Optimization and research of operating modes of wind-solar power plants under different load configurations

Capstone Report

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Abstract:

This study focuses on the design, simulation, and optimization of a hybrid wind-solar power system integrated with a Battery Management System (BMS), with the primary objective of enhancing the efficiency and sustainability of renewable energy sources. Employing MATLAB Simulink, the project models the interactions between photovoltaic (PV) panels, wind turbines, and battery storage to achieve maximal energy capture and effective storage management. The key objectives include implementing Maximum Power Point Tracking (MPPT) and passive cell balancing techniques within the BMS to optimize energy conversion and battery longevity. The methodology involved developing detailed system models and incorporating a Perturb & Observe (P&O) algorithm for MPPT, which dynamically adjusts power conversion parameters to suit changing environmental conditions. Additionally, a Machine Learning algorithm was integrated to predict energy generation, providing a sophisticated tool for enhanced energy management. Experimental results demonstrated the system's ability to adaptively optimize operations, significantly improving the energy efficiency and operational stability of the hybrid system. The MPPT controller effectively maintained optimal power levels, while the BMS ensured uniform charge distribution among batteries, thereby prolonging their lifespan and performance. This project establishes a foundational framework for future research in hybrid renewable energy systems, suggesting that further exploration into adaptive control strategies and the integration of additional renewable sources could enhance system reliability and efficiency.

Contents

Preface

As the world faces severe environmental challenges and increased demand for sustainable energy sources, the integration of renewable energy systems has become a priority Wind and solar energy integration holds great promise to provide clean and reliable energy, but its effectiveness and utility depend on effective optimization, especially under varying load conditions. The complex world of wind-solar power plants is explored in this study, with a focus on comprehending and improving their working modes across a range of load combinations. Our goal is to reach local communities with sustainable energy while also utilizing these renewable resources to the fullest extent possible.

I would like to express my sincere gratitude to my supervisor, Gulsim Kulsharova, for her unwavering support and guidance throughout this research journey. Her dedication, understanding, and provision of powerful computing resources have been instrumental in the successful completion of this project. Without her invaluable assistance, the quality and timeliness of my research would not have been achievable. I also extend my appreciation to Anvar Kolumbetov, the co-supervisor of this project, for his innovative ideas and the significant amount of time he dedicated to working with me. His contributions have greatly enriched the development of this project. Moreover, I would like to acknowledge the crucial role played by Technopark, which provided access to the power plant and valuable data essential for this research. Their support and the data they made available have been indispensable in the advancement of this project.

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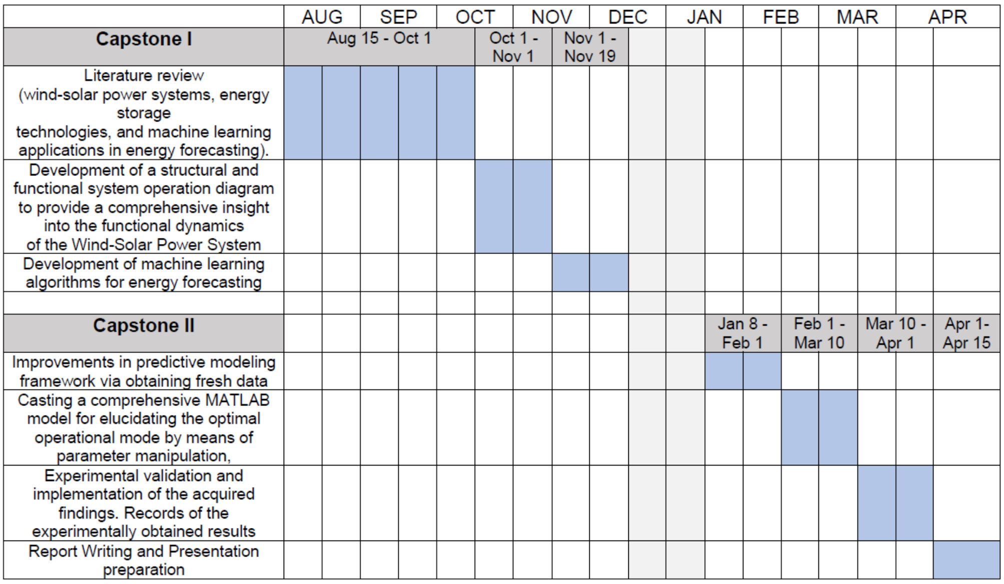
Chapter 1

Introduction

Renewable energy sources, such as wind and solar power, are gaining popularity due to their potential to provide clean and sustainable energy. However, to fully realize benefits of renewable enrgy sources, optimising the operating modes of wind-solar power plants, particularly those with low power outputs, it is crucial to ensure efficient energy production. In addition, different load configurations can significantly impact the performance of such power plants, making it important to research the optimal configurations for each system.

