OFF-GRID RENEWABLE ENERGY SYSTEMS FOR RESIDENTIAL POOLS

Bilal Rashid

Master of Engineering (Electrical & Electronics)

Master Thesis (18 units)

Supervisor: Dr. Amin Mahmoudi

October 2022

Submitted to the College of Science and Engineering in partial fulfilment of the requirements for the degree of "Master of Engineering (Electrical & Electronics)" at Flinders University, Adelaide, Australia

Declaration

I certify that this thesis:

1. Does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university
2. The research within will not be submitted for any other future degree or diploma without the permission of Flinders University; and
3. To the best of my knowledge and belief, it does not contain any material previously published or written by another person except where due reference is made in the text.

Signature of student...

Print name of student.......Bilal Rashid...........................

Date.........12-12-2022.......................................

I certify that I have read this thesis. In my opinion, it is fully adequate, in scope and quality, as a thesis for the Master of Engineering (Electrical and Electronics) degree. Furthermore, I confirm that I have provided feedback on this thesis, and the student has implemented it entirely.

Signature of Principal Supervisor.......Amin Mahmoudi Digitally signed by Amin Mahmoudi Date: 2022.12.12 09:55:06 +10'30'

Print name of Principal Supervisor........Amin Mahmoudi...

Date..............12/12/2022.......................................

Acknowledgment

بِسْمِ اللهِ الرَّحْمٰنِ الرَّحِيمِ

In the name of God, most Gracious, the most Merciful.

Firstly, I would like to express my sincere appreciation and deepest gratitude to my academic supervisor Dr Amin Mahmoudi for his utmost guidance and continuous support throughout my thesis. His unwavering support and coordination led me to my final research execution.

My profound appreciation goes to my family, especially my brother (**Kashif Rashid**), for always believing in me and supporting me throughout my life. I cannot thank him enough for his wisdom and for instilling the habit of thinking positively in me.

Likewise, I thank my cohort (Saif and Ana) for their utmost support throughout the study. You guys made this challenging time serene and memorable.

Thank You!!

Executive Summary

Due to the lack of availability of electrical power in the Adelaide region, it is essential to use renewable energy resources such as solar heat energy and wind kinetic energy to obtain electrical energy with minimum interruption and failure. Sunlight and kinetic energy obtained from wind are the types of renewable energy resources available in surplus amounts.

The project is related to designing and implementing an optimized, efficient, and robust power system by using maximum power point tracking (MPPT) for solar modules and a pitch control system for wind turbine systems to obtain the maximum possible power. The solar module is used under variable load conditions despite the variations of supplied input of solar irradiance for the solar photovoltaic (PV) system and variable wind speed for the wind turbine power system. A complete and comprehensive comparative analysis shall be done to suggest and choose the most optimum, efficient, and robust power system for the required load demand.

The electrical load used for the analysis will be swimming pool equipment, including the water pump, a chlorinator that will chlorinate the water from bacteria, and an electric heater that will warm up the water on winter days. Depending upon these load requirements and demands, the two central power systems will be designed and simulated; first, one is based on Solar PV, and the second one will be a wind turbine system. Via simulation-based testing and comprehensive critical comparative analysis, the best, optimized, effective, and efficient system will be recommended and chosen for the required loads' of electrical equipment of the swimming pool. The designed systems were analyzed in different seasons of Adelaide city at other times and hours of the day. The solar PV system was analyzed for twelve hours of the day for hot summer, hot winter, cold summer, and cold winter.

Moreover, the solar PV system was well analyzed at different times, like morning, noon, and evening in summer and winter. Similarly, the wind turbine system was analyzed for the summer and winter seasons with low and high-speed wind. The wind system was also simulated and studied during the morning, noon, and evening hours.

Keywords: Photovoltaic, Solar PV System, Renewable Resources, Maximum Power Point Tracking, Wind Turbine, Energy Management System, Renewable Energy.

TABLE OF CONTENTS

List of Figures

List of Tables

1. Introduction

Renewable energy is an environmentally friendly energy source called 'clean energy' or 'green energy.' Several types of renewable energy alternatives exist all across the globe: wind, biogas, hydro, solar, geothermal, tidal, and biogas energy that exists in different concentrations in different regions and climates of the world (Azad *et al.*, 2019).

Endowed with a plethora of diversified renewable and non-renewable means of energy, Australia tends to be the globe's ninth-largest energy-producing nation. If classified according to the countries, it secures the 11th spot in the world ranking for generating wind energy per person, leaving massive economies like France and China behind. However, Australia's wind energy generation sites are highly inclined to the Tasmanian and South Australian regions of the country that depict the most excellent wind generation rates across the globe, comparable to that of Texas and Iowa in the United States. Behind Iowa, South Australia (SA) of the National Electricity Market region holds the second highest per-person potential of renewable solar and wind energy while forming around 39% contribution to the country's electricity demand/entire generation. The SA trial and investigation of renewables is much more substantial than other areas. Countries such as Germany, Denmark, and Iowa with more significant renewables have been incorporated into larger grids. The SA grid is partly limited to only two electricity transmission lines; therefore, only 20% of its peak load can be procured from Victoria. On the contrary, Denmark has an extensive grid system to procure its whole peak load from other nations (Aziz, Oo and Stojcevski, 2018).

Wind energy forms one of the most significant contributors to energy within the renewable energy domain, which also alleviates the harmful environmental effects caused by greenhouse gases generated by burning fossil fuels. The domain of wind energy for energy production is significant for studying due to the massive potential that wind has to facilitate. According to a research study, wind energy utilisation comprised around 52% of the total global renewable consumption, whereas solar contributed only 21% of the entire global renewable consumption share. One reason for the distinction of wind energy from all other renewable energy forms is its capability to generate vast amounts of electricity at lesser costs. Furthermore, being one of the most promising forms of renewable energy, wind energy can be a significant resource for electricity generation in remote areas of Australia due to its abundant resources (Azad *et al.*, 2019; Tzen, 2020; Sadorsky, 2021).

As a potential renewable energy resource, solar energy is a viable alternative and has reduced fossil fuel dependencies. However, the photovoltaic and wind energy system outputs are governed by the geographical position of the system installation (Sawle, Gupta and Bohre, 2018a). While having the benefits of being a green energy resource that can generate significant amounts of electricity wherever sunlight is present, it also has some drawbacks, including lesser installed system efficiency (only 9-17%). In addition, being highly intermittent and impact several environmental factors, such as irradiation and temperature, on the voltage and current characteristics of the solar installation (Yilmaz, Kircay and Borekci, 2018)

Figure removed due to copyright restriction.

Figure 1.1 Components of the photovoltaic energy system (Hannan et al., 2019, p.24937)

Within the photovoltaic-energy system, including an energy system helps stabilise the intermittent nature of solar irradiation and circumvent the uncertainties associated with the system. Also, the energy system enables the users to store a certain amount of energy during daylight hours and eventually use it in the hours of darkness at night. Adding an energy system to a solar system only can enhance the economic yield of a 100kWp rooftop solar installation associated with a grid (Lian *et al.*, 2019a).

The entire world adopting resilient and optimal hybrid renewable energy systems can be attributed to two aspects: the future technological and economic benefits of the hybrid systems and the rapidly changing environment due to global warming caused by greenhouse gases resulting from fossil fuel burning. Hybrid renewable energy systems (HRES), particularly those with photovoltaic panels and wind turbines, can be constructed to operate either as a standalone or a grid-connected system. The currently designed control units have made it feasible to observe the grid's energy level measurement, energy requirement from autonomous charges, and the battery's state of charge. In contrast, the energy system can be grid-connected or operate independently (Basaran, Cetin, and Borekci, 2017).

For isolated regions, it is imperative to adequately size and chooses the system components that fulfil the energy demand and overcome system constraints at the most optimal system cost (Sawle, Gupta, and Bohre, 2018b; Combe et al., 2019; Lian et al., 2019b).

Figure removed due to copyright restriction.

Figure 1.2. Basic features of PV-wind HRES (Ganguly et al. 2018, p. 222)

1.1.Research Aims & Objectives

The research study aims to:

- Investigate and compare the solar PV and wind energy systems.
- Evaluate the feasibility and cost of powering a residential pool in Adelaide through an off-grid renewable energy system.
- Examine the effectiveness of battery systems for residential pools.
- Determine the most efficient renewable energy system for a residential pool.

1.2.Hypothesis

The hypothesis is that the resulting renewable energy system will fulfil the energy demands of the residential pools in Adelaide in varying weather conditions and for the different daily requirements. In addition, the designed system will be the most cost-feasible and efficient for residential pools.

1.3.Experimental Methodology

To achieve the defined aims and objectives, the project's first task was to collect yearly data on the daily usage of several residential areas across Australia. After data collection, an optimal-sized battery-PV system was designed to power a residential pool in a household. Then the designed system was optimised to function effectively in variable weather conditions throughout the year through simulation on MATLAB. Eventually, the best possible configuration was determined based on the simulation results.

2. Literature Review

2.1. Introduction

This literature review section will thoroughly review the works of the authors to present a detailed critique of the utilised approaches and the relevant outcomes with a particular focus on the following trends:

- On and off-grid wind energy systems, discussing the global trends of wind energy for a sustainable outlook and wind energy systems for Australian households.
- On and off-grid solar energy systems reviewing photovoltaic system design consideration and optimal PV sizing for residential areas.
- Hybrid renewable energy systems, addressing off-grid HRES, hybrid microgrids in remote areas, optimal capacity, and optimal sizing of HRES in Australia.
- Fuzzy logic approach examining the solar irradiance prediction using fuzzy logic policy and Fuzzy logic-based maximum power point tracking for PV systems.
- Deep neural networks, exploring the hourly solar irradiance forecast and PV/wind HRES applications.

2.2.On and Off-Grid Wind Energy Systems

2.2.1. Global Trends of Wind Energy for the Sustainable Future Outlook

Due to its massive potential, wind energy can fulfil energy demands at competitive prices to drive the globe toward a green economy and mitigate greenhouse gases. Therefore, strategic frameworks at the national and global levels are imperative to utilise the maximum potential of wind energy. As emphasised by Sadorsky (2021), who researched the driving elements for a batch of seventeen nationalities, including Australia, Ireland, China, Greece, India, Germany, Japan, Denmark, Italy, Canada, Portugal, Sweden, Spain, UK, Netherlands, France, and the US, that drive their consumption of renewable energy, specifically wind energy. The intent was to determine how each driving element varied with time for each country and the outlook of wind energy consumption soon. Renewable energy, renewable energy share, population, energy intensity, and financial circumstances have been determined as the factors that drive the use of renewable means for energy generation. It was asserted that the increased wind energy consumption was primarily driven by growth in renewable energy share. In contrast, wind energy consumption declined due to increased energy intensity.

2.2.2. Wind Energy Systems for South Australian Households

Several studies have investigated the optimal capacities of wind turbines and battery energy storage systems for Australian households to reduce the cost of electricity. Still, none of the studies has reported the power feasibility and cost analysis for powering a residential pool in a South-Australian household. Khezri et al. (2019) optimised the small wind turbine and battery energy storage system for grid-connected households (GCH) to obttain the most optimal capacity of 6kW for both small wind turbine (SWT) and SWT with a battery energy storage system (BES) within three distinct scenarios. The study affirmed the satisfaction of the zero-energy home criterion for two designs and the optimised system's capability to alter the peak load. Again, Khezri et al. (2022) developed home energy systems for GCH having: a small wind turbine (SWT) system only, and those having an SWT system assisted with battery energy systems with the aim of cost reductions. For the two configurations, a system was designed, with the inclusion of uncertainties, to operate with and without an electric vehicle. The study has validated the developed system by using a South Australian household as a case study considering the annual load profile, electricity rates, and hourly wind speed in the area as optimisation parameters. In addition, the statistics of ten-year wind speed, along with the relative load and EV uncertainties, have been used to determine the impact of EVs, household load, and power generation from the wind turbine on several aspects of the system. It has been concluded that a 6-kW SWT with optimal capacity can effectively reduce the electricity costs for both approaches (35% without EV & 27% with EV) of GCH.

In contrast, battery costs do not reduce household electricity expenses. The study also determined the SWT capacity for different EV models, with the highest power (7kW) being that of the Tesla and Nissan Leaf. At the same time, BMW and Zoe had 6kW optimal capacities.

2.3.On and Off-Grid Solar Systems

2.3.1. Photovoltaic System Design Considerations

Kumar et al. (2018) conducted research within the educational premises of a university "Karunya Institute of Technology and Sciences" in Coimbatore, to study the elements, operation, and installation design factors for technical sizing of on-grid solar photovoltaic (PV) energy systems. The study's system used as a sample is 95kWp with around 312 PV modules installed and four inverters of 25kWA. The research results indicate minimal greenhouse gas emissions, data on the amount of electricity generation, and electricity prevented from being wasted, concluding that PV installations within universities result in considerably lesser electricity costs and assist in modern-day research. Furthermore, the study verified the experimental evaluation using PV Watt and PVGIS tools to reveal the software results in complete synchronization with the experimental data.

2.3.2. Optimal Sizing of PV System for Households

Several research studies have reported sizing the PV capacity to obtain the optimal number for household applications like Donnellan, Soong, and Vowles (2018). They proposed the critical capacity methodology for technical sizing and energy storage capacity of PV installations that contribute to a deeper understanding of the optimisation process and enhance potential runtime compared to traditional methods. The proposed method was applied to a typical household along with a sensitivity analysis for the factors, including load profile for the house, mean PV data, and PV cost, to attain maximum benefit per investment route. The study identified the advantage of benefit per investment route in determining the three types of investment trends: small, medium and large. These are significant to locate as variations can influence the overall benefit.

In comparison to Donnellan, Soong, and Vowles (2018), Khezri, Mahmoudi, and Haque (2020) used a rule-based home energy management system incorporating real-time annual statistics of electricity utilisation, atmospheric temperature, electricity tariffs, and solar insulation factors to evaluate the most feasible PV capacity as 9kW and BES capacity as 11kW for a grid-connected house to eventually develop a cost-efficient solution (40% reduction in electricity cost). The research implemented uncertainty analysis (real-time data of ten years) and cash flow analysis to validate the ideal outcomes and determine the customer bills clearance during the project timeline, respectively. A case study of a South Australian residence was considered for practical implications. Standard operating procedures for all the households in the region are provided for them to choose as per the quotidian electricity demand and rooftop space at hand for the PV structure instalment of each of them. It has been concluded that the current prices of the battery system in the SA market do not result in the economic feasibility of being integrated into household energy systems. The study adopted the suggested novel approach in several states of Australia to deduce the feasibility of PV-only systems for the residential areas of SA due to their higher retail price.

2.4.Hybrid Renewable Energy Systems

Ganguly, Kalam, and Sayegh (2018) introduced renewable energy systems and the meteorological factors critical in determining power generation from HRES. Current research on several aspects related to HRES has been reviewed, including simulation, optimisation, sizing, and control both for individual energy systems and hybrid (solar-wind) systems. Furthermore, the authors continued to examine the system cost and power reliability through several optimisation methodologies, including the probabilistic method, iterative approach, and graphic construction method, to conclude that artificial intelligence can effectively reduce system expenses. Moreover, it has been deduced that a hybrid energy system indicates better performance metrics than a single renewable energy resource.

2.4.1. Optimal Sizing of HRES in South Australia

Saiprasad, Kalam, and Zayegh (2017) studied the feasibility of renewable energy systems within a university in Warrnambool, Australia, using HOMER software to determine economic versatility. Environmental aspects of the system, whereas Combe et al., 2019 have developed four approaches to hybrid scenarios for a minimal net cost over a 20-year timeframe by optimising the capacity of system components using particle swarm optimisation (PSO).

Combe et al. have developed the AC mini-grid for an isolated South Australian region to assert the viability of renewable hybrid power systems compared to diesel power systems. Real-time data was made part of the study to examine the hourly intervals while the AC system facilitates flexible power availability to the storage system. The economic superiority of the HRES in comparison to diesel power systems was reported through an appropriate sensitivity analysis of the suggested algorithm. However, Saiprasad, Kalam, and Zayegh (2017), despite having developed a green energy solution that resolved the issues of peak load requirements, greater sized HRES, and grid failure issues, resulted in higher costs of the hybrid renewable system for energy supply. Saiprasad, Kalam, and Zayegh (2017) mentioned the economic optimisation of HRES to claim revenues through feed-in tariffs.

Khezri, Mahmoudi, and Haque (2021) present a case study of a South Australian household to integrate the ideal sizing of the wind turbine (WT), photovoltaic (PV), and battery storage (BS) to develop a new demand side management (DSM) methodology for an independent house. The novel approach uses wind speed and solar insulation's day-ahead forecast and the state-of-charge level of the battery. A fuzzy logic approach has been utilised to manage load shifting effectively. In contrast, a realistic model for the battery has been obtained using the Rainflow algorithm to determine a better lifetime. The prominent feature of the proposed system was its timely implementation in houses.

Furthermore, it has been investigated that the PV-WT-BS system is the optimal configuration with the least LCOE of 57 ¢/kWh and BS capacity of 24kWh. Both of the operational parameters were considerably lesser than in previous studies. Also, it results in zero carbon dioxide emissions compared to the existing SA system and the two latest articles due to its entirely renewable energy storage dependency.

2.4.2. Hybrid Microgrids for Remote Areas

In addition to Combe et al. (2019), Mohamed et al. (2019) also worked on hybrid microgrids for remote areas by developing an effective algorithm with a two-stage framework to target cost-effective systems. Instead of assuming a specific microgrid topology, the novel algorithm took an optimal topology for the grid, where the first step involved topology selection and allocation of the appropriate equipment. In contrast, the second step constituted reliable functioning for the selected topology.

2.5.Fuzzy Logic Approach

2.5.1. Fuzzy Logic for Solar Irradiance Prediction

Mehta & Basak (2019) present a case study in Patiala, India, proposing a new methodology for predicting short-term solar radiation using a combined approach of fuzzy logic and multilinear regression. A barometer, pyranometer, and anemometer are the devices that have been part of the study. The novel method was utilised in the light of five variables, including humidity, temperature, speed of the wind, atmospheric pressure, and the day interval, to finally compare and contrast the results with the actual time solar radiance data for the selected location. A root means square error of 10.011, while an absolute percentage error of 1.703% was reported by the proposed combined approach compared with the real-time solar irradiance statistics to conclude the fuzzy logic method was adequate based on the error analysis. Another research study by Al-Kaissi & Al-Taai (2021) also employed the fuzzy logic technique for greater precision and accuracy in predicting solar irradiation. Still, the areas for the case study were four locations within Iraq. The employed approach used cloud cover and temperature as data for input statistics to reduce the influence of uncertainties, including wind speed, amount of rainfall, solar irradiation, and air pressure. The research incorporated data for two consecutive years (2018 & 2019) to conclude the importance of topography in receiving the flux of radiation with the most excellent flux of radiation received in the Mosul region of the country (1100, 5 w/m^2), while Al-Basra is the region of the smallest flux amount of solar radiation (802, 7 w/m^2). In addition, the primary factor affecting solar irradiance was determined to be cloud cover.

2.5.2. FLC-Based Maximum Point Power Tracking

The use of fuzzy logic control approach in PV system design is to reduce the uncertainty due to more significant error percentages and maximize the system power output. Recently, Li et al. (2019) proposed a new FLC approach by introducing a third beta factor with maximum point power tracking (MPPT) algorithm for PV applications. The authors claim that the novel approach can overcome the shortcomings of the conventional fuzzy logic technique, simplifying the membership functions of fuzzy logic by reducing to eleven, encompassing an extensive range of operating conditions (rapidly varying environmental factors and cloud cover resulting in lesser irradiation), and decreasing the system dependence on the user's understanding and comprehension. The developed algorithm was tested for varying conditions of solar irradiance and load resistance data to validate the algorithm's accuracy, unlike the conventional FLC that exhibited universality for altering operating specifications. It has also been said to eradicate the MPPT oscillations while enhancing the converging speed through validation on an experimental prototype and simulation results. Also, the decreased user dependency was attributed to the direct calculation of the beta factor from modulated current and voltage values.

Another effort in this regard has been made by Khan & Mathew (2019), who proposed an FLC-based MPPT system to enhance the power efficiency and reliability of the wind turbine, photovoltaic, and fuel-cell-based hybrid energy system along with direct current (DC) converters. The authors aimed to develop an HRES with maximum power output at DC-link. Several input variables had been altered to determine an optimal outcome with maximum power efficiency for both grid-connected and standalone energy systems, as validated through simulations on Simulink. The study results revealed increased efficiency of the devised HRES system due to the MPPT method.

2.6.Deep Neural Networks (DNNs)

2.6.1. Deep Neural Network for Hourly PV Irradiance Forecast

The forecast of power generation of PV systems has been of particular interest to researchers due to its highly intermittent nature. Several studies have been conducted in several world regions to propose novel techniques for improving the solar irradiance forecast.

While Alzahrani et al. (2017) presented DNNs as the most appropriate approach for predicting solar irradiance, He et al. (2020) highlighted the shortcomings of the conventional DNNs methods (catastrophic forgetting). They proposed two continuous learning situations to overcome the challenges of neural network architecture modification to acclimatise to novel circumstances and incorporate the latest/new data into the existing neural network model after extracting the data from the consecutively obtained measurement values. Getting the statistics from a German grid power station, the two situations had been derived from the historical power data values to conclude that continuous learning algorithms enhance power predictions resulting in sustainable prediction systems for the rapidly advancing energy markets and addressing the continual changes in intelligent grids due to growing cities, i.e. new residential areas or corporate buildings. The study presented a lesser forgetting ratio of elastic weight consideration (EWC) and online EWC algorithm; however, the training time was the function of the scenario. It has been highlighted how essential it is to integrate the changes in the control algorithms as they are the founding frameworks for intelligent renewable energy drives.

In addition to the contributions of Alzahrani et al. (2017) and He et al. (2020), Succetti et al. (2020) developed four deep neural models based on long short-term memory (LSTM) networks (RNN having the capacity to address long-term coupling) as a means of practical system management tools for forecasting solar system output and enhancing the robustness of smart grids. While two of the four models also utilised neural networks due to their greater conceptuality levels, the suggested models were applied to real-time energy issues. The reference (standard) for the study was the traditional univariate methodology. However, the study's results deduced the potential applications of the multivariate approach in real-time situations, as multi-LSTM networks are the most acceptable way to deal with more significant data variability without retraining.

Bamisile et al. (2022) researched to compare the predictive capacity of the deep learning model with the machine learning model to determine the most efficient algorithm for both diffuse solar radiation and global solar radiation forecast through practical application in Nigeria. The machine learning models, including random forest, support vector regression and polynomial regression, have been assessed in the study, while the deep learning models that have become a part of the study constitute a recurrent neural network, artificial neural network, and convolutional neural network. The developed model was tested by using twelve-year meteorological statistics in an hourly time step within four different regions in Nigeria to explicitly determine adequate prediction accuracy (root mean square error of 82.22 W/m^2) of deep learning models than the machine learning models for both diffuse solar radiation and global solar radiation. The research results suggested RNN as the most appropriate for two locations, while CNN was the most appropriate method for the other two locations. However, except for support variable regression, machine learning models depicted a smaller period for testing and training, making them potential candidates for less computational approaches.

2.6.2. DNN for PV/Wind HRES

Ab-Belkhair et al. (2020) suggested a novel algorithm for MPPT-based deep neural network controllers to serve wind-only applications and PV/wind hybrid renewable energy systems under variable climatic conditions. The novel algorithm was developed in MATLAB to test the operating performance of the HRES DNN controller under several circumstances with lesser total harmonic distortion (less than 5%) and enhanced power quality for grid integration. A simulation model was developed to integrate wind and hybrid energy systems with an inverter-based microgrid. Voltage, current profiles, and full harmonic displays of the photovoltaic inverter system enhanced power quality.

2.7.Summary

In conclusion, Sadorsky (2021) talked about the importance of wind energy as a massive renewable resource in seventeen countries to determine the factors that drive wind energy consumption along with the changes in the consumption level for each country. Khezri et al. (2019) and Khezri et al. (2022) determined the optimal capacities of SWT turbine and SWT assisted with BES systems, the latter with the inclusion of EV consideration.

Reviewing the PV systems, Kumar et al. (2020) studied the elements, operation, and installation design factors for a university to conclude cost-effective electricity and research assistance. Donnellan, Soong, and Vowles (2018) and Khezri, Mahmoudi, and Haque (2020) studied the optimal sizing of PV systems with critical capacity and rule-based home energy management systems, respectively. Khezri, Mahmoudi, and Haque (2020) developed two configurations to identify 9kW as optimal PV capacity and 11kW BES capacity with a 40% reduction in electricity cost in a South Australian household, while Donnellan, Soong, and Vowles (2018) considered a home for optimal PV and storage determination for most significant benefit per investment.

Several researchers studied HRES in their attempts to try different combinations of renewable energy means for optimal sizing of energy systems. For example, Saiprasad, Kalam, and Zayegh (2017) used Homer Pro, Combe et al. (2019) utilised particle swarm optimisation while Khezri, Mahmoudi, and Haque (2021) applied a fuzzy logic-based DSM approach to study the optimal sizing and capacities of the HRES. Saiprasad, Kalam, and Zayegh (2017) conducted research at a university in Australia, Khezri, Mahmoudi, and Haque (2021) case-studied a household in SA while Come et al. (2019) developed a mini-grid system for a remote area in Australia. While researching remote areas, Mohamed et al. (2019) conducted a study to establish an effective planning algorithm for hybrid microgrids indicating the possible capital costs while ensuring technical stability.

Outlining the fuzzy logic approach discussion, Mehta & Basak (2019) and Al-Kaissi & Al-Taai (2021) predicted solar irradiance for India and Iraq, respectively. Mehta & Basak (2019) used a combined approach of multivariate linear regression and fuzzy logic approach to indicate the superiority of fuzzy logic over regression analysis. At the same time, Al-Kaissi Al-Taai (2021) determined the primary factor influencing solar irradiance along with the topology-dictated flux values in different regions of the study. In addition, Li et al. (2019) and Khan & Mathews (2019) used FLC-based MPPT tracking to enhance the algorithm's accuracy and power efficiency, respectively. Finally, Li et al. (2019) introduced a new parameter to develop a novel algorithm.

Deep neural networks have become a widespread approach to predicting the most accurate irradiance for PV systems, as done by He et al. (2020), Succetti et al. (2020), and Bamisile et al. (2022). They used deep neural networks to study solar irradiance in different world regions. He et al. (2020) highlighted the issue of catastrophic forgetting of DNNs and proposed two continuous learning scenarios to mitigate the forgetting problem for more innovative and resilient grids. Succetti et al. (2020) utilised the LSTM network to develop four deep neural models capable of handling more extensive data sets without retraining. Bamisile et al. (2022) also determined solar irradiation by comparing deep learning and machine learning models to conclude RNN and CNN as the appropriate models for respective locations.

2.8.Research Gap

After an extensive literature survey, it has been identified that no research has identified an effective renewable system for residential power pools in Australia while being cost feasible and power-efficient all over the year. Therefore, this research aims to bridge the gap and develop a viable renewable energy system for a residential pool in Adelaide.

2.9.Research Limitations

The study aims to research an optimal-sized off-grid PV energy system for residential pools in Australia only, particularly in Adelaide. Therefore, the research results are valid mainly for the Adelaide region only. For other regions of the country, the research results could not be helpful due to different weather conditions and environmental factors that could require a completely different type of PV system. In addition, the limited availability of solar and wind irradiation data could affect the accuracy of the research outcomes.

3. Methodology

3.1.Related and Relevant Resources for Solar and Wind Speed Data for Adelaide City

To ensure a proper analysis of the solar PV and wind turbine system, it is essential to obtain or collect data on solar irradiance or solar intensity for summer and winter, especially on hot and cold days, to ensure efficient analysis. Similarly, the different wind speed is for the complete and comprehensive simulation-based analysis of the wind turbine's developed power system. For example, the resource for wind speed for Adelaide city had been obtained from the same web page (*Renewables.ninja*, 2019).

3.2.Importance of Summer and Winter Days Analysis

The load consumption or load demand is variable in each season. For example, the heater is required for heating the pool water in the winter season only, whereas it is not used in the summer season. Similarly, each of the other pieces of equipment, including the chlorinator, water pump, and electric heater, will not be used simultaneously; therefore, it is necessary to conduct a complete and comprehensive analysis of the system during the summer and winter seasons. Thus, the load operations or working of load have been analysed for one hour according to the given time slot.

Table 3.1 Working period of the loads in an hour

Sr. No	Season	Load	Operating Time in One hour
1	Hot Summer Day	Water Pump Chlorination Heater	Turn on after 15 Minutes Turn it on after 30 Minutes off
2	Cold Summer Day	Water Pump Chlorination Heater	Turn on after 15 Minutes Turn it on after 30 Minutes off
3	Hot Winter Day	Water Pump Chlorination Heater	Turn on after 15 Minutes Turn it on after 30 Minutes Turn it on after 45 Minutes
4	Cold Winter Day	Water Pump Chlorination Heater	Turn ON after 15 Minutes Turn it on after 30 Minutes Turn it on after 45 Minutes

Table 3.2 Working period of the loads for twelve-hour daytime

The system designed is to run for 12 hours in a day from 6 am till 6 pm. Table 3.3 shows the start time of each load after the solar system starts generating enough power to operate the load.

Sr. No	Electrical Components	Operating Hours
1	Electrical Heater	10 am - 3 pm, 3 hours
2	Chlorinator	10 am - 4 pm, 6 hours
3	Water Pump	10 am - 3 pm, 5 hours

The above-mentioned operational time for working equipment represents the twelve hours of daytime working. The water pump is run for 5 hours during which the pool fills up and the chlorinator is run for 6 hours to keep the pool clean for the entire day. Heater is utilized in winter season and can heat up the entire pool in 3 hours, hence the 3 hours operating time. Output electrical load demand and pool technical data can be observed in table 3.3.

Table 3.3 Technical specifications of the pool and electrical load

Sr. No	Pool Size (L*W*D) in m	Water capacity (litres)	Pump capacity (lpm)	Water Pump (W)	Solar heater	Chlorination (W)	Lighting
1	7*3*1.5	30000	62.5	750	500W	120	Normal LEDs
2	9*4*1.5	48000	100	900	1000	150	Normal LEDs
3	10*5*1.5	75000	156	1100	1200	190	Normal LEDs

The system in such a way that can provide enough power to run all the equipment simultaneously. The maximum power that the equipment can use during the running of the pool is calculated as:

$$P_{out\ max} = P_{water\ Pump} + P_{chlorination} + P_{solar\ Heater} \tag{3.1}$$

$$P_{out\ max} = 900 + 150 + 1000 = 2050\ W \tag{3.2}$$

Solar power systems along close loop MPPT control designed should deliver at least 2050 watts to drive all the loads. As all the electrical load elements required 220 volts to operate so:

$$V_L = 220\ V \tag{3.3}$$

It is necessary to obtain the maximum possible power from the solar system via Maximum power point tracking technique and control. The power efficiency of the solar PV system was determined with the help of the power efficiency formula shown in equation 3.4. When the entire load is applied to the system, it is required to operate the solar PV system at the maximum possible efficiency.

$$Power\ efficiency = \frac{output\ usefull\ power}{Input\ delivered\ Total\ power} * 100 \qquad (3.4)$$

$$Max. Power\ efficiency = \frac{2050}{2500} * 100 = 82\% \qquad (3.5)$$

Software used for modelling and simulations:

1. MATLAB
2. MS Excel
3. Fuzzy Logic Editor
4. Simulink
5. Draw IO

3.3.Simulink Model for Open Loop System of Solar PV System

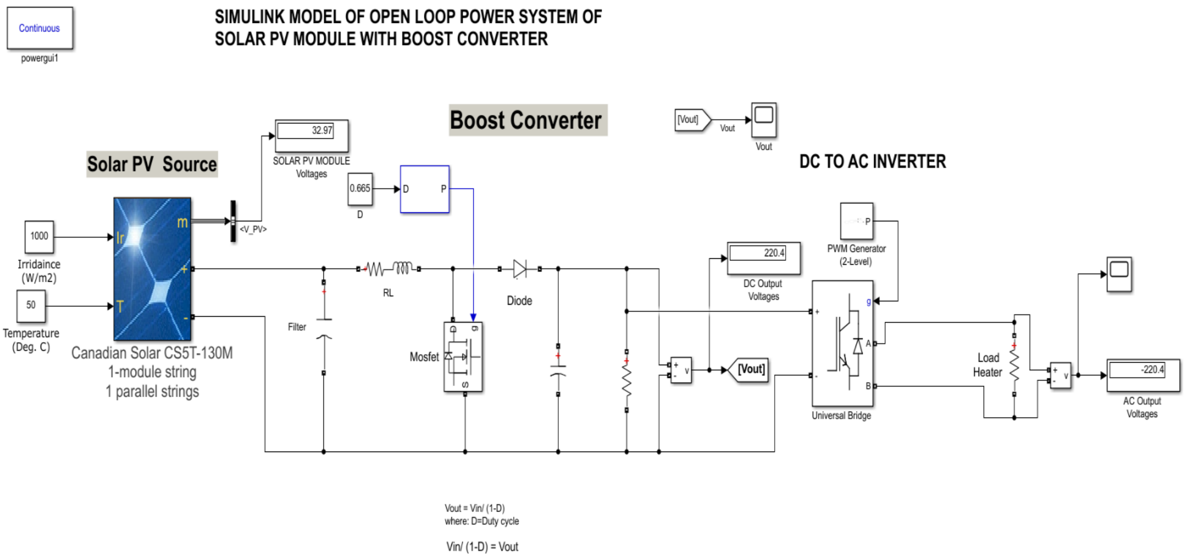


Figure 3.1 Simulink model for open loop system of solar PV system

Figure 3.1 represents the designed solar PV Simulink model with the open loop system. The output of PV solar is connected directly to the boost converter, and there is no implementation of feedback along MPPT control. Instead, the production from PV is boosted depending upon the manually selected duty cycle value for the PWM gate pulse signal applied to the gate of MOSFET of the boost converter. This open loop system has the maximum possible output power, rather than non-uniform, fluctuating power.

3.4.Boost Converter Design Calculations

$$V_{in} = V_L + V_o \tag{3.6}$$

$$V_L = L\frac{d_{iL}}{dt} = V_{in} - V_o \tag{3.7}$$

$$\frac{di_L}{dt} = \frac{d_{iL}}{(1-D)T} = \frac{V_{in} - V_o}{L} \tag{3.8}$$

$$\frac{di_L}{dt} = \frac{V_{in} - V_o}{L}(1-D)T \tag{3.9}$$

$$d_i closed + d_i open = 0 \tag{3.10}$$

$$\frac{V_{in} - V_o}{L}(1-D)T + \left(-\frac{V_o}{L}\right)DT = 0 \tag{3.11}$$

$$\frac{V_o}{V_{in}} = \frac{1}{1-D} \tag{3.12}$$

The inductor value was calculated as follows:

$$L = \frac{V_s * D}{F_s * I_s} \tag{3.13}$$

The capacitor value was calculated as follows:

$$C = \frac{I_o * D}{F_s * V_o} \tag{3.14}$$

Where:

Fs➔ is switching frequency

Io➔ output load current

Vs➔ supplied voltages

D➔ Duty cycle

Is➔ supplied current

The designed system should be able to work in minimum time for which the switching frequency was set as follows:

$$F_s = 20KHz = 20000Hz$$

The value of the inductor was calculated as follows:

$$L = \frac{30 * 0.5}{20000 * 3.33} \tag{3.15}$$

$$L = \frac{30 * 0.5}{20000 * 3.33} \tag{3.16}$$

$$L = 2.25 * 10^{-4}H = 225\, mH \tag{3.17}$$

For an ideal case, the output power equals the input power.

$$P_{out} = P_{in} \tag{3.18}$$

$$P_{out} = 100\ W \tag{3.19}$$

Required output voltages for the heating system:

$$V_o = 220\ V \tag{3.20}$$

The output load current will be:

$$I_o = \frac{P}{V_o} \tag{3.21}$$

$$I_o = \frac{100}{220} = 2.2\ A \tag{3.22}$$

The output capacitance is

$$C = \frac{I_o * D}{F_s * V_o} \tag{3.23}$$

$$C = \frac{2.2 * 50}{20{,}000 * 220} \tag{3.24}$$

$$C = 2.5 * 10^{-5}f = 25uf \tag{3.25}$$

3.5.Simulink Model for Closed Loop Solar MPPT System Design

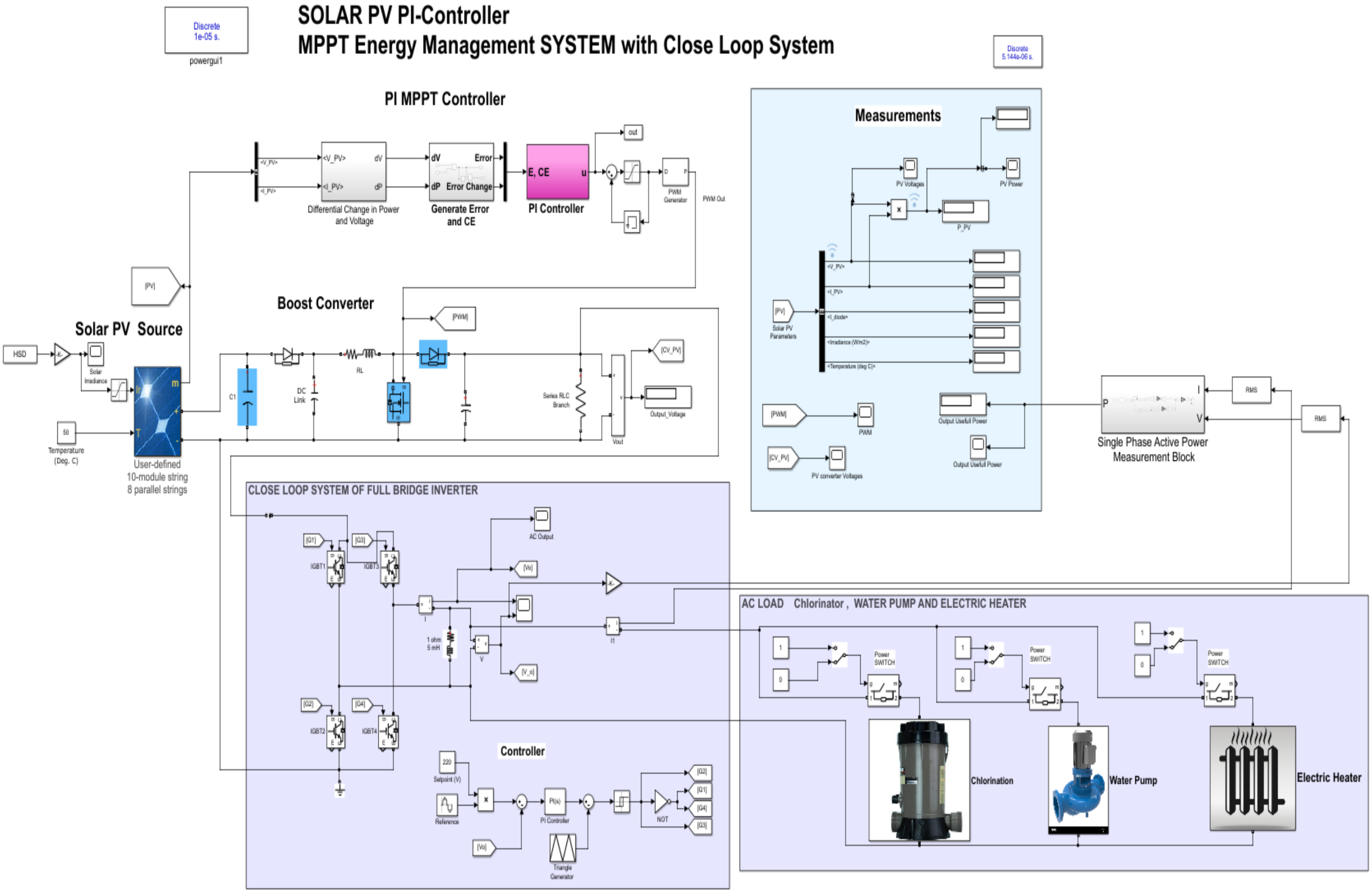


Figure 3.2 Simulink model for closed-loop solar MPPT system

Figure 3.2 shows the complete designed Simulink block model of the PV system with the MPPT control system, inverter, load, and monitoring sections. The actual values of PV power in the form of current and voltages are fed to the MPPT control unit, where the error of output power is calculated. Depending upon actual and error values, the control signal was generated in the form of PWM. The closed loop full bridge inverter ensured the controlled voltages of AC 220 V with a sine wave. The electrical heater, chlorinator, and water pump will be used as AC load (Ravindran and Padmanabhan, 2017).

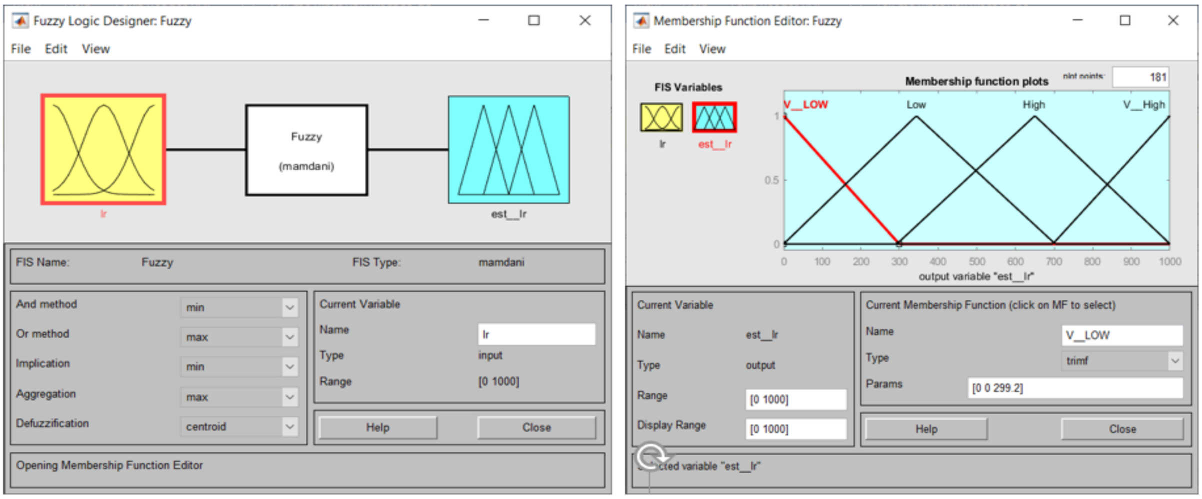
3.6.Fuzzy Logic inference Model Design and Implementation for Solar Irradiance and Wind

3.6.1. Speed Data Estimation

To better understand the working of the system an in-depth hourly analysis was performed. The solar irradiance data was limited to hour based hence, it was imperative to design and develop the fuzzy logic inference model to estimate the solar irradiance and obtain the number of data sets to perform the in-depth hourly analysis.

3.6.2. Reason for Designing the Fuzzy Logic Inference System

- Due to access to limited data or minimum data points for solar irradiance as well as wind analysis like sunrise, noon as well as a sunset.
- It is required to estimate solar irradiance data with a more extensive data set for smooth and uniform data analysis.



FIS Name: Fuzzy
FIS Type: mamdani
And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid
Current Variable
Name: Ir
Type: input
Range: [0 1000]
Opening Membership Function Editor

Current Variable
Name: est__Ir
Type: output
Range: [0 1000]
Display Range: [0 1000]
Current Membership Function (click on MF to select)
Name: V__LOW
Type: trimf
Params: [0 0 299.2]
plot points: 181
…cted variable "est__Ir"

Figure 3.3 Defining the crisp inputs and outputs of fuzzy logic inference model

With a limited solar irradiance dataset, the input for the fuzzy logic system is solar irradiance with few data points. Therefore, the information and output were defined by triangular membership functions with maximum overlapping to ensure smooth and uniform production of estimated solar irradiance for a PV system and wind speed for a wind power system (Allah Hamadi *et al.*, 2018).

3.7.Solar PV with Lithium-Ion Battery Interface

To get smoother, uniform, robust, and resilient performance metrics from solar PV systems, installing and connecting the lithium-ion energy storage bank is required. The reason to choose lithium-ion batteries instead of other batteries was that these batteries have a higher charge-to-mass density, lesser weight, longer lifetime, smaller charging duration, and more extended power backup compared to other family batteries.

3.7.1. Solar PV System with Lithium-Ion Battery Electrical Energy Storage

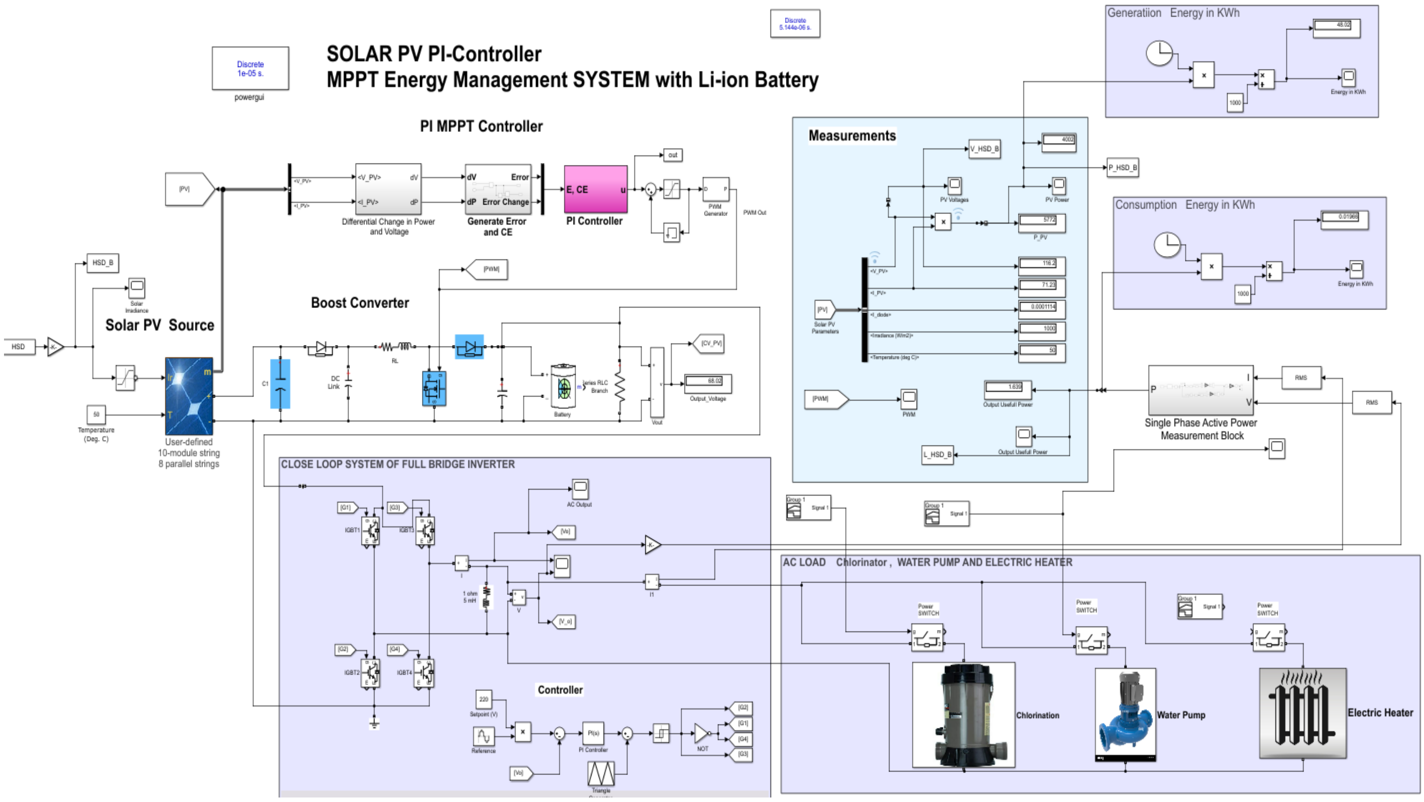


Figure 3.4 Solar PV system with a lithium-ion battery electrical energy storage

The Lithium-ion battery is installed with a solar PV system to store an ample amount of energy and deliver uniform and smooth output power when required. However, the solar PV system provides a non-uniform output when the battery or energy-storing unit is disconnected. Moreover, to get rid of variations or fluctuations of obtained power from the PV system, it is necessary to integrate the battery.

3.8.Wind Turbine Power System

To analyse the system with different renewable energy resource power systems such as wind energy, we have to design, develop and implement the wind turbine power system to deliver the electrical power to the required electrical loads of pools. Wind turbine simulink block is interfaced or connected with a wind turbine permanent magnet synchronous generator. The input parameter, wind speed, is applied for different seasons, like summer and winter days. A simulation-based analysis was performed for wind turbine power systems to get a comparative study with a solar PV system, and we will observe the differences. The significant advantage of installing the wind turbine is that we can get the electrical power directly and supply to the load without inversion of DC to AC or conversion from AC to DC etc.

3.8.1. Simulink Block Model of Wind Turbine Power System

The complete designed wind turbine system has multiple subsystems, blocks, and components is shown in figure 3.5.

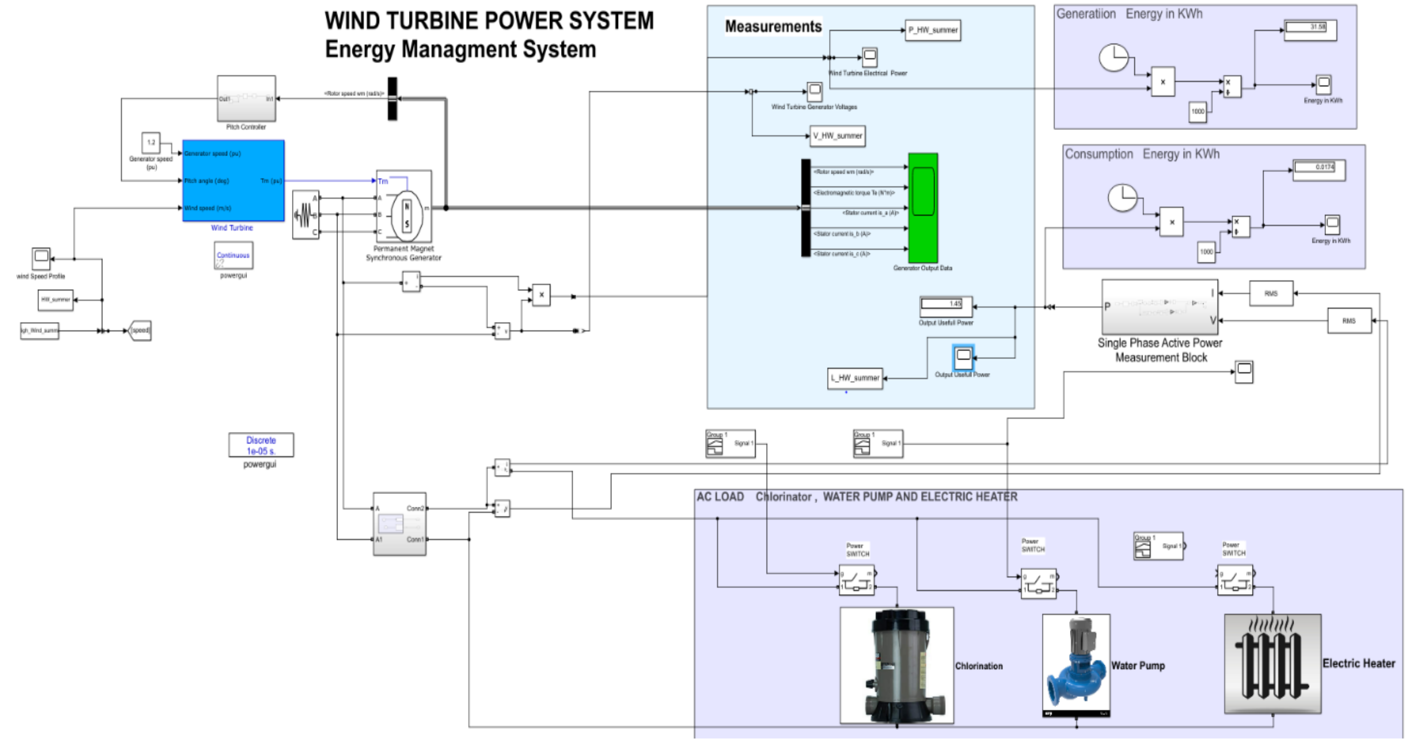


Figure 3.5 Simulink block model of wind turbine power system

3.8.2. Wind Turbine

This section will discuss the implementation of wind turbines for the energy management system of the pool. The wind energy converts to mechanical strength, and mechanical power is transferred to a permanent magnet synchronous generator PMSG. As a result, the AC power is obtained from PMSG, eliminating the need to rectify the AC power into DC or vice versa. This results in lesser power losses in the wind turbine power system.

3.8.3. Pitch Controller Block

The output power obtained from the wind turbine system depends on two primary inputs. The first one is wind speed, and the second one is pitch angle. The pitch angle must be controlled to get robust and maximized results. Therefore, a pitch controller was implemented for the system. A PI based pitch controller was designed in order to get maximum mechanical torque from the wind turbine in a controlled manner.

4. Results and Discussions

4.1.Simulation for Solar PV Close MPPT System without Battery

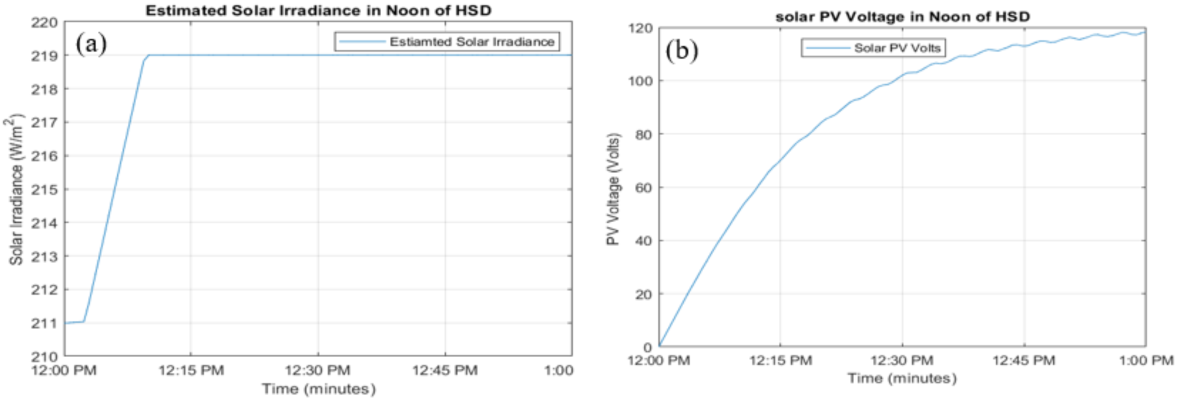


Figure 4.1 (a). Solar irradiance on a hot summer day (b). Solar PV voltage on hot summer day

Figure 4.1 (a) shows the in-depth hourly analysis of the system from 12 pm to 1 pm, the system is turned on at 12 pm and the system response are analysed for 1 hour to understand the working of the system. The results shown for the simulation of solar PV without battery interface are the maximised and optimised results obtained on hot summer days (HSD) the noon as solar irradiance or solar intensity is maximum at

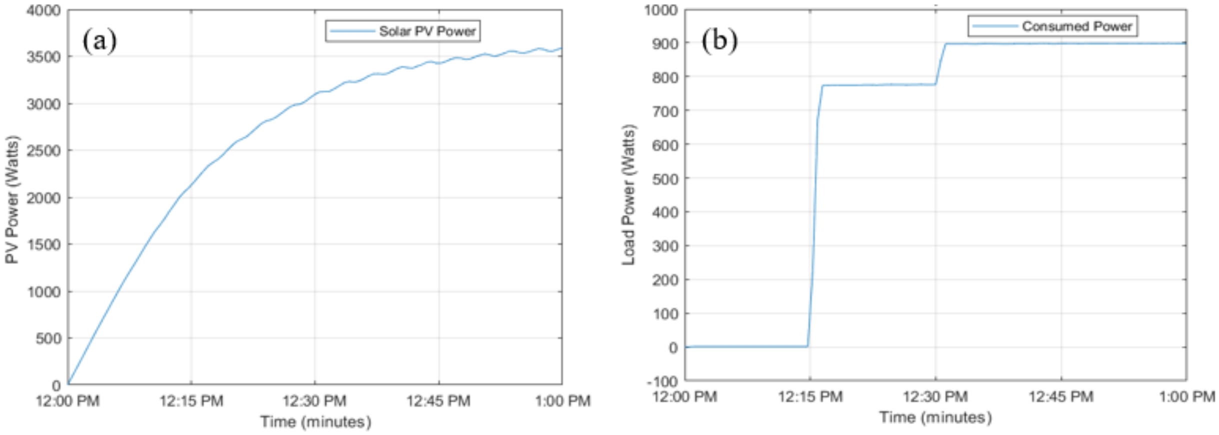


Figure 4.2. (a). Solar PV system output power in HSD noon (b). Hot summer noon load power consumption

noon of the summer day. The fuzzy logic inference model obtains the estimated solar irradiance profile. Two points are in the fuzzy inference system saturation block. First, the output voltage received by the solar PV system is almost 120 volts (maximum voltage).

The power delivered by the solar PV system in HSD noon is almost 3700 W. This power is practically maximum, allowing the chlorinator and water pump to run at noon of HSD. It was observed that the water pump is turned on after 15 minutes; it consumes 790 to 800 W which is suitable for the pump as we have surplus input supply power at noon on a hot summer day. Then the chlorinator is turned on after 30 minutes; the pump and chlorinator both consume just 950 W; it is best to turn on these loads at this time.

4.2.Simulation For Solar Cell PV Close MPPT System with Lithium-Ion Battery

4.2.1. Energy Storage

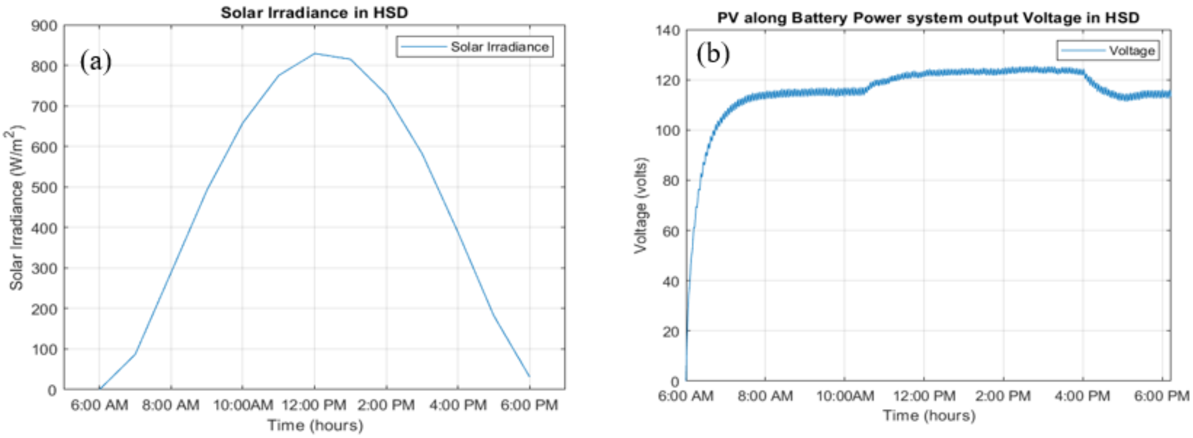


Figure 4.3 (a). Solar Irradiance profile in HSD (b). Solar PV voltage

Figure 4.3 shows the solar irradiance data profile on hot summer days for twelve hours. The maximum irradiance is obtained at noon of the daytime. This solar irradiance data is supplied to the solar PV system, and the results of solar PV output voltages are accepted along with consumed power by the load. Solar PV system battery unit supplied the output voltage with PI MPPT controller on a hot summer day of almost 120 V. These are the maximum possible voltages of solar PV systems in HSD that are possible only through the installed battery.

The system's output power, along with the battery, is obtained at almost 4500 W with a battery system on hot summer days. And this is the maximum possible power with a battery system on a hot summer day. Moreover, it is observed that the output power response is smooth regardless of the variations in solar Irradiances.

It is observed that the heater is not being used on a hot summer day. The chlorinator and the water pump are working; both consume the required power of almost 1150 W. Both loads work efficiently on hot summer days connected with solar PV systems along the battery unit.

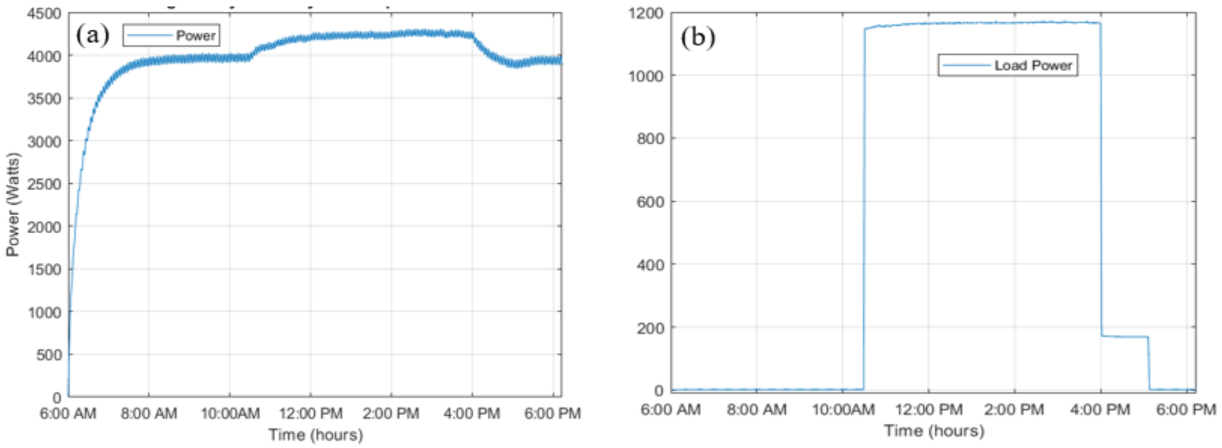


Figure 4.4 (a). Solar PV along battery system power in HSD (b). Output load consumed power on a hot summer day

4.3.Simulation of the Wind Power System on a Summer Day

Figure 4.5(a) shows the wind speed profile of obtained data of high wind speed on summer days. The wind speed profile has a maximum value of 12m/s, as observed in the wind speed profile. This wind speed data is fed to the wind turbine Simulink model and analysed in the developed power system based on the wind turbine connected to the loads via electric PMSG. Figure 4.5(b) shows the output voltages obtained by the wind power system with high wind speed applied to the wind turbine. The voltages are 120 V, the maximum possible voltage obtained by wind power systems using high wind speed on summer days.

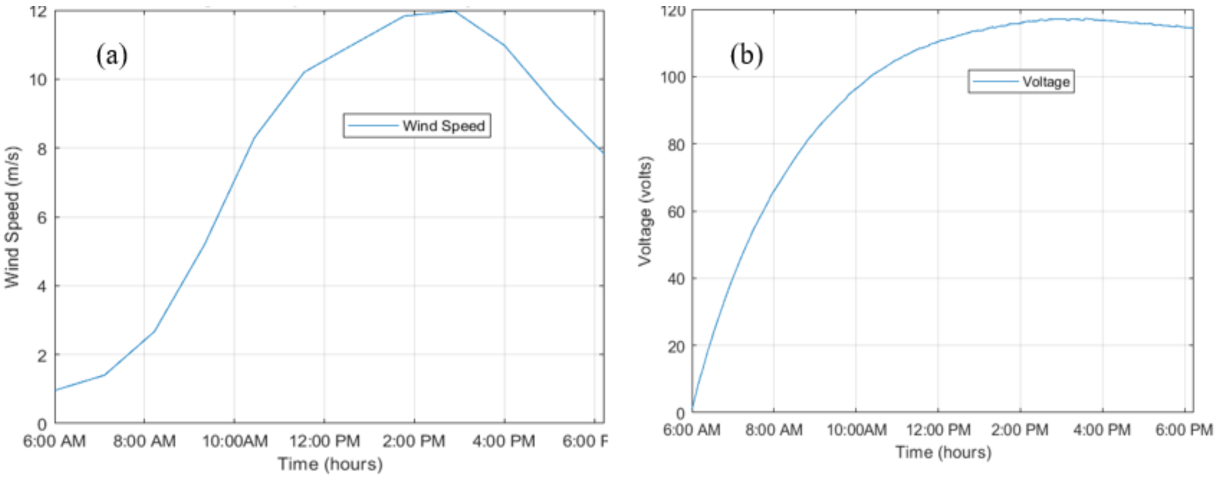


Figure 4.5 (a). Wind speed on a summer day (b). Wind power system output voltage

Initially the system was at rest due to which there was no power and at 6 pm the wind turbine was turned on and the power generated can be seen in figure 4.6. the system It was observed that the strength received by the wind turbine is not smooth relative to the output power obtained by the solar PV system. The power waveform is high peak and drastically reduced depending upon the wind speed supplied to the wind turbine. The maximum possible power obtained by the wind turbine is almost 4800 W with high wind speed delivered on a summer day, and 4100 W with high wind speed supplied power on a summer night. Chlorinator and the water pump can be turned on due to a surplus amount of energy from the source.

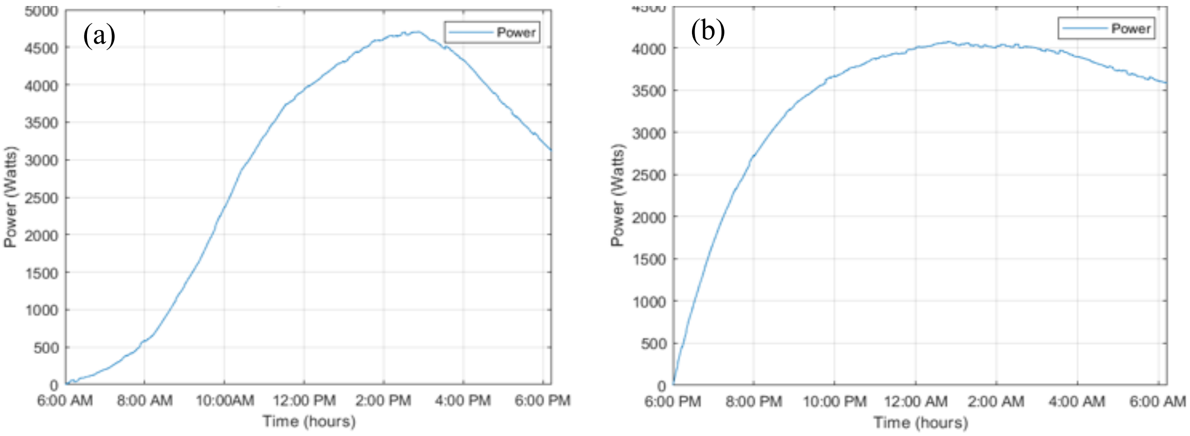


Figure 4.6 (a). Wind system obtained power on a summer day (b). The wind system derived power on summer night

4.4.Simulation of the Wind Power System on a Summer Night

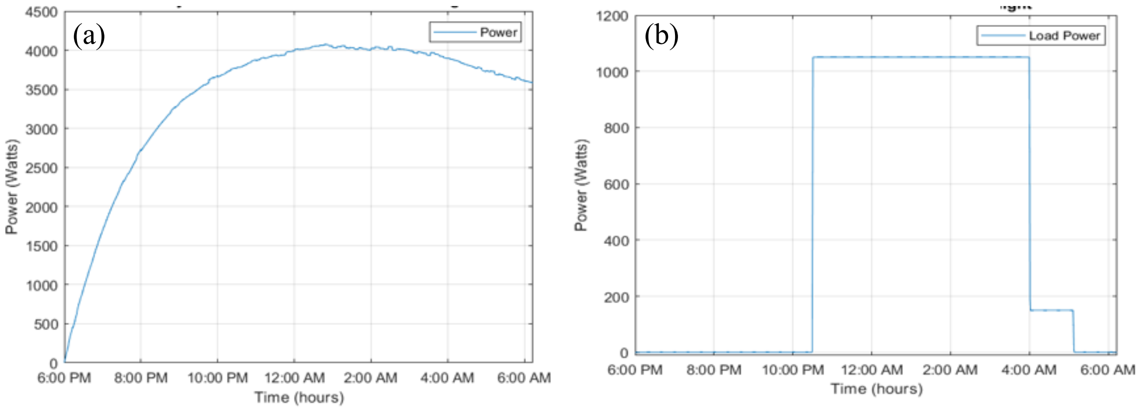


Figure 4.7 (a) Wind system power on a summer night (b). Load consumed on a summer night

Figure 4.7 shows the output power obtained by the wind power system with wind speed applied to the wind turbine on a summer night. The power is almost 4200 W, the maximum possible power obtained by a wind power system using wind speed on a summer night. The consumed load power on a summer night is also shown.

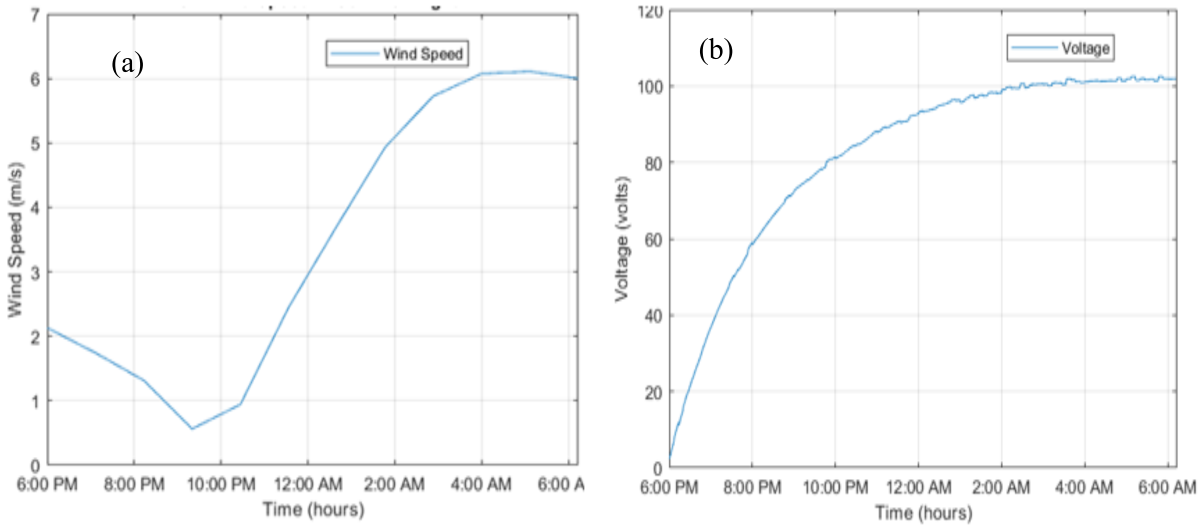


Figure 4.8 (a). Wind speed on a summer night (b). Wind system output voltages on a summer night

Figure 4.8 shows the wind speed profile obtained from wind speed data on a summer night and output voltages on a summer night. The wind speed profile has a maximum value of 6 m/s. This wind speed data is fed to the turbine Simulink model, and analysed the obtained voltage for the wind system is based on the wind turbine connected to the loads via electric PMSG.

4.5.Output Power of a Wind Energy System on a Winter Day

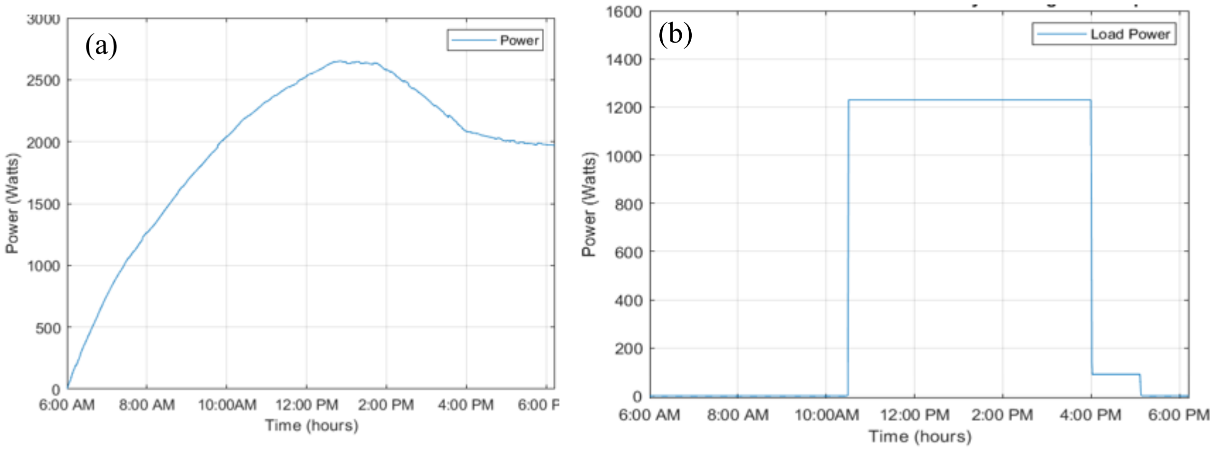


Figure 4.9 (a). Wind system obtained power on a winter day (b). Load consumed power on a winter day

Figure 4.9 shows the wind speed profile of obtained data for wind speed on a winter day. The wind speed profile has a maximum value of 7.7 m/s. This wind speed data was fed to the wind turbine Simulink model and analysed the obtained voltages and power by the system. the maximum possible voltages received were 95 V on a winter day.

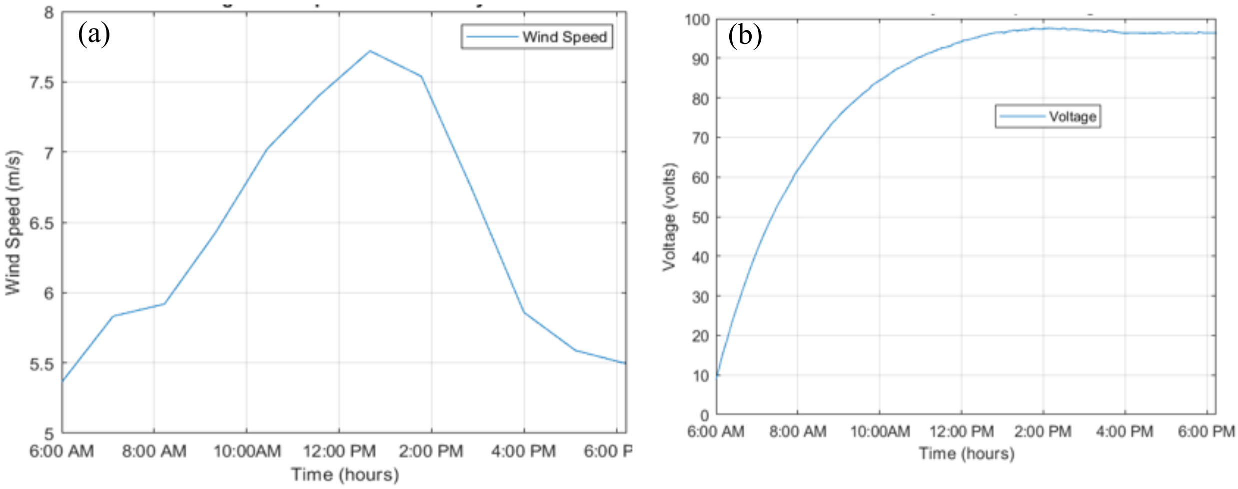


Figure 4.10 (a). Wind speed on a winter day (b). Wind system voltage on a winter day

Figure 4.10 shows the power obtained by the wind power system with wind speed supplied to the wind turbine on winter days. It was noticed that the energy received by the wind turbine is not smooth relative to the output power obtained by the solar PV system. The maximum possible power obtained by the wind turbine is almost 2800 W, with wind speed supplied on winter days. The load consumption plot represents the power consumption by the pool electrical loads in winter day energy obtained by the wind turbine system.

4.6.Simulation of the Wind Power System on a Winter Night

Fig 4.11 shows the wind speed profile of obtained data of high wind speed on a winter night. As shown in figure 4.11, the wind speed profile was fed to the wind turbine. The voltage of the wind system is also shown in the above figure by the wind system analysis performed on a winter night.

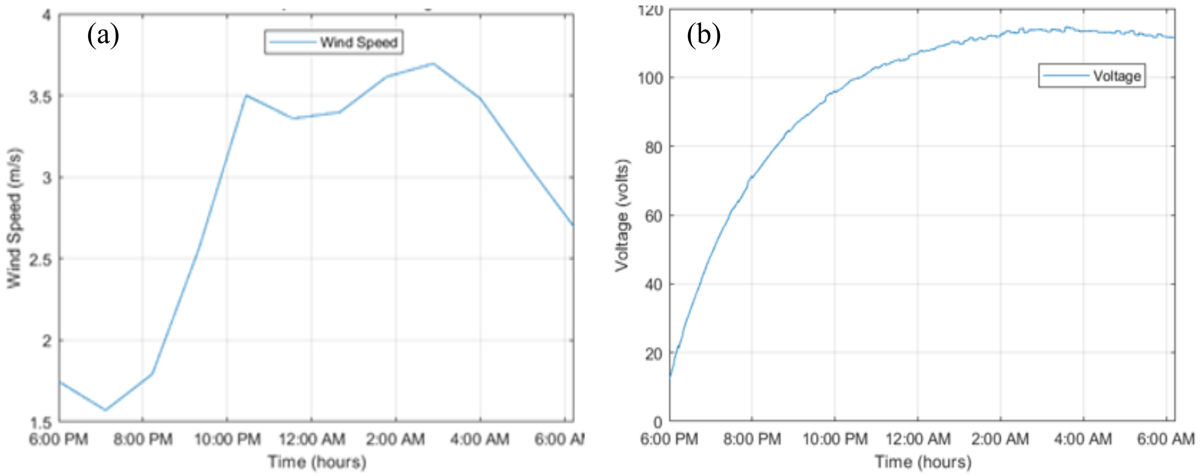


Figure 4.11 (a). Wind speed on a winter night (b). Wind system voltage on a winter night

Figure 4.12 shows the power obtained by the wind power system with high wind speed supplied to the wind turbine on a winter night. It was noticed that the energy received by the wind turbine is not smooth relative to the output power obtained by the solar PV system. The power consumed by the loads is almost 2100 W because the water heater is turned on in winter with the other equipment. The chlorinator, water pump, and heater cannot be turned on simultaneously from the wind turbine source as surplus power is obtained from the system.

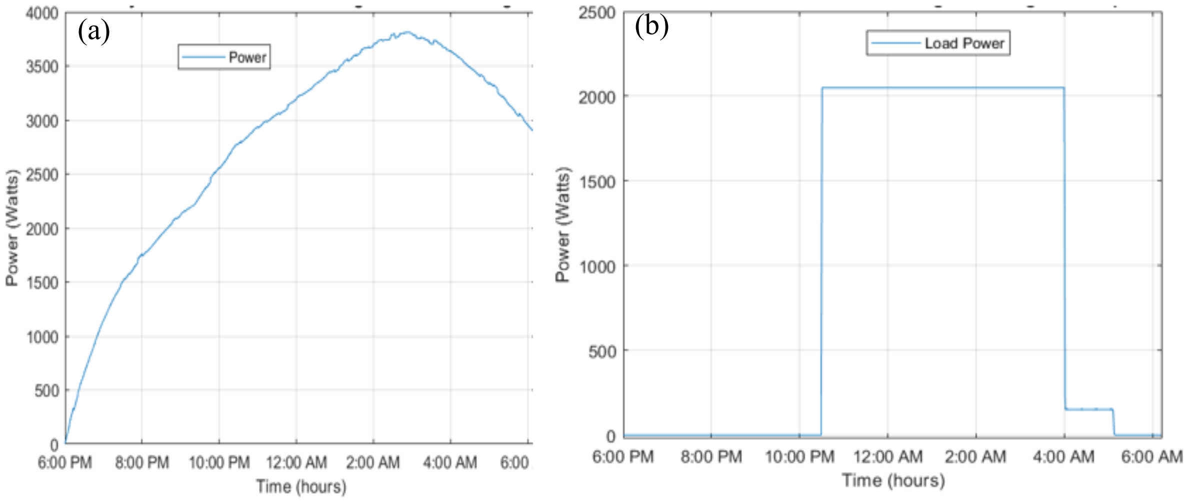


Figure 4.12 (a). The output power of a wind system on a winter night (b). Consumed power by load

Table 4.1 Obtained power comparison for wind turbine system on summer and winter day and night

Season and Time	**Obtained Output Power**	Response Behavior / Characteristics
Summer Day	4800 W	Not-Smooth, irregular, fluctuated output response
Summer Night	4100 W	Not-Smooth, irregular, fluctuated output response
Winter Day	2800 W	Not-Smooth, irregular, fluctuated output response
Winter Night	3800 W	Not-Smooth, irregular, fluctuated output response

4.7.Comparative Analysis Table

Table 4.2 Comparative analysis table

Type of System	Output Power (W)	Voltages **(V)**	Response Behavior / Characteristics
Solar PV along MPPT without Battery	3700 W	119 V	Non-Uniform, irregular, fluctuated output response, exhibit discontinuity
Solar PV along MPPT with Battery	4300 W	122 V	Uniform, regular, Optimised output response exhibits continuity
Wind Power system	4700 W Max 4300 W Final	118 V Max 115 V Final	Not-Smooth, irregular, fluctuated output response, exhibit discontinuity

4.8.Cost Analysis

4.8.1. Average Energy Generated by the Solar PV System on a Hot Summer Day

- **Hot summer day**

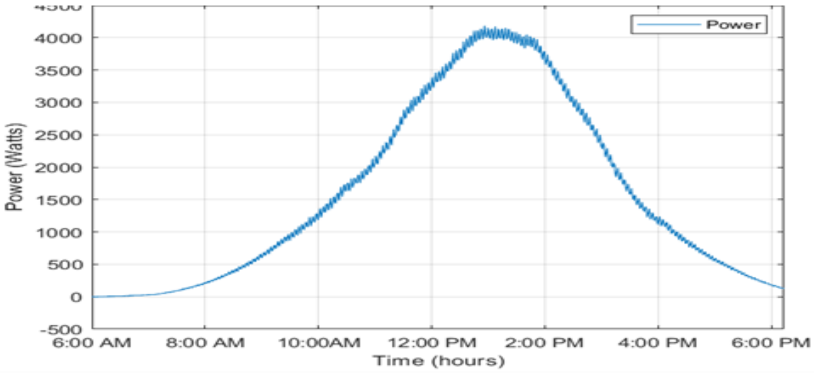


Figure 4.13 Power generated by the PV system on a single hot summer day

$$Energy\ produced = \frac{\left(\frac{(5*4000)}{2} + \frac{(5*4000)}{2}\right)}{1000} = 20\ kWh \tag{4.1}$$

There is an efficiency factor involved as the power generated by the PV system cannot be consumed directly as the produced DC output has to be converted into AC by an inverter for usage in the home appliances. Similarly, the surplus DC power is stored in the batteries and released once the direct solar energy is less than the load power (James, 2022). Assuming a power conversion efficiency of 85%.

$$Available\ Energy = 0.85 * 20\ kW.h = 17\ kW.h \tag{4.2}$$

4.8.2. Average Energy Generated by the Solar PV System on a Cold Summer Day

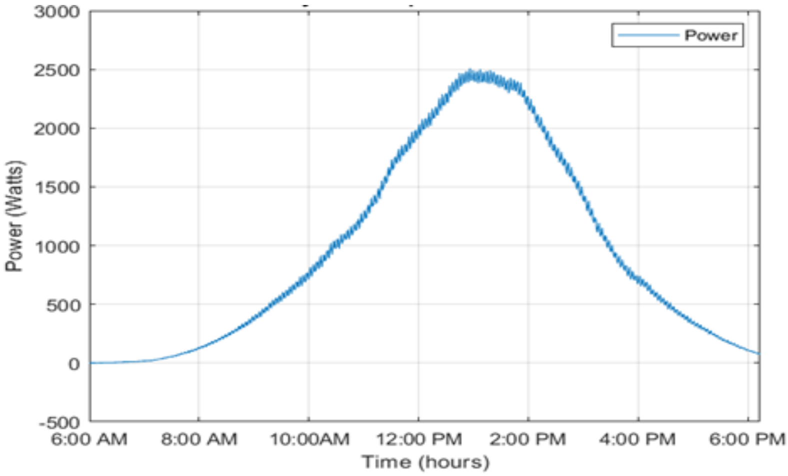


Figure 4.14 Power generation by PV system on a cold summer day

The area under the curve can be calculated to get the total Kilowatt-hours of energy generated by the PV cell. Triangular approximation is used to calculate the exact data as generated by the system.

$$Energy\ produced = \frac{\left(\frac{(5*2400)}{2} + \frac{(5*2400)}{2}\right)}{1000} = 12\ kWh \tag{4.3}$$

The efficiency of the power conversion of the solar inverter would be around 85%. Therefore, on a cold summer day:

$$Available\ Energy = 0.85 * 12\ kW.h = 10.2\ kW.h \tag{4.4}$$

4.8.3. Average Energy Generated by the Solar PV System on a Cold Winter Day

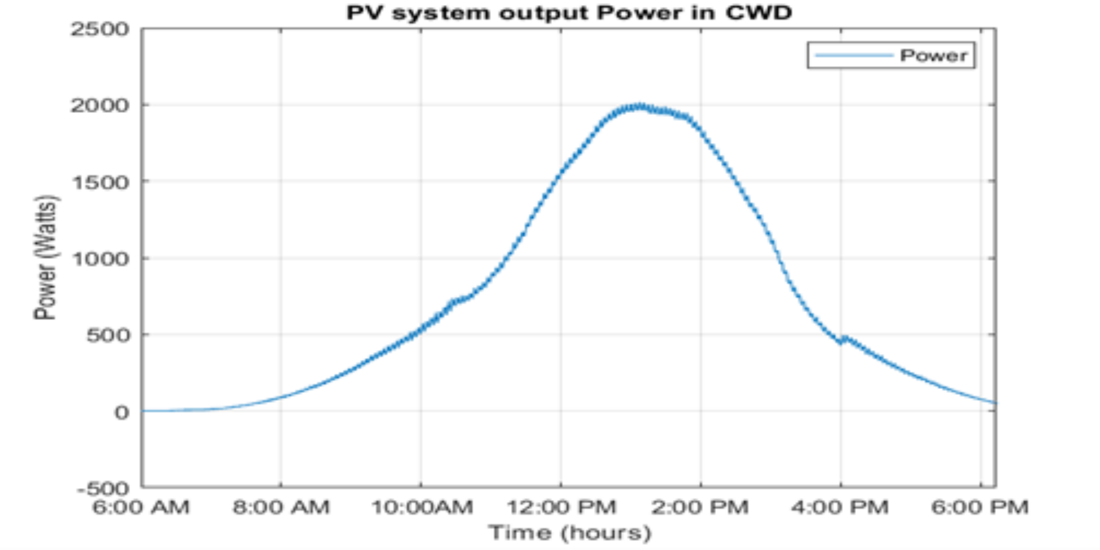


Figure 4.15. Power generated by the solar PV system on a cold winter day

The area under the curve can be calculated to calculate the total Kilowatt-hours of energy generated by the PV cell. From Figure 4.15, the area under the curve is:

$$Energy\ produced = \frac{\left(\frac{(5*1900)}{2}+\frac{(5*1900)}{2}\right)}{1000} = 9.5\ kWh \qquad (4.5)$$

Assuming a power conversion of the solar inverter of around 85%,

$$Available\ Energy = 0.85 * 9.5\ kW.h = 8.075\ kW.h \qquad (4.6)$$

4.8.4. Energy Generated by the Solar PV System per Year

On average, winters in South Australia range from June to August, while the rest of the months account for summers and spring (Australia, 2022). Based on the analysis performed by the system for several weather conditions i.e. HSD, CSD, HWD, and CWD and approximation of the yearly generated power can be done. To calculate the overall kilowatt-hours (units) of power generated by the solar PV system per year can be calculated as follows:

June – October (winter season) = 5 months = approx. 140 days

November – May (summer season) = 7 months = approx. 225 days

(4.7)

$$Energy\ gnerated\ per\ year = \left((140\ *\ 8.9) + (225\ *\ 13.6)\right) = 4309.5\ kWh/yr$$

$$Avg.Energy\ generated\ per\ day = \frac{4309.5kWh}{365days} = 11.81\ kWh/day \quad (4.8)$$

4.8.5. Evaluation of the Load Power Consumption on the Pool When Operated on a Solar PV System

- **Hot and cold summer day**

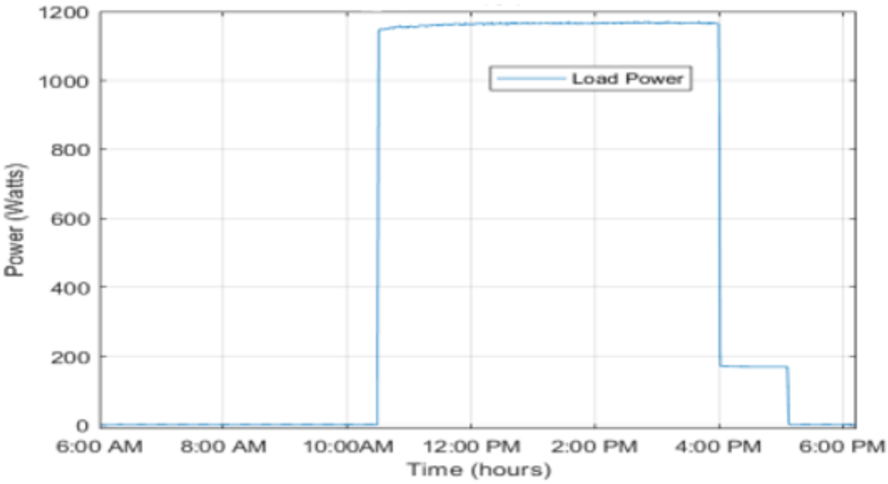


Figure 4.16 Energy consumed by the load on a hot and cold summer day

The summer season eliminates the need for a heater, so the chlorinator and the water pump are turned on between 10 am to 5 pm, which consumes approximately 1150 Watts/hour of energy. The total power consumed in kWh = ((1150 * 5.5) + (175 * 1))/1000 = 6.5 kWh with an additional 1 kWh for lighting operations during the nighttime, assuming that the pool is open till late at night.

- **Hot and cold winter day**

In winter, hot water requires the heater to be turned on. The water heater, chlorinator, and water pump are turned on between 10 am to 5 pm consuming approximately 2250 watts/hour of energy. The total power consumed in kWh = ((2250 * 5.5) + (200 * 1))/1000 = 12.5 kWh with an additional 1 kWh for lighting operations during the nighttime, assuming that the pool is open till late at night.

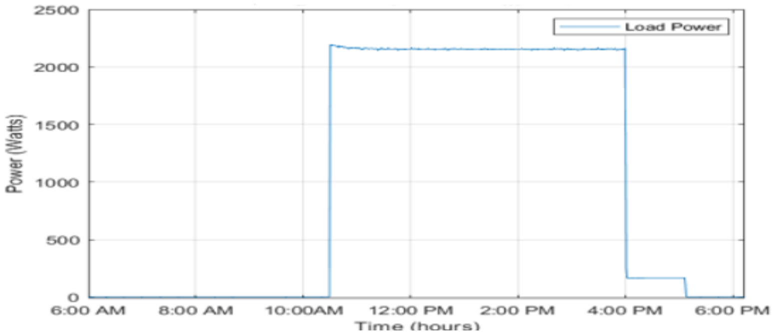


Figure 4.17 Energy consumed by the load on a hot and cold winter day

4.8.6. Evaluation of PV System

- **Without battery**

During the day, production is at its peak, whereas all of the energy is not consumed; therefore, the surplus energy can be sent back to the grid. However, the system cannot generate enough energy during the night, so the energy can be retrieved from the grid and consumed.

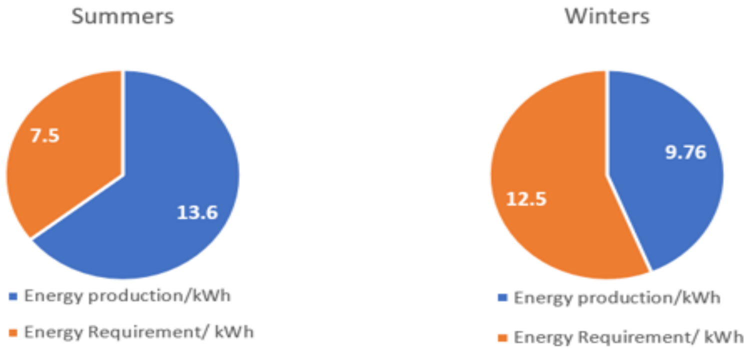


Figure 4.18 Charts representing energy production and requirements in summers and winters

Figure 4.18 compares the energy production with that of the energy required during the summer and winter. Blue color shows the energy produced by the system whereas the orange color signifies the energy needed in a particular weather.

Table 4.3 Evaluation of PV system in winters

Additional energy requirement from the grid (kWh/day)	4
The daily cost of additional energy needed from the grid	4 * c30.734 = $1.23
The yearly cost of additional energy needed from the grid	$200

- **With battery**

In summer, the surplus energy can be stored in the batteries and consumed anytime during the day or night. Battery brings additional benefits to the system by stabilising the power available to the load in case of fluctuations and allowing the user an off-grid system. In winter, surplus energy during the day might be stored and supplied to the equipment at night; however, since the energy demand exceeds the stored energy, additional power from the national grid is imperative.

4.8.7. Charging/Discharging Cycles of the Battery

Batteries have life in energy cycles (charging and discharging), lasting around 4-10 years, depending on the energy cycles, build quality, and build type. The batteries are generally used for powering the system during the night. However, different batteries have different charging/discharging cycles ranging from 300-2000 cycles until they become inefficient and must be replaced (Veldboom, 2021). Therefore, a household PV system requires battery replacement every 4-6 years to ensure efficient backup during off-hours (nighttime), resulting in additional costs for the solar PV system.

4.8.8. Evaluation of the Load Power Consumption on the Pool When Operated on a Wind Energy System

- **Hot summer day**

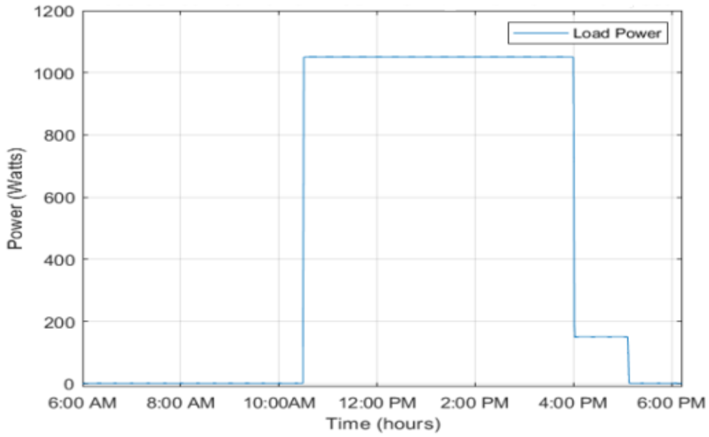


Figure 4.19 Energy consumed by the load on a hot and cold summer day

In summer, hot water is not essential, so only the chlorinator and the water pump are on between 10 am to 5 pm, and they consume approximately 1050 watts/hour of energy. Therefore, the total energy consumed in kWh = ((1050 * 5.5) + (175 * 1))/1000 = 6.0 kWh with an additional 1 kWh for lighting operations during the nighttime, assuming that the pool is open till late at night.

- **Hot and cold winter day**

In winter, hot water requires the heater to be turned on. The peak power available from the system in winter is around 1250 Watts, which is insufficient to power the water heater and pump simultaneously. The total energy consumed in kWh = ((1250 * 5.5) + (100 * 1))/1000 = 7 kWh with an additional 1 kWh for lighting operations during the nighttime, assuming that the pool is open till late at night. As the amount of energy available is less than the required energy, all the load cannot be turned on simultaneously.

4.8.9. Analysis and Evaluation of the Total Costs Incurred for Buying and Installation of the Solar PV System (With and Without Battery)

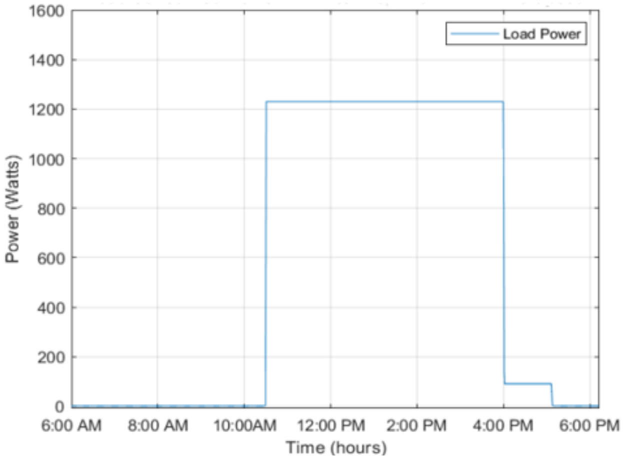


Figure 4.20. Energy consumed by the load on a hot and cold summer day

The solar PV system has been designed for a small household with a nominally capacity of 3-kWh of load. While the national average cost is around $4300, the average cost of installing such a system would be about $3800 in Southern Australia (Wrigley, 2022). This section evaluates the cost of the system completely installed at home with all payments upfront.

An initial cost of $4000 is expected to be spent on installing the PV solar system, with an additional charge of around $800 - $1000 for installing the tubular batteries once the initially installed ones complete their energy cycles (5–6 years life cycle) (Energy Matters, no date b; MI Battery Engineering, no date; Wrigley, 2022). The batteries designed by Tesla, Redflow, Imergy, and Aquion last more than ten years (Energy Matters, no date; Martin, 2016). These batteries are way too expensive to be utlised in a typical household due to which they are not considered for our system. The developed system is meant to be for a typical household, so a cheaper option of batteries is considered.

4.8.10. Evaluation of the Total Cost Incurred on the Same Amount of Energy Consumed from the National Grid

Figure 4.21 shows the national energy tariff based on the AGL standard Retail Contract rates (*AGL Standard Retail Contract Rates*, 2020). The energy requirement from the previous section shows that the load requires a total of approximately 7.5 kWh of energy per day during summer.

Figure removed due to copyright restriction.

Figure 4.21 National energy-based tariff *(*AGL Standard Retail Contract Rates*, 2020)*

10:30 am – 3 pm (Off-Peak) => Usage – 5.175 kWh, 3 pm onwards (Peak) => Usage – 2.325 kWh

Total energy bill/day including GST = **(2.325 * c44.539) + (5.175 * c30.734) = $2.626.**

The energy requirement from the previous section shows that the load requires a total of approximately 13.5 kWh of energy per day during winter, as heating is required for water.

10:30 am – 3 pm (Off-Peak) => Usage – 10.125 kWh, 3 pm onwards (Peak) => Usage – 3.375 kWh

Total energy bill/day including GST = **(3.375 * c44.539) + (10.125 * c30.734) = $4.615.**

Annual costs of the energy from the national grid would be:

($4.615/day * 140 winter days) + ($2.626/day * 225 summer days) = $1200 / year

Table 4.4 highlights the total energy cost from the national grid over the next 15 years, assuming a 2% increase in the price over two years. Figure 4.22 represents a line chart highlighting the total cost of the energy from the PV system with and without battery and national grid over the next 15 years, assuming a 2% increase in the price of electricity every two years.

Table 4.4 Total cost of energy from the national grid over 15 years

Year	***Total cost ($)***	***Details***
0	*0*	*Assuming no initial cost*
2	*2400*	*Cost of electricity over 2 years @ $1200/year*
4	*4840*	*Cost of electricity over 2 years @ $1220/year (2% increase)*
6	*7330*	*Cost of electricity over 2 years @ $1245/year (2% increase)*
8	*9870*	*Cost of electricity over 2 years @ $1270/year (2% increase)*
10	*12460*	*Cost of electricity over 2 years @ $1295/year (2% increase)*
12	*15100*	*Cost of electricity over 2 years @ $1320/year (2% increase)*
14	*17800*	*Cost of electricity over 2 years @ $1350/year (2% increase)*

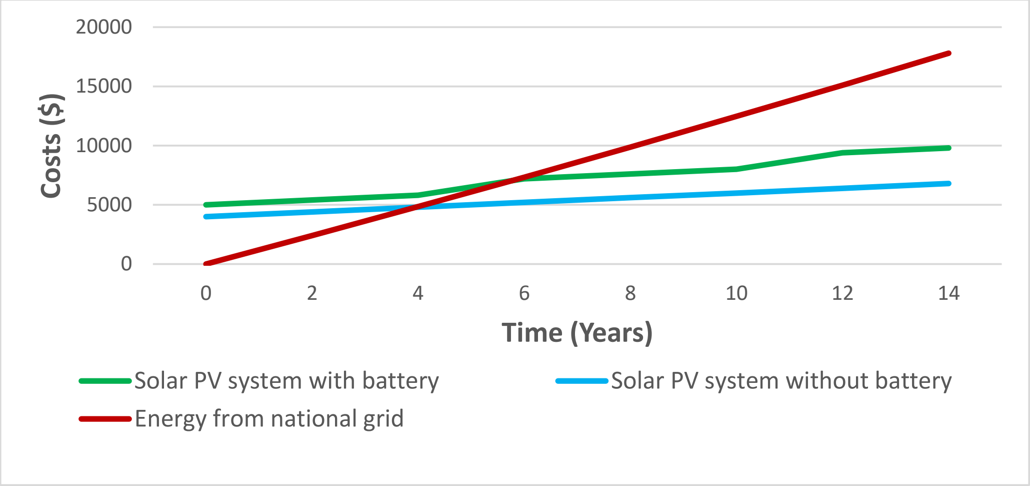


Figure 4.22 Total cost of solar PV system with and without battery and national grid for a period of 15 years

4.8.11. Costs Savings by Comparison Between the Designed PV System and Grid System

Table 4.5 compares the energy costs of solar PV systems with and without batteries and the national grid systems over 15 years. The data clearly shows that the initial price of the solar PV system is very high, i.e. around $4000 for a system of 3 kW capacity; however, energy from the national grid doesn't require any upfront payment. The PV system with a battery costs $1000 every six years to replace the batteries. In the long run, the total energy cost from the solar PV system accumulates to $7000 - $9000 at the end of 14 years, while that from the national grid is approximately twice. Cost analysis shows that solar PV systems are more effective as long-term energy sources. Figure 4.22 highlights the total energy cost from the national grid and the solar PV system with and without a battery. It validates the results from table 4.5

Table 4.5 Comparison of energy costs of the PV system with and without battery along with the national grid for 15 years

Year	*Total energy cost of solar PV system with battery*	*Total energy cost ($) of solar PV system without battery*	*Total energy cost ($) from the National grid*
0	*5000*	*4000*	*0*
2	*5400*	*4400*	*2400*
4	*5800*	*4800*	*4840*
6	*7200*	*5200*	*7330*
8	*7600*	*5600*	*9870*
10	*8000*	*6000*	*12460*
12	*9400*	*6400*	*15100*
14	*9800*	*6800*	*17800*

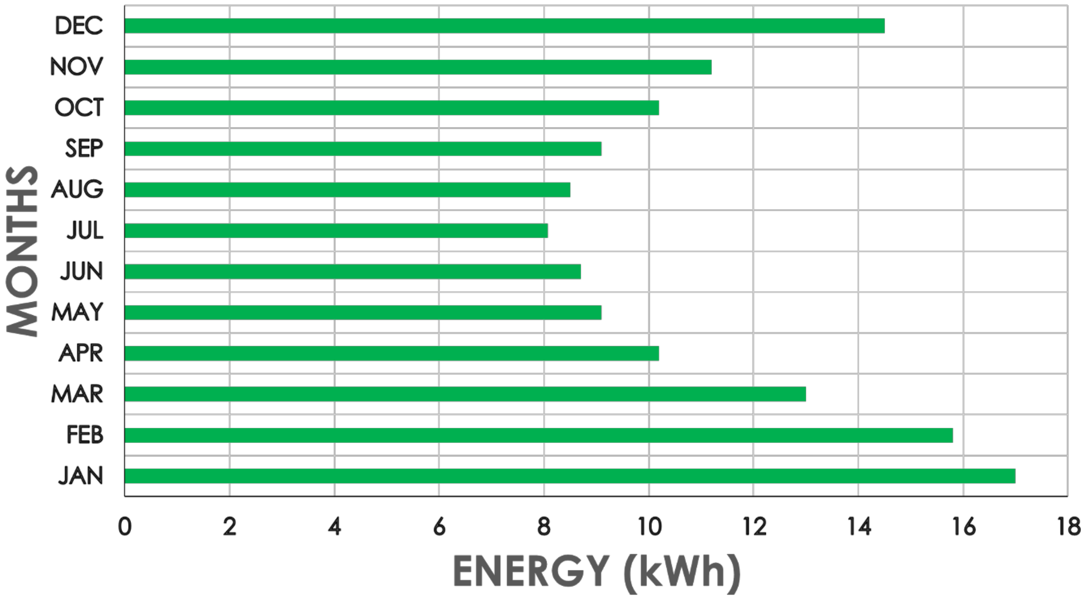


Figure 4.23 Monthly average enrgy production of the designed PV system

4.9.Recommendations

Although the initial cost of the solar PV system seems higher, these costs can be highly reduced by opting for an on-grid system (intelligent energy) which eradicates the requirement of the high-cost energy storage system (batteries) for the surplus energy produced.

The extra power generated by the solar PV system during the day will be sent to the shared energy network when there is no one to consume it. In exchange, the consumer gets a "feed-in tariff," a reimbursement of roughly 5 to 10 cents for each kWh of electricity exported, thereby reducing electricity bills and the later costs of the expensive modular batteries (Wrigley, 2022).

5. Conclusion & Future Work

A 3kWh PV solar system has been designed as an efficient, reliable, and cost-effective energy system to power the residential pool throughout the year in Adelaide, Australia. The developed system has been compared with the wind energy system through simulation results to reach energy production on hot and cold summer days and hot and cold winter days. In addition, the developed PV system is analysed with and without battery to present an economic cost analysis of the system with expenses incurred from the national grid. The following are the conclusions inferred from the study:

- The 3kWh PV system generated 9kWh energy on a summer day when the energy requirement was only 6.5kWh resulting in a surplus amount of energy. However, on a winter day, the energy production was only 7.5kWh while the required amount was 12.5kWh requiring an additional amount from the national grid (assuming 85% inverter conversion efficiency).
- Batteries can be effectively used to store the surplus energy in the summer season for use at night. However, the batteries incur costs higher than systems without battery with additional replacement costs of battery systems costs every 5-6 years.
- The wind energy system results in 7kWh energy production on hot summer days resulting in no surplus energy to be sent to the grid or stored. As a result, it barely fulfils the energy demands of the hot summer day. In contrast, in winter, energy production is deficient, preventing the heater and other features from being used simultaneously unless energy is taken from the national grid.
- Despite having an upfront payment of zero dollars, the energy from the national grid system costs $17800, almost twice that of the $ 6800 of the PV system without batteries over 14 years (assuming a 2% increase per year in the electricity cost). However, for the PV system with batteries, it costs $8800 for the same time frame, which is still significantly lesser than that cost by the national grid.

The research faced several challenges, including the unavailability of continuous data that limited in-depth analysis and complexities of the machine learning concepts. Machine learning was used to design fuzzy logic to estimate the solar irradiance to perform the in-depth analysis of the systemFuture studies may address the PV system requirements for residential pools in other regions of the country to develop an on/off grid PV system optimal for the variable topologies and areas. In addition, the feasibility, optimal capacity, and cost-effectiveness of HRES for residential pools can be studied since HRES have been known to overcome the shortcomings of a single renewable energy resource. The system could be developed to operate on solar energy during the daytime and utilise wind energy at night for electricity generation to determine the system's feasibility, cost, and optimal capacity. Another area that could be explored would be the determination of solar PV capacity at different angle adjustments to determining the maximum conversion efficiency angle. The study exploration could include three to four regions for the investigation to present a country analysis.

Nomenclature

AC	Alternating Current
BES	Battery Energy storage system
BS	Battery Storage
C	Output Current
CNN	Convolutional Neural Network
CSD	Cold Summer Day
D	Duty Cycle
DC	Direct Current
DNNs	Deep Neural Networks
DSM	Demand Side Management
EMS	Energy Management System
EVs	Electric Vehicles
EWC	Elastic Weight Consideration
FLC	Fuzzy Logic Controller
Fs	Switching Frequency
GCH	Grid Connected Households
HOMER	Hybrid optimisation of multiple energy resources
HSD	Hot Summer Day
HWD	Hot Winter Day
HRES	Hybrid Renewable Energy Systems
Io	Output load Current
Is	Supplied Current
LCOE	Localised Cost of Energy
LEDS	Light Emitting Diodes
LSTM	Long Short-term Memory
kWh	Kilowatt-hour
kWp	Kilowatt Peak
L	Inductance
MOSFET	Metal–oxide–semiconductor field-effect transistor
MPPT	Maximum Point Power Tracking

PMSG	Permanent Magnet Synchronous Generator
PSO	Particle Swarm Optimisation
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
PWM	Pulse Width Modulation
RNN	Recurrent Neural Network
SA	South Australia
SWT	Small Wind Turbine
Vs	Supplied Voltages
W	Watt
WT	Wind Turbine
UK	United Kingdom
US	United States

References

Ab-Belkhair, A., Rahebi, J. and Abdulhamed Mohamed Nureddin, A. (2020) ‘A study of deep neural network controller-based power quality improvement of hybrid PV/Wind systems by using smart inverter’, *International Journal of Photoenergy*, 2020. Available at: https://doi.org/10.1155/2020/8891469.

AGL Standard Retail Contract Rates (2020).

Al-Kaissi, S.M. and Al-Taai, O.T. (2021) ‘Prediction of Global Solar Irradiation by Using Fuzzy Logic’, in *1st Babylon International Conference on Information Technology and Science 2021, BICITS 2021*. Institute of Electrical and Electronics Engineers Inc., pp. 92–97. Available at: https://doi.org/10.1109/BICITS51482.2021.9509916.

Allah Hamadi, S. *et al.* (2018) ‘Comparison of Fuzzy Logic and P&O MPPT Techniques for solar Photovoltaic system’, *The 2nd International Workshop on Signal Processing Applied to Rotating Machinery Diagnostics, SIGPROMD’2018* [Preprint]. Available at: https://www.researchgate.net/publication/333703537.

Azad, K. *et al.* (2019) ‘Assessment of wind energy prospect by weibull distribution for prospective wind sites in Australia’, in *Energy Procedia*. Elsevier Ltd, pp. 348–355. Available at: https://doi.org/10.1016/j.egypro.2019.02.167.

Aziz, A., Oo, A.M.T. and Stojcevski, A. (2018) ‘Issues and mitigations of wind energy penetrated network: Australian network case study’, *Journal of Modern Power Systems and Clean Energy*, 6(6), pp. 1141–1157. Available at: https://doi.org/10.1007/s40565-018-0430-4.

Bamisile, O. *et al.* (2022) ‘Comparison of machine learning and deep learning algorithms for hourly global/diffuse solar radiation predictions’, *International Journal of Energy Research*, 46(8), pp. 10052–10073. Available at: https://doi.org/10.1002/er.6529.

Basaran, K., Cetin, N.S. and Borekci, S. (2017) ‘Energy management for on-grid and off-grid wind/PV and battery hybrid systems’, *IET Renewable Power Generation*, 11(5), pp. 642–649. Available at: https://doi.org/10.1049/iet-rpg.2016.0545.

Combe, M. *et al.* (2019) ‘Cost Effective Sizing of an AC Mini-Grid Hybrid Power System for a Remote Area in South Australia’, *IET Generation, Transmission & Distribution* [Preprint]. Available at: https://doi.org/10.1049/iet-gtd.2018.5657.

Donnellan, B.J., Soong, W.L. and Vowles, D.J. (2018) ‘Critical Capacity Analysis for Optimal Sizing of PV and Energy Storage for a Household’, *IEEE Energy Conversion Congress and Exposition (ECCE), 2018*, pp. 5125–5132. Available at: https://doi.org/10.1109/ECCE.2018.8557833.

Energy Matters (no date a) *Home Battery FAQ - What You Need To Know About Home Battery Storage*. Available at: https://www.energymatters.com.au/residential-solar/home-battery-faq-know-storage/ (Accessed: 10 October 2022).

Energy Matters (no date b) *South Australian Home Battery Scheme: Subsidies and Loans*. Available at: https://www.energymatters.com.au/residential-solar/battery-system-rebates/south-australian-home-battery-scheme/ (Accessed: 10 October 2022).

Ganguly, P., Kalam, A. and Zayegh, A. (2018) ‘Solar-wind hybrid renewable energy system: Current status of research on configurations, control, and sizing methodologies’, in *Hybrid-renewable energy systems in microgrids: Integration, developments and control*. Elsevier, pp. 219–248. Available at: https://doi.org/10.1016/B978-0-08-102493-5.00012-1.

Hannan, M.A. *et al.* (2019) ‘Fuzzy logic inverter controller in photovoltaic applications: Issues and recommendations’, *IEEE Access*, 7, pp. 24934–24955. Available at: https://doi.org/10.1109/ACCESS.2019.2899610.

He, Y., Henze, J. and Sick, B. (2020) ‘Continuous learning of deep neural networks to improve forecasts for regional energy markets’, in *IFAC-PapersOnLine*. Elsevier B.V., pp. 12175–12182. Available at: https://doi.org/10.1016/j.ifacol.2020.12.1017.

James (2022) *Sizing inverters to optimise solar panel system efficiency - Solar Choice*. Available at: https://www.solarchoice.net.au/blog/optimizing-solar-panel-system-efficiency-through-inverter-sizing/ (Accessed: 10 October 2022).

Khan, M.J. and Mathew, L. (2019) ‘Fuzzy logic controller-based MPPT for hybrid photo-voltaic/wind/fuel cell power system’, *Neural Computing and Applications*, 31(10), pp. 6331–6344. Available at: https://doi.org/10.1007/s00521-018-3456-7.

Khezri, R., Mahmoudi, A. and Haque, M. (2021) ‘A Demand Side Management Approach for Optimal Sizing of Standalone Renewable-Battery Systems’, *IEEE Transactions on Sustainable Energy*, 12(4), pp. 2184–2194. Available at: https://doi.org/10.1109/TSTE.2021.3084245.

Khezri, R., Mahmoudi, A. and Haque, M.H. (2019) ‘SWT and BES Optimisation for Grid-connected Households in South Australia’, *In IEEE Energy Conversion Congress and Exposition (ECCE)*, pp. 418–425.

Khezri, R., Mahmoudi, A. and Haque, M.H. (2020) ‘Optimal Capacity of Solar PV and Battery Storage for Australian Grid-Connected Households’, *IEEE Transactions on Industry Applications*, 56(5), pp. 5319–5329. Available at: https://doi.org/10.1109/TIA.2020.2998668.

Khezri, R., Mahmoudi, A. and Haque, M.H. (2022) ‘Impact of Optimal Sizing of Wind Turbine and Battery Energy Storage for a Grid-Connected Household With/Without an Electric Vehicle’, *IEEE Transactions on Industrial Informatics*, 18(9), pp. 5838–5848. Available at: https://doi.org/10.1109/TII.2022.3140333.

Kumar, N.M., Subathra, M.S.P. and Moses, J.E. (2018) ‘On-Grid Solar Photovoltaic System: Components, Design Considerations, and Case Study’, in *Proceedings of the 4th International Conference on Electrical Energy Systems, ICEES 2018*. Institute of Electrical and Electronics Engineers Inc., pp. 616–619. Available at: https://doi.org/10.1109/ICEES.2018.8442403.

Li, X. *et al.* (2019) ‘A novel beta parameter based fuzzy-logic controller for photovoltaic MPPT application’, *Renewable Energy*, 130, pp. 416–427. Available at: https://doi.org/10.1016/j.renene.2018.06.071.

Lian, J. *et al.* (2019a) ‘A review on recent sizing methodologies of hybrid renewable energy systems’, *Energy Conversion and Management*. Elsevier Ltd. Available at: https://doi.org/10.1016/j.enconman.2019.112027.

Lian, J. *et al.* (2019b) ‘A review on recent sizing methodologies of hybrid renewable energy systems’, *Energy Conversion and Management*. Elsevier Ltd. Available at: https://doi.org/10.1016/j.enconman.2019.112027.

Martin, J. (2016) *Depth of discharge and solar energy storage - Solar Choice*. Available at: https://www.solarchoice.net.au/blog/depth-of-discharge-for-solar-battery-storage/ (Accessed: 10 October 2022).

Mehta, S. and Basak, P. (2019) ‘Solar irradiance forecasting using fuzzy logic and multilinear regression approach: A case study of Punjab, India’, *International Journal of Advances in Applied Sciences*, 8(2), p. 125. Available at: https://doi.org/10.11591/ijaas.v8.i2.pp125-135.

MI Battery Engieering (no date) *Battery Shelf Life & Shortage - Master Instruments Australian Rechargeable Lithium Battery & Lead Acid Batteries*. Available at: https://www.master-instruments.com.au/pages/battery-shelf-life-storage.html (Accessed: 10 October 2022).

Mohamed, S. *et al.* (2019) ‘An Efficient Planning Algorithm for Hybrid Remote Microgrids’, *IEEE Transactions on Sustainable Energy*, 10(1), pp. 257–267. Available at: https://doi.org/10.1109/TSTE.2018.2832443.

Ravindran, S. and Padmanabhan, V. (2017) ‘Drift Avoidance in Photovoltaic Systems by Modification in Perturb and Observe MPPT Algorithm Sreelakshmi Ravindran and Vipin Padmanabhan’, *International Journal of Engineering Research & Technology (IJERT)*, 6(5). Available at: www.ijert.org.

Renewables.ninja (2019). Available at: https://www.renewables.ninja/ (Accessed: 26 September 2022).

Richards, E.S. (no date) *South Australia - Climate | Britannica*. Available at: https://www.britannica.com/place/South-Australia/Climate (Accessed: 10 October 2022).

Sadorsky, P. (2021) ‘Wind energy for sustainable development: Driving factors and future outlook’, *Journal of Cleaner Production*, 289. Available at: https://doi.org/10.1016/j.jclepro.2020.125779.

Saiprasad, N., Kalam, A. and Zayegh, A. (2017) ‘Optimal Sizing of Renewable Energy System for a University in Australia’, *Australasian Universities Power Engineering Conference (AUPEC)*, pp. 1–6. Available at: https://doi.org/10.1109/AUPEC.2017.8282483.

Sawle, Y., Gupta, S.C. and Bohre, A.K. (2018a) ‘Review of hybrid renewable energy systems with comparative analysis of off-grid hybrid system’, *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, pp. 2217–2235. Available at: https://doi.org/10.1016/j.rser.2017.06.033.

Sawle, Y., Gupta, S.C. and Bohre, A.K. (2018b) ‘Review of hybrid renewable energy systems with comparative analysis of off-grid hybrid system’, *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, pp. 2217–2235. Available at: https://doi.org/10.1016/j.rser.2017.06.033.

Succetti, F. *et al.* (2020) ‘Deep Neural Networks for Multivariate Prediction of Photovoltaic Power Time Series’, *IEEE Access*, 8, pp. 211490–211505. Available at: https://doi.org/10.1109/ACCESS.2020.3039733.

Tzen, E. (2020) ‘Small wind turbines for on grid and off grid applications’, in *IOP Conference Series: Earth and Environmental Science*. Institute of Physics Publishing. Available at: https://doi.org/10.1088/1755-1315/410/1/012047.

Veldboom, B. (2021) *How Do Battery Charging Cycles Work? at Batteries Plus*. Available at: https://www.batteriesplus.com/blog/power/battery-discharge-cycle (Accessed: 10 October 2022).

Wrigley, K. (2022) *SA Solar Guide | Costs, Rebates & Tariffs – Canstar Blue*. Available at: https://www.canstarblue.com.au/solar/guide-solar-power-south-australia/ (Accessed: 10 October 2022).

Yilmaz, U., Kircay, A. and Borekci, S. (2018) ‘PV system fuzzy logic MPPT method and PI control as a charge controller’, *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, pp. 994–1001. Available at: https://doi.org/10.1016/j.rser.2017.08.048.

6. Appendices

6.1. MPPT and Inverter

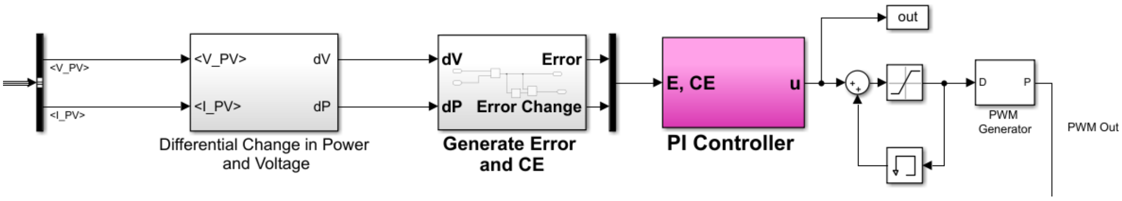


Figure 6.1 PI MPPT controller

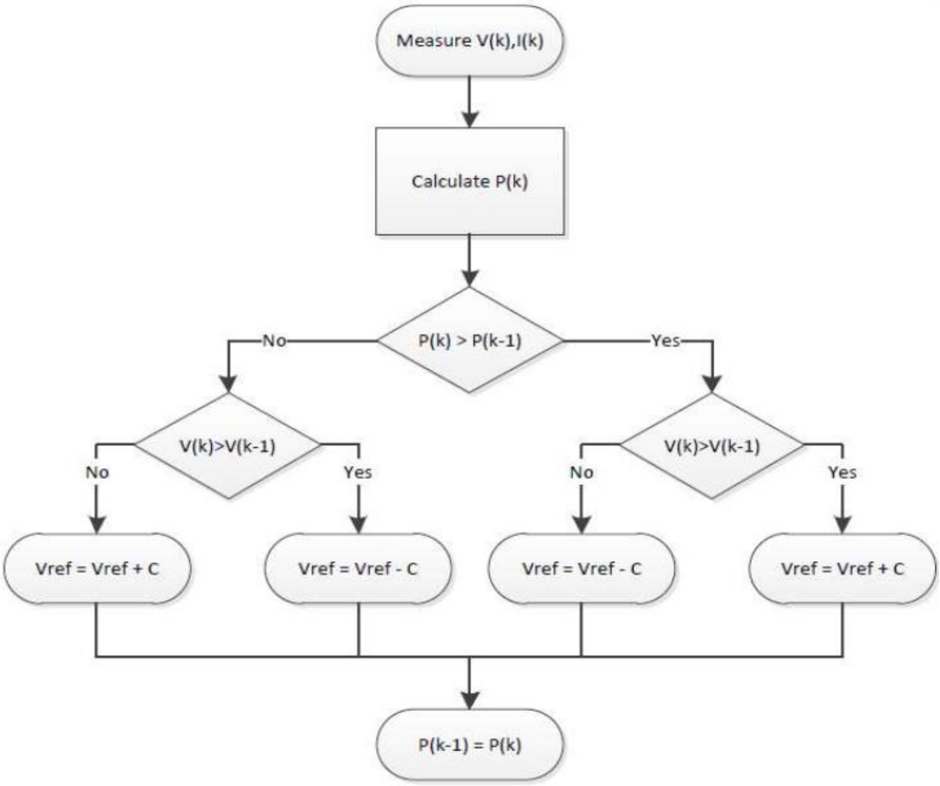


Figure 6.2 Perturb and observe algorithm

Figure removed due to copyright restriction.

Figure 6.3 Schematic of boost converter

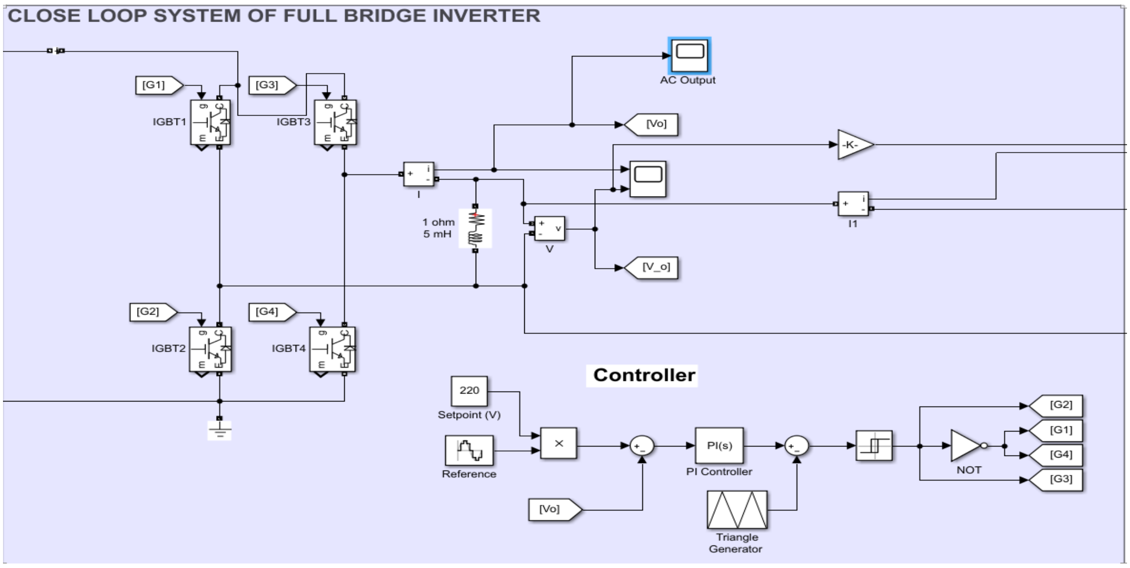
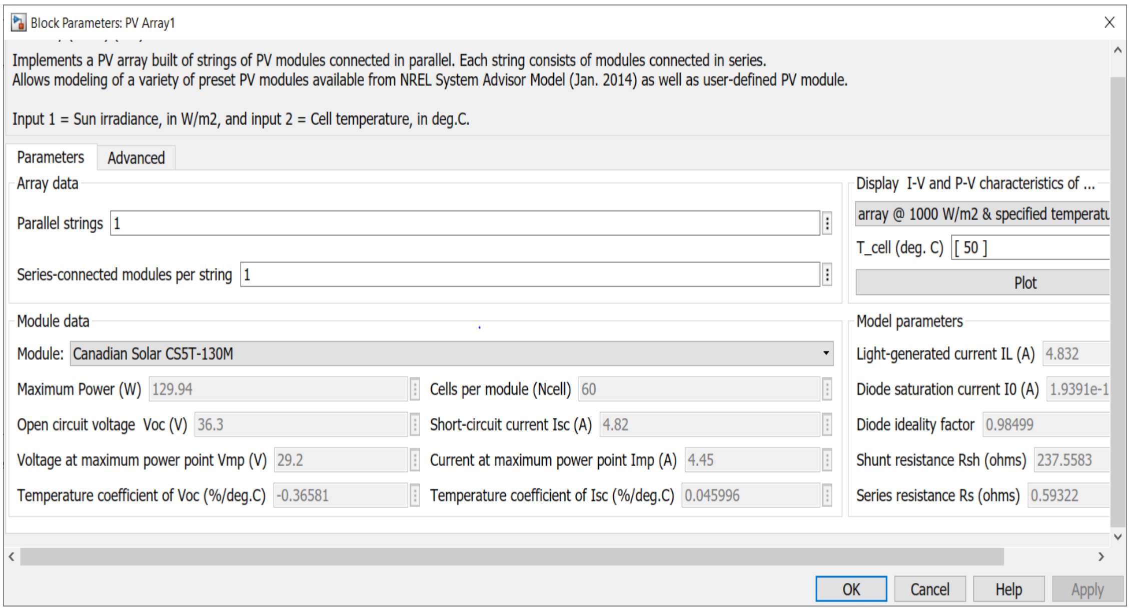


Figure 6.4 Closed loop full bridge inverter

6.2.PV Solar System



Block Parameters: PV Array1

Implements a PV array built of strings of PV modules connected in parallel. Each string consists of modules connected in series.
Allows modeling of a variety of preset PV modules available from NREL System Advisor Model (Jan. 2014) as well as user-defined PV module.

