimization techniques (graphical construction, probabilistic, deterministic, iterative, artificial intelligence, software-based) that allowed me to further research which methods would be most beneficial to helping me achieve my analytical and optimization modeling goals. Luna-Rubio et al. (2010) were also instrumental in listing a variety of modeling methodologies that gave me great insight into how I wanted to structure my model. Luna-Rubio et al. (2010) even developed their own decision-making algorithm.

Perera et al. (2013) developed their own multi-criterion, multi-objective decision making matrix. The structure of their model influenced my own model the most because of their straightforward tiers of evaluation. Moreover, their mathematical analysis was useful due to its multi-objective output. The most reliable power production sites might not equate to the highest levels of total energy generation, and the greatest energy generation sites might not result in the lowest system cost. A multi-objective mathematical matrix model such as the one designed by Perera et al. is an excellent tool for this type of comparison, and I incorporated many of that study's techniques.

Sengupta, Das, Jayram, and Seetharam (2012) utilized an optimal mix algorithm that is constrained by land size. Given that my contact at the wind industry company Iberdrola explained that land size is one of the most important attributes to developing any utility-scale renewable energy project (L. Bowers, personal communication, April, 2, 2016), the Sengupta et al. study was beneficial in helping me construct the parametric constraint framework of my study.

Although the above optimization models were exceedingly well developed, Supriya & Siddarthan (2011) used quadratic programming combined with constrained optimization to create the most sophisticated mathematical model of all the research I discovered. Their time-series data included hourly energy generation and featured an extensive use of charts to plot load versus an optimized number of PV panels and wind turbines. Based on their work, I developed a similarly styled optimization model.

Custom decision making models and algorithms using an iterative approach (dynamic, linear, multi-objective) that fully encompass every aspect of a study provide the potential to target exact outcomes desired and increased levels of automation, but they are also the most time consuming to develop. My model incorporates irradiance and wind data files from as many geographical locations as possible and leverages software with built-in power production algorithms to iteratively generate annual productivity data for various weather patterns. The PV and wind productivity outputs from the software were combined into a custom Excel-based iterative optimization analysis that optimizes for the total lowest system cost that always meets the hourly load and reserve margin objective.

In summary, I borrowed techniques from the probabilistic approach, which uses statistical data analysis; the software approach, which accepts my collected data as input files; and a combination iterative approach using both dynamic and multi-objective optimization programming.

Complementary Nature of Solar and Wind

Many studies used various methodologies to analyze and substantiate the complementary nature of irradiance and wind. Celik (2002) calculated autonomy percentages of hourly weather data from an eight year-long monthly analysis to categorize months into either solar biased, wind biased, or even (i.e., equal inputs from each source). Engin (2012) used meteorological station data collected from the roof of the Solar Energy Institute Building at Ege University in Turkey as inputs into his model, which shows that hybrid systems reduce CO_2 emissions. Solomon, Faiman, and Meron (2010) found that deploying co-located PV and wind systems could significantly improve the amount of renewable energy injected into the Israeli grid because of the diurnal and seasonal differences of solar and wind. Music, Merzic, Redzic, and Aganovic (2013) analyzed irradiance and wind power density values of ten-minute intervals in Bosnia and Herzegovina. In contrast, Agyenim-Boateng (2011) did not find a high correlation between sun and wind, but his study only focused on the desert of Nevada.

In summary, the underlying theme present in almost all of the studies above was that the differences in diurnal and seasonal weather patterns of solar and wind can be utilized in hybrid or co-located systems to make the systems more reliable. The increase in reliability comes from the reduction in energy generation intermittency. Intermittency is reduced because a co-located PV and wind system maximizes the amount of time during which energy is being produced by exploiting differences of PV and wind's diurnal and seasonal patterns. However, as noted by Agyenim-Boateng (2011), the magnitude of this effect varies depending on each location's specific weather pattern. A location with only one primary renewable energy source will not experience much of an increase in reliability from a co-located PV and wind system in comparison to a single technology system because the diurnal and seasonal weather patterns don't vary as much in areas where either sun or wind dominates.

Power Production Intermittency Reduction

The ability for renewable energy technologies to produce power more consistently increases their reliability and efficiency. One article claims that a hybrid PV/wind system could be up to twice as efficient due to shading losses caused by wind turbines only amounting to a mere 1 to 2% of the total energy generated (Ludwig, 2013). Reducing shading in a hybrid PV/wind system increases its reliability in producing power. Pattison's (2010) research showed that when he combined the wind and PV datasets for the Reese MesoNet station at Texas Tech University there were only thirteen times during the first six months of 2009 when there was a greater than three hour period of non-production. Times of intermittency were reduced by 50% when solar and wind measurements were combined. This study further demonstrated that hybrid PV/wind systems also limit the *duration* of the non-productive times. Basically, the length of time of each period of non-power production is reduced due to wind and solar's different diurnal and seasonal weather patterns. Essentially, co-locating wind and PV systems eliminates periods of substantially extended no power production. Explaining these results could be the fact that Texas Tech is located in an area (Lubbock, TX) that experiences both an abundance of wind and sun, but neither resource dominates the other. The Yang et al. (2003) study also found that, depending on local weather patterns, solar and wind compensate for each other very well, and when combined with battery storage appropriately sized to load, probabilities for power loss can be reduced to 0%.

Reserve Margins

In order to maintain the reliability of power being supplied to the grid, meet any unexpected spikes in demand, and replace any unexpected losses of supply, electric utilities always have more supply available than demand (Energy Information Administration [EIA], 2013). This extra supply capacity is called reserve capacity. The amount of extra supply capacity greater than maximum demand (called "peak load") is the electric utilities' reserve margin.

The current common equation for calculating the Planning Reserve Margin is:

$$\frac{Capacity - Peak\ Load}{Peak\ Load} \tag{1}$$

If an electric utility has a reserve margin of 15%, that utility has 15% more capacity than its expected peak demand.

Current electric utility reserve margin estimates vary across states and seasons, and range from 14% to 36% (see Figure 2) (EIA, 2012). According to the Energy Information Administration (EIA), regional target reserve margins are established by the North American Reliability Council's (NERC) Regional Entities (EIA, 2012). However, some utilities carry more reserve capacity than the NERC target because changes in demand growth may have been slower than expected. If demand growth was slower than expected, utilities were left with overcapacity. Furthermore, it is difficult for electric utilities to match their investment in new capacity to the timing of demand growth. Because building new power plants requires long lead times, sometimes investment in capacity is required before demand growth actually occurs. In these cases, power plants with overcapacity are waiting for the demand growth to catch up to their capacity investment. In addition, sometimes capacity build growth spurts occur to gain market share in newer energy technologies such as natural gas, wind, and solar. These growth spurts to gain market share in a newer technology markets can render overcapacities.

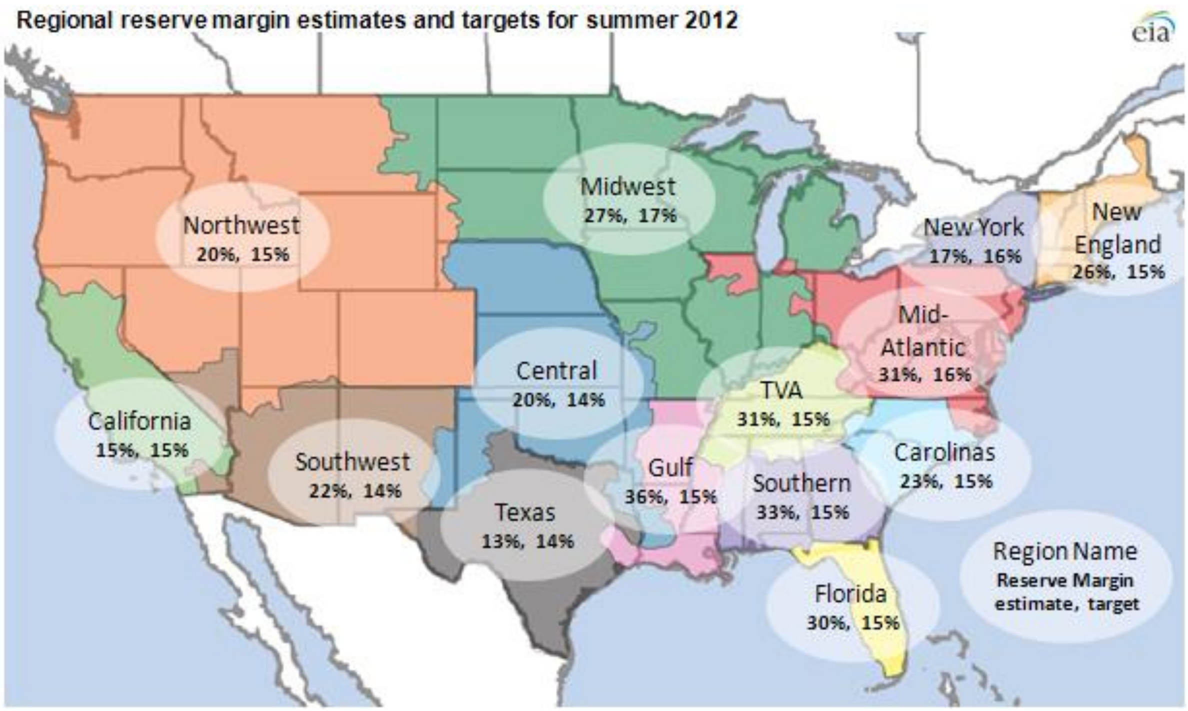


Figure 2. United States reserve margin estimates and targets per region. From "Reserve electric generating capacity helps keep the lights on," by the U.S. Energy Information Administration [EIA], 2012 (https://www.eia.gov/todayinenergy/detail.php?id=6510). In the public domain.

Reserve margin is important to my study because it is a foundational parameter to my optimization algorithm. For a system to be considered "optimized," it must always meet the required reserve margin. Therefore, the value of the reserve margin parameter serves as a key decision making condition.

However, the calculations of reserve margins in a 100% renewable environment with variable supply must be treated differently than our current non-variable supply electricity domain. Currently, our levels of reserve margin take into consideration the probability of demand change, but not supply change. In a 100% renewable environment, supply changes constantly due to the intermittency and variability of renewables sources. Therefore, the equations to calculate adequate reserve margins must reflect this intermittency and variability of supply.

Many sources state that it is typical to use a 1-day-in-10-year Loss of Load Probability (LOLP) when determining the needed Planning Reserve Margin (Ventyx, 2008; Kueck & Kirby, 2004; Phoon, 2006; Pfeifenberger & Spees, 2013). A 1-day-in-10-year LOLP equates to failing to serve the energy requirements of a system for 2.4 hours each year, or 24 hours during a 10-year period.

Traditional LOLP Calculations

According to the energy enterprise software company Ventyx, "in the past, company's [*sic*] often computed an annual LOLP index as the summation of daily probabilities (often termed the 'daily risks') over the entire year being studied" (Ventyx, 2008, p. 2-10). To improve upon the standard LOLP calculation, Ventyx computed LOLP based on a stochastic production cost model simulation where all relevant factors and uncertainties were included in the simulation. Their analysis predicted the probability of not serving a specific amount of load and provided insights into the dimension and amount of energy that would not be served—referred to as *unserved energy* or *expected unserved energy* (EUE). The Ventyx LOLP methodology calculated LOLP for each hour, where the LOLP is the probability that available generation capacity in a given hour is less than the system load (Ventyx, 2008).

Load Loss Probability Techniques

Various techniques for calculating the probability of load loss are provided by a multitude of studies (Ventyx, 2008; Phoon, 2006; Hogan, 2009; Boroujeni, Eghtedari, Abdollahi, Behzadipour, 2012). The methodology presented by Ventyx (2008) and prepared for the Public Service Company of Colorado involved comparing the hourly economic dispatch of resources against loads for multiple iterations of one year due to the uncertainties of unit forced outage and load level variations caused by weather. Phoon (2006) developed his own LOLP model for including renewable energy sources that combined the probability of load and capacity outage into one table using a reliability curve method and retrospective approach. Borounjeni et al. (2012) tested the traditional LOLP model at various capacities and forced outage rates. My reserve margin calculation is a combination of the Ventyx time-series model, and the retrospective approach used by Phoon.

CHAPTER 3: METHODOLOGY, PART 1 – DATA SOURCES

This chapter includes discussion and reasoning in support of the decisions I made concerning the foundational parameters of my model, including its inputs and pricing. I also describe the background and process of my GIS resource map building process. In addition, further explanation of the model's three different reserve margin scenarios is presented.

Weather Source Data

For each location that was optimized, a pair of x,y coordinates was selected to serve as the source of the weather file for that particular location. Many of the x,y coordinates match a nearby United States Climate Reference Network (USCRN) location. The goal in selecting locations was to obtain a highly differentiated and variant grouping of weather and load patterns. Obtaining data comparisons of locations within and between the combined wind/PV GIS Weather Zones was also an underlying motive (see Figures 3 & 4). Lastly, some locations were chosen to discover how varying topographies might result in differentiating energy output results.

Longitude	Latitude	Description	GIS Weather Zone
-118.125	35	CA_Mojave	High_PV_High_Wind
-101.875	35.5	TX_Amarillo	High_PV_High_Wind
-109.375	32	AZ_Bowie	High_PV_Mod_Wind
-103.125	34.5	NM_Clovis	High_PV_Mod_Wind
-112.5	33	AZ_Phoenix	High_PV_Low_Wind
-120	36.5	CA_Fresno	High_PV_Low_Wind
-105.625	40	CO_Boulder	Mod_PV_High_Wind
-99.375	38.5	KS_Hays	Mod_PV_High_Wind
-96.875	41	NE_Lincoln	Mod_PV_Mod_Wind
-96.975	36	OK_Stillwater	Mod_PV_Mod_Wind
-100	32	TX_Bronte	Mod_PV_Mod_Wind
-105.625	41.5	WY_Laramie	Mod_PV_Mod_Wind
-123.125	38.5	CA_Bodega	Mod_PV_Low_Wind
-120	34.5	CA_Santa_Barbara	Mod_PV_Low_Wind
-81.25	26	FL_Everglades_City	Mod_PV_Low_Wind
-90	32.5	MS_Jackson	Mod_PV_Low_Wind
-79.375	36	NC_Durham	Mod_PV_Low_Wind
-98.125	30.5	TX_Austin	Mod_PV_Low_Wind
-96.875	43.5	SD_Sioux_Falls	Low_PV_High_Wind
-106.26	41.5	WY_McFadden	Low_PV_High_Wind
-88.125	40	IL_Champaign	Low_PV_Mod_Wind
-85	45	MI_Gaylord	Low_PV_Mod_Wind
-74.375	40.5	NJ_Edison	Low_PV_Mod_Wind
-73.75	42	NY_Millbrook	Low_PV_Low_Wind
-71.875	41.5	RI_Kingston	Low_PV_Low_Wind
-86.875	36	TN_Nashville	Low_PV_Low_Wind

Figure 3. List of modeled weather locations. Mod = moderate.

GIS Weather Zone	Count	Description					
High_PV_High_Wind	2	CA_Mojave	TX_Amarillo				
High_PV_Mod_Wind	2	AZ_Bowie	NM_Clovis				
High_PV_Low_Wind	2	AZ_Phoenix	CA_Fresno				
Mod_PV_High_Wind	2	CO_Boulder	KS_Hays				
Mod_PV_Mod_Wind	4	NE_Lincoln	OK_Stillwater	TX_Bronte	WY_Laramie		
Mod_PV_Low_Wind	6	CA_Bodega	CA_Santa_Barbara	FL_Everglades_City	NC_Durham	TX_Austin	MS_Jackson
Low_PV_High_Wind	2	SD_Sioux_Falls	WY_McFadden				
Low_PV_Mod_Wind	3	MI_Gaylord	IL_Champaign	NJ_Edison			
Low_PV_Low_Wind	3	NY_Millbrook	RI_Kingston	TN_Nashville			
Total	**26**						

Figure 4. Count of modeled weather locations per GIS Weather Zone.

Wind Energy Simulation Data

Wind Weather File

The wind data weather file per location was sourced from the National Aeronautics and Space Administration Modern-Era Retrospective analysis for Research and Applications Version 2 (NASA MERRA-2) server via Windographer's Data Download portal. The selected x,y coordinates were entered into Windographer's Data Download interface, and the nearest available NASA MERRA-2 data source location was selected to download the weather data file. The NASA MERRA-2 data system is a major new version of the Goddard Earth Observing System Data Assimilation System Version 5 (GEOS-5) produced by the NASA GSFC Global Modeling and Assimilation Office (GMAO) (Smith, 2010). NASA MERRA-2 is an enhanced meteorological reanalysis tool that assimilates satellite-based radiance and microwave observations into a climate context — GPS-Radio Occultation datasets (GMAO, 2015). It is also the first meteorological assimilation system to reanalyze aerosol-climate system interactions. There are many wind data parameters included in the Windographer Data Download. This analysis primarily utilized the wind speed at 50 meters data.

Wind Weather File Import

After the NASA MERRA-2 wind data file was downloaded, it was given the name of the closest city, and was opened in Windographer 4. Windographer 4 is the latest version of an industry-standard wind energy simulation and modeling software provided by AWS Truepower. Upon opening the wind data file, Windographer automatically calculated base measurements such as average wind speed and wind direction for the entire duration of the NASA MERRA-2 wind data file.

Wind System Parameters

Each wind energy simulation used the specific wind data file associated with its selected x,y coordinates. The selected parameters for wind data shearing heights and exponents, turbine type, and losses were kept constant in every iteration of the wind energy simulations.

Wind data shearing.

The NASA MERRA-2 baseline hub height is 50 meters. The average utility-scale hub height installed in 2015 was 82 meters (USDOE, 2016). Therefore, Windographer's Vertical Extrapolation tool was used to extrapolate the wind data from 50 meters to a rounded 85 meters. This extrapolation, or "shearing," of the wind data used the industry accepted Power Law equation:

$$V(Z) = V(Z_{ref}) \text{ x } \left(\frac{Z}{Z_{ref}}\right)^{\alpha} \qquad (2)$$

where $V(Z)$ is wind velocity at sheared hub height, $V(Z_{ref})$ is wind velocity at reference height, Z is sheared hub height, Z_{ref} is reference height, and alpha (α), is the wind shear exponent that relates the wind speeds at the two different heights (Katabatic Power, n.d.). For this study, the wind shear exponent was set to the industry default value of .14. The default shearing value of .14 equates to installing turbines on agriculture land with some nearby houses and 8-meter tall hedgerows with a distance of approximately 350 meters (Katabatic Power, n.d.). Shearing the wind data to an 85-meter hub height resulted in a wind energy simulation that more closely resembles an actual utility-scale wind system, since the average hub height of a utility-scale wind turbine is 82 meters.

Baseline turbine.

After shearing the wind data to an 85-meter hub height, a baseline turbine to model the wind energy output was selected. In 2015, General Electric (GE) was the wind turbine market leader with a 40% market share (USDOE, 2016). The average size turbine installed in 2015 was 2.0 Megawatt (MW) (USDOE, 2016). Therefore, to match current average industry trends, I selected the GE 2.5 MW wind turbine for my baseline wind turbine for Windographer's wind energy simulations. GE does not manufacture a 2.0 MW turbine.

All wind energy simulations were computed with the GE 2.5 MW turbine at an 85-meter hub height. I felt this combination of hub height and turbine produced results that most closely match today's utility-scale wind system environment. Although, the industry trends is moving toward taller hub heights. Future wind energy analysis may warrant simulations at 100-meter hub heights.

Loss assumptions.

The Windographer wind energy simulation was performed with the following loss assumption parameters:

- Availability loss (5.6%),
- Wake effects loss (6.4%),
- Turbine performance loss (4%),
- Environmental loss (2.7%).

Total losses equate to 17.4662%. These loss parameters are the Windographer defaults, and are in line with industry standards (L. Bowers, personal communication, July 3, 2016).

Wind Energy Data Export

Using the GE 2.5 MW, 85-meter hub height parameters, Windographer simulated wind energy output for a single turbine for the duration of the NASA MERRA-2 wind data file. Upon completion of the wind energy simulation, Windographer was instructed to export all of the hourly wind data statistics for the year 2015 to a comma separated value (.csv) file.

On a procedural note, Windographer calculates wind energy for one turbine. In order to match the model's baseline 1 GW system, Windographer's wind energy generation data was multiplied by 400, since the baseline turbine is 2.5 MW *(400 x 2.5 MW = 1 GW)*. Therefore, the data from both Windographer, and the PV energy simulation software, PVSyst, were matched to a 1 GW baseline system.

PV Energy Simulation

Solar Weather File

The solar data files were sourced from the National Renewable Energy Laboratory's National Solar Radiation Database (NREL NSRDB) in comma separated value (.csv) format. The exact x,y coordinates selected in the Windographer Data Download interface were pin-pointed on the NSRDB map. After pinpointing the x.y coordinates on the NSRDB map, Physical Solar Model (PSM) data that included Global Horizontal Irradiance (GHI), Diffuse Horizontal Irradiance (DHI), Direct Normal Irradiance (DNI), Pressure (mbar), Relative Humidity (%), and Solar Zenith Angle (°) was downloaded. "The Physical Solar Model (PSM) developed by NREL in collaboration with the University of Wisconsin and the National Oceanic and Atmospheric Administration (NOAA) computes global horizontal irradiance (GHI) using the visible and infrared channel measurements from the Geostationary Operational Environmental Satellites (GOES) system" (Sengupta, Weekley, Habte, Lopez, & Molling, 2015, p. 1). To compute Direct Normal Irradiance (DNI) and GHI, the PSM models uses a variety of sources to calculate cloud mask, aerosol optical depth, and precipitable water vapor (Sengupta et al., 2015).

Solar Weather File Import

After downloading the NREL PSM solar data file for the selected x,y coordinates, it was given a name of the closest city and was imported into PVSyst using PVSyst's Import ASCII meteo file function. PVSyst is an industry standard PV system energy simulation software. PVSyst converted the ASCII .csv solar data file into the meteorological file format that is used for PV energy simulation, and checked the ASCII .csv solar data file for errors.

PV System Parameters

Each PV energy simulation used the specific meteorological file associated with its selected x,y coordinates. The selected parameters for PV panel orientation, PV panel type, and losses were kept constant for every iteration of the PV energy simulations.

PV panel orientation.

Single-axis tracker. In 2015, 65% of all newly built projects used single-axis trackers (Bolinger & Seel, 2016). Of these projects, over 95% were horizontal single-axis tracking systems that track the sun from east to west each day. East to west horizontal trackers are mounted on a north-south axis so the panels can face east in the morning and begin rotating their tilt angle to follow the sun as it moves across the sky from east to west on a daily basis (Sandia, 2014). Therefore, to match current PV system installation trends, PV energy was simulated based on a utility-scale PV system utilizing a horizontal east to west single-axis tracking system.

Rotating limits. PVSyst provides a default PV panel rotating limit of ± 60° when mounted with a single-axis east to west tracking system. Theoretically, ± 90° is the geometrical maximum/minimum rotating limit, but the limitations of racking technologies do not allow for a full rotating range.

Although the Sandia text mentioned a common maximum allowed ± 45° rotating limit (Sandia, 2014), I chose to maintain the default ± 60° provided by PVSyst to account for a wider range of geometric topographies across the United States where a PV system may be installed. Therefore, with a horizontal single-axis tracking system, the PV panels face east in the morning at a maximum tilt angle between 30°and 60° to the horizontal, and throughout the day rotate to follow the sun. The final tilt angle at the end of the day will between -30° and -60°. The exact maximum rotational limits vary per rack manufacturer.

Axis Tilt. In a fixed-tilt PV system, the panels are typically pointed south and tilted to an angle that matches the latitude of the location (Markham, 2015). This tilt and orientation configuration captures the most irradiance and maximizes energy generation. Seasonal adjustments may be made to a fixed-tilt PV system to optimize irradiance capture, but require manual labor.

With a horizontal single-axis tracking system, the face of the PV panels is oriented parallel to the axis of rotation (Bhatia, 2014). Therefore, the axis tilt in the PVSyst software is set to 0°, because the panels are directly facing the sun and tracking it throughout the day (PVSyst, n.d.; NREL, 2014).

Axis Azimuth. A very simple definition of a PV panel's axis azimuth is the direction in which the panels are pointed or oriented in relation to the ground. An easy way to think about azimuth is an example of a 360° cockpit gunner. How far the cockpit gunner spins around in relation to where he started is the azimuth degree. The goal is to install the PV panel array at an angle so that the largest amount of each panel's surface area is pointed directly at the sun, and to maintain this direct line throughout the day using a tracking mechanism. Therefore, varying latitudes will have varying optimal axis azimuth degrees. The setting that best correlates to the southern area of the northern hemisphere is 0° (PVSyst, n.d.). An axis azimuth of 0° equates to the face of the panels being installed in a perfectly east to west orientation.

PV panel type.

Thin film vs. crystalline silicon. In 2010, thin-film PV panels accounted for 66% of newly installed utility-scale PV capacity (Bolinger & Seel, 2015). In 2011, 2012, and 2013, crystalline silicon (c-Si) panels dominated the market with a 70% share of all new utility-scale PV projects. In 2014, the six largest projects used thin-film panels, resulting in a 70% market share of new utility-scale projects for thin-film panels. When I began my model with PV energy simulations in July 2016, Berkeley Lab's Mark Bolinger and Joachim Seel had not yet released their Utility-Scale Solar 2015 report. Therefore, to match the most current industry trends at the time, I decided to base my PV energy simulation assumptions on the thin-film panel's market dominance portrayed in the Bolinger and Seel 2014 report.

As a follow-up note, the trend did reverse back to c-Si panels in 2015 (Bolinger & Seel, 2016), but comparing the energy output of various types of PV panels was outside the scope of this study.

Manufacturer. The thin-film PV panel market is dominated by First Solar. First Solar's Cadmium Telluride (CdTe) panels accounted for 100% of the new thin-film capacity in 2014 (Bolinger & Seel, 2015). Therefore, to match industry trends, I based my PV energy simulation on First Solar's newest and most efficient panel (123 Watts, 59 Volts, model FS-4122A-2).

Loss assumptions.

The PV energy simulation was performed with the following loss assumption parameters:

- Array ohmic wiring loss (~1.5%, variable),
- Module quality loss (2.5%),
- Module mismatch loss (0.8%),
- Incident Angle Modifier loss (IAM) (~2.2%, variable),
- Module temperature loss (~10.0%, variable),
- Soiling loss (2.5%).

The total of these losses equates to approximately 19.5%. PVSyst calculated losses depending on the actual weather conditions uploaded per location, so the loss items marked as variable varied from site to site. The non-variable losses of PV panel module quality and mismatch used PVSyst default values.

PV Energy Data Export

Using the First Solar 123 W panel, and each specific location's meteorological file, PVSyst simulated PV energy output for a 1 GW system for the duration of the meteorological data file. Upon completion of the PV energy simulation, PVSysyt was instructed to export all of the hourly PV data statistics for the year 2015 to a tab delimited comma separated value (.csv) file.

Turbine/PV Panel Only Simulation

For both wind and PV system energy simulations, the energy generation calculations were only computed for wind turbines and PV panels, making it a DC energy simulation. No conversion to AC energy using inverters was calculated. Therefore, no losses associated with AC wiring or AC-DC conversion were included in this analysis. I chose to model a DC-only energy simulation because I wanted to isolate the energy generation comparison to wind turbines and PV panels only.

Storage

Due to the intermittency and variability of wind and solar resources, storage of the energy that they produce is a key component to a fully integrated renewable energy system. Without renewable energy storage, load demands might not be adequately met due to wind and/or solar resources being unavailable. Therefore, storage of renewable energy is essential for the overall operation and stability of a renewable energy system.

Utility-Scale Storage

Pumped hydro.

Pumped hydro energy storage amounts to over 93% of all currently operative energy storage capacity (see Table 1). The average-size pumped hydro storage project is 593.68 MW. The entire remaining energy storage industry's average size project is 3.47 MW. Pumped hydro's substantially larger project size and market share versus the rest of the industry make it the current dominant energy storage technology. However, in the near future, utility-scale battery technology will garner significant increases in market share (Table 2). Comparing the optimization results from various energy storage technologies was outside the scope of this project.

Table 1. *A Rank of the United States Energy Storage Projects Currently in Operation*

Operational Energy Storage Projects (USA)			
Storage Type	# of Projects	Capacity (GW)	% of Total
Pumped Hydro	38	22.56	93.19%
Battery (All Types)	300	0.65	2.68%
Heat & Molten Salt Thermal Storage	13	0.62	2.55%
Ice & Chilled Water Thermal	128	0.20	0.84%
Compressed Air	4	0.11	0.47%
Flywheel	21	0.06	0.24%
Electrochemical	10	0.01	0.03%
Total	514	24.21	100.00%

Note. Adapted from "DOE Global Energy Storage Database," by Sandia National Laboratories, 2016 (https://www.energystorageexchange.org/projects). In the public domain.

Battery energy storage systems (BESS).

I would be remiss not to mention the impact that emerging BESS technologies are having on the energy storage market. Although most small off-grid renewable energy systems find battery technology adequate to meet their desired load demands, renewable battery energy storage systems (BESS) have only just begun adding any sizeable capacities online at a utility-scale level (Wang, 2017). BESS now account for 14.69% of energy capacity currently under contract (Table 2). A few larger (> 10 MW) BESS have made recent headlines (Power Engineering, 2016; Geuss, 2017), but large-scale battery technology is still in the infancy stage of testing. Even though batteries currently experience only limited utility-scale implementation (2.68% of all total projects in the United States), I modeled them in this study because of their versatility. In other words, utility-scale battery arrays can be deployed almost anywhere, regardless of topography. Pumped hydro facilities require large reservoirs, and not all states are endowed with landscapes that can hold large capacities of water. In summary, large scale BESS is an emerging market that is worthy of modeling because their current integration into utility-scale systems has increased significantly (Table 2).

Table 2. *A Rank of the United States Energy Storage Projects Currently Under Contract*

Contracted Energy Storage Projects (USA)			
Storage Type	# of Projects	Capacity (GW)	% of Total
Pumped Hydro	2	1.70	76.70%
Battery (All Types)	37	0.33	14.69%
Electrochemical	4	0.01	6.18%
Flywheel	3	0.03	1.28%
Ice & Chilled Water Thermal	1	0.03	1.15%
Total	47	2.09	100.00%

Note. Adapted from "DOE Global Energy Storage Database," by Sandia National Laboratories, 2016 (https://www.energystorageexchange.org/projects). In the public domain.

Load Data

The reliability of the United States' electrical grid is regulated and monitored by the Federal Energy Regulatory Commission (FERC). One of FERC's major responsibilities is the regulation of the transmission and wholesale sales of electricity in interstate commerce (Federal Energy Regulatory Commission [FERC], 2016b). Interstate electricity commerce and transmission is comprised of two types of market structures: (a) traditional wholesale markets typically consisting of vertically integrated utilities who own the generation, transmission, and distribution systems used to serve electricity consumers; and (b) the combination of Independent System Operators (ISO) and Regional Transmission Operators (RTO) (see Figures 5 & 6). ISOs operate but do not own transmission systems (PJM, 2017). RTOs operate transmission systems in multi-state areas while focusing on developing innovative procedures to manage transmission equitably by fostering competition in bid-based markets that determine economic dispatch (FERC, 2016a). RTOs and ISOs are also known as Balancing Authorities (EIA, 2016c). I obtained hourly load data from both types of entities, RTO/ISO and traditional electric utility entities.

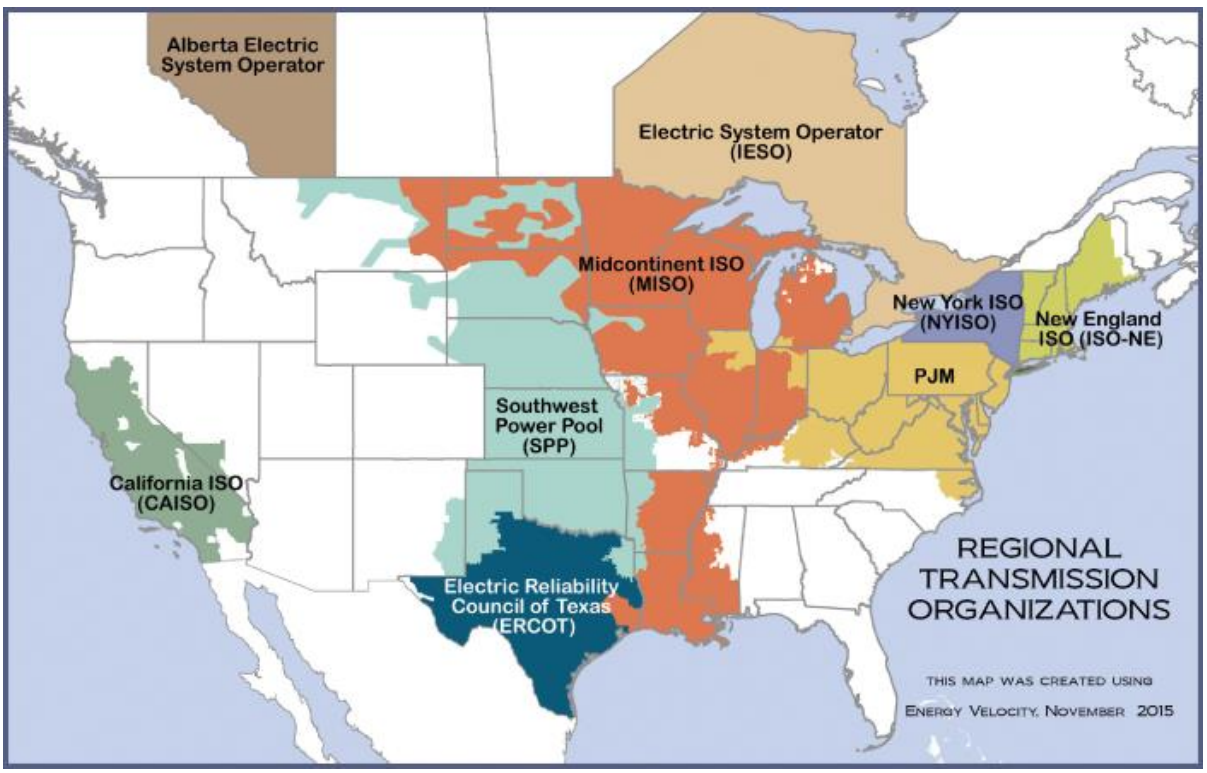


Figure 5. A Map of the RTO/ISO regions of the United States. From "Regional Transmission Organizations (RTO)/Independent System Operators (ISO)," by the Federal Energy Regulatory Commission (FERC, 2017) (https://www.ferc.gov/industries/electric/indus-act/rto.asp). In the public domain.

Each RTO/ISO is comprised of local electricity generating companies. For example, PJM consists of 27 local electricity providers like the Public Service Electric and Gas Company (PSE&G) of New Jersey, and Baltimore Gas & Electric of Maryland (PJM, 2017). ISO/RTO companies like PJM typically supply annual hourly load data for each of their member companies. I downloaded member company annual hourly load data from either the ISO/RTO directly, or from a website such as www.energyonline.com that provides ISO/RTO load data (LCG Consulting, 2017).

Annual hourly load data for the more traditional, vertically integrated electric markets was available from the US. Energy Information Administration (EIA). However, the EIA only started publishing annual hourly load data in July 2015; hence, the reason I needed to provide a seasonal matching solution for mismatched 2015-2016 weather-load dates, as explained in the Limitations section in Chapter 1.

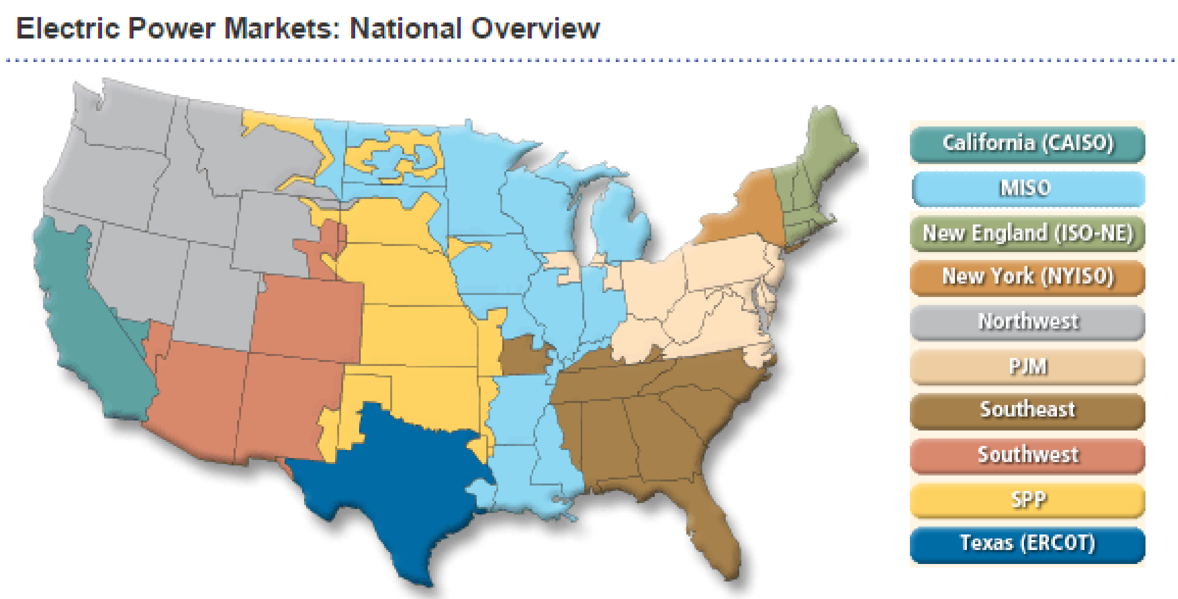


Figure 6. A map of the United States power markets, including the vertically integrated markets of Northwest, Southeast, and Southwest. From "*Electric Power Markets: National Overview*," by the Federal Energy Regulatory Commission (FERC, 2016a), (https://www.ferc.gov/market-oversight/mkt-electric/overview.asp). In the public domain.

Pricing

One of the main cruxes of my optimization model was that the optimized system for any given weather location and load profile had to be the lowest-cost system that met the margin reserve requirement for every hour of the year. Each system to be optimized consisted of a combination of wind capacity, PV capacity, and storage capacity. Dollar per kW prices for the initial development costs of wind capacity and PV capacity were assigned depending on the region or state of the targeted location. Wind capacity pricing was assigned according to the region of the area to be optimized. PV capacity pricing was assigned according to the state of the area to be optimized. Storage capacity pricing was fixed.

Each system consists of initial development costs and annual operating and maintenance costs (O & M). The O & M costs for wind, PV, and storage were fixed. The initial development costs were added to one year of operating and maintenance (O & M) cost, for a combined total system cost that represented the system's first year of operation (Equation 3).

$$\text{Initial development cost}_{(\$/kW)} + \text{annual O \& M cost}_{(\$/kW)} = \text{Total System Cost}_{(\$/kW)} \quad (3)$$

Wind Pricing

Wind pricing was sourced from the U.S. DOE's 2015 *Wind Technologies Market Report* authored by Lawrence Berkeley National Laboratory's Mark Bolinger and Ryan Wiser. Wind system development pricing was classified per region (Northeast, Great Lakes, Interior, West, Southeast) (see Table 3 & Figure 7). Wind system annual O & M cost was fixed at $26.00 per kW.

Table 3. *Average Wind Project Development Cost in the United States per Region*

WIND PROJECT AVERAGE COST	
Region	**($/kW)**
Northeast	$ 2,600
Great Lakes	$ 2,130
Interior	$ 1,640
West	$ 2,050
Southeast	$ 2,000

Note. Adapted from "*2015 Wind Technologies Market Report*," by the U.S. Department of Energy (USDOE), 2016 (https://energy.gov/sites/.../2015-Wind-Technologies-Market-Report-08162016.pdf).

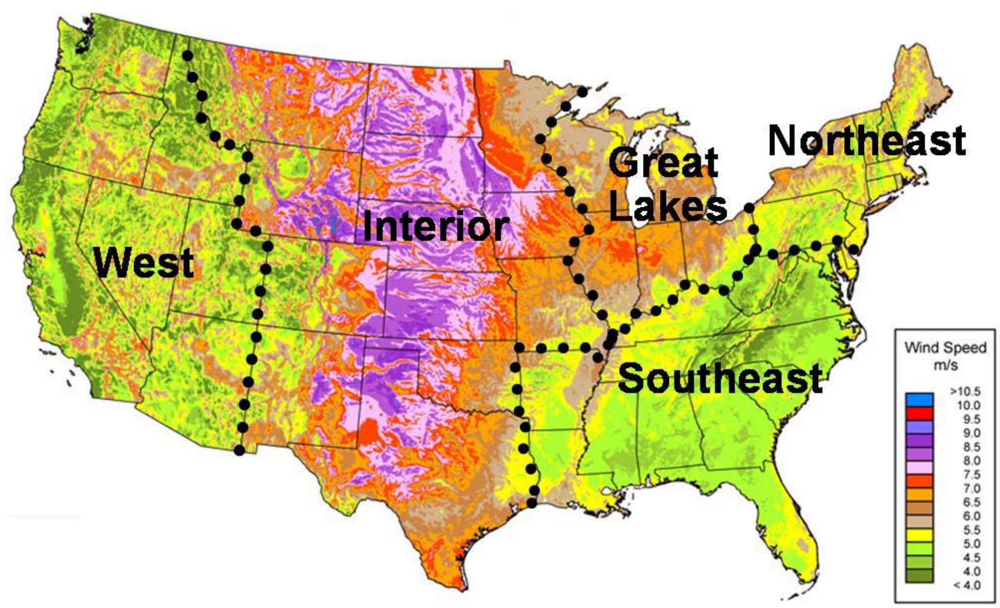


Figure 7. U.S. DOE's wind pricing regions. From *2015 Wind Technologies Market Report*, by the U.S. Department of Energy (USDOE), 2016 (https://energy.gov/sites/.../2015-Wind-Technologies-Market-Report-08162016.pdf). In the public domain.

PV Pricing

PV pricing was sourced from the NREL's *U.S. Solar Photovoltaic System Cost Benchmark: Q1 2016*. Single-axis tracking PV system development pricing was classified per state (see Table 4). Single-axis tracking PV system annual O & M cost was fixed at $18.00 per kW.

Table 4. *NREL's Average PV Project Development Cost in the United States, per State*

PV PROJECT AVERAGE COST			
State/Territory	**($/kW)**	**State/Territory**	**($/kW)**
Alabama	1197	Montana	1196
Alaska	1380	Nebraska	1235
Arizona	1220	Nevada	1286
Arkansas	1197	New Hampshire	1218
California	1335	New Jersey	1370
Colorado	1219	New Mexico	1221
Connecticut	1372	New York	1334
DC	1289	North Carolina	1199
Delaware	1215	North Dakota	1278
Florida	1259	Ohio	1260
Georgia	1200	Oklahoma	1195
Hawaii	1360	Oregon	1200
Idaho	1239	Pennsylvania	1282
Illinois	1360	Puerto Rico	1248
Indiana	1276	Rhode Island	1338
Iowa	1248	South Carolina	1237
Kansas	1238	South Dakota	1198
Kentucky	1244	Tennessee	1223
Louisiana	1214	Texas	1215
Maine	1260	Utah	1220
Maryland	1254	Vermont	1242
Massachusetts	1374	Virginia	1222
Michigan	1277	Washington	1290
Minnesota	1365	West Virginia	1260
Mississippi	1240	Wisconsin	1290
Missouri	1260	Wyoming	1215

Note. Adapted from "*U.S. Solar Photovoltaic System Cost Benchmark: Q1 2016*," by the National Renewable Energy Laboratory (NREL, 2016b), (www.nrel.gov/docs/fy16osti/66532.pdf). In the public domain.

Storage Pricing

As mentioned earlier in this paper, utility-scale battery arrays were the only type of energy storage system that was modeled in this analysis. Battery system development pricing was fixed at $2,352 per kWh. Battery system annual O & M cost was fixed at $3.00 per kWh. Storage capacity pricing was assigned a double multiplicative factor. In other words, the battery pricing found in Lazard's *Levelized Cost of Storage Analysis—Version 2.0* (2016), was doubled in order to provide a conservative estimate of total future storage deployment costs. This was done in consideration of the uncertainties relating to scaling battery array technology; the future need to place battery arrays closer to load centers, where land pricing increases significantly; required grid upgrades; and unknown failure rates of battery array sizes larger than ever previously deployed.

Reserve Margin

Ventyx versus My Baseline Method

Both the Ventyx reserve margin probability method and my own baseline reserve margin probability method compute the ability of the renewable energy generation system to meet customer loads in a given year under different technology combination mixes. Both of our methods resulted in technology combination mixes producing different levels of planning reserve (Ventyx, 2008). My reserve calculation was also similar to the Ventyx model in that it compared time and region varying renewable energy generation versus loads, on an hourly basis, for an entire year, for any given location. However, the Ventyx reserve margin probability method differed from my own baseline method in that it "computes LOLP based on a stochastic production cost model simulation where all relevant factors and uncertainties are included in the simulation" (Ventyx, 2008, p. 2-10). My probability computations were based on hourly net load, which was the result of each hour's energy generation minus load. Ventyx computed probabilities of energy generation and load individually.

To make my reserve margin computation more compatible with a 100% renewable energy scenario in a retrospective style analysis, I calculated the probability of any hourly net load being less than the satisfactory 2.4 loss hours multiplied by the peak load, multiplied by the maximum number of consecutive negative net load days, multiplied by the average load of the entire year (Equation 4).

$$RM_{(kwh)} = Prob(NL < (2.4_{(hrs)} * PL_{(kW)})) * Max \# \text{ consec. neg. } NL \text{ hours} * AL_{(kW)} \quad (4)$$

where

RM = Reserve Margin

Prob = Probability

NL = Net Load

PL = Peak Load

Max - Maximum

consec. = consecutive

neg. = negative

AL = Average Load

The result was a reserve margin, given in kWh, that I felt was an adequate level of reserve energy for an intermittent and variable 100% renewable energy environment, because it considers our current loss assumptions, peak load, the potential maximum duration of negative net loads, and the overall average load for the year.

Even though I found this method to be potentially accurate, I also believe it was conservative and may have overstated total system cost. Although future methods that calculate summation probabilities of individual hourly energy generation and load may prove to be more accurate, that type of probability calculation was outside the scope of this paper.

Each of my reserve margin calculations was completed for the 40 different wind and PV potential optimal mix percentages. This provided the capability for the reserve margin to change with the given PV and wind mix.

Alternative Reserve Margin Calculations

Because the future of our renewable energy environment is a shifting paradigm, and predicting the future of a constantly changing energy landscape is difficult, I also computed wind and PV optimization mixes for a zero reserve margin scenario, as well as a scenario that computes the probability of a negative hourly net load, instead of the probability of 2.4 loss hours multiplied by peak load.

Zero reserve margin.

It is possible that our future energy domain will utilize sophisticated weather and load prediction models deployed in a real-time smart grid that allows long-distance energy sharing, so that reserve margins are not required. To accompany this potential alternative 100% renewable energy future, I computed wind and PV optimization mixes based on a zero reserve margin. This would be the most aggressive computation, and one that resulted in the lowest overall system cost. The equation is:

$$Reserve\ Margin_{(kwh)} = 0 \tag{5}$$

Probability of negative net load.

Instead of computing the probability of hourly net load being lower than 2.4 loss hours multiplied by peak load, I included a reserve margin scenario that computed the probability of any negative hourly net load, multiplied by the maximum number of consecutive negative net load hours, multiplied by the average hourly load for the year. This reserve margin calculation method provided a middle ground reserve margin calculation in kWh that was between conservative baseline and aggressive zero reserve margin environments. The equation is:

$$RM_{(kwh)} = Prob(NL < 0) * Max\ \#\ consec.\ neg.\ NL\ hours * AL_{(kW)} \qquad (6)$$

This probability computation method for negatively hourly net loads was similar to the Ventyx probability computation method in that both methods computed the probability that energy generation capacity in a given hour was less than load (Ventyx, 2008).

GIS Combined Wind + PV Map

The optimal mix of solar and wind technologies in each load area was highly dependent on that location's solar and wind resource. Therefore, it was imperative to combine the United States' wind and PV resource maps into one map that very clearly delineated the areas that were favorable to wind, PV, or both. With a combined PV/wind map, the goal was to identify patterns and anomalies that otherwise might go unnoticed when strictly analyzing my non-visual data sources.

Identifying the geographical mix of PV and wind resources in the United States, and clearly mapping the predominant resource(s) per region, could help state administrators craft a more informed renewable portfolio standard. Without a map that combines PV and wind resources, it would be difficult to visually justify a particular region's optimal mix determination or discover anomalous conclusions.

Input Map Sources

The specific goal of this part of my study was to use ArcGIS to combine the NREL Wind and PV maps. NREL provided Wind Power Class maps at an 80-meter hub height (see Figure 8). Unfortunately, the downloadable Wind Power Class data provided by NREL was a 50-meter hub height (NREL, 2016c). Therefore, I addressed this discrepancy by reclassifying the

Wind Power Class groups to match the 80-meter hub height (reclassification procedure further explained later).

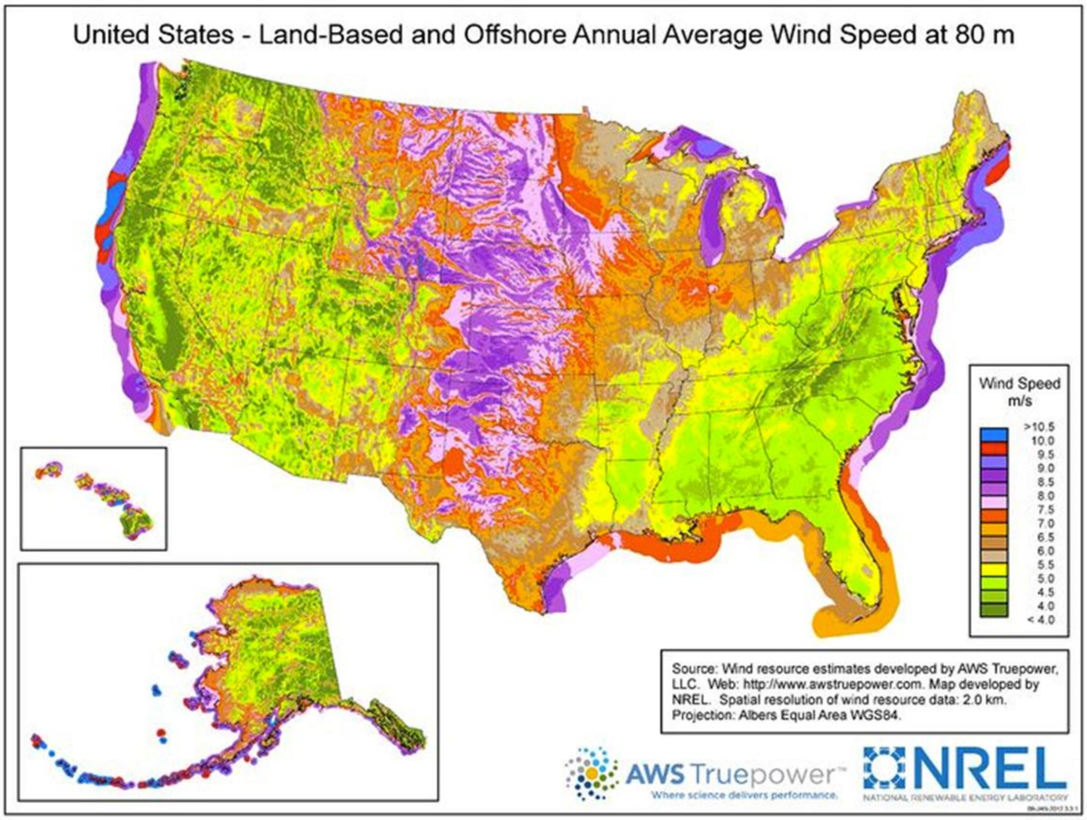


Figure 8. NREL United States wind speed at 80 meters. From "Wind Maps," by NREL (2016b) (http://www.nrel.gov/gis/wind.html). In the public domain.

The NREL PV source map displays the PV irradiance data across the United States by converting the total direct (DNI) and diffuse horizontal irradiance (DHI) data into tilted surface collector data (see Figure 9). The angle of the tilted surface collector equals the location's latitude (NREL, 2014). When performing irradiance analysis, it is important to use data that simulates a tilted collecting surface that closely resembles actual in-the-field installation conditions. Although my optimization model simulated PV energy using a horizontal single-axis tracking system that varied from the fixed tilt system that NREL used to develop their irradiance map, both methods maximized PV performance for their given task.

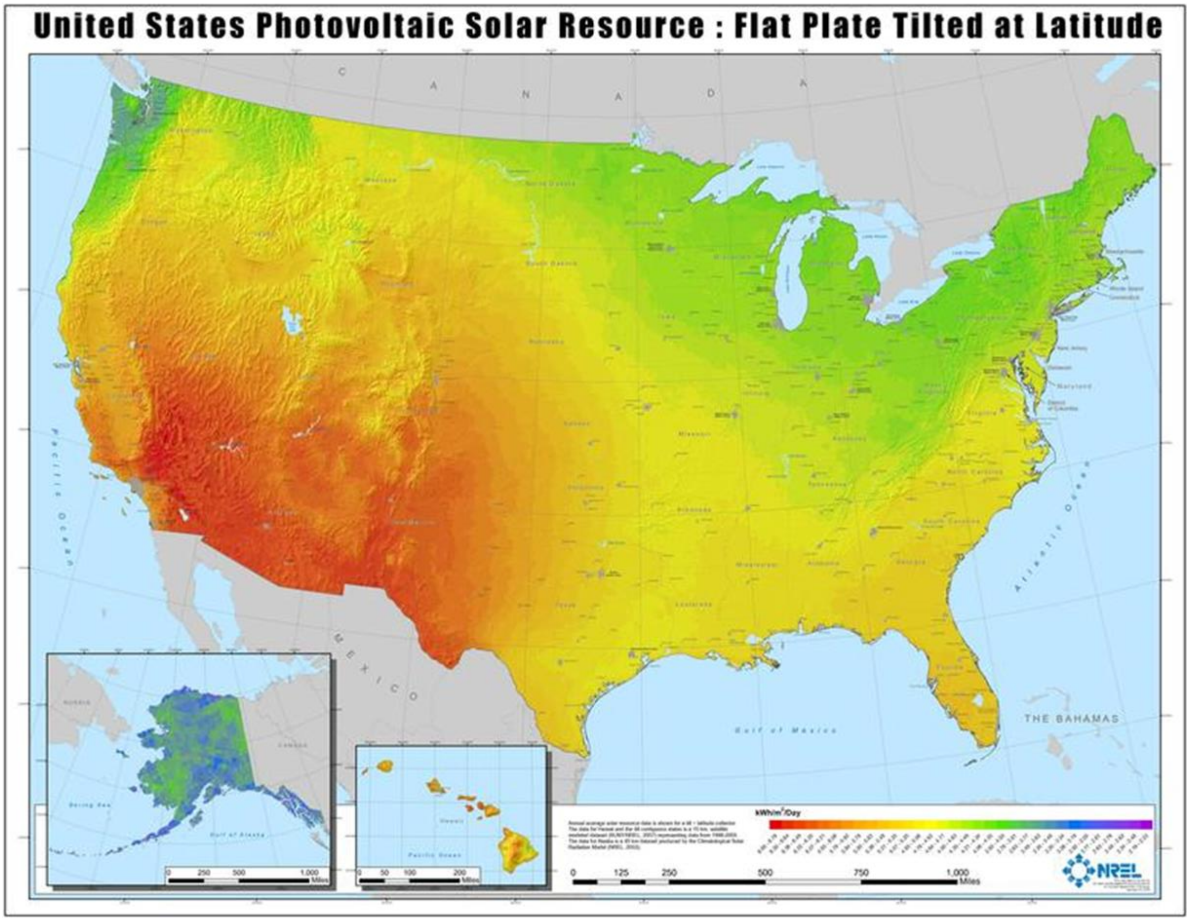


Figure 9. NREL United States PV irradiance map. From "Solar Maps," by NREL (2016a) (http://www.nrel.gov/gis/solar.html).

Wind Raster Data

I downloaded a contiguous United States 50-meter hub height Wind Power Class geographic shapefile from the NREL website and imported it into Esri's industry leading ArcMap software. The original raster data for this shapefile had various resolutions ranging from 200 meter to 1000 meter cell sizes (NREL, 2016c), and was created with the GCS_WGS_1984 geographic coordinate system. I projected the Wind Power Class shapefile using the North

American Lambert Conformal Conic projection because it minimizes distortion at middle latitudes and preserves the map's shape. I also wanted to maintain the ability to include Alaska and Hawaii in future analysis. After the projection, I used ArcMap's Polygon to Raster tool to convert the Wind Power Class shapefile back to its original raster layer using Maximum Area as the cell assignment type and a 10km cell size. Since the Wind Power Class data was already classified as a 7-group layer, no further reclassification was needed at this stage (Figure 10).

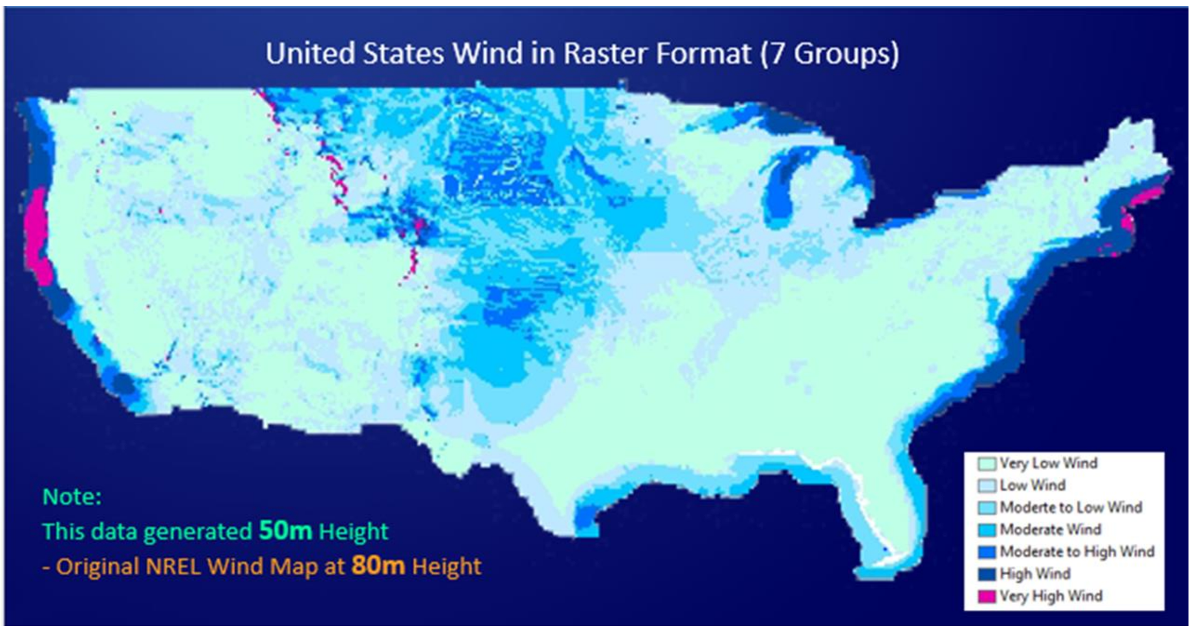


Figure 10. United States wind resource map in raster format.

PV Raster Data

I downloaded a contiguous United States 10km PV irradiance data shapefile from the NREL website and imported it into Esri's ArcMap software. To maintain consistency with the Wind Power Class shapefile, I projected the PV shapefile using the North American Lambert Conformal Conic projection. After the projection, I used ArcMap's Polygon to Raster tool to convert the PV shapefile into raster data. To match the Wind Power Class raster data, I used the

Reclassify tool to convert the continuous PV irradiance raster data into a 7-group layer using the Natural Breaks (Jenks) method (Figure 11).

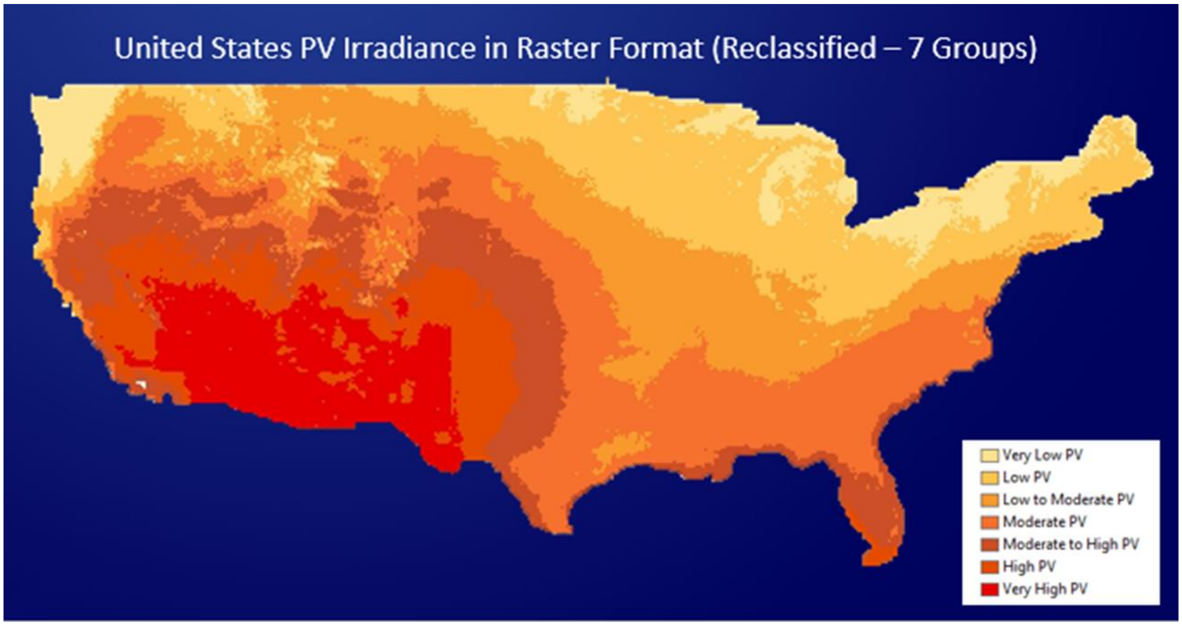


Figure 11. United States PV irradiance resource map in raster format.

Combining Wind and PV Raster Data

I used ArcMap's Spatial Analyst Local Combine tool to combine the 7-group wind and the 7-group PV raster data layers into a continuous scale 49-group combined wind and PV raster data layer. The Combine tool multiples rasters so that a unique output value is assigned to each unique combination of input values (Esri, 2017). Fundamentally, it multiplies each group in one raster layer by each group in another raster layer to create a matrix group layer. Hence, my new matrix group raster layer is a map that depicts the combined wind and PV resources across the contiguous United States (see Figure 12). However, one cannot determine which area is more favorable to wind or PV because the map only displays the combined resources. Also, after analyzing this combined resource map, I immediately noticed a few select areas that were not accurately represented in comparison to the original NREL maps. Specifically, the western Great

Lakes region, eastern North and South Dakota, and Kansas areas were not depicting enough combined wind and PV resources (see orange-circled areas of Figure 12). Further reclassification was needed to achieve the initial goal of clearly depicting which areas of the United States are favorable to wind, PV, or both (explained below).

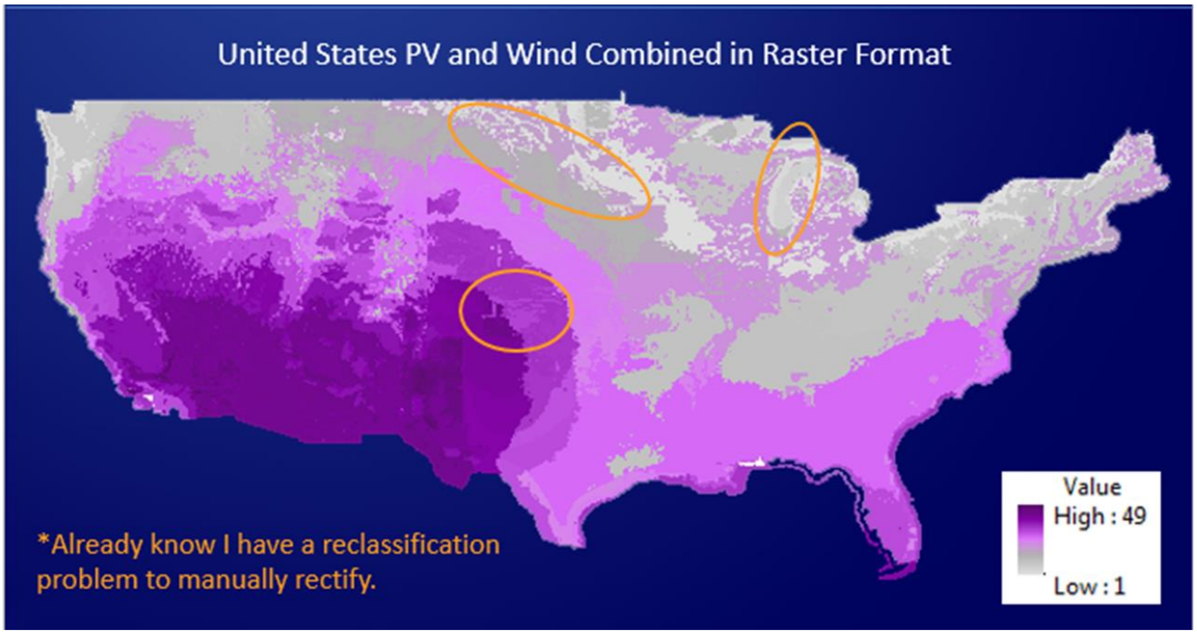


Figure 12. United States PV and wind combined resource in raster format. Orange circles indicate areas of identified data errors.

Reclassifying Combined Wind and PV Raster Data

To achieve a much more easily understood categorical resources map, I reclassified the 7-group wind raster data and the 7-group PV raster data independently. The wind raster data was manually reclassified into three distinct groups – High Wind, Moderate Wind, Low Wind (Figure 13). The PV raster data was also manually reclassified into three distinct groups – High PV, Moderate PV, Low PV (Figure 14). Careful consideration and multiple iterations of reclassification were required to closely match the three group output layer maps to the original NREL wind and PV maps. I determined that the inadequacy of the combined resource representation in the 49-group layer map mentioned above was due to the wind layer's natural breaks reclassification not providing enough weight to the higher speed classes. Although the natural breaks reclassification method was accurate at a 50-meter hub height, it did not translate well to an 80-meter hub height. Therefore, a manual reclassification method that weighted the Moderate Wind class groups (4, 5) of the 7-group layer into the High Wind class groups (6,7) of the 3-Group layer was required to accurately depict the areas of higher wind speeds (Figure 17).

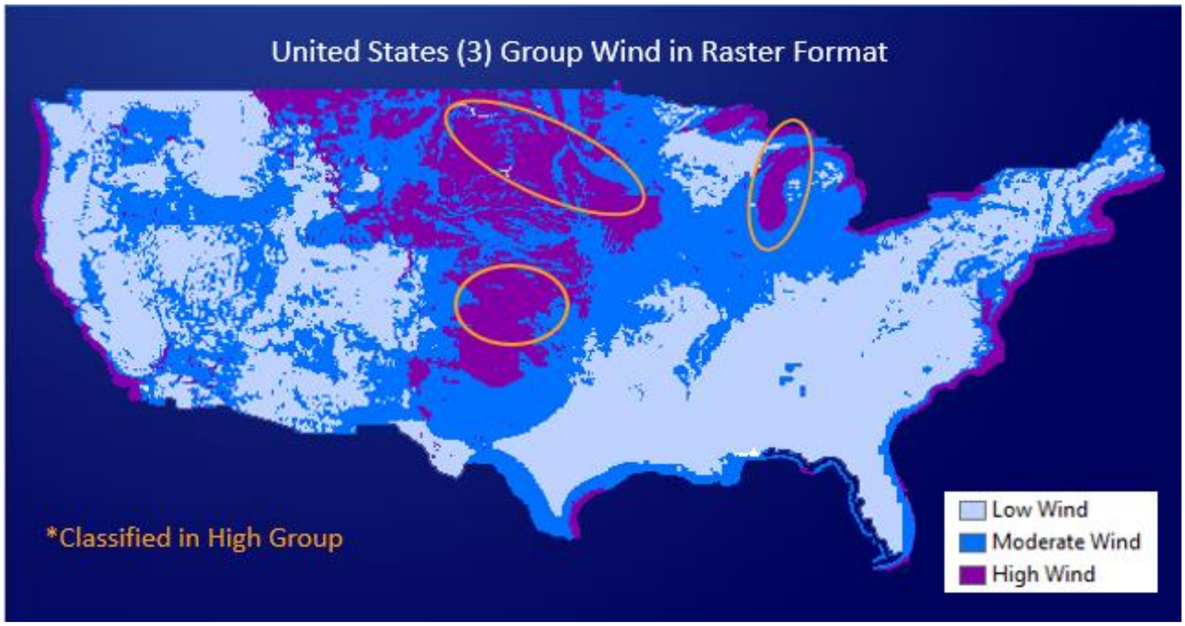


Figure 13. United States wind power reclassified to three groups. Orange circles indicate areas where reclassification of the Moderate Wind class group into the High Wind class group provided a closer resemblance to the original 80-meter wind map.

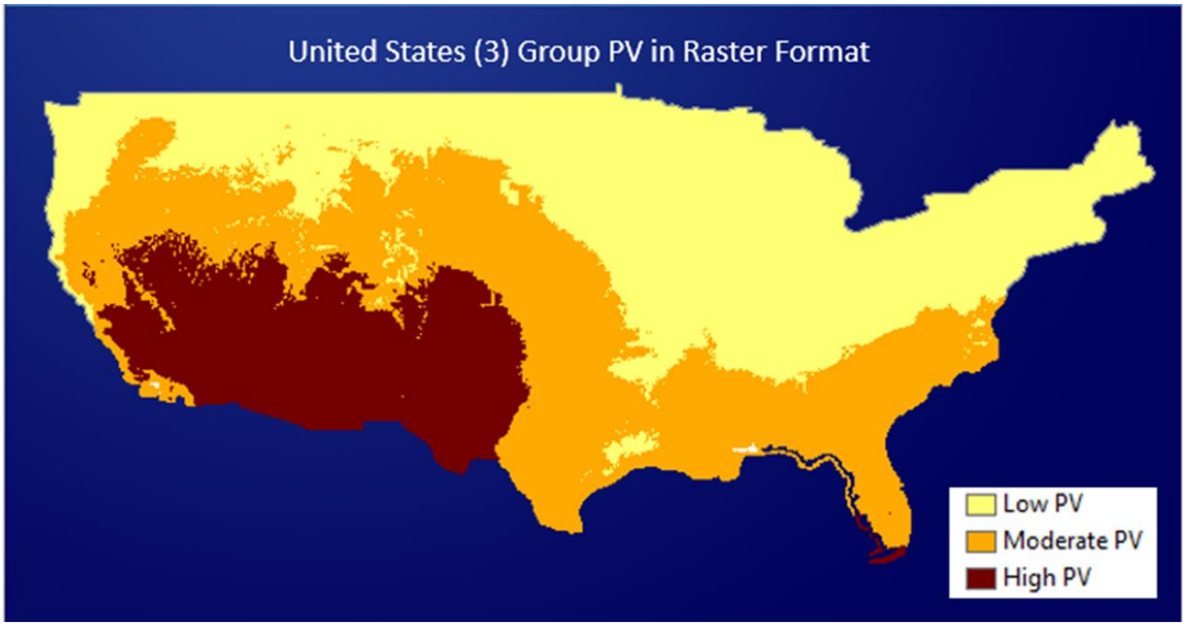


Figure 14. United States irradiance resource reclassified to three groups.

Recombining the 3-group Wind and PV Raster Data Layers

After reclassifying the wind and PV groups into three easy to understand categories, I used the Combine tool to combine the 3-group wind and 3-group PV raster data layers into one 9-group PV/Wind combined raster layer. The resulting groups were:

- High PV - High Wind
- High PV - Moderate Wind
- High PV - Low Wind
- Moderate PV - High Wind
- Moderate PV - Moderate Wind
- Moderate PV - Low Wind
- Low PV - High Wind
- Low PV - Moderate Wind
- Low PV - Low PV

Categorizing the combined resource map layer in this manner made it very easy to depict which areas in the United States are favorable to wind, PV, or both; and to what degree of each resource (Figure 15).

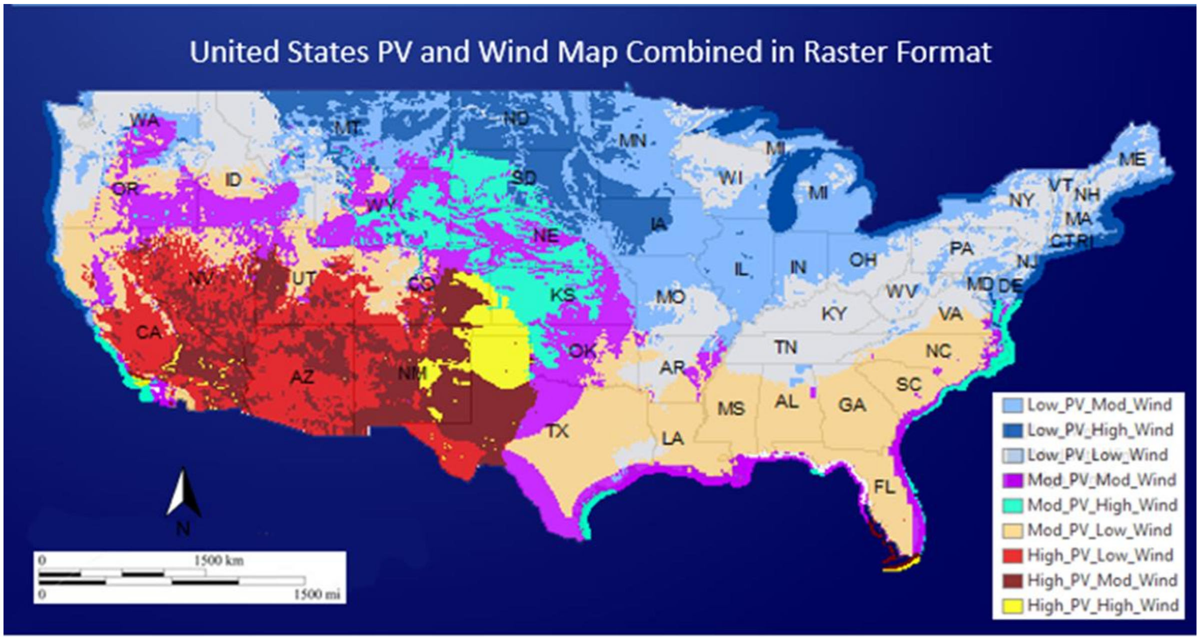


Figure 15. United States PV and wind combined resource map.

Combined PV and Wind Resource Results Summary

My reclassification and combination methods of wind and PV raster map layers produced a combined resource raster map that very clearly shows which areas in the United States are favorable to wind, PV, or a combination of both resources. The areas of east Texas and Wisconsin are still not quite accurate due to the original wind data only being supplied at a 50-meter height. However, the rest of the map seems to match a combination of the original NREL wind and PV maps very accurately.

According to this map, the desert Southwest region is very abundant with PV irradiance, while the middle states of Nebraska, Kansas, Oklahoma, Wyoming, North Dakota, and South Dakota, are more wind intensive. Very close to the middle of the United States, where north

Texas, west Oklahoma, southwest Kansas, southeast Colorado, and northwest New Mexico meet, is a unique area rich in both wind and PV resources. The southeast United States has a moderate PV resource, but is low in wind. Unfortunately, the northeast region of the United States does not have much of either resource.

CHAPTER 4: METHODOLOGY, PART 2 -- OPTIMIZATION MODEL

One of the main functions of my thesis was the creation of a novel optimization model for co-located wind, PV, and storage systems. My optimization model combined the software and iterative optimization techniques with empirical inputs that were sourced from substantiated organizations (NASA, DOE, NREL, Lazard). In regard to the software optimization technique, industry standard software platforms such as Windographer, PVSyst, and ArcGIS were utilized for PV energy simulations, wind energy simulations, and mapping of renewable resource combinations, respectively. In regard to the iterative optimization technique, I developed a custom Microsoft Excel VBA-based energy analysis spreadsheet specifically for analyzing and optimizing wind, PV, and storage capacities for any specified weather, load, and cost parameters. The final result produced an optimized percentage mix of PV, wind, and storage system capacity that is based on the lowest system cost that always met the given reserve margin. Weather, load, and capacity factor parameters were also calculated and displayed for the purpose of trend analysis. I believe these types of models that are data-driven, flexible, and encompass a wide variety of variables are essential for guiding our future renewable energy investments.

Optimization Model Inputs

As mentioned above, the inputs of my optimization model were hourly wind, PV, and load data for one year, typically 2015, unless load data began on July 1st, 2016, in which case the season matching weather-load date rule applied. However, the model can accept any time-step or time-frame. Wind and PV data are always downloaded for a specified pair of x,y coordinates, and in the model any pair of coordinates may be chosen. Load data can be obtained and entered into the model for any level of granularity (e.g., region, sub-region, RTO/ISO, county). I used the most-local load data available to produce more targeted weather and energy versus load comparisons. However, in some cases, only regional load data were available.

To begin the optimization model process, the following inputs were downloaded and then simulated. The results of the simulations were entered into the custom Excel optimization model spreadsheet (Figures 16 & 18):

- NASA
    - 85 meter wind speed (m/s)
- Windographer
    - Wind power, GE 2.5 MW turbine (kW)
- DOE/Berkeley Labs
    - Wind pricing ($/kW)
- NREL
    - Relative humidity (%)
    - Surface pressure (mbar)
    - Irradiance (W/m^2)
    - PV pricing ($/kW)
- PVSyst
    - PV power (kW)
    - Ambient temperature (C°)
- Lazard
    - Storage pricing ($/kWh)
- FERC–RTO/ISO

- Load data (kW)

- EIA
  - Load data (kW)

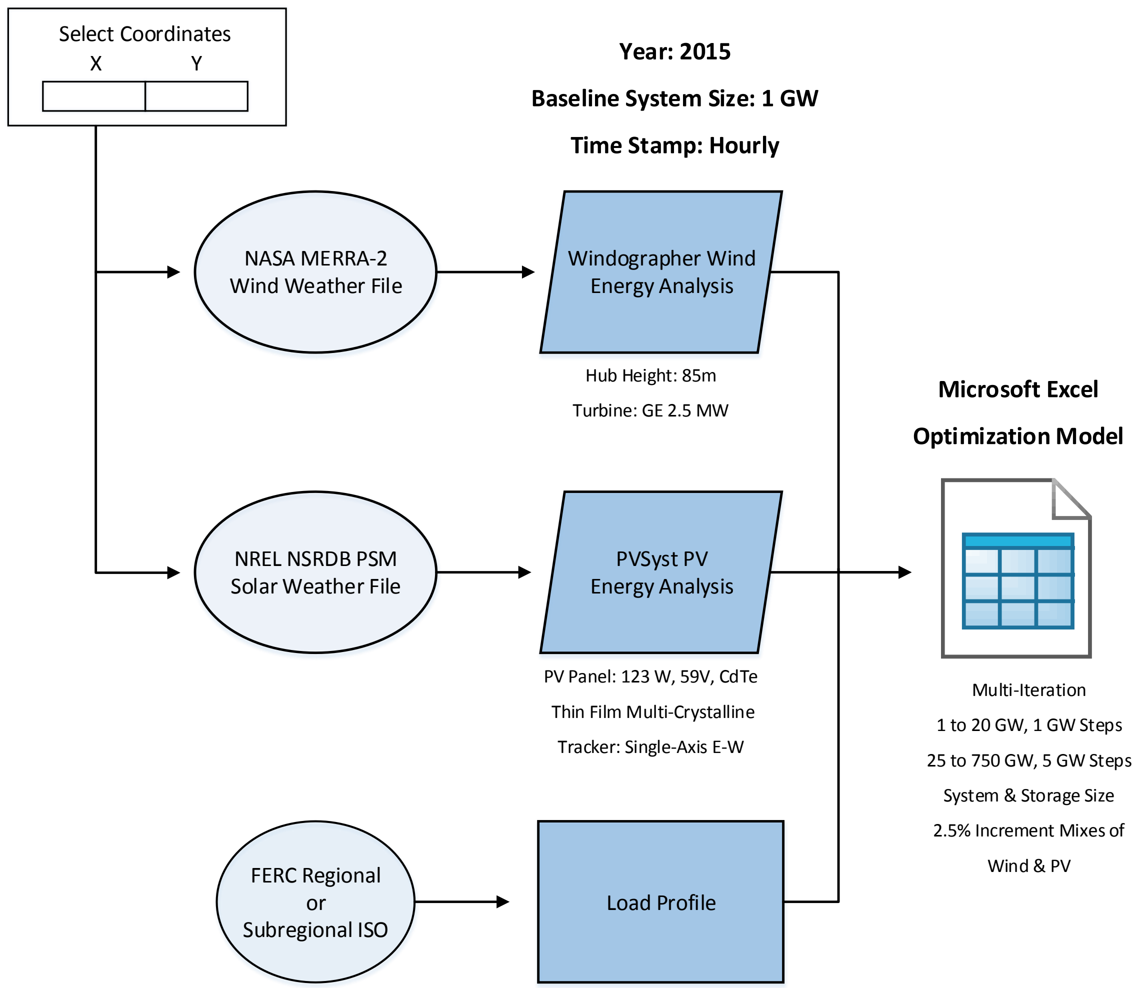


Figure 16. Graphical representation of the software-based inputs of the optimization model.

Output: Energy Generation Combination of PV and Wind

For every co-located PV and Wind system per pair of selected x,y coordinates, I placed the two following restrictive parameters:

- PV and Wind capacity generated 100% of the energy output
- PV and Wind energy generation summed to 100% of the total system output

In other words, PV and wind technologies were the only technologies modeled—no other renewable technologies such as hydro, bio, or wave were modeled; the energy generated from PV and wind was set up as a closed system that sums to 100% for the particular area being modeled. For example, the area could deploy 50% wind capacity and 50% PV capacity, or 75% wind and 25% PV, or 37.5% wind and 62.5% PV, and so on and so forth.

Mix Percentage Parameter

The allowed increment of wind and PV capacity was calculated in 2.5% steps for each combination mix. This equated to 40 different combinations of wind and PV capacity mixes, ranging from [100% wind, 0% PV] to [0% wind, 100% PV], and every variant capacity combination mix of 2.5% increments in between. Therefore, all of the hourly energy generation was multiplied by the same combination mix of 2.5% increments that always summed to 100% (Figure 20). Figure 17 is a graphical representation of the 40 different PV/wind combinations.

[100%, wind, 0% PV], [97.5% wind, 2.5% PV] →

→ [50% wind. 50% PV] →

→ [2.5% wind, 97.5% PV], [0% wind, 100%.PV]

Figure 17. Graphical summary representing the 2.5% increments of combination mixes.

Mix Combination Algorithm

The equation used to calculate the total energy generated from the given wind and PV capacity combination mix was:

$$(WE_{(kWh)} * WC\ \%) + (PVE_{(kWh)} * PVC\ \%) = Total\ combined\ energy\ generation_{(kWh)} \quad (7)$$

where

WE = Wind Energy

WC = Wind Capacity

PVE = PV Energy

PVC = PV Capacity

Net Load/Storage Level Calculations

For every hour of the given year, the total energy generated by the wind and PV capacity combination mix was compared to the load in the specified location (see Figures 19 & 20). Load was subtracted from the combined wind and PV energy generation, and the result was a positive or negative net load (Figure 21). A positive net load added to stored energy, if the storage "tank" was not full. A negative net load subtracted from stored energy (Figure 22). Positive net loads could not add more energy to any storage capacity that was at its maximum level. In other words, you could not add more chemicals to a battery array to increase its holding capacity.

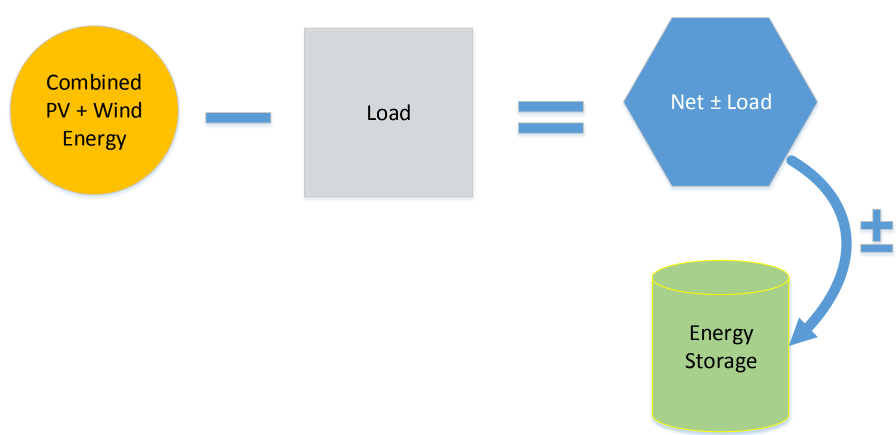


Figure 18. Net load and energy storage basic equation.

Disqualified Capacity Mix Combinations

For any hour, any combination mix of wind, PV, and storage capacity that resulted in an energy storage level that was lower than the specified reserve margin was automatically disqualified as an optimal capacity combination mix because an energy storage level being lower than the specified reserve margin meant the system could not satisfy a fundamental parameter (see Figure 24). Any system that could not satisfy the fundamental reserve margin parameter was deemed unreliable, and therefore, not optimal.

Optimization Algorithm

The algorithm used in the optimization model was built around two fundamental conditions:

<u>1st Condition</u> - For every hour:

$$WE_{(kWh)} + PVE_{(kWh)} + \text{available } SE_{(kWh)} \geq Load_{(kWh)} + \text{minimum reserve}_{(kWh)} \quad (8)$$

where

SE = Storage Energy

<u>2rd Condition</u> - If 1st Condition true,

$$[\text{Wind Cost}] + [\text{PV Cost}] + [\text{Storage Cost}] = \text{Minimum Cost} =$$

$$[WC_{(GW)} * \$/kW\ W] + [PVC_{GW)} * \$/GW\ PV] + [SC_{(GWh)} * \$/GWh\ S] = \text{Minimum Cost}_{(\$)} \quad (9)$$

where

WC = Wind Capacity

W = of Wind

PVC = PV Capacity

PV = of PV

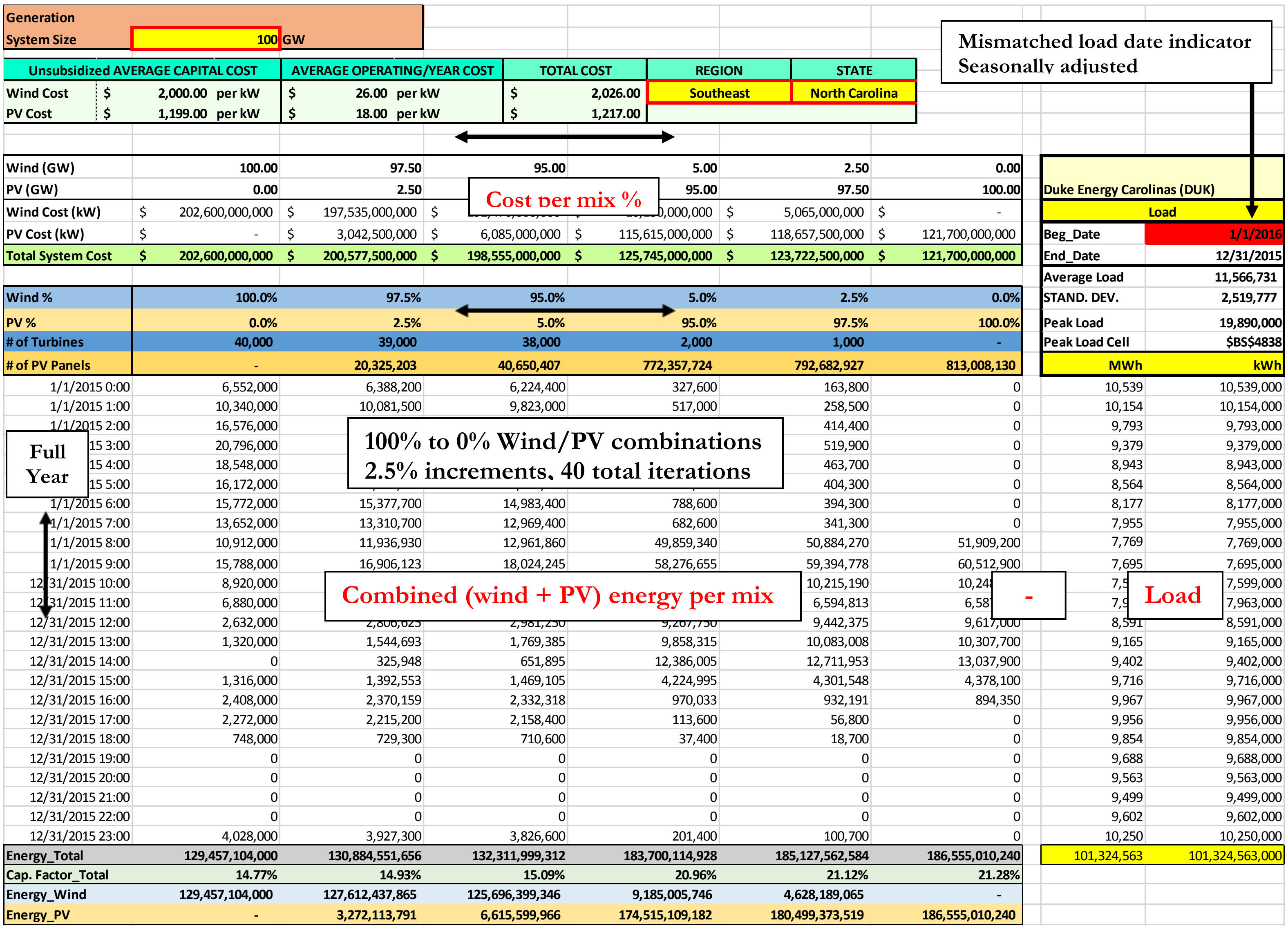
SC = Storage Capacity

S = of Storage

Durham, NC	Turbine Size	2.5	MW				
Latitude = N 36.000	Base System Size	1	GW			Base PV Panel	123 Watts
Longitude = W 79.375	Multiplication Factor	400	=1GW/2.5MW Turbines			Tracking System	Single-Axis

Date/Time	Wind Speed 85 m Synthesized [m/s]	GE 2.5-100 (85m) Power Output [kW]	1 GW System Wind Power [kW]	Surface Pressure [mbar]	Relative Humidity [%]	Ambient Temp °C	GHI [w/m2]	1 GW System PV Power [kW]
1/1/2015 0:00	4.44	163.80	65,520	1006.12	71.26	-3.80	0	0
1/1/2015 1:00	5.01	258.50	103,400	1005.90	71.08	-4.00	0	0
1/1/2015 2:00	5.73	414.40	165,760	1005.83	70.62	-4.20	0	0
1/1/2015 3:00	6.15	519.90	207,960	1005.58	70.46	-4.40	0	0
1/1/2015 4:00	5.92	463.70	185,480	1005.26	71.10	-4.40	0	0
1/1/2015 5:00	5.68	404.30	161,720	1005.30	72.32	-4.20	0	0
1/1/2015 6:00	5.63	394.30	157,720	1005.32	73.89	-4.30	0	0
1/1/2015 7:00	5.41	341.30	136,520	1005.09	75.61	-4.20	0	0
1/1/2015 8:00	5.06	272.80	109,120	1004.84	77.13	-1.30	143	519,092
1/1/2015 9:00	5.63	394.70	157,880	1004.85	77.98	1.60	310	605,129
1/1/2015 10:00	6.09	506.20	202,480	1005.14	78.43	4.60	443	572,163
1/1/2015 11:00	5.83	442.30	176,920	1005.36	78.99	6.60	524	514,779
1/1/2015 12:00	5.46	353.30	141,320	1005.42	74.49	7.70	543	489,375
12/31/2015 13:00	3.37	33.00	13,200	998.46	100.00	13.40	129	103,077
12/31/2015 14:00	2.78	0.00	0	998.71	98.17	13.20	163	130,379
12/31/2015 15:00	3.36	32.90	13,160	998.61	95.84	13.10	70	43,781
12/31/2015 16:00	3.65	60.20	24,080	998.11	94.95	12.80	23	8,944
12/31/2015 17:00	3.62	56.80	22,720	997.50	95.22	12.00	0	0
12/31/2015 18:00	3.19	18.70	7,480	997.27	95.48	11.40	0	0
12/31/2015 19:00	2.79	0.00	0	997.47	95.33	-0.60	0	0
12/31/2015 20:00	2.60	0.00	0	997.84	95.67	-1.70	0	0
12/31/2015 21:00	2.03	0.00	0	998.12	96.60	-2.30	0	0
12/31/2015 22:00	2.47	0.00	0	998.35	97.40	-2.90	0	0
12/31/2015 23:00	4.04	100.70	40,280	998.47	97.78	-3.40	0	0
	4.87	369.46	1,294,571,040	997.35	72.52	15.51	184.7908676	1,865,550,102
	Avg. Wind Speed		14.78%				Avg. IRR	21.28%
			Total Wind Energy					Total PV Energy
			Cap. Factor Wind					Cap. Factor PV

Figure 19. Input data part of custom Excel optimization model.



Generation System Size	100	GW

	Unsubsidized AVERAGE CAPITAL COST	AVERAGE OPERATING/YEAR COST	TOTAL COST	REGION	STATE
Wind Cost	$ 2,000.00 per kW	$ 26.00 per kW	$ 2,026.00	Southeast	North Carolina
PV Cost	$ 1,199.00 per kW	$ 18.00 per kW	$ 1,217.00		

Wind (GW)	100.00	97.50	95.00	5.00	2.50	0.00
PV (GW)	0.00	2.50	[illegible]	95.00	97.50	100.00
Wind Cost (kW)	$ 202,600,000,000	$ 197,535,000,000	$ [illegible]	[illegible],000,000	$ 5,065,000,000	$ -
PV Cost (kW)	$ -	$ 3,042,500,000	$ 6,085,000,000	$ 115,615,000,000	$ 118,657,500,000	$ 121,700,000,000
Total System Cost	$ 202,600,000,000	$ 200,577,500,000	$ 198,555,000,000	$ 125,745,000,000	$ 123,722,500,000	$ 121,700,000,000
Wind %	100.0%	97.5%	95.0%	5.0%	2.5%	0.0%
PV %	0.0%	2.5%	5.0%	95.0%	97.5%	100.0%
# of Turbines	40,000	39,000	38,000	2,000	1,000	-
# of PV Panels	-	20,325,203	40,650,407	772,357,724	792,682,927	813,008,130
1/1/2015 0:00	6,552,000	6,388,200	6,224,400	327,600	163,800	0
1/1/2015 1:00	10,340,000	10,081,500	9,823,000	517,000	258,500	0
1/1/2015 2:00	16,576,000	[illegible]	[illegible]	[illegible]	414,400	0
15 3:00	20,796,000	[illegible]	[illegible]	[illegible]	519,900	0
15 4:00	18,548,000	[illegible]	[illegible]	[illegible]	463,700	0
15 5:00	16,172,000	[illegible]	[illegible]	[illegible]	404,300	0
1/1/2015 6:00	15,772,000	15,377,700	14,983,400	788,600	394,300	0
1/1/2015 7:00	13,652,000	13,310,700	12,969,400	682,600	341,300	0
1/1/2015 8:00	10,912,000	11,936,930	12,961,860	49,859,340	50,884,270	51,909,200
1/1/2015 9:00	15,788,000	16,906,123	18,024,245	58,276,655	59,394,778	60,512,900
12/31/2015 10:00	8,920,000	[illegible]	[illegible]	[illegible]	10,215,190	[illegible]
12/31/2015 11:00	6,880,000	[illegible]	[illegible]	[illegible]	6,594,813	[illegible]
12/31/2015 12:00	2,632,000	[illegible]	[illegible]	[illegible]	9,442,375	9,617,000
12/31/2015 13:00	1,320,000	1,544,693	1,769,385	9,858,315	10,083,008	10,307,700
12/31/2015 14:00	0	325,948	651,895	12,386,005	12,711,953	13,037,900
12/31/2015 15:00	1,316,000	1,392,553	1,469,105	4,224,995	4,301,548	4,378,100
12/31/2015 16:00	2,408,000	2,370,159	2,332,318	970,033	932,191	894,350
12/31/2015 17:00	2,272,000	2,215,200	2,158,400	113,600	56,800	0
12/31/2015 18:00	748,000	729,300	710,600	37,400	18,700	0
12/31/2015 19:00	0	0	0	0	0	0
12/31/2015 20:00	0	0	0	0	0	0
12/31/2015 21:00	0	0	0	0	0	0
12/31/2015 22:00	0	0	0	0	0	0
12/31/2015 23:00	4,028,000	3,927,300	3,826,600	201,400	100,700	0
Energy_Total	129,457,104,000	130,884,551,656	132,311,999,312	183,700,114,928	185,127,562,584	186,555,010,240
Cap. Factor_Total	14.77%	14.93%	15.09%	20.96%	21.12%	21.28%
Energy_Wind	129,457,104,000	127,612,437,865	125,696,399,346	9,185,005,746	4,628,189,065	-
Energy_PV	-	3,272,113,791	6,615,599,966	174,515,109,182	180,499,373,519	186,555,010,240

Duke Energy Carolinas (DUK)	
Load	
Beg_Date	1/1/2016
End_Date	12/31/2015
Average Load	11,566,731
STAND. DEV.	2,519,777
Peak Load	19,890,000
Peak Load Cell	BS4838
MWh	kWh
10,539	10,539,000
10,154	10,154,000
9,793	9,793,000
9,379	9,379,000
8,943	8,943,000
8,564	8,564,000
8,177	8,177,000
7,955	7,955,000
7,769	7,769,000
7,695	7,695,000
[illegible]	7,599,000
[illegible]	7,963,000
8,591	8,591,000
9,165	9,165,000
9,402	9,402,000
9,716	9,716,000
9,967	9,967,000
9,956	9,956,000
9,854	9,854,000
9,688	9,688,000
9,563	9,563,000
9,499	9,499,000
9,602	9,602,000
10,250	10,250,000
101,324,563	101,324,563,000

Figure 20. Wind + PV combined energy. Multiplied by mix % and cost parameters. Load is subtracted.

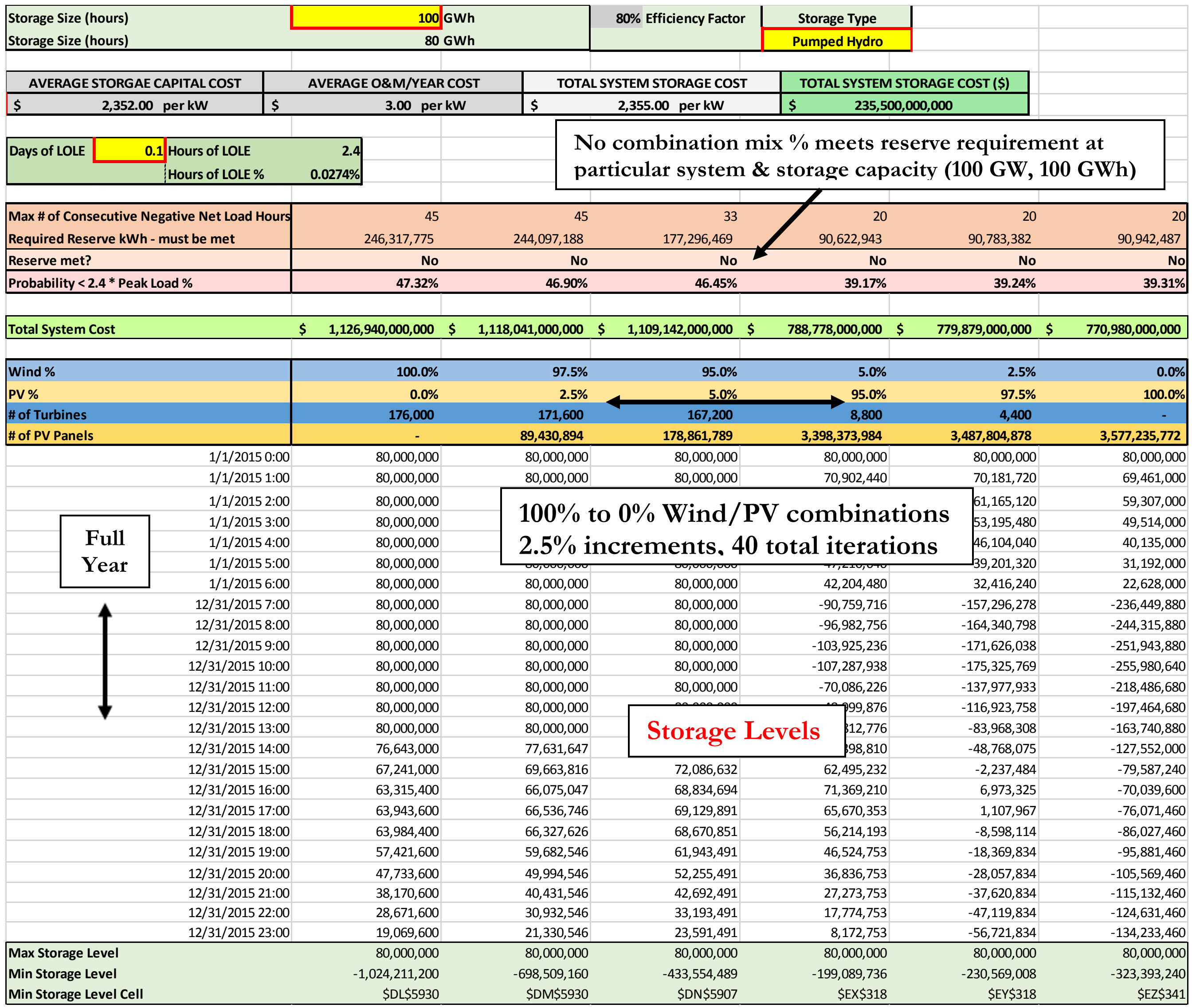
Generation - Load = NET LOAD						
Wind %	100.0%	97.5%	95.0%	5.0%	2.5%	0.0%
PV %	0.0%	2.5%	5.0%	95.0%	97.5%	100.0%
# of Turbines	40,000	39,000	38,000	2,000	1,000	-
# of PV Panels	-	20,325,203	40,650,407	772,357,724	792,682,927	813,008,130
1/1/2015 0:00	-3,987,000	-4,150,800	-4,314,600	-10,211,400	-10,375,200	-10,539,000
1/1/2015 1:00	186,000	-72,500	-331,000	-9,637,000	-9,895,500	-10,154,000
1/1/2015 2:00	6,783,000	[illegible]	[illegible]	[illegible]	-9,378,600	-9,793,000
1/1/2015 3:00	11,417,000	[illegible]	[illegible]	[illegible]	-8,859,100	-9,379,000
1/1/2015 4:00	9,605,000	[illegible]	[illegible]	[illegible]	-8,479,300	-8,943,000
1/1/2015 5:00	7,608,000	7,203,700	6,799,400	-7,755,400	-8,159,700	-8,564,000
1/1/2015 6:00	7,595,000	7,200,700	6,806,400	-7,388,400	-7,782,700	-8,177,000
1/1/2015 7:00	5,697,000	5,355,700	5,014,400	-7,272,400	-7,613,700	-7,955,000
1/1/2015 8:00	3,143,000	4,167,930	5,192,860	42,090,340	43,115,270	44,140,200
1/1/2015 9:00	8,093,000	9,211,123	[illegible]	50,581,655	51,699,778	52,817,900
12/31/2015 10:00	1,321,000	1,354,210	[illegible]	2,582,980	2,616,190	2,649,400
12/31/2015 11:00	-1,083,000	-1,090,313	-1,097,625	-1,360,875	-1,368,188	-1,375,500
12/31/2015 12:00	-5,959,000	-5,784,375	-5,609,750	676,750	851,375	1,026,000
12/31/2015 13:00	-7,845,000	-7,620,308	-7,395,615	693,315	918,008	1,142,700
12/31/2015 14:00	-9,402,000	-9,076,053	-8,750,105	2,984,005	3,309,953	3,635,900
12/31/2015 15:00	-8,400,000	-8,323,448	-8,246,895	-5,491,005	-5,414,453	-5,337,900
12/31/2015 16:00	-7,559,000	-7,596,841	-7,634,683	-8,996,968	-9,034,809	-9,072,650
12/31/2015 17:00	-7,684,000	-7,740,800	-7,797,600	-9,842,400	-9,899,200	-9,956,000
12/31/2015 18:00	-9,106,000	-9,124,700	-9,143,400	-9,816,600	-9,835,300	-9,854,000
12/31/2015 19:00	-9,688,000	-9,688,000	-9,688,000	-9,688,000	-9,688,000	-9,688,000
12/31/2015 20:00	-9,563,000	-9,563,000	-9,563,000	-9,563,000	-9,563,000	-9,563,000
12/31/2015 21:00	-9,499,000	-9,499,000	-9,499,000	-9,499,000	-9,499,000	-9,499,000
12/31/2015 22:00	-9,602,000	-9,602,000	-9,602,000	-9,602,000	-9,602,000	-9,602,000
12/31/2015 23:00	-6,222,000	-6,322,700	-6,423,400	-10,048,600	-10,149,300	-10,250,000
Net Load Mean	3,211,477	3,374,428	3,537,379	9,403,602	9,566,552	9,729,503
Net Load Standard Dev.	19,730,163	19,175,098	18,649,306	27,727,357	28,497,080	29,275,723
Probability < 2.4 * Peak Load %	98.80%	98.97%	99.11%	91.66%	90.98%	90.29%

100% to 0% Wind/PV combinations
2.5% increments, 40 total iterations

Full Year

Net Load

Figure 21. Combined wind + PV energy generation – Load = Net Load (shown here).



Storage Size (hours)	100 GWh	80% Efficiency Factor	Storage Type
Storage Size (hours)	80 GWh		Pumped Hydro

AVERAGE STORGAE CAPITAL COST	AVERAGE O&M/YEAR COST	TOTAL SYSTEM STORAGE COST	TOTAL SYSTEM STORAGE COST ($)
$ 2,352.00 per kW	$ 3.00 per kW	$ 2,355.00 per kW	$ 235,500,000,000

Days of LOLE	0.1	Hours of LOLE	2.4
		Hours of LOLE %	0.0274%

Max # of Consecutive Negative Net Load Hours	45	45	33	20	20	20
Required Reserve kWh - must be met	246,317,775	244,097,188	177,296,469	90,622,943	90,783,382	90,942,487
Reserve met?	No	No	No	No	No	No
Probability < 2.4 * Peak Load %	47.32%	46.90%	46.45%	39.17%	39.24%	39.31%
Total System Cost	$ 1,126,940,000,000	$ 1,118,041,000,000	$ 1,109,142,000,000	$ 788,778,000,000	$ 779,879,000,000	$ 770,980,000,000
Wind %	100.0%	97.5%	95.0%	5.0%	2.5%	0.0%
PV %	0.0%	2.5%	5.0%	95.0%	97.5%	100.0%
# of Turbines	176,000	171,600	167,200	8,800	4,400	-
# of PV Panels	-	89,430,894	178,861,789	3,398,373,984	3,487,804,878	3,577,235,772
1/1/2015 0:00	80,000,000	80,000,000	80,000,000	80,000,000	80,000,000	80,000,000
1/1/2015 1:00	80,000,000	80,000,000	80,000,000	70,902,440	70,181,720	69,461,000
1/1/2015 2:00	80,000,000	[illegible]	[illegible]	[illegible]	61,165,120	59,307,000
1/1/2015 3:00	80,000,000	[illegible]	[illegible]	[illegible]	53,195,480	49,514,000
1/1/2015 4:00	80,000,000	[illegible]	[illegible]	[illegible]	46,104,040	40,135,000
1/1/2015 5:00	80,000,000	[illegible]	[illegible]	[illegible]	39,201,320	31,192,000
1/1/2015 6:00	80,000,000	80,000,000	80,000,000	42,204,480	32,416,240	22,628,000
12/31/2015 7:00	80,000,000	80,000,000	80,000,000	-90,759,716	-157,296,278	-236,449,880
12/31/2015 8:00	80,000,000	80,000,000	80,000,000	-96,982,756	-164,340,798	-244,315,880
12/31/2015 9:00	80,000,000	80,000,000	80,000,000	-103,925,236	-171,626,038	-251,943,880
12/31/2015 10:00	80,000,000	80,000,000	80,000,000	-107,287,938	-175,325,769	-255,980,640
12/31/2015 11:00	80,000,000	80,000,000	80,000,000	-70,086,226	-137,977,933	-218,486,680
12/31/2015 12:00	80,000,000	80,000,000	[illegible]	[illegible]	-116,923,758	-197,464,680
12/31/2015 13:00	80,000,000	80,000,000	[illegible]	[illegible]	-83,968,308	-163,740,880
12/31/2015 14:00	76,643,000	77,631,647	[illegible]	[illegible]	-48,768,075	-127,552,000
12/31/2015 15:00	67,241,000	69,663,816	72,086,632	62,495,232	-2,237,484	-79,587,240
12/31/2015 16:00	63,315,400	66,075,047	68,834,694	71,369,210	6,973,325	-70,039,600
12/31/2015 17:00	63,943,600	66,536,746	69,129,891	65,670,353	1,107,967	-76,071,460
12/31/2015 18:00	63,984,400	66,327,626	68,670,851	56,214,193	-8,598,114	-86,027,460
12/31/2015 19:00	57,421,600	59,682,546	61,943,491	46,524,753	-18,369,834	-95,881,460
12/31/2015 20:00	47,733,600	49,994,546	52,255,491	36,836,753	-28,057,834	-105,569,460
12/31/2015 21:00	38,170,600	40,431,546	42,692,491	27,273,753	-37,620,834	-115,132,460
12/31/2015 22:00	28,671,600	30,932,546	33,193,491	17,774,753	-47,119,834	-124,631,460
12/31/2015 23:00	19,069,600	21,330,546	23,591,491	8,172,753	-56,721,834	-134,233,460
Max Storage Level	80,000,000	80,000,000	80,000,000	80,000,000	80,000,000	80,000,000
Min Storage Level	-1,024,211,200	-698,509,160	-433,554,489	-199,089,736	-230,569,008	-323,393,240
Min Storage Level Cell	DL5930	DM5930	DN5907	EX318	EY318	EZ341

Figure 22. Storage levels per hour, reserve margin requirement check, storage cost.

Iterative Optimization

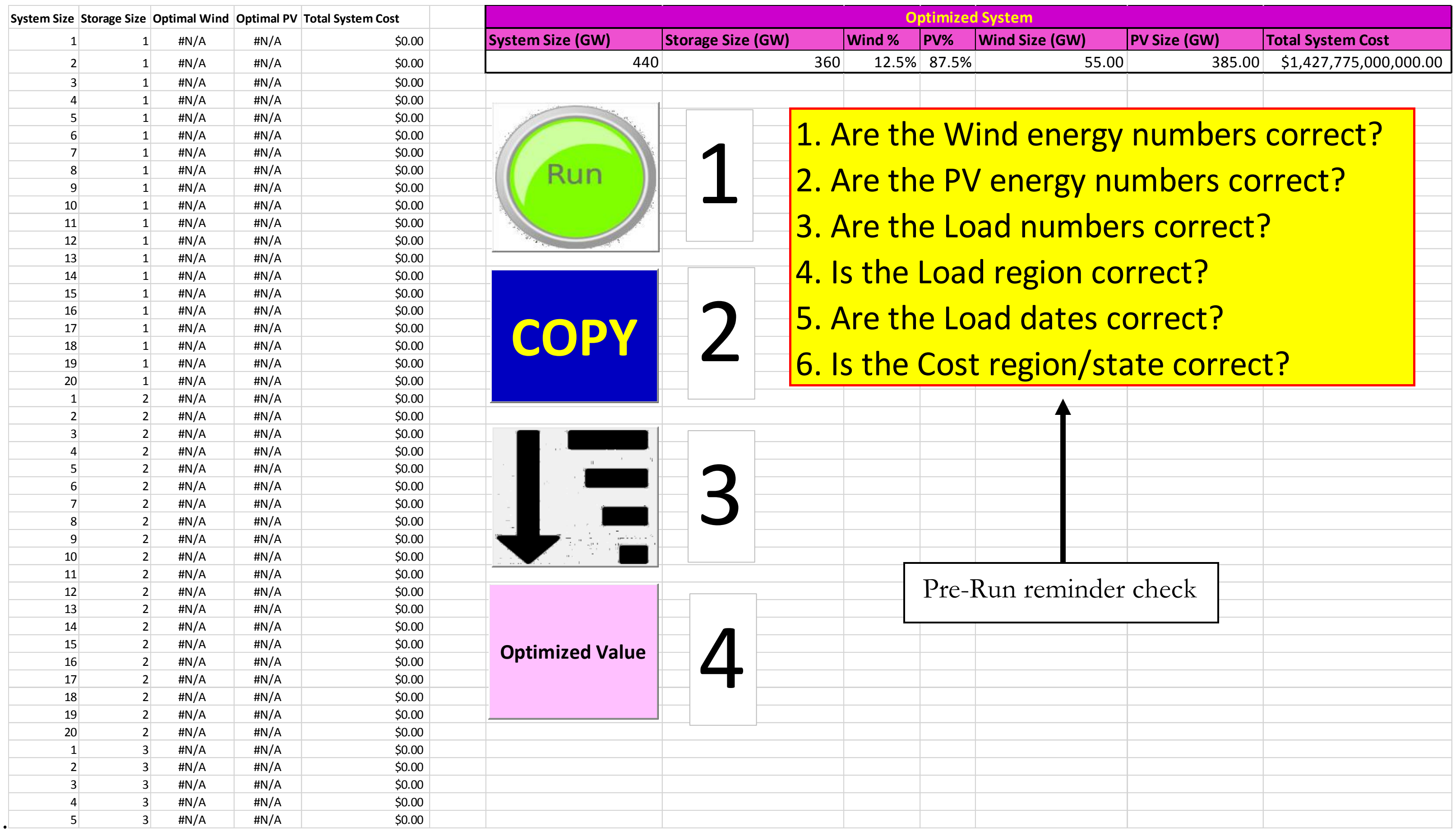
To run my multi-iterative optimization algorithm, I developed a custom Microsoft Visual Basic script that utilized a matrix list of every possible combination of system and storage (GWh) capacities from 1 GW to 20 GW by increments of 1 GW, and every possible combination of system and storage capacities from 25 GW to 750 GW by increments of 5 GW (see Figure 23). The total number of system and storage capacity combinations was 22,897.

After running multiple optimization iterations at system and storage capacities of 2000 GW maximum, it became obvious that no optimized capacity combination needed to be larger than 750 GW. Using Microsoft Excel 2016 (64-bit version), on a 3.5 GHz, 16 GB RAM, Windows 10 Dell PC, the 2000 GW maximum capacity optimizations required approximately 2.5 days to complete. After I reduced the maximum capacity level to 750 GW, the optimization model required less than one day to complete. The load profile data inputs did not warrant any larger maximum capacities than 750 GW. The average and peak load data magnitudes were small and targeted enough to cap the maximum capacities at 750 GW.

For every combination of system and storage capacity, the script copied/pasted the wind and PV mix percentage of the lowest cost system with storage levels that always met the minimum reserve requirement. If no combination mix of wind and PV capacity resulted in a storage level that always met the minimum reserve requirement, #N/A was the result, and that combination mix was disqualified (see Figure 24).

After the initial "Run" script completed every iteration of system and storage capacity, the "copy/paste values only" script copied/pasted all results to available nearby columns. The copy/paste of values only was necessary for Excel's Sort function to work properly. Next, the Sort script sorted all results by total system cost, from lowest to highest.

After sorting the results by total system cost, the optimization script found the lowest cost system where the storage level always met the minimum reserve requirement. This value was always the first value that is not #N/A, because the system and storage capacities were previously sorted lowest to highest by total system cost (see Figure 24). The lowest cost system with a storage capacity that always met the minimum reserve requirement designated the optimal wind/PV combination mix (see Figure 25).



System Size	Storage Size	Optimal Wind	Optimal PV	Total System Cost
1	1	#N/A	#N/A	$0.00
2	1	#N/A	#N/A	$0.00
3	1	#N/A	#N/A	$0.00
4	1	#N/A	#N/A	$0.00
5	1	#N/A	#N/A	$0.00
6	1	#N/A	#N/A	$0.00
7	1	#N/A	#N/A	$0.00
8	1	#N/A	#N/A	$0.00
9	1	#N/A	#N/A	$0.00
10	1	#N/A	#N/A	$0.00
11	1	#N/A	#N/A	$0.00
12	1	#N/A	#N/A	$0.00
13	1	#N/A	#N/A	$0.00
14	1	#N/A	#N/A	$0.00
15	1	#N/A	#N/A	$0.00
16	1	#N/A	#N/A	$0.00
17	1	#N/A	#N/A	$0.00
18	1	#N/A	#N/A	$0.00
19	1	#N/A	#N/A	$0.00
20	1	#N/A	#N/A	$0.00
1	2	#N/A	#N/A	$0.00
2	2	#N/A	#N/A	$0.00
3	2	#N/A	#N/A	$0.00
4	2	#N/A	#N/A	$0.00
5	2	#N/A	#N/A	$0.00
6	2	#N/A	#N/A	$0.00
7	2	#N/A	#N/A	$0.00
8	2	#N/A	#N/A	$0.00
9	2	#N/A	#N/A	$0.00
10	2	#N/A	#N/A	$0.00
11	2	#N/A	#N/A	$0.00
12	2	#N/A	#N/A	$0.00
13	2	#N/A	#N/A	$0.00
14	2	#N/A	#N/A	$0.00
15	2	#N/A	#N/A	$0.00
16	2	#N/A	#N/A	$0.00
17	2	#N/A	#N/A	$0.00
18	2	#N/A	#N/A	$0.00
19	2	#N/A	#N/A	$0.00
20	2	#N/A	#N/A	$0.00
1	3	#N/A	#N/A	$0.00
2	3	#N/A	#N/A	$0.00
3	3	#N/A	#N/A	$0.00
4	3	#N/A	#N/A	$0.00
5	3	#N/A	#N/A	$0.00

Optimized System						
System Size (GW)	Storage Size (GW)	Wind %	PV%	Wind Size (GW)	PV Size (GW)	Total System Cost
440	360	12.5%	87.5%	55.00	385.00	$1,427,775,000,000.00

Figure 23. Optimization sheet with custom Visual Basic programs.

[1] Run – increments System and Storage capacity per combination mix list values. Copy/Paste values into Wind/PV columns.

[2] Copy – after Run completes, copy/paste "values only" of results so sort will work properly.

[3] Sort – sorts results by Total System Cost.

[4] Optimized Value – finds lowest Total System Cost value that meets reserve requirement (is not #N/A value). Copy/Paste to Optimized System fields.

Total System Size (GW)	100
Total Storage Size (GWh)	100
Total Wind Size (GW)	#N/A
Total PV Size (GW)	#N/A
Storage Price (kW)	$2,355
Wind Price (kW)	$2,026
PV Price (kW)	$1,217
Total System Cost for Optimal Mix (1st Year)	$ -
Optimal Wind %	#N/A
Optimal PV %	#N/A
# of Turbines	#N/A
# of PV Panels	#N/A
Avg Wind Speed (m/s)	4.87
Avg Wind Speed (mph)	10.90
Wind Capacity Factor (%)	14.78%
PV Capacity Factor (%)	21.28%
Avg IRR (w/m2)	184.79
Combined Capacity Factor (%)	#N/A
Average Ambient Temperature (°C)	15.51
Average Surface Pressure (mbar)	997.35
Average Relative Humidity (%)	72.52
Max Consecutive Hours NO WIND Power	23
Max Consecutive Hours NO SUN Power	17
Max Consecutive Hours NO POWER	14
Optimal System Max Consecutive Negative Net Load Hours	45
Load Region	DUK
Average Hourly Load (kW)	11,566,731
Peak Load (kW)	19,890,000
Peak Load Season	SUMMER
Optimal System Required Reserve (kWh)	#N/A
Reserve %	#N/A
Hours of Reserve at Average Load	#N/A
Hours of Reserve at Peak Load	#N/A
Annual Total Energy Produced (kWh)	#N/A
20 Year Levelized Cost of Energy (LCOE) - Energy Only ($/kWh)	#N/A
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage ($/kWh)	#N/A

Figure 24. Example data output list of a disqualified system and storage capacity mix. #N/A is the result when no wind/PV combination mix meets the reserve requirement for the specified system and storage capacity.

Total System Size (GW)	**440**
Total Storage Size (GWh)	**360**
Total Wind Size (GW)	**55**
Total PV Size (GW)	**385**
Storage Price (kW)	**$2,355**
Wind Price (kW)	**$2,026**
PV Price (kW)	**$1,217**
Total System Cost for Optimal Mix (1st Year)	**$ 1,427,775,000,000**
Optimal Wind %	**12.5%**
Optimal PV %	**87.5%**
# of Turbines	**22,000**
# of PV Panels	**3,130,081,301**
Avg Wind Speed (m/s)	**4.87**
Avg Wind Speed (mph)	**10.90**
Wind Capacity Factor (%)	**14.78%**
PV Capacity Factor (%)	**21.28%**
Avg IRR (w/m2)	**184.79**
Combined Capacity Factor (%)	**20.47%**
Average Ambient Temperature (°C)	**15.51**
Average Surface Pressure (mbar)	**997.35**
Average Relative Humidity (%)	**72.52**
Max Consecutive Hours **NO WIND** Power	**23**
Max Consecutive Hours **NO SUN** Power	**17**
Max Consecutive Hours **NO POWER**	**14**
Optimal System Max Consecutive Negative Net Load Hours	**16**
Load Region	**DUK**
Average Hourly Load (kW)	**11,566,731**
Peak Load (kW)	**19,890,000**
Peak Load Season	**SUMMER**
Optimal System Required Reserve (kWh)	**81,127,805**
Reserve %	**28.17%**
Hours of Reserve at Average Load	**7.01**
Hours of Reserve at Peak Load	**4.08**
Annual Total Energy Produced (kWh)	**789,438,196,624**
20 Year Levelized Cost of Energy (LCOE) - Energy Only ($/kWh)	**$0.0351**
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage ($/kWh)	**$0.0722**

Figure 25. Example of an optimized system data output list.

CHAPTER 5: RESEARCH FINDINGS

The Two-Hand Rule

One of the most fascinating results that I discovered while analyzing my output data is that the total amount of energy generated by any co-located wind and PV system always favored 100% of the strongest renewable resource. In other words, if one only looks at the amount of total energy generated by any co-located or hybrid PV/wind system, the greatest amount of total energy generated is always sourced from 100% PV or 100% wind, never a combination mix of percentages of the two technologies.

For example, a 75% PV and 25% wind system never generates more total energy than a 100% PV system, and vice versa. It is a mathematical certainty that I have coined the "Two-Hand Rule." Imagine you have four apples in your left hand and five apples in your right hand. You can never take 40% of the four apples in your left hand and 60% of the five apples in your right hand and sum them together to be greater than five apples. In fact, you can never take 99% of the five apples in your right hand and 1% of the four apples in your left hand and sum them together to be greater than five apples.

The same mathematical certainty applies to co-located or hybrid PV/wind energy systems. The greatest amount of total energy generated will always be generated by 100% of the renewable resource that is strongest in any particular area; 100% PV or 100% wind always generates the greatest amount of total energy when comparing any combination mix percentage of the two technologies. A mathematical proof supporting this claim was supplied by Dr. Rick Klima, Professor and Assistant Chair of the Appalachian State University Department of Mathematical Sciences (see Appendix A).

Implications of the Two-Hand Rule

Although the total amount of energy generated always favors any area's strongest renewable resource, total energy generated does not consider the intermittency and variability of renewable energy generation. In addition, total amount of energy generated does not consider the timing aspects of load and generation. In addition, total amount of energy generated does not consider the price of the energy generated. All of the renewable energy questions listed below were factors that played a significant role in my optimization model of a renewable energy system:

1. How much energy was generated?
2. When was the energy generated?
3. How often was the energy generated?
4. What was the load when the energy was generated?
5. At what price was the energy generated?
6. How much of the energy was stored?
7. At what price was the energy stored?

A model such as the one I developed consisting of PV and wind generation and energy storage needs to take into consideration, at the very least, all of the primary factors listed above, in order to produce an optimized renewable energy system.

Other factors, such as additional energy storage systems (batteries, compressed air, thermal), potential strategic locations of the energy storage systems in regard to load, vicinity of current transmission substations and high-voltage lines, and the costs to add any required electrical infrastructure, would all need to be included and analyzed in another, larger model to achieve a fully comprehensive optimization model of our future renewable energy environment.

Renewable energy developer difficulties.

One aspect of our current renewable energy environment is that much difficulty lies in convincing a utility-scale renewable energy system developer to develop a co-located PV and wind system when doing so equates to the project generating less total energy, and therefore, the development company receiving less money. Almost all utility-scale renewable projects generate revenue per kWh of energy produced. A co-located or hybrid system will always generate less total energy than one of 100% PV or 100% wind because of the Two-Hand Rule. Thus, there is no inherent financial incentive for a renewable energy development company to develop anything other than 100% PV or 100% wind systems.

RPS laws.

Due to the lack of inherent financial benefit for renewable energy developers to develop co-located renewable energy systems, our RPS laws must be structured in ways that incentivize renewable energy developers to match their developments according to the optimal mix of renewable technologies that are in the best interest of each state. The best interest of each state is a mix of renewable energy technologies that are optimized to match the state's weather resources, load profiles, and energy storage capabilities, at the lowest cost possible. To achieve the goal of matching developer projects to optimal state resources and parameters, states' RPS mandates need to be founded in sound and comprehensive scientific research.

Optimal PV/Wind Combination Mixes

Combined Resources Map of Data Points and Corresponding Tables

Figure 26 displays a cartographical list of data points overlaid on a United States GIS map of combined PV/wind resources. Each data point number references a pair of x,y coordinates that were optimized for the lowest cost PV/wind combination mix that always met the minimum reserve requirement. Figures 27, 28, and 29 show the name of the nearest city, its map ID number, the optimal system capacity (GW), storage size capacity (GWh), optimal percentage of PV and wind technology capacity (%), average annual wind speed (m/s), irradiance (W/m^2), average load (MW), and the total system cost ($), for each area optimized. Each figure represents a different reserve margin calculation used for the optimization (baseline, middle ground, zero).

Baseline reserve margin data table.

The table denoted Figure 27 uses my novel baseline reserve margin calculation method that takes into consideration the probability of hourly net load being less than 2.4 peak load hours. This is the most conservative of the reserve margin constraints because it requires the highest amount of reserve margin to be maintained for every hour of the year.

Middle ground reserve margin data table.

The map denoted Figure 28 uses my middle ground reserve margin calculation that calculates the probability of a negative net load for any hour of the year. This calculation is less conservative than my baseline method, because it does not require a reserve margin amount as high as the baseline's

Zero reserve margin data table.

The map denoted Figure 29 does not require any reserve margin. The storage level cannot go below zero for any hour of the year, but no additional reserve storage capacity is required. This is the most aggressive of the reserve margin calculation methods because no reserve margin is required.

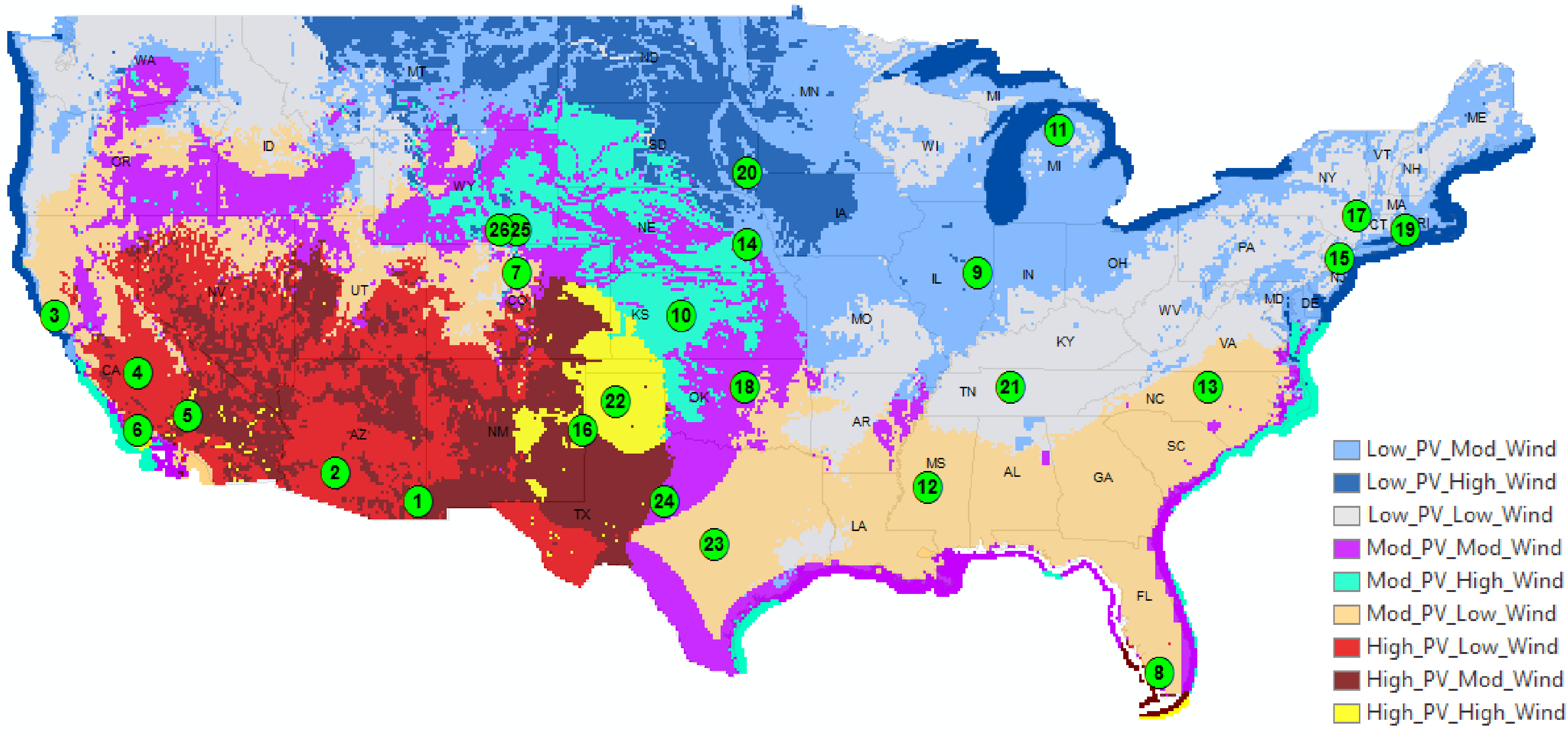


Figure 26. United States combined PV/wind resources with data points indicating locations optimized in this study.

Optimized Systems - Baseline Reserve Margin (Conservative)									
Map ID #	ST_City	System Size (GW)	Storage Size (GW)	Optimal Wind (%)	Optimal PV (%)	Avg Wind Speed (m/s)	Avg Irradiance (W/m^2)	Avg Hourly Load (kW)	Total System Cost (1st Year) ($)
1	**AZ_Bowie**	345	400	47.5%	52.5%	5.80	237.43	12,232,454	$1,506,437,250,000
2	**AZ_Phoenix**	205	540	5.0%	95.0%	4.89	244.72	12,232,454	$1,534,079,500,000
3	**CA_Bodega**	430	345	15.0%	85.0%	5.16	216.58	12,085,209	$1,440,898,500,000
4	**CA_Fresno**	280	345	17.5%	82.5%	5.02	224.71	12,085,209	$1,226,742,000,000
5	**CA_Mojave**	235	385	20.0%	80.0%	5.69	245.08	11,970,836	$1,258,611,000,000
6	**CA_Santa_Barbara**	225	385	15.0%	85.0%	5.02	233.33	11,970,836	$1,235,501,250,000
7	**CO_Boulder**	145	85	10.0%	90.0%	5.60	176.92	2,872,491	$385,760,500,000
8	**FL_Everglades_City**	290	515	5.0%	95.0%	5.09	204.66	14,379,352	$1,594,015,500,000
9	**IL_Champaign**	190	165	35.0%	65.0%	7.33	172.90	5,620,706	$702,132,000,000
10	**KS_Hays**	25	20	10.0%	90.0%	7.74	202.47	711,464	$79,525,000,000
11	**MI_Gaylord**	480	545	20.0%	80.0%	7.27	144.15	18,772,505	$1,987,731,000,000
12	**MS_Jackson**	715	635	2.5%	97.5%	4.69	190.51	19,431,885	$2,408,623,000,000
13	**NC_Durham**	440	360	12.5%	87.5%	4.87	184.79	11,566,731	$1,427,775,000,000
14	**NE_Lincoln**	10	12	42.5%	57.5%	7.61	178.91	394,619	$42,545,250,000
15	**NJ_Edison**	160	150	25.0%	75.0%	5.59	174.28	5,046,987	$624,850,000,000
16	**NM_Clovis**	40	80	20.0%	80.0%	7.53	223.49	1,589,393	$241,376,000,000
17	**NY_Millbrook**	60	35	12.5%	87.5%	4.55	169.79	1,149,023	$173,100,000,000
18	**OK_Stillwater**	125	145	42.5%	57.5%	7.27	194.28	3,620,070	$517,165,625,000
19	**RI_Kingston**	25	30	17.5%	82.5%	5.35	173.37	927,537	$110,106,250,000
20	**SD_Sioux_Falls**	2	3	47.5%	52.5%	7.86	174.22	87,571	$9,924,500,000
21	**TN_Nashville**	470	560	20.0%	80.0%	5.44	180.36	17,652,869	$1,975,860,000,000
22	**TX_Amarillo**	60	95	52.5%	47.5%	7.62	218.28	3,566,076	$311,344,500,000
23	**TX_Austin**	145	200	67.5%	32.5%	6.60	202.57	6,515,835	$692,164,875,000
24	**TX_Bronte**	50	40	5.0%	95.0%	7.17	217.29	1,134,484	$156,932,500,000
25	**WY_Laramie**	70	65	75.0%	25.0%	8.12	187.11	2,872,491	$262,117,500,000
26	**WY_McFadden**	105	90	15.0%	85.0%	6.95	184.22	2,872,491	$348,234,750,000

Figure 27. Optimized system data using conservative baseline reserve margin calculation.

Optimized Systems - Reserve Margin (Middle Ground)									
Map ID #	ST_City	System Size (GW)	Storage Size (GW)	Optimal Wind (%)	Optimal PV (%)	Avg Wind Speed (m/s)	Avg Irradiance (W/m^2)	Avg Hourly Load (kW)	Total System Cost (1st Year) ($)
1	**AZ_Bowie**	290	380	35.0%	65.0%	5.80	237.43	12.23	$1,338,977,000,000
2	**AZ_Phoenix**	210	450	5.0%	95.0%	4.89	244.72	12.23	$1,328,529,000,000
3	**CA_Bodega**	405	310	22.5%	77.5%	5.16	216.58	12.09	$1,343,898,375,000
4	**CA_Fresno**	280	285	17.5%	82.5%	5.02	224.71	12.09	$1,085,442,000,000
5	**CA_Mojave**	180	315	22.5%	77.5%	5.69	245.08	11.97	$1,014,646,500,000
6	**CA_Santa_Barbara**	180	305	22.5%	77.5%	5.02	233.33	11.97	$991,096,500,000
7	**CO_Boulder**	145	75	10.0%	90.0%	5.60	176.92	2.87	$362,210,500,000
8	**FL_Everglades_City**	235	440	7.5%	92.5%	5.09	204.66	14.38	$1,349,496,125,000
9	**IL_Champaign**	185	150	32.5%	67.5%	7.33	172.90	5.62	$654,957,250,000
10	**KS_Hays**	20	20	2.5%	97.5%	7.74	202.47	0.71	$72,425,000,000
11	**MI_Gaylord**	475	440	20.0%	80.0%	7.27	144.15	18.77	$1,733,120,000,000
12	**MS_Jackson**	710	575	2.5%	97.5%	4.69	190.51	19.43	$2,260,937,000,000
13	**NC_Durham**	430	325	12.5%	87.5%	4.87	184.79	11.57	$1,332,168,750,000
14	**NE_Lincoln**	6	12	55.0%	45.0%	7.61	178.91	0.39	$37,140,900,000
15	**NJ_Edison**	135	120	42.5%	57.5%	5.59	174.28	5.05	$541,010,250,000
16	**NM_Clovis**	35	70	25.0%	75.0%	7.53	223.49	1.59	$211,951,250,000
17	**NY_Millbrook**	55	35	10.0%	90.0%	4.55	169.79	1.15	$163,792,000,000
18	**OK_Stillwater**	120	135	37.5%	62.5%	7.27	194.28	3.62	$483,870,000,000
19	**RI_Kingston**	15	25	50.0%	50.0%	5.35	173.37	0.93	$88,740,000,000
20	**SD_Sioux_Falls**	3	2	65.0%	35.0%	7.86	174.22	0.09	$9,235,500,000
21	**TN_Nashville**	415	460	32.5%	67.5%	5.44	180.36	17.65	$1,704,191,875,000
22	**TX_Amarillo**	50	80	35.0%	65.0%	7.62	218.28	3.57	$257,627,500,000
23	**TX_Austin**	105	165	52.5%	47.5%	6.60	202.57	6.52	$541,909,125,000
24	**TX_Bronte**	45	40	10.0%	90.0%	7.17	217.29	1.13	$151,633,500,000
25	**WY_Laramie**	50	60	57.5%	42.5%	8.12	187.11	2.87	$215,398,750,000
26	**WY_McFadden**	120	65	30.0%	70.0%	6.95	184.22	2.87	$316,623,000,000

Figure 28. Optimized system data using middle ground reserve margin calculation.

Optimized Systems - No Reserve Margin (Aggressive)									
Map ID #	ST_City	System Size (GW)	Storage Size (GW)	Optimal Wind (%)	Optimal PV (%)	Avg Wind Speed (m/s)	Avg Irradiance (W/m^2)	Avg Hourly Load (kW)	Total System Cost (1st Year) ($)
1	**AZ_Bowie**	245	375	17.5%	82.5%	5.80	237.43	12,232,454	$1,222,364,250,000
2	**AZ_Phoenix**	210	385	5.0%	95.0%	4.89	244.72	12,232,454	$1,175,454,000,000
3	**CA_Bodega**	395	265	20.0%	80.0%	5.16	216.58	12,085,209	$1,215,627,000,000
4	**CA_Fresno**	280	230	17.5%	82.5%	5.02	224.71	12,085,209	$955,917,000,000
5	**CA_Mojave**	140	290	2.5%	97.5%	5.69	245.08	11,970,836	$874,900,500,000
6	**CA_Santa_Barbara**	175	250	22.5%	77.5%	5.02	233.33	11,970,836	$853,993,125,000
7	**CO_Boulder**	140	65	5.0%	95.0%	5.60	176.92	2,872,491	$329,258,000,000
8	**FL_Everglades_City**	235	355	7.5%	92.5%	5.09	204.66	14,379,352	$1,149,321,125,000
9	**IL_Champaign**	200	130	12.5%	87.5%	7.33	172.90	5,620,706	$601,200,000,000
10	**KS_Hays**	20	17	2.5%	97.5%	7.74	202.47	711,464	$65,360,000,000
11	**MI_Gaylord**	490	365	10.0%	90.0%	7.27	144.15	18,772,505	$1,536,314,000,000
12	**MS_Jackson**	710	465	2.5%	97.5%	4.69	190.51	19,431,885	$2,001,887,000,000
13	**NC_Durham**	435	260	12.5%	87.5%	4.87	184.79	11,566,731	$1,185,684,375,000
14	**NE_Lincoln**	6	11	52.5%	47.5%	7.61	178.91	394,619	$34,723,950,000
15	**NJ_Edison**	130	105	42.5%	57.5%	5.59	174.28	5,046,987	$496,114,500,000
16	**NM_Clovis**	35	65	25.0%	75.0%	7.53	223.49	1,589,393	$200,176,250,000
17	**NY_Millbrook**	50	30	15.0%	85.0%	4.55	169.79	1,149,023	$147,805,000,000
18	**OK_Stillwater**	115	130	35.0%	65.0%	7.27	194.28	3,620,070	$463,878,250,000
19	**RI_Kingston**	16	19	45.0%	55.0%	5.35	173.37	927,537	$75,585,000,000
20	**SD_Sioux_Falls**	3	2	40.0%	60.0%	7.86	174.22	87,571	$8,898,000,000
21	**TN_Nashville**	420	375	27.5%	72.5%	5.44	180.36	17,652,869	$1,495,012,500,000
22	**TX_Amarillo**	45	70	25.0%	75.0%	7.62	218.28	3,566,076	$225,206,250,000
23	**TX_Austin**	105	145	52.5%	47.5%	6.60	202.57	6,515,835	$494,809,125,000
24	**TX_Bronte**	55	30	2.5%	97.5%	7.17	217.29	1,134,484	$139,060,375,000
25	**WY_Laramie**	55	50	52.5%	47.5%	8.12	187.11	2,872,491	$198,067,875,000
26	**WY_McFadden**	110	60	15.0%	85.0%	6.95	184.22	2,872,491	$284,074,500,000

Figure 29. Optimized system data using zero reserve margin.

Key Statistics

The 26 areas modeled produced the following hourly key statistics for one year. These key statistics provided a framework that aided in comparing the renewable resources of each location modeled. Maximum and minimum values set the magnitudinal range of each location's renewable resources, the average value established a norm, and quartiles helped distinguish how strong or weak a renewable resource in one location was compared to another location.

Wind.

- Minimum wind speed: 4.55 m/s (Millbrook, NY)
- Average wind speed: 6.22 m/s
- Maximum wind speed: 8.12 m/s (Laramie, WY)
- Wind speed quartiles (Figure 30)

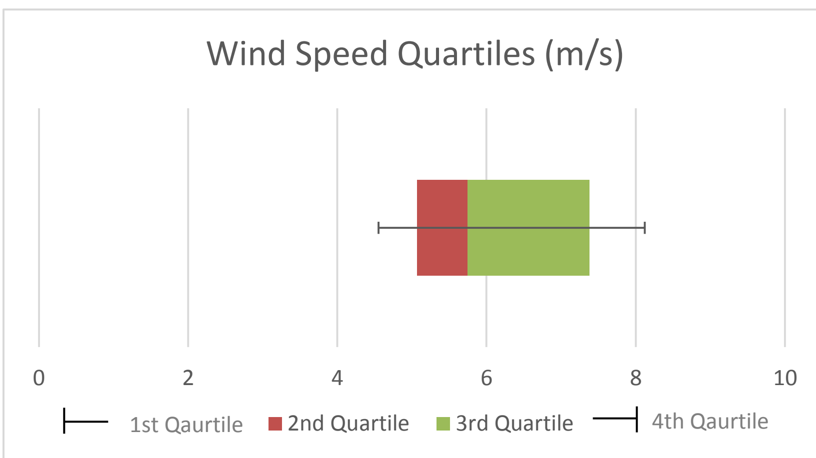


Figure 30. Wind speed quartiles for all 26 locations modeled.

Irradiance.

- Minimum irradiance: 144.15 W/m^2 (Gaylord, MI)
- Average irradiance: 198.32 W/m^2
- Maximum irradiance: 245.08 W/m^2 (Mojave, CA)

- Irradiance quartiles (Figure 31)

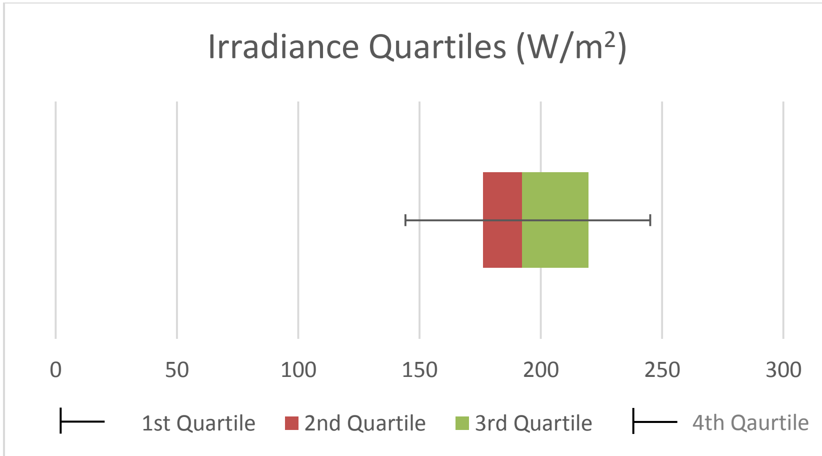


Figure 31. Irradiance quartiles for all 26 locations modeled.

Quartile Analysis of Optimal Wind and PV Percentage Differences

I could not decipher many distinguishing patterns between quartile differences and optimal combination mix percentages (see Figure 32). One might logically conclude that if a location's wind and PV resource quartile differences are large, the percentage difference between the optimal PV and wind combination mix would be large. However, the data do not support this logic. The average differences of the optimal PV and wind combination mixes in comparison to the wind and PV resource quartile differences is approximately null. I believe I can attribute this result to two possible explanations.

Sample size too small.

The first possible explanation for the wind and PV resource quartile differences having little effect on the average differences of optimal PV/wind mix combinations is that the sample size of 26 locations is not large enough to fully render comprehensive quartile analysis results. A much greater number of locations would need to be simulated in order to gain a more accurate quartile analysis.

Another indication this may be a valid explanation is that the two quartile difference calculations for the baseline and middle ground reserve margins are significantly lower than all other quartile difference calculations (Figure 32). This seems to be an unusual result not easily attributable to any specific variable. Therefore, lack of sample size may be the reason for this type of result.

Resource and load timings.

The second possible explanation is that a quartile analysis does not take into consideration the timing of the resources and loads. In some locations, the timing of when a location's renewable resources are capable of providing energy is not compatible with when that location's loads are maximized. An example is Lincoln, Nebraska: although its wind resource registered in the 4th quartile (high), and its PV resource registered in the 2nd quartile (moderately low), its peak load season is during the end of summer and beginning of fall. In the summer, wind resources are typically weak. Therefore, the optimal combination mix result included more PV to make up for this energy generation-load timing shortcoming.

Avg PV - Wind % Difference Baseline Reserve Margin (Conservative)	
0 Quartile Difference	49.29%
1 Quartile Difference	59.50%
2 Quartile Difference	23.00%
3 Quartile Difference	57.50%

Avg PV - Wind % Difference Middle Ground Reserve Margin	
0 Quartile Difference	49.29%
1 Quartile Difference	52.00%
2 Quartile Difference	25.00%
3 Quartile Difference	45.00%

Avg PV - Wind % Difference Zero Reserve Margin (Aggressive)	
0 Quartile Difference	53.57%
1 Quartile Difference	62.00%
2 Quartile Difference	48.00%
3 Quartile Difference	57.50%

Figure 32. PV/wind resource differences for each quartile and reserve margin method.

Effects of Varying Reserve Margins

Wind percentage change.

It is easy to determine from Figure 33 that reserve margin has an impact on the optimal combination mix percentage of PV and wind. The Wind (%) Change column compares the optimized wind percentage of the baseline reserve margin scenario to the optimized wind percentage of the zero reserve margin scenario. Of the 26 areas optimized, the Wind % Change registered:

- 5 unchanged
- 9 increased
- 12 decreased

I could not decipher any distinguishing pattern to the changes. I believe these results support my earlier statement that each system is a complex mix of variables. The magnitudes and timings of all of the involved variables affected the resulting optimal combination mix of renewable energy technologies. The only discernible pattern was that the optimized combination mix of renewable energy technologies was sensitive to the required reserve margin.

Comparison of Optimized Wind and PV % for Different Reserve Margins									
Map ID #	ST_City	Wind (%) Baseline	PV (%) Baseline	Wind (%) Middle	PV (%) Middle	Wind (%) 0 Reserve	PV (%) 0 Reserve	Wind (%) Change	Wind (%) Change
1	AZ_Bowie	47.5%	52.5%	35.0%	65.0%	17.5%	82.5%	Decrease	-30.0%
2	AZ_Phoenix	5.0%	95.0%	5.0%	95.0%	5.0%	95.0%	No	0.0%
3	CA_Bodega	15.0%	85.0%	22.5%	77.5%	20.0%	80.0%	Increase	5.0%
4	CA_Fresno	17.5%	82.5%	17.5%	82.5%	17.5%	82.5%	No	0.0%
5	CA_Mojave	20.0%	80.0%	22.5%	77.5%	2.5%	97.5%	Decrease	-17.5%
6	CA_Santa_Barbara	15.0%	85.0%	22.5%	77.5%	22.5%	77.5%	Increase	7.5%
7	CO_Boulder	10.0%	90.0%	10.0%	90.0%	5.0%	95.0%	Decrease	-5.0%
8	FL_Everglades_City	5.0%	95.0%	7.5%	92.5%	7.5%	92.5%	Increase	2.5%
9	IL_Champaign	35.0%	65.0%	32.5%	67.5%	12.5%	87.5%	Decrease	-22.5%
10	KS_Hays	10.0%	90.0%	2.5%	97.5%	2.5%	97.5%	Decrease	-7.5%
11	MI_Gaylord	20.0%	80.0%	20.0%	80.0%	10.0%	90.0%	Decrease	-10.0%
12	MS_Jackson	2.5%	97.5%	2.5%	97.5%	2.5%	97.5%	No	0.0%
13	NC_Durham	12.5%	87.5%	12.5%	87.5%	12.5%	87.5%	No	0.0%
14	NE_Lincoln	42.5%	57.5%	55.0%	45.0%	52.5%	47.5%	Increase	10.0%
15	NJ_Edison	25.0%	75.0%	42.5%	57.5%	42.5%	57.5%	Increase	17.5%
16	NM_Clovis	20.0%	80.0%	25.0%	75.0%	25.0%	75.0%	Increase	5.0%
17	NY_Millbrook	12.5%	87.5%	10.0%	90.0%	15.0%	85.0%	Increase	2.5%
18	OK_Stillwater	42.5%	57.5%	37.5%	62.5%	35.0%	65.0%	Decrease	-7.5%
19	RI_Kingston	17.5%	82.5%	50.0%	50.0%	45.0%	55.0%	Increase	27.5%
20	SD_Sioux_Falls	47.5%	52.5%	65.0%	35.0%	40.0%	60.0%	Decrease	-7.5%
21	TN_Nashville	20.0%	80.0%	32.5%	67.5%	27.5%	72.5%	Increase	7.5%
22	TX_Amarillo	52.5%	47.5%	35.0%	65.0%	25.0%	75.0%	Decrease	-27.5%
23	TX_Austin	67.5%	32.5%	52.5%	47.5%	52.5%	47.5%	Decrease	-15.0%
24	TX_Bronte	5.0%	95.0%	10.0%	90.0%	2.5%	97.5%	Decrease	-2.5%
25	WY_Laramie	75.0%	25.0%	57.5%	42.5%	52.5%	47.5%	Decrease	-22.5%
26	WY_McFadden	15.0%	85.0%	30.0%	70.0%	15.0%	85.0%	No	0.0%

Figure 33. Comparison of the PV/wind optimization percentages differences between the three different reserve margin calculation methods. Wind % Change = Wind % 0 Reserve - Wind % Baseline.

When one compares my baseline reserve margin method to the zero reserve margin method, the total average wind % change for the 26 areas analyzed is 3.5% (see Figure 34). This result, in combination with the above individual location analysis, leads me to conclude that reserve margin has an impact, but the magnitude and direction (increase or decrease) of the impact is difficult to ascertain due to the large number and complexity of variables that have an impact on the final optimization result.

	Baseline Reserve Margin		Zero Reserve Margin		
ST_City	Optimal Wind (%)	Optimal PV (%)	Optimal Wind (%)	Optimal PV (%)	Wind % Change
AZ_Bowie	47.5%	52.5%	17.5%	82.5%	30.0%
AZ_Phoenix	5.0%	95.0%	5.0%	95.0%	0.0%
CA_Bodega	15.0%	85.0%	20.0%	80.0%	-5.0%
CA_Fresno	17.5%	82.5%	17.5%	82.5%	0.0%
CA_Mojave	20.0%	80.0%	2.5%	97.5%	17.5%
CA_Santa_Barbara	15.0%	85.0%	22.5%	77.5%	-7.5%
CO_Boulder	10.0%	90.0%	5.0%	95.0%	5.0%
FL_Everglades_City	5.0%	95.0%	7.5%	92.5%	-2.5%
IL_Champaign	35.0%	65.0%	12.5%	87.5%	22.5%
KS_Hays	10.0%	90.0%	2.5%	97.5%	7.5%
MI_Gaylord	20.0%	80.0%	10.0%	90.0%	10.0%
MS_Jackson	2.5%	97.5%	2.5%	97.5%	0.0%
NC_Durham	12.5%	87.5%	12.5%	87.5%	0.0%
NE_Lincoln	42.5%	57.5%	52.5%	47.5%	-10.0%
NJ_Edison	25.0%	75.0%	42.5%	57.5%	-17.5%
NM_Clovis	20.0%	80.0%	25.0%	75.0%	-5.0%
NY_Millbrook	12.5%	87.5%	15.0%	85.0%	-2.5%
OK_Stillwater	42.5%	57.5%	35.0%	65.0%	7.5%
RI_Kingston	17.5%	82.5%	45.0%	55.0%	-27.5%
SD_Sioux_Falls	47.5%	52.5%	40.0%	60.0%	7.5%
TN_Nashville	20.0%	80.0%	27.5%	72.5%	-7.5%
TX_Amarillo	52.5%	47.5%	25.0%	75.0%	27.5%
TX_Austin	67.5%	32.5%	52.5%	47.5%	15.0%
TX_Bronte	5.0%	95.0%	2.5%	97.5%	2.5%
WY_Laramie	75.0%	25.0%	52.5%	47.5%	22.5%
WY_McFadden	15.0%	85.0%	15.0%	85.0%	0.0%
Total Average Wind % Change					3.5%

Figure 34. Total average wind % change when comparing baseline reserve margin (conservative) with a zero reserve margin (aggressive) scenarios.

Reserve Margin Percentage Quantification

The goal of studying optimization results based on three different reserve margin calculation methods was rooted in the fact that reserve margin served as a foundational principle of my optimization algorithm. Given the optimal results are highly sensitive to the reserve margin's value, incorporating three different reserve margin calculation methodologies into the analysis seemed appropriate to provide a more comprehensive analysis.

Figure 35 displays the average reserve margin of each of the three calculation methods for all 26 locations analyzed. Reserve margin is the amount of energy storage reserve that always must remain in the energy storage "tank" in order to ensure a reliable grid.

Reserve Margin Scenario	Reserve Margin %
Baseline Reserve Margin (Conservative)	27.86%
Middle Ground Reserve Margin	15.20%
Zero Reserve Margin (Aggressive)	0.00%

Figure 35. Reserve margin average percentages for each reserve margin calculation method.

One can determine from Figure 35 above that my baseline reserve margin calculation method resulted in reserve margin percentages that are higher than our currently mandated 15% reserve margins. This scenario would be appropriate if one believes that the intermittency and variability of renewable energy generation will require us to increase our level of energy storage capacity reserves.

The middle ground reserve margin calculation method resulted in reserve margins that equal our currently mandated 15% reserve margins. This scenario would be appropriate if one believes that we will be able to maintain our current level of grid reliability through increasing our energy prediction and smart grid technologies.

The zero reserve margin calculation method does not require any additional energy storage capacity. This scenario would be manifested in extremely advanced and accurate weather prediction tools and algorithms. In addition, this scenario would require smart grid technology that can automatically route adequate levels of available energy to a multitude of different requirement points (or grid nodes).

Model Factors

All of the following factors affected this model's optimization outcome:

- Magnitude of wind power production
- Magnitude of PV power production
- Consistency of wind power production
- Consistency of PV power production
    - Consistency =
        - Variability of magnitude of power production
        - Duration of power production
            - Conversely, the intermittency of power production
                - Number of consecutive days with zero or little power production
- Magnitude of Average Load
- Magnitude of Peak Load
- Peak Load Season
    - Timing between renewable power production and peak load
- Wind cost
- PV cost

- Reserve Margin

The fixed constraints of the model were:

- Wind turbine type
- PV panel type
- Storage type
- Storage cost
- Storage efficiency
- Baseline system size

Optimal PV/Wind Mixes Compared to GIS Map Resource Zone

Baseline reserve margin (conservative).

The analysis summarized in Figure 36 compares the model's optimal combination mix percentages and the GIS map resource zones for my baseline reserve method.

Optimal PV/Wind Mixes Compared to GIS Map Resource Zone Baseline Reserve Margin (Conservative)							
ST_City (Weather)	Optimal Wind (%)	Optimal PV (%)	Wind Speed Quartile	Irradiance Quartile	GIS Map Zone	PV - Wind %	Match
CA_Mojave	20.0%	80.0%	2	4	High_PV_High_Wind	60.0%	No
TX_Amarillo	52.5%	47.5%	4	3	High_PV_High_Wind	-5.0%	Yes
AZ_Phoenix	5.0%	95.0%	1	4	High_PV_Low_Wind	90.0%	Yes
CA_Fresno	17.5%	82.5%	1	4	High_PV_Low_Wind	65.0%	Yes
AZ_Bowie	47.5%	52.5%	3	4	High_PV_Mod_Wind	5.0%	Yes
NM_Clovis	20.0%	80.0%	4	4	High_PV_Mod_Wind	60.0%	No
SD_Sioux_Falls	47.5%	52.5%	4	1	Low_PV_High_Wind	5.0%	No
WY_McFadden	15.0%	85.0%	3	2	Low_PV_High_Wind	70.0%	No
NY_Millbrook	12.5%	87.5%	1	1	Low_PV_Low_Wind	75.0%	No
RI_Kingston	17.5%	82.5%	2	1	Low_PV_Low_Wind	65.0%	No
TN_Nashville	20.0%	80.0%	2	2	Low_PV_Low_Wind	60.0%	No
IL_Champaign	35.0%	65.0%	3	1	Low_PV_Mod_Wind	30.0%	No
MI_Gaylord	20.0%	80.0%	3	1	Low_PV_Mod_Wind	60.0%	No
NJ_Edison	25.0%	75.0%	2	1	Low_PV_Mod_Wind	50.0%	No
CO_Boulder	10.0%	90.0%	2	2	Mod_PV_High_Wind	80.0%	No
KS_Hays	10.0%	90.0%	4	3	Mod_PV_High_Wind	80.0%	No
CA_Bodega	15.0%	85.0%	2	3	Mod_PV_Low_Wind	70.0%	No
CA_Santa_Barbara	15.0%	85.0%	1	4	Mod_PV_Low_Wind	70.0%	No
FL_Everglades_City	5.0%	95.0%	2	3	Mod_PV_Low_Wind	90.0%	No
MS_Jackson	2.5%	97.5%	1	2	Mod_PV_Low_Wind	95.0%	No
NC_Durham	12.5%	87.5%	1	2	Mod_PV_Low_Wind	75.0%	No
TX_Austin	67.5%	32.5%	3	3	Mod_PV_Low_Wind	-35.0%	No
NE_Lincoln	42.5%	57.5%	4	2	Mod_PV_Mod_Wind	15.0%	Yes
OK_Stillwater	42.5%	57.5%	3	3	Mod_PV_Mod_Wind	15.0%	Yes
TX_Bronte	5.0%	95.0%	3	3	Mod_PV_Mod_Wind	90.0%	No
WY_Laramie	75.0%	25.0%	4	2	Mod_PV_Mod_Wind	-50.0%	No

Figure 36. Optimization combination mix percentages compared to GIS map resource zones. Highlighted area indicates interesting result (baseline reserve method).

When using my baseline reserve margin, six optimal mix PV/wind combinations of the 26 locations matched their corresponding GIS map resource zone. This is a 23% match rate. I believe this low match rate can be possibly attributed to several factors.

Mismatch between weather source and map.

One of the potential reasons for the low match rate between optimal PV/wind combination mixes and the GIS map of resource zones is that the weather data for the optimal PV/wind combination mixes was sourced from a pair of granular x,y coordinates, whereas the GIS map of resource zones was developed from a more macro set of data. This mismatch of data granularity could lead to a variance in wind speed and irradiance data between the macro map and granular x,y coordinates.

Reclassification of GIS map.

My reclassifications of the GIS map to match the NREL baseline maps also could have resulted in some resource-map variances and irregularities. In particular, the High Wind_Mod_PV areas of the interior United States such as Hays, Kansas, might be less sunny, and Boulder, Colorado might be less windy than what is displayed on the GIS map of resource zones.

Low PV dominated almost any wind category.

Another reason for the low match rate is the particular area of Figure 36 that is highlighted in red and outlined in yellow. The optimal combination mix for every area designated Low PV was comprised of mostly PV. In addition, the optimal combination mix of almost every area designated Moderate PV_Low Wind, was comprised of significantly higher percentage amounts of PV (>=70%). As mentioned earlier, it is difficult to ascertain the exact cause for PV's dominance, but PV's superior pricing in combination with generation-load timing factors are potentially plausible significant factors.

Intra-category comparison – an interesting practical example.

In the cases of Mojave, California and Amarillo, Texas, it appears that there was a major and a minor weather data source-map mismatch, respectively. If the weather data source had matched the GIS map resource zones exactly, both cities should have ranked in the highest quartiles in both categories. However, Mojave ranked in the 2^{nd} quartile for wind and the 4^{th} quartile (highest) for irradiance. Amarillo ranked in the 4^{th} quartile (highest) for wind and the 3^{rd} quartile for irradiance. One might logically conclude that the wind and PV combination mixes should be of similar capacities if their GIS map resource zone is the same, but the data do not support this claim because the model's optimal PV/wind combination mix for Mojave is 80%/20%.

It is interesting to note that a wind farm and solar plant are currently co-located approximately three miles southwest of downtown Mojave. These can be seen in the Google Earth map shown in Figure 37. The wind turbines are on the left, and PV panels on the right.

Figure 37. Mojave, California's co-located PV and wind systems.

So, which data are correct? Maybe none, maybe all. The model used x,y coordinates of 35° N, 118° W to model Mojave. These coordinates are approximately 6.5 miles from the center of the wind farm, and 3.5 miles from the center of the PV plant (see Figure 38). The NASA MERRA-2 data for 2015 calculated the average hourly wind speed during 2015 for this set of x,y coordinates at 5.69 m/s, resulting in a quartile rank of 2 (moderately low). The NREL NSRDB calculated the average hourly irradiance during 2015 for this set of x,y coordinates to be 245.08—the highest among the 26 locations analyzed.

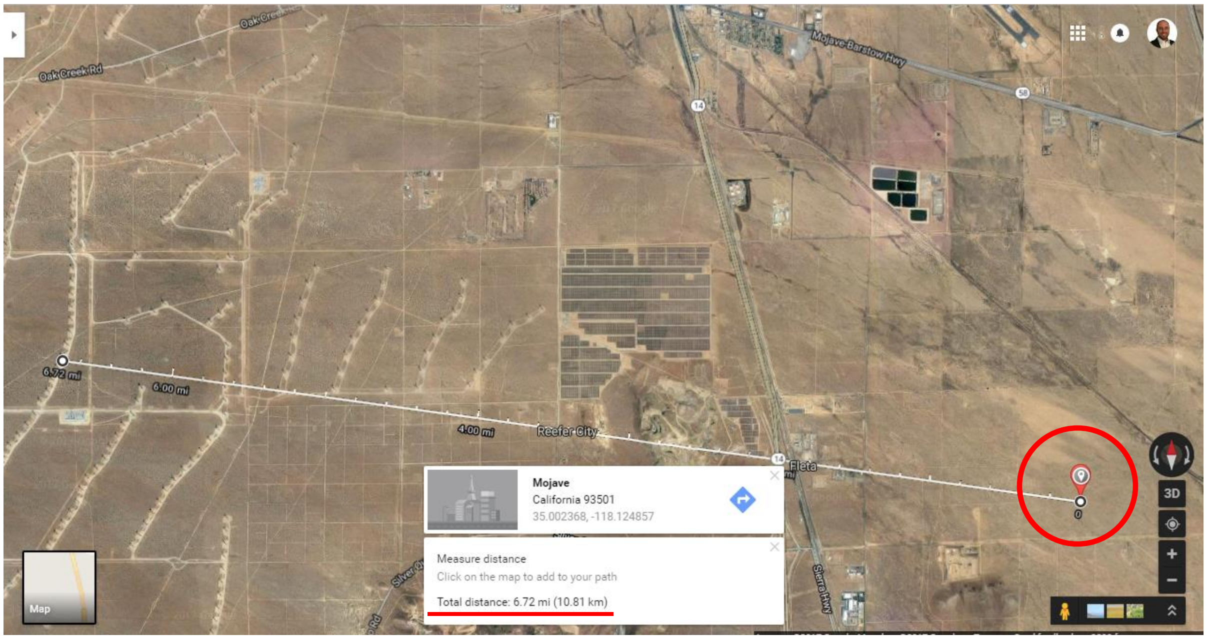


Figure 38. Distance from Mojave's x,y coordinates modeled to the nearby wind and PV plants.

In practice, a wind development company's analysis found the Mojave area windy enough to build a wind farm, and a solar development company found this area sunny enough to build a PV plant. When looking at 2015 in isolation, my model determined that the area should be comprised of 80% solar and 20% wind in order to optimally utilize the area's renewable resources at the lowest possible cost.

Middle ground reserve margin.

When using my middle ground reserve margin, the match rate between optimal PV/wind combination mix and GIS resource map zone improved slightly, to 31% (Figure 39). PV's dominance in the Low and Moderate PV GIS map resource zone categories was still prevalent.

Optimal PV/Wind Mixes Compared to GIS Map Resource Zone Middle Ground Reserve Margin							
ST_City (Weather)	Optimal Wind (%)	Optimal PV (%)	Wind Speed Quartile	Irradiance Quartile	GIS Map Zone	PV - Wind %	Match
CA_Mojave	22.5%	77.5%	2	4	High_PV_High_Wind	55.0%	No
TX_Amarillo	35.0%	65.0%	4	3	High_PV_High_Wind	30.0%	No
AZ_Phoenix	5.0%	95.0%	1	4	High_PV_Low_Wind	90.0%	Yes
CA_Fresno	17.5%	82.5%	1	4	High_PV_Low_Wind	65.0%	Yes
AZ_Bowie	35.0%	65.0%	3	4	High_PV_Mod_Wind	30.0%	Yes
NM_Clovis	25.0%	75.0%	4	4	High_PV_Mod_Wind	50.0%	Yes
SD_Sioux_Falls	65.0%	35.0%	4	1	Low_PV_High_Wind	-30.0%	No
WY_McFadden	30.0%	70.0%	3	2	Low_PV_High_Wind	40.0%	No
NY_Millbrook	10.0%	90.0%	1	1	Low_PV_Low_Wind	80.0%	No
RI_Kingston	50.0%	50.0%	2	1	Low_PV_Low_Wind	0.0%	Yes
TN_Nashville	32.5%	67.5%	2	2	Low_PV_Low_Wind	35.0%	No
IL_Champaign	32.5%	67.5%	3	1	Low_PV_Mod_Wind	35.0%	No
MI_Gaylord	20.0%	80.0%	3	1	Low_PV_Mod_Wind	60.0%	No
NJ_Edison	42.5%	57.5%	2	1	Low_PV_Mod_Wind	15.0%	No
CO_Boulder	10.0%	90.0%	2	2	Mod_PV_High_Wind	80.0%	No
KS_Hays	2.5%	97.5%	4	3	Mod_PV_High_Wind	95.0%	No
CA_Bodega	22.5%	77.5%	2	3	Mod_PV_Low_Wind	55.0%	No
CA_Santa_Barbara	22.5%	77.5%	1	4	Mod_PV_Low_Wind	55.0%	No
FL_Everglades_City	7.5%	92.5%	2	3	Mod_PV_Low_Wind	85.0%	No
MS_Jackson	2.5%	97.5%	1	2	Mod_PV_Low_Wind	95.0%	No
NC_Durham	12.5%	87.5%	1	2	Mod_PV_Low_Wind	75.0%	No
TX_Austin	52.5%	47.5%	3	3	Mod_PV_Low_Wind	-5.0%	No
NE_Lincoln	55.0%	45.0%	4	2	Mod_PV_Mod_Wind	-10.0%	Yes
OK_Stillwater	37.5%	62.5%	3	3	Mod_PV_Mod_Wind	25.0%	Yes
TX_Bronte	10.0%	90.0%	3	3	Mod_PV_Mod_Wind	80.0%	No
WY_Laramie	57.5%	42.5%	4	2	Mod_PV_Mod_Wind	-15.0%	Yes

Figure 39. Optimization combination mix percentages compared to GIS map resource zones. Highlighted area indicates interesting result (middle ground reserve method).

Zero reserve margin.

When using a zero reserve margin, the match rate between optimal PV/wind combination mix and GIS resource map zone decreased to 19% (see Figure 40). PV's dominance in the Low and Moderate PV GIS map resource zone categories was still prevalent, but the model had consistently decreased the optimal wind percentage for the High_PV_High_Wind area of Amarillo, Texas, and High_PV_Mod_Wind area of Bowie, Arizona, as the reserve margin requirement decreased.

Optimal PV/Wind Mixes Compared to GIS Map Resource Zone Zero Reserve Margin							
ST_City (Weather)	Optimal Wind (%)	Optimal PV (%)	Wind Speed Quartile	Irradiance Quartile	GIS Map Zone	PV - Wind %	Match
CA_Mojave	2.5%	97.5%	2	4	High_PV_High_Wind	95.0%	No
TX_Amarillo	25.0%	75.0%	4	3	High_PV_High_Wind	50.0%	No
AZ_Phoenix	5.0%	95.0%	1	4	High_PV_Low_Wind	90.0%	Yes
CA_Fresno	17.5%	82.5%	1	4	High_PV_Low_Wind	65.0%	Yes
AZ_Bowie	17.5%	82.5%	3	4	High_PV_Mod_Wind	65.0%	No
NM_Clovis	25.0%	75.0%	4	4	High_PV_Mod_Wind	50.0%	No
SD_Sioux_Falls	40.0%	60.0%	4	1	Low_PV_High_Wind	20.0%	No
WY_McFadden	15.0%	85.0%	3	2	Low_PV_High_Wind	70.0%	No
NY_Millbrook	15.0%	85.0%	1	1	Low_PV_Low_Wind	70.0%	No
RI_Kingston	45.0%	55.0%	2	1	Low_PV_Low_Wind	10.0%	Yes
TN_Nashville	27.5%	72.5%	2	2	Low_PV_Low_Wind	45.0%	No
IL_Champaign	12.5%	87.5%	3	1	Low_PV_Mod_Wind	75.0%	No
MI_Gaylord	10.0%	90.0%	3	1	Low_PV_Mod_Wind	80.0%	No
NJ_Edison	42.5%	57.5%	2	1	Low_PV_Mod_Wind	15.0%	No
CO_Boulder	5.0%	95.0%	2	2	Mod_PV_High_Wind	90.0%	No
KS_Hays	2.5%	97.5%	4	3	Mod_PV_High_Wind	95.0%	No
CA_Bodega	20.0%	80.0%	2	3	Mod_PV_Low_Wind	60.0%	No
CA_Santa_Barbara	22.5%	77.5%	1	4	Mod_PV_Low_Wind	55.0%	No
FL_Everglades_City	7.5%	92.5%	2	3	Mod_PV_Low_Wind	85.0%	No
MS_Jackson	2.5%	97.5%	1	2	Mod_PV_Low_Wind	95.0%	No
NC_Durham	12.5%	87.5%	1	2	Mod_PV_Low_Wind	75.0%	No
TX_Austin	52.5%	47.5%	3	3	Mod_PV_Low_Wind	-5.0%	No
NE_Lincoln	52.5%	47.5%	4	2	Mod_PV_Mod_Wind	-5.0%	Yes
OK_Stillwater	35.0%	65.0%	3	3	Mod_PV_Mod_Wind	30.0%	No
TX_Bronte	2.5%	97.5%	3	3	Mod_PV_Mod_Wind	95.0%	No
WY_Laramie	52.5%	47.5%	4	2	Mod_PV_Mod_Wind	-5.0%	Yes

Figure 40. Optimization combination mix percentages compared to GIS map resource zones. Highlighted area indicates interesting result (zero reserve method).

Explanations for PV's Dominance

One reason that the majority of optimal combination mixes favored PV over wind is that PV pricing was always lower than wind pricing. Combine lower-priced PV with a majority of summer peak loads when the wind does not blow as strong and you have a recipe for an optimization model that favors PV. As mentioned previously, my model is a complex mix of variables, but pricing and renewable energy generation-load timing serve as very significant functions in the my optimization model's results. This topic is discussed more at length later in the paper.

Required Future Renewable Capacity versus Current Capacity

Baseline Reserve Margin (Conservative)

One of the most interesting results of my study was how much renewable energy generation and storage capacity will be required in the future to achieve a 100% renewable energy environment that would meet our current load demand. Below I have listed each location's optimized system size (kW), storage size (GWh), and peak load (kW) for my baseline reserve margin, middle ground reserve margin, and zero reserve margin scenarios (see Figures 41,44, & 47, respectively). I also computed the amount of renewable energy generating capacity that is required in comparison to our current fossil-fueled environment. This calculation is called "% Optimal System Size Capacity vs. Current Capacity." I also computed the percentage of optimal storage capacity required versus the optimal renewable energy system size. This calculation determined the amount of additional hours of energy storage that must be developed for every GW of renewable capacity developed. This calculation is called "% Optimal Storage Size Capacity > Optimal System Size Capacity."

The current capacity value is calculated by multiplying each location's peak load by 1.15. This represents our current regulatory environment, which requires electric utilities to maintain at least a 15% capacity reserve. As mentioned earlier in this paper, some utilities currently have capacity greater than the mandated 15%. However, to keep the comparison consistent to amounts that are currently required, I used the 15% capacity reserve limit for a baseline reserve multiple.

Essentially, these calculations show how much energy generation capacity, and energy storage capacity in terms of percentage, is needed compared to our current electric utility capacity in order to serve the same loads. Figure 42 shows the average of all 26 locations analyzed in my baseline reserve margin scenario. Basically, to achieve a 100% wind and PV environment serving the same load quantities as our current, mostly fossil-fueled technologies, wind and PV energy technology capacities need to be approximately 14 times larger than current electric utility capacity. Storage capacity would need to be 1.21 times larger than generation capacity. This is my most conservative estimate, because my baseline reserve margin methodology requires the highest percentage of energy storage reserves.

ST_City (Weather)	AZ_Bowie	AZ_Phoenix	CA_Bodega	CA_Fresno
System Size (kW)	**345,000,000**	**205,000,000**	**430,000,000**	**280,000,000**
Storage Size (kWh)	**400,000,000**	**540,000,000**	**345,000,000**	**345,000,000**
Peak Load (kW)	22,955,800	22,955,800	20,470,000	20,470,000
Current Capacity (kW) 15% Reserve Margin	26,399,170	26,399,170	23,540,500	23,540,500
% Optimal System Size Capacity vs. Current Capacity	1307%	777%	1827%	1189%
% Optimal Storage Size Capacity > Optimal System Size Capacity	116%	263%	80%	123%
CA_Mojave	**CA_Santa_Barbara**	**CO_Boulder**	**FL_Everglades_City**	**IL_Champaign**
235,000,000	**225,000,000**	**145,000,000**	**290,000,000**	**190,000,000**
385,000,000	**385,000,000**	**85,000,000**	**515,000,000**	**165,000,000**
22,822,000	22,822,000	7,038,000	24,754,000	9,280,470
26,245,300	26,245,300	8,093,700	28,467,100	10,672,541
895%	857%	1792%	1019%	1780%
164%	171%	59%	178%	87%
KS_Hays	**MI_Gaylord**	**MS_Jackson**	**NC_Durham**	**NE_Lincoln**
25,000,000	**480,000,000**	**715,000,000**	**440,000,000**	**10,000,000**
20,000,000	**545,000,000**	**635,000,000**	**360,000,000**	**12,000,000**
1,193,494	31,142,290	32,386,090	19,890,000	747,686
1,372,518	35,813,634	37,244,004	22,873,500	859,839
1821%	1340%	1920%	1924%	1163%
80%	114%	89%	82%	120%
NJ_Edison	**NM_Clovis**	**NY_Millbrook**	**OK_Stillwater**	**RI_Kingston**
160,000,000	**40,000,000**	**60,000,000**	**125,000,000**	**25,000,000**
150,000,000	**80,000,000**	**35,000,000**	**145,000,000**	**30,000,000**
9,594,939	3,836,153	2,203,500	6,533,372	1,748,505
11,034,180	4,411,576	2,534,025	7,513,378	2,010,781
1450%	907%	2368%	1664%	1243%
94%	200%	58%	116%	120%
SD_Sioux_Falls	**TN_Nashville**	**TX_Amarillo**	**TX_Austin**	**TX_Bronte**
2,000,000	**470,000,000**	**60,000,000**	**145,000,000**	**50,000,000**
3,000,000	**560,000,000**	**95,000,000**	**200,000,000**	**40,000,000**
167,000	29,823,000	5,696,955	12,032,553	1,883,889
192,050	34,296,450	6,551,498	13,837,436	2,166,472
1041%	1370%	916%	1048%	2308%
150%	119%	158%	138%	80%
WY_Laramie	**WY_McFadden**			
70,000,000	**105,000,000**			
65,000,000	**90,000,000**			
7,038,000	7,038,000			
8,093,700	8,093,700			
865%	1297%			
93%	86%			

Figure 41. List of each location's optimal renewable energy capacity vs. current capacity (conservative baseline reserve margin). The % of optimal storage capacity vs. the optimal renewable energy system size is also listed.

Average % Optimal System Size Capacity vs. Current Capacity	1388%	or	13.88x
Average % Optimal Storage Size Capacity > Optimal System Size Capacity	121%	or	1.21x

Figure 42. Average of all analyzed locations' renewable capacities required versus current capacity (conservative baseline reserve margin). Average of optimal storage capacity greater than optimal renewable capacity also listed.

Representation of the Whole United States (Baseline Reserve Margin)

Given that only 26 locations were modeled, one could question how well this sample represents the whole nation's future renewable energy and storage capacity requirements. Statistical calculation averages for required capacity magnitudes, in comparison to current capacity magnitudes in terms of greater capacity multiplicative factors, for the 26 locations are listed in Figure 43.

Standard Deviation (σ)	
Renewable Energy Generation	4.51x
Storage > Generation	0.46x
Coefficient of Variance (CV)	
Renewable Energy Generation	0.32
Storage > Generation	0.38

Figure 43. Required capacity vs. current electric utility capacity (Baseline Reserve Margin). A standard rule of thumb is that any CV below 1 is considered low variance.

Middle Ground Reserve Margin

For my middle ground reserve margin scenario, Figure 44 below shows how much renewable energy generation capacity, and energy storage capacity in terms of percentage, is required to serve the same loads as the current overall capacity of the electric utilities per location. Figure 45 shows the average of all 26 locations analyzed in my middle ground reserve margin scenario. Basically, to achieve a 100% wind and PV environment serving the same load quantities as our current fossil-fueled technologies, wind and PV energy technology capacities need to be approximately 12.5 times larger than current electric utility capacity. Storage capacity would need to be 1.20 times larger than generation capacity. This is my middle ground estimate because my middle ground reserve margin methodology requires an amount of energy storage reserves that is in between my conservative baseline reserve margin methodology, and a zero reserve margin scenario.

ST_City (Weather)	AZ_Bowie	AZ_Phoenix	CA_Bodega	CA_Fresno
System Size (kW)	**290,000,000**	**210,000,000**	**405,000,000**	**280,000,000**
Storage Size (kWh)	**380,000,000**	**450,000,000**	**310,000,000**	**285,000,000**
Peak Load (kW)	22,955,800	22,955,800	20,470,000	20,470,000
Current Capacity (kW) 15% Reserve Margin	26,399,170	26,399,170	23,540,500	23,540,500
% Optimal System Size Capacity vs. Current Capacity	1099%	795%	1720%	1189%
% Optimal Storage Size Capacity > Optimal System Size Capacity	131%	214%	77%	102%
CA_Mojave	**CA_Santa_Barbara**	**CO_Boulder**	**FL_Everglades_City**	**IL_Champaign**
180,000,000	**180,000,000**	**145,000,000**	**235,000,000**	**185,000,000**
315,000,000	**305,000,000**	**75,000,000**	**440,000,000**	**150,000,000**
22,822,000	22,822,000	7,038,000	24,754,000	9,280,470
26,245,300	26,245,300	8,093,700	28,467,100	10,672,541
686%	686%	1792%	826%	1733%
175%	169%	52%	187%	81%
KS_Hays	**MI_Gaylord**	**MS_Jackson**	**NC_Durham**	**NE_Lincoln**
20,000,000	**475,000,000**	**710,000,000**	**430,000,000**	**6,000,000**
20,000,000	**440,000,000**	**575,000,000**	**325,000,000**	**12,000,000**
1,193,494	31,142,290	32,386,090	19,890,000	747,686
1,372,518	35,813,634	37,244,004	22,873,500	859,839
1457%	1326%	1906%	1880%	698%
100%	93%	81%	76%	200%
NJ_Edison	**NM_Clovis**	**NY_Millbrook**	**OK_Stillwater**	**RI_Kingston**
135,000,000	**35,000,000**	**55,000,000**	**120,000,000**	**15,000,000**
120,000,000	**70,000,000**	**35,000,000**	**135,000,000**	**25,000,000**
9,594,939	3,836,153	2,203,500	6,533,372	1,748,505
11,034,180	4,411,576	2,534,025	7,513,378	2,010,781
1223%	793%	2170%	1597%	746%
89%	200%	64%	113%	167%
SD_Sioux_Falls	**TN_Nashville**	**TX_Amarillo**	**TX_Austin**	**TX_Bronte**
3,000,000	**415,000,000**	**50,000,000**	**105,000,000**	**45,000,000**
2,000,000	**460,000,000**	**80,000,000**	**165,000,000**	**40,000,000**
167,000	29,823,000	5,696,955	12,032,553	1,883,889
192,050	34,296,450	6,551,498	13,837,436	2,166,472
1562%	1210%	763%	759%	2077%
67%	111%	160%	157%	89%
WY_Laramie	**WY_McFadden**			
50,000,000	**120,000,000**			
60,000,000	**65,000,000**			
7,038,000	7,038,000			
8,093,700	8,093,700			
618%	1483%			
120%	54%			

Figure 44. List of each location's optimal renewable energy capacity vs. current capacity (middle ground reserve margin). The % of optimal storage capacity vs. the optimal renewable energy system size is also listed.

Average % Optimal System Size Capacity vs. Current Capacity	1261%	or	12.61x
Average % Optimal Storage Size Capacity > Optimal System Size Capacity	120%	or	1.20x

Figure 45. Average of all analyzed locations' renewable capacities required versus current capacity (middle ground reserve margin). Average of optimal storage capacity greater than optimal renewable capacity also listed.

Representation of the Whole United States (Middle Ground Reserve Margin)

Statistical calculation averages for required capacity magnitudes, in comparison to current capacity magnitudes in terms of greater capacity multiplicative factors, for the 26 locations are listed in Figure 46.

Standard Deviation (σ)	
Renewable Energy Generation	4.85x
Storage > Generation	0.49x
Coefficient of Variance (CV)	
Renewable Energy Generation	0.38
Storage > Generation	0.41

Figure 46. Required capacity vs. current electric utility capacity (Middle Ground Reserve Margin). A standard rule of thumb is that any CV below 1 is considered low variance.

Zero Reserve Margin (Aggressive)

For a zero reserve margin scenario, Figure 47 shows how much renewable energy generation capacity, and energy storage capacity in terms of percentage, is required to serve the same loads as the current overall capacity of our electric utilities per location. Figure 48 shows the average of all 26 locations analyzed in a zero reserve margin scenario. Basically, to achieve a 100% wind and PV environment serving the same load quantities as our current fossil-fueled technologies, wind and PV energy technology capacities need to be approximately 12.5 times larger than current electricity utility capacity. Storage capacity needs to be approximately 1.07 times larger than energy generation capacity. This is an aggressive estimate because a zero reserve margin methodology requires no amount of energy storage reserves.

ST_City (Weather)	AZ_Bowie	AZ_Phoenix	CA_Bodega	CA_Fresno
System Size (kW)	**245,000,000**	**210,000,000**	**395,000,000**	**280,000,000**
Storage Size (kWh)	**375,000,000**	**385,000,000**	**265,000,000**	**230,000,000**
Peak Load (kW)	**22,955,800**	**22,955,800**	**20,470,000**	**20,470,000**
Current Capacity (kW) 15% Reserve Margin	26,399,170	26,399,170	23,540,500	23,540,500
% Optimal System Size Capacity vs. Current Capacity	928%	795%	1678%	1189%
% Optimal Storage Size Capacity > Optimal System Size Capacity	153%	183%	67%	82%
CA_Mojave	**CA_Santa_Barbara**	**CO_Boulder**	**FL_Everglades_City**	**IL_Champaign**
140,000,000	**175,000,000**	**140,000,000**	**235,000,000**	**200,000,000**
290,000,000	**250,000,000**	**65,000,000**	**355,000,000**	**130,000,000**
22,822,000	**22,822,000**	**7,038,000**	**24,754,000**	**9,280,470**
26,245,300	26,245,300	8,093,700	28,467,100	10,672,541
533%	667%	1730%	826%	1874%
207%	143%	46%	151%	65%
KS_Hays	**MI_Gaylord**	**MS_Jackson**	**NC_Durham**	**NE_Lincoln**
20,000,000	**490,000,000**	**710,000,000**	**435,000,000**	**6,000,000**
17,000,000	**365,000,000**	**465,000,000**	**260,000,000**	**11,000,000**
1,193,494	**31,142,290**	**32,386,090**	**19,890,000**	**747,686**
1,372,518	35,813,634	37,244,004	22,873,500	859,839
1457%	1368%	1906%	1902%	698%
85%	74%	65%	60%	183%
NJ_Edison	**NM_Clovis**	**NY_Millbrook**	**OK_Stillwater**	**RI_Kingston**
130,000,000	**35,000,000**	**50,000,000**	**115,000,000**	**16,000,000**
105,000,000	**65,000,000**	**30,000,000**	**130,000,000**	**19,000,000**
9,594,939	**3,836,153**	**2,203,500**	**6,533,372**	**1,748,505**
11,034,180	4,411,576	2,534,025	7,513,378	2,010,781
1178%	793%	1973%	1531%	796%
81%	186%	60%	113%	119%
SD_Sioux_Falls	**TN_Nashville**	**TX_Amarillo**	**TX_Austin**	**TX_Bronte**
3,000,000	**420,000,000**	**45,000,000**	**105,000,000**	**55,000,000**
2,000,000	**375,000,000**	**70,000,000**	**145,000,000**	**30,000,000**
167,000	**29,823,000**	**5,696,955**	**12,032,553**	**1,883,889**
192,050	34,296,450	6,551,498	13,837,436	2,166,472
1562%	1225%	687%	759%	2539%
67%	89%	156%	138%	55%
WY_Laramie	**WY_McFadden**			
55,000,000	**110,000,000**			
50,000,000	**60,000,000**			
7,038,000	**7,038,000**			
8,093,700	8,093,700			
680%	1359%			
91%	55%			

Figure 47. List of each location's optimal renewable energy capacity vs. current capacity (zero reserve margin). The % of optimal storage capacity vs. the optimal renewable energy system size is also listed.

Average % Optimal System Size Capacity vs. Current Capacity	1255%	or	12.55x
Average % Optimal Storage Size Capacity > Optimal System Size Capacity	107%	or	1.07x

Figure 48. Average of all analyzed locations' renewable capacities required versus current capacity (zero reserve margin). Average of optimal storage capacity greater than optimal renewable capacity also listed.

Representation of the Whole United States (Zero Reserve Margin)

Statistical calculation averages for required capacity magnitudes, in comparison to current capacity magnitudes in terms of greater capacity multiplicative factors, for the 26 locations are listed in Figure 49.

Standard Deviation (σ)	
Renewable Energy Generation	5.20x
Storage > Generation	0.48x
Coefficient of Variance (CV)	
Renewable Energy Generation	0.41
Storage > Generation	0.45

Figure 49. Required capacity vs. current electric utility capacity (Zero Reserve Margin). A standard rule of thumb is that any CV below 1 is considered low variance.

Representation of the Whole United States (Total)

The magnitude of difference in renewable generation and storage capacity between sites is a function of the interrelated variables of the each site's optimization parameters (strength and variability of the wind and irradiance resources, renewable energy generation vs. load timing, locational price of wind and PV technology, etc.). Given that all nine Coefficient of Variance calculations were significantly below 1, one may consider these 26 locations to be a fair representation of the United States as a whole.

Required Renewable Capacities versus Current Renewable Capacities

Based on the multiplicative factors derived from my model, instead of measuring our future renewable energy and storage capacity requirements in comparison to our current electric utility capacity, I calculated the United States' future renewable energy and storage capacity required to achieve a 100% renewable energy environment in comparison to our current renewable energy and storage capacities. In other words, the amount of expansion that would be required beyond our currently installed wind/PV generating capacity. This calculation assumes zero growth in load demand. I also calculated an estimate of the total cost of the United States obtaining a 100% renewable energy environment.

Current Renewable Energy Generation and Storage Capacity

Currently, the United States' total energy generation capacity equals approximately 1,079.38 GW (EIA, 2017b). The United States current renewable energy generation capacity (including conventional hydroelectric) is 199.41 GW (18.47%). This leaves the United States with a renewable energy shortfall of 879.97 GW.

Currently, the United States total energy storage capacity equals approximately 24.21 GW (Sandia National Laboratories, 2016). There are 541 currently operable renewable energy storage projects. This equates to 0.047 GW of storage per existing project. However, the total United States energy storage capacity in GWh is 399.18.

Baseline reserve margin.

Using my baseline reserve margin, the average multiplicative factor of renewable energy capacity to current capacity was 13.88 (see Figure 42; 1388% = 13.88x). Therefore, 879.97 GW x 13.88 = 12,213.93 GW of additional renewable energy would be required to achieve a 100% renewable energy environment (Figure 50). At an estimated $1,500/kW, the total additional cost for renewable energy capacity in a 100% renewable energy environment would be over $18 trillion dollars.

Using my baseline reserve margin, the average ratio for storage capacity in kilowatt-hours to renewable energy capacity was 1.21. Therefore, for every GW of renewable energy capacity developed, 1.21 times more storage capacity in gigawatt-hours must be developed. If the additional renewable energy capacity required is 12,213.93 GW then the additional energy storage capacity required equals 12,213.93 GW x 1.21 hours = 14, 736.73 GWh – 399.18 GWh (current) = 14,337.55 GWh. An estimated additional total energy storage cost at $2,000/kWh equates to over $28.5 trillion dollars. Therefore, the additional combined renewable energy and storage capacity required to achieve a 100% renewable energy environment would be a little under $47 trillion dollars.

Baseline Reserve Margin		
Current Energy Capacity (12/2016)	**(GW)**	**(%) calculations**
Total United States	1,079.38	
Renewable Energy (include Hydro)	199.41	18.47%
Non-Renewable Deficit	879.97	81.53%
Average Overcapacity Required (xFactor)	13.88	1388%
RE Capacity Increase Required	12,213.93	
Average Renewable Energy Cost ($/kW)	$1,500	
Total Renewable Energy Cost ($)	$18,320,894,568,619	
Current Storage Capacity (12/2016)	**(GWh)**	**(%) calculations**
Total United States	399.18	
Average Storage/Renewable Energy Ratio	1.21	
Future Storage Capacity Required	14,736.73	
Storage Deficit	14,337.55	
Storage Capacity Increase Required (xFactor)	35.92	3592%
Average Storage Cost ($/kW)	$2,000	
Total Storage Cost ($)	$28,675,097,374,430	
Total Renewable Energy + Storage Cost ($)	**$46,995,991,943,049**	

Figure 50. Future renewable energy and storage capacity and dollars required to achieve 100% renewable energy environment (baseline reserve margin).

Middle ground reserve margin.

Using my middle ground reserve margin, the average multiplicative factor of renewable energy capacity to current capacity was 12.61 (see Figure 45; 1261% = 12.61). Therefore, 879.97 GW x 12.61 = 11,099.65 GW of additional renewable energy required to achieve a 100% renewable energy environment (Figure 51). At an estimated $1,500/kW, the total additional cost for renewable energy capacity in a 100% renewable energy environment would be over $16.5 trillion dollars.

Using my middle ground reserve margin, the average ratio for storage capacity in kilo-watt-hours to renewable energy capacity was 1.20. Therefore, if the additional renewable energy capacity required is 11,099.65 GW then the additional energy storage capacity required equals 11,099.65 GW x 1.20 hours = 13, 348.32 GWh – 399.18 GWh (current) = 12,949.14 GWh. An estimated additional total energy storage cost at $2,000/kWh equates to a little under $26 trillion dollars. Therefore, the additional combined renewable energy and storage capacity required to achieve a 100% renewable energy environment would be approximately $42.5 trillion dollars.

Middle Ground Reserve Margin		
Current Energy Capacity (12/2016)	**(GW)**	**(%) calculations**
Total United States	1,079.38	
Renewable Energy (include Hydro)	199.41	18.47%
Non-Renewable Deficit	879.97	81.53%
Average Overcapacity Required (xFactor)	12.61	1261%
RE Capacity Increase Required	11,099.65	
Average Renewable Energy Cost ($/kW)	$1,500	
Total Renewable Energy Cost ($)	$16,649,475,286,951	
Current Storage Capacity (12/2016)	**(GWh)**	**(%) calculations**
Total United States	399.18	
Average Storage/Renewable Energy Ratio	1.20	
Future Storage Capacity Required	13,348.32	
Storage Deficit	12,949.14	
Storage Capacity Increase Required (xFactor)	32.44	3244%
Average Storage Cost ($/kW)	$2,000	
Total Storage Cost ($)	$25,898,280,331,109	
Total Renewable Energy + Storage Cost ($)	**$42,547,755,618,060**	

Figure 51. Future renewable energy and storage capacity and dollars required to achieve 100% renewable energy environment (middle ground reserve margin).

Zero reserve margin.

Using my zero reserve margin, the average multiplicative factor of renewable energy capacity to current capacity was 12.55 (see Figure 48 above, 1255% = 12.55x). Therefore, 879.97 GW x 12.55 = 11,044.39 GW of additional renewable energy required to achieve a 100% renewable energy environment (Figure 52). At an estimated $1,500/kW, the total additional cost for renewable energy capacity in a 100% renewable energy environment would over $16.5 trillion dollars.

Using my baseline reserve margin, the average ratio for storage capacity in kilowatt-hours to renewable energy capacity was 1.07. Therefore, if the additional renewable energy capacity required is 11,044.39 GW then the additional energy storage capacity required equals 11,099.65

GW x 1.07 hours = 11,783.88 GWh – 399.18 GWh (current) = 11,384.70 GWh. An estimated additional total energy storage cost at $2,000/kWh equates to a little under $22.75 trillion dollars. Therefore, the additional combined renewable energy and storage capacity required to achieve a 100% renewable energy environment would be a little under $40 trillion dollars.

Zero Reserve Margin		
Current Energy Capacity (12/2016)	**(GW)**	**(%) calculations**
Total United States	1,079.38	
Renewable Energy (include Hydro)	199.41	18.47%
Non-Renewable Deficit	879.97	81.53%
Average Overcapacity Required (xFactor)	12.55	1255%
RE Capacity Increase Required	11,044.39	
Average Renewable Energy Cost ($/kW)	$1,500	
Total Renewable Energy Cost ($)	$16,566,589,541,136	
Current Storage Capacity (12/2016)	**(GWh)**	**(%) calculations**
Total United States	399.18	
Average Storage/Renewable Energy Ratio	1.07	
Future Storage Capacity Required	11,783.88	
Storage Deficit	11,384.70	
Storage Capacity Increase Required (xFactor)	28.52	2852%
Average Storage Cost ($/kW)	$2,000	
Total Storage Cost ($)	$22,769,395,975,461	
Total Renewable Energy + Storage Cost ($)	**$39,335,985,516,597**	

Figure 52. Future renewable energy and storage capacity and dollars required to achieve 100% renewable energy environment (zero reserve margin).

30-Year Levelized Cost of Energy (LCOE)

Levelized cost of energy (LCOE) calculates the present cost of developing, operating, and maintaining a power system over an assumed lifetime, typically 20-30 years (USDOE Office of Indian Energy, n.d.). LCOE measures the total lifetime costs of the project divided by total energy generated. It is a useful measurement because it allows for the comparison of varying technologies, lifespans, capital costs, and capacities.

A simplified LCOE equation is:

$$\frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

I_t = Investment expenditures in year t (including financing)
M_t = Operations and maintenance expenditures in year t
F_t = Fuel expenditures in year t
E_t = Electricity generation in year t
r = Discount rate
n = Life of the system (10)

Note. Simplified LCOE equation. From "Levelized Cost of Energy (LCOE)," by the U.S. DOE Office of Indian Energy, n.d., (https://energy.gov/sites/prod/files/2015/08/f25/LCOE.pdf).

In 2016, the U.S. Energy Information Administration (EIA) published an LCOE report that covers almost all current energy producing technologies (EIA, 2016b). Included in the EIA's LCOE (2016) report is a capacity-weighted average LCOE ($/MWh) in 2015 dollars for plants entering service in 2022 (see Figure 54). According to the EIA's *Capital Cost Estimates for Utility Scale Electricity Generating Plants* (2016) report, the EIA's LCOE report was generated using overnight capital costs (EIA, 2016a). Overnight capital costs assume the project was constructed overnight (World Nuclear Association, 2016). Overnight costs do not include financing costs of capital. Therefore, to match the EIA's LCOE calculations, I did not include capital financing costs in my LCOE calculation. Therefore, the variable *r*, in equation 10 above, is zero.

The life of the system, the variable *n*, in equation 10 is assumed to be 30 years. My 30-year assumption matches the system lifespan assumption found in the EIA's *Assumptions to the Annual Energy Outlook 2016* report (EIA, 2017a). The EIA's LCOE report references the

Assumptions report as a source of its parameter assumptions. In addition, wind and PV do not require any fuel for energy generation. Therefore, the variable F_t in equation 10 is zero.

In summary, the equation used by the EIA and myself to calculate LCOE was:

$$30\ year\ LCOE = \sum_{t=1}^{n} \frac{I_t + M_t}{E_t} \tag{11}$$

In basic terms, this means that a 30-year LCOE equals the total of project development expenses added to the 30-year sum of annual operation and maintenance expenses, divided by the total energy produced over 30 years.

One of the reasons I used the EIA's LCOE calculation for comparison was because the EIA used a capacity-weighted average to calculate their LCOE values. My sources of pricing, the US. DOE and NREL, also used a capacity-weighted average to calculate their wind and PV prices, respectively. Therefore, the baseline method of calculating averages was the same between my pricing source and the source I used to compare LCOE values. This is important, because price valuates cost. Cost is one of the key variables in a LCOE calculation.

However, the differences in my calculated LCOE values to the EIA's calculated LCOE values is significant. The LCOE values for PV and wind circled on the EIA chart shown in Figure 54 compared to my model's LCOE values illustrated in Figure 53 show marked disparity.

The differences in value between my LCOE calculations and the EIA's LCOE calculations may be attributable to the difference in cost parameters between the three government entities providing data. NREL's utility-scale solar with tracker capacity-weighted average price in 2016 was \$1,490/kW (NREL, 2016b). EIA's utility-scale solar with tracker capacity-weighted average price in 2016 was \$2,534/kW (EIA, 2016a). The DOE's utility-scale wind capacity-weighted average price in 2015 was \$1,690/kW (DOE, 2016). EIA's utility-scale wind capacity-weighted average price in 2016 was \$1,877/kW. O&M PV prices were \$18/kW versus $22/kW, for NREL and EIA, respectively. O&M wind prices were $26/kW versus $40/kW, for NREL and EIA, respectively. In summary, the pricing differences between the three government entities providing pricing data were highly discrepant. It is probable that these significant pricing differences account for the differences between my model's LCOE results in comparison to the EIA's LCOE results.

Below are my model's calculated LCOE capacity-weighted averages for renewable energy generation, and renewable energy generation plus storage, for all three of my reserve margin calculation methods (see Figure 53). All of the individual locations' 30-year LCOE data can be found in Appendix F, G, and H. All of the individual locations' 20-year LCOE data can be found in Appendix B, C, and D.

Baseline Reserve Margin (Conservative)	
30 Year Levelized Cost of Energy (LCOE) PV + Wind Only (MWh)	**$32.39**
30 Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (MWh)	**$80.03**

Middle Ground Reserve Margin	
30 Year Levelized Cost of Energy (LCOE) PV + Wind Only (MWh)	**$32.92**
30 Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (MWh)	**$77.78**

Zero Reserve Margin (Aggressive)	
30 Year Levelized Cost of Energy (LCOE) PV + Wind Only (MWh)	**$32.80**
30 Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (MWh)	**$74.32**

Figure 53. 30-year capacity-weighted optimal system LCOE calculations.

Plant Type	Capacity Factor (%)	Levelized Capital Cost	Fixed O&M	Variable O&M (including fuel)	Transmission Investment	Total System LCOE	Levelized Tax Credit	Total LCOE including Tax Credit[2]
		U.S. Capacity-Weighted[1] Average LCOE (2015 $/MWh) for Plants Entering Service in 2022						
Dispatchable Technologies								
Advanced Coal with CCS[3]	N/B							
Natural Gas-fired								
Conventional Combined Cycle	87	12.8	1.4	41.2	1.0	56.4	N/A	56.4
Advanced Combined Cycle	87	15.4	1.3	38.1	1.1	55.8	N/A	55.8
Advanced CC with CCS	N/B							
Conventional Combustion Turbine	30	37.1	6.5	58.9	2.9	105.4	N/A	105.4
Advanced Combustion Turbine	30	25.9	2.5	61.9	3.3	93.6	N/A	93.6
Advanced Nuclear	90	75.0	12.4	11.3	1.0	99.7	N/A	99.7
Geothermal	91	27.8	13.1	0.0	1.4	42.3	-2.8	39.5
Biomass	N/B							
Non-Dispatchable Technologies								
Wind	42	43.3	12.5	0.0	2.7	58.5	-7.6	50.9
Wind – Offshore	N/B							
Solar PV[4]	26	61.2	9.5	0.0	3.5	74.2	-15.9	58.2
Solar Thermal	N/B							
Hydroelectric[5]	60	54.1	3.1	5.0	1.5	63.7	N/A	63.7

Figure 54. EIA weighted average of regional values based on projected capacity additions.

Optimal Candidate Sites for Various Weather Patterns in the United States

This part of the study analyzed the optimization model's results for three types of PV/wind combination mixes (optimal mixes of similar PV/wind capacity, optimal mixes comprised mostly of wind, optimal mixes comprised mostly of PV), and listed the corresponding site locations. The weather patterns characterizing these site locations were also identified and analyzed.

One important result of my data that must be realized when attempting to categorize any site as an optimal PV only, wind only, or co-located PV/wind area is that the optimization results are highly dependent on the complex variable mix of inputs. For example, changing the baseline pricing parameters to match ones closer to the pricing provided by the EIA would have a significant impact on the optimal mix of PV and wind for any given location. As explained earlier in this paper, changing the reserve margin also has as a significant impact on the model's optimized combination mix result. Changing the load data to a different year might impact the results as well.

In summary, it is difficult to determine optimal PV/wind combination mix percentages without fully analyzing the most probable cases for all of the input parameters. Analyzing the probabilities for every input variable was outside the scope of this analysis, but would be a worthy study in the future.

Optimal Candidate Sites for Co-Located PV and Wind Systems of Similar Capacity

Baseline reserve margin.

When I used my conservative baseline reserve margin as a parameter, I found seven locations with optimal PV/wind combination mixes of similar percentage capacities. I designated similar capacities as those being within a 75%/25% combination mix ratio (see Figure 55). Therefore, when utilizing my baseline reserve margin methodology, 27% (7 of 26) of the total locations optimized were of similar PV/wind capacities.

Optimal Co-Located Systems (Baseline Reserve Margin)							
City, State	Wind %	PV %	Avg Wind Speed (m/s)	Avg Irradiance (W/m^2)	Wind Speed Quartile	Irradiance Quartile	Quartile Separation
Bowie, Arizona	47.5%	52.5%	5.80	237.43	3	4	1
Champaign, Illinois	35.0%	65.0%	7.33	172.90	3	1	2
Lincoln, Nebraska	42.5%	57.5%	7.61	178.91	4	2	2
Stillwater, Oklahoma	42.5%	57.5%	7.27	194.28	3	3	0
Sioux Falls, South Dakota	47.5%	52.5%	7.86	174.22	4	1	3
Amarillo, Texas	52.5%	47.5%	7.62	218.28	4	3	1
Austin, Texas	67.5%	32.5%	6.60	202.57	3	3	0

Figure 55. Optimal PV/wind systems of similar capacity (conservative baseline reserve margin).

When using my conservative baseline reserve margin, one of the optimal PV/wind systems of similar capacity was of the highest quartile in wind or PV, and the lowest quartile in the other. Two of the optimal PV/wind systems of similar capacity had quartile ranks of two separations. Two of the optimal PV/wind systems of similar capacity had quartile ranks of one separation. Two of the optimal PV/wind systems of similar capacity had the same quartile rank. Therefore, 57% of the optimal systems of similar capacity were also similar (within 1 quartile separation) in weather pattern quartile rank.

Middle ground reserve margin.

When I used my middle ground reserve margin as a parameter, I found twelve locations with optimal PV/wind combination mixes of similar percentage capacities (Figure 56). Therefore, when utilizing my middle ground reserve margin methodology, 46% (12 of 26) of the total locations optimized were of similar PV/wind capacities.

Optimal Co-Located Systems (Middle Ground Reserve Margin)							
City, State	Wind %	PV %	Avg Wind Speed (m/s)	Avg Irradiance (W/m^2)	Wind Speed Quartile	Irradiance Quartile	Quartile Separation
Bowie, Arizona	35.0%	65.0%	5.80	237.43	3	4	1
Champaign, Illinois	32.5%	67.5%	7.33	172.90	3	1	2
Lincoln, Nebraska	55.0%	45.0%	7.61	178.91	4	2	2
Edison, NJ	42.5%	57.5%	5.59	174.28	2	1	1
Stillwater, Oklahoma	37.5%	62.5%	7.27	194.28	3	3	0
Kingston, Rhode Island	50.0%	50.0%	5.35	173.37	2	1	1
Sioux Falls, South Dakota	65.0%	35.0%	7.86	174.22	4	1	3
Nashville, Tennessee	32.5%	67.5%	5.44	180.36	2	2	0
Amarillo, Texas	35.0%	65.0%	7.62	218.28	4	3	1
Austin, Texas	52.5%	47.5%	6.60	202.57	3	3	0
Laramie, Wyoming	57.5%	42.5%	8.12	187.11	4	2	2
McFadden, Wyoming	30.0%	70.0%	6.95	184.22	3	2	1

Figure 56. Optimal PV/wind systems of similar capacity (middle ground reserve margin).

When using my middle ground reserve margin, one of the optimal PV/wind systems of similar capacity was of the highest quartile in wind or PV, and the lowest quartile in the other. Three of the optimal PV/wind systems of similar capacity had quartile ranks of two separations. Five of the optimal PV/wind systems of similar capacity had quartile ranks of one separation. Three of the optimal PV/wind systems of similar capacity had the same quartile rank. Therefore, 75% of the optimal systems of similar capacity were also similar (within 1 quartile separation) in weather pattern quartile rank.

Zero reserve margin.

When I used no reserve margin as a parameter, I found eight locations with optimal PV/wind combination mixes of similar percentage capacities (Figure 57). Therefore, when utilizing no reserve margin, 31% (8 of 26) of the total locations optimized were of similar PV/wind capacities.

Optimal Co-Located Systems (Zero Reserve Margin)							
City, State	Wind %	PV %	Avg Wind Speed (m/s)	Avg Irradiance (W/m^2)	Wind Speed Quartile	Irradiance Quartile	Quartile Separation
Lincoln, Nebraska	55.0%	45.0%	7.61	178.91	4	2	2
Edison, NJ	42.5%	57.5%	5.59	174.28	2	1	1
Stillwater, Oklahoma	37.5%	62.5%	7.27	194.28	3	3	0
Kingston, Rhode Island	50.0%	50.0%	5.35	173.37	2	1	1
Sioux Falls, South Dakota	65.0%	35.0%	7.86	174.22	4	1	3
Nashville, Tennessee	32.5%	67.5%	5.44	180.36	2	2	0
Austin, Texas	52.5%	47.5%	6.60	202.57	3	3	0
McFadden, Wyoming	30.0%	70.0%	6.95	184.22	3	2	1

Figure 57. Optimal PV/wind systems of similar capacity (zero reserve margin).

When using no reserve margin, one of the optimal PV/wind systems of similar capacity was of the highest quartile in wind or PV, and the lowest quartile in the other. One of the optimal PV/wind systems of similar capacity had quartile ranks of two separations. Three of the optimal PV/wind systems of similar capacity had quartile ranks of one separation. Three of the optimal PV/wind systems of similar capacity had the same quartile rank. Therefore, 75% of the optimal systems of similar capacity were also similar (within 1 quartile separation) in weather pattern quartile rank.

Optimal Candidate Sites for Systems Comprised of Mostly Wind

Baseline reserve margin.

When I used my conservative baseline reserve margin as a parameter, I found one location with an optimal PV/wind combination mix comprised mostly of wind. I designated mostly wind capacities as those being greater than or equal to a 75% combination mix ratio in favor of wind (see Figure 58). Therefore, when utilizing my baseline reserve margin, 4% (1 of 26) of the total locations optimized favored a combination mix mostly comprised of wind.

Optimal Wind Systems (Baseline Reserve Margin)							
City, State	Wind %	PV %	Avg Wind Speed (m/s)	Avg Irradiance (W/m^2)	Wind Speed Quartile	Irradiance Quartile	Quartile Separation
Laramie, Wyoming	75.0%	25.0%	8.12	187.11	4	2	2

Figure 58. Optimal PV/wind systems comprised mostly of wind (conservative baseline reserve margin).

Laramie, Wyoming was the only location that qualified for comprising mostly wind energy when I utilized my conservative baseline reserve margin. Laramie, Wyoming also had the highest average wind speed of all locations analyzed.

Middle ground reserve margin.

When I used my middle ground reserve margin as a parameter, I found no locations with an optimal PV/wind combination mix comprised mostly of wind.

Zero reserve margin.

When I used no reserve margin as a parameter, I found no locations with an optimal PV/wind combination mix comprised mostly of wind.

Optimal Candidate Sites for Systems Comprised of Mostly PV

Baseline reserve margin.

When I used my conservative baseline reserve margin as a parameter, I found eighteen locations with an optimal PV/wind combination mix comprised mostly of PV. I designated mostly PV capacities as those being greater than or equal to a 75% combination mix ratio in favor of PV (see Figure 59). Therefore, when utilizing my baseline reserve margin, 69% (18 of 26) of the total locations optimized favored a combination mix mostly comprised of PV.

Optimal PV Systems (Baseline Reserve Margin)							
City, State	Wind %	PV %	Avg Wind Speed (m/s)	Avg Irradiance (W/m^2)	Wind Speed Quartile	Irradiance Quartile	Quartile Separation
Phoenix, Arizona	5.0%	95.0%	4.89	244.72	1	4	3
Bodega, California	15.0%	85.0%	5.16	216.58	2	3	1
Fresno, California	17.5%	82.5%	5.02	224.71	1	4	3
Mojave, California	20.0%	80.0%	5.69	245.08	2	4	2
Santa_Barbara, California	15.0%	85.0%	5.02	233.33	1	4	3
Boulder, Colorado	10.0%	90.0%	5.60	176.92	2	2	0
Everglades City, Florida	5.0%	95.0%	5.09	204.66	2	3	1
Hays, Kansas	10.0%	90.0%	7.74	202.47	4	3	1
Gaylord, Michigan	20.0%	80.0%	7.27	144.15	3	1	2
Jackson, Mississippi	2.5%	97.5%	4.69	190.51	1	2	1
Durham, North Carolina	12.5%	87.5%	4.87	184.79	1	2	1
Edison, New Jersey	25.0%	75.0%	5.59	174.28	2	1	1
Clovis, New Mexico	20.0%	80.0%	7.53	223.49	4	4	0
Millbrook, New York	12.5%	87.5%	4.55	169.79	1	1	0
Kingston, Rhode Island	17.5%	82.5%	5.35	173.37	2	1	1
Nashville, Tennessee	20.0%	80.0%	5.44	180.36	2	2	0
Bronte, Texas	5.0%	95.0%	7.17	217.29	3	3	0
McFadden, Wyoming	15.0%	85.0%	6.95	184.22	3	2	1

Figure 59. Optimal PV/wind systems comprised mostly of PV (conservative baseline reserve margin).

When using my conservative baseline reserve margin, three of the optimal PV/wind systems comprised mostly of PV were of the highest quartile in wind or PV, and the lowest quartile in the other. Two of the optimal PV/wind systems of similar capacity had quartile ranks of two separations. Eight of the optimal PV/wind systems of similar capacity had quartile ranks of one separation. Five of the optimal PV/wind systems of similar capacity had the same quartile rank. Therefore, 72% of the optimal systems comprised mostly of PV were also similar (within 1 quartile separation) in weather pattern quartile rank.

Middle ground reserve margin.

When I used my middle ground reserve margin as a parameter, I found fourteen locations with optimal PV/wind combination mixes comprised mostly of PV (see Figure 60). Therefore, when utilizing my middle ground reserve margin, 54% (14 of 26) of the total locations optimized favored a combination mix mostly comprised of PV.

Optimal PV Systems (Middle Ground Reserve Margin)							
City, State	Wind %	PV %	Avg Wind Speed (m/s)	Avg Irradiance (W/m^2)	Wind Speed Quartile	Irradiance Quartile	Quartile Separation
Phoenix, Arizona	5.0%	95.0%	4.89	244.72	1	4	3
Bodega, California	15.0%	85.0%	5.16	216.58	2	3	1
Fresno, California	17.5%	82.5%	5.02	224.71	1	4	3
Mojave, California	20.0%	80.0%	5.69	245.08	2	4	2
Santa_Barbara, California	15.0%	85.0%	5.02	233.33	1	4	3
Boulder, Colorado	10.0%	90.0%	5.60	176.92	2	2	0
Everglades City, Florida	5.0%	95.0%	5.09	204.66	2	3	1
Hays, Kansas	10.0%	90.0%	7.74	202.47	4	3	1
Gaylord, Michigan	20.0%	80.0%	7.27	144.15	3	1	2
Jackson, Mississippi	2.5%	97.5%	4.69	190.51	1	2	1
Durham, North Carolina	12.5%	87.5%	4.87	184.79	1	2	1
Clovis, New Mexico	20.0%	80.0%	7.53	223.49	4	4	0
Millbrook, New York	12.5%	87.5%	4.55	169.79	1	1	0
Bronte, Texas	5.0%	95.0%	7.17	217.29	3	3	0

Figure 60. Optimal PV/wind systems comprised mostly of PV (middle ground reserve margin).

When using my middle ground reserve margin, three of the optimal PV/wind systems comprised mostly of PV were of the highest quartile in wind or PV, and the lowest quartile in the other. Two of the optimal PV/wind systems of similar capacity had quartile ranks of two separations. Five of the optimal PV/wind systems of similar capacity had quartile ranks of one separation. Four of the optimal PV/wind systems of similar capacity had the same quartile rank.

Therefore, 64% of the optimal systems comprised mostly of PV were similar (within 1 quartile separation) in weather pattern quartile rank.

Zero reserve margin.

When I used no reserve margin as a parameter, I found eighteen locations with optimal PV/wind combination mixes comprised mostly of PV (see Figure 61). Therefore, when utilizing my middle ground reserve margin, 69% (18 of 26) of the total locations optimized favored a combination mix mostly comprised of PV.

Optimal PV Systems (Zero Reserve Margin)							
City, State	Wind %	PV %	Avg Wind Speed (m/s)	Avg Irradiance (W/m^2)	Wind Speed Quartile	Irradiance Quartile	Quartile Separation
Bowie, Arizona	17.5%	82.5%	5.80	237.43	3	4	1
Phoenix, Arizona	5.0%	95.0%	4.89	244.72	1	4	3
Bodega, California	20.0%	80.0%	5.16	216.58	2	3	1
Fresno, California	17.5%	82.5%	5.02	224.71	1	4	3
Mojave, California	2.5%	97.5%	5.69	245.08	2	4	2
Santa_Barbara, California	22.5%	77.5%	5.02	233.33	1	4	3
Boulder, Colorado	5.0%	95.0%	5.60	176.92	2	2	0
Everglades City, Florida	7.5%	92.5%	5.09	204.66	2	3	1
Champaign, Illinois	12.5%	87.5%	7.33	172.90	3	1	2
Hays, Kansas	2.5%	97.5%	7.74	202.47	4	3	1
Gaylord, Michigan	10.0%	90.0%	7.27	144.15	3	1	2
Jackson, Mississippi	2.5%	97.5%	4.69	190.51	1	2	1
Durham, North Carolina	12.5%	87.5%	4.87	184.79	1	2	1
Clovis, New Mexico	25.0%	75.0%	7.53	223.49	4	4	0
Millbrook, New York	15.0%	85.0%	4.55	169.79	1	1	0
Amarillo, Texas	25.0%	75.0%	7.62	218.28	4	3	1
Bronte, Texas	2.5%	97.5%	7.17	217.29	3	3	0
McFadden, Wyoming	15.0%	85.0%	6.95	184.22	3	2	1

Figure 61. Optimal PV/wind systems comprised mostly of PV (zero reserve margin).

When utilizing no reserve margin, three of the optimal PV/wind systems comprised mostly of PV were of the highest quartile in wind or PV, and the lowest quartile in the other. Three of the optimal PV/wind systems of similar capacity had quartile ranks of two separations. Eight of the optimal PV/wind systems of similar capacity had quartile ranks of one separation.

Four of the optimal PV/wind systems of similar capacity had the same quartile rank. Therefore, 67% of the optimal systems comprised mostly of PV were similar (within 1 quartile separation) in weather pattern quartile rank.

Intermittency Analysis

One of the most interesting results that this model provided was that zero of the optimized 26 PV/wind combination mixes favored a 100%/0% mix. Even in the middle of the desert (Phoenix, AZ), the model predicts a small bit of wind (5%) as optimal. Also, one of the windiest places in the United States (Laramie, Wyoming) can benefit from PV (25% to 47.5% depending on reserve margin method). I believe the result of no 100%/0% optimal combination mixes to be attributable to the reduction in intermittency of a co-located PV/wind system, and the advantage of deploying wind that provides a greater capacity factor than PV.

One method of measuring intermittency is to calculate the maximum numbers of consecutive hours without a renewable energy technology producing power (see Figure 62). It is fairly easy to confirm from the data shown in Figure 56 below that wind it much more variable than sun. The average number of maximum consecutive hours without wind producing power was 32, with a standard deviation of 13.7. The average number of maximum consecutive hours without sun producing power was 18, with a standard deviation of .97. In summary, the sun as a source of power production is a lot more consistent. The average maximum consecutive number of hours of no power being produced decreases to 14 when both the sun and wind are combined.

Interestingly, however, the optimal system average maximum number of consecutive negative net load hours increases to 17. This is further evidence that the model's optimal system is determined by a complex mix of significantly influential variables.

Even though the sun is more consistent than wind, wind turbines on average have higher capacity factors than PV. Of course, capacity factors are location dependent. Even in this study, in which the number of sunny locations outnumbered the windy locations by 10 to 7 (the remaining nine locations had GIS zones of equal sun and wind), the average capacity factor for wind was higher (28% wind vs. 23.5% PV).

Therefore, I believe it is the combination of the consistency of the sun, and the higher capacity factor of the wind, that influences the optimization result. Even in some of the windiest places like Sioux Falls, SD, a significant percentage of PV is required (~50%) because of wind's variability and higher price, in spite of wind's more than double capacity factor and slightly shorter (2 hours) maximum consecutive hours without producing power.

	# of Max Consecutive Hours					
ST_City (Weather)	NO WIND Power	NO SUN Power	NO POWER	Negative Net Load Hours	Wind Capacity Factor (%)	PV Capacity Factor (%)
AZ_Bowie	53	17	14	15	22.06%	27.79%
AZ_Phoenix	53	16	16	18	16.42%	28.52%
CA_Bodega	37	18	15	17	18.09%	26.36%
CA_Fresno	40	17	15	17	18.01%	26.31%
CA_Mojave	37	18	14	17	20.28%	29.74%
CA_Santa_Barbara	37	17	15	17	17.25%	28.73%
CO_Boulder	36	18	14	16	19.53%	21.81%
FL_Everglades_City	74	16	13	17	18.19%	22.28%
IL_Champaign	30	18	16	19	40.80%	20.52%
KS_Hays	28	16	14	17	43.88%	24.30%
MI_Gaylord	31	19	16	17	40.23%	17.30%
MS_Jackson	32	17	14	17	12.10%	21.43%
NC_Durham	23	17	14	16	14.78%	21.28%
NE_Lincoln	20	18	11	18	43.81%	21.53%
NJ_Edison	26	18	15	17	21.66%	20.62%
NM_Clovis	26	17	16	17	39.54%	26.60%
NY_Millbrook	55	18	12	15	11.95%	20.52%
OK_Stillwater	25	17	13	17	39.62%	22.86%
RI_Kingston	19	18	14	16	18.78%	21.04%
SD_Sioux_Falls	18	20	9	19	45.69%	20.93%
TN_Nashville	38	17	15	17	20.06%	20.97%
TX_Amarillo	17	17	12	15	41.33%	25.98%
TX_Austin	24	17	13	16	31.41%	22.68%
TX_Bronte	21	17	16	18	37.82%	24.76%
WY_Laramie	16	19	10	14	43.16%	22.30%
WY_McFadden	21	19	12	14	30.91%	22.51%
Total Average	32	18	14	17	27.98%	23.45%
Total Standard Deviation	13.70575183	0.969963093	1.846153846	1.269230769	0.116106789	0.030906692

Figure 62. Maximum number of consecutive hours of no wind, sun, productions. The maximum number of consecutive negative net load hours for the optimal system is also listed. In addition, capacity factors for wind and PV technologies are displayed. Total average and standard deviation is computed for all factors.

CHAPTER 6: DISCUSSION AND CONCLUSIONS

Timing

One of the most significant concepts that I learned from this study is the importance of timing of power production and load. Even if the location being analyzed has a strong wind resource, if the strong wind resource does not produce power during the location's season of peak loads, significant amounts of PV are required. This is evident in the locations highlighted in Figure 64. All of the wind locations that ranked in the upper quartile still benefitted from significant percentages of PV. Five of those six locations had a summer peak load season.

Another great example of the importance of renewable energy generation-load timing is Lincoln, Nebraska. Lincoln had the 5th highest wind speed average of the 26 locations analyzed (4th quartile). However, using my baseline reserve margin, its optimal combination mix was 42.5% wind/57.5% PV. One plausible explanation why the optimal mix does not favor a greater percentage of wind is that Lincoln's peak load time is during the summer, when wind energy generation is at its weakest (see Figure 63). Therefore, to compensate for the lack of wind energy during this time of peak loads, the model must utilize more PV in order to maintain the required reserve margin.

For my middle ground reserve margin scenario, Lincoln's optimal combination mix changes to 55% wind/45% PV. For a zero reserve margin scenario, Lincoln's optimal combination mix changes to 52.5% wind/47.5% PV. Therefore, without needing to meet a higher reserve requirement during the peak loads of summer, the optimal mix uses more wind energy because of wind's higher capacity factor (43.81% capacity factor for wind, 33.21% capacity factor for PV).

In summary, *when* a renewable energy technology produces power is as important as *how much* power it produces. For the full year, the wind of Lincoln, Nebraska produced 75% of maximum power (750 MW) 25.67% of the time. PV in Lincoln, Nebraska produced 75% of maximum power only 5.67% of the time. Therefore, wind in Lincoln produced 75% of maximum power, a magnitude of five times more than PV. However, during the summer hours (lines 4128 to 6336 in the model), wind's production of 75% of maximum power dropped to 14.52% of the time, while PV production of 75% of maximum power increased to 7.6%.Thus, during the time of Lincoln's peak loads, wind's production decreased while PV's production increased. Even though wind's production of 75% of maximum power was still higher, PV is both less expensive and less variable. Therefore, my model favored PV to always meet the minimum reserve margin requirement. These results provide solid evidence to support my claims that timing of renewable energy generation and load is significant, and that each system is a complex mix of interrelated variables.

In my opinion, studies that consider the timing of power production and load are absolutely essential to optimizing our future renewable energy environment. Without looking at the granular time comparisons of renewable energy generation versus load, a model might underestimate the total system and storage capacities required to maintain a reliable grid.

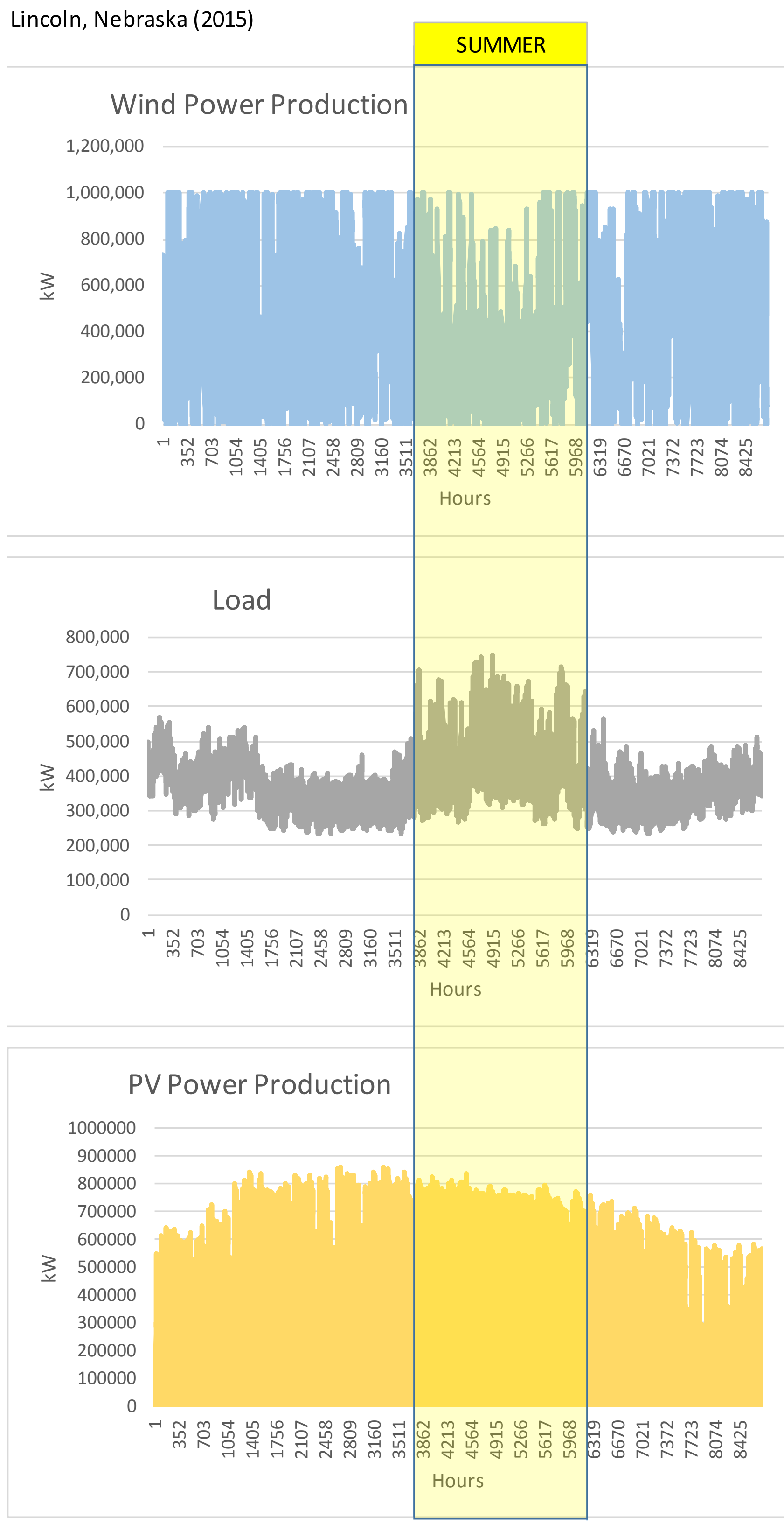


Figure 63. Lincoln, Nebraska (2015) – wind/PV/load timing comparison.

Peak Load Season Comparison with Optimal Combination Mixes Baseline Reserve Method					
ST_City (Weather)	Peak Load Season	Optimal Wind (%)	Optimal PV (%)	Wind Speed Quartile	Irradiance Quartile
AZ_Bowie	Spring	47.5%	52.5%	3	4
AZ_Phoenix	Spring	5.0%	95.0%	1	4
CA_Bodega	Summer	15.0%	85.0%	2	3
CA_Fresno	Summer	17.5%	82.5%	1	4
CA_Mojave	Summer/Fall	20.0%	80.0%	2	4
CA_Santa_Barbara	Summer/Fall	15.0%	85.0%	1	4
CO_Boulder	Summer & Winter	10.0%	90.0%	2	2
FL_Everglades_City	Summer	5.0%	95.0%	2	3
IL_Champaign	Summer	35.0%	65.0%	3	1
KS_Hays	Summer	10.0%	90.0%	4	3
MI_Gaylord	Summer	20.0%	80.0%	3	1
MS_Jackson	Summer	2.5%	97.5%	1	2
NC_Durham	Summer	12.5%	87.5%	1	2
NE_Lincoln	Summer	42.5%	57.5%	4	2
NJ_Edison	Summer	25.0%	75.0%	2	1
NM_Clovis	Fall	20.0%	80.0%	4	4
NY_Millbrook	Summer	12.5%	87.5%	1	1
OK_Stillwater	Summer	42.5%	57.5%	3	3
RI_Kingston	Summer	17.5%	82.5%	2	1
SD_Sioux_Falls	Summer & Winter	47.5%	52.5%	4	1
TN_Nashville	Summer & Winter	20.0%	80.0%	2	2
TX_Amarillo	Summer	52.5%	47.5%	4	3
TX_Austin	Summer	67.5%	32.5%	3	3
TX_Bronte	Summer & Winter	5.0%	95.0%	3	3
WY_Laramie	Summer & Winter	75.0%	25.0%	4	2
WY_McFadden	Summer & Winter	15.0%	85.0%	3	2

Figure 64. Peak load seasons compared to optimal combination mixes.

Reserve Margin Sensitivity

In this study, I presented PV/wind combination mix optimizations based on two different novel reserve margin calculation methodologies, and optimizations based on a zero reserve margin scenario. Twenty-one of the 26 (81%) sites' optimal PV/wind combination mixes changed when the reserve margin changed from my conservative baseline reserve margin to the zero reserve margin scenario (see Figure 33). Based on this high percentage of changing optimizations, it is evident that optimization is sensitive to reserve margin. However, neither the degree of sensitivity nor the direction (positive or negative) of the change could be easily ascertained from the data. In other words, when the reserve margin was changed, I could not ascertain any distinguishing patterns that explained the magnitudinal change of percentage in any location's optimal PV/wind combination mix. In addition, when the reserve margin was changed, I could not ascertain any distinguishing patterns that explained the new optimal combination mix favoring more PV or more wind. Changing the reserve margin definitely invoked changes in almost every location's optimal combination mix of PV and wind. However, identifying the trends that underlie these changes was beyond the scope of this analysis. I believe a future study on how reserve margins affect renewable energy optimization mixes is warranted.

Given that optimal mixes of renewable energy technology capacities are sensitive to the size of the reserve margin, calculating reserve margin in a 100% renewable energy environment is important for grid stability, and for developing optimal renewable energy capacities. Reserve margins are a fundamental parameter to ensure grid reliability and performance. Adding another variable parameter such as renewable energy generation to the energy reliability equation further increases the need for a sound reserve margin calculation methodology.

In addition to ensuring grid stability, correctly calculating adequate reserve margins will also provide a true baseline for optimizing capacities of renewable energy technology combination mixes. As mentioned previously, optimized capacities of renewable energy technology combination mixes provides reliable energy at the lowest possible cost. Providing reliable energy at the lowest possible cost saves resources for every human that uses energy. In other words, pretty much everyone on earth benefits from optimized renewable energy technology mixes.

Renewable Energy Generation and Storage Capacities Compared to Fossil Fuels

Another important aspect of this study was determining the quantity of optimized renewable energy technology capacities that meet our current energy demand load requirements. Even with the most aggressive scenario of zero reserve margin, a 100% renewable energy environment requires approximately 12.55 times more renewable energy generation capacity, than our current fossil-fuel capacity.

In summary, due to the intermittent and variable nature and lower capacity factors of renewable energy, significant amounts more of it are required to reliably generate the same amount of energy production in comparison to our fossil fuel alternatives. For reference, coal and natural gas capacity factors are approximately 53% and 56%, respectively (EIA, 2017d). In comparison, utility-scale wind and PV average capacity factors are 34.7% and 27.2%, respectively (EIA, 2017d).

Storage Capacities

Another important lesson learned from this study was the enormous amount of storage capacity that is required to ensure a stable 100% renewable energy environment. In two of my scenarios, the baseline reserve method and middle ground reserve method, more storage capacity would be required than energy generation capacity. The magnitudes of required storage capacities elevate their importance to that of equaling the renewable energy generation technologies. Again, due to the intermittent and variable nature of renewable energy, a reliable grid cannot be ensured without adequate amounts of energy storage, at least as we currently approach provision of electricity to utility customers.

Another interesting set of data derived from this study was the difference, or lack thereof, in average storage capacity levels in relation to renewable energy generation system capacity between systems dominated by either PV or wind. Utilizing my conservative baseline reserve margin scenario—the only reserve margin method that had significant optimal wind percentages that could provide an adequate comparison baseline—for any system that included an optimal combination mix of greater than or equal to 25% wind, storage capacity levels required were 10% greater than that of the combination mix percentages of systems dominated by PV. Given wind's higher variability in comparison to PV, I had logically expected that wind systems would require significantly more storage than the model's finding of 10% greater than PV. This result is more evidence that provides support for my belief that each location is influenced by a complex mix of variables.

Whole System Perspective

Given that storage capacity requirements rival that of renewable energy technology capacities, it is ever more important that we consider our energy environment from a whole (and complex) system perspective. Only taking into consideration one part of our energy system could lead to perilous results of wasted resources and lost time. Wasted resources hurt the entire population's overall well-being. Lost time could result in a drastic reduction of our environment's health.

Co-Location Optimization – No 100%/0%

A very interesting result of this study was that of the 26 locations analyzed, each with three different reserve margin scenarios (78 iterations), not one of the optimal results was 100%/0%. This means that even the middle of the desert, where the sun reigns supreme, can benefit from a bit of wind technology. The closet result to 100%/0% was the zero reserve margin scenario of Mojave, California that was optimized at 97.5% PV and 2.5% wind.

In addition, it was obvious that the windy locations could benefit from the more consistent sun. The highest optimized wind dominated result was the baseline reserve margin scenario of Laramie, Wyoming that was optimized at 75% wind and 25% PV.

As mentioned previously, the different variability, intermittency, and capacity factor patterns of wind and solar renewable energy technologies make them excellent complements to one another.

Cost

There is both good news and bad news concerning the cost parameters that my study predicts.

The Bad News

Using the most aggressive zero reserve margin method (lowest cost), the capacity-weighted average cost for an optimal combined 100% renewable energy and storage system, based on the 26 locations that I analyzed, is $1,132,729,602,163. That's over a trillion dollars… per location. Some of the locations that I analyzed incorporated extremely large loads, including one that comprises half the state of California. Some of the locations that I analyzed incorporated extremely small loads; for example, only the city of Lincoln, Nebraska. However, the trillion-dollar figure is a capacity-weighted average, so it takes into consideration the size of the loads each location incorporated.

In summary, it is going to cost this nation a lot of money to source its energy from 100% renewable sources. Mark Jacobson, professor at Stanford University, put the United States 100% renewable energy price tag at $12 trillion dollars, but this includes 40% electrification of almost everything we own and use (Jacobson, 2015). Greenpeace put the world's renewable energy price tag at just under $65 trillion dollars (Greenpeace, 2015). Based on my model, I find these calculations to be extremely low. In my opinion, neither the Jacobson nor the Greenpeace analysis adequately accounts for the levels of energy storage capacity required to maintain grid reliability, and did not analyze the solutions required with enough granularity. Hourly empirical data comparisons between renewable energy generation and load at county levels are required to adequately assess the total capacities required to maintain grid reliability in a 100% renewable energy environment. My model estimates the total cost of achieving a 100% renewable energy environment for the United States at a range of $36.5 – $45 trillion dollars.

The Good News

Using my baseline conservative reserve margin method (highest cost), the average optimal LCOE of the 26 locations analyzed was $0.0329/kWh for energy and $0.8003/kWh for energy plus storage. Currently (as of January 2017), this nation's average cost of energy is $0.1015/kWh (EIA, 2017c).

So, a hefty price tag up front could lead us into a low cost renewable energy future, and at the same time avert potentially disastrous environmental catastrophe resulting from fossil fuel combustion.

Unusual or Contradictory Results/Patterns

Pricing Parameters that Favor PV

For all regions and states of my model, PV pricing was always lower than wind. In the case of the windiest location analyzed, Laramie, Wyoming, the Interior region wind pricing of $1,666/kW competed against a Wyoming state PV price of $1,233/kW. This price ratio difference is 26%. Laramie's simulated wind capacity factor for 2015 was 43.16%, while Laramie's simulated PV capacity factor for 2015 was 22.30%. Even though Laramie's wind capacity factor was almost double that of its PV capacity, the standard deviation of the amount of power that a baseline 1 GW PV system produced was 17% more closely related to its mean than the a baseline 1 GW wind system. Therefore, the combination of lower PV pricing, and its capacity to provide power more consistently, may have resulted in optimal systems that favor PV.

PV/Wind System Energy Generation Timings Compared to Load Timings

Fifteen of the 26 locations analyzed had their peak load season during summer. Two of the locations analyzed had their peak load season during the end of summer, beginning of fall. Six locations analyzed had their peak load season during summer and winter. Therefore, 23 of the 26 locations (88.46%) had their peak load season during some part of summer. Summer is when wind speeds are the lowest, therefore wind power production is at the lowest. In order to meet peak demand loads for every hour during the summer, PV is the more optimal technology for the following three reasons:

- PV power production increases during the summer,
- PV produces power more consistently during the summer,
- PV maximum power production duration is longer.

In a 100% renewable energy environment, the total sum of power a technology can produce is only one factor. The main goal is to always meet load demand for the least expensive cost. A mix of renewable energy technologies that can always satisfy load demand at exceedingly high probabilities, and do so at the lowest expense, should be preferred.

Further Studies

Future models that consider the following factors in addition to the ones identified in this study would provide a more comprehensive perspective of the entire 100% renewable energy solution required:

- GIS parameters

    - Available geographical locations for wind and PV technology plants
        - Wetlands, government land, nature preserves, etc.
        - Topography (mountains, terrain roughness)
    - Vicinity of high voltage transmission lines to potential plant locations
        - Costs associated with transmission line installation to potential plant locations
- More types of energy storage technologies
    - Geographic energy storage type availability (e.g., pumped hydro)
    - Costs comparisons between different storage types
    - Optimal and strategic locations for energy storage nodes
        - Relative to load centers
- Add other renewables to the model
    - Hydro, biomass, etc.

Based on the results of this model, I believe that a county-level analysis is required to adequately model every state's optimal renewable energy combination mixes. This level of granularity is required to adequately assess and match the counties' weather patterns with the counties' loads. Therefore, each individual analysis of a state's counties would aggregate to the state's optimal renewable energy combination mix. Only a county-level model can provide adequate comparisons between geographical weather patterns, topography, vicinity of transmission lines, and load. In summary, optimization modeling per county with consideration of intra-county overlaps of weather and load patterns would be ideal (see, for example, Figure 65).

Overall, in order to deploy an economically viable and technically sound 100% renewable energy future, prudent decisions regarding energy sourcing, processing, and transmission are fundamentally required. In-depth studies, in combination with governmental support, would help ensure that energy is provided reliably and judiciously to everyone. Energy is a foundational element of our existence. Let's make sure we treat it as such.

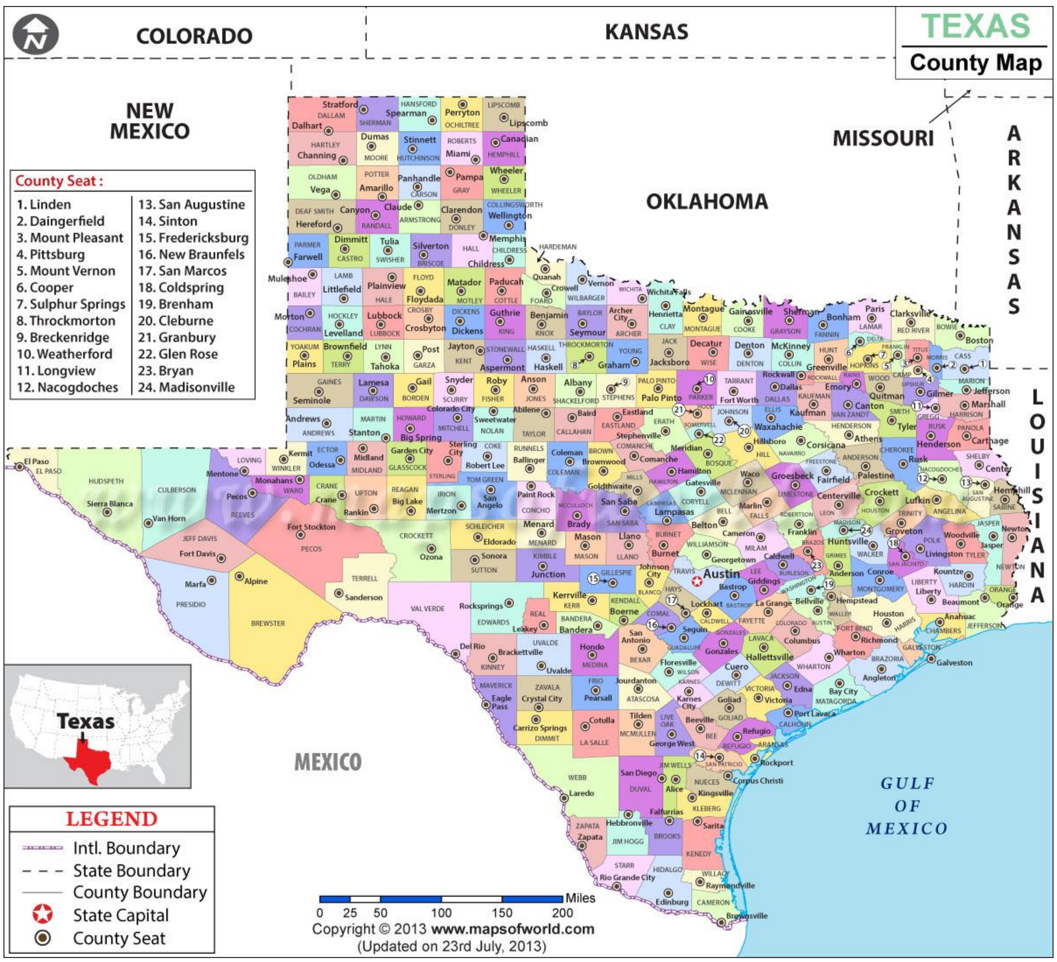


Figure 65. Map of individual Texas counties.

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APPENDIX A

The Two-Hand Proof

Summary

Statement: One can never take fractions (percentages) of two integers so that the sum of the resulting fractions (percentages) is greater than the greatest integer, when the original fractions (percentages) equate to 1.

Assumptions: Let the fractions (percentages) be x and $1-x$, with $0<x<1$, and let the two integers be y and z, both positive and sum to 1.

The **combination in consideration** is $xy + (1-x)z$.

Variables

$\% x$

$int\ y$

$int\ z$

Parameters

$0 < x\% < 100\%$

$y > 0$

$z > 0$

$y + z = 100\%$

Proof Equations

If $z < y$, then $[xy + (1-x)z] < [xy + (1-x)y] = [xy + y - xy] = y$.

And if $y < z$, then $[xy + (1-x)z] = [xy + z - xz] = [x(y - z) + z] < x(0) + z = z$.

And if $y=z$, then $[xy + (1 - x)z] = [xy + (1 - x)y] = [xy + y - xy] = y$.

Example - Condition 1

$Y = .6$

$Z = .4$

$X = .25$

$[.25(.6) + (.75)(.4)] < [.25(.6) + (.75).6] = [.25(.6) + .6 - .25(.6)] = .6$

Example - Condition 2

$Y = .4$

$Z = .6$

$X = .25$

$[.25(.4) + (.75)(.6)] = [.25(.4) + .6 - (.25).6] = [.25(.4 - .6) + .6] < .25(0) + .6 = .6$

Example - Condition 3

$Y = .5$

$Z = .5$

$X = .25$

$[.25(.5) + (.75)(.5)] = [.25(.5) + (.75).5] = [.25(.5) + .5 - .25(.5)] = .5$

APPENDIX B

Data Results – Baseline Reserve Margin (Conservative)

ST_City (Weather)	AZ_Bowie	AZ_Phoenix	CA_Bodega
Map ID #	1	2	3
System Size (GW)	345	205	430
Storage Size (GW)	400	540	345
Wind Size (GW)	163.875	10.25	64.5
PV Size (GW)	181.125	194.75	365.5
Current Capacity @ 20% Reserve Margin (GW)	28	28	25
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$2,076	$2,076	$2,076
PV Price (kW)	$1,238	$1,238	$1,353
Total System Cost (1st Year) ($)	$ 1,506,437,250,000	$ 1,534,079,500,000	$ 1,440,898,500,000
Optimal Wind (%)	47.5%	5.0%	15.0%
Optimal PV (%)	52.5%	95.0%	85.0%
# of Turbines	65,550	4,100	25,800
# of PV Panels	1,472,560,976	1,583,333,333	2,971,544,715
Avg Wind Speed (m/s)	5.80	4.89	5.16
Avg Wind Speed (mph)	12.97	10.94	11.55
Wind Capacity Factor	22.06%	16.42%	18.09%
PV Capacity Factor	27.79%	28.52%	26.36%
Avg Irradiance (w/m2)	237.43	244.72	216.58
Combined Capacity Factor	25.06%	27.92%	25.12%
Average Ambient Temperature (°C)	16.97	23.67	14.33
Average Surface Pressure (mbar)	854.10	967.42	1011.33
Average Relative Humidity (%)	45.85	31.92	79.68
Max Consecutive Hours **NO WIND** Power	53	53	37
Max Consecutive Hours **NO SUN** Power	17	16	18
Max Consecutive Hours **NO POWER**	14	16	15
Optimal System Max Consecutive Negative Net Load Hours	15	18	17
Load Region	WAPA - DSW	WAPA - DSW	CAISO - PGE
Avg Hourly Load (kW)	12,232,454	12,232,454	12,085,209
Peak Load (kW)	22,955,800	22,955,800	20,470,000
Peak Load Season	Spring/Summer	Spring/Summer	Summer/Fall
Optimal System Required Reserve (kWh)	81,367,268	123,807,415	70,780,881
Reserve %	25.43%	28.66%	25.65%
Hours of Reserve at Average Load	6.65	10.12	5.86
Hours of Reserve at Peak Load	3.54	5.39	3.46
Annual Total Energy Produced (kWh)	757,790,008,722	501,668,800,050	946,726,702,346
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0472	$0.0337	$0.0419
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.1109	$0.1636	$0.0859
GIS Map Zone	High_PV_Mod_Wind	High_PV_Low_Wind	Mod_PV_Low_Wind

Data Results – Baseline Reserve Margin (Conservative)

ST_City (Weather)	CA_Fresno	CA_Mojave	CA_Santa_Barbara
Map ID #	4	5	6
System Size (GW)	280	235	225
Storage Size (GW)	345	385	385
Wind Size (GW)	49	47	33.75
PV Size (GW)	231	188	191.25
Current Capacity @ 20% Reserve Margin (GW)	25	27	27
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$2,076	$2,076	$2,076
PV Price (kW)	$1,353	$1,353	$1,353
Total System Cost (1st Year) ($)	$ 1,226,742,000,000	$ 1,258,611,000,000	$ 1,235,501,250,000
Optimal Wind (%)	17.5%	20.0%	15.0%
Optimal PV (%)	82.5%	80.0%	85.0%
# of Turbines	19,600	18,800	13,500
# of PV Panels	1,878,048,780	1,528,455,285	1,554,878,049
Avg Wind Speed (m/s)	5.02	5.69	5.02
Avg Wind Speed (mph)	11.22	12.72	11.22
Wind Capacity Factor	18.01%	20.28%	17.25%
PV Capacity Factor	26.31%	29.74%	28.73%
Avg Irradiance (w/m2)	224.71	245.08	233.33
Combined Capacity Factor	24.86%	27.84%	27.01%
Average Ambient Temperature (°C)	19.98	16.85	17.78
Average Surface Pressure (mbar)	998.64	908.01	993.71
Average Relative Humidity (%)	46.63	43.05	62.18
Max Consecutive Hours NO WIND Power	40	37	37
Max Consecutive Hours NO SUN Power	17	18	17
Max Consecutive Hours NO POWER	15	14	15
Optimal System Max Consecutive Negative Net Load Hours	17	17	17
Load Region	CAISO - PGE	CAISO - SCE	CAISO - SCE
Avg Hourly Load (kW)	12,085,209	11,970,836	11,970,836
Peak Load (kW)	20,470,000	22,822,000	22,822,000
Peak Load Season	Summer/Fall	Fall	Fall
Optimal System Required Reserve (kWh)	93,457,311	103,368,291	109,419,666
Reserve %	33.86%	33.56%	35.53%
Hours of Reserve at Average Load	7.73	8.64	9.14
Hours of Reserve at Peak Load	4.57	4.53	4.79
Annual Total Energy Produced (kWh)	610,116,623,085	573,552,475,294	532,688,525,007
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0429	$0.0387	$0.0390
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.1111	$0.1198	$0.1262
GIS Map Zone	High_PV_Low_Wind	High_PV_High_Wind	Mod_PV_Low_Wind

APPENDIX B, CONT.

Data Results – Baseline Reserve Margin (Conservative)

ST_City (Weather)	CO_Boulder	FL_Everglades_City	IL_Champaign
Map ID #	7	8	9
System Size (GW)	145	290	190
Storage Size (GW)	85	515	165
Wind Size (GW)	14.5	14.5	66.5
PV Size (GW)	130.5	275.5	123.5
Current Capacity @ 20% Reserve Margin (GW)	8	30	11
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$1,666	$2,026	$2,156
PV Price (kW)	$1,237	$1,277	$1,378
Total System Cost (1st Year) ($)	$ 385,760,500,000	$ 1,594,015,500,000	$ 702,132,000,000
Optimal Wind (%)	10.0%	5.0%	35.0%
Optimal PV (%)	90.0%	95.0%	65.0%
# of Turbines	5,800	5,800	26,600
# of PV Panels	1,060,975,610	2,239,837,398	1,004,065,041
Avg Wind Speed (m/s)	5.60	5.09	7.33
Avg Wind Speed (mph)	12.53	11.39	16.39
Wind Capacity Factor	19.53%	18.19%	40.80%
PV Capacity Factor	21.81%	22.28%	20.52%
Avg Irradiance (w/m2)	176.92	204.66	172.90
Combined Capacity Factor	21.58%	22.08%	27.61%
Average Ambient Temperature (°C)	4.12	25.96	11.77
Average Surface Pressure (mbar)	769.47	1016.53	992.58
Average Relative Humidity (%)	64.76	84.31	71.94
Max Consecutive Hours NO WIND Power	36	74	30
Max Consecutive Hours NO SUN Power	18	16	18
Max Consecutive Hours NO POWER	14	13	16
Optimal System Max Consecutive Negative Net Load Hours	16	17	19
Load Region	WAPA - RM	FPL	MISO - LRZ4
Avg Hourly Load (kW)	2,872,491	14,379,352	5,620,706
Peak Load (kW)	7,038,000	24,754,000	9,280,470
Peak Load Season	Summer	Summer	Summer/Fall
Optimal System Required Reserve (kWh)	18,843,179	134,038,496	27,897,957
Reserve %	27.71%	32.53%	21.13%
Hours of Reserve at Average Load	6.56	9.32	4.96
Hours of Reserve at Peak Load	2.68	5.41	3.01
Annual Total Energy Produced (kWh)	274,279,747,567	561,268,996,267	459,784,322,977
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0438	$0.0435	$0.0427
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.0812	$0.1543	$0.0860
GIS Map Zone	Mod_PV_High_Wind	Mod_PV_Low_Wind	Low_PV_Mod_Wind

APPENDIX B, CONT.

Data Results – Baseline Reserve Margin (Conservative)

ST_City (Weather)	KS_Hays	MI_Gaylord	MS_Jackson
Map ID #	10	11	12
System Size (GW)	25	480	715
Storage Size (GW)	20	545	635
Wind Size (GW)	2.5	96	17.875
PV Size (GW)	22.5	384	697.125
Current Capacity @ 20% Reserve Margin (GW)	1	37	39
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$1,666	$2,156	$2,026
PV Price (kW)	$1,256	$1,295	$1,258
Total System Cost (1st Year) ($)	$ 79,525,000,000	$ 1,987,731,000,000	$ 2,408,623,000,000
Optimal Wind (%)	10.0%	20.0%	2.5%
Optimal PV (%)	90.0%	80.0%	97.5%
# of Turbines	1,000	38,400	7,150
# of PV Panels	182,926,829	3,121,951,220	5,667,682,927
Avg Wind Speed (m/s)	7.74	7.27	4.69
Avg Wind Speed (mph)	17.31	16.27	10.48
Wind Capacity Factor	43.88%	40.23%	12.10%
PV Capacity Factor	24.30%	17.30%	21.43%
Avg Irradiance (w/m2)	202.47	144.15	190.51
Combined Capacity Factor	26.25%	21.88%	21.20%
Average Ambient Temperature (°C)	14.13	4.12	18.84
Average Surface Pressure (mbar)	940.75	985.37	1006.05
Average Relative Humidity (%)	56.71	82.79	76.00
Max Consecutive Hours NO WIND Power	28	31	32
Max Consecutive Hours NO SUN Power	16	19	17
Max Consecutive Hours NO POWER	14	16	14
Optimal System Max Consecutive Negative Net Load Hours	17	17	17
Load Region	SPP - SECI	MISO LRZ2+7	MISO - LRZ8+9+10
Avg Hourly Load (kW)	711,464	18,772,505	19,431,885
Peak Load (kW)	1,193,494	31,142,290	32,386,090
Peak Load Season	Summer/Fall	Summer/Fall	Summer/Fall
Optimal System Required Reserve (kWh)	4,007,770	144,641,628	136,784,132
Reserve %	25.05%	33.17%	26.93%
Hours of Reserve at Average Load	5.63	7.70	7.04
Hours of Reserve at Peak Load	3.36	4.64	4.22
Annual Total Energy Produced (kWh)	57,531,149,654	920,681,324,467	1,328,578,934,218
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0363	$0.0485	$0.0442
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.0783	$0.1199	$0.1019
GIS Map Zone	Mod_PV_High_Wind	Low_PV_Mod_Wind	Mod_PV_Low_Wind

Data Results – Baseline Reserve Margin (Conservative)

ST_City (Weather)	NC_Durham	NE_Lincoln	NJ_Edison
Map ID #	13	14	15
System Size (GW)	440	10	160
Storage Size (GW)	360	12	150
Wind Size (GW)	55	4.25	40
PV Size (GW)	385	5.75	120
Current Capacity @ 20% Reserve Margin (GW)	24	1	12
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$2,026	$1,666	$2,626
PV Price (kW)	$1,217	$1,253	$1,388
Total System Cost (1st Year) ($)	$ 1,427,775,000,000	$ 42,545,250,000	$ 624,850,000,000
Optimal Wind (%)	12.5%	42.5%	25.0%
Optimal PV (%)	87.5%	57.5%	75.0%
# of Turbines	22,000	1,700	16,000
# of PV Panels	3,130,081,301	46,747,967	975,609,756
Avg Wind Speed (m/s)	4.87	7.61	5.59
Avg Wind Speed (mph)	10.90	17.03	12.51
Wind Capacity Factor	14.78%	43.81%	21.66%
PV Capacity Factor	21.28%	21.53%	20.62%
Avg Irradiance (w/m2)	184.79	178.91	174.28
Combined Capacity Factor	20.47%	30.98%	20.87%
Average Ambient Temperature (°C)	15.51	11.12	11.67
Average Surface Pressure (mbar)	997.35	968.54	1008.09
Average Relative Humidity (%)	72.52	64.20	71.45
Max Consecutive Hours NO WIND Power	23	20	26
Max Consecutive Hours NO SUN Power	17	18	18
Max Consecutive Hours NO POWER	14	11	15
Optimal System Max Consecutive Negative Net Load Hours	16	18	17
Load Region	DUK	SPP - LES	PJM - PS
Avg Hourly Load (kW)	11,566,731	394,619	5,046,987
Peak Load (kW)	19,890,000	747,686	9,594,939
Peak Load Season	Summer	Summer/Fall	Summer/Fall
Optimal System Required Reserve (kWh)	81,127,805	2,393,514	39,715,941
Reserve %	28.17%	24.93%	33.10%
Hours of Reserve at Average Load	7.01	6.07	7.87
Hours of Reserve at Peak Load	4.08	3.20	4.14
Annual Total Energy Produced (kWh)	789,438,196,624	27,160,338,425	292,778,875,068
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0473	$0.0342	$0.0573
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.1024	$0.0875	$0.1192
GIS Map Zone	Mod_PV_Low_Wind	Mod_PV_Mod_Wind	Low_PV_Mod_Wind

APPENDIX B, CONT.

Data Results – Baseline Reserve Margin (Conservative)

ST_City (Weather)	NM_Clovis	NY_Millbrook	OK_Stillwater
Map ID #	16	17	18
System Size (GW)	40	60	125
Storage Size (GW)	80	35	145
Wind Size (GW)	8	7.5	53.125
PV Size (GW)	32	52.5	71.875
Current Capacity @ 20% Reserve Margin (GW)	5	3	8
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$1,666	$2,626	$1,666
PV Price (kW)	$1,239	$1,352	$1,213
Total System Cost (1st Year) ($)	$ 241,376,000,000	$ 173,100,000,000	$ 517,165,625,000
Optimal Wind (%)	20.0%	12.5%	42.5%
Optimal PV (%)	80.0%	87.5%	57.5%
# of Turbines	3,200	3,000	21,250
# of PV Panels	260,162,602	426,829,268	584,349,593
Avg Wind Speed (m/s)	7.53	4.55	7.27
Avg Wind Speed (mph)	16.85	10.18	16.25
Wind Capacity Factor	39.54%	11.95%	39.62%
PV Capacity Factor	26.60%	20.52%	22.86%
Avg Irradiance (w/m2)	223.49	169.79	194.28
Combined Capacity Factor	29.18%	19.45%	29.97%
Average Ambient Temperature (°C)	14.82	8.77	15.82
Average Surface Pressure (mbar)	867.25	984.40	984.12
Average Relative Humidity (%)	53.60	74.44	67.66
Max Consecutive Hours NO WIND Power	26	55	25
Max Consecutive Hours NO SUN Power	17	18	17
Max Consecutive Hours NO POWER	16	12	13
Optimal System Max Consecutive Negative Net Load Hours	17	15	17
Load Region	SPP - WFEC	NYISO - HV-Zone G	SPP - OKGE
Avg Hourly Load (kW)	1,589,393	1,149,023	3,620,070
Peak Load (kW)	3,836,153	2,203,500	6,533,372
Peak Load Season	Winter	Summer/Fall	Summer/Fall
Optimal System Required Reserve (kWh)	12,632,088	7,462,836	16,810,204
Reserve %	19.74%	26.65%	14.49%
Hours of Reserve at Average Load	7.95	6.49	4.64
Hours of Reserve at Peak Load	3.29	3.39	2.57
Annual Total Energy Produced (kWh)	102,318,099,469	102,275,253,915	328,424,498,051
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0336	$0.0555	$0.0349
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.1280	$0.0968	$0.0882
GIS Map Zone	High_PV_Mod_Wind	Low_PV_Low_Wind	Mod_PV_Mod_Wind

Data Results – Baseline Reserve Margin (Conservative)

ST_City (Weather)	RI_Kingston	SD_Sioux_Falls	TN_Nashville
Map ID #	19	20	21
System Size (GW)	25	2	470
Storage Size (GW)	30	3	560
Wind Size (GW)	4.375	0.95	94
PV Size (GW)	20.625	1.05	376
Current Capacity @ 20% Reserve Margin (GW)	2	0	36
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$2,626	$1,666	$2,026
PV Price (kW)	$1,356	$1,216	$1,241
Total System Cost (1st Year) ($)	$ 110,106,250,000	$ 9,924,500,000	$ 1,975,860,000,000
Optimal Wind (%)	17.5%	47.5%	20.0%
Optimal PV (%)	82.5%	52.5%	80.0%
# of Turbines	1,750	380	37,600
# of PV Panels	167,682,927	8,536,585	3,056,910,569
Avg Wind Speed (m/s)	5.35	7.86	5.44
Avg Wind Speed (mph)	11.96	17.58	12.16
Wind Capacity Factor	18.78%	45.69%	20.06%
PV Capacity Factor	21.04%	20.93%	20.97%
Avg Irradiance (w/m2)	173.37	174.22	180.36
Combined Capacity Factor	20.65%	32.68%	20.79%
Average Ambient Temperature (°C)	10.40	9.62	15.33
Average Surface Pressure (mbar)	1011.35	962.70	993.09
Average Relative Humidity (%)	76.62	63.13	74.81
Max Consecutive Hours NO WIND Power	19	18	38
Max Consecutive Hours NO SUN Power	18	20	17
Max Consecutive Hours NO POWER	14	9	15
Optimal System Max Consecutive Negative Net Load Hours	16	19	17
Load Region	ISO-NE - RI	WAPA - WAUW	TVA
Avg Hourly Load (kW)	927,537	87,571	17,652,869
Peak Load (kW)	1,748,505	167,000	29,823,000
Peak Load Season	Summer/Fall	Summer & Winter	Summer & Winter
Optimal System Required Reserve (kWh)	8,761,772	577,162	148,742,758
Reserve %	36.51%	24.05%	33.20%
Hours of Reserve at Average Load	9.45	6.59	8.43
Hours of Reserve at Peak Load	5.01	3.46	4.99
Annual Total Energy Produced (kWh)	45,244,571,657	5,728,809,805	856,451,637,483
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0543	$0.0326	$0.0491
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.1344	$0.0958	$0.1281
GIS Map Zone	Low_PV_Low_Wind	Low_PV_High_Wind	Low_PV_Low_Wind

Data Results – Baseline Reserve Margin (Conservative)

ST_City (Weather)	TX_Amarillo	TX_Austin	TX_Bronte
Map ID #	22	23	24
System Size (GW)	60	145	50
Storage Size (GW)	95	200	40
Wind Size (GW)	31.5	97.875	2.5
PV Size (GW)	28.5	47.125	47.5
Current Capacity @ 20% Reserve Margin (GW)	7	14	2
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$1,666	$1,666	$1,666
PV Price (kW)	$1,233	$1,233	$1,233
Total System Cost (1st Year) ($)	$ 311,344,500,000	$ 692,164,875,000	$ 156,932,500,000
Optimal Wind (%)	52.5%	67.5%	5.0%
Optimal PV (%)	47.5%	32.5%	95.0%
# of Turbines	12,600	39,150	1,000
# of PV Panels	231,707,317	383,130,081	386,178,862
Avg Wind Speed (m/s)	7.62	6.60	7.17
Avg Wind Speed (mph)	17.05	14.77	16.03
Wind Capacity Factor	41.33%	31.41%	37.82%
PV Capacity Factor	25.98%	22.68%	24.76%
Avg Irradiance (w/m2)	218.28	202.57	217.29
Combined Capacity Factor	34.02%	28.55%	25.42%
Average Ambient Temperature (°C)	15.22	20.17	18.66
Average Surface Pressure (mbar)	893.06	981.66	946.09
Average Relative Humidity (%)	55.65	79.02	63.43
Max Consecutive Hours NO WIND Power	17	24	21
Max Consecutive Hours NO SUN Power	17	17	17
Max Consecutive Hours NO POWER	12	13	16
Optimal System Max Consecutive Negative Net Load Hours	15	16	18
Load Region	SPP - SPS	ERCOT - SC	ERCOT - W
Avg Hourly Load (kW)	3,566,076	6,515,835	1,134,484
Peak Load (kW)	5,696,955	12,032,553	1,883,889
Peak Load Season	Summer/Fall	Summer/Fall	Summer/Fall
Optimal System Required Reserve (kWh)	21,572,309	43,799,030	6,421,276
Reserve %	28.38%	27.37%	20.07%
Hours of Reserve at Average Load	6.05	6.72	5.66
Hours of Reserve at Peak Load	3.79	3.64	3.41
Annual Total Energy Produced (kWh)	178,957,829,509	362,941,199,778	111,395,888,340
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0319	$0.0398	$0.0364
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.0960	$0.1064	$0.0798
GIS Map Zone	High_PV_High_Wind	Mod_PV_Low_Wind	Mod_PV_Mod_Wind

Data Results – Baseline Reserve Margin (Conservative)

ST_City (Weather)	WY_Laramie	WY_McFadden
Map ID #	25	26
System Size (GW)	70	105
Storage Size (GW)	65	90
Wind Size (GW)	52.5	15.75
PV Size (GW)	17.5	89.25
Current Capacity @ 20% Reserve Margin (GW)	8	8
Storage Price	$2,355	$2,355
Wind Price (kW)	$1,666	$1,666
PV Price (kW)	$1,233	$1,233
Total System Cost (1st Year) ($)	$ 262,117,500,000	$ 348,234,750,000
Optimal Wind (%)	75.0%	15.0%
Optimal PV (%)	25.0%	85.0%
# of Turbines	21,000	6,300
# of PV Panels	142,276,423	725,609,756
Avg Wind Speed (m/s)	8.12	6.95
Avg Wind Speed (mph)	18.17	15.54
Wind Capacity Factor	43.16%	30.91%
PV Capacity Factor	22.30%	22.51%
Avg Irradiance (w/m2)	187.11	184.22
Combined Capacity Factor	37.92%	23.77%
Average Ambient Temperature (°C)	7.08	4.71
Average Surface Pressure (mbar)	786.20	763.25
Average Relative Humidity (%)	58.96	60.80
Max Consecutive Hours NO WIND Power	16	21
Max Consecutive Hours NO SUN Power	19	19
Max Consecutive Hours NO POWER	10	12
Optimal System Max Consecutive Negative Net Load Hours	14	14
Load Region	WAPA - RM	WAPA - RM
Avg Hourly Load (kW)	2,872,491	2,872,491
Peak Load (kW)	7,038,000	7,038,000
Peak Load Season	Summer/Fall	Summer/Fall
Optimal System Required Reserve (kWh)	14,634,496	21,913,631
Reserve %	28.14%	30.44%
Hours of Reserve at Average Load	5.09	7.63
Hours of Reserve at Peak Load	2.08	3.11
Annual Total Energy Produced (kWh)	232,698,189,337	218,771,326,155
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0306	$0.0404
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.0644	$0.0900
GIS Map Zone	Mod_PV_Mod_Wind	Low_PV_High_Wind

APPENDIX C

Data Results – Middle Ground Reserve Margin

ST_City (Weather)	AZ_Bowie	AZ_Phoenix	CA_Bodega
Map ID #	1	2	3
System Size (GW)	290	210	405
Storage Size (GW)	380	450	310
Wind Size (GW)	101.5	10.5	91.125
PV Size (GW)	188.5	199.5	313.875
Current Capacity @ 20% Reserve Margin (GW)	28	28	25
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$2,076	$2,076	$2,076
PV Price (kW)	$1,238	$1,238	$1,353
Total System Cost (1st Year) ($)	$ 1,338,977,000,000	$ 1,328,529,000,000	$ 1,343,898,375,000
Optimal Wind (%)	35.0%	5.0%	22.5%
Optimal PV (%)	65.0%	95.0%	77.5%
# of Turbines	40,600	4,200	36,450
# of PV Panels	1,532,520,325	1,621,951,220	2,551,829,268
Avg Wind Speed (m/s)	5.80	4.89	5.16
Avg Wind Speed (mph)	12.97	10.94	11.55
Wind Capacity Factor	22.06%	16.42%	18.09%
PV Capacity Factor	27.79%	28.52%	26.36%
Avg Irradiance (w/m2)	237.43	244.72	216.58
Combined Capacity Factor	25.77%	27.92%	24.49%
Average Ambient Temperature (°C)	16.97	23.67	14.33
Average Surface Pressure (mbar)	854.10	967.42	1011.33
Average Relative Humidity (%)	45.85	31.92	79.68
Max Consecutive Hours NO WIND Power	53	53	37
Max Consecutive Hours NO SUN Power	17	16	18
Max Consecutive Hours NO POWER	14	16	15
Optimal System Max Consecutive Negative Net Load Hours	17	18	18
Load Region	WAPA - DSW	WAPA - DSW	CAISO - PGE
Avg Hourly Load (kW)	12,232,454	12,232,454	12,085,209
Peak Load (kW)	22,955,800	22,955,800	20,470,000
Peak Load Season	Spring/Summer	Spring/Summer	Summer/Fall
Optimal System Required Reserve (kWh)	34,706,522	52,842,121	42,297,910
Reserve %	11.42%	14.68%	17.06%
Hours of Reserve at Average Load	2.84	4.32	3.50
Hours of Reserve at Peak Load	1.51	2.30	2.07
Annual Total Energy Produced (kWh)	655,235,451,950	513,904,624,442	869,620,395,073
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0431	$0.0337	$0.0445
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.1131	$0.1394	$0.0876
GIS Map Zone	High_PV_Mod_Wind	High_PV_Low_Wind	Mod_PV_Low_Wind

APPENDIX C, CONT.

Data Results – Middle Ground Reserve Margin

ST_City (Weather)	CA_Fresno	CA_Mojave	CA_Santa_Barbara
Map ID #	4	5	6
System Size (GW)	280	180	180
Storage Size (GW)	285	315	305
Wind Size (GW)	49	40.5	40.5
PV Size (GW)	231	139.5	139.5
Current Capacity @ 20% Reserve Margin (GW)	25	27	27
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$2,076	$2,076	$2,076
PV Price (kW)	$1,353	$1,353	$1,353
Total System Cost (1st Year) ($)	$ 1,085,442,000,000	$ 1,014,646,500,000	$ 991,096,500,000
Optimal Wind (%)	17.5%	22.5%	22.5%
Optimal PV (%)	82.5%	77.5%	77.5%
# of Turbines	19,600	16,200	16,200
# of PV Panels	1,878,048,780	1,134,146,341	1,134,146,341
Avg Wind Speed (m/s)	5.02	5.69	5.02
Avg Wind Speed (mph)	11.22	12.72	11.22
Wind Capacity Factor	18.01%	20.28%	17.25%
PV Capacity Factor	26.31%	29.74%	28.73%
Avg Irradiance (w/m2)	224.71	245.08	233.33
Combined Capacity Factor	24.86%	27.61%	26.15%
Average Ambient Temperature (°C)	19.98	16.85	17.78
Average Surface Pressure (mbar)	998.64	908.01	993.71
Average Relative Humidity (%)	46.63	43.05	62.18
Max Consecutive Hours NO WIND Power	40	37	37
Max Consecutive Hours NO SUN Power	17	18	17
Max Consecutive Hours NO POWER	15	14	15
Optimal System Max Consecutive Negative Net Load Hours	17	17	17
Load Region	CAISO - PGE	CAISO - SCE	CAISO - SCE
Avg Hourly Load (kW)	12,085,209	11,970,836	11,970,836
Peak Load (kW)	20,470,000	22,822,000	22,822,000
Peak Load Season	Summer/Fall	Fall	Fall
Optimal System Required Reserve (kWh)	45,134,463	43,354,910	45,180,325
Reserve %	19.80%	17.20%	18.52%
Hours of Reserve at Average Load	3.73	3.62	3.77
Hours of Reserve at Peak Load	2.20	1.90	1.98
Annual Total Energy Produced (kWh)	610,116,623,085	435,583,262,038	412,552,904,099
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0429	$0.0395	$0.0417
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.0993	$0.1268	$0.1310
GIS Map Zone	High_PV_Low_Wind	High_PV_High_Wind	Mod_PV_Low_Wind

Data Results – Middle Ground Reserve Margin

ST_City (Weather)	CO_Boulder	FL_Everglades_City	IL_Champaign
Map ID #	7	8	9
System Size (GW)	145	235	185
Storage Size (GW)	75	440	150
Wind Size (GW)	14.5	17.625	60.125
PV Size (GW)	130.5	217.375	124.875
Current Capacity @ 20% Reserve Margin (GW)	8	30	11
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$1,666	$2,026	$2,156
PV Price (kW)	$1,237	$1,277	$1,378
Total System Cost (1st Year) ($)	$ 362,210,500,000	$ 1,349,496,125,000	$ 654,957,250,000
Optimal Wind (%)	10.0%	7.5%	32.5%
Optimal PV (%)	90.0%	92.5%	67.5%
# of Turbines	5,800	7,050	24,050
# of PV Panels	1,060,975,610	1,767,276,423	1,015,243,902
Avg Wind Speed (m/s)	5.60	5.09	7.33
Avg Wind Speed (mph)	12.53	11.39	16.39
Wind Capacity Factor	19.53%	18.19%	40.80%
PV Capacity Factor	21.81%	22.28%	20.52%
Avg Irradiance (w/m2)	176.92	204.66	172.90
Combined Capacity Factor	21.58%	21.98%	27.10%
Average Ambient Temperature (°C)	4.12	25.96	11.77
Average Surface Pressure (mbar)	769.47	1016.53	992.58
Average Relative Humidity (%)	64.76	84.31	71.94
Max Consecutive Hours NO WIND Power	36	74	30
Max Consecutive Hours NO SUN Power	18	16	18
Max Consecutive Hours NO POWER	14	13	16
Optimal System Max Consecutive Negative Net Load Hours	16	17	19
Load Region	WAPA - RM	FPL	MISO - LRZ4
Avg Hourly Load (kW)	2,872,491	14,379,352	5,620,706
Peak Load (kW)	7,038,000	24,754,000	9,280,470
Peak Load Season	Summer	Summer	Summer/Fall
Optimal System Required Reserve (kWh)	11,596,590	68,102,836	12,767,727
Reserve %	19.33%	19.35%	10.64%
Hours of Reserve at Average Load	4.04	4.74	2.27
Hours of Reserve at Peak Load	1.65	2.75	1.38
Annual Total Energy Produced (kWh)	274,279,747,567	452,706,304,993	439,475,098,750
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0438	$0.0443	$0.0430
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.0768	$0.1616	$0.0842
GIS Map Zone	Mod_PV_High_Wind	Mod_PV_Low_Wind	Low_PV_Mod_Wind

APPENDIX C, CONT.

Data Results – Middle Ground Reserve Margin

ST_City (Weather)	KS_Hays	MI_Gaylord	MS_Jackson
Map ID #	10	11	12
System Size (GW)	20	475	710
Storage Size (GW)	20	440	575
Wind Size (GW)	0.5	95	17.75
PV Size (GW)	19.5	380	692.25
Current Capacity @ 20% Reserve Margin (GW)	1	37	39
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$1,666	$2,156	$2,026
PV Price (kW)	$1,256	$1,295	$1,258
Total System Cost (1st Year) ($)	$ 72,425,000,000	$ 1,733,120,000,000	$ 2,260,937,000,000
Optimal Wind (%)	2.5%	20.0%	2.5%
Optimal PV (%)	97.5%	80.0%	97.5%
# of Turbines	200	38,000	7,100
# of PV Panels	158,536,585	3,089,430,894	5,628,048,780
Avg Wind Speed (m/s)	7.74	7.27	4.69
Avg Wind Speed (mph)	17.31	16.27	10.48
Wind Capacity Factor	43.88%	40.23%	12.10%
PV Capacity Factor	24.30%	17.30%	21.43%
Avg Irradiance (w/m2)	202.47	144.15	190.51
Combined Capacity Factor	24.79%	21.88%	21.20%
Average Ambient Temperature (°C)	14.13	4.12	18.84
Average Surface Pressure (mbar)	940.75	985.37	1006.05
Average Relative Humidity (%)	56.71	82.79	76.00
Max Consecutive Hours NO WIND Power	28	31	32
Max Consecutive Hours NO SUN Power	16	19	17
Max Consecutive Hours NO POWER	14	16	14
Optimal System Max Consecutive Negative Net Load Hours	17	17	17
Load Region	SPP - SECI	MISO LRZ2+7	MISO - LRZ8+9+10
Avg Hourly Load (kW)	711,464	18,772,505	19,431,885
Peak Load (kW)	1,193,494	31,142,290	32,386,090
Peak Load Season	Summer/Fall	Summer/Fall	Summer/Fall
Optimal System Required Reserve (kWh)	2,871,015	61,015,254	87,916,411
Reserve %	17.94%	17.33%	19.11%
Hours of Reserve at Average Load	4.04	3.25	4.52
Hours of Reserve at Peak Load	2.41	1.96	2.71
Annual Total Energy Produced (kWh)	43,453,248,567	911,090,894,004	1,319,288,172,441
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0375	$0.0485	$0.0442
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.0931	$0.1068	$0.0968
GIS Map Zone	Mod_PV_High_Wind	Low_PV_Mod_Wind	Mod_PV_Low_Wind

Data Results – Middle Ground Reserve Margin

ST_City (Weather)	NC_Durham	NE_Lincoln	NJ_Edison
Map ID #	13	14	15
System Size (GW)	430	6	135
Storage Size (GW)	325	12	120
Wind Size (GW)	53.75	3.3	57.375
PV Size (GW)	376.25	2.7	77.625
Current Capacity @ 20% Reserve Margin (GW)	24	1	12
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$2,026	$1,666	$2,626
PV Price (kW)	$1,217	$1,253	$1,388
Total System Cost (1st Year) ($)	$ 1,332,168,750,000	$ 37,140,900,000	$ 541,010,250,000
Optimal Wind (%)	12.5%	55.0%	42.5%
Optimal PV (%)	87.5%	45.0%	57.5%
# of Turbines	21,500	1,320	22,950
# of PV Panels	3,058,943,089	21,951,220	631,097,561
Avg Wind Speed (m/s)	4.87	7.61	5.59
Avg Wind Speed (mph)	10.90	17.03	12.51
Wind Capacity Factor	14.78%	43.81%	21.66%
PV Capacity Factor	21.28%	21.53%	20.62%
Avg Irradiance (w/m2)	184.79	178.91	174.28
Combined Capacity Factor	20.47%	33.77%	21.05%
Average Ambient Temperature (°C)	15.51	11.12	11.67
Average Surface Pressure (mbar)	997.35	968.54	1008.09
Average Relative Humidity (%)	72.52	64.20	71.45
Max Consecutive Hours NO WIND Power	23	20	26
Max Consecutive Hours NO SUN Power	17	18	18
Max Consecutive Hours NO POWER	14	11	15
Optimal System Max Consecutive Negative Net Load Hours	16	19	17
Load Region	DUK	SPP - LES	PJM - PS
Avg Hourly Load (kW)	11,566,731	394,619	5,046,987
Peak Load (kW)	19,890,000	747,686	9,594,939
Peak Load Season	Summer	Summer/Fall	Summer/Fall
Optimal System Required Reserve (kWh)	49,617,440	874,265	15,152,612
Reserve %	19.08%	9.11%	15.78%
Hours of Reserve at Average Load	4.29	2.22	3.00
Hours of Reserve at Peak Load	2.49	1.17	1.58
Annual Total Energy Produced (kWh)	771,496,419,428	17,759,369,104	249,157,402,430
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0473	$0.0326	$0.0635
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.0982	$0.1142	$0.1216
GIS Map Zone	Mod_PV_Low_Wind	Mod_PV_Mod_Wind	Low_PV_Mod_Wind

APPENDIX C, CONT.

Data Results – Middle Ground Reserve Margin

ST_City (Weather)	NM_Clovis	NY_Millbrook	OK_Stillwater
Map ID #	16	17	18
System Size (GW)	35	55	120
Storage Size (GW)	70	35	135
Wind Size (GW)	8.75	5.5	45
PV Size (GW)	26.25	49.5	75
Current Capacity @ 20% Reserve Margin (GW)	5	3	8
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$1,666	$2,626	$1,666
PV Price (kW)	$1,239	$1,352	$1,213
Total System Cost (1st Year) ($)	$ 211,951,250,000	$ 163,792,000,000	$ 483,870,000,000
Optimal Wind (%)	25.0%	10.0%	37.5%
Optimal PV (%)	75.0%	90.0%	62.5%
# of Turbines	3,500	2,200	18,000
# of PV Panels	213,414,634	402,439,024	609,756,098
Avg Wind Speed (m/s)	7.53	4.55	7.27
Avg Wind Speed (mph)	16.85	10.18	16.25
Wind Capacity Factor	39.54%	11.95%	39.62%
PV Capacity Factor	26.60%	20.52%	22.86%
Avg Irradiance (w/m2)	223.49	169.79	194.28
Combined Capacity Factor	29.83%	19.66%	29.14%
Average Ambient Temperature (°C)	14.82	8.77	15.82
Average Surface Pressure (mbar)	867.25	984.40	984.12
Average Relative Humidity (%)	53.60	74.44	67.66
Max Consecutive Hours NO WIND Power	26	55	25
Max Consecutive Hours NO SUN Power	17	18	17
Max Consecutive Hours NO POWER	16	12	13
Optimal System Max Consecutive Negative Net Load Hours	17	16	17
Load Region	SPP - WFEC	NYISO - HV-Zone G	SPP - OKGE
Avg Hourly Load (kW)	1,589,393	1,149,023	3,620,070
Peak Load (kW)	3,836,153	2,203,500	6,533,372
Peak Load Season	Winter	Summer/Fall	Summer/Fall
Optimal System Required Reserve (kWh)	4,466,973	5,300,140	7,557,535
Reserve %	7.98%	18.93%	7.00%
Hours of Reserve at Average Load	2.81	4.61	2.09
Hours of Reserve at Peak Load	1.16	2.41	1.16
Annual Total Energy Produced (kWh)	91,508,827,333	94,786,555,457	306,486,741,758
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0334	$0.0538	$0.0353
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.1258	$0.0984	$0.0885
GIS Map Zone	High_PV_Mod_Wind	Low_PV_Low_Wind	Mod_PV_Mod_Wind

APPENDIX C, CONT.

Data Results – Middle Ground Reserve Margin

ST_City (Weather)	RI_Kingston	SD_Sioux_Falls	TN_Nashville
Map ID #	19	20	21
System Size (GW)	15	3	415
Storage Size (GW)	25	2	460
Wind Size (GW)	7.5	1.95	134.875
PV Size (GW)	7.5	1.05	280.125
Current Capacity @ 20% Reserve Margin (GW)	2	0	36
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$2,626	$1,666	$2,026
PV Price (kW)	$1,356	$1,216	$1,241
Total System Cost (1st Year) ($)	$ 88,740,000,000	$ 9,235,500,000	$ 1,704,191,875,000
Optimal Wind (%)	50.0%	65.0%	32.5%
Optimal PV (%)	50.0%	35.0%	67.5%
# of Turbines	3,000	780	53,950
# of PV Panels	60,975,610	8,536,585	2,277,439,024
Avg Wind Speed (m/s)	5.35	7.86	5.44
Avg Wind Speed (mph)	11.96	17.58	12.16
Wind Capacity Factor	18.78%	45.69%	20.06%
PV Capacity Factor	21.04%	20.93%	20.97%
Avg Irradiance (w/m2)	173.37	174.22	180.36
Combined Capacity Factor	19.91%	37.01%	20.67%
Average Ambient Temperature (°C)	10.40	9.62	15.33
Average Surface Pressure (mbar)	1011.35	962.70	993.09
Average Relative Humidity (%)	76.62	63.13	74.81
Max Consecutive Hours NO WIND Power	19	18	38
Max Consecutive Hours NO SUN Power	18	20	17
Max Consecutive Hours NO POWER	14	9	15
Optimal System Max Consecutive Negative Net Load Hours	20	18	18
Load Region	ISO-NE - RI	WAPA - WAUW	TVA
Avg Hourly Load (kW)	927,537	87,571	17,652,869
Peak Load (kW)	1,748,505	167,000	29,823,000
Peak Load Season	Summer/Fall	Summer & Winter	Summer & Winter
Optimal System Required Reserve (kWh)	4,734,419	118,676	67,992,580
Reserve %	23.67%	7.42%	18.48%
Hours of Reserve at Average Load	5.10	1.36	3.85
Hours of Reserve at Peak Load	2.71	0.71	2.28
Annual Total Energy Produced (kWh)	26,174,665,239	9,731,685,685	752,023,103,160
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0697	$0.0304	$0.0526
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.1850	$0.0552	$0.1265
GIS Map Zone	Low_PV_Low_Wind	Low_PV_High_Wind	Low_PV_Low_Wind

APPENDIX C, CONT.

Data Results – Middle Ground Reserve Margin

ST_City (Weather)	TX_Amarillo	TX_Austin	TX_Bronte
Map ID #	22	23	24
System Size (GW)	50	105	45
Storage Size (GW)	80	165	40
Wind Size (GW)	17.5	55.125	4.5
PV Size (GW)	32.5	49.875	40.5
Current Capacity @ 20% Reserve Margin (GW)	7	14	2
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$1,666	$1,666	$1,666
PV Price (kW)	$1,233	$1,233	$1,233
Total System Cost (1st Year) ($)	$ 257,627,500,000	$ 541,909,125,000	$ 151,633,500,000
Optimal Wind (%)	35.0%	52.5%	10.0%
Optimal PV (%)	65.0%	47.5%	90.0%
# of Turbines	7,000	22,050	1,800
# of PV Panels	264,227,642	405,487,805	329,268,293
Avg Wind Speed (m/s)	7.62	6.60	7.17
Avg Wind Speed (mph)	17.05	14.77	16.03
Wind Capacity Factor	41.33%	31.41%	37.82%
PV Capacity Factor	25.98%	22.68%	24.76%
Avg Irradiance (w/m2)	218.28	202.57	217.29
Combined Capacity Factor	31.34%	27.25%	26.07%
Average Ambient Temperature (°C)	15.22	20.17	18.66
Average Surface Pressure (mbar)	893.06	981.66	946.09
Average Relative Humidity (%)	55.65	79.02	63.43
Max Consecutive Hours NO WIND Power	17	24	21
Max Consecutive Hours NO SUN Power	17	17	17
Max Consecutive Hours NO POWER	12	13	16
Optimal System Max Consecutive Negative Net Load Hours	16	18	18
Load Region	SPP - SPS	ERCOT - SC	ERCOT - W
Avg Hourly Load (kW)	3,566,076	6,515,835	1,134,484
Peak Load (kW)	5,696,955	12,032,553	1,883,889
Peak Load Season	Summer/Fall	Summer/Fall	Summer/Fall
Optimal System Required Reserve (kWh)	8,615,770	16,087,305	4,029,843
Reserve %	13.46%	12.19%	12.59%
Hours of Reserve at Average Load	2.42	2.47	3.55
Hours of Reserve at Peak Load	1.51	1.34	2.14
Annual Total Energy Produced (kWh)	137,381,368,282	250,794,632,830	102,827,136,132
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0328	$0.0399	$0.0362
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.1031	$0.1193	$0.0831
GIS Map Zone	High_PV_High_Wind	Mod_PV_Low_Wind	Mod_PV_Mod_Wind

APPENDIX C, CONT.

Data Results – Middle Ground Reserve Margin

ST_City (Weather)	WY_Laramie	WY_McFadden
Map ID #	25	26
System Size (GW)	50	120
Storage Size (GW)	60	65
Wind Size (GW)	28.75	36
PV Size (GW)	21.25	84
Current Capacity @ 20% Reserve Margin (GW)	8	8
Storage Price	$2,355	$2,355
Wind Price (kW)	$1,666	$1,666
PV Price (kW)	$1,233	$1,233
Total System Cost (1st Year) ($)	$ 215,398,750,000	$ 316,623,000,000
Optimal Wind (%)	57.5%	30.0%
Optimal PV (%)	42.5%	70.0%
# of Turbines	11,500	14,400
# of PV Panels	172,764,228	682,926,829
Avg Wind Speed (m/s)	8.12	6.95
Avg Wind Speed (mph)	18.17	15.54
Wind Capacity Factor	43.16%	30.91%
PV Capacity Factor	22.30%	22.51%
Avg Irradiance (w/m2)	187.11	184.22
Combined Capacity Factor	34.28%	25.03%
Average Ambient Temperature (°C)	7.08	4.71
Average Surface Pressure (mbar)	786.20	763.25
Average Relative Humidity (%)	58.96	60.80
Max Consecutive Hours NO WIND Power	16	21
Max Consecutive Hours NO SUN Power	19	19
Max Consecutive Hours NO POWER	10	12
Optimal System Max Consecutive Negative Net Load Hours	17	14
Load Region	WAPA - RM	WAPA - RM
Avg Hourly Load (kW)	2,872,491	2,872,491
Peak Load (kW)	7,038,000	7,038,000
Peak Load Season	Summer/Fall	Summer/Fall
Optimal System Required Reserve (kWh)	5,779,690	7,907,525
Reserve %	12.04%	15.21%
Hours of Reserve at Average Load	2.01	2.75
Hours of Reserve at Peak Load	0.82	1.12
Annual Total Energy Produced (kWh)	150,233,990,452	263,251,122,593
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0322	$0.0404
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.0804	$0.0702
GIS Map Zone	Mod_PV_Mod_Wind	Low_PV_High_Wind

APPENDIX D

Data Results – Zero Reserve Margin (Aggressive)

ST_City (Weather)	AZ_Bowie	AZ_Phoenix	CA_Bodega
Map ID #	1	2	3
System Size (GW)	245	210	395
Storage Size (GW)	375	385	265
Wind Size (GW)	42.875	10.5	79
PV Size (GW)	202.125	199.5	316
Current Capacity @ 20% Reserve Margin (GW)	28	28	25
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$2,076	$2,076	$2,076
PV Price (kW)	$1,238	$1,238	$1,353
Total System Cost (1st Year) ($)	$ 1,222,364,250,000	$ 1,175,454,000,000	$ 1,215,627,000,000
Optimal Wind (%)	17.5%	5.0%	20.0%
Optimal PV (%)	82.5%	95.0%	80.0%
# of Turbines	17,150	4,200	31,600
# of PV Panels	1,643,292,683	1,621,951,220	2,569,105,691
Avg Wind Speed (m/s)	5.80	4.89	5.16
Avg Wind Speed (mph)	12.97	10.94	11.55
Wind Capacity Factor	22.06%	16.42%	18.09%
PV Capacity Factor	27.79%	28.52%	26.36%
Avg Irradiance (w/m2)	237.43	244.72	216.58
Combined Capacity Factor	26.78%	27.92%	24.70%
Average Ambient Temperature (°C)	16.97	23.67	14.33
Average Surface Pressure (mbar)	854.10	967.42	1011.33
Average Relative Humidity (%)	45.85	31.92	79.68
Max Consecutive Hours NO WIND Power	53	53	37
Max Consecutive Hours NO SUN Power	17	16	18
Max Consecutive Hours NO POWER	14	16	15
Optimal System Max Consecutive Negative Net Load Hours	17	18	18
Load Region	WAPA - DSW	WAPA - DSW	CAISO - PGE
Avg Hourly Load (kW)	12,232,454	12,232,454	12,085,209
Peak Load (kW)	22,955,800	22,955,800	20,470,000
Peak Load Season	Spring/Summer	Spring/Summer	Summer/Fall
Optimal System Required Reserve (kWh)	0	0	0
Reserve %	0.00%	0.00%	0.00%
Hours of Reserve at Average Load	9.18	9.94	6.48
Hours of Reserve at Peak Load	4.89	5.30	3.82
Annual Total Energy Produced (kWh)	575,149,341,478	513,904,624,442	855,321,375,087
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0378	$0.0337	$0.0436
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.1165	$0.1241	$0.0810
GIS Map Zone	High_PV_Mod_Wind	High_PV_Low_Wind	Mod_PV_Low_Wind

Data Results – Zero Reserve Margin (Aggressive)

ST_City (Weather)	CA_Fresno	CA_Mojave	CA_Santa_Barbara
Map ID #	4	5	6
System Size (GW)	280	140	175
Storage Size (GW)	230	290	250
Wind Size (GW)	49	3.5	39.375
PV Size (GW)	231	136.5	135.625
Current Capacity @ 20% Reserve Margin (GW)	25	27	27
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$2,076	$2,076	$2,076
PV Price (kW)	$1,353	$1,353	$1,353
Total System Cost (1st Year) ($)	$ 955,917,000,000	$ 874,900,500,000	$ 853,993,125,000
Optimal Wind (%)	17.5%	2.5%	22.5%
Optimal PV (%)	82.5%	97.5%	77.5%
# of Turbines	19,600	1,400	15,750
# of PV Panels	1,878,048,780	1,109,756,098	1,102,642,276
Avg Wind Speed (m/s)	5.02	5.69	5.02
Avg Wind Speed (mph)	11.22	12.72	11.22
Wind Capacity Factor	18.01%	20.28%	17.25%
PV Capacity Factor	26.31%	29.74%	28.73%
Avg Irradiance (w/m2)	224.71	245.08	233.33
Combined Capacity Factor	24.86%	29.50%	26.15%
Average Ambient Temperature (°C)	19.98	16.85	17.78
Average Surface Pressure (mbar)	998.64	908.01	993.71
Average Relative Humidity (%)	46.63	43.05	62.18
Max Consecutive Hours NO WIND Power	40	37	37
Max Consecutive Hours NO SUN Power	17	18	17
Max Consecutive Hours NO POWER	15	14	15
Optimal System Max Consecutive Negative Net Load Hours	17	17	17
Load Region	CAISO - PGE	CAISO - SCE	CAISO - SCE
Avg Hourly Load (kW)	12,085,209	11,970,836	11,970,836
Peak Load (kW)	20,470,000	22,822,000	22,822,000
Peak Load Season	Summer/Fall	Fall	Fall
Optimal System Required Reserve (kWh)	0	0	0
Reserve %	0.00%	0.00%	0.00%
Hours of Reserve at Average Load	7.73	13.52	11.57
Hours of Reserve at Peak Load	4.57	7.09	6.07
Annual Total Energy Produced (kWh)	610,116,623,085	362,017,819,671	401,093,101,207
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0429	$0.0335	$0.0417
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.0884	$0.1303	$0.1170
GIS Map Zone	High_PV_Low_Wind	High_PV_High_Wind	Mod_PV_Low_Wind

Data Results – Zero Reserve Margin (Aggressive)

ST_City (Weather)	CO_Boulder	FL_Everglades_City	IL_Champaign
Map ID #	7	8	9
System Size (GW)	140	235	200
Storage Size (GW)	65	355	130
Wind Size (GW)	7	17.625	25
PV Size (GW)	133	217.375	175
Current Capacity @ 20% Reserve Margin (GW)	8	30	11
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$1,666	$2,026	$2,156
PV Price (kW)	$1,237	$1,277	$1,378
Total System Cost (1st Year) ($)	$ 329,258,000,000	$ 1,149,321,125,000	$ 601,200,000,000
Optimal Wind (%)	5.0%	7.5%	12.5%
Optimal PV (%)	95.0%	92.5%	87.5%
# of Turbines	2,800	7,050	10,000
# of PV Panels	1,081,300,813	1,767,276,423	1,422,764,228
Avg Wind Speed (m/s)	5.60	5.09	7.33
Avg Wind Speed (mph)	12.53	11.39	16.39
Wind Capacity Factor	19.53%	18.19%	40.80%
PV Capacity Factor	21.81%	22.28%	20.52%
Avg Irradiance (w/m2)	176.92	204.66	172.90
Combined Capacity Factor	21.69%	21.98%	23.05%
Average Ambient Temperature (°C)	4.12	25.96	11.77
Average Surface Pressure (mbar)	769.47	1016.53	992.58
Average Relative Humidity (%)	64.76	84.31	71.94
Max Consecutive Hours NO WIND Power	36	74	30
Max Consecutive Hours NO SUN Power	18	16	18
Max Consecutive Hours NO POWER	14	13	16
Optimal System Max Consecutive Negative Net Load Hours	16	17	18
Load Region	WAPA - RM	FPL	MISO - LRZ4
Avg Hourly Load (kW)	2,872,491	14,379,352	5,620,706
Peak Load (kW)	7,038,000	24,754,000	9,280,470
Peak Load Season	Summer	Summer	Summer/Fall
Optimal System Required Reserve (kWh)	0	0	0
Reserve %	0.00%	0.00%	0.00%
Hours of Reserve at Average Load	7.53	10.81	6.72
Hours of Reserve at Peak Load	3.07	6.28	4.07
Annual Total Energy Produced (kWh)	266,224,309,973	452,706,304,993	404,105,950,825
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0428	$0.0443	$0.0459
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.0722	$0.1389	$0.0848
GIS Map Zone	Mod_PV_High_Wind	Mod_PV_Low_Wind	Low_PV_Mod_Wind

Data Results – Zero Reserve Margin (Aggressive)

ST_City (Weather)	KS_Hays	MI_Gaylord	MS_Jackson
Map ID #	10	11	12
System Size (GW)	20	490	710
Storage Size (GW)	17	365	465
Wind Size (GW)	0.5	49	17.75
PV Size (GW)	19.5	441	692.25
Current Capacity @ 20% Reserve Margin (GW)	1	37	39
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$1,666	$2,156	$2,026
PV Price (kW)	$1,256	$1,295	$1,258
Total System Cost (1st Year) ($)	$ 65,360,000,000	$ 1,536,314,000,000	$ 2,001,887,000,000
Optimal Wind (%)	2.5%	10.0%	2.5%
Optimal PV (%)	97.5%	90.0%	97.5%
# of Turbines	200	19,600	7,100
# of PV Panels	158,536,585	3,585,365,854	5,628,048,780
Avg Wind Speed (m/s)	7.74	7.27	4.69
Avg Wind Speed (mph)	17.31	16.27	10.48
Wind Capacity Factor	43.88%	40.23%	12.10%
PV Capacity Factor	24.30%	17.30%	21.43%
Avg Irradiance (w/m2)	202.47	144.15	190.51
Combined Capacity Factor	24.79%	19.59%	21.20%
Average Ambient Temperature (°C)	14.13	4.12	18.84
Average Surface Pressure (mbar)	940.75	985.37	1006.05
Average Relative Humidity (%)	56.71	82.79	76.00
Max Consecutive Hours NO WIND Power	28	31	32
Max Consecutive Hours NO SUN Power	16	19	17
Max Consecutive Hours NO POWER	14	16	14
Optimal System Max Consecutive Negative Net Load Hours	17	17	17
Load Region	SPP - SECI	MISO LRZ2+7	MISO - LRZ8+9+10
Avg Hourly Load (kW)	711,464	18,772,505	19,431,885
Peak Load (kW)	1,193,494	31,142,290	32,386,090
Peak Load Season	Summer/Fall	Summer/Fall	Summer/Fall
Optimal System Required Reserve (kWh)	0	0	0
Reserve %	0.00%	0.00%	0.00%
Hours of Reserve at Average Load	6.93	9.33	7.06
Hours of Reserve at Peak Load	4.13	5.62	4.24
Annual Total Energy Produced (kWh)	43,453,248,567	841,507,808,368	1,319,288,172,441
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0375	$0.0512	$0.0442
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.0848	$0.1035	$0.0867
GIS Map Zone	Mod_PV_High_Wind	Low_PV_Mod_Wind	Mod_PV_Low_Wind

APPENDIX D, CONT.

Data Results – Zero Reserve Margin (Aggressive)

ST_City (Weather)	NC_Durham	NE_Lincoln	NJ_Edison
Map ID #	13	14	15
System Size (GW)	435	6	130
Storage Size (GW)	260	11	105
Wind Size (GW)	54.375	3.15	55.25
PV Size (GW)	380.625	2.85	74.75
Current Capacity @ 20% Reserve Margin (GW)	24	1	12
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$2,026	$1,666	$2,626
PV Price (kW)	$1,217	$1,253	$1,388
Total System Cost (1st Year) ($)	$ 1,185,684,375,000	$ 34,723,950,000	$ 496,114,500,000
Optimal Wind (%)	12.5%	52.5%	42.5%
Optimal PV (%)	87.5%	47.5%	57.5%
# of Turbines	21,750	1,260	22,100
# of PV Panels	3,094,512,195	23,170,732	607,723,577
Avg Wind Speed (m/s)	4.87	7.61	5.59
Avg Wind Speed (mph)	10.90	17.03	12.51
Wind Capacity Factor	14.78%	43.81%	21.66%
PV Capacity Factor	21.28%	21.53%	20.62%
Avg Irradiance (w/m2)	184.79	178.91	174.28
Combined Capacity Factor	20.47%	33.21%	21.05%
Average Ambient Temperature (°C)	15.51	11.12	11.67
Average Surface Pressure (mbar)	997.35	968.54	1008.09
Average Relative Humidity (%)	72.52	64.20	71.45
Max Consecutive Hours **NO WIND** Power	23	20	26
Max Consecutive Hours **NO SUN** Power	17	18	18
Max Consecutive Hours **NO POWER**	14	11	15
Optimal System Max Consecutive Negative Net Load Hours	16	19	17
Load Region	DUK	SPP - LES	PJM - PS
Avg Hourly Load (kW)	11,566,731	394,619	5,046,987
Peak Load (kW)	19,890,000	747,686	9,594,939
Peak Load Season	Summer	Summer/Fall	Summer/Fall
Optimal System Required Reserve (kWh)	0	0	0
Reserve %	0.00%	0.00%	0.00%
Hours of Reserve at Average Load	7.06	10.59	9.21
Hours of Reserve at Peak Load	4.10	5.59	4.85
Annual Total Energy Produced (kWh)	780,467,308,026	17,466,735,894	239,929,350,488
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0473	$0.0329	$0.0635
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.0875	$0.1089	$0.1163
GIS Map Zone	Mod_PV_Low_Wind	Mod_PV_Mod_Wind	Low_PV_Mod_Wind

Data Results – Zero Reserve Margin (Aggressive)

ST_City (Weather)	NM_Clovis	NY_Millbrook	OK_Stillwater
Map ID #	16	17	18
System Size (GW)	35	50	115
Storage Size (GW)	65	30	130
Wind Size (GW)	8.75	7.5	40.25
PV Size (GW)	26.25	42.5	74.75
Current Capacity @ 20% Reserve Margin (GW)	5	3	8
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$1,666	$2,626	$1,666
PV Price (kW)	$1,239	$1,352	$1,213
Total System Cost (1st Year) ($)	$ 200,176,250,000	$ 147,805,000,000	$ 463,878,250,000
Optimal Wind (%)	25.0%	15.0%	35.0%
Optimal PV (%)	75.0%	85.0%	65.0%
# of Turbines	3,500	3,000	16,100
# of PV Panels	213,414,634	345,528,455	607,723,577
Avg Wind Speed (m/s)	7.53	4.55	7.27
Avg Wind Speed (mph)	16.85	10.18	16.25
Wind Capacity Factor	39.54%	11.95%	39.62%
PV Capacity Factor	26.60%	20.52%	22.86%
Avg Irradiance (w/m2)	223.49	169.79	194.28
Combined Capacity Factor	29.83%	19.23%	28.72%
Average Ambient Temperature (°C)	14.82	8.77	15.82
Average Surface Pressure (mbar)	867.25	984.40	984.12
Average Relative Humidity (%)	53.60	74.44	67.66
Max Consecutive Hours NO WIND Power	26	55	25
Max Consecutive Hours NO SUN Power	17	18	17
Max Consecutive Hours NO POWER	16	12	13
Optimal System Max Consecutive Negative Net Load Hours	17	16	17
Load Region	SPP - WFEC	NYISO - HV-Zone G	SPP - OKGE
Avg Hourly Load (kW)	1,589,393	1,149,023	3,620,070
Peak Load (kW)	3,836,153	2,203,500	6,533,372
Peak Load Season	Winter	Summer/Fall	Summer/Fall
Optimal System Required Reserve (kWh)	0	0	0
Reserve %	0.00%	0.00%	0.00%
Hours of Reserve at Average Load	8.76	7.49	5.50
Hours of Reserve at Peak Load	3.63	3.91	3.05
Annual Total Energy Produced (kWh)	91,508,827,333	84,289,160,655	289,499,422,173
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0334	$0.0572	$0.0355
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.1192	$0.1001	$0.0897
GIS Map Zone	High_PV_Mod_Wind	Low_PV_Low_Wind	Mod_PV_Mod_Wind

APPENDIX D, CONT.

Data Results – Zero Reserve Margin (Aggressive)

ST_City (Weather)	RI_Kingston	SD_Sioux_Falls	TN_Nashville
Map ID #	19	20	21
System Size (GW)	16	3	420
Storage Size (GW)	19	2	375
Wind Size (GW)	7.2	1.2	115.5
PV Size (GW)	8.8	1.8	304.5
Current Capacity @ 20% Reserve Margin (GW)	2	0	36
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$2,626	$1,666	$2,026
PV Price (kW)	$1,356	$1,216	$1,241
Total System Cost (1st Year) ($)	$ 75,585,000,000	$ 8,898,000,000	$ 1,495,012,500,000
Optimal Wind (%)	45.0%	40.0%	27.5%
Optimal PV (%)	55.0%	60.0%	72.5%
# of Turbines	2,880	480	46,200
# of PV Panels	71,544,715	14,634,146	2,475,609,756
Avg Wind Speed (m/s)	5.35	7.86	5.44
Avg Wind Speed (mph)	11.96	17.58	12.16
Wind Capacity Factor	18.78%	45.69%	20.06%
PV Capacity Factor	21.04%	20.93%	20.97%
Avg Irradiance (w/m2)	173.37	174.22	180.36
Combined Capacity Factor	20.02%	30.82%	20.72%
Average Ambient Temperature (°C)	10.40	9.62	15.33
Average Surface Pressure (mbar)	1011.35	962.70	993.09
Average Relative Humidity (%)	76.62	63.13	74.81
Max Consecutive Hours NO WIND Power	19	18	38
Max Consecutive Hours NO SUN Power	18	20	17
Max Consecutive Hours NO POWER	14	9	15
Optimal System Max Consecutive Negative Net Load Hours	19	18	18
Load Region	ISO-NE - RI	WAPA - WAUW	TVA
Avg Hourly Load (kW)	927,537	87,571	17,652,869
Peak Load (kW)	1,748,505	167,000	29,823,000
Peak Load Season	Summer/Fall	Summer & Winter	Summer & Winter
Optimal System Required Reserve (kWh)	0	0	0
Reserve %	0.00%	0.00%	0.00%
Hours of Reserve at Average Load	18.94	4.33	9.69
Hours of Reserve at Peak Load	10.05	2.27	5.73
Annual Total Energy Produced (kWh)	28,079,163,374	8,105,298,574	762,786,077,947
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0672	$0.0337	$0.0512
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.1489	$0.0635	$0.1106
GIS Map Zone	Low_PV_Low_Wind	Low_PV_High_Wind	Low_PV_Low_Wind

APPENDIX D, CONT.

Data Results – Zero Reserve Margin (Aggressive)

ST_City (Weather)	TX_Amarillo	TX_Austin	TX_Bronte
Map ID #	22	23	24
System Size (GW)	45	105	55
Storage Size (GW)	70	145	30
Wind Size (GW)	11.25	55.125	1.375
PV Size (GW)	33.75	49.875	53.625
Current Capacity @ 20% Reserve Margin (GW)	7	14	2
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$1,666	$1,666	$1,666
PV Price (kW)	$1,233	$1,233	$1,233
Total System Cost (1st Year) ($)	$ 225,206,250,000	$ 494,809,125,000	$ 139,060,375,000
Optimal Wind (%)	25.0%	52.5%	2.5%
Optimal PV (%)	75.0%	47.5%	97.5%
# of Turbines	4,500	22,050	550
# of PV Panels	274,390,244	405,487,805	435,975,610
Avg Wind Speed (m/s)	7.62	6.60	7.17
Avg Wind Speed (mph)	17.05	14.77	16.03
Wind Capacity Factor	41.33%	31.41%	37.82%
PV Capacity Factor	25.98%	22.68%	24.76%
Avg Irradiance (w/m2)	218.28	202.57	217.29
Combined Capacity Factor	29.81%	27.25%	25.09%
Average Ambient Temperature (°C)	15.22	20.17	18.66
Average Surface Pressure (mbar)	893.06	981.66	946.09
Average Relative Humidity (%)	55.65	79.02	63.43
Max Consecutive Hours NO WIND Power	17	24	21
Max Consecutive Hours NO SUN Power	17	17	17
Max Consecutive Hours NO POWER	12	13	16
Optimal System Max Consecutive Negative Net Load Hours	17	18	18
Load Region	SPP - SPS	ERCOT - SC	ERCOT - W
Avg Hourly Load (kW)	3,566,076	6,515,835	1,134,484
Peak Load (kW)	5,696,955	12,032,553	1,883,889
Peak Load Season	Summer/Fall	Summer/Fall	Summer/Fall
Optimal System Required Reserve (kWh)	0	0	0
Reserve %	0.00%	0.00%	0.00%
Hours of Reserve at Average Load	12.70	11.36	5.59
Hours of Reserve at Peak Load	7.95	6.15	3.37
Annual Total Energy Produced (kWh)	117,600,293,924	250,794,632,830	120,964,410,347
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0333	$0.0399	$0.0366
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.1052	$0.1097	$0.0665
GIS Map Zone	High_PV_High_Wind	Mod_PV_Low_Wind	Mod_PV_Mod_Wind

Data Results – Zero Reserve Margin (Aggressive)

ST_City (Weather)	WY_Laramie	WY_McFadden
Map ID #	25	26
System Size (GW)	55	110
Storage Size (GW)	50	60
Wind Size (GW)	28.875	16.5
PV Size (GW)	26.125	93.5
Current Capacity @ 20% Reserve Margin (GW)	8	8
Storage Price	$2,355	$2,355
Wind Price (kW)	$1,666	$1,666
PV Price (kW)	$1,233	$1,233
Total System Cost (1st Year) ($)	$ 198,067,875,000	$ 284,074,500,000
Optimal Wind (%)	52.5%	15.0%
Optimal PV (%)	47.5%	85.0%
# of Turbines	11,550	6,600
# of PV Panels	212,398,374	760,162,602
Avg Wind Speed (m/s)	8.12	6.95
Avg Wind Speed (mph)	18.17	15.54
Wind Capacity Factor	43.16%	30.91%
PV Capacity Factor	22.30%	22.51%
Avg Irradiance (w/m2)	187.11	184.22
Combined Capacity Factor	33.23%	23.77%
Average Ambient Temperature (°C)	7.08	4.71
Average Surface Pressure (mbar)	786.20	763.25
Average Relative Humidity (%)	58.96	60.80
Max Consecutive Hours NO WIND Power	16	21
Max Consecutive Hours NO SUN Power	19	19
Max Consecutive Hours NO POWER	10	12
Optimal System Max Consecutive Negative Net Load Hours	17	14
Load Region	WAPA - RM	WAPA - RM
Avg Hourly Load (kW)	2,872,491	2,872,491
Peak Load (kW)	7,038,000	7,038,000
Peak Load Season	Summer/Fall	Summer/Fall
Optimal System Required Reserve (kWh)	0	0
Reserve %	0.00%	0.00%
Hours of Reserve at Average Load	9.27	7.40
Hours of Reserve at Peak Load	3.78	3.02
Annual Total Energy Produced (kWh)	160,235,417,462	229,189,008,353
20 Year Levelized Cost of Energy (LCOE) - Energy Only (kWh)	$0.0327	$0.0404
20 Year Levelized Cost of Energy (LCOE) - Energy & Storage (kWh)	$0.0704	$0.0720
GIS Map Zone	Mod_PV_Mod_Wind	Low_PV_High_Wind

APPENDIX E

Load Symbol Descriptions

Symbol	Name
DUK	Duke Energy Carolinas
ERCOT	Electric Reliability Council of Texas
SC	South Central
W	West
FPL	Florida Power & Light
ISO-NE	Independent System Operator-New England
RI	Rhode Island
PJM	PJM Interconnection
PS	PSE&G of New Jersey
MISO	Midcontinent Independent System Operator
LRZ	Load Region Zone
SPP	Southwest Power Pool
LES	Lincoln Electric System
OKGE	Oklahoma Gas & Electric
SECI	Sunflower Electric
SPS	Southwest Public Service
WFEC	Western Farmers Electric Cooperative
TVA	Tennessee Valley Authority
WAPA	Western Area Power Administration
DSW	Desert Southwest Region
RM	Rocky Mountain Region
WAUW	Upper Great Plains West

APPENDIX F

30-Year LCOE Calculations for Baseline Reserve Margin (Conservative)

ST_City (Weather)	AZ_Bowie	AZ_Phoenix	CA_Bodega
Map ID #	1	2	3
System Size (GW)	345	205	430
Storage Size (GW)	400	540	345
Wind Size (GW)	163.875	10.25	64.5
PV Size (GW)	181.125	194.75	365.5
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$2,076	$2,076	$2,076
PV Price (kW)	$1,238	$1,238	$1,353
Total System Cost (1st Year) ($)	$ 1,506,437,250,000	$ 1,534,079,500,000	$ 1,440,898,500,000
Optimal Wind (%)	47.5%	5.0%	15.0%
Optimal PV (%)	52.5%	95.0%	85.0%
Combined Capacity Factor	25.06%	27.92%	25.12%
Annual Total Energy Produced (kWh)	757,790,008,722	501,668,800,050	946,726,702,346
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0348	$0.0250	$0.0308
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.0778	$0.1127	$0.0605

ST_City (Weather)	CA_Fresno	CA_Mojave	CA_Santa_Barbara
Map ID #	4	5	6
System Size (GW)	280	235	225
Storage Size (GW)	345	385	385
Wind Size (GW)	49	47	33.75
PV Size (GW)	231	188	191.25
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$2,076	$2,076	$2,076
PV Price (kW)	$1,353	$1,353	$1,353
Total System Cost (1st Year) ($)	$ 1,226,742,000,000	$ 1,258,611,000,000	$ 1,235,501,250,000
Optimal Wind (%)	17.5%	20.0%	15.0%
Optimal PV (%)	82.5%	80.0%	85.0%
Combined Capacity Factor	24.86%	27.84%	27.01%
Annual Total Energy Produced (kWh)	610,116,623,085	573,552,475,294	532,688,525,007
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0315	$0.0285	$0.0287
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.0776	$0.0832	$0.0876

APPENDIX F, CONT.

30-Year LCOE Calculations for Baseline Reserve Margin (Conservative)

ST_City (Weather)	CO_Boulder	FL_Everglades_City	IL_Champaign
Map ID #	7	8	9
System Size (GW)	145	290	190
Storage Size (GW)	85	515	165
Wind Size (GW)	14.5	14.5	66.5
PV Size (GW)	130.5	275.5	123.5
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$1,666	$2,026	$2,156
PV Price (kW)	$1,237	$1,277	$1,378
Total System Cost (1st Year) ($)	$ 385,760,500,000	$ 1,594,015,500,000	$ 702,132,000,000
Optimal Wind (%)	10.0%	5.0%	35.0%
Optimal PV (%)	90.0%	95.0%	65.0%
Combined Capacity Factor	21.58%	22.08%	27.61%
Annual Total Energy Produced (kWh)	274,279,747,567	561,268,996,267	459,784,322,977
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0325	$0.0321	$0.0313
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.0578	$0.1069	$0.0606

ST_City (Weather)	KS_Hays	MI_Gaylord	MS_Jackson
Map ID #	10	11	12
System Size (GW)	25	480	715
Storage Size (GW)	20	545	635
Wind Size (GW)	2.5	96	17.875
PV Size (GW)	22.5	384	697.125
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$1,666	$2,156	$2,026
PV Price (kW)	$1,256	$1,295	$1,258
Total System Cost (1st Year) ($)	$ 79,525,000,000	$ 1,987,731,000,000	$ 2,408,623,000,000
Optimal Wind (%)	10.0%	20.0%	2.5%
Optimal PV (%)	90.0%	80.0%	97.5%
Combined Capacity Factor	26.25%	21.88%	21.20%
Annual Total Energy Produced (kWh)	57,531,149,654	920,681,324,467	1,328,578,934,218
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0270	$0.0357	$0.0327
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.0553	$0.0840	$0.0717

APPENDIX F, CONT.

30-Year LCOE Calculations for Baseline Reserve Margin (Conservative)

ST_City (Weather)	NC_Durham	NE_Lincoln	NJ_Edison
Map ID #	13	14	15
System Size (GW)	440	10	160
Storage Size (GW)	360	12	150
Wind Size (GW)	55	4.25	40
PV Size (GW)	385	5.75	120
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$2,026	$1,666	$2,626
PV Price (kW)	$1,217	$1,253	$1,388
Total System Cost (1st Year) ($)	$ 1,427,775,000,000	$ 42,545,250,000	$ 624,850,000,000
Optimal Wind (%)	12.5%	42.5%	25.0%
Optimal PV (%)	87.5%	57.5%	75.0%
Combined Capacity Factor	20.47%	30.98%	20.87%
Annual Total Energy Produced (kWh)	789,438,196,624	27,160,338,425	292,778,875,068
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0351	$0.0254	$0.0419
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.0722	$0.0614	$0.0836

ST_City (Weather)	NM_Clovis	NY_Millbrook	OK_Stillwater
Map ID #	16	17	18
System Size (GW)	40	60	125
Storage Size (GW)	80	35	145
Wind Size (GW)	8	7.5	53.125
PV Size (GW)	32	52.5	71.875
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$1,666	$2,626	$1,666
PV Price (kW)	$1,239	$1,352	$1,213
Total System Cost (1st Year) ($)	$ 241,376,000,000	$ 173,100,000,000	$ 517,165,625,000
Optimal Wind (%)	20.0%	12.5%	42.5%
Optimal PV (%)	80.0%	87.5%	57.5%
Combined Capacity Factor	29.18%	19.45%	29.97%
Annual Total Energy Produced (kWh)	102,318,099,469	102,275,253,915	328,424,498,051
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0249	$0.0407	$0.0260
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.0886	$0.0686	$0.0620

30-Year LCOE Calculations for Baseline Reserve Margin (Conservative)

ST_City (Weather)	RI_Kingston	SD_Sioux_Falls	TN_Nashville
Map ID #	19	20	21
System Size (GW)	25	2	470
Storage Size (GW)	30	3	560
Wind Size (GW)	4.375	0.95	94
PV Size (GW)	20.625	1.05	376
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$2,626	$1,666	$2,026
PV Price (kW)	$1,356	$1,216	$1,241
Total System Cost (1st Year) ($)	$ 110,106,250,000	$ 9,924,500,000	$ 1,975,860,000,000
Optimal Wind (%)	17.5%	47.5%	20.0%
Optimal PV (%)	82.5%	52.5%	80.0%
Combined Capacity Factor	20.65%	32.68%	20.79%
Annual Total Energy Produced (kWh)	45,244,571,657	5,728,809,805	856,451,637,483
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0398	$0.0242	$0.0363
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.0938	$0.0669	$0.0896

ST_City (Weather)	TX_Amarillo	TX_Austin	TX_Bronte
Map ID #	22	23	24
System Size (GW)	60	145	50
Storage Size (GW)	95	200	40
Wind Size (GW)	31.5	97.875	2.5
PV Size (GW)	28.5	47.125	47.5
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$1,666	$1,666	$1,666
PV Price (kW)	$1,233	$1,233	$1,233
Total System Cost (1st Year) ($)	$ 311,344,500,000	$ 692,164,875,000	$ 156,932,500,000
Optimal Wind (%)	52.5%	67.5%	5.0%
Optimal PV (%)	47.5%	32.5%	95.0%
Combined Capacity Factor	34.02%	28.55%	25.42%
Annual Total Energy Produced (kWh)	178,957,829,509	362,941,199,778	111,395,888,340
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0238	$0.0297	$0.0270
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.0670	$0.0746	$0.0563

30-Year LCOE Calculations for Baseline Reserve Margin (Conservative)

ST_City (Weather)	WY_Laramie	WY_McFadden
Map ID #	25	26
System Size (GW)	70	105
Storage Size (GW)	65	90
Wind Size (GW)	52.5	15.75
PV Size (GW)	17.5	89.25
Storage Price	$2,355	$2,355
Wind Price (kW)	$1,666	$1,666
PV Price (kW)	$1,233	$1,233
Total System Cost (1st Year) ($)	$ 262,117,500,000	$ 348,234,750,000
Optimal Wind (%)	75.0%	15.0%
Optimal PV (%)	25.0%	85.0%
Combined Capacity Factor	37.92%	23.77%
Annual Total Energy Produced (kWh)	232,698,189,337	218,771,326,155
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0228	$0.0300
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.0456	$0.0635

APPENDIX G

30-Year LCOE Calculations for Middle Ground Reserve Margin

ST_City (Weather)	AZ_Bowie	AZ_Phoenix	CA_Bodega
Map ID #	1	2	3
System Size (GW)	290	210	405
Storage Size (GW)	380	450	310
Wind Size (GW)	101.5	10.5	91.125
PV Size (GW)	188.5	199.5	313.875
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$2,076	$2,076	$2,076
PV Price (kW)	$1,238	$1,238	$1,353
Total System Cost (1st Year) ($)	$ 1,338,977,000,000	$ 1,328,529,000,000	$ 1,343,898,375,000
Optimal Wind (%)	35.0%	5.0%	22.5%
Optimal PV (%)	65.0%	95.0%	77.5%
Combined Capacity Factor	25.77%	27.92%	24.49%
Annual Total Energy Produced (kWh)	655,235,451,950	513,904,624,442	869,620,395,073
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0318	$0.0250	$0.0328
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.0791	$0.0963	$0.0618

ST_City (Weather)	CA_Fresno	CA_Mojave	CA_Santa_Barbara
Map ID #	4	5	6
System Size (GW)	280	180	180
Storage Size (GW)	285	315	305
Wind Size (GW)	49	40.5	40.5
PV Size (GW)	231	139.5	139.5
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$2,076	$2,076	$2,076
PV Price (kW)	$1,353	$1,353	$1,353
Total System Cost (1st Year) ($)	$ 1,085,442,000,000	$ 1,014,646,500,000	$ 991,096,500,000
Optimal Wind (%)	17.5%	22.5%	22.5%
Optimal PV (%)	82.5%	77.5%	77.5%
Combined Capacity Factor	24.86%	27.61%	26.15%
Annual Total Energy Produced (kWh)	610,116,623,085	435,583,262,038	412,552,904,099
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0315	$0.0291	$0.0307
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.0696	$0.0880	$0.0909

30-Year LCOE Calculations for Middle Ground Reserve Margin

ST_City (Weather)	CO_Boulder	FL_Everglades_City	IL_Champaign
Map ID #	7	8	9
System Size (GW)	145	235	185
Storage Size (GW)	75	440	150
Wind Size (GW)	14.5	17.625	60.125
PV Size (GW)	130.5	217.375	124.875
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$1,666	$2,026	$2,156
PV Price (kW)	$1,237	$1,277	$1,378
Total System Cost (1st Year) ($)	$ 362,210,500,000	$ 1,349,496,125,000	$ 654,957,250,000
Optimal Wind (%)	10.0%	7.5%	32.5%
Optimal PV (%)	90.0%	92.5%	67.5%
Combined Capacity Factor	21.58%	21.98%	27.10%
Annual Total Energy Produced (kWh)	274,279,747,567	452,706,304,993	439,475,098,750
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0325	$0.0327	$0.0316
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.0548	$0.1119	$0.0594

ST_City (Weather)	KS_Hays	MI_Gaylord	MS_Jackson
Map ID #	10	11	12
System Size (GW)	20	475	710
Storage Size (GW)	20	440	575
Wind Size (GW)	0.5	95	17.75
PV Size (GW)	19.5	380	692.25
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$1,666	$2,156	$2,026
PV Price (kW)	$1,256	$1,295	$1,258
Total System Cost (1st Year) ($)	$ 72,425,000,000	$ 1,733,120,000,000	$ 2,260,937,000,000
Optimal Wind (%)	2.5%	20.0%	2.5%
Optimal PV (%)	97.5%	80.0%	97.5%
Combined Capacity Factor	24.79%	21.88%	21.20%
Annual Total Energy Produced (kWh)	43,453,248,567	911,090,894,004	1,319,288,172,441
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0278	$0.0357	$0.0327
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.0653	$0.0751	$0.0682

30-Year LCOE Calculations for Middle Ground Reserve Margin

ST_City (Weather)	NC_Durham	NE_Lincoln	NJ_Edison
Map ID #	13	14	15
System Size (GW)	430	6	135
Storage Size (GW)	325	12	120
Wind Size (GW)	53.75	3.3	57.375
PV Size (GW)	376.25	2.7	77.625
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$2,026	$1,666	$2,626
PV Price (kW)	$1,217	$1,253	$1,388
Total System Cost (1st Year) ($)	$ 1,332,168,750,000	$ 37,140,900,000	$ 541,010,250,000
Optimal Wind (%)	12.5%	55.0%	42.5%
Optimal PV (%)	87.5%	45.0%	57.5%
Combined Capacity Factor	20.47%	33.77%	21.05%
Annual Total Energy Produced (kWh)	771,496,419,428	17,759,369,104	249,157,402,430
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0351	$0.0242	$0.0462
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.0694	$0.0793	$0.0854

ST_City (Weather)	NM_Clovis	NY_Millbrook	OK_Stillwater
Map ID #	16	17	18
System Size (GW)	35	55	120
Storage Size (GW)	70	35	135
Wind Size (GW)	8.75	5.5	45
PV Size (GW)	26.25	49.5	75
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$1,666	$2,626	$1,666
PV Price (kW)	$1,239	$1,352	$1,213
Total System Cost (1st Year) ($)	$ 211,951,250,000	$ 163,792,000,000	$ 483,870,000,000
Optimal Wind (%)	25.0%	10.0%	37.5%
Optimal PV (%)	75.0%	90.0%	62.5%
Combined Capacity Factor	29.83%	19.66%	29.14%
Annual Total Energy Produced (kWh)	91,508,827,333	94,786,555,457	306,486,741,758
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0248	$0.0395	$0.0263
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.0872	$0.0696	$0.0622

30-Year LCOE Calculations for Middle Ground Reserve Margin

ST_City (Weather)	RI_Kingston	SD_Sioux_Falls	TN_Nashville
Map ID #	19	20	21
System Size (GW)	15	3	415
Storage Size (GW)	25	2	460
Wind Size (GW)	7.5	1.95	134.875
PV Size (GW)	7.5	1.05	280.125
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$2,626	$1,666	$2,026
PV Price (kW)	$1,356	$1,216	$1,241
Total System Cost (1st Year) ($)	$ 88,740,000,000	$ 9,235,500,000	$ 1,704,191,875,000
Optimal Wind (%)	50.0%	65.0%	32.5%
Optimal PV (%)	50.0%	35.0%	67.5%
Combined Capacity Factor	19.91%	37.01%	20.67%
Annual Total Energy Produced (kWh)	26,174,665,239	9,731,685,685	752,023,103,160
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0506	$0.0227	$0.0389
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.1285	$0.0394	$0.0887

ST_City (Weather)	TX_Amarillo	TX_Austin	TX_Bronte
Map ID #	22	23	24
System Size (GW)	50	105	45
Storage Size (GW)	80	165	40
Wind Size (GW)	17.5	55.125	4.5
PV Size (GW)	32.5	49.875	40.5
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$1,666	$1,666	$1,666
PV Price (kW)	$1,233	$1,233	$1,233
Total System Cost (1st Year) ($)	$ 257,627,500,000	$ 541,909,125,000	$ 151,633,500,000
Optimal Wind (%)	35.0%	52.5%	10.0%
Optimal PV (%)	65.0%	47.5%	90.0%
Combined Capacity Factor	31.34%	27.25%	26.07%
Annual Total Energy Produced (kWh)	137,381,368,282	250,794,632,830	102,827,136,132
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0244	$0.0297	$0.0268
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.0718	$0.0833	$0.0585

30-Year LCOE Calculations for Middle Ground Reserve Margin

ST_City (Weather)	WY_Laramie	WY_McFadden
Map ID #	25	26
System Size (GW)	50	120
Storage Size (GW)	60	65
Wind Size (GW)	28.75	36
PV Size (GW)	21.25	84
Storage Price	$2,355	$2,355
Wind Price (kW)	$1,666	$1,666
PV Price (kW)	$1,233	$1,233
Total System Cost (1st Year) ($)	$ 215,398,750,000	$ 316,623,000,000
Optimal Wind (%)	57.5%	30.0%
Optimal PV (%)	42.5%	70.0%
Combined Capacity Factor	34.28%	25.03%
Annual Total Energy Produced (kWh)	150,233,990,452	263,251,122,593
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0240	$0.0300
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.0565	$0.0501

APPENDIX H

30-Year LCOE Calculations for No Reserve Margin (Aggressive)

ST_City (Weather)	AZ_Bowie	AZ_Phoenix	CA_Bodega
Map ID #	1	2	3
System Size (GW)	245	210	395
Storage Size (GW)	375	385	265
Wind Size (GW)	42.875	10.5	79
PV Size (GW)	202.125	199.5	316
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$2,076	$2,076	$2,076
PV Price (kW)	$1,238	$1,238	$1,353
Total System Cost (1st Year) ($)	$ 1,222,364,250,000	$ 1,175,454,000,000	$ 1,215,627,000,000
Optimal Wind (%)	17.5%	5.0%	20.0%
Optimal PV (%)	82.5%	95.0%	80.0%
Combined Capacity Factor	26.78%	27.92%	24.70%
Annual Total Energy Produced (kWh)	575,149,341,478	513,904,624,442	855,321,375,087
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0279	$0.0250	$0.0321
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.0811	$0.1241	$0.0574

ST_City (Weather)	CA_Fresno	CA_Mojave	CA_Santa_Barbara
Map ID #	4	5	6
System Size (GW)	280	140	175
Storage Size (GW)	230	290	250
Wind Size (GW)	49	3.5	39.375
PV Size (GW)	231	136.5	135.625
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$2,076	$2,076	$2,076
PV Price (kW)	$1,353	$1,353	$1,353
Total System Cost (1st Year) ($)	$ 955,917,000,000	$ 874,900,500,000	$ 853,993,125,000
Optimal Wind (%)	17.5%	2.5%	22.5%
Optimal PV (%)	82.5%	97.5%	77.5%
Combined Capacity Factor	24.86%	29.50%	26.15%
Annual Total Energy Produced (kWh)	610,116,623,085	362,017,819,671	401,093,101,207
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0315	$0.0247	$0.0307
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.0623	$0.0900	$0.0815

30-Year LCOE Calculations for No Reserve Margin (Aggressive)

ST_City (Weather)	CO_Boulder	FL_Everglades_City	IL_Champaign
Map ID #	7	8	9
System Size (GW)	140	235	200
Storage Size (GW)	65	355	130
Wind Size (GW)	7	17.625	25
PV Size (GW)	133	217.375	175
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$1,666	$2,026	$2,156
PV Price (kW)	$1,237	$1,277	$1,378
Total System Cost (1st Year) ($)	$ 329,258,000,000	$ 1,149,321,125,000	$ 601,200,000,000
Optimal Wind (%)	5.0%	7.5%	12.5%
Optimal PV (%)	95.0%	92.5%	87.5%
Combined Capacity Factor	21.69%	21.98%	23.05%
Annual Total Energy Produced (kWh)	266,224,309,973	452,706,304,993	404,105,950,825
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0317	$0.0327	$0.0337
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.0516	$0.0966	$0.0600

ST_City (Weather)	KS_Hays	MI_Gaylord	MS_Jackson
Map ID #	10	11	12
System Size (GW)	20	490	710
Storage Size (GW)	17	365	465
Wind Size (GW)	0.5	49	17.75
PV Size (GW)	19.5	441	692.25
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$1,666	$2,156	$2,026
PV Price (kW)	$1,256	$1,295	$1,258
Total System Cost (1st Year) ($)	$ 65,360,000,000	$ 1,536,314,000,000	$ 2,001,887,000,000
Optimal Wind (%)	2.5%	10.0%	2.5%
Optimal PV (%)	97.5%	90.0%	97.5%
Combined Capacity Factor	24.79%	19.59%	21.20%
Annual Total Energy Produced (kWh)	43,453,248,567	841,507,808,368	1,319,288,172,441
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0278	$0.0378	$0.0327
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.0597	$0.0731	$0.0614

30-Year LCOE Calculations for No Reserve Margin (Aggressive)

ST_City (Weather)	NC_Durham	NE_Lincoln	NJ_Edison
Map ID #	13	14	15
System Size (GW)	435	6	130
Storage Size (GW)	260	11	105
Wind Size (GW)	54.375	3.15	55.25
PV Size (GW)	380.625	2.85	74.75
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$2,026	$1,666	$2,626
PV Price (kW)	$1,217	$1,253	$1,388
Total System Cost (1st Year) ($)	$ 1,185,684,375,000	$ 34,723,950,000	$ 496,114,500,000
Optimal Wind (%)	12.5%	52.5%	42.5%
Optimal PV (%)	87.5%	47.5%	57.5%
Combined Capacity Factor	20.47%	33.21%	21.05%
Annual Total Energy Produced (kWh)	780,467,308,026	17,466,735,894	239,929,350,488
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0351	$0.0245	$0.0462
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.0622	$0.0758	$0.0818

ST_City (Weather)	NM_Clovis	NY_Millbrook	OK_Stillwater
Map ID #	16	17	18
System Size (GW)	35	50	115
Storage Size (GW)	65	30	130
Wind Size (GW)	8.75	7.5	40.25
PV Size (GW)	26.25	42.5	74.75
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$1,666	$2,626	$1,666
PV Price (kW)	$1,239	$1,352	$1,213
Total System Cost (1st Year) ($)	$ 200,176,250,000	$ 147,805,000,000	$ 463,878,250,000
Optimal Wind (%)	25.0%	15.0%	35.0%
Optimal PV (%)	75.0%	85.0%	65.0%
Combined Capacity Factor	29.83%	19.23%	28.72%
Annual Total Energy Produced (kWh)	91,508,827,333	84,289,160,655	289,499,422,173
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0248	$0.0419	$0.0264
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.0827	$0.0709	$0.0630

30-Year LCOE Calculations for No Reserve Margin (Aggressive)

ST_City (Weather)	RI_Kingston	SD_Sioux_Falls	TN_Nashville
Map ID #	19	20	21
System Size (GW)	16	3	420
Storage Size (GW)	19	2	375
Wind Size (GW)	7.2	1.2	115.5
PV Size (GW)	8.8	1.8	304.5
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$2,626	$1,666	$2,026
PV Price (kW)	$1,356	$1,216	$1,241
Total System Cost (1st Year) ($)	$ 75,585,000,000	$ 8,898,000,000	$ 1,495,012,500,000
Optimal Wind (%)	45.0%	40.0%	27.5%
Optimal PV (%)	55.0%	60.0%	72.5%
Combined Capacity Factor	20.02%	30.82%	20.72%
Annual Total Energy Produced (kWh)	28,079,163,374	8,105,298,574	762,786,077,947
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0489	$0.0251	$0.0379
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.1041	$0.0452	$0.0779

ST_City (Weather)	TX_Amarillo	TX_Austin	TX_Bronte
Map ID #	22	23	24
System Size (GW)	45	105	55
Storage Size (GW)	70	145	30
Wind Size (GW)	11.25	55.125	1.375
PV Size (GW)	33.75	49.875	53.625
Storage Price	$2,355	$2,355	$2,355
Wind Price (kW)	$1,666	$1,666	$1,666
PV Price (kW)	$1,233	$1,233	$1,233
Total System Cost (1st Year) ($)	$ 225,206,250,000	$ 494,809,125,000	$ 139,060,375,000
Optimal Wind (%)	25.0%	52.5%	2.5%
Optimal PV (%)	75.0%	47.5%	97.5%
Combined Capacity Factor	29.81%	27.25%	25.09%
Annual Total Energy Produced (kWh)	117,600,293,924	250,794,632,830	120,964,410,347
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0248	$0.0297	$0.0271
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.0733	$0.0768	$0.0473

30-Year LCOE Calculations for No Reserve Margin (Aggressive)

ST_City (Weather)	WY_Laramie	WY_McFadden
Map ID #	25	26
System Size (GW)	55	110
Storage Size (GW)	50	60
Wind Size (GW)	28.875	16.5
PV Size (GW)	26.125	93.5
Storage Price	$2,355	$2,355
Wind Price (kW)	$1,666	$1,666
PV Price (kW)	$1,233	$1,233
Total System Cost (1st Year) ($)	$ 198,067,875,000	$ 284,074,500,000
Optimal Wind (%)	52.5%	15.0%
Optimal PV (%)	47.5%	85.0%
Combined Capacity Factor	33.23%	23.77%
Annual Total Energy Produced (kWh)	160,235,417,462	229,189,008,353
30-Year Levelized Cost of Energy (LCOE) PV + Wind Only (kWh)	$0.0243	$0.0300
30-Year Levelized Cost of Energy (LCOE) PV + Wind + Storage (kWh)	$0.0498	$0.0513

Vita

Robb O'Brien hails from the state of Michigan, where he was born in Detroit to parents Jim and Linda O'Brien. Robb graduated from the University of Michigan with a Bachelor of Arts in Economics degree in 1998. After graduation, Robb worked in downtown Ann Arbor as a Portfolio Analyst for a capital management firm.

Robb left the financial industry in 2003 and moved to Chicago. During his five years of living in Chicago he studied Computer Science at DePaul University and owned his own audio/video company. He sold his half of the audio/video company to his partner in 2009, and moved to California to live with his brother. In California, Robb learned the importance of trusting God with life's decisions.

In 2012, Robb returned to Michigan and began working as an Account Executive for a control and automation start-up company called iRule. In early 2015, Robb was "called" by God to help the environment. In the fall of 2015, Robb enrolled in Appalachian State University's Master of Science in Technology program.

During Robb's two years at Appalachian State, he primarily focused his study on wind and photovoltaic technology. Robb and Appalachian State professor Brent Summerville crafted an anemometer-based weather station for the U.S. Army Corp of Engineers, and spent many hours at the University's Beech Mountain wind testing facility, where wind gusts above 100 mph were recorded. In addition, Robb led the U.S. Department of Energy-supported Wind for Schools grant program. The Wind for Schools program provided opportunities for Robb and Brent to establish online wind energy data reporting technology at various North Carolina schools that housed Skystream wind turbines. Wind for Schools also provided Robb the opportunity to interact with science teachers of all age groups and encourage education about wind technology in their curriculum.

Robb's graduate school experience concluded with an in-depth analysis of the benefits of co-locating wind and PV technology. Helping the environment is not a one-time endeavor. After graduation, Robb will continue his pursuits to ensure a 100% renewable energy world.