INVESTIGATION AND ANALYSIS OF AUTONOMOUS HYBRID RENEWABLE ENERGY SOLAR PHOTOVOLTAIC/WIND-TURBINE SYSTEMS

By

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EXECUTIVE SUMMARY

Through technological advancements, the capability and need to research the significance of renewable energy systems and implementation has grown exponentially. This piece presents an investigation of the advanced design of a hybrid renewable energy system consisting of solar photovoltaic, wind turbine and energy storage technologies. Within this paper, topics of discussion developed contextual evidence that the integration of the alternative energy resources have addressed underlying dilemmas discovered when applied independently. An in-depth review was conducted in order to identify an optimal process and criteria for the system's optimization, configuration, sources of energy, sizing, modeling, and control strategies. The primary focus acknowledges the utilization of renewable resources in order to digress from the dependency on fossil fuel for electrical power production. To assure this idea is enveloped within the research, the developed power generation system was analyzed and evaluated as a stand-alone hybrid system, making it exclusively autonomous. In perspective, the research simulates an energy independent Photovoltaic-Wind Hybrid system, separate from a concentrated electrical grid connection. The off-grid Photovoltaic-Wind hybrid energy system is designed, and performance is simulated with consideration of a subjected location. Initial investigation incorporates Michigan, United States as the primary location of analysis due to favorable conditions of the hybrid system as well as to gather optimal experimental values. From the results discovered the following objective has established a feasible process with a globally applicable procedure to a secondary location.

This research investigates the demand load with a designed system of the following concepts:

I. Solar photovoltaic and Wind Turbine system Analyzed separately at 100 kilowatts
II. Combined alternative energy system with varied shared percentage to equate 100 kilowatts

This piece highlights imperative problems, disputes in the availability of resources and the importance of hybrid renewable systems. Additional concepts established include case methodology, numerical and simulated analysis, and the investigative results.

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CHAPTER 1: INTRODUCTION AND BACKGROUND

1.1 Introduction

To meet energy needs, energy resources depend heavily on the use of fossil fuels. With population rising at an exponential growth, and the advances in industry, energy demand is expected to rise rapidly. The main energy sources include the fossil fuels, oil, coal and natural gas; then the utilization of the less common sources include nuclear and renewable energy. The U.S. Energy Information Administration reports a projection of the world energy consumption will have a growth of nearly 50% between 2018 and 2050 (U.S. Energy Information Administration, 2020). The leading drive towards demand and where the growth is most visible include the regions where there is economic progress. Electricity generation at end use consumption is predicted to increase by 79% between the 2018 to 2050 (U.S. Energy Information Administration, 2020). Worldwide initiatives have been set to confront the challenges nonrenewable energy sources present, with the forefront solution being the increased implementation of renewable energy resources. Due to the abundant characteristics and innate attributes, solar and wind energies are the most promising options for long term future use.

The integration of these renewable energy sources within the electrical power generation has transpired the investigation into the development of a hybrid system, consisting of both wind and solar energies. A plethora of research into the solar photovoltaic and wind turbine technologies has made it possible to arrive at the conclusion that the hybrid photovoltaic (PV) - wind turbine power (WT) system will produce a higher reliability of continuous power. However, investigative research begins to narrow when attempting to confront primary challenges presented by the unpredictability of weather and climate change of a location. Although there is much research on the ability to maximize energy output from the hybrid system, there is less consideration towards the attempt to approach the power fluctuation obstacle. The amount of research narrows even more with the attempting to investigate the use of the hybrid PV/wind system in certain regions of the world. Within the case studies later discussed in the literature review portion of the piece, majority of the locations analyzed reside in the eastern hemisphere. The research investigated during the fundamental development stage has reviewed several differing methods of approach to the viability of the hybrid system. Each method varied at several stages of the analysis and simulation portions of the study due primarily to project location and system components. As a result, the analysis performed within this study has intentionally attempted to develop a fundamental process that would be applicable to varying locations. To maintain a solid base towards this intent, the investigation initially removed the factor of integration of existing electrical grid. Performing the analysis of a hybrid photovoltaic-wind turbine system presumed to be energy independent removes an additional obstacle in achieving energy independence of a location. Further research is required to comprehend and establish the systems and realistic challenges that the system must acknowledge to perform proficiently. To understand potential challenges, the systems and location variables were researched independently to discover initial drawbacks of the system.

1.2 Background Information

The following section is a description of the systems being researched within the graduate technical project. The two systems researched are the alternative energy technologies, solar energy of photovoltaics and wind energy of turbines. These technologies were investigated to gain understanding on an integrated energy system. To analyze the hybrid solar-wind system, it is important to gather the fundamentals of the components and operations of both systems.

1.2.1 Environmental Resources

According to the Figure 1.2-1, at 10 Meters above Surface Level, much of the United States has a classification color which indicates that many states have a wind speed of less than 3.0 meters per second, and is assessed as wind class 3 or 4, except for portions of the mountain west, which are class 5 or 6. According to the NREL, wind energy optimal when wind classes are at 3 or above. (NREL, 2017).

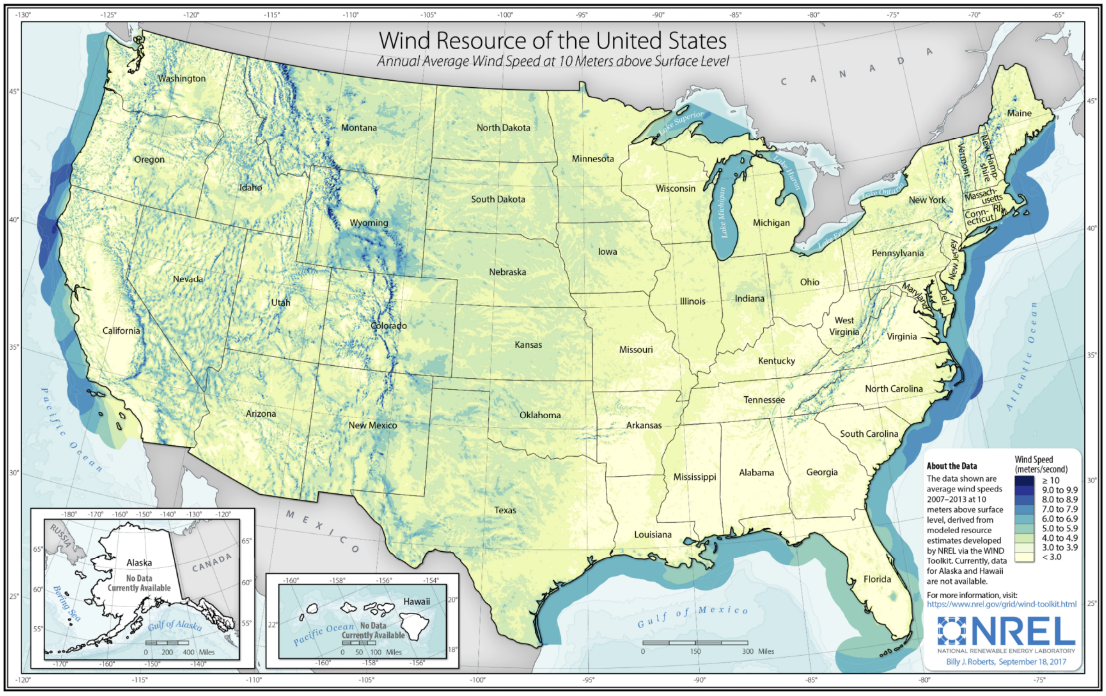

Figure 1.2-1: U.S. Wind Speed at 10 Meters(m) Above Surface Level

The NREL also has a solar irradiance database that measures the Global Horizontal Solar Irradiance in the United States. With this map in Figure 1.2-2 that shows the annual average daily total solar resource data. According to the map, much of the Midwest has an average daily total of less than 4.25kWh per day, with much of the Western states getting as much as 5.75kWh per day. Although these are the average totals, the Midwest sees an increase in solar irradiance during the months of April through August. (NREL, 2017).

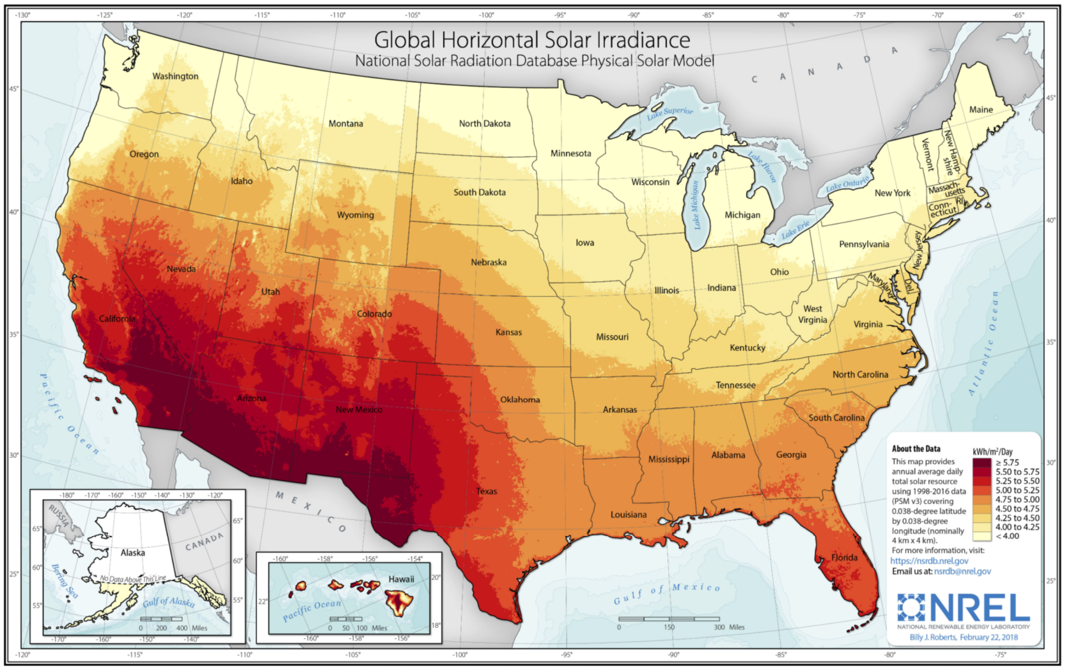

Figure 1.2-2: U.S. Solar Global Horizontal Irradiance (GHI)

Traditionally, the electrical grid system consists of a stabilized relationship between electrical load supply and demand. The current system of power relies on the foundational design of a dynamic system that responds reactively. There is a clear hierarchical organization of energy transfer with this typical design. In the case of the investigation, the original design layout must consider the penetration of renewables, electrical storage, and transportation means with the growing traditional demand. Similar to the solar and wind variables, the load demand is location dependent, which are affected by geographical properties, population, and living standards. (Pabla, 2011). The geographical constraints may cause increased difficulty in the construction of electrical lines and plant configuration. Population and living standards directly affect the increase in the consumption of energy.

Throughout the investigation the load will be referenced as a parameter of the analysis. This load capacity will equate to the sum of power from the system that is able to be applied at a point. The load demand describes the user power requested or required by the electrical system with the expectation that it will not exceed the amount of electricity the system is able to generate. Generally, the load type can be segmented into the categories of residential, domestic, community commercial, and industrial. The load necessities differ based on the community's category being served by the energy system. These categories are different to acknowledge the diversity of system requirements. This process simplifies the process when attempting to evaluate the electrical load profile. The analysis of the load profile can be distinguished as a yearly electrical load profile and is one of the necessary steps in the preliminary study to design and plan an optimized hybrid system (Pabla, 2011)

1.2.2 Photovoltaic Systems

The term photovoltaic is described as direct generation of electricity by solar irradiation with the use of solar cells (Hodge B. K., Photovoltaic Systems, 2017). The solar cells are the energy producing material, which holds critical importance to the photovoltaic overall efficiency to produce energy. Some common materials used as semiconductors include silicon, gallium arsenide, cadmium telluride, indium phosphide, and copper indium diselenide. Intensive research has been conducted to determine material gap energies, dislodgement energy required, and excess energy; all equations which contribute to the overall efficiencies of the photovoltaic cells. Table 1.2-1 displays collected theoretical values and measured values presented by the National Renewable Energy Laboratory (NREL). Recent progression has reported higher efficiencies with the use of a multijunction device however the ability of the conversion efficiency does incorporate increased manufacturing cost (Hodge B. K., Photovoltaic Systems, 2017)

Table 1.2-1: Theoretical/ Measured Efficiencies of Photovoltaic Cells (Hodge B. K., Photovoltaic Systems, 2017)

Material	Efficiency (%)	
	Theoretical	Measured
Si, silicon	28	25
Si (amorphous)	23	14
CdTe, cadmium telluride	29	22
CuInSe2, copper indium diselenide	27	22
GaAs, gallium arsenide	30	29

This information contributed to the overall selection of the module configuration which then combines into the assembled photovoltaic array. The configuration of the solar cells and modules followed electrical principles of direct current circuits in terms of parallel and series arrangements. The necessary system design is composed in series, parallel or a combination both depending on the project necessities of load. Modules were assembled by product manufactures and arranged to product specifications. The specifications provided by the manufacture assisted in determining proper selection of photovoltaic module.

There are various photovoltaic systems that can be separated into two categories of either stand alone or grid connected. For the purpose of this investigation, the focus on stand-alone photovoltaic system initially in the simplest form of a direct coupled system. This system is typically implemented when the project contains low load requirements and the inability to connect to an electrical grid source. This type of system relies solely and is fully dependent on solar irradiation for electrical power generation. Figure 1.2-3 displays the convectional direct coupled PV system. Components of this system include an inverter which primary function is to change direct current to the typical alternating current used generally at the demand load. The key function of the charge controller is to direct the energy output of the PV array to the demand load during electrical generation.

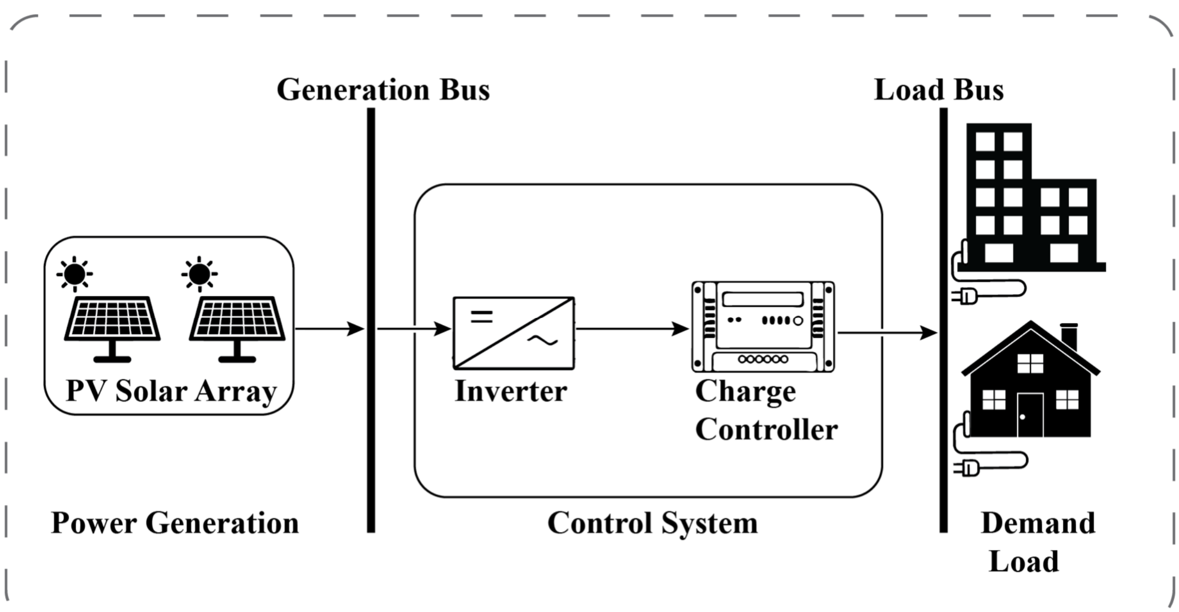

Figure 1.2-3: Direct-Coupled Photovoltaic System Schematic

1.2.3 Photovoltaic System challenges and drawbacks

A present disadvantage of this configuration is the inability to perform without exposure to solar irradiation. This causes the issue previously described of power fluctuations. Without incorporating a secondary source to provide electrical generation during times where solar irradiation is insufficient, the system decreases in its efficiency and ability to function as a stand-alone system. For improved performance, the implementation of an energy storage system is considered for the proposal. This additional portion of the design is critical for the proposed hybrid system, especially when developing a process that implies location a variable in design. Battery components and requirements provided its own set of challenges and are subject to review within the methodology analysis. The incorporation of this system will require additional analysis to confirm feasibility.

1.2.4 Wind Turbine Systems

When referring to the utilization of wind to create energy for power generation, the term is described as wind harvesting (Hodge B. K., Wind Energy, 2017).The fundamental of the wind devices used for this function are categorized into a horizontal axis wind turbine (HAWT) or vertical axis wind turbine (VAWT). These are subject to the plane axis the turbine rotates upon. For the purpose of this research, the investigation incorporates the most common configuration, a two to three bladed HAWT system. The HAWT system is recognized for being suitable for commercial power generation, and more easily implanted regarding size (Hodge B. K., Wind Energy, 2017). The configuration also is determined by upwind and downwind setup, for the purpose of this project the configuration is a design of an upwind system. These features can be observed in Figure 1.2-4 including rotor diameter, swept area and hub height. Typical wind turbine system consists of the base mounted tower, which is connected to nacelle. The nacelle contains critical components such as the gearbox, control and generator subsystems. The rotor, gearbox and generator are all attached by a central shaft. All portions of the system depicted in the figure are incorporated when determining the methodology of the investigation.

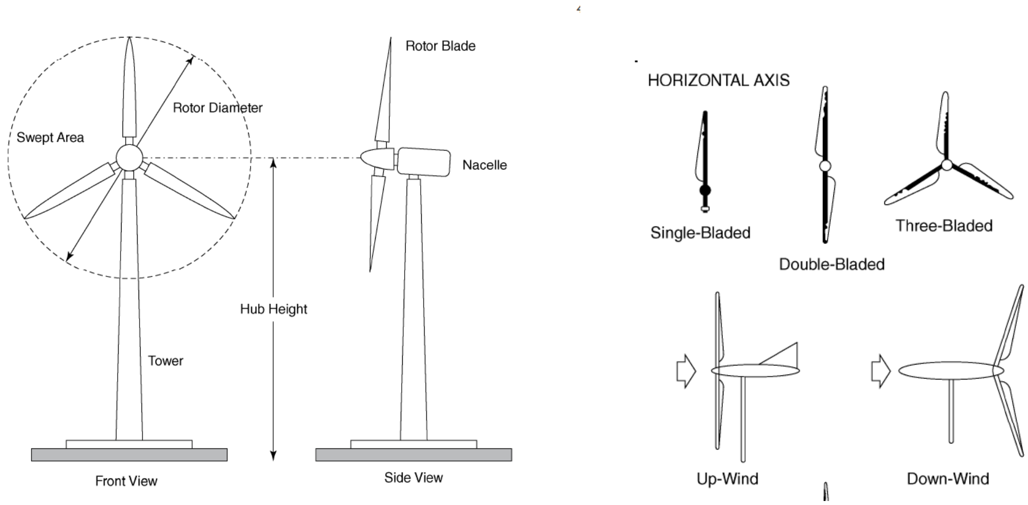

Figure 1.2-4: HAWT Schematic and Nomenclature (Hodge B. K., Wind Energy, 2017)

Several strategies may be implemented when determining the full system of the wind turbine components. These operating functions of the wind turbine is further discussed as the methodology is presented. The primary system of the program to function lies within the nacelle system for generation of power. Key features to acknowledge such as the yaw motor, drive, pitch mechanism is implemented within the turbine to improve efficiency within the control strategies. Similar components are observed when researching the components of power generation transfer to the end consumer. Like the Photovoltaic system, a charge controller is utilized to direct electrical power towards demand load. Typical wind turbine system configuration is seen in Figure 1.2-5 along with an inverter battery, which is also incorporated in this figure. Unlike the direct-coupled PV system, this is a required necessity in a wind turbine system due to the heavy fluctuation of wind speeds. Wind turbines are typically distributed by alternating current, so the primary purpose of the inverter is to give the ability to convert current for energy storage.

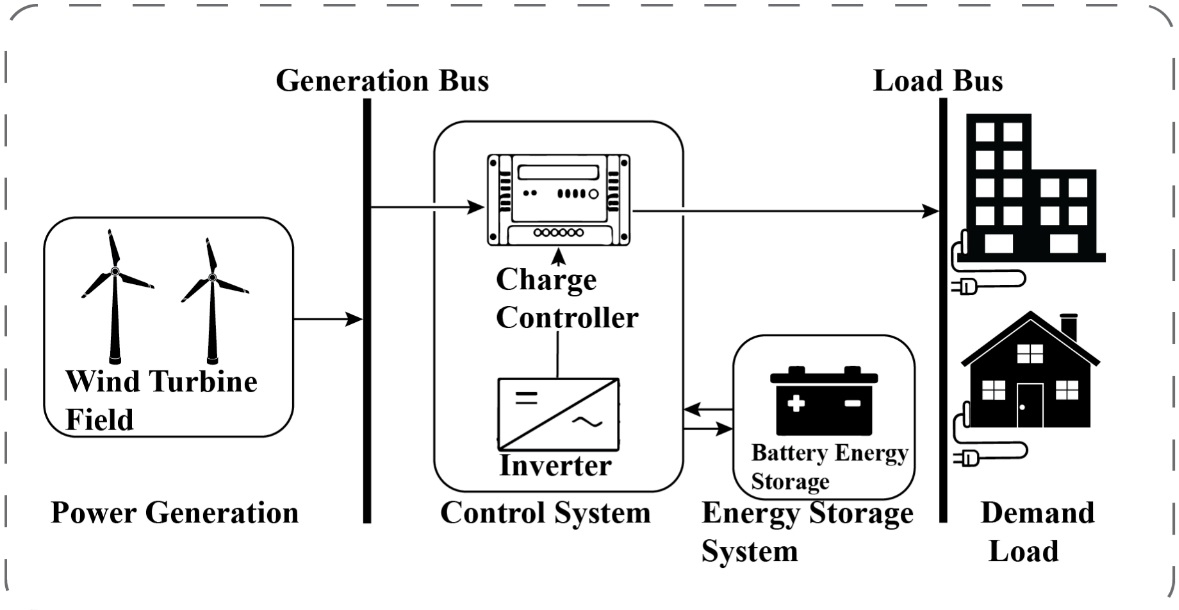

Figure 1.2-5: Wind Turbine System Schematic

1.2.5 Wind Turbine System Challenges and Drawbacks

A common drawback seen previously in the photovoltaic system is the unpredictability in weather and climate conditions of a location. Due to this, the energy storage will be critical portion of the analysis to overcome the difference between supplied energy to the demand load. An additional drawback is the size of the systems. The size of wind turbines ranges extensively based on the load required which causes difficult installation and increased costs. The sizes also cause additional issues as wind fluctuations and interior components of the system may cause additional stress to the tower. Along with the challenges described in the photovoltaic section, the analysis incorporated these obstacles to assure demand, feasibility and capacity is met.

1.2.6 Hybrid Photovoltaic/ Wind Turbine and Energy Storage System

The hybrid photovoltaic-wind turbine energy system is the integration of both renewable energy power generation systems. The combination of the PV-Wind system along with an established energy storage (ESS) holds the ability to improve electrical generation performance and stabilization. The attempt of the system is to provide supporting evidence towards increased efficiency and power optimization by minimizing drawbacks presented in the individual systems. The system described is presented in Figure 1.2-6. The schematic displays the combination of the PV-Wind system within power generation. The energy storage and control system become more intricate with the varying systems. To confront this complexity, an energy management system is required to communicate with stages from generation to distribution. The investigation analyzes the hybrid system of low demand load hybrid PV-Wind energy storage system. Along with this analysis it also investigated a separate similar load photovoltaic system as a comparison reference. Both system results assisted in the pursuit of system development with the overall goal of establishing a stand-alone renewable energy system.

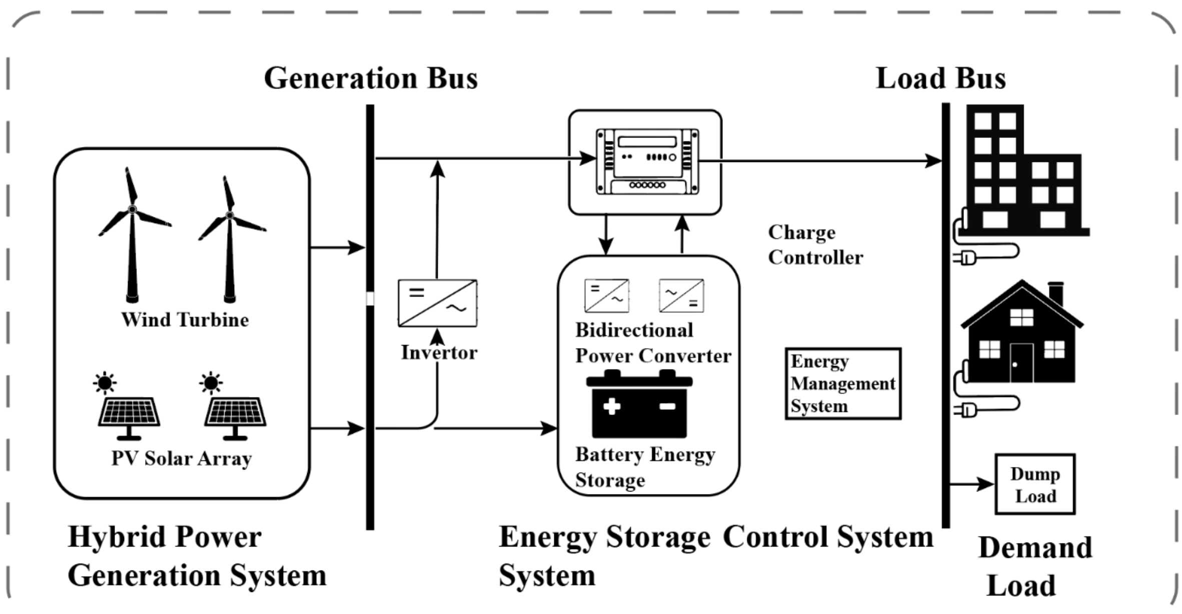

Figure 1.2-6: Hybrid Photovoltaic/Wind Turbine and Energy Storage System

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CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This section provides supportive evidence behind the fundamentals of the investigation presented. The following articles have been researched objectively to provide an overview into the previous and continuing studies related to the topic of the selected hybrid renewable energy systems. The literature review section of this piece has been applied towards the development of the finalized investigation. The subject matter discussed is categorically structured to support the principal aspects established during the design process with the purpose to delineate a sufficient method towards ample results. These concepts of the literature review have also provided practical considerations to the planning and design process. The research available to date has incorporated an array of extensive methods on the approach of implementing the photovoltaic – wind turbine energy systems, and while doing so, a pattern of essential subject topics can be recognized. The study of the literature pieces gives insight into the research in the criteria of energy sources, planning, configuration, modeling techniques, and strategies of optimization.

2.2 Environmental Acknowledgement

Within the conceptual portion of the preliminary assessment, the acknowledgement of the environmental need for the renewable energy system is addressed. This information presented includes both macro and specific micro characteristics that influences the decision to produce a system using renewable energy. Similar to the aforementioned statistical data used within the introductory section, the pieces mention the global aspects that acquired immediate attention of depleting conventional sources of energy. Being the primary motivation to the array of research, attention is placed across sectors of government, countries, regions, and fixed locations to critically evaluate the need and priority of implementation. This can be viewed in large scale movements such as the Energy Roadmap 2050 adopted by the European Union which encompasses the reduction of Greenhouse Gas emissions by 80% in the European energy system as a feasible target (Al-falahi, Jayasinghe, & Enshaei, 2017). This effort has expanded across the technologically advanced region with an increase of photovoltaic power capacity in Italy and Germany holding the largest number of installed photovoltaic capacity and wind turbines (Al-falahi, Jayasinghe, & Enshaei, 2017).

This need becomes exponential in developing areas due to the resource circumstances and the ability to acquire the conventional means of energy. This can be seen in several pieces as they attempt to address the issue of populated areas that are either labeled rural or remote; areas without access to the typical sources of power. A country considered as a location is India, where a large amount of the population lives in what is categorized as both rural and remote (Siddaiah & Saini, 2015). Subsequently, developing countries face a crucial issue as the advancement of the societies correlates with the energy consumption. This scenario is apparent in the country of Malaysia that has spanned over the last few decades. Because of Malaysia's significant economic growth while obtaining inadequate insight into energy preservation, a dramatic increase was noted for electrical energy consumption (Shezan, et al., 2016). Similar circumstances influenced the framework of the presented analysis when determining a location of investigation. The above-mentioned situations have revealed incentives, developing means and current limitations which were taken into consideration and implemented in the formation of the study. Much of the extent of the literature has tended to focus on locations specific to the Eastern Hemisphere. The United States is noted in the progression to implement renewable energies as explained in the preliminary information; however, the research of system integration and optimization of hybrid renewable energies have focused primarily in areas of countries and regions of Eurasia and Africa, with some exceptions. This type of occurrence can be distinguished during an evaluated review of hybrid system case studies. The study incorporated approximately 40 different investigations into the designing of a hybrid system. Of the investigations reviewed, 36 were location specific with only four studies being located in the Western Hemisphere; while two of the four being located in the United States, and the other two located in Brazil (Sawle, Gupta, & Bohre, 2016). Multiple factors may have persuaded researchers to stray away from the United States specifically, which may include the United States being classified a fully developed country with 100 percent electrical connectivity. Other factors may include the private industries investment in the United States and renewable energy implementation. It would seem more plausible to choose a location with higher necessity in order to fully grasp the potential of the autonomous hybrid energy system. Within recent studies this seems to be a common occurrence, which persuades the current investigation of to focus on the area of familiarity and known conditions while comparing that same system method and technique in a juxtaposed area with distinct differences. These findings assist in establishing preliminary criteria involved in selecting a possible location for a renewable energy system.

2.3 Site Evaluation

Central to the discipline of the renewable energy system's preliminary criteria, an emphasis is placed on the potential resource options as they are evaluated. As a means to fully take advantage of the photovoltaic-wind turbine system, the geographical data must be analyzed. Depending on availability, the resources will determine the accuracy of the design incorporated and its feasibility. The evaluation of this site potential differs with slight variations between the studies but holds fundamental similarities. As the preliminary assessment continues to elaborate on the criteria, the location parameters are established. This will include geographical information along with environmental conditions, specifically the meteorological data. The methods of obtaining and evaluating this information depends on site location and the applicable method taken by the researchers. This information may be found difficult to collect depending on the location and level of detail that is attempted to be obtained. Both general public information and detailed private information were used in the reviewed pieces for the foundational data. In this case the information would include the wind speed and solar insolation. In some cases, the renewable resources underwent an additional selection process to determine the most convenient resource for the system. Solar and wind hold several advantages in most cases as they have a higher probability of penetration potential to a site. As established by Madhlopa (Madhlopa, et al., 2015) water holds a vital role in energy production with the conventional and renewable methods. Research has concluded that water consumption and withdrawal find the lowest demand with photovoltaic and wind energy technologies (Madhlopa, et al., 2015). A similar study considers biomass and tidal power energy as potential sources for a site located in Malaysia

(Shezan, et al., 2016). These methods were ruled out as wind and solar resources were found to be more efficient.

For the purpose of the investigation the studies focused on plausible reasons to use a hybrid solar and wind energies. In the prior study of the Malaysia site, the daily wind speed and solar irradiation values were collected from the Malaysian meteorological department by the month in 2009 and implemented in the design. Information availability is a key constraint of a location. The year of the case study previously discussed occurred in the year of 2015 which one could conclude was the most adequate data available for the analysis. Other investigations take different sites to develop and detailed comparison of multiple possible locations with the effort to choose the optimal choice. Al-Masri selected six possible sites in Jordan as candidates for the hybrid energy system in which solar and wind characteristics were compared (Al-Masri & Ehsani, 2016). The provided information was collected by the Energy Center in the Jordanian Royal Scientific Society which the author was able to compare by the monthly averages and choose the best suitable location. Similar information has been more available for global weather data as discussed in a pre-feasibility analysis where solar insolation levels and wind energy potential were illustrated in world maps (Nema, Nema, & Rangnekar, 2008). In another mentioned case, the use of a synthetically generated weather data was used as a method to obtain potential energy values. Arguments have been made in regard to optimization of a system using the data parameters of historical data presented in multiple case studies. Inadequacies have been presented which suggest that forecasted data has the ability to improve the accuracy of the size optimization results (Al-falahi, Jayasinghe, & Enshaei, 2017). Although this may be a valid conclusion, the scope of investigation will increase in complexity for most presented methods. The methods discussed in artificial and adaptive algorithms to be designed and programmed to predict solar and wind data for future occurrence. This type of accuracy would be beneficial if applied when developing large energy system configurations measured in gigawatts, where energy potential will significantly affect the investment.

2.4 System Configuration

The system configuration is set to be the main focus when determining the components' integration. This investigation focuses on a specific combination of an autonomous solar, wind power, and battery storage system. The literature that was researched engulfed various combinations such as the one resembling this system, but also different yet equally complex designs. The articles reviewed included variations which involve the options of grid connection, energy storage, energy assurance strategies, with several configuration layouts. Other components are incorporated depending on energy variables which are derived during the preliminary feasibility study with the purpose of generating adequate power. In the majority of the pieces described, the grid connectivity is dependent on location specifics. The hybrid energy systems selected are considered both off-grid and grid operated systems. If grid connection is a possibility, there are several advantages and benefits that are discovered. As explained by Indragandhi, the power generation sufficiency is corrected when connected to the grid and the avoidance of the renewable energy system inability to provide continuous power is solved (Indragandhi. V, 2017). Additionally, incentive occurs during a surplus of energy as the unused power generated by the system is supplied back to the utility grid for a monetary value (Indragandhi. V, 2017). It has been demonstrated to hold these benefits, however developing the system with the assumption of autonomy will enhance the system's flexibility. This type of flexibility is a necessity in remote and isolated areas as described in the pre-feasibility portion of the review. Researchers have addressed this when referring to the high electricity cost for isolated areas or the inaccessible electrical locations, the optimized system's competitiveness increases as a substitute. (Petrakopoulou, 2016). When designing the hybrid system for the investigation, the goal is to provide enough power to satisfy a given load. The analysis will shortly provide information towards the possibility of grid connection as a general method to be dismissed. Furthermore, within the simulated analysis, the implementation of grid connectivity must be justified by parameters of energy load and price.

Once the general idea of the system is established, the next phase of system design is the configuration of the entire system. This portion of the design occurs typically after the pre-feasibility studies. This configuration is the methodological design for integration of all components of the system. The investigation provides the selected configuration in Figure

1.2-7 in the previous section. In order to fulfill the energy requirements of a distant location, several pieces analyze methods for comparison. The general overview of the hybrid renewable energy configurations can be categorized as DC-coupled, AC-coupled, and Hybrid-coupled (Al-falahi, Jayasinghe, & Enshaei, 2017). The dc-couple configuration incorporates the dc energy resources and ac energy resources being connected to the main dc bus line. Within this configuration, the dc resources have the ability to connect directly to the bus line or using dc/dc power converter which supplies power to dc loads. Similarly, an ac energy resource can connect to the same bus line with the incorporation of ac/dc power converter. In the case of this investigation, the system must also take into context an energy storage system. The energy storage requires a bi-directional converter for the purpose of supply the power to the dc loads (Sunanda & Chandel , 2015). This system is represented in the schematic figure 2.4-1. The next hybrid renewable energy configuration to be described is the ac-coupled configuration. Ac-coupled holds several similarities in the primary design with the exception that the system instead includes an ac renewable energy resource connected to an ac bus line. The dc powered equipment and energy resources will require a dc/ac converter to be properly installed into the system. The differences between the two configurations can be seen by comparing the two layouts in Figure 2.4-1 (Siddaiah & Saini, 2015). Power converter configuration and combination of such, play a vital role for power conversion as they are a necessary component. As Indragandhi indicates, there has been little effort in optimizing circuit configuration but through the process of investigation, general knowledge has been obtained as a means to understand system reliability and efficiency with the effects of cost reduction (Indragandhi. V, 2017). Lastly, the hybrid-coupled configuration is also presented as a possible design layout in Figure 2.4-2. The configuration contains both dc and an ac bus line giving the ability to connect ac renewable energy resources to the ac bus line and the dc directly to the dc bus line.

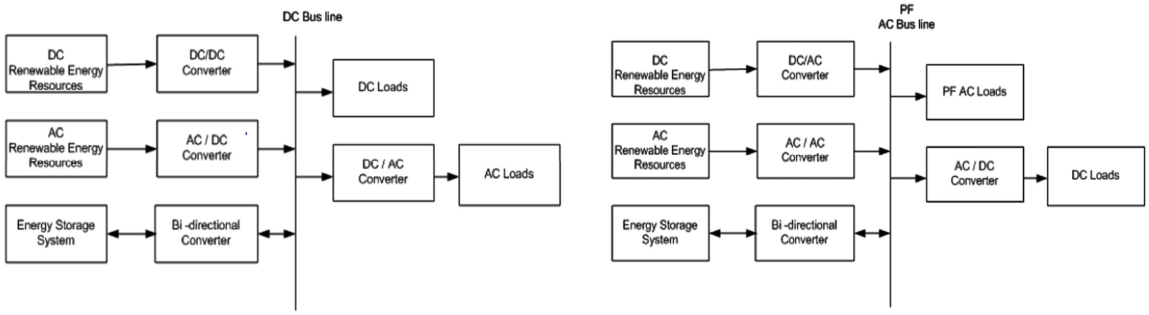


Figure 2.4-1: DC-Coupled and AC-Coupled HRES Configuration

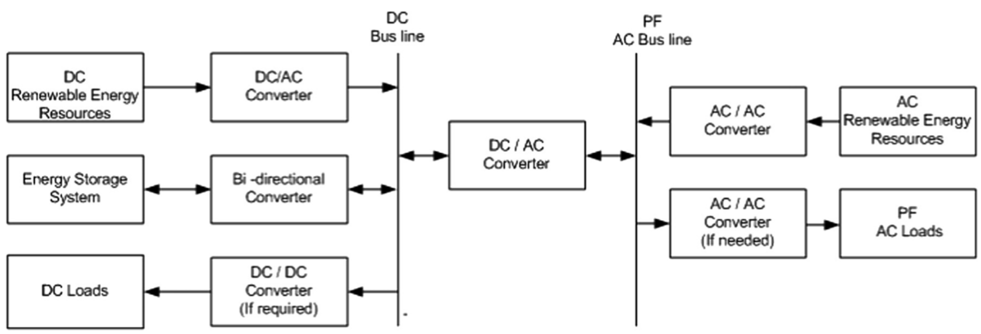


Figure 2.4-2: Hybrid-Coupled HRES Configuration

This type of configuration can assist in the reduction of conversion losses and eliminate the use of the number of converters implemented. Al-falahi has elaborated on this configuration as it combines the advantages of both systems while generating a flexible and cost-effective design (Al-falahi, Jayasinghe, & Enshaei, 2017). System efficiency is increased due to the systems having the ability to connect directly to the respective bus line. Limitations of the study design include the dependency of design, which can lead to complex controls and management. The software programming selected acknowledges the converter constraints and creates a design with appropriate efficiency.

2.5 Modeling Techniques

Each article developed a methodology of the proposed investigated systems to determine measurable results. The evaluation process is detailed in each article to explain the supportive case study. Analyzation and simulation results discovered in study presents adequate evidence and supports reasoning behind the established methods. To ensure the proper design of systems, modeling techniques are utilized in these methods. With proper designing and analysis of a mathematical representation of a system, changes to the system and variables are observed. Optimization techniques are carried out in several ways and are classified into different categories such as classical, modern, and software tools. With these methods being heavily researched and studied, the results delivered have been promising. With doing this, the results can help determine the best system globally and have better accuracy in finding an optimal set of solutions as well as find the best performance with the least amount of cost.

Classical techniques include iterative, analytical, numerical, and graphical construction methods. Most of these classical techniques use single algorithms with single objective optimization functions, to find the optimal solution that corresponds to both the minimum or maximum value defined by the function. (Al-falahi, Jayasinghe, & Enshaei, 2017). Single algorithms use techniques such as both classical and artificial to solve for size optimization. Despite classical techniques being commonly used, they are not the most efficient in solving complex problems, therefore, more modern techniques based on meta-heuristic algorithm are used more extensively (Al-falahi, Jayasinghe, & Enshaei, 2017). Iterative methods generate approximate solutions for problems using mathematical procedures and are often utilized from the beginning to assist with designing and optimization. With iterative methods, more computational efforts are necessary, and the process ceases when the best configuration is achieved (Sunanda & Chandel , 2015). Classical techniques also use analytical methods that are based on theoretical methods and mathematical analysis as well as calculations. Unlike numerical methods, the analytical methods are more complex as they follow a clearly defined set of steps as a means to achieve the solution that is needed, whereas the numerical method doesn't require a specified procedure to follow to be able to achieve a set of solutions. Graphical techniques are designed to be basic and easy to understand methods with little to no complexity. Although easy to use, because the technique isn't as flexible as others and are based on various approximations, it's not currently used (Sunanda & Chandel , 2015). While classical techniques use single algorithms, modern techniques solve problems by utilizing both single and hybrid algorithms. More specifically, artificial single algorithms are utilized to provide competent solutions while needing less time to compute (Al-falahi, Jayasinghe, & Enshaei, 2017). Due to this, modern techniques can provide more accurate results while being more flexible with solving complex optimization problems. thus, becoming more popular than classical algorithms. Artificial intelligence techniques take the applications the engineering components to create intelligent computer programs. Researchers implemented these programs to solve size and cost optimization programs in off-grid hybrid energy systems. Because of this, AI techniques yield the best results for optimization. Modern methodology also has seen a trend increase in using the hybrid algorithm technique in place of a single algorithm because of their ability to provide more accurate optimization results. Hybrid algorithms are a combination of two or more single algorithms, and it has the advantage of having complementary optimization problems (Al-falahi, Jayasinghe, & Enshaei, 2017). Majority of the techniques, however, require intricate coding which may lead to input variable effects. Due to this, several modifications are needed, some that are conflicting in nature, which tends to increase the complexity of the design (Siddaiah & Saini, 2015).

Multiple software tools are essential to help run the proper simulations. A known software is Hybrid Optimization Model for Electric Renewables, typically referred to as HOMER. With this program, prior meteorological data can be used to conduct optimization based on the site location. The program also has a more advanced version, HOMER Pro, which allows the user to use an advanced battery, and other sources while also having the capability to connect with software such as MATLAB. HOMER is a popular and widely used software program, and has many advantages, such as the results obtained being detailed for analyzing and evaluating. It also helps to find all possible combinations and is fast at evaluating real and complex combinations. However, this program's capabilities are limited due to it only performing a single-objective optimization by limiting the input variables. The other software program, Hybrid Optimization by Genetic algorithm or iHOGA, is also used for sizing stand-alone component, economic, and constrained resources, optimization can be conducted. It can also perform analysis for the buying and selling of electric energy when the hybrid system is connected to the utility grid. This program considers a large amount of information while performing optimization. However, the program does have disadvantages in comparison to HOMER. For example, iHOGA takes longer (1 hour) to run a simulation while HOMER takes a shorter time to evaluate equally complex iterations. iHOGA also requires internet connection when starting the software and only 10 kWh total average daily loads are permitted (Abishek, et al., 2018). Due to the investigation, the requirements necessary are best suited by utilizing the HOMER software program to simulate a hybrid algorithmic process for the evaluation.

2.6 Case Study Methodology/ Evaluation Criteria

Four article cases are discussed in depth which pertain to the integrated hybrid photovoltaic-wind turbine systems. The systems parameters vary regarding the components and experimental parameters; however, the essential goal is to provide reliable energy through the reported constraints. In the initial case study, the renewable energy system is composed of a solar photovoltaic wind turbine hybrid system with the incorporation of a hybrid energy storage system, which is designed to be connected to microgrid (Umer Akram, 2017). The second case follows the utilization of a photovoltaic array and wind turbine plant integrated with advanced power management controls and assumed to be connected to provide energy to a main utility grid (Indragandhi. V, 2017). The next case described is designed with a hybrid concentrating solar and wind power plant combined a thermal and electrical storage system (Fontina Petrakopoulou, 2016). The final case researched involves retrofitting an existing utility grid with the power generation of the hybrid photovoltaic-wind turbine system (Ehsan, 2016). Each article developed a methodology of the proposed investigated systems to determine measurable results. The process of evaluation is elaborated within each article to explain the supportive case study. Analyzation and simulation results discovered in study present effective evidence and support reasoning behind established methods.

The process of approach Umer focuses on optimizing a power generation microgrid by utilizing hybrid wind turbine Photovoltaic and battery energy storage integrated supercapacitor systems (Umer Akram, 2017). The method attempts to utilize the characteristics of the components to determine the beneficial aspects of each portion. A distinct difference from the process compared to the counterpart studies involve the incorporation of hybrid integrated storage system. The implementation of a supercapacitor within the battery energy storage system is a feature theorized to improve efficiency and lifetime of the energy storage system (Umer Akram, 2017). The system is separated into subsystems which are individually designed to function at the highest optimized potential once integrated. The methodology then addresses realistic obstacles with the objective to create a system to three primary goals of cost minimization, reliability, and the response to greenhouse gas emissions.

The methodology discuss by Indragandhi initially relies on analytical studies of the Photovoltaic/ wind-based power generation (Indragandhi. V, 2017). The ideal system selection discussed within the piece are taken from the historical data collected internationally. This information is then categorized as potential challenges that may arise when developing the study. The primary portion of the study uses an analytical process of comparing various configurations with the purpose of distinguishing the process of selection. These processes determine the overall options for power conversion then power control determinations further researched to optimize power generation. The Several systems are compared however, for this topic the section regarding energy management for stand-alone systems is prioritized for research purposes. This portion of the study introduces a power management algorithm which provides technological assistance towards consistent power generation for a remote structure (Indragandhi. V, 2017).

The following review uses a methodology that gives mathematical representation on the factors involving the energy analysis. The primary tool used to analyze the thermodynamic systems is defined as Exergy. Exergy is explained in this piece as a measured theoretical value that displays a system's maximum useful work. For this value to be obtained, the system is set to the equivalent of the environment (Fontina Petrakopoulou, 2016). The methodology is formed around initial assumptions of a stand-alone hybrid concentrating solar- wind turbine system with the goal to reach energy independence. The system analysis incorporates the exergy functions to discover the inefficiencies during the design and planning process. This process is intended to locate the irreversibility factors a system contains. This methodology relies heavily on the simulation software to provide the results of the system components.

Within the fourth case study the methodology was designed to determine the overall feasibility of implementation in an existing utility system. The selection of the photovoltaic-wind system was determined based on the reliability of the resources. The methodology separates the portions of focus into analysis of the system plant, and site analysis to determine the possibilities of the system components (Ehsan, 2016). This method is similar to case study 1 and addresses the realistic obstacles with the objective that ensures validity to the investigation. Two methods are explored to size the components of the system, the first being a numerical iterative analysis followed by and analytical modeling process. The correlation between both approaches is to assure the study contains the best optimal solutions regarding system information and other external factors that may alter results.

The process established is tested on realistic world data based on solar, wind, and demand load information collected. The information provided within the case studies differ in these variables due primarily to the geographic information of the designated location. The collection of information gathered is indicated within the initial parameters of the thesis. The first case study reviewed selected Dammam City, in Saudi Arabia. The second study however takes a broader approach and observes the activity of implementation internally. The systems listed in the projects consists of power generation loads of tens of kilowatts to some as hundreds of megawatts. The location of the projects primarily resides in the western hemisphere with majority in Asia. The following study's primary focus is providing autonomous energy on an island located in the Mediterranean area. The island chosen was the Greek island, Skyros. This location was selected for the study due to the environmental potential and economic circumstances regarding existing electrical costs and future financial opportunity. The final case study examined focused its site selection in the area of Jordan in the Middle East. A part of the methodology previously discussed incorporates discovering the most suitable site base on the environmental features.

Within the scope of the literature, several aspects of hybrid renewable energy system designed has the section as areas of focus. Within the investigation the areas in which the investigation attempts to address is the acknowledgement of conventional system substitution. Secondly, this will involve the incorporation in a region less explored compared to similar literature reviews. Continuing with the investigation the approach has established a method to incorporate both a numerical and software simulation to decreases program error and increase accuracy in optimization by cross referencing.

CHAPTER 3: OBJECTIVE/METHODOLOGY

3.1 Introduction

The objective supports the process of investigation to supply continuous power of a renewable energy system. The research investigated the advanced design of the following two concepts:

- Solar photovoltaic and Wind Turbine system Analyzed separately at 100 kilowatts
- Combined alternative energy system with varied shared percentage to equate 100 kilowatts

The system underwent a set of numerical and analytical investigation in order to compute sizing and configuration of components. Both systems were then modeled and analyzed based on the realistic constraints set by Michigan's geographical, climate and weather conditions. Once this objective is reached, comparison between systems and an additional comparison of a referenced location using the simulation process is conducted. From this investigation sufficient results were formed.

3.2 Initial Approach

To develop the most effective results, the system in its entirety has been evaluated in the individual components. This process will ensure maximum optimization in each element which in turn should provide supportive evidence to the overall solution. The methodology will provide the descriptions of the several components along with calculation models and analysis software of sizing and evaluating of elements. To further elaborate on the methodology of the investigation, the components will be establishing the given system selection and configuration. Concepts listed under Feasibility Criteria for PV-Wind Hybrid system have undergone an economic analysis and conduct a high-level assessment of performance and cost parameters. The following section to be further established in the methodology are as follows:

I) Pre-Feasibility Site Analysis

- Solar Energy Resource
- Wind Energy Resource

- Electrical Load Demands

II) Component Configuration/Sizing

- Solar Energy (Photovoltaic) System
- Wind Energy (Wind Turbine) System
- Hybrid energy system Components
- Batter Energy Storage and Conversion Criteria
- Initial Numerical System Optimization

III) Modeling of Hybrid Renewable Energy System Components

- Modeling of Photovoltaic System
- Modeling of Wind Energy System
- Modeling of Battery System

IV) Feasibility Criteria for PV-Wind Hybrid System

- Reliability Analysis
- Cost Analysis
- Sensitivity analysis

Throughout the Investigation several models and software tools were utilized for the evaluation of the system. Each section will address assumptions, equations, and methods used to analyze the discussed information. This approach was determined by the extensive research and conclusions derived from general subject knowledge and the literature review. Below are brief descriptions of the software used to establish the data provided in the investigation.

Cove.tool: Cove.tool is an automated 3D performance platform that was implemented during the site analysis investigation. Climate information and graphics are referenced.

NREL: The National Renewable Energy Laboratory is a public source of information which includes solar and wind information. This source was used as the primary source for the site parameters.

Microsoft Excel: Excel was employed as the primary software for the numerical analysis throughout the range of the investigative analysis. The software was used to provide values and figures to support the study.

Adobe Illustrator: Illustrator is a graphics editor and design program which is applied to create graphics and diagrams for supportive understanding.

Revit: Revit is a building information and modeling (BIM) software which was implemented in the design process for component specifications and configuration as an asset to system optimization.

HOMER Energy: Hybrid Optimization of Multiple Energy Resources (HOMER) Pro is a microgrid software that was used to develop the finalized optimized system by incorporating the finalized parameters of the system.

3.2.1 Geographical Location

The autonomous photovoltaic-wind turbine battery storage system is designed to perform in the specific subjected location. The investigation incorporates a site in Michigan, United States as the initial location for analysis. There are numerous reasons for selecting a location in Michigan, one primary reason is the researcher's accessibility to site evaluation, familiarity, and data. As discussed during the review of previous literature, detailed site information varies based on location. Selecting this location gave additional certainty of current information to be applied to the investigation. The following information is the available landscape site ad set as the designated geographical location:

Primary Location

Lot Address: 41787 Grand River Avenue, Novi, Michigan 48375, United States

Coordinates: 42° 28’ 50” N, Longitude 83° 27’ 60” W

Elevation: 273 meters

Approximated Acreage: 26.5l

City Population: 60,014 Growth: .652%

Location Classification: Community

Figure: 3.2-1 Site Location Image

Several software tools were used to evaluate this specific site location. Figure 3.2-1 displays the physical two-dimensional site view highlighted in yellow. The information given describes the general site information including coordinates, elevation, and site footprint. Information also included is the city population, growth rate and location classification. These additional characteristics will be incorporated as the investigation continues to assist in classifying the electrical load needs and economic parameters.

3.2.2 Solar Insolation

This study builds on the accurate collection of solar information. The attempt is to increase the efficiency throughout the design process and minimalize error. To grasp an understanding of the solar position an effective method is to calculate the solar path based on the investigative factors. The solar path is calculated with respect to the location on the Earth while considering the Earth and sun's relationship geometrically. Two angles, the solar altitude angle and solar azimuth angle, are examined in regards to determining the effect of the solar potential energy. The aspects of the sun path are applied when configuring the angle of incidence in the design process of the photovoltaic systems. A characteristic to note when analyzing the solar information is the 120 degrees of 240 degree change in position sun azimuth angle during the time span of 11:00 A.M. to 1:00 P.M (Hodge B. , 2017). Both angles are functions of locations latitude, solar hour angle and the solar declination. The solar declination angle is made between a ray of the Sun, when extended to the center of the earth and the true equatorial plane.

$$\delta = 23.5 * Sin\left[\frac{360}{365}(284 + n)\right] \quad (1)$$

Where:

n=day number (Jan 1^{st} =1)

$$h = 15(AST - 12) \quad (2)$$

$$AST = LST + \frac{ET}{60} + \frac{4(L_O + L_S)}{60} \quad (3)$$

LST= local Standard Time (Decimal hours)

ET= Equation of Time Adjustment (In Minutes)

Ls=Longitude of local standard time meridian (In degrees)

Lo=Longitude of the site measurement (In degrees)

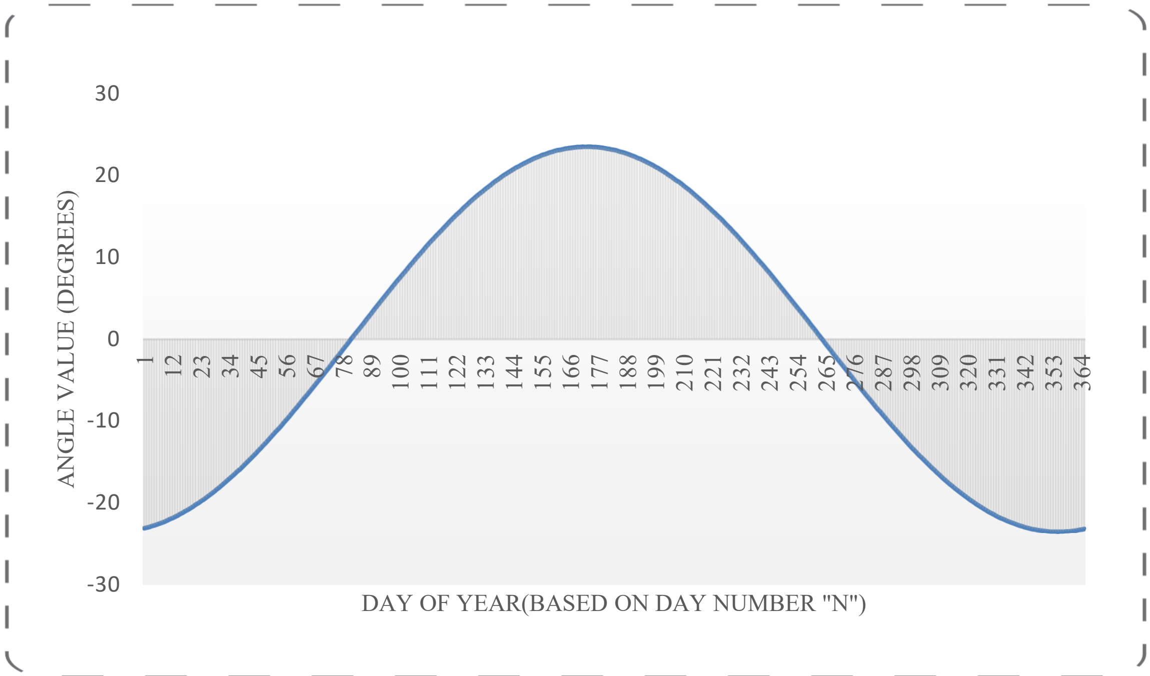


Figure 3.2-2 Solar Declination Angle Variation

The meteorological data was collected from the National Solar Radiation Database (NSRDB) provided by the National Renewable Energy Laboratory (NREL). The data was an accumulation of half hourly values of the site location. This source of information is essential for solar energy applications such as sizing the solar energy equipment. The values provided include solar radiation measurements such as the global horizontal, direct normal and diffuse horizontal irradiance. This set of information has also included the climate conditions as it plays a role in systems efficiency. The NSRDB has collected over 40 years of the meteorological data from National Weather Service sites, one being located in within a 50-mile radius of the selected project site. With using the data provided by the NREL, the primary investigation contains its validity with the variable parameters. The secondary investigative location will implement the NASA insolation database for the simulation comparison. Solar information provided by the NREL utilizes the typical meteorological year data, which represents the median weather conditions over a multiyear period (U.S. Department of Energy, NREL, 2020). For this investigative analysis the most current available year from NSRDB is 2020. With the attempt to increase the accuracy of the solar irradiation, the incorporation of forecasting estimation method was implemented. Several studies have revealed that forecasted meteorological data improves the results of optimization (Al-falahi, Jayasinghe, & Enshaei, 2017). The results were derived using a statistical modeling method with Weibull distribution and probability functions. The process includes collecting the direct normal, diffuse horizontal, and global horizontal irradiance. These variables can be calculated and are expressed as Equation (4 - 7). The data formed employs the year half hourly data obtaining over 52,000 values for each year from the previous five years. These values are then placed through a mathematical modeling using Microsoft Excel which determines the percentile growth, deviation, margin of error in the effort to determine the regression of the data set. Using the modeled functions of the observed data the excel program was able to extrapolate a set of irradiation values and produce an estimated data set for the year 2022.

$$I_{Total} = I_{DN} + I_{DH} + I_{R} \tag{4}$$

Where:

I_{Total}= Total incident irradiation

I_{DN}= Direct Normal Irradiance

I_{DH}=Diffused Irradiance

I_{R}= Reflected Irradiance

$$I_{dir} = \frac{A}{e^{B/sin\beta}} \tag{5}$$

Where:

A= Apparent Solar Irradiance

B= Apparent Optical Attenuation factor

β = Solar altitude angle

$$I_{dif} = C * I_{dir} * \frac{(1+Cos\Sigma)}{2} \tag{6}$$

Where:

C = Sky Diffuse factor

Σ = Surface Tilt Angle

$$I_{ref} = I_{dir}(C + Sin\beta) * \rho_g * \frac{(1-Cos\Sigma)}{2} \tag{7}$$

Where:

ρ_g = Ground Reflectance

The preliminary investigation includes site and geographical analysis of the location presented in the study. Several studies indicate the Midwest region in the United states provides optimal conditions (Hodge B. , 2017). With this initial information, a climate analysis was conducted to review general solar condition of the location. The equations analyzed can be visually represented by the sky segment radiation. Figure 3.2-3 displays the radiation study in order to view site potential. These figures will assist in indicating the location of photovoltaic panel placement. The figure titled "Radiation by Sky Segment", graphs a map of the radiation potential of the site to show the intensity of the direction and solar radiation annually. The diagram which also known as the radiation dome, developed by Cove Tool, archives in segmented form the sun angle and solar intensity from the sun on a area. This radiation dome will attribute to the process of determining orientation of system components and flexibility of orientation.

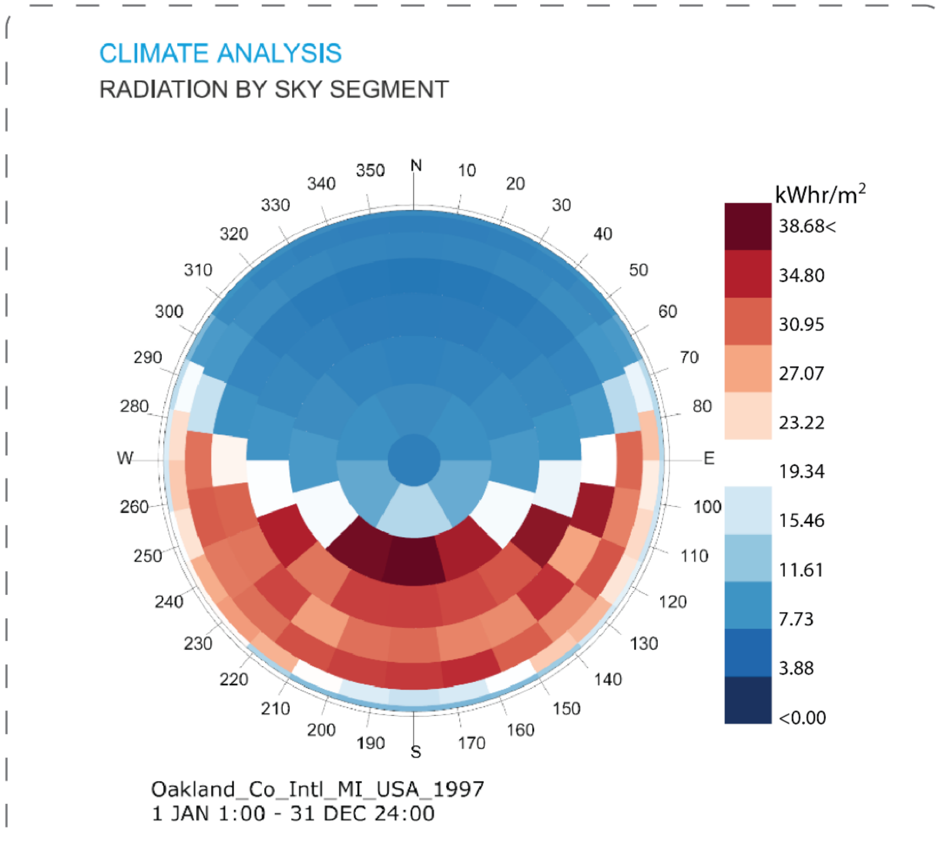


Figure 3.2-3: Radiation by Sky Segment

Data collection of solar information is critical to determining accurate system sizing to meet the demand load. Forecasting the solar data assist in the optimization of the final results of the investigation. The preliminary pre-feasibility analysis has been incorporated with the numerical portion of the analysis. During the simulation the NREL information is utilized for optimization purposes.

3.2.3 Wind Analysis

The following section presents a description for wind power as renewable energy source in terms of the potential by utilizing the wind direction and speed. As discussed in the Solar section of the methodology, the data for wind speed and direction was provided the National Renewable Energy Laboratory (NREL). This data is an accumulation of half hourly values of the site location. This information collected are contributive factors of the design optimization of the wind turbine's size and configuration. These frequencies were determined and categorized into their respective attributes. With the evaluation of the abovementioned parameters, the annual accumulated monthly frequency of winds individual was determined. Furthermore, the data observed includes the average hourly and monthly wind frequencies and speed at the initial reference height of 10 meters.

The Wind analysis envelops wind intensity and direction at a given location. The Figure 3.2-4 displays monthly graphs of the results from the investigation in Michigan. The hours of wind speed are also reflected in the size of indicator. The composed data was derived from the National Renewable Energy Laboratory (NREL), which collects wind information to develop an annual average wind power density (Draxl, 2015).

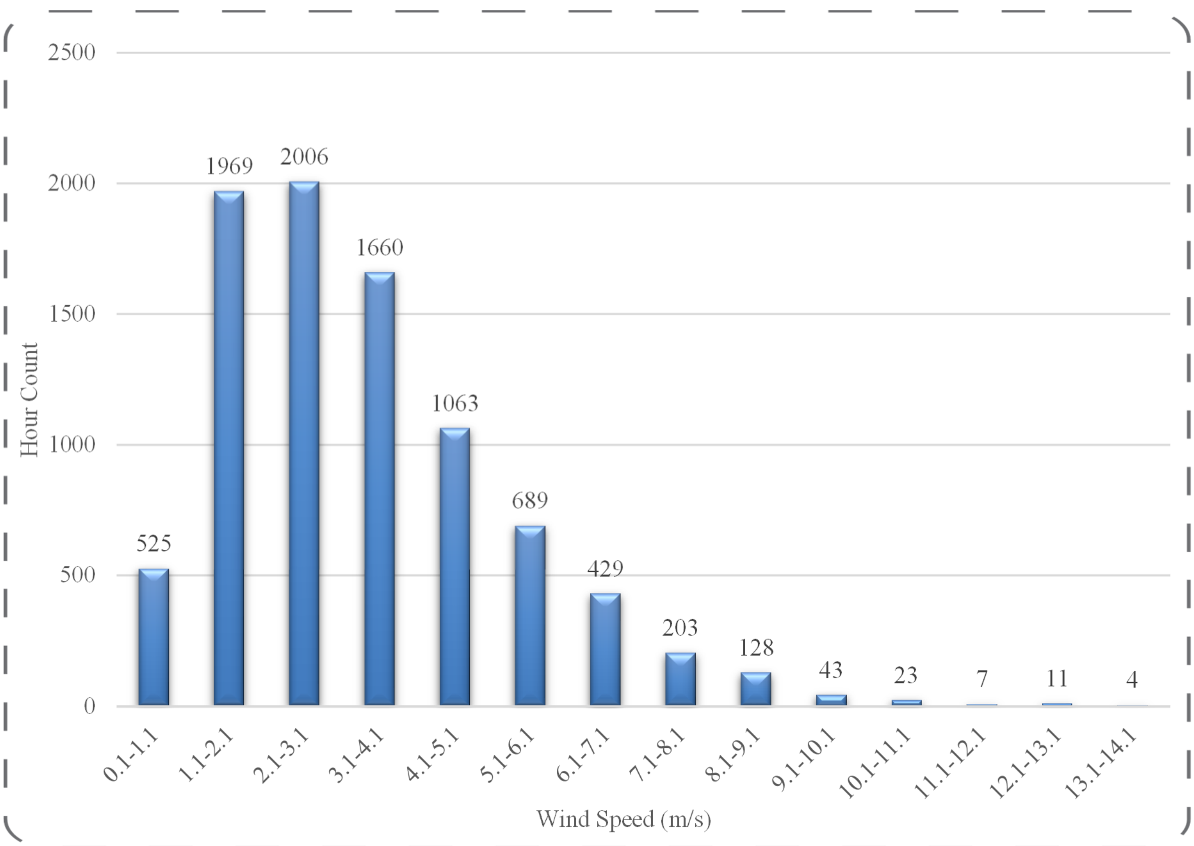


Figure 3.2-4: Hours per Year at Wind Speed (Vi) at 10 m Height

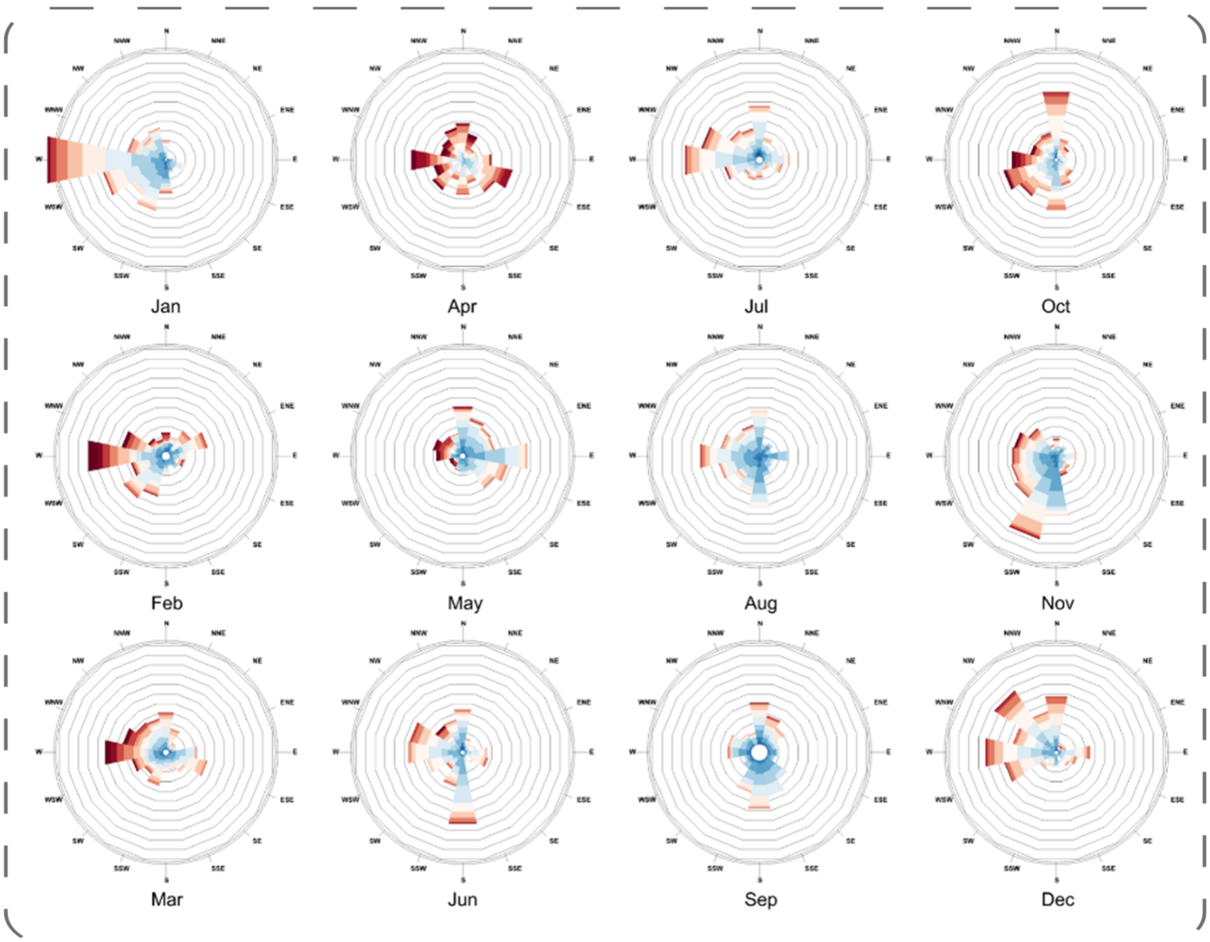


Figure 3.2-5: Monthly Wind Analysis

Harnessing wind energy incorporates fluid dynamics as the mechanical power generation by converting the kinetic energy of the wind. Since kinetic energy can be defined as a source of air with mass moving at specific speed, the power equation can be established as Equations (8-10). The power in the wind equation demonstrates the available power is proportional to the swept area by wind turbine and cube of the wind speed. The swept area also contains a proportional power-available relationship. Typically, when wind power data is presented, the air density and temperature is assumed at industry default. Since air density effects power in the wind, essentially power is dependent on the atmospheric pressure and temperature. Determining density than must take into consideration a temperature and altitude correction to estimate wind power above sea level. This equation is represented in Equation (11). The height at which the analysis is evaluated will impact the wind speed. A relationship with the wind speed calculated at an initial reference height is used to determine wind speeds at higher elevations. This correlation can be indicated with relative power seen in Equation (12) with respect to roughness of the earth's surface. The equations discussed in this section is further expanded within the sizing methodology section.

$$P_A = \frac{Energy}{Time} * \frac{1}{2}(\dot{m})v^2 \tag{8}$$

$$\dot{m} = \rho A v \tag{9}$$

Combining the equations, the power in the wind is derived:

$$P_W = \frac{1}{2}\rho A v^3 \tag{10}$$

Where:

P_W= Power

ρ = air density (kg/m^3)

A= Cross Sectional Area(m^2)

v= Wind speed normal to A(m/s)

$$\rho = \frac{353.1e^{-\frac{.0342z}{T}}}{T} \tag{11}$$

Where:

T= Temperature (Kelvin)

Z= Height/Elevation(m)

$$\frac{P}{P_0} = \left(\frac{\frac{1}{2}\rho A v^3}{\frac{1}{2}\rho A v_0^3}\right) = \left(\frac{v}{v_0}\right)^3 = \left(\frac{H}{H_0}\right)^{3\alpha} \quad (12)$$

Where:

v= Wind Speed at Height (H)

v_0= Wind Speed at Height (H_0)

α= Friction Coefficient ≈ 1/7

The wind Frequency of the location is of primary importance as it used to determine not only the direction but commonality of wind speeds. This is directly implemented in the selection of the wind turbine as it assists in the aspects in selection based on speed characteristics of the system. The wind speeds determined during the investigation are assumed within accuracy as it was able to conform to the Weibull distribution formula and the probability distribution function given in Equation 13. The calculated frequency of the wind speed annually is displayed in Figure 3.2-6. With the collected and analyzed wind information the investigation concluded that an adequate amount of wind resource is available at the specified site for the size of the investigated system.

$$f(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} e^{-\left(\frac{V}{k}\right)^k} \quad (13)$$

Where:

k = Shape Parameter

c = Scale Parameter

v = Wind speed

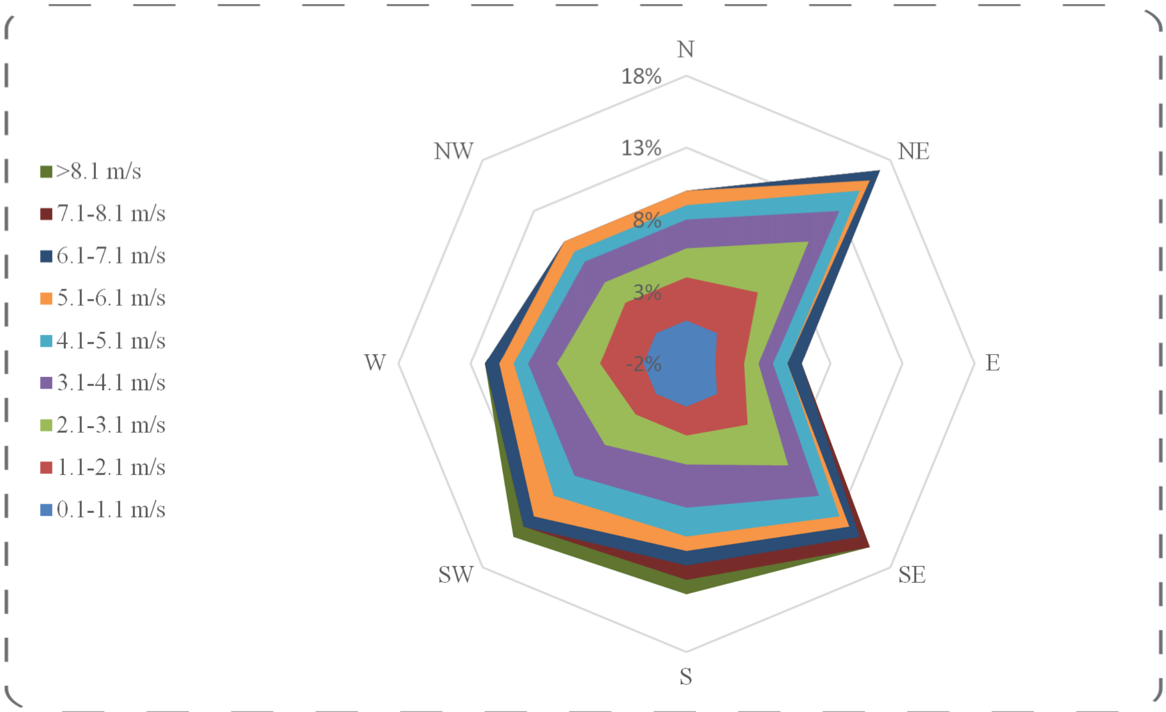
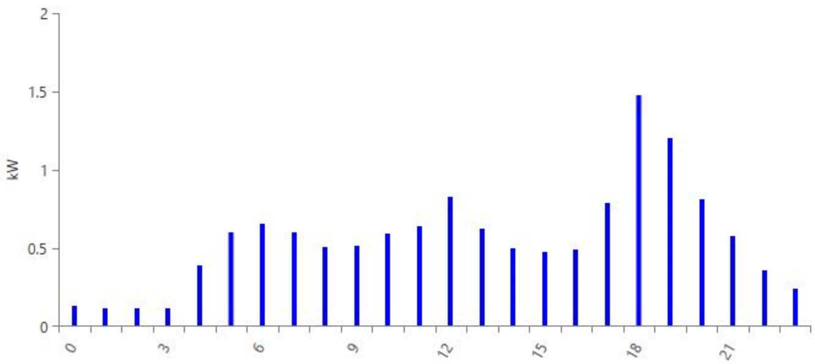


Figure 3.2-6: Wind Rose Plot Annual Direction Frequency

3.2.4 Electrical Load Profile

The investigation of the selection, size and optimization incorporated a mixed method approach which involved numerical calculation and software simulation. Hybrid Optimization of Multiple Energy Resources (HOMER) Pro and Microsoft Excel were the primary programs utilized in the sizing, optimizing and analysis of the established system. For the purpose of the investigation the electrical load profile was established in order to be a measuring point of reliability. The developed structure of the investigation consists of utilizing the preliminary analysis and HOMER's software's database as supportive tools during the initial computation established in Excel. The Forefront the calculations in regard to the size of the solar, wind, energy storage systems are carried out. Firstly, the size of solar photovoltaic system that is required to satisfy the load demand which is calculated throughout the year is determined. This process than integrates the use of the wind turbine technology as a power distributed relationship as a sharing percentage between the two renewable energy systems. The system classification has established a 100 Kilowatt Photovoltaic-wind turbine and battery energy system which attempts to satisfy a span of residential and community loads. Figures 3.2-7 – Figure 3.2-10 display the electrical load profiles for both residential and commercial locations. The residential load was calculated based on the national monthly and annual average for residential electrical consumption of households (U.S. Energy Information Administration, 2020). The annual averages were then extrapolated using Excel's linear fitting regression method in order to find the growth percentage based on the electrical consumption from historical data over the past decade (Pabla, 2011). The community source has taken a similar approach with information collected from the U.S. Department of Energy Database for commercial reference buildings (EERE, 2020). The load daily profile for both residential and community style buildings are established in Figure 3.2-7 and Figure 3.2-9. These figures display the seasonal and typical daily profiles and are derived from the hourly breakdown of load consumption. Analysis of the profile displays a peak value in January with a daily average of 22.8 kWh. The initial sensitivity variable is implemented as load fluctuation is addressed with random variability function as 10% day-to-day and 20% timestep as a means to confront the randomness often occurring in electrical consumption. Similarly, the community contains a load profile with same variables but contains a random variability function of 30.4% day-to-day and a 33.45% timestep. In this case the selected community style building represents a 5,500 square foot structure, with the represented parameters of small office obtain from the OpenEI database (EERE, 2020).The office electrical load contains a peak month in June with annual average of 178.47 kWh/day. Both profiles are applied to the analysis separately to determine the system's capability on each building type.



Metric	Baseline
Average (kWh/day)	22.8
Average (kW)	0.95
Peak (kW)	4.69
Load Factor	0.2

Figure 3.2-7: Residential Electrical Load Daily Profile

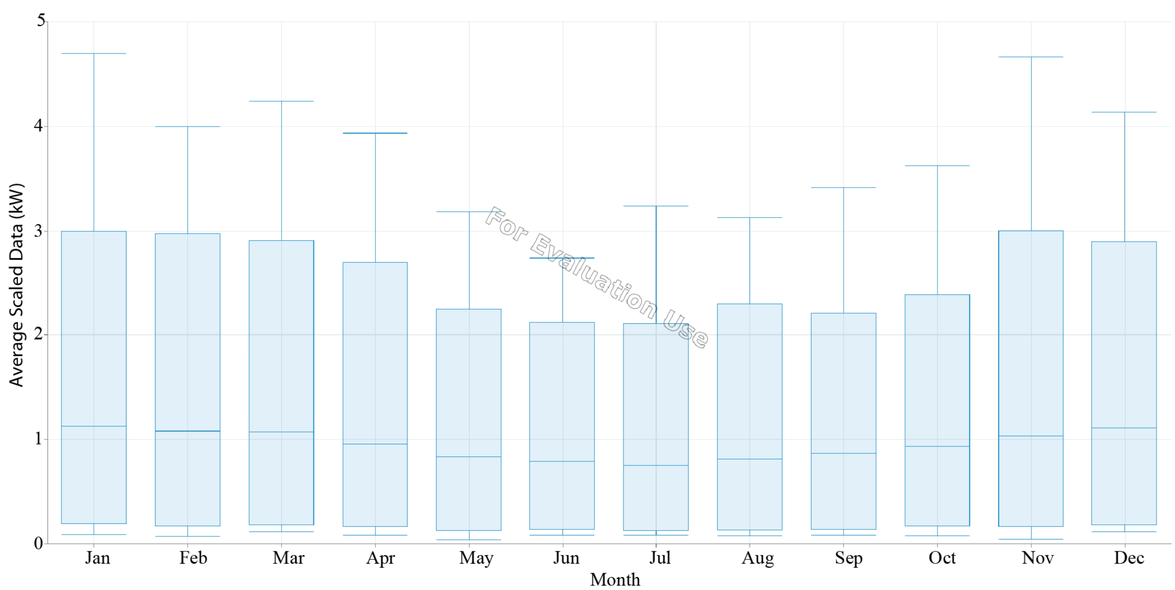
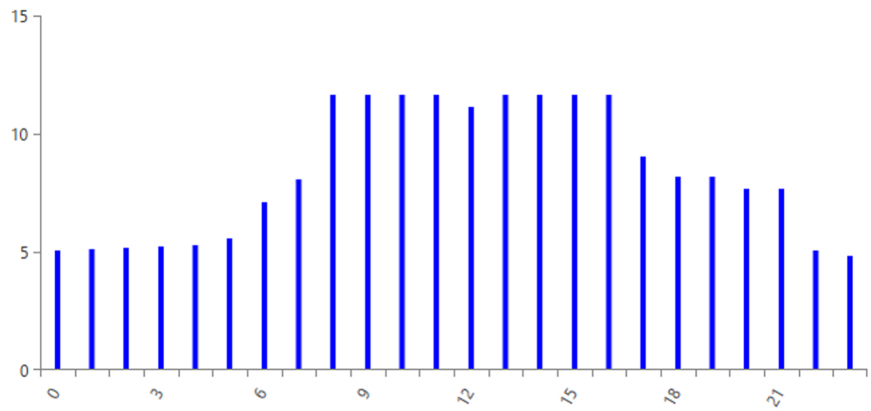


Figure 3.3-8: Residential Electrical Load Seasonal Profile



Metric	Baseline
Average (kWh/day)	178.47
Average (kW)	7.44
Peak (kW)	19.38
Load Factor	.38

Figure 3.2-9: Community Electrical Load Daily Profile

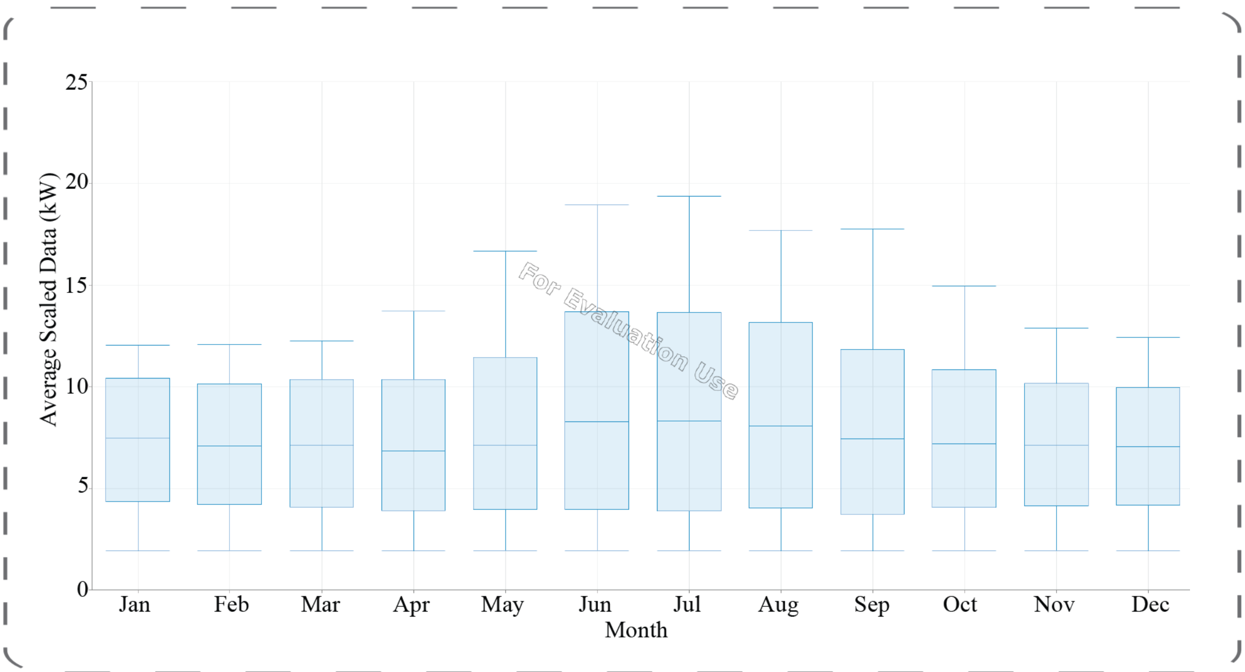


Figure 3.2-10: Community Electrical Load Seasonal Profile

3.3 Numerical Analysis

3.3.1 Component Selection

For analysis purposes, the photovoltaic module and wind turbine were selected during the design investigation. Both components are representative of current technological characteristics and features available in the renewable energy systems. The system specifications are seen in Table 3.3-1 and Table 3.3-2. The tables display parameter values tested under standard test conditions and are used to determine the energy produced. These values correspond to a single piece of renewable energy equipment. As the EO cycle parameters display the value of a single wind turbine whereas the TallMax M+ displays the values of a single photovoltaic panel. The power output for both the PV system and WT system were calculated based on a single component than determined as cumulative function of the entire system.

Table 3.3-1: Photovoltaic Module Specifications

System Parameters	
Model Type	TallMax M+ 490
Cell Type(kW)	Monocrystalline
Rated Output(kW)	0.49
Open Circuit Voltage (Voc)	43.4
Short Circuit Current (Isc)	14.07
Vmp	36.5
Efficiency	20.8
Panel Area	2.35 m^2

Table 3.3-2: Wind Turbine Specifications

System Parameters	
Model Type	E0 10 (EO 25)
Rated Output(kW)	11.5
Rotor Diameter(m)	12.6
Number of Blades	3
Swept Area	125.1
Cut-in Wind Speed	2.75
Cut-Out Wind Speed	20

3.3.2 Photovoltaic Sizing

The foundation of the photovoltaic sizing and configuration is based on the solar radiation that was discussed in the Solar Insolation section. These values were then incorporated with the continued calculation of Total Solar radiation of the site. Equation (14) calculated the amount of total radiation incident on a surface at a given time. For the purpose of the analysis these were determine hourly and half hourly per the collected meteorological information. Equations (15-17) determined the relative angles associated with the photovoltaic module used to develop an optimized angle.

$$I_{Total} = I_{dir} * Cos\theta + I_{dif} + I_{ref} \tag{14}$$

Where:

I_{Total}= Total radiation

I_{dir}= Direct radiation of sun incident

I_{dif}= Indirect diffused radiation incident

I_{ref} = Reflected (short wave) radiation of surroundings

$$Sin(\beta) = Sin\ (L) * Sin(\delta) + Cos(L) + Cos(\delta) * Cos(h) \tag{15}$$

Where:

β = Solar Altitude/ Elevation Angle

L= Latitude

h = Hour Angle

δ = Declination Angle

$$Sin(\emptyset) = \frac{Cos(\delta) * Sin(h)}{Cos(\beta)} \quad (16)$$

Where:

h = Hour Angle

δ = Declination Angle

β = Solar Altitude/ Elevation Angle

$$\theta = Cos^{-1}(Cos(\beta) * Cos(\emptyset - \varphi) * Sin(\beta) + Sin(\Sigma) * Cos(\Sigma) \quad (17)$$

Where:

Σ = Surface Tilt Angle

φ = Surface Azimuth Angle

θ = Angle of Incidence

The values are calculated and presented in Table 3.3-3 represented by the total monthly solar insolation for given surface tilt angles. The total solar insolation account for the kilowatt hour in an area of one square meter for a day of the specified month. Through this analysis, the optimal tilt angles were discovered for the bi-annual adjustments to optimized solar insolation potential. Adjusting the tilt twice a year increases optimum percentage while maintaining a relatively lower operation cost and maintenance feasibility (Guha, 2020). During the simulation this variable is compared to a system that explores axis tracking to increase system efficiency and reliability. The highlighted portions of the table indicate the near optimal angles for the winter and summer seasons. The summer months were evaluated between April to September and winter months from October to March. These angles were further evaluated passed the 15 degree increments to distinguish the exact angle implemented in the investigation. This further evaluation is conducted where the angle for the summer and winter equated to approximately 20 degrees and 57.5 degrees. These angles displayed the most optimal total insolation values for the months of the season. This approach maximizes the solar potential that is established during the summer and winter solstice.

Table 3.3-3: Total Solar Insolation Based on Angled Tilt

Month	Day Count	Solar Radiation(kWh/m^2/day)						
		0-degree Tilt	15-degree Tilt	30-degree Tilt	45-degree Tilt	60-degree Tilt	75-degree Tilt	90-degree Tilt
Jan	31	1.71	2.28	2.73	3.02	3.15	3.1	2.87
Feb	28	2.63	3.34	3.87	4.18	4.26	4.09	3.69
Mar	31	3.82	4.43	4.8	4.91	4.74	4.31	3.65
Apr	30	4.75	5.14	5.26	5.1	4.68	4.01	3.14
May	31	5.97	6.09	5.91	5.43	4.72	3.79	2.78
Jun	30	6.35	6.41	6.15	5.57	4.77	3.75	2.66
Jul	31	6.65	6.76	6.53	5.97	5.14	4.08	2.92
Aug	31	5.56	5.91	5.93	5.65	5.09	4.27	3.26
Sep	30	4.39	5.01	5.35	5.4	5.14	4.6	3.82
Oct	31	2.94	3.6	4.07	4.3	4.3	4.05	3.57
Nov	30	1.76	2.34	2.8	3.1	3.22	3.15	2.91
Dec	31	1.28	1.77	2.16	2.44	2.58	2.57	2.41

Modeling the photovoltaic system incorporates the power output based on the solar insolation with the PV module's area. In the present work, the solar PV system is taken as the initial source of energy. The design of the panels is carried as the investigative size of 100 kilowatts initially. The design size of the system is carried out and then balanced with the load requirements from the building type throughout the year. The load profile is continuously duplicated for the loads discussed until the system's power generated presents a deficiency in the or matches the load. For this case the final load being supplied is equated to the energy generated containing a relatively small excess of power due to the variable constraints of load and power generation. This is taken into consideration when evaluating the amount of energy that the PV system produces. The power output produced by a single PV module with respect to solar insolation and efficiency is given in Equation (18)

$$P_{pv} = I_T * A_{pv} * \eta_{pv} \tag{18}$$

Where:

I_T = Total Solar radiation

A_{pv} = PV module area

η_{pv} = PV module efficiency

$$\eta_{pv} = \eta_m * \eta_{pc}[1 - \beta(T_C - T_R) \tag{19}$$

Where:

η_m = module efficiency

η_{pc} = Power conditioning efficiency

β = Temperature Coefficient

T_C = Cell Temperature

T_R = Reference Temperature

The TallMax PV module is a 252 cell Monocrystalline module that has a power output range of 470 to 490 watts with a five percent power tolerance. The maximum efficiency of the module itself is 20.8 percent not including the effects of temperature differences. These values were placed in the Excel analysis and were computed for the single panel. System evaluation includes system losses as well account for a total of 12.1 to 14.1 percent. Losses discovered in the system account for mechanisms which include dirt depreciation, wiring, connections, shading, and manufacturing imperfections. Table 3.3-4 displays the values calculated for the single PV module with the biannual tilt adjustment. Calculations derived that a 30-kilowatt hour increase in power output per panel adjusting angle biannually.

Table 3.3-4: Total Solar Insolation Based on Angled Tilt

Month	Solar Radiation ($kWh/m^2/day$)	Plane of Array Irradiance (W/m^2)	DC array Output (kWh)	AC System Output(kWh)
1	3.14	97.37	43.91	41.23
2	4.26	119.31	52.95	49.12
3	4.79	148.35	63.08	59.78
4	5.22	156.46	64.79	61.89
5	6.07	188.08	75.22	71.98
6	6.36	190.71	75.47	72.23
7	6.72	208.38	80.58	77.17
8	5.95	184.47	72.34	69.30
9	5.16	154.72	61.27	58.67
10	4.32	133.77	54.36	52.00
11	3.21	96.33	40.56	38.75
12	2.57	79.55	34.91	33.22
Total	57.75	1757.50	719.44	685.34

For the total system calculation pertaining to a 100 percent PV system, the finalized output power for a 100-kilowatt system calculates a total of 206 PV modules. The AC power output calculated for the PV system is an estimated 132,740.5 kWh per year. According to the load profiles discussed previously, the PV system is able to provide power for an estimated 12 residential single-family homes. When analyzing the community commercial load of the small office, the energy renewable system is able to provide yearly power for approximately two equal structures. This same approach was taken with the wind turbine design to determine load satisfaction. Further Configuration for the system implicates technical evaluation for PV module quantity layout. This portion of the investigation is not pertinent to the module power generation as the percentage difference of module quantity is less than one percent.

3.3.3 Wind Turbine Sizing

Numerically modeling the wind turbine systems takes a similar iterative approach as the photovoltaic system. The selected wind turbine for the investigation is an EOCycle 10 kilowatt direct-drive generator wind turbine system. Wind turbine characteristics includes a horizontal axis, designed for upwind production, active yaw along with variable speed and electronic rotor speed and power control. The typical application for this system contains both grid connected or hybrid diesel power generation. The wind turbine has been designed for the lower range wind classes as which the defined site is classified under. The power generated from the wind turbine can be generalized from the Equation (20) as a function of wind velocity. This equation takes into consideration of the Betz limit power coefficient as a system constraint.

$$P_{wt} = \begin{cases} 0, & v < v_{ci}, v > v_{co} \\ \frac{\rho * A * v^3 * C_p}{2}, & v_{ci} < v < v_r \\ P_r, & v_r < v < v_{co} \end{cases} \tag{20}$$

Where:

ρ = air density

A= Swept Area, m^2

v_r = Rated Wind Speed

v_{ci} = Cut-in Wind Speed

v_{co} = Cut-out Wind Speed

C_p= Power Coefficient

The wind turbine system contains values at which a power curve could be created to show the relationship between the power output and the wind speed. These are the ideal values in the tested condition of the determined wind speeds. In this power curve the cut-in, cut-out, and rated wind speeds are visible. Figure 3.3-1 displays this relationship and is further analyzed as the figure is overlapped with the possible wind occurrence to construct a representation of wind speed and power correspondence. This connection is required to predict the energy delivered by the wind turbine. For the case the data that was obtained did include the half hourly data information for wind speed which essentially created the means to calculate the energy delivered. The combination of the integration of the power curve and collected wind information function can be seen in Figure 3.3-2. The overlapping area is representative of the area under the curve in which the wind is able to be utilized in for power generation.

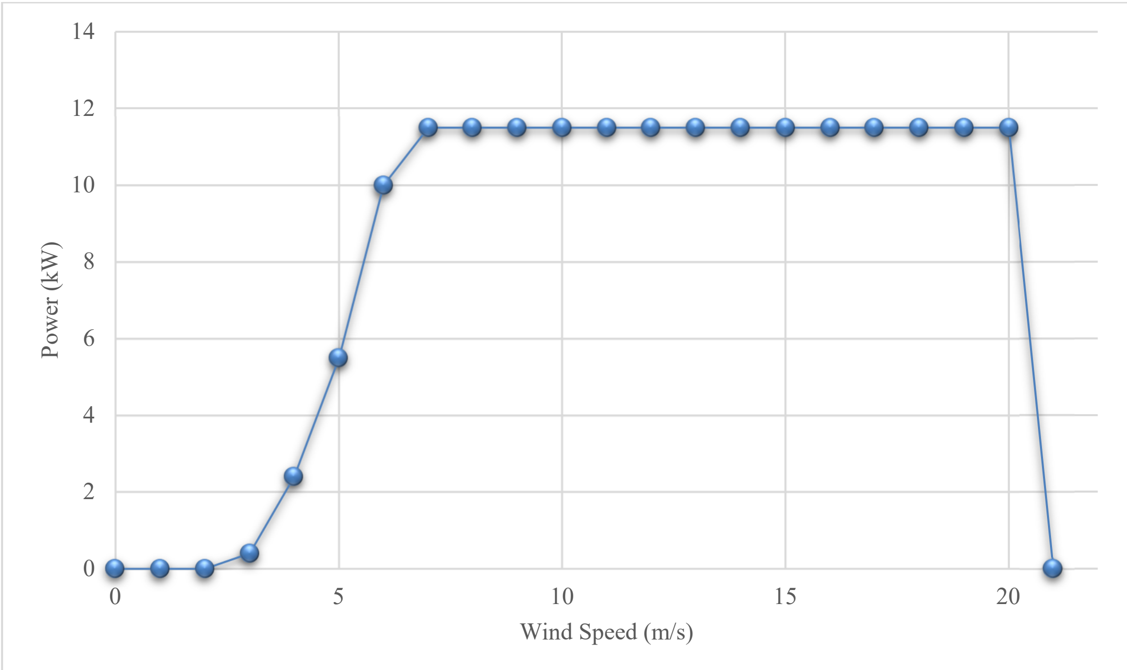


Figure 3.3-1: EO 10 Ideal Wind Power Generation in kW

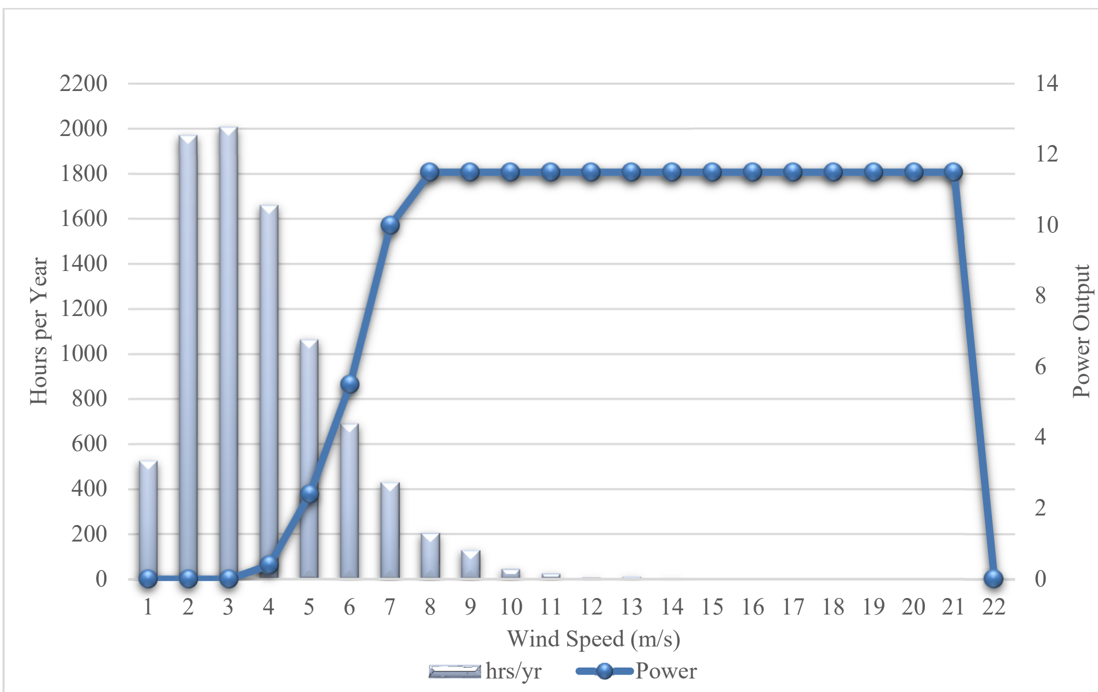


Figure 3.3-2: EO 10 Power Output Compared to Wind Frequency

To estimate the energy that is delivered by from a wind turbine, it is essential to link the power curve for the selected WT to the statistical model of the wind pattern. Analysis of Figure 3.3-2 displays that the majority of the wind speed is derived from the lower end of the power curve. Hours of the windspeed at the power output are analyzed in order to determine the power generation at the specific velocity. The corresponding hours based on the data provided, contribute to the wind speed probability for the hourly annual data. Table 3.3-5 displays the energy generated from a single EO 10 turbine with respect to the wind speed range. The results confirm that the power generation is derived from wind speeds below five meters per second. Power output is dispersed primarily through the wind speeds between 3.1 to 8.1 meters per second, where a gradual increase at the 4.1 to 5.1 meters per second occurs. The constraint of the cut-in wind speed limits the amount of wind speed utilization as it pertains to power generation. Due to Michigan's low wind speeds approximately 2,494 hours were unable to provide any power due to wind speeds being lower than 2.1 meters per second. This factor is further investigated based on the monthly power generated seen in table 3.3-6. The table presents a monthly breakdown of available hours in a month versus the hours of wind speed with power generating capability based on the wind turbine's cut-in and cut-out wind speed. Through the analysis it was discovered that a total of 5448 hours of the wind speed is utilized for energy generation annually in the forecasted wind data. Due to the wind variability further analysis of wind system function of the cumulative distribution function hourly percentage may fluctuate as average wind speeds change. Within this investigation a total of 28,607.6 kWh per year is produced for a single wind turbine.

Table 3.3-5: E0 10 Energy Generation by Wind Speed

Wind Speed	Hours at v	Fraction Probability	Power Output (kW)
0.1-1.1	525	0.0599	0.0
1.1-2.1	1969	0.2248	0.0
2.1-3.1	2006	0.2290	879.4
3.1-4.1	1660	0.1895	3613.1
4.1-5.1	1063	0.1213	5112.1
5.1-6.1	689	0.0787	5865.8
6.1-7.1	429	0.0490	5685.2
7.1-8.1	203	0.0232	3461.5
8.1-9.1	128	0.0146	1851.5
9.1-10.1	43	0.0049	1196.0
10.1-11.1	23	0.0026	425.5
11.1-15.1	22	0.0025	517.5

Table 3.3-6: EO 10 Monthly Wind Generation

Month	Total Hours per Month	Hours With Power Capability	Sum of Wind Power(kW)
1	744	527	3082.98
2	672	518	3554.71
3	744	520	3066.36
4	720	530	2892.74
5	744	433	1858.06
6	720	404	1371.48
7	744	251	674.04
8	744	318	960.77
9	720	294	759.48
10	744	500	2808.82
11	720	572	3744.73
12	744	581	3833.45
Grand Total			28607.61

Similar to the PV system analysis, the total system calculation pertaining to a 100 percent WT system, the finalized output power for a 100-kilowatt system calculates a total of 10 wind turbines. The AC power output calculated for the WT system is an estimated 286,076 kWh per year. According to the load profiles discussed previously, the WT system is able to provide power for an estimated 26 residential single-family homes. When analyzing the community commercial load of the small office, the energy renewable system is able to provide yearly power for the approximately four structures.

3.3.4 Supporting Equipment

The hybrid renewable energy system contains a number of components that make up the optimized system. For the purpose of the investigation the focus remained on the two primary renewable components of the photovoltaic modules and wind turbines. The system also consists of battery energy storage, charge controller, converter/inverter, energy management components, along with a number of disconnect switches. The system is equipped with both a charge controller and inverter for energy delivery configuration throughout the system. The charge controller itself is an essential component directs the output of the renewable energy systems to the load and battery energy storage during energy generation. During excess demands the charge controller will also extract electrical energy to serve the load. Three functions included for the controller include charge control functions for battery protection and disconnection. Another function includes Maximum Power Point Tracking (MPPT) which is incorporated at the key components of energy efficiency for adequate operating points (Masters, 2013). The MPPT is integrated in the energy renewable systems and voltage conversion components as well. For the autonomous system the inverter typical requirements involve inverter to be sized to match the total amount of load demand at a point. For this investigation the inverter is to be sized with 25 percent safety factor to meet the load profiles. The inverter's efficiency is operating relatively high, within the 90-percentile range when referring to high load.

Several batteries are available for energy renewable systems that contain differing features and characteristics. Battery characteristics placed in the analysis include the voltage, charge capacity, depth of discharge and cycle capacity (Masters, 2013). The battery primary duty is to store excess generated energy, regulate the energy system voltage and supply energy during deficient of the supply load. Variables that effect the battery sizing include load autonomy, temperature, state of charge (SOC) and depth of discharge (DOD). The batteries charging and discharging process can be mathematically represented by the Equations (21-22). The maximum depth of discharge in a deep cycle battery type that is permitted for the DOD of the battery is 80 percent.

$$SOC_c(t+1) = SOC(t) * [1 - \sigma(t)] + [I_{bat}(t) * \Delta t * \eta_c(t)/C_{bat}] \qquad (21)$$

Where:

$\sigma(t)$ = hourly Self Discharge Rate

C_{bat} = Nominal battery Capacity

$\eta_c(t)$ = Charge Efficiency

$$SOC_d(t+1) = SOC(t) * [1 - \sigma(t)] - [(I_{bat}(t) * \Delta t * \eta_{dis}(t))/C_{bat}] \qquad (22)$$

Where:

SOC max value is equal to 1

$1\text{-DOD} \leq SOC(t) \leq 1$

The implementation of the supporting components of the systems are evaluated in the next portion of the investigation. The software simulation incorporated the numerical factors as it pertains to the system's optimizations. Determination of the battery system is designed to provide load satisfaction for 99 percent of the 8760 hours of the year. Table 3.3-7 displays the general inputs of the software simulations that were established during the numerical analysis.

Table 3.3-7: Supporting Equipment Criteria

Battery Data	
System Availability	99%
Days of Autonomy	3.0-4.0
System Voltage(V)	48.0
Maximum Depth of Discharge (DOD)	0.8
Temp and Discharge Rate (TDR) Adjustment	1.0
Additional component Input	
MPPT factor	1.0
Inverter Efficiency	.90-.95
Charger Controller	0.97

3.3.5 System Integration

The photovoltaic modules and wind turbines have been sized accordingly with the provided data individually. The next phase was to integrate the system to a respective sharing percentage between the systems. The sharing percentage is taken by incremental steps of 10 percent through this evaluation. At each increment the total power out of energy produced is measured for comparison. The evaluation of sharing percentage gives the initial parameters that are further investigated in the software simulation. Additional factors that are implemented towards sharing percentage in the simulation that have influenced final selection of the sharing percentage. Table 3.3-8 displays the sharing percentage (SP_{wt}, SP_{pv}) for the hybrid renewable energy system along with the respective output power. The quantity of the photovoltaic system (N_{pv}) and wind turbine (N_{wt}) The Power generated holds a minimum of 132,740.5 kWh/year and a maximum value of 286,076.1 kWh/year. The optimization of the system is finalized with the simulation of the analysis.

Table 3.3-8: System Integration Power Generation

SP_{pv}	SP_{wt}	N_{wt}	kWh	N_{pv}	kWh	Total kWh
0	1	10.0	286,076.1	0.0	0.0	286,076.1
0.1	0.9	9.0	257,468.5	20.6	13,274.1	270,742.5
0.2	0.8	8.0	228,860.9	41.2	26,548.1	255,409.0
0.3	0.7	7.0	200,253.2	61.8	39,822.2	240,075.4
0.4	0.6	6.0	171,645.6	82.4	53,096.2	224,741.8
0.5	0.5	5.0	143,038.0	103.0	66,370.3	209,408.3
0.6	0.4	4.0	114,430.4	123.6	79,644.3	194,074.7
0.7	0.3	3.0	85,822.8	144.2	92,918.4	178,741.2
0.8	0.2	2.0	57,215.2	164.8	106,192.4	163,407.6
0.9	0.1	1.0	28,607.6	185.4	119,466.5	148,074.1
1	0	0.0	0.0	206.0	132,740.5	132,740.5

3.4 Software Simulation

3.4.1 Methodology

The results from the numerical analysis contained two individual studies of a photovoltaic energy system and wind turbine system which was then integrated as the hybrid renewable energy system. The systems were analyzed to develop a list of comparative values of probable power generation of the hybrid system. From this investigation, results were provided supportive evidence towards the systems' ability to meet established load demands, and reliability for power generation. These results were procured by utilizing a site-specific pre-feasibility study. The numerical analysis concluded that a 100 percent wind turbine system produced the most power for the system load. Although, the wind turbine system produces more energy, further analysis of the optimization into the economics and reliability have proven that this is not feasible for the project site. Within the next phase of the investigation, HOMER simulation was implemented to build support on the systems functionality in realistic conditions of power demand in regards feasibility and utilization. The results can be represented in final numerical values when comparing initial and operational cost, power efficiency and load reliability based in respect to time, project lifetime. Lastly a sensitivity analysis conducted classify the variable system parameters set during the investigation as variables which have high probability of change that may affect the results with real world implementation. One of these variables will include location which is analyzed separately and compared to the original Michigan investigation.

The simulation optimization methodology envelopes an array of established inputs for system development. These inputs cover the several aspects of the numerical analysis which includes the meteorological data, load demands, and selected renewable components. Also incorporated in the initial inputs are values involved with the economic analysis such as the constraints, costs of systems, and economic rates. The methodological framework for the Homer Pro simulation is illustrated in Figure 3.4-1 separated into three phases, data inputs, system optimization and system analysis.

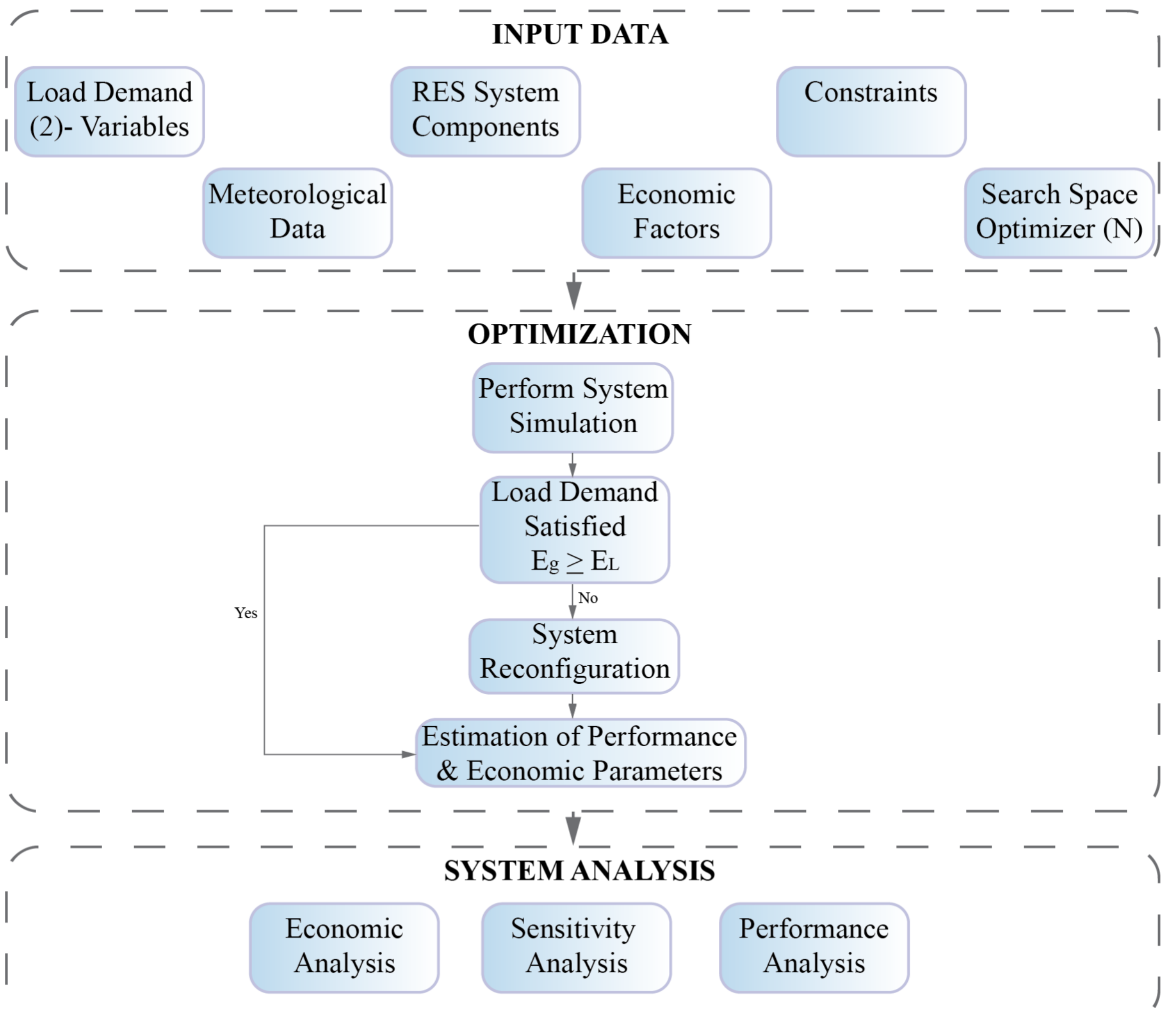


Figure 3.4-1: Simulation Methodology Framework

In the aforementioned analysis the location parameters and hypothetical load profile were constructed which consisted of a residential house load or a community structure classified as a small office. The results from the numerical analysis declared the renewable energy system could sustain a minimum amount of 12 residential households or two small offices. For the initial simulation the sum of the load demand of the households was chosen to optimize the hybrid system develop the results. The load implemented has an identical random variability of 10 percent day to day and 20 percent timestep. The load was scaled from the original demand to account for the multiple residential loads which equated to an average 273.6 kWh/day with a peak wattage of 56.32, giving a load factor of .2. Figure 3.4-2 and Figure 3.4-3 display the yearly and monthly load profile scenario. Further load profile information is found in the Appendix A-5.

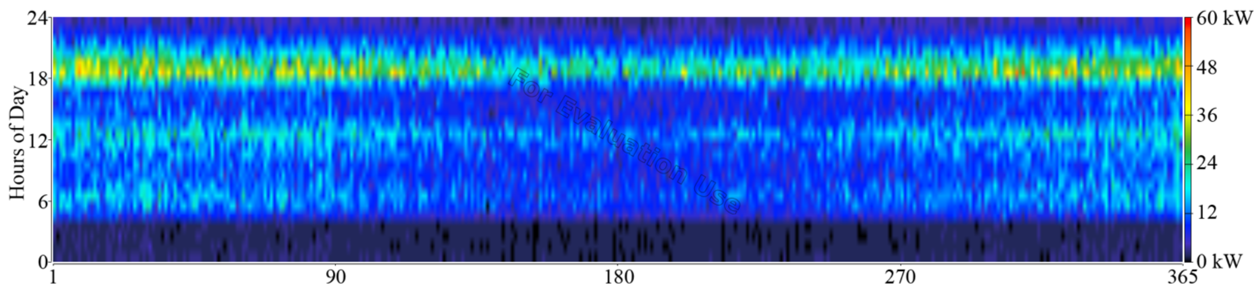


Figure 3.4-2: Scaled Residential Electrical Load Yearly Profile

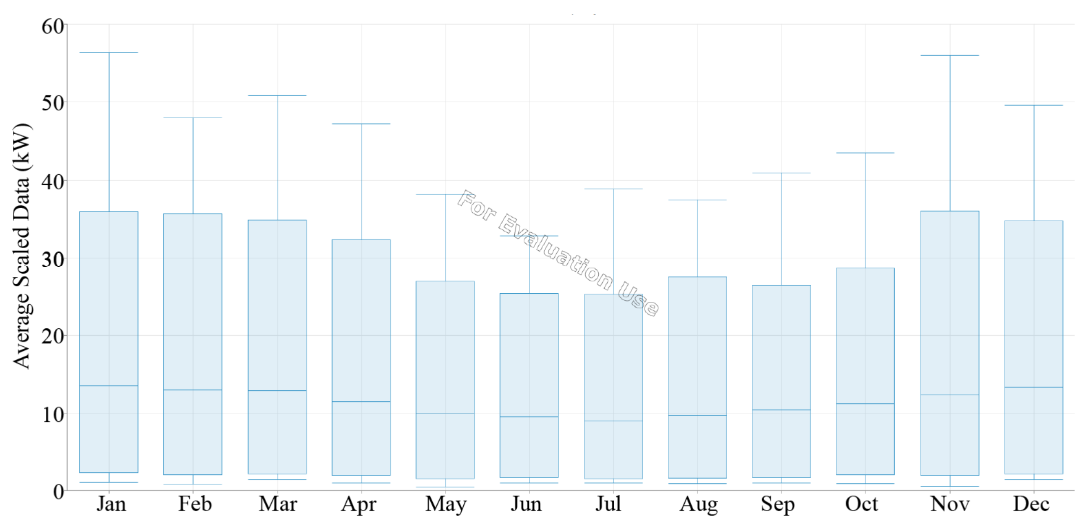


Figure 3.4-3: Scaled Residential Electrical Load Seasonal Profile

To Avoid additional variability between the numerical and simulation analysis the resources used for solar, and wind were implemented for the Homer simulation. In the simulation the characteristics of both resources are able to be combined visually to see possible excess and deficient times throughout the year. Figure 3.4-4 illustrates the solar and wind resources near the spring equinox and the complimentary relationship that is obtainable between the two resources. The figure assists in indicating during the times of low solar potential, wind potential is at or near an elevated potential to secure adequate energy generation.

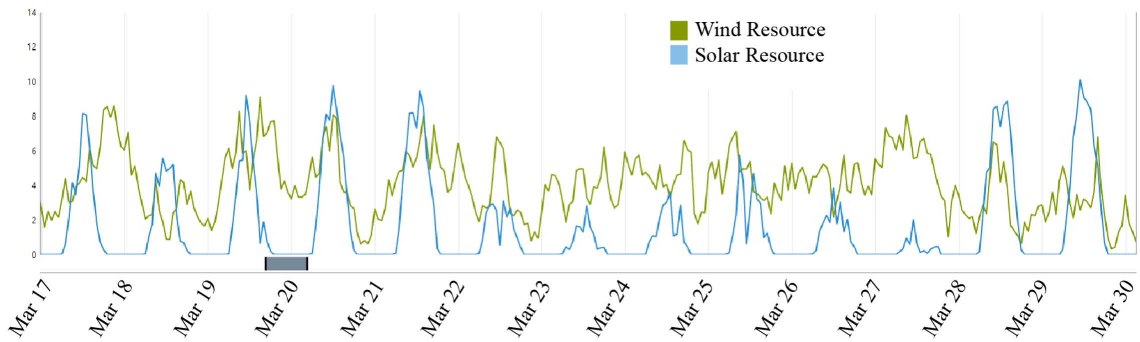


Figure 3.4-4: Spring Equinox Solar/Wind Resource Data

Additional inputs for the simulation include the initial economic parameters of the system. Homer Pro incorporates the nominal discount rate which is the rate at currency can be borrowed. This value is set to 6 percent. Secondly the expected inflation rate was included which accounts for the inflation rate of the project's lifetime. In this case the average 18-year breakeven rate for the United States at 2.32 percent was set (Federal Reserve Bank of St. Louis, 2021). The project lifetime is anticipated to be 25 years and allows the estimated operating, maintenance and replacement cost over the years. Lastly for the initial economic parameters are set, the Load requirement capacity shortage is set. The capacity shortage is considered the load deficiency between required capacity and the actual operating capacity the system is able to provide. For reliability purposes, Homer accounts for the constraint to be set in the preliminary design. As previously discussed, the system is designed to be a completely autonomous hybrid system. For this purpose and as indicated with the energy storage portion of the piece, the design is set to provide up to 99% of the anticipated load with a capacity shortage less than or equal to 1%.

3.4.2 RES System Components and Optimization

Due to the site project site and requirements of placement, the component selection was limited to certain design conditions. The photovoltaic modules and wind turbine were selected during the numerical analysis to account for these constraints. In the initial investigation the sizing of the two primary components were considered, and with the simulation the incorporation of system conversion and energy storage are also analyzed further. For the photovoltaic module NREL has concluded that average cost per watt for commercial ground-mount systems is approximately $1.72 USD per watt (NREL, 2020). For the PV panel selected the estimated capital cost is set to $842.80 USD with an operating and maintenance cost(O&M) of $14 USD per year with a 25-year lifetime. The EO 10 wind turbine capital cost is set to $33,000 USD with and O&M cost of $600 US per year and a 20-year lifetime. The battery selected is a 1.0-kilowatt hour 24 volts Lithium-Ion battery which is based on the parameters the numerical analysis assumed. The capital cost is set at $1,500 USD with a lifetime of 10 years. System converter is set to Homer's default at 95% efficiency with a lifetime of 15 years, assumed to have a $500 USD capital cost. These values influenced the final analysis of the optimization.

3.4.3 Simulation and Results

During the Homer Pro analysis, the program underwent a total of 4,930 simulations. It was determined that through the thousands of simulations, 788 solutions were found to be feasible. Within the system analysis, three categories of results are identified as the economic, sensitivity, and performance analysis. Each portion of system analysis integrated into the conclusion of system feasibility. From this point the software delegated the most reasonable solution in regards to the NPC, load generation and renewable fraction. The simulation derived the best configuration of a PV-WT-BES system to contain 64.4 kilowatts of PV, 4 EO-10 WT, and 414 battery units. The Trina Solar PV system has a nominal capacity of 64.4 kilowatt with the annual production is 92,142-kilowatt hour per year. Power output from the Eocycle wind turbine system, rated at 40.0 kW, is 114,424-kilowatt hour per year. System component breakdown can be seen in Appendix A-6. The Discover Battery storage system's nominal capacity is 397-kilowatt hour. The annual throughput is 33,759-kilowatt hour per year. The system converter has been sized with a 48.3-kilowatt capacity with a total of 47,586-kilowatt hour per year. System component breakdown for the battery system and converter can be seen in Appendix A-7.

System performance or reliability is distinguished by the excess of power generation and deficiency of power of this system. Table 3.4-1 the electrical data calculated based on the individual inputs. The sharing percentage of total kilowatt hour of the renewable system are nearly equivalent to each other as they satisfy a total load of 99,154 kilowatt per year. The system itself contains 49.6 percent of excess electricity which in turn will proceed to a dump load as it is unusable for the establish residential load. The unmet load falls under a one percent target, confirming an adequate percentage of error. Figure 3.4-5 presents the systems monthly electrical production separated by the photovoltaic and wind turbine contributions. Within the graph it is apparent the systems dependency on solar and wind energy depending on the season.

Table 3.4-1: Simulated Electrical Production

Component	Power Output(kWh/yr)	Percentage (%)
TallMax M+ 490	92,120	44.6
Eocyle EO 10	114,424	55.4
Total	206,556	100
AC Primary Load	99,154	100
Quantity	**Power Output(kWh/yr)**	**Percentage (%)**
Excess Electricity	102,548	49.6
Unmet Electric Load	706	0.707
Capacity Shortage	1,098	1.1

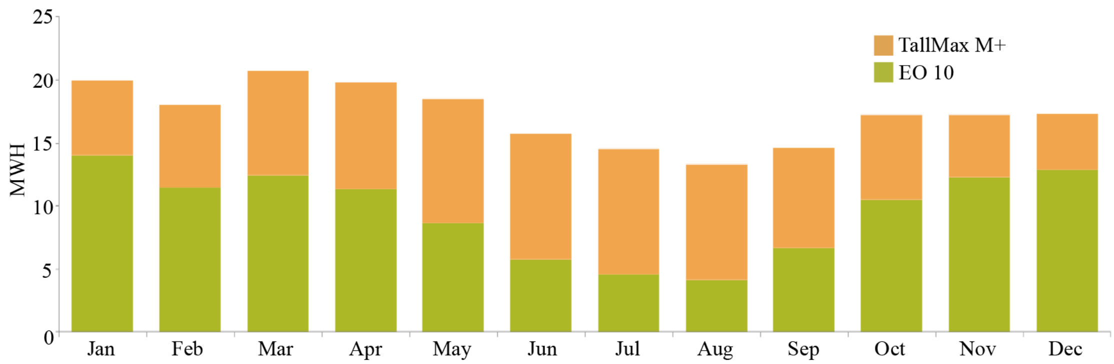


Figure 3.4-5: Monthly Electrical Production by System

The economic analysis is one of the primary driving forces to the system selection and optimization. The primary order of presented options are prioritized by the calculated cost during the simulation process. Through the simulation, Homer attempted to evaluate by optimizing the hybrid system through the evaluation of the net present costs (NPC). The net present cost can be described as the value of the costs associated with installing and operating the component over the span of its lifetime less the present value of the revenues the component earns over its project lifetime. This model can also be represented by Equation (23). The final cost breakdown is seen in Table 3.4-2 and Figure 3.4-6

$$C_{NPC} = C_{an,tot}/CRF(i, R_{proj}) \quad (23)$$

Where:

C_{NPC} = Net Present Cost

$C_{ann,\ tot}$ = Total Annualized Cost

i = Annual Real Discount

R_{proj} = Project Lifetime

CRF = Function Returning the Capital Recovery Factor

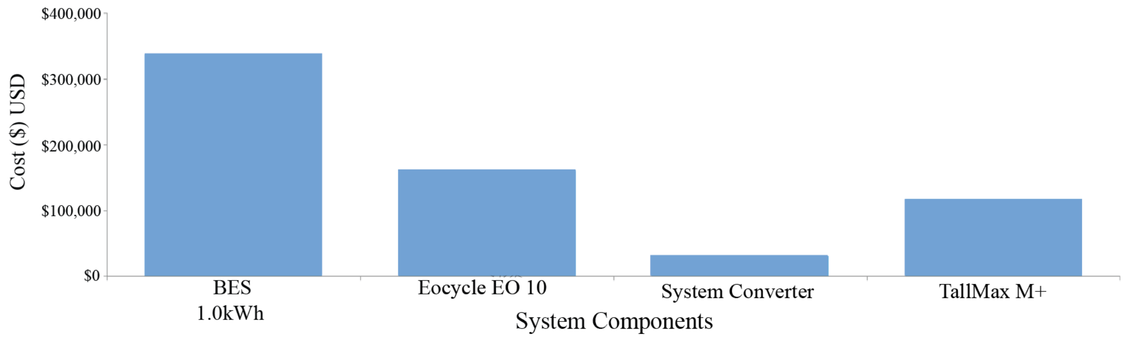


Figure 3.4-6: HRES Component Cost Comparison

Table 3.4-2: HRES Component Cost Breakdown

Component	Capital ($) USD	O&M ($) USD	Salvage ($) USD	Total ($) USD
AES 1.0kWh 24VDC	$ 258,750.00	$ 202,669.43	$(124,546.91)	$ 336,872.52
Eocycle EO 10	$ 120,000.00	$ -	$ -	$ 160,634.40
System Converter	$ 24,145.24	$ 18,912.09	$ (11,622.09)	$ 31,435.24
TallMax M+	$ 110.769.18	$ -	$ (15,995.31)	$ 117,023.08
System	$ 513,664.42	$ 221,581.42	$ (152,164.31)	$ 645,967.88
			Total NPC	$ 645,967.88
			Operating Cost	$7,814.34

The levelized cost of energy (COE) is also computed in regards to the economic analysis. The levelized cost of energy is described from Homer as the average cost per kilowatt hour of useful electrical energy produced by the system. The COE can be represented by the formula in Equation (24). The renewable energy components are calculated of their separate COE while the entire system is calculated as well. The total levelized cost of the system is $.3848 USD per kilowatt hour. For comparison purpose, a baseline traditional system was constructed of a grid connected system with a backup diesel generator to be applied to the identical load and site parameters. The input parameters for the traditional system include full grid connection at the average electricity rate with regards to peak at approximately 18 cents per kilowatt hour (U.S. EIA, 2020), and generator capital cost for the Midwest region of $1,549 USD per kilowatt (U.S. EIA, 2020). Diesel fuel prices were also set however due to the average power outage and reliability of the electrical grid at the site location fuel cost is negligible. The systems were compared for the various system costs, cost of energy, and Co2 emissions. The results of the two systems are illustrated in Table 3.4-3.

$$COE = \frac{C_{ann,tot}}{E_{prim}+E_{def}+E_{gs}} \quad (24)$$

Where:

$C_{an,tot}$ = Total Annualized Cost

E_{prim}= Primary Load Served

E_{def}= Deferable Load

E_{gs}= Energy Grid Sales

Table 3.4-3: HRES Vs Traditional System Cost Comparison Breakdown

Component	Capital ($) USD	O&M ($) USD	Salvage ($) USD	Total ($) USD	COE	Co2 Emission (kg/yr)
HRE System	$ 513,664.42	$ 221,581.42	$ (152,164.31)	$ 645,967.88	$ 0.385	6,716
Traditional System	$ 108,518.00	$ 327,617.51	$ -	$ 436,135.51	$ 0.256	63,114

The total net present cost calculated for the two system displays a cost difference of $209,833 USD with the hybrid system being more expensive. The cost of energy also is increase for the renewable system by $.129 USD per kilowatt hour. The carbon emissions were also evaluated as a part of the analysis which derived a significant difference. Homer has a set grid connect Carbon Dioxide at 632 grams per kilowatt hour. For the hybrid system components values were set to systems averages for the PV and WT as 44 and 11 grams per kilowatt hour and the battery as 50 grams per kilowatt hour (NREL, 2020). The values concluded that the hybrid renewable system holds an 89.4 percent decrease per year against the traditional system. Additionally, a grid extension analysis was conducted to determine an alternative to a stand-alone system. Grid Extension competes with the cost of each standalone system that you model in Homer, calculated the break even in the grid extension distance 31.9 kilometers from the site location. Grid Connection implemented in the hybrid system has the benefit of generating an estimated $79,323 USD, assuming a 5-cent sellback rate, from routing the excess electricity into the grid.

3.16 System Analysis

Lastly a sensitivity analysis identified three variable system parameters during the investigation as variables that may alter the final results. The three parameters represent each portion of the optimization analysis, selecting one variable in the economic, resource and component performance as variable representation. These variables include varying nominal discount rates, wind speed differentials, and solar energy capturing. The nominal discount rate directly effects the real discount (interest) rate in which homer uses to calculate discount factors and the annualized costs from the net present cost. Equation (25) shows the relationship between the real and nominal discount rate.

$$i = \frac{i\prime - f}{1 + f} \tag{25}$$

Where:

i = Real Discount Rate

i' = Nominal Discount Rate

f = Expected Inflation Rate

The nominal discount rate was evaluated on intervals of four percent starting at four and increasing to 12 percent. The analysis concluded that with as the nominal discount rate increased the COE from $.385 USD to $1.15 USD at the final 14 percent. Since the real interest rate increased a lower capital was allowed which caused an increase in the yearly operating cost. The higher interest rates are able to simulate remote areas and the inability to access capital causing larger these larger yearly costs.

The wind sensitivity accounts for the varying wind speed that may occur in different years. During the numerical analysis wind forecasting was performed by using historical data and a forecasted evaluation in Excel. In the case of the simulation, the minimum selected range of 3 meters per second and a maximum set at 4 meters per second was analyzed based on NREL average range. Small incremental changes were selected due to the cubic relationship in the power generation equation for the wind formula. The electrical production comparison in kilowatt hour per year is shown in Figure 3.4-7.

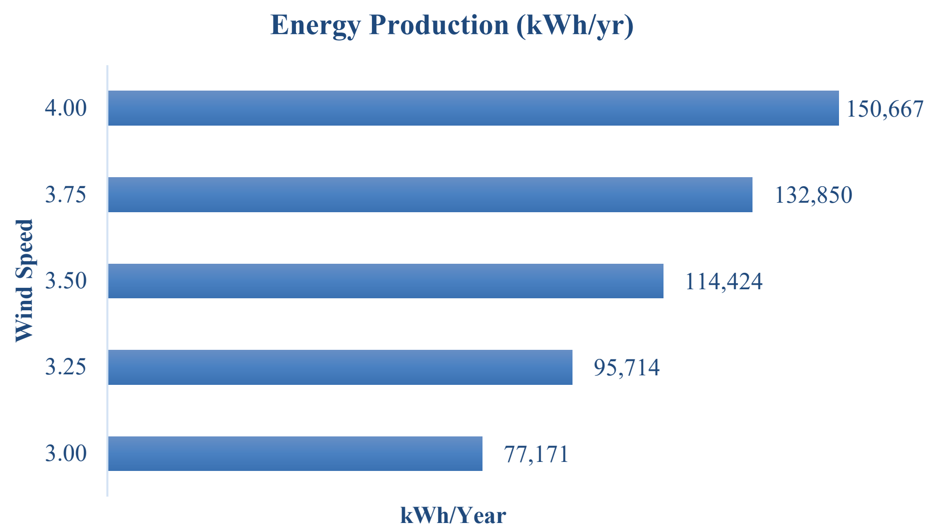


Figure 3.4-7: Wind Speed Sensitivity Comparison

A comparative study by towards system performance and reliability was also explored using the photovoltaic module system. During the numerical analysis the PV module angles were determined to optimize the energy generation. For convenience and simplicity of maintenance the solar design implemented a biannual adjustment which in turn maximized solar potential of the winter and summer seasons. For the Homer Pro simulation, the renewable system was analyzed using the horizontal monthly adjustment which in turn slightly increased the final power output originally calculated in the numerical analysis. To see the effects of the component configuration of tilt technology a sensitivity analysis was conducted comparing four component options for tilt in a photovoltaic array. Figure 3.4-8 displays the tracking system options and the respective energy production. The additional three systems compared included continuous single axis and continuous two axis tracking which can be perceived as 100 percent energy generation potential by tilt. The results shown show that with two axis tracking system the power generation increased 23,082 kilowatt hours per year. The results as seen in the figure indicate that the continuous tracking systems improve energy production, however the overall cost will increase with the addition of these features.

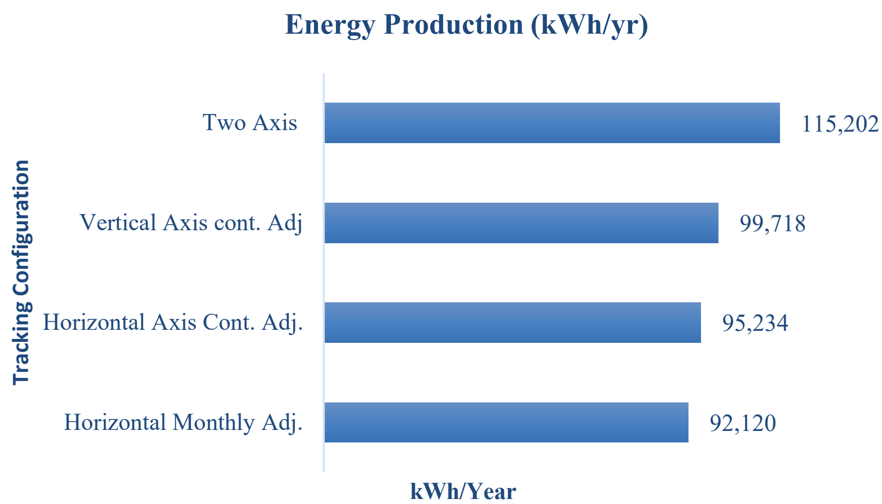


Figure 3.4-8: Photovoltaic Tracking System Sensitivity Analysis

3.4.4 Reference Study

An additional reference study was conducted based on the site-specific consideration of the initial investigation. The analysis utilizes the optimized system discovered in the primary Homer Pro analysis conduction in Novi, Michigan and implements the system in a site with differing meteorological and geographical characteristics. The secondary location considered was the island of the Dominican Republic. Central to the optimization, the feasibility of an autonomous system is heavily influenced by electrical infrastructure. Island locations fall within the category of expensive power grid extensions and fuel resources are costly and difficult to transport. Studies into renewable systems have shown that island locations can commit over 25 percent of their gross domestic product solely to the conventional resources. Additional reviews have concluded that in the Caribbean islands, where the dependency on fossil fuels is high the oil prices are able to surge four times higher than the mainland in comparison (The Economist Intelligent Unit, 2015). According to The Economist Intelligence Unit, the current state of the electricity industry in the Dominican Republic has been in a state of crisis for many years. Mainly as a result of low output capacity, poor management, rising demand, as well as transmissions and distribution issues leave communities to rely heavily on diesel generators. (Al-falahi, Jayasinghe, & Enshaei, 2017)

Figure 3.4-9: Reference Site Location Image

The site selected was Carretera Sabana Miches, Dominican Republic and is displayed in Figure 3.4-9. For the investigation the parameters of the systems remain identical in regard to equipment selection, and quantity to remove additional variables. The variables to change are the solar and wind resources and the load profile. The load profile input used a baseline average of 95 percent of Hawaii's electrical load due to similar meteorological characteristics. This system was compared to diesel generator system sized according to the simulation for the cost comparison. The generator cost was set at $1444.25 USD by the average taken EIA's average construction cost per kilowatt by region (U.S. EIA, 2020). Operation and management values were set to $.05 USD per hour and fuel price at $1.00 USD per liter.

During the analysis 936 solutions were simulated and 839 were found feasible. This microgrid required 193 kilowatt hours per day and has a peak of 44 kilowatts. In the proposed system, the following generation sources serve the electrical load. The findings in the present study show the baseline system is comprised of a 44 kilowatts generator which has an operating cost of $104,683 USD per year. Figure 3.4-10 shows the Monthly Electric Production of the PV array and wind turbines. With the proposed system, adding a 64-kilowatt PV, a 397-kilowatt hour battery, and 40 kilowatt of wind generation, would reduce operating costs to $15,759 USD per year. This system has an investment payback time of 4.48 years and an internal rate of return of 20.6 percent. Figure 3.4-11 refers to the Cumulative Cash Flower over Project Lifetime for both the current and proposed systems. The proposed system reduces net present costs, emissions, and cost of energy as seen in Table 3.4-4. Further results can be reviewed in Appendix A-8, 9.

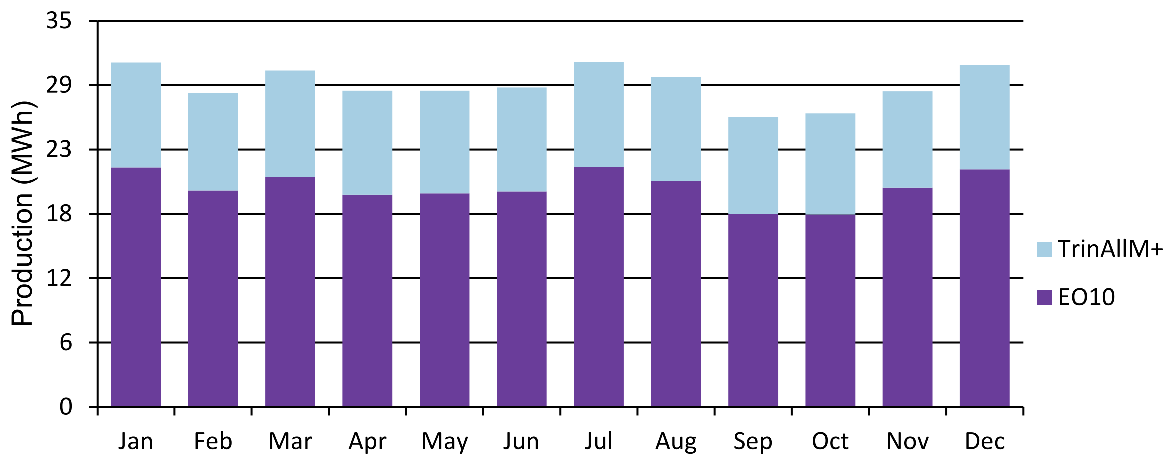


Figure 3.4-10: Monthly Electrical Production by System

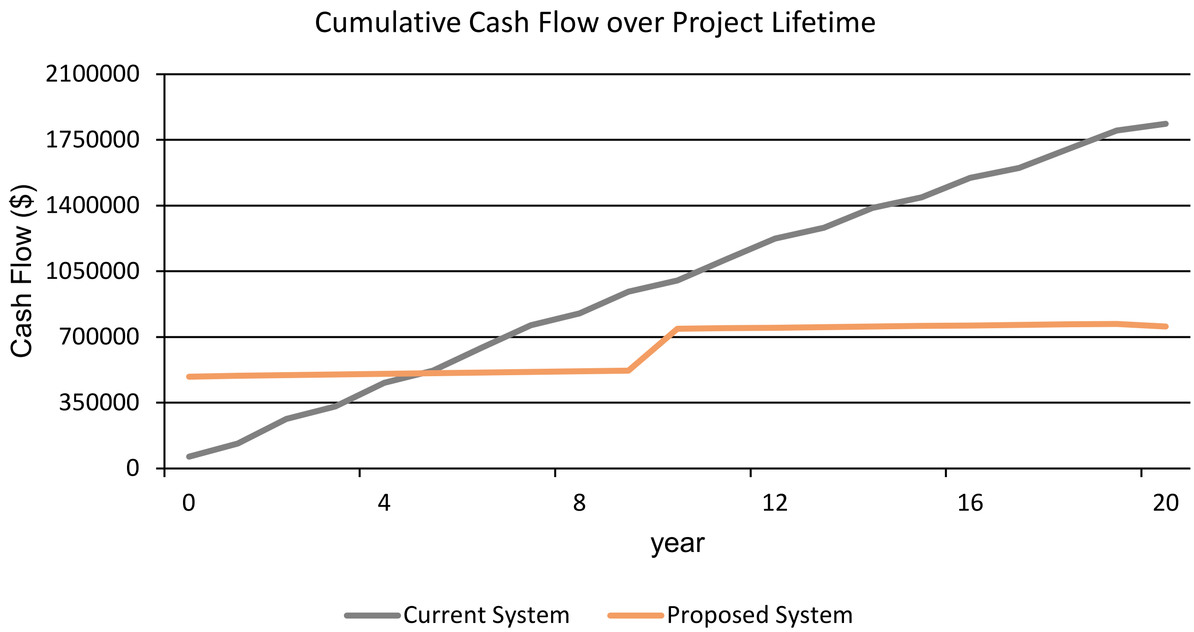


Figure 3.4-11: Reference Study System Cost Comparison Over Project Lifetime

Table 3.4-4: HRES Vs Baseline System Comparison

Component	Net Present Cost ($) USD	COE	Co2 Emission (kg/yr)
Proposed System	$ 756,511	$ 0.634	6,716
Baseline System	$ 1.84 M	$ 1.54	134,064

CHAPTER 4: CONCLUSIONS

This paper developed an iterative approach towards an autonomous hybrid renewable energy photovoltaic – wind turbine and battery storage system. A wide range of research and design methods have been developed for the analysis of the system but fail to sufficiently identify fundamental processes towards location applicability. The investigation analyzed the optimization of a 100-kilowatt hybrid renewable energy system to be applied to the primary site location of Novi, Michigan, United States. The results from the investigation are derived from both a numerical analysis and software simulation. The numerical analysis discovered a potential energy generation range of the photovoltaic-wind turbine between 132,740 to 286,076 kilowatt hours per year. The analysis provided results on the systems' ability to meet established load demand classifications of residential and community. With this hybrid system it is possible to establish an autonomous power generation system for both load demands, while addressing realistic challenges and obstacles from nature's unpredictability. With a Homer simulation process set forth, the optimization of a highly efficient system is recognized while maintaining key constraints seen in renewable energy systems such as feasibility, and utilization. Over 4,900 simulations were conducted with power sharing percentage for the photovoltaic- wind turbine of approximately 60/40. System optimization results can be represented in final numerical values when comparing power reliability, net present cost, and greenhouse gas emissions. Through the evaluation it was determined that the implementation of the autonomous system is not economically feasible compared to the traditional system. However, the system is classified as feasible when priority is set on power reliability, autonomy, and emission reduction. A sensitivity analysis was also conducted for variable parameters of the nominal discount rates, wind speed range, and solar tracking components. The effects of the analysis proved to set a range of cost of energy of $.385 USD to $1.15 USD from the discount rate. The additional variables concluded an increase in power generation for the system with the varying energy potential meteorological consideration and system innovation. The wind speed sensitivity developed a conservative range of 75,000 kilowatts. The increased energy production seen in the single axis tracking system aren't substantial enough to increase cost of the modules. The two-axis tracking is a considerable amount however the cost of energy is set to increase per panel.

Lastly, a reference study of the Dominican Republic was incorporated as a variable to determine system effectiveness in an alternate location with differing electrical infrastructure. Compared to the diesel generator baseline system, the autonomous hybrid system is proven to be both reliable and feasible to the applicable load. Further extent of the investigation that could be considered is developing a similar methodology for the energy storage system and power conversion system like the PV-WT selection process. The study can also extend to total system configuration based on installment impact on the final sizing of the system. This study may focus on the logistical analysis towards the design and construction of the hybrid system. This may also include the scope of the sequences and controls of the energy management system. Additional recommendations could incorporate the effect of economic feasibility in the extent of renewable energy incentives available in Michigan. A final recommendation could elaborate upon is the analysis of the electrical reliability of the renewable energy system in case of extreme weather conditions of a specified location.

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APPENDICES

Year	Month	Day	Hour	Minute	DHI	DNI	GHI
2020	6	20	0	0	0	0	0
2020	6	20	0	30	0	0	0
2020	6	20	1	0	0	0	0
2020	6	20	1	30	0	0	0
2020	6	20	2	0	0	0	0
2020	6	20	2	30	0	0	0
2020	6	20	3	0	0	0	0
2020	6	20	3	30	0	0	0
2020	6	20	4	0	0	0	0
2020	6	20	4	30	0	0	0
2020	6	20	5	0	5	27	5
2020	6	20	5	30	30	198	46
2020	6	20	6	0	52	367	113
2020	6	20	6	30	69	490	194
2020	6	20	7	0	83	581	282
2020	6	20	7	30	94	650	373
2020	6	20	8	0	104	702	465
2020	6	20	8	30	112	743	553
2020	6	20	9	0	119	775	637
2020	6	20	9	30	125	799	713
2020	6	20	10	0	130	818	781
2020	6	20	10	30	134	833	839
2020	6	20	11	0	138	842	885
2020	6	20	11	30	139	851	920
2020	6	20	12	0	141	855	942
2020	6	20	12	30	156	831	941
2020	6	20	13	0	368	448	790
2020	6	20	13	30	397	402	769
2020	6	20	14	0	398	360	722
2020	6	20	14	30	361	395	702
2020	6	20	15	0	277	506	689
2020	6	20	15	30	200	633	680
2020	6	20	16	0	150	713	644
2020	6	20	16	30	144	674	562
2020	6	20	17	0	137	623	475
2020	6	20	17	30	127	562	385
2020	6	20	18	0	115	484	295
2020	6	20	18	30	95	397	208

Figure A-1: Sample Data- Solar Insolation of Summer Solstice

Year	Month	Day	Hour	Minute	DHI	DNI	GHI
2020	6	20	19	0	73	281	128
2020	6	20	19	30	43	145	59
2020	6	20	20	0	10	28	11
2020	6	20	20	30	0	0	0
2020	6	20	21	0	0	0	0
2020	6	20	21	30	0	0	0
2020	6	20	22	0	0	0	0
2020	6	20	22	30	0	0	0
2020	6	20	23	0	0	0	0
2020	6	20	23	30	0	0	0

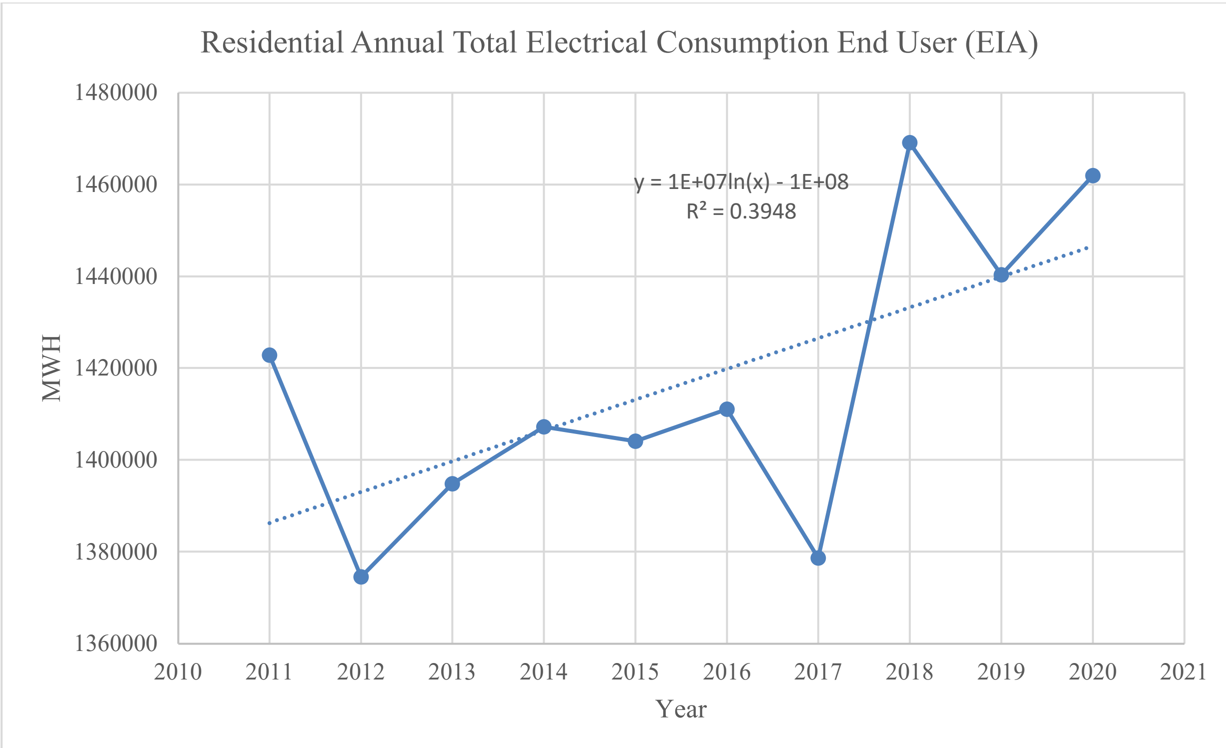
Month	Day	Hour	Beam Irradiance (W/m^2)	Diffuse Irradiance (W/m^2)	Ambient Temperature (C)	Plane of Array Irradiance (W/m^2)	Cell Temperature (C)	AC System Output (W)
6	20	0	0	0	12	0	12	0
6	20	1	0	0	12	0	12	0
6	20	2	0	0	11	0	11	0
6	20	3	0	0	11	0	11	0
6	20	4	0	0	11	0	11	0
6	20	5	222	26	13	20.486	11.139	6.378
6	20	6	543	63	16	129.222	17.685	39.144
6	20	7	704	85	18	334.125	25.629	123.752
6	20	8	794	101	20	552.612	33.996	212.096
6	20	9	845	114	21	749.858	44.199	281.845
6	20	10	854	136	22	896.256	49.965	330.798
6	20	11	874	140	23	996.714	54.144	362.103
6	20	12	880	141	24	1033.511	56.404	372.134
6	20	13	873	140	25	1004.646	56.698	361.377
6	20	14	856	134	25	912.999	54.165	331.644
6	20	15	825	125	25	769.835	49.956	283.477
6	20	16	770	113	24	578.155	43.098	215.714
6	20	17	679	98	23	364.803	35.102	133.378
6	20	18	524	75	22	159.796	29.676	50.145
6	20	19	242	37	20	28.616	20.295	9.52
6	20	20	0	0	18	0	18	0
6	20	21	0	0	16	0	16	0
6	20	22	0	0	16	0	16	0
6	20	23	0	0	15	0	15	0

Figure A-2: Sample Data- Solar Insolation/ Power Output of Summer Solstice

Month	Day	Hour	Minute	Direction	Adjusted Wind speed	Kelvin Temp	Adjusted Density	Wind Power(kW)
1	1	0	30	SE	3.31	272.15	1.25	1.69
1	1	1	30	SE	3.09	271.15	1.26	1.38
1	1	2	30	SE	2.87	270.15	1.26	1.11
1	1	3	30	SE	2.76	270.15	1.26	0.98
1	1	4	30	SE	2.43	270.15	1.26	0.00
1	1	5	30	SE	2.21	269.15	1.27	0.00
1	1	6	30	SE	1.99	269.15	1.27	0.00
1	1	7	30	E	2.32	270.15	1.26	0.00
1	1	8	30	E	2.76	271.15	1.26	0.98
1	1	9	30	E	3.09	272.15	1.25	1.37
1	1	10	30	NE	3.09	273.15	1.25	1.37
1	1	11	30	NE	2.98	273.15	1.25	1.23
1	1	12	30	NE	2.87	273.15	1.25	1.10
1	1	13	30	NE	2.87	274.15	1.24	1.09
1	1	14	30	N	3.09	274.15	1.24	1.36
1	1	15	30	N	2.76	273.15	1.25	0.97
1	1	16	30	N	2.65	273.15	1.25	0.00
1	1	17	30	N	2.98	273.15	1.25	1.23
1	1	18	30	N	3.75	272.15	1.25	2.46
1	1	19	30	N	4.64	272.15	1.25	4.63
1	1	20	30	N	4.97	272.15	1.25	5.70
1	1	21	30	N	4.97	272.15	1.25	5.70
1	1	22	30	N	5.08	273.15	1.25	6.07
1	1	23	30	NW	4.97	273.15	1.25	5.68

Wind Speeds	N	NE	E	SE	S	SW	W	NW
0.1-1.1 m/s	1%	1%	0%	1%	1%	1%	1%	1%
1.1-2.1 m/s	4%	5%	2%	4%	3%	3%	4%	4%
2.1-3.1 m/s	6%	10%	3%	8%	5%	6%	7%	6%
3.1-4.1 m/s	8%	13%	4%	11%	8%	9%	9%	8%
4.1-5.1 m/s	9%	15%	5%	13%	10%	11%	10%	9%
5.1-6.1 m/s	10%	16%	5%	14%	11%	13%	11%	10%
6.1-7.1 m/s	10%	17%	6%	15%	12%	14%	12%	10%
7.1-8.1 m/s	10%	17%	6%	16%	13%	14%	12%	10%
>8.1 m/s	10%	17%	6%	16%	14%	15%	12%	10%

Figure A-3: Sample Data- Wind Factors/ Frequencies of Wind



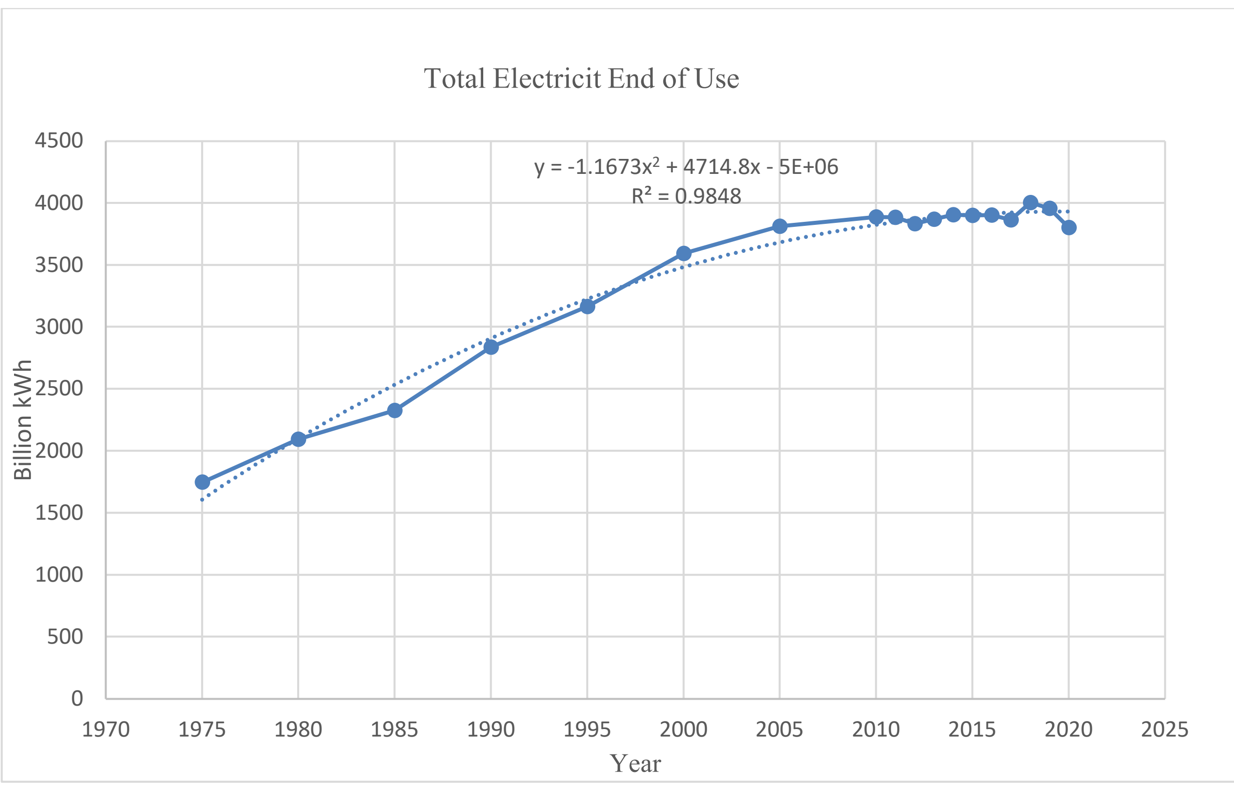


Figure A-4: Electrical Load Forecasting-Linear Regression

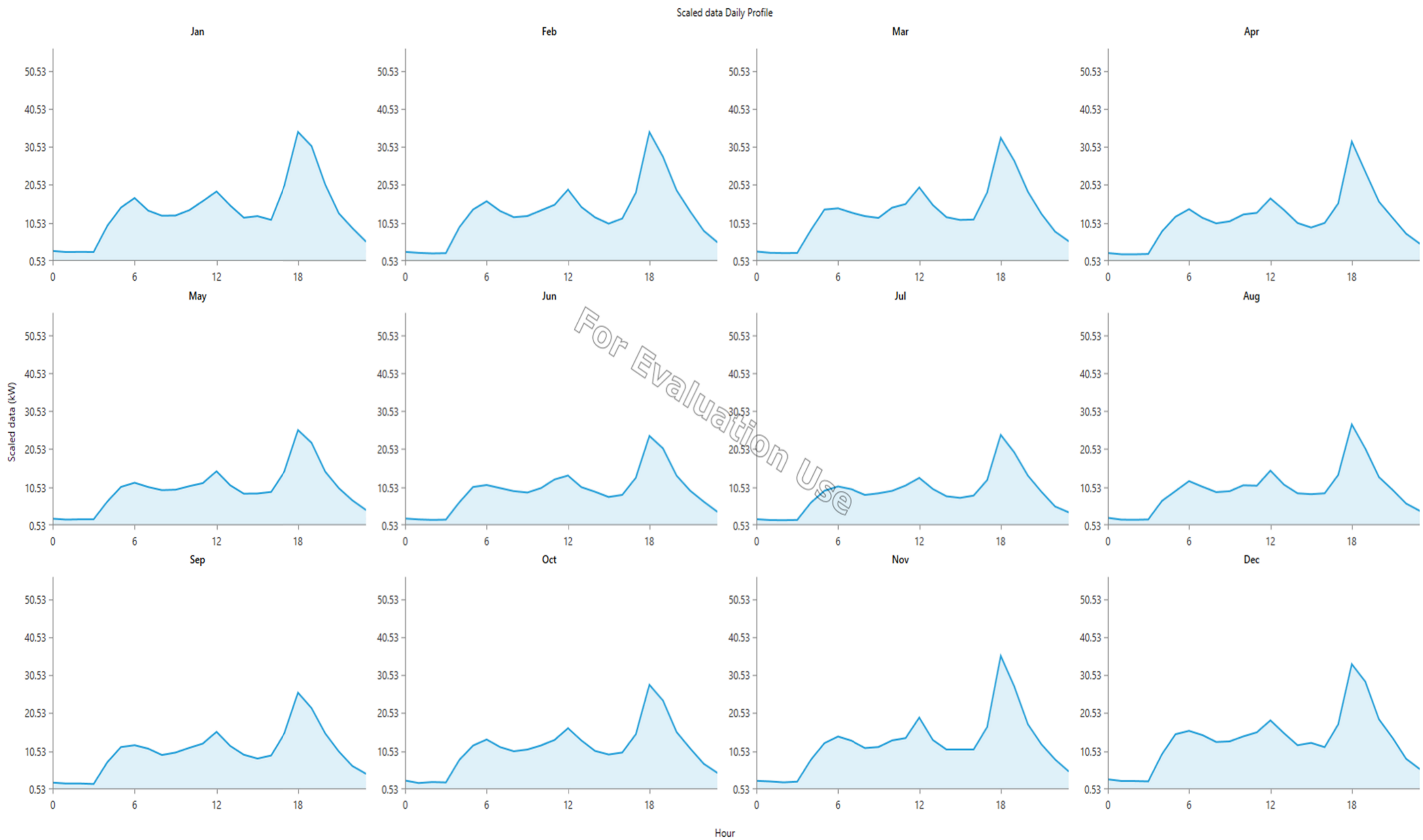
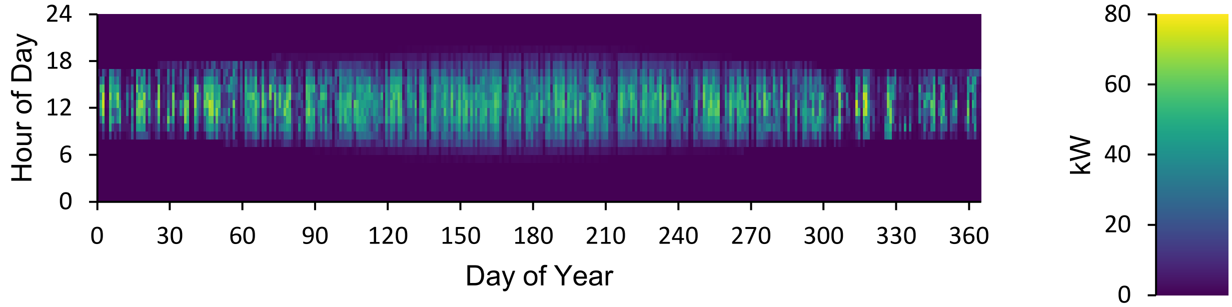


Figure A-5: Electrical Load Daily Profile by Month

PV: Trina Allmax M plus (490)			
Rated Capacity	64.4 kW	Total Production	92,142 kW
Capital Cost	$110,769	Maintenance Cost	1,314 $/yr
Specific Yield	1,431 kWh/kW	LCOE	0.0750 $/kWh
PV Penetration	92.3 %		



Wind Turbine: Eocycle EO10			
Quantity	4	Rated Capacity	40.0 kW
Wind Turbine Total Production	114,424 kWh/yr	Hours of Operation	5,718 hrs/yr
Capital Cost	$120,000	Maintenance Cost	2,400 $/yr
Wind Turbine Lifetime	20.0 years		

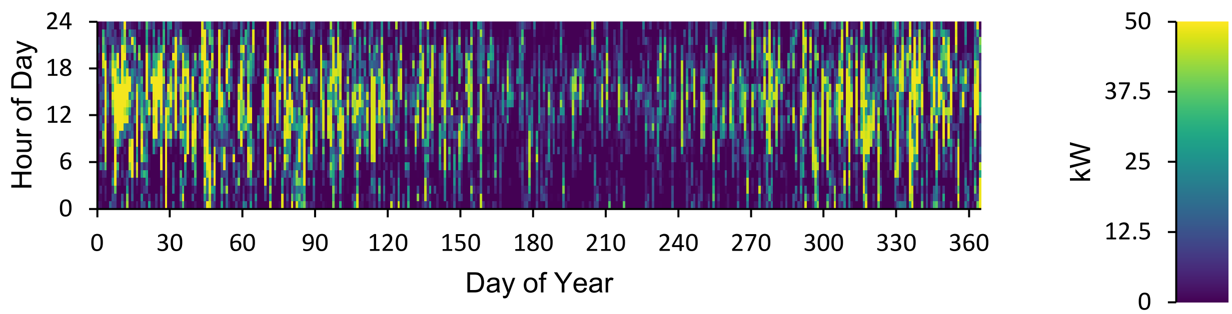
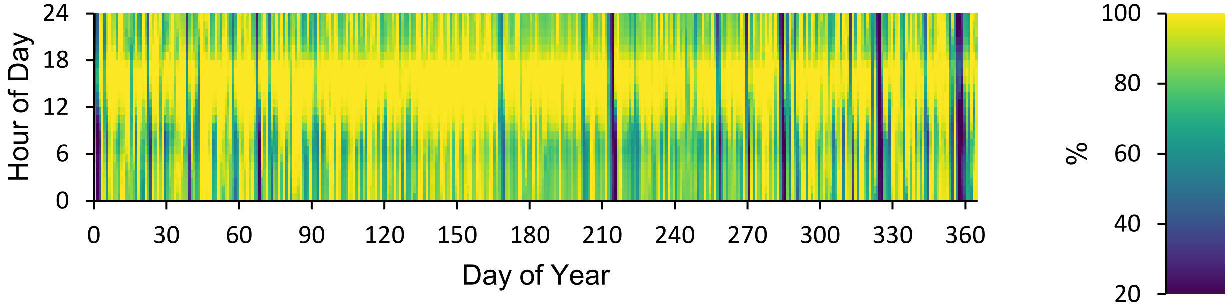


Figure A-6: Engineering Detail Component Data- Novi, Michigan

Storage: Discover AES 1.0kWh 24VDC			
Rated Capacity	397 kWh	Expected Life	15.0 yr
Annual Throughput	33,759 kWh/yr	Capital Costs	$258,750
Losses	1,731 kWh/yr	Autonomy	27.9 hr



Converter: System Converter

Capacity	**48.3 kW**	**Hours of Operation**	**5,298 hrs/yr**
Mean Output	5.43 kW	Energy Out	47,586 kWh/yr
Minimum Output	0 kW	Energy In	50,091 kWh/yr
Maximum Output	48.3 kW	Losses	2,505 kWh/yr
Capacity Factor	11.2 %		

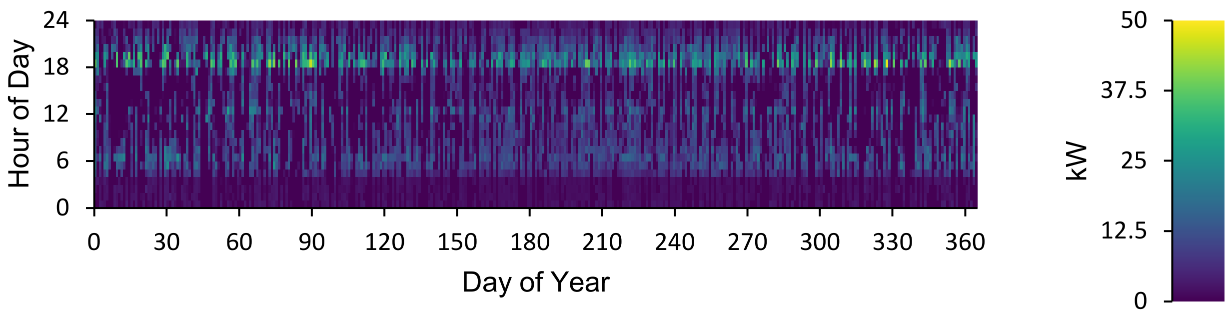
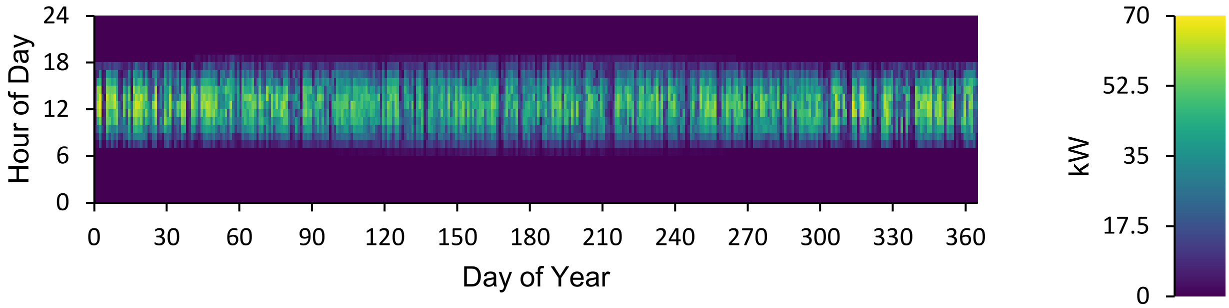


Figure A-7: Engineering Detail Component Data- Novi, Michigan

PV: Trina Allmax M plus (490)			
Rated Capacity	64.4 kW	Total Production	111,281 kW
Capital Cost	$110,768	Maintenance Cost	1,314 $/yr
Specific Yield	1,728 kWh/kW	LCOE	0.0621 $/kWh
PV Penetration	158 %		



Wind Turbine: Eocycle EO10			
Quantity	4	Rated Capacity	40.0 kW
Wind Turbine Total Production	238,754 kWh/yr	Hours of Operation	7,525 hrs/yr
Capital Cost	$120,000	Maintenance Cost	2,400 $/yr
Wind Turbine Lifetime	20.0 years		

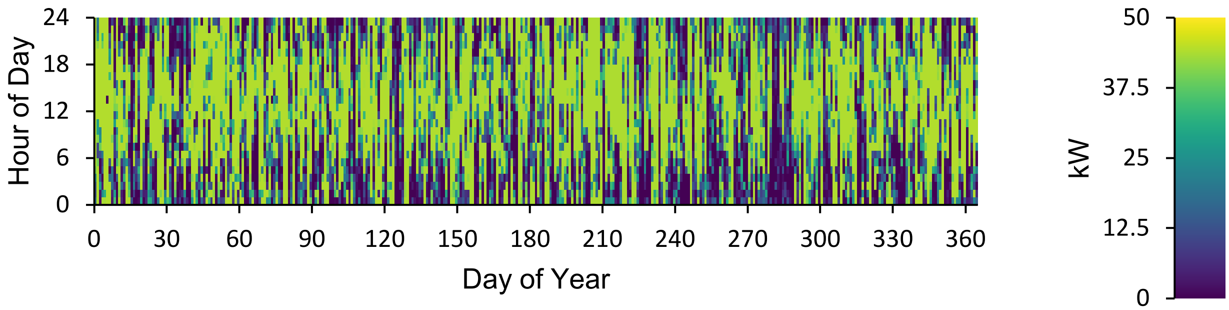
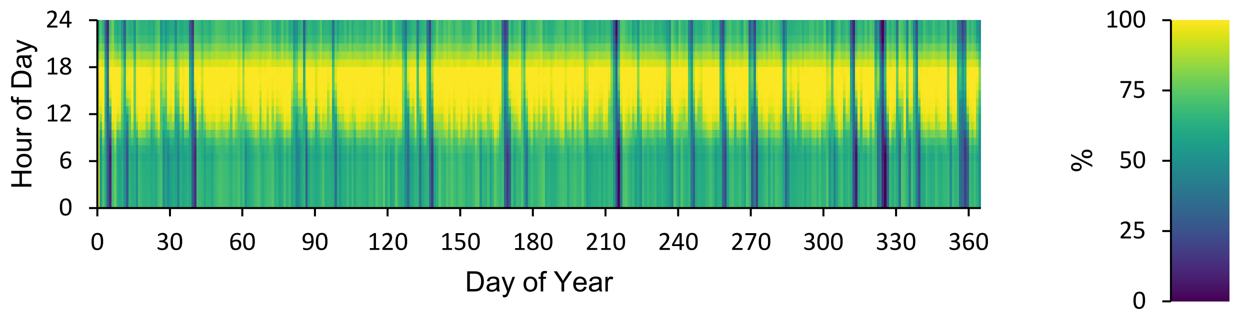


Figure A-8: Engineering Detail Component Data- Carretera Sabana Miches, Dominican Republic

Storage: Discover AES 1.0kWh 24VDC			
Rated Capacity	397 kWh	Expected Life	10.0 yr
Annual Throughput	54,432 kWh/yr	Capital Costs	$258,750
Losses	2,787 kWh/yr	Autonomy	49.4 hr



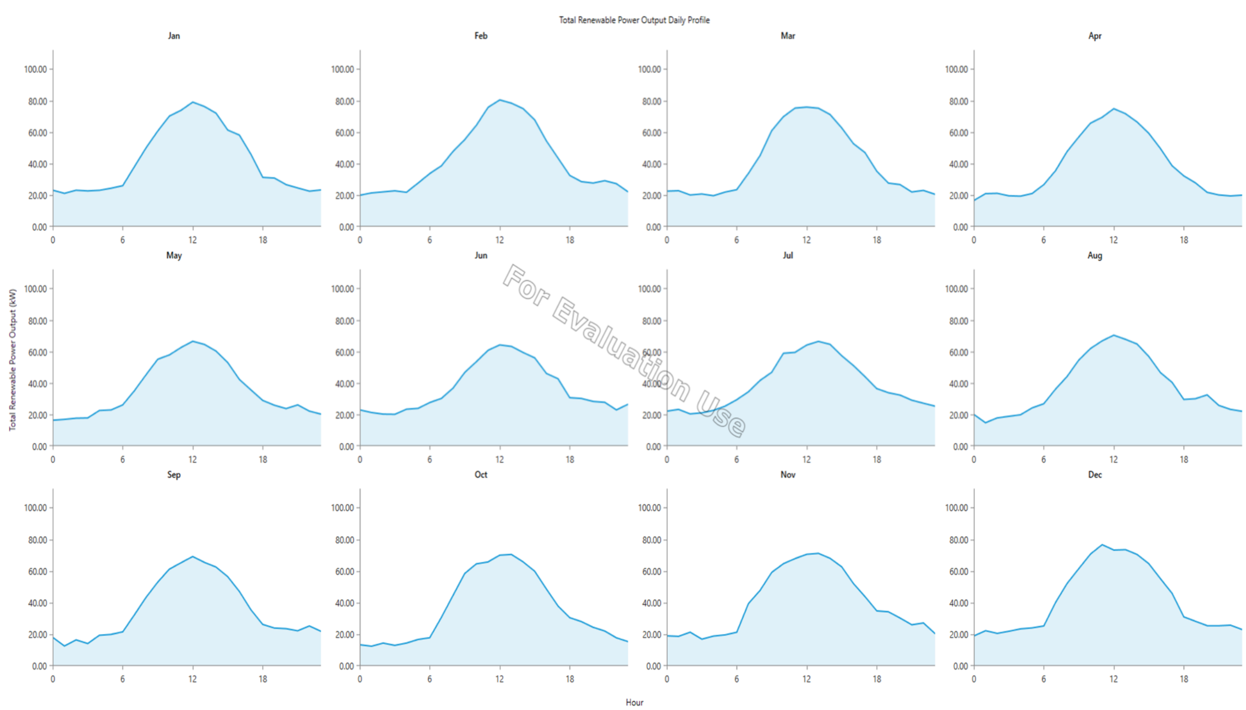


Figure A-9: Engineering Detail Component Data- Carretera Sabana Miches, Dominican Republic