Input 1 = Sun irradiance, in W/m2, and input 2 = Cell temperature, in deg.C.

Array data

Parallel strings: 1

Series-connected modules per string: 1

Display I-V and P-V characteristics of ...: array @ 1000 W/m2 & specified temperatu

T_cell (deg. C): [50]

Module data

Module: Canadian Solar CS5T-130M

Maximum Power (W): 129.94

Cells per module (Ncell): 60

Open circuit voltage Voc (V): 36.3

Short-circuit current Isc (A): 4.82

Voltage at maximum power point Vmp (V): 29.2

Current at maximum power point Imp (A): 4.45

Temperature coefficient of Voc (%/deg.C): -0.36581

Temperature coefficient of Isc (%/deg.C): 0.045996

Model parameters

Light-generated current IL (A): 4.832

Diode saturation current I0 (A): 1.9391e-1

Diode ideality factor: 0.98499

Shunt resistance Rsh (ohms): 237.5583

Series resistance Rs (ohms): 0.59322

Figure 6.5 Solar PV parameters

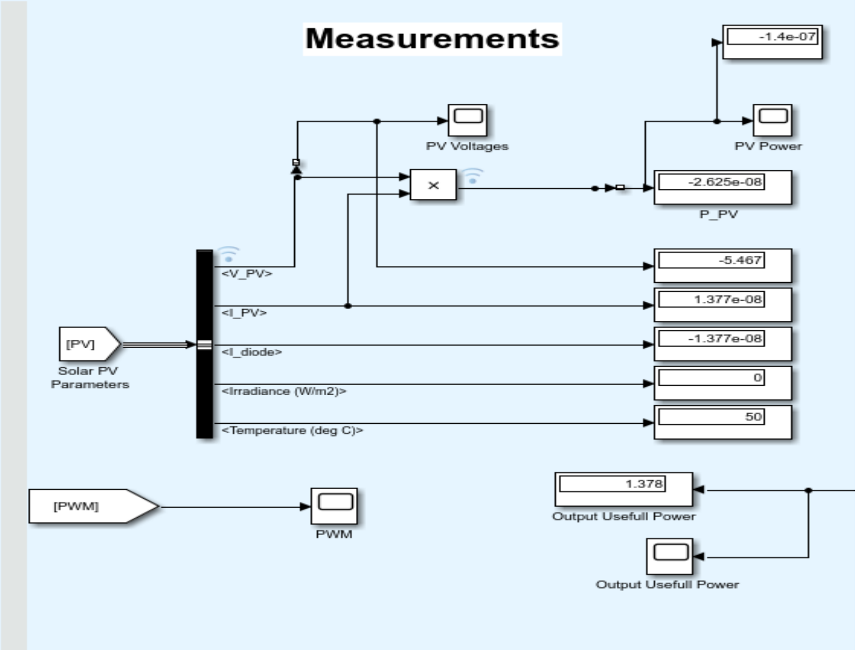


Figure 6.6 Monitoring and measurement section

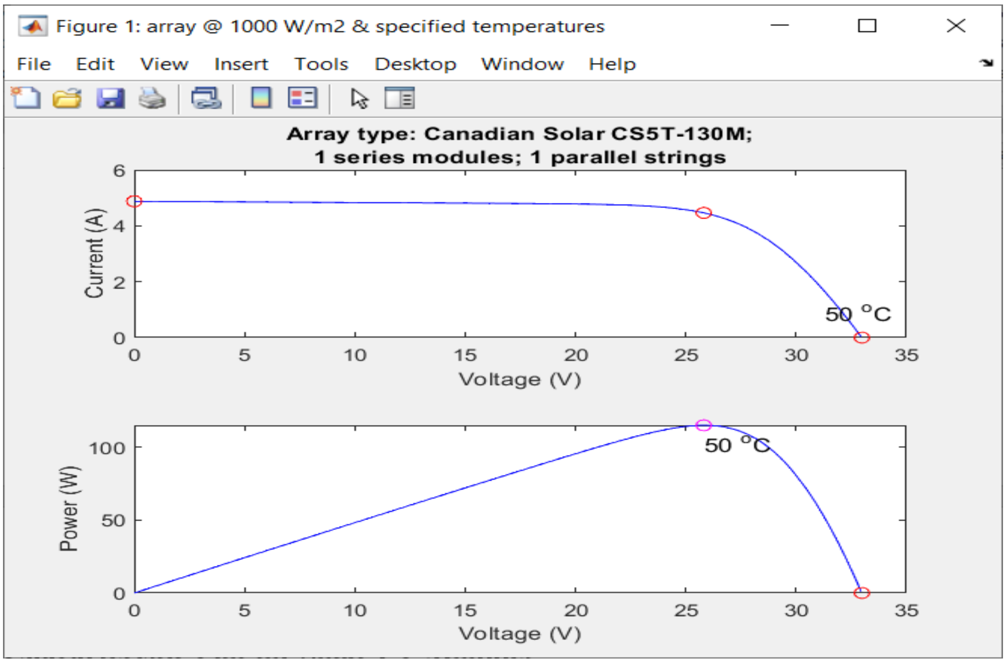


Figure 6.7 Characteristic plot for solar PV module

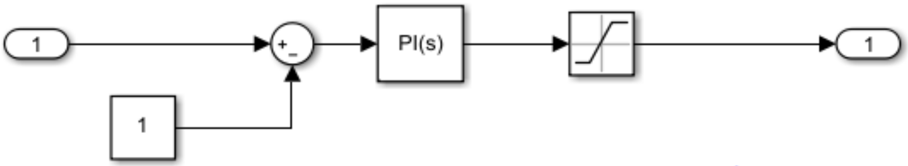


Figure 6.8 Pitch controller block

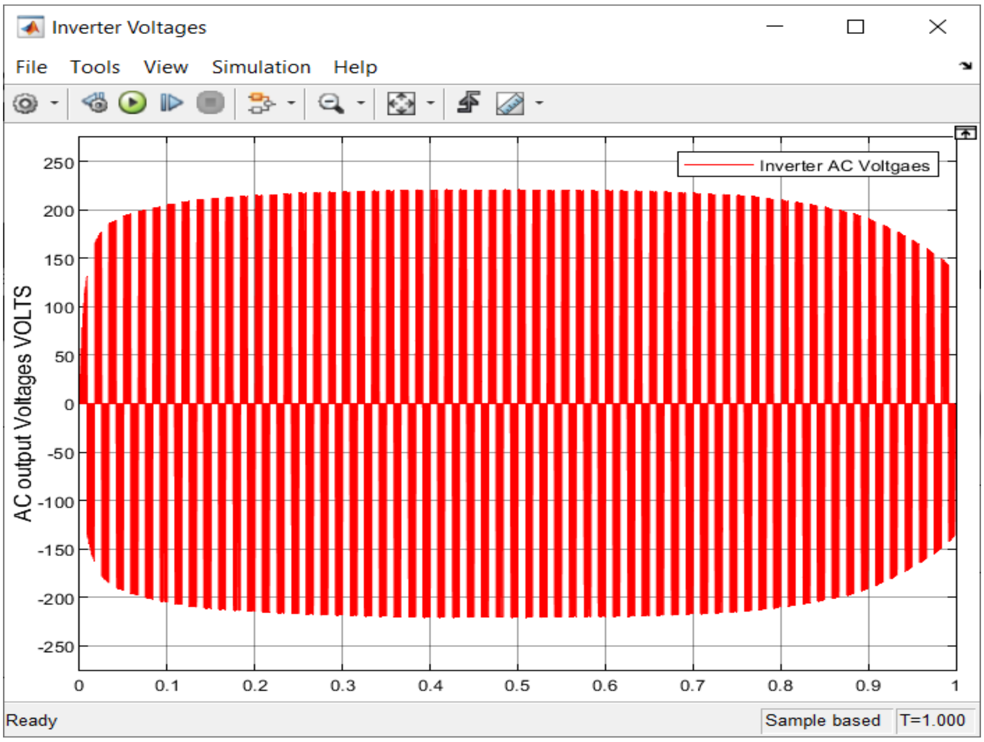
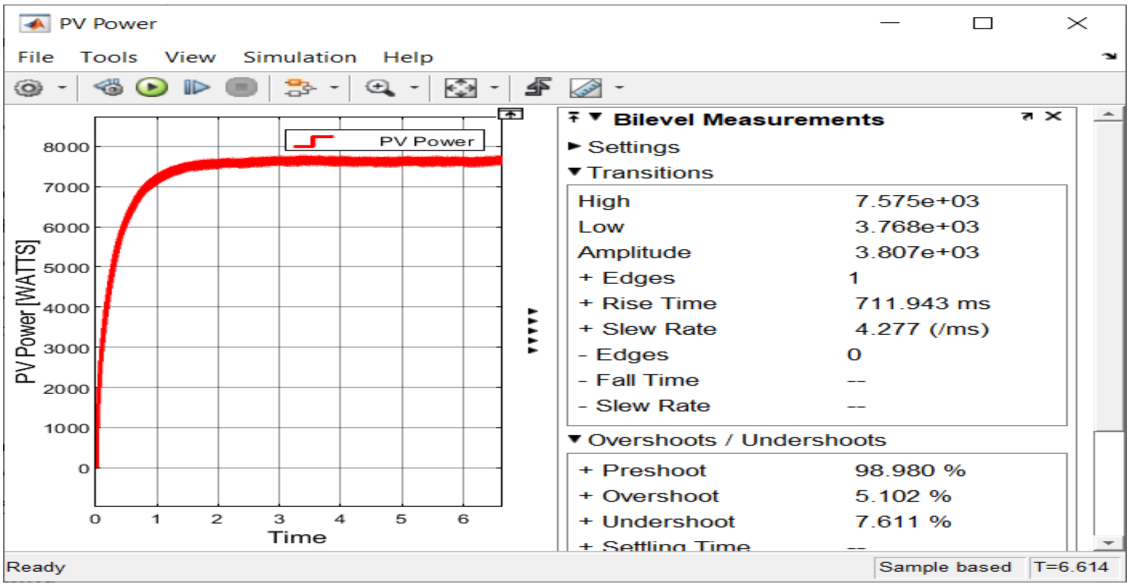


Figure 6.9 Inverter output AC voltages under variable solar irradiance



Bilevel Measurements

► Settings

▼ Transitions

High	7.575e+03
Low	3.768e+03
Amplitude	3.807e+03
+ Edges	1
+ Rise Time	711.943 ms
+ Slew Rate	4.277 (/ms)
- Edges	0
- Fall Time	--
- Slew Rate	--

▼ Overshoots / Undershoots

+ Preshoot	98.980 %
+ Overshoot	5.102 %
+ Undershoot	7.611 %
+ Settling Time	--

Figure 6.10 Tuned PI controller output response

6.3. Wind Energy Simulation

6.3.1. Profiles for Low Wind Speed in Summer and Winter

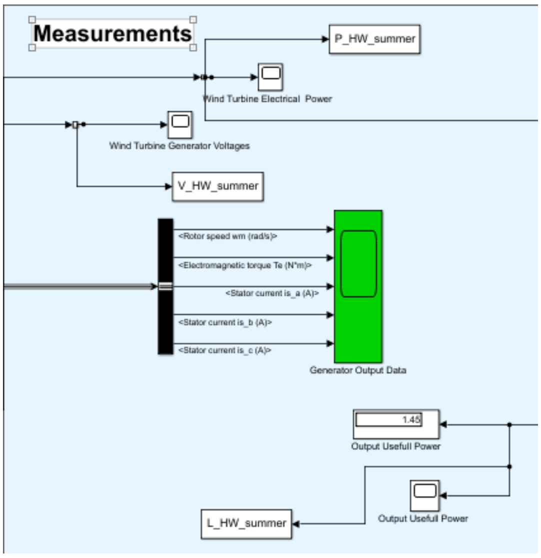


Figure 6.11 Measurement section of wind system

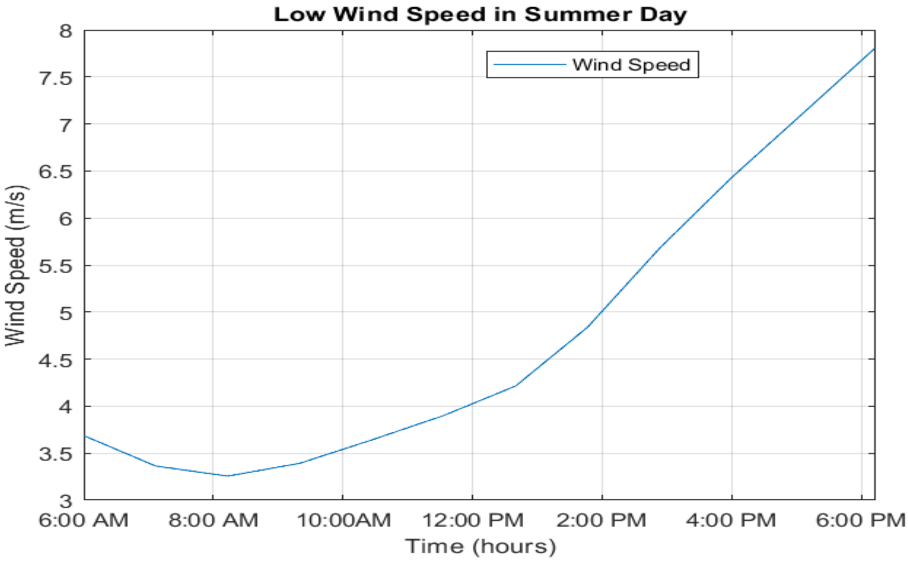


Figure 6.12 Low wind speed profile on summer day

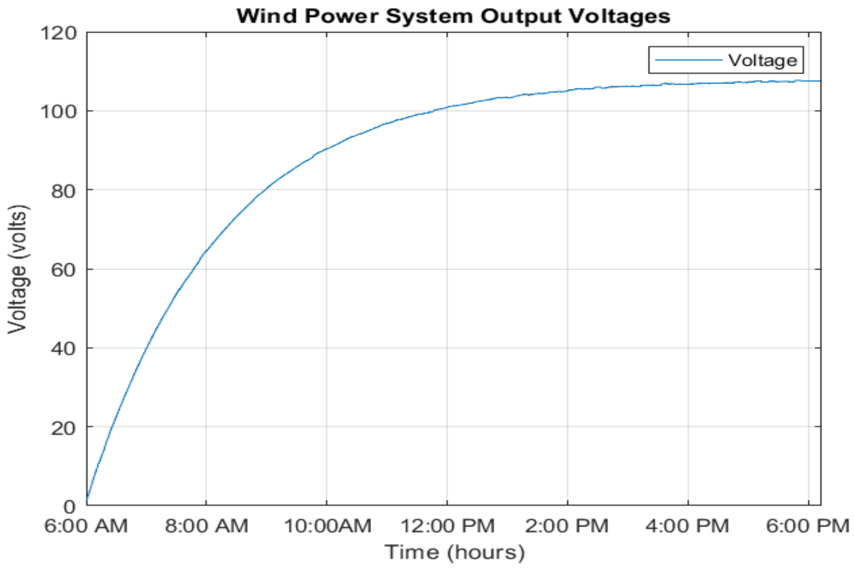


Figure 6.13 Wind energy system output voltages with low wind speed

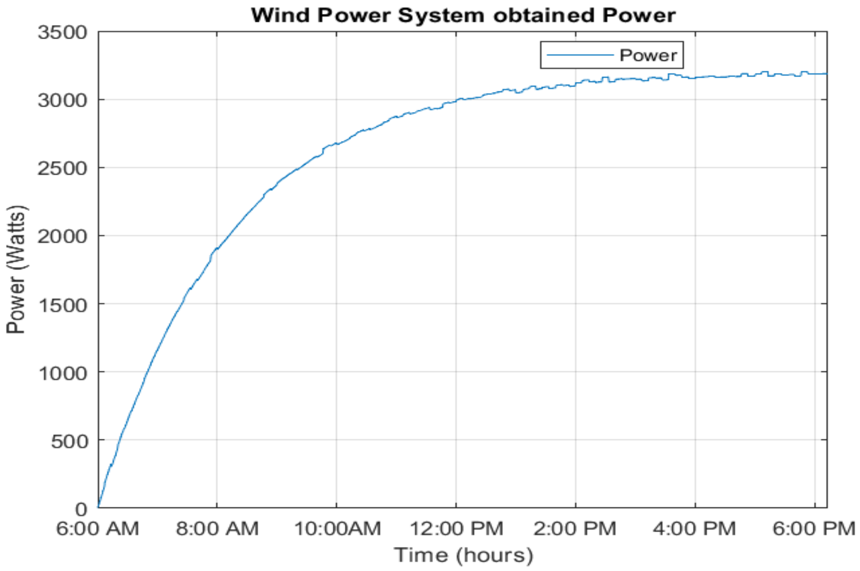


Figure 6.14 Wind energy system output power with low wind speed in summers

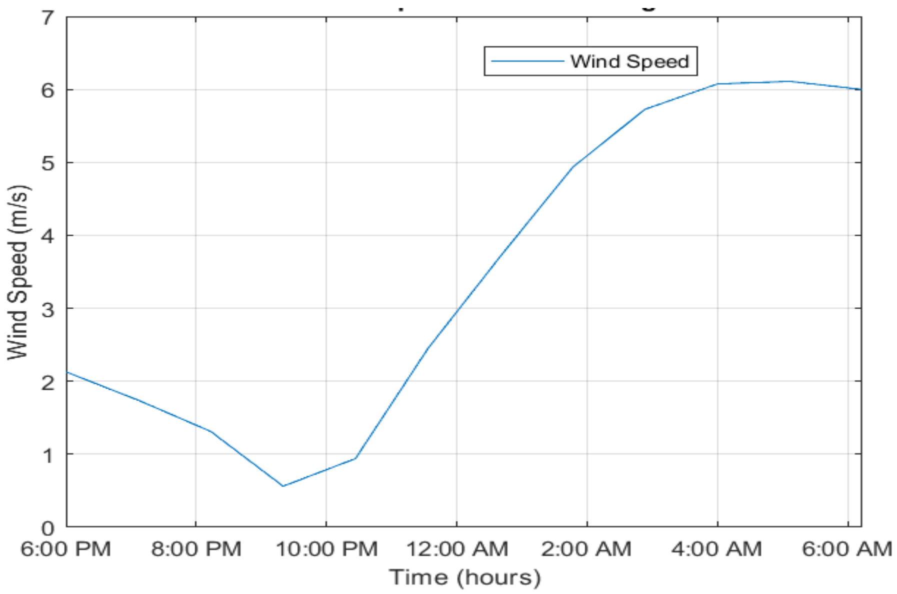


Figure 6.15 Low wind speed profile on a summer night

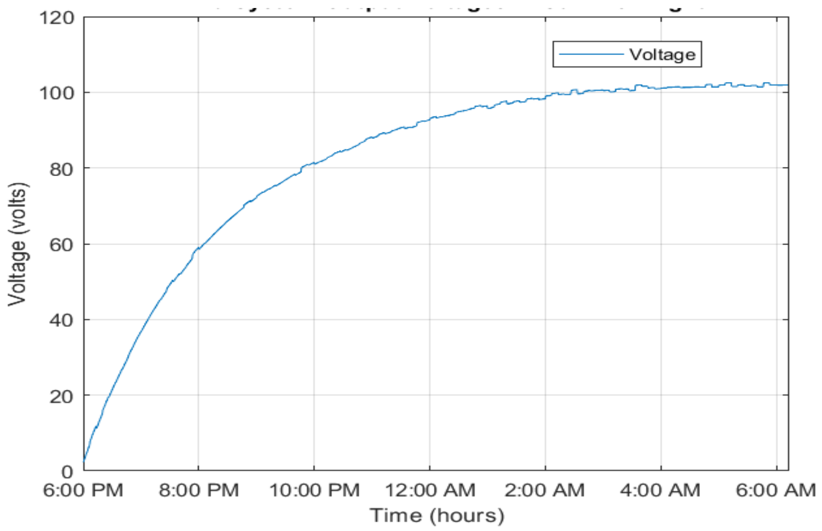


Figure 6.16 Wind system output voltage on a summer night with low wind speed

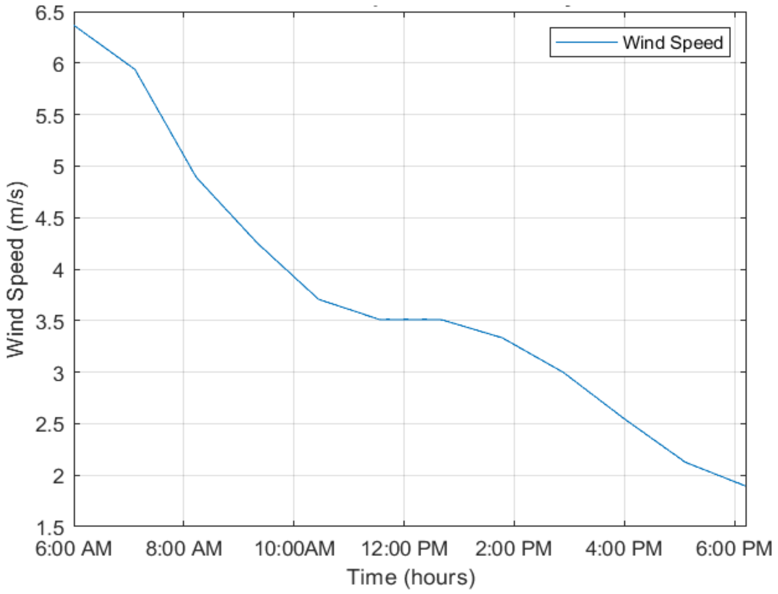


Figure 6.17 Wind energy profile for a winter day with low speed

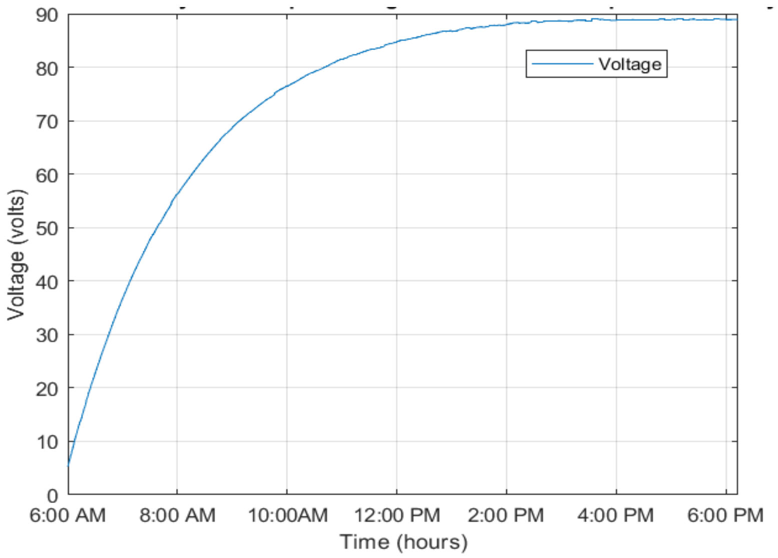


Figure 6.18 Wind power system output voltage for a winter day with low wind speed

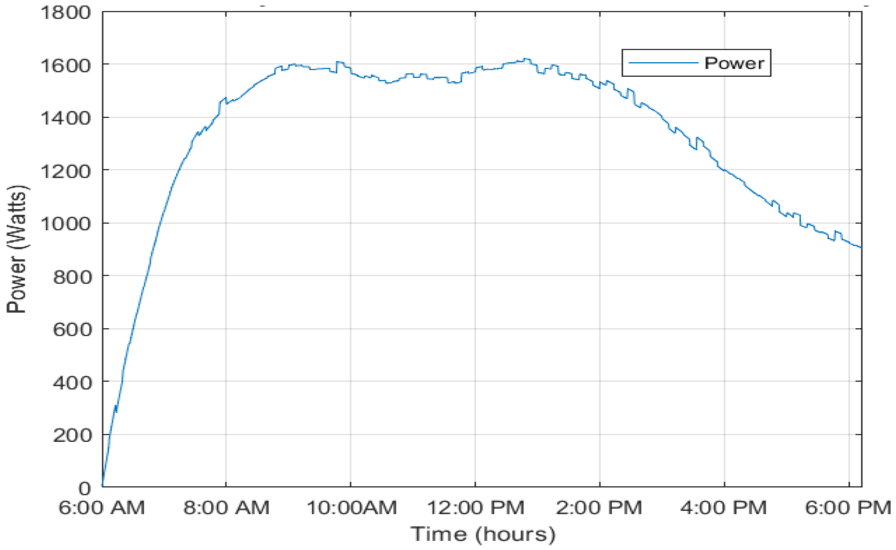


Figure 6.19 Wind power system obtained power on a winter day with low wind

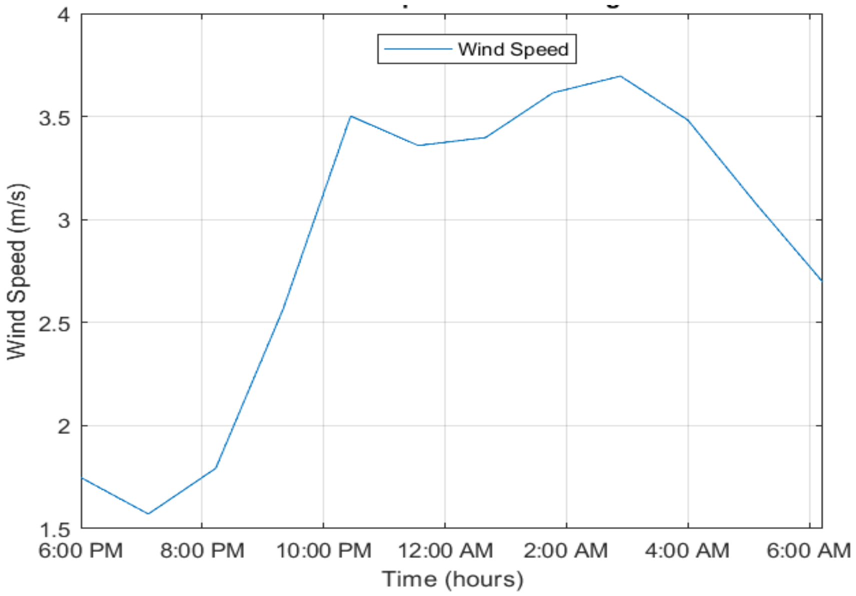


Figure 6.20 Low wind speed profile on a winter night

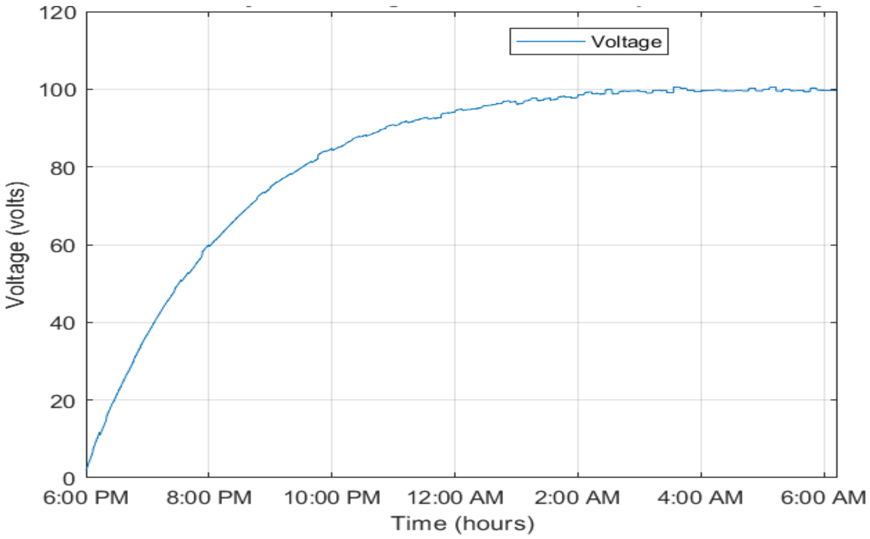


Figure 6.21 Wind power system voltage on a winter night with low speed

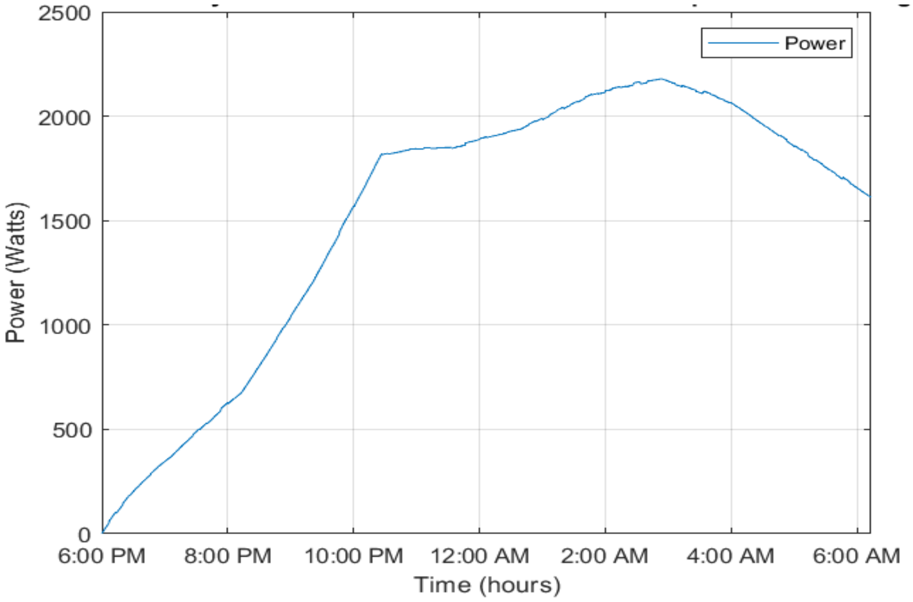


Figure 6.22 Wind system obtained power on a winter night with a low speed

6.3.2. Profiles for High Wind Speed in Summer and Winter

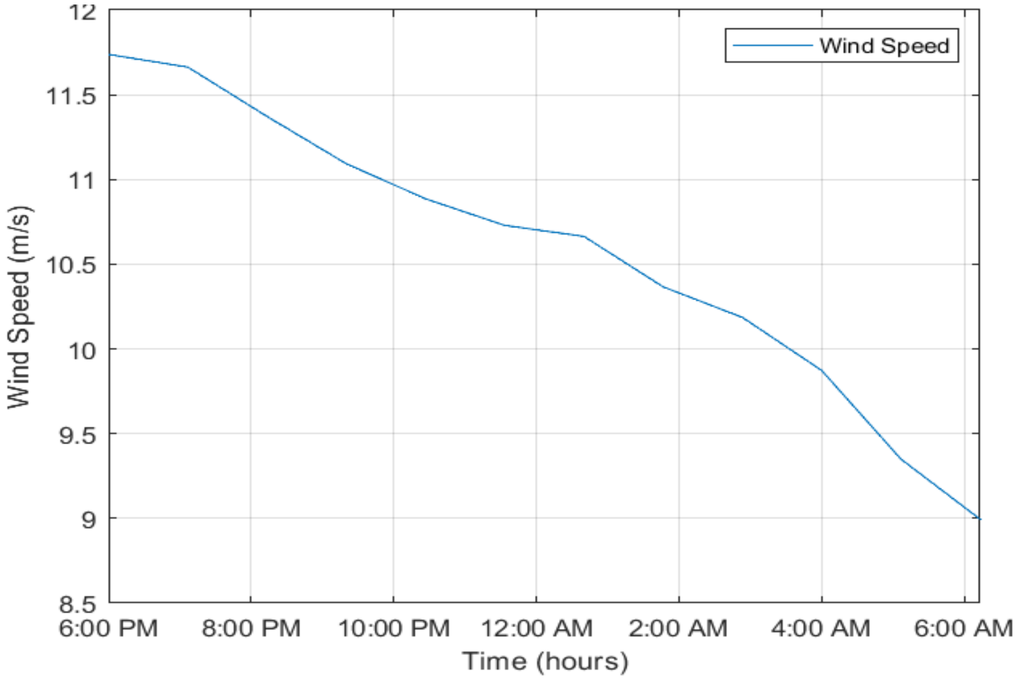


Figure 6.24 Wind speed on a typical summer night

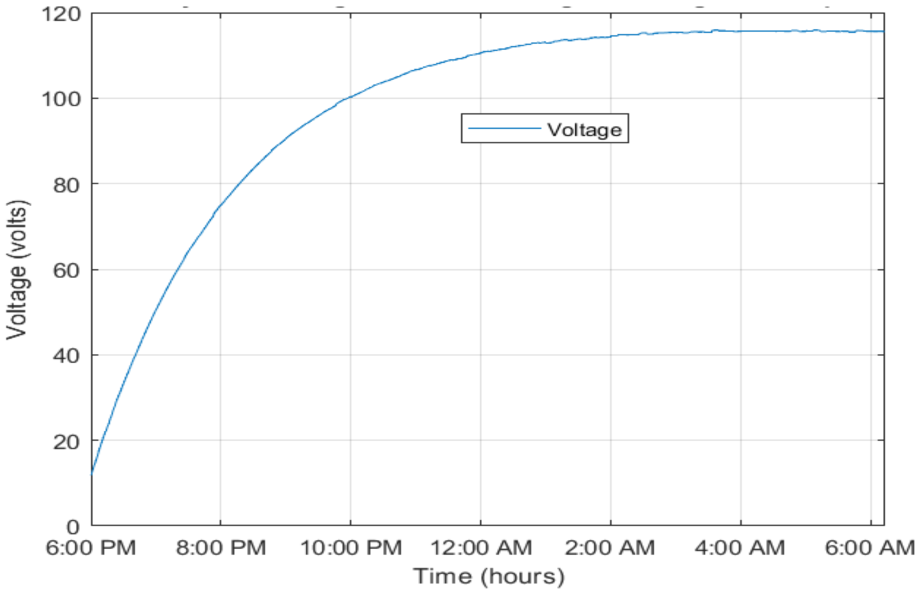


Figure 6.23 Wind power system voltage on a summer night with high wind speed

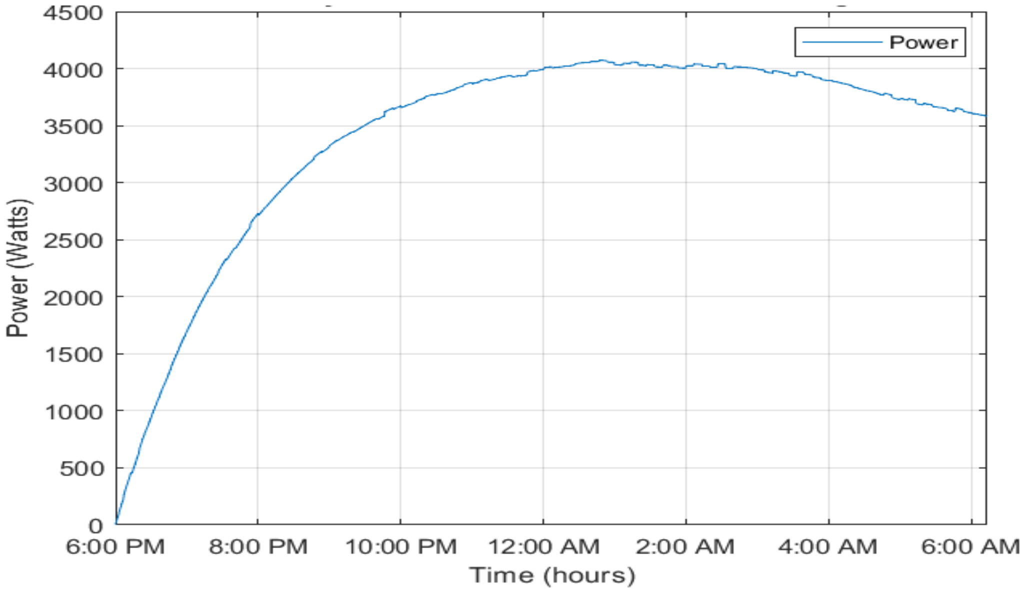


Figure 6.25 Wind energy system obtained power on a summer night

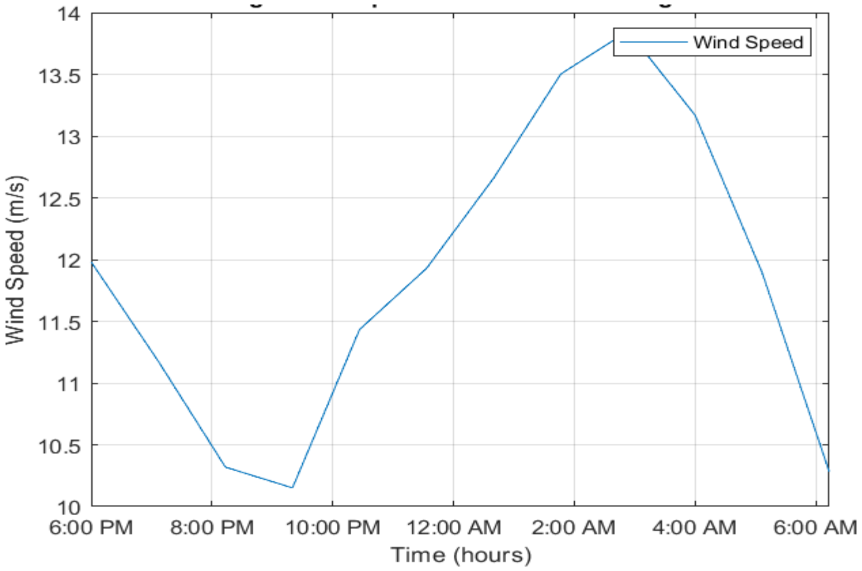


Figure 6.26 Wind speed profile for a winter night

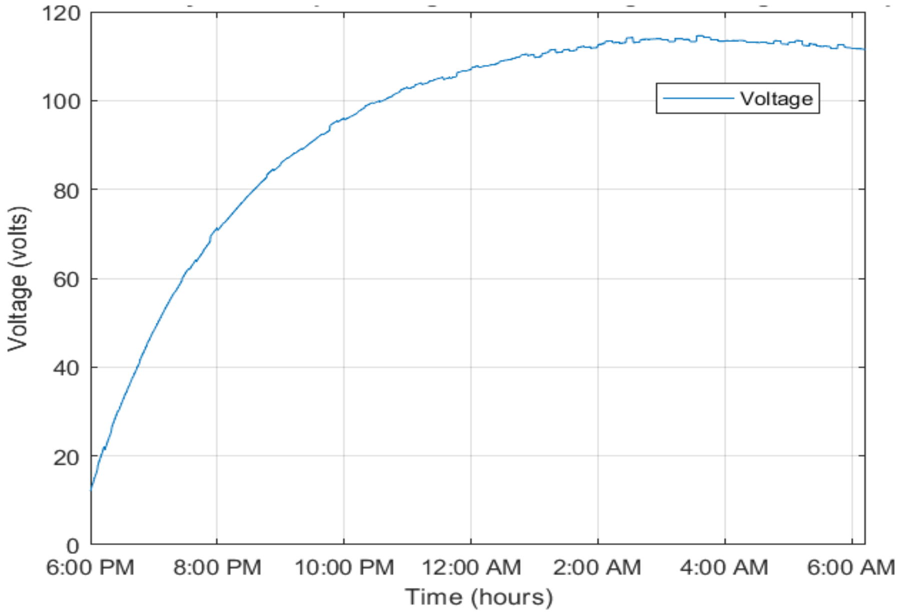


Figure 6.27 Wind power system voltage on a winter night with high wind speed

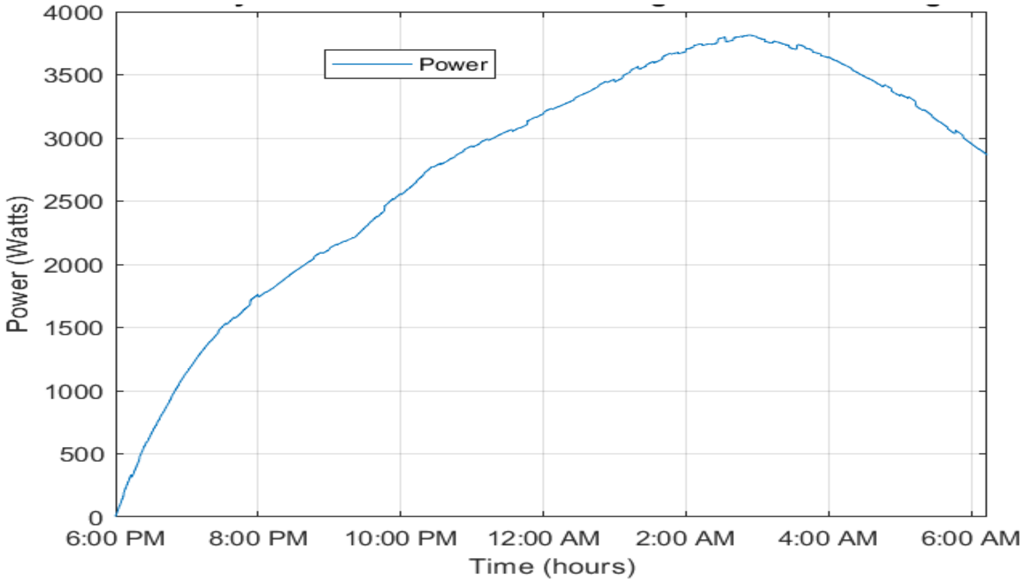


Figure 6.28 Wind system obtained power on a winter night with high wind speed