The are several reasons to work on the optimization of wind-solar power plants. First, solar energy has immense potential in Kazakhstan as a renewable resource due to its favourable climate conditions and sparsely populated large areas, particularly in southern Kazakhstan, where the sunshine ranges between two thousand to three thousand hours for one year. The southern region of the country receives direct sun radiation for the majority of the daylight hours during the summer, which amounts to around 85% of the maximum value. In contrast, only about two thousand hours of sunshine are typically received in northern Kazakhstan. In cities like Shymkent and Kyzylorda in southern Kazakhstan, where there are 2,936 and 2,892 hours of sunshine each year, respectively, solar power generation is sufficient to meet the energy demands of the region. In comparison to other countries, such as China, which receive an average of 2350 hours of sunshine annually, and the United Kingdom, Japan, and Norway, which receive less than one thousand hours annually, Kazakhstan has the potential to harness solar energy for its energy needs [1]. The solar radiation and photovoltaic potential map of Kazakhstan can be seen in Figure A.9 and in Figure A.10. Moreover, most modern solar panels are made of solar cells (photovoltaic cells), whose main component is a silicon semiconductor. According to U.S. Geological Survey [2], Kazakhstan is the tenth silicon production country in the world, which around 67 thousand tons per year. Additionally, according to Samruk Kazyna [3], Kazakhstan possesses significant wind resources capable of supporting the establishment of large-scale wind farms. Around half of Kazakhstan's land area experiences average wind speeds appropriate for energy production, ranging between 4 to 6 meters per second. The regions with the greatest potential for wind energy generation are the Caspian Sea and the central and northern areas. The above-mentioned facts and findings make Kazakhstan the main beneficiary of the optimization of wind-solar power plants and research to be done on it. The findings of this project will have important implications for the design and operation of low-power wind-solar power plants and could contribute to the development of more efficient and sustainable energy systems.

The objective of this project is to investigate the operating modes of low-power wind-solar power plants with different load configurations in order to optimize their energy production and efficiency. The project will involve simulations and experiments to determine the optimal configurations for each system. Additional milsedtone are reflected in Gantt's chart in Figure 1.1 Optimizing these power plants' operating modes can improve their performance, reduce their environmental impact, and promote the adoption of renewable energy sources on a wider scale.



	AUG		SEP		OCT		NOV		DEC		JAN		FEB		MAR		APR	
Capstone I	Aug 15 - Oct 1					Oct 1 - Nov 1		Nov 1 - Nov 19										
Literature review (wind-solar power systems, energy storage technologies, and machine learning applications in energy forecasting).	■	■	■	■	■													
Development of a structural and functional system operation diagram to provide a comprehensive insight into the functional dynamics of the Wind-Solar Power System						■	■											
Development of machine learning algorithms for energy forecasting								■	■									
Capstone II												Jan 8 - Feb 1		Feb 1 - Mar 10		Mar 10 - Apr 1		Apr 1- Apr 15
Improvements in predictive modeling framework via obtaining fresh data												■	■					
Casting a comprehensive MATLAB model for elucidating the optimal operational mode by means of parameter manipulation,														■	■			
Experimental validation and implementation of the acquired findings. Records of the experimentally obtained results																■	■	
Report Writing and Presentation preparation																		■

Figure 1.1: Gantt's Chart

There are wide range of reports forcused on wind-solar hybrid power plants, most of which specified on optimization of these power plants under different conditions. First, wind-solar hybrid power plants can improve the efficiency and reliability of renewable energy generation by using both wind and solar power. An integrated power generation system has the capacity to mitigate peak load demands and lower the installed capacity of the system [4, 5].Wind and solar power are complementary because they can generate energy at different times of the day and under different weather conditions. Thus, combining them can help to balance the intermittency of both sources and increase the system's overall energy output. Another optimization solution could be done on energy storage: energy storage systems can store surplus energy generated by wind and solar power plants during low-demand periods and supply it during high-demand periods. This can help to improve the utilization of renewable energy sources, reduce curtailment, and provide a reliable power supply to the grid. The battery system has a shortfall in battery operation, which can also be made up for by supercapacitor hybrid energy storage system assist, which allows for much higher energy storage in a shorter period [6]. However, using batteries alone may not be sufficient. Hence, using the battery balancer system is critical since it will ensure the battery's efficient operation and long life, especially if the battery has several battery cells [7]. Battery balancers, balancing circuits, or battery management systems, are implemented to ensure that the battery pack's individual cells are distributed evenly. Balancing, however, is vital in minimizing problems such as overheating, capacity deficiency, and uneven wear hence increasing safety and efficiency of the battery system further [8]. Moreover, the BMS continuously monitors the energy storage system voltage and current levels to prevent energy from being wasted and to keep them within a certain predetermined limit to avoid any excess heating damage. Due to resistance to materials, differences in production equipment, and processes, there may be differences in the state of energy in each ejected battery[9]. BMS also control and update crucial data while carefully identifying future faults, allowing optimum available battery potential at any given time throughout the ESS operational life [10]. The internal resistance changes take place with ageing and temperature differences, creating varying energy cell conditions, post charging, and discharging causes this phenomenon known as the barrel effect. Battery equalizing is done on equalized batteries to counteract this effect thereby increasing the battery life and efficiency of the pack [11]. Thirdly, optimizing the system is possible by optimizing load management. Load management can also be achieved by peak shaving or load shifting, ensuring that the load's needs are managed based on the power available during peak and off peaks periods. This will get the work slim for a longer duration without much costly opens running it. Beside, the use of optimization techniques where optimizing algorithms are applied to the process. These algorithms use data analytical techniques to form forecasting techniques which assist the machine to come with the optimization for the energy use. It should be mentioned that it is recommended to explore the option of implementing and creating hybrid learning approaches along with additional optimization methods to enhance and refine the development of these techniques [12]. Finally, integrating with the smart grid will make the wind-solar power plant more effective and efficient. For example, the right choice of battery could entirely impact the on/off rate of solar panel wind: when the rate is off connected to the battery [13]. Put another way, it involves sophisticated communication and onboard control systems monitoring the energy distributed between the plant and the grid. These improvements will increase the plant's responsive power to changes in power demand, undoubtedly subject to changes in optimizing emergence. One such change I plan to implement use of Maximum Power Point Tracking. The MPPT controller is the core of both a photovoltaic and a wind energy system and it is designed and engineered to optimize a source of energy extraction by matching an operating point to the maximum power point of the energy source In photovoltaic systems, the MPPT controller pursued optimized the panel electrical load on sunlight this is accompanied by a temperature in this case to optimize where the panel operates. However, In a wind system, the MPPT controller optimized here by continually matching an electrical load to the current rotations per minute required by a turbine to publicly optimize itself. The algorithms involved are not straightforward that determine a sufficient amount of rotations per minute that a turbine blades should rotate in wind thus arrives at optimal tip-speed ratios. It has greatly improved the output irregardless of resultant environmental evidences, MPPT controllers in Renewable systems improve energy capture on the PV system between10-30% and similarly improve the output of the turbine on a windmill [14]. This increase in efficiency not only maximizes the energy harvested but also improves the economic viability of the renewable energy projects by increasing the return on investment and reducing payback periods. The adaptability and effectiveness of MPPT controllers in managing variable power sources make them indispensable in modern renewable energy implementations.

The project's main work will be done on RES Technopark Polygon at Nazarbayev University. This centre is equipped with all the tools necessary for the project. It consists of solar panels of two types: monocrystalline and polycrystalline, which have different efficiency levels; three wind turbines; inverters; charge controllers; a battery centre; equipment for receiving weather data, etc. Necessary data sheets are provided in the appendix. Besides, there is an autonomous energy-efficient home named the "Shell Yurt". Since the yurt is autonomous, it has a heating system, its own server room, and other electronic installations that act as different types of load with various power consumption. The yurt is mainly powered by the energy produced by the wind-solar installation. Thus it can be used as the main source of load to conduct experiments on it.

Chapter 2

Methodology

2.1 Hybrid Renewable Energy based microgrid system model construction

First, the study commences with a detailed exploration of the wind-solar power plant, conducted to examine the complex elements constituting the system. This initial phase involves a meticulous examination of various elements, including the quantity and power output of solar panels, the configuration of charge controllers within the system, the specific type of battery employed for energy storage, and other important components. All of the described details were efficiently documented and edited to gain a holistic view of the system's composition. An electrical principle diagram was also created with the help of online diagram builders to portray clearly all the components of the wind-solar power plant and their connections. The diagram contained information on the quantity of solar panels, their performance, the configuration of charge controllers, the type of battery, and more. This visual document acts as a basis for further development. Having the understanding caused by the system examination and electrical principle diagram, a developed Matlab model can be designed. Its aim is to create a dynamic and life-like simulation of a wind-solar power plant, while at the same time be able to tamper with system parameters in the MATLAB environment. The model developed in this part can be assumed to be used as a tool for further optimization experiments.

To summarize the technical characteristics of the system in a precise manner, the following extensive table has been compiled in the given figure 3.2. It provides a more general description of each part's essential properties in order to outline the wind-solar power plant in a brief manner. In addition, a functional diagram illustrating the operational process of the system was created to comprehend the entire sequence, beginning with energy generation and concluding with the transfer of energy to the consumer. Parameters such as solar panel efficiency, charge controller specifications, battery type, and other relevant details are systematically organized for clarity (Figure 3.3). For more in-depth understanding, an appendix is included, containing an elaborate version of the technical specifications. This section provides a breakdown of each component's specifications, facilitating a thorough examination of the intricacies involved in the wind-solar power plant.

As previously indicated, a local hybrid photovoltaic (PV) and wind power generation system incorporating a battery system was developed using MATLAB Simulink. This model was crafted based on the system overview provided by RES Technopark, depicted in figure 3.1. Additionally, the parameters for each component and subsystem are detailed in figure 3.3. The primary objective of this model is to demonstrate how the integration of optimization methods, specifically battery management systems (BMS) and Maximum Power Point Tracking (MPPT), influences the overall efficiency and functionality of the system. The simulation was conducted using MATLAB R2023a to ensure full compatibility with the latest updates in the Simulink libraries [15]. The components of the wind generation system, the PV system, and the BMS were initially developed as independent modules and subsequently integrated into a cohesive subsystem. A critical aspect of this integrated system is the battery charging process. The specifications for the battery indicate that it operates at approximately 13.8V in booster mode per battery, culminating in a total of 276V for the system. Additionally, the capacity of each battery is 200Ah, leading to a total capacity of 600Ah for the entire array. The use of these parameters is useful in creating and running both buck and boost converters. This is because the mentioned elements are highly beneficial in customizing the charging process hence creating a maximized level of energy consumption and a solid form of the system.

2.1.1 Construction of PV subsystem

In addition to the parameters shown in figure 3.3 the PV panel characteristics were imported onto the MATLAB Simulink environment . This enabled the derivation of the systems maximum power characteristics on the PV array block properties that then facilitated a comparison with the experimental results after simulation of the model. It is important to appreciate that the MPPT system can be built using the MATLAB functions and the simulink building blocks too. The MPPT system built on this model was built by the construction of the MPPT system using the MATLAB Simulink building blocks and the pulses using the Perturb and Observe (P&O) algorithm. The P&O algorithm synched with an integration of two sensors measuring the voltage and the current of the PV cell helping the MPPT system to track the MPP accurately and efficiently. The empirical results of the simulation show that the system takes approximately 2.5 seconds to reach and track the MPP accurately. The tracking efficiency of this system stands at approximately 97.6% equivalent to an error rate of 2.4% indicating an effective tracking system of the

MPP with a low level of error. It is an effective methodology that underscores the accuracy of the model and effectiveness of the MPPT system using the P&O algorithm in power optimization under varying conditions.

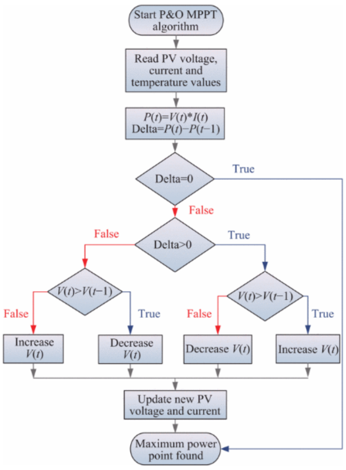


Figure 2.1: Perturb and Observe (P&O) MPPT algorithm [16]

The constructed current-driven DC to DC buck converter was aimed to provide better control over the output voltage produced and exert more efficiency control to reach the required voltage levels. The figure 2.2 is referred to as a step-down converter based on its ability to reduce the voltage values. The schematic for the buck converter provided necessary framework for its implementation in the system. The buck converter mathematical calculations for its components including inductance and capacitance was calculated by following a mathematical model sourced from H.M. Rashid's influential text, "Power Electronics" [17]. The solution model guides and provides a calculated guideline to obtain a better inductance and capacitance rating that fuels the designed and constructed buck converter. Following Rashid's information, the converter is expected to realize a voltage optimization target process to conduct stable voltage down-adjustment to either match the voltage output received from the renewable to the expected load or the battery charging level.

$$L = \frac{V_{op}(V_{ip} - V_{op})}{F_{sw} \cdot I_{ripple} \cdot e \cdot V_{ip}} \tag{2.1}$$

$$C = \frac{I_{ripple}}{8 \cdot F_{sw} \cdot V_{ripple}} \tag{2.2}$$

For the design of the DC-to-DC buck converter for the hybrid PV and wind power generation system, the following crucial parameters should be defined accurately to achieve the maximum efficiency and power dissipated in the system with compatibility with the system requirements:

1. Output Voltage (Vop): The output voltage of that the PV array. It is the high voltage site of the buck converter that will be stepped down.
2. Desired Input Voltage (Vip): The desired voltage aimed to charge the battery system. The stepped down voltage as the result of buck converter work.
3. Switching Frequency (fsw): The switching frequency is an essential design parameter for the buck regulator, affecting its efficiency and output voltage smoothness. The frequency at which the buck converter's switch rapidly interrupts the current flow thus determines the rate at which it responds to the input and output voltages over the load.
4. Voltage Ripple (Vripple): Vripple is the variation within the converter's output; in other words, the voltage fluctuation quantified as a percentage. The output voltage will experience a variation of approximately 1% without causing any instabilities on sensitive electronic loads or battery charging stability.
5. Current Ripple (Iripples): Similar to voltage ripple, current ripple refers to the fluctuation in the output current. In this design, the current ripple is maintained around 10%, which is a balance between efficiency and preventing excessive heat generation or potential damage to the system components.

These parameters are integral to the design and functionality of the buck converter within the renewable energy system. By carefully setting and managing these values, the buck converter can effectively regulate the power from the PV array, ensuring that the battery is charged at the correct voltage level, thereby maximizing the system's overall efficiency and lifespan.

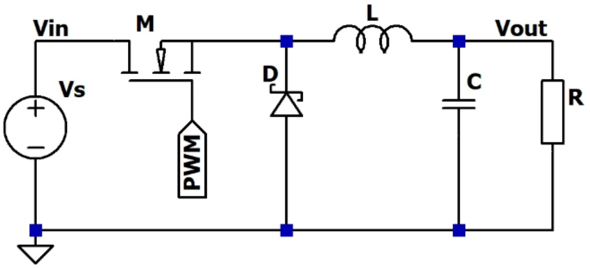


Figure 2.2: Buck Converter schematic

2.1.2 Modeling Wind Energy generation subsystem

In the simulation of the wind energy generation system within the hybrid renewable energy setup, the model includes a wind turbine, a Permanent Magnet Synchronous Generator (PMSG), a 2-mass drive train, a uniform rectification block, and a DC-DC boost converter with an integrated Maximum Power Point Tracking (MPPT) controller. The wind turbine traps wind's kinetic energy and transforms it to rotational energy. This energy powers the PMSG, which is efficient and can produce electricity at different revolution speeds. The 2-mass drive train design insulates the generator from mechanical pressure and vibrations, which could compromise its lifetime. The PMSG produces alternating current (AC) that is converted into direct current (DC) through a uniform rectification block. Since the voltage obtained from the initial rectification process is relatively low, it is then elevated to a usable level through a DC-DC boost converter (figure 2.3). The inclusion of an MPPT controller in this stage is critical, optimizing the voltage and current levels to maximize the energy output and efficiency of the system. This controller dynamically adjusts the operation of the boost converter to align with changes in wind speed and turbine output, ensuring the system operates at its maximum efficiency.

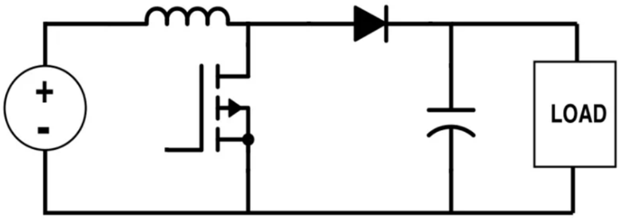


Figure 2.3: Boost Converter schematic

2.1.3 Battery Management System (BMS) Modeling

In the hybrid renewable energy system, the Battery Management System (BMS) plays a crucial role in maintaining the efficiency and longevity of the battery storage. According to the system specifications, the battery system is comprised of 60 batteries arranged in three rows of 20 series-connected batteries each. However, due to the complexity of the design, it was decided to simplify the configuration in the MATLAB model by grouping four batteries as one unit. This adjustment resulted in a total of 15 battery units, each with a nominal voltage of 48V, culminating in a total nominal voltage of 240V and a capacity of 600 Ah.

To effectively model the BMS, a passive cell balancing strategy was adopted. Each battery in the model is associated with a connected resistor and a MOSFET, which are critical components in the passive cell balancing circuit. The schematic detailing how to build the passive cell balancer is illustrated in figure 2.4. It was observed that for optimal system performance, it is advisable to construct separate control blocks for each row of batteries. This approach facilitates more precise control and monitoring of the battery states.

Several control algorithms were evaluated for equalizing the voltage levels across the batteries. For this project, a State of Charge (SOC)-based algorithm was implemented. This algorithm was realized through a dedicated MATLAB function that iteratively loops through each battery's SOC level, comparing it with others, and adjusting until the voltage level of each battery matches that of the battery with the lowest voltage. This SOC-based control is advantageous as it functions effectively both during charging and discharging phases, ensuring a balanced state across all battery units. The charging input to the battery system is derived from a constant DC source, which in this model, is the combined energy output from the PV panels and wind turbine. This integrated approach not only ensures a consistent energy supply to the batteries but also enhances the overall energy management and efficiency of the hybrid system. By leveraging the SOC-based algorithm, the BMS optimizes the health and performance of the battery array, thereby improving the system's reliability and operational lifespan.

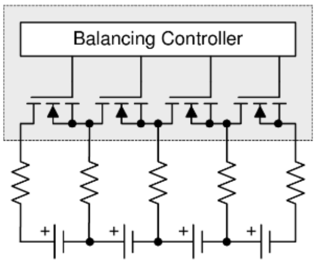


Figure 2.4: Schematic of the passive cell equalizer [18]

2.2 Methods and Procedure of Data Analysis

2.2.1 Development of Machine Learning Algorithm

The machine learning algorithm for predicting energy output was meticulously constructed within the Anaconda distribution and Jupyter Notebook, harnessing the versatility of the Python programming language. This choice, informed by Python's prominence in data science and machine learning, provided a robust platform for model development. To gain proficiency in leveraging Python programming language for machine learning, the foundational resource utilized was the book "Machine Learning with Python," which imparted insights into key concepts, methodologies, and practical applications within the domain of machine learning. In the process of constructing the energy output prediction model, a range of algorithms was explored to identify the most effective approach. The considered algorithms encompassed: KNeighborsRegressor from the scikit-learn library, Decision tree regressor, Linear Regression, K-fold Cross-Validation (CV) with KNeighborsRegressor, K-fold CV with CART (Classification and Regression

Trees), RandomForestRegressor with GridSearch. To implement and optimize these algorithms, essential Python libraries included: NumPy and Pandas for data manipulation and preprocessing, Scikit-learn for machine learning algorithms and model evaluation, Matplotlib and Seaborn: for data visualization. The algorithms underwent meticulous tuning and optimization, with an emphasis on hyperparameter adjustment. This involved extensive experimentation with parameters to enhance model performance. GridSearch, a method available in scikit-learn, was employed for systematic exploration, identifying the optimal combination of hyperparameters (maximimun depth, number of esimators, minimum number of samples per leaf and per split) for the RandomForestRegressor algorithm.

2.2.2 Data Data Evaluation and Preprocessing

The initial phase in constructing predictive models involves the thorough collection of data. The dataset, sourced from RES Technopark, encompasses minute-level recordings of crucial variables, including solar irradiation, wind speed, outside temperature, and output energy spanning from January to May. Recognizing the importance of a comprehensive feature set, additional attributes like humidity, pressure, and precipitation in Astana were acquired from external sources. Subsequent to data collection, the evaluation and preprocessing phase took place, conducted using Python within the Jupyter Notebook environment. The data evaluation process included the transformation of minute-level recordings into daily aggregates, optimizing the dataset for daily predictive insights. Python libraries NumPy and Pandas played a pivotal role in facilitating this transformation. The critical aspect of feature selection followed suit, recognizing the intricacies of model sensitivity. The identification of salient features employed robust methodologies. Utilizing a Correlation Matrix to unveil interrelationships among variables and a Random Forest Regressor to gauge feature importance, the most impactful features for the predictive model were discerned. These systematic steps ensured the meticulous preparation of the dataset and the identification of essential features, laying a solid foundation for the subsequent phases of model construction.

Chapter 3

Results and Discussions

3.1 Literature Review

The methodology used here to write the project is, at first the literature review and then the corresponding data results obtained experimentally. The experiments, as discussed in the previous section, are going to be conducted at the “Technopark” research area. As discussed in Introduction section of the report, there are numerous reports conducted on renewable energy sources, especially wind-solar power generating systems. Most of the articles on wind-solar power plant optimization consider three main aspects of improving the performance of the system. First, when the energy storage is included, energy consumption time duration can significantly be increased in such a way that the energy can be stored and fulfilled in storage when the system is not loaded. Secondly, there is a significant reason to combinate wind and solar generators under different weather conditions. Besides, the optimal load configuration could be found that would help to improve the system performance. The article "A review on planning, configurations, modelling and optimization techniques of hybrid renewable energy systems for off-grid applications" by Siddaiah and Saini provides a comprehensive review of different hybrid renewable energy systems and their modelling and optimization techniques for off-grid applications [19]. The authors discussed on the importance of hybrid renewable energy systems for distant areas and provided an insight into the different components as well as configurations, and optimization techniques of such systems. The importance of accurate modeling and optimization for the proper functioning of the system was outlined in this article. Numerical data from various research were provided on the performance of different systems of hybrid renewable energy. For example, a hybrid wind-solar system could provide a capacity factor of 50% in favorable locations . Different parameters of optimization such as the sizing of the system components and the study of control algorithm were also discussed in the article to improve the performance and reliability of the system [19]. Regarding the project, the results of this article can be used to understand different optimization methods and parameters which can boost the performance and reliability of the hybrid power system. The numerical information can also help in predicting the performance of the system at certain operating scenarios. Another related article that uses optimization is proposed by Ma et al.. They use a multi-objective optimization method to identify the most economically beneficial configuration of a stand-alone wind-solar-battery hybrid power system. In this article, the following three objectives are considered: COE, system reliability, and carbon emission. They use the genetic algorithm to get the Pareto optimal solutions of the multi-objective optimization problem.Researchers implemented their proposed method to a case study that involves a remote Chinese island experiencing abundant wind and solar energy but lacks grid access. Their findings indicate that the ideal system setup includes a wind turbine as well as solar panels, and a battery bank. They found that, compared to a setup without optimization, this optimal configuration can reduce the cost of energy by 17.2%, carbon emissions by 33.3%, and system reliability by 10.7% [20]. Chauhan and Saini explained that in a case study based on a small Indian island, Majuli, designers developed a hybrid system with wind turbines, solar photovoltaic panels, and battery storage and analyzed it. The system efficiency was calculated at 55.67%, with wind contributing to 63% of the overall power output and solar to 37%. At the same time, the battery bank provided almost one-third of the consumed energy and became an essential source of power during low wind and solar period, and the system was avle to met 84.5% of the total load demand. Moreover, the authors performed the sensitivity analysis using the wind turbine and solar panel's sizing and observed that the increase in rated capacity of the wind turbines lead to the higher system efficiency and higher power generation from wind. Furthermore, the higher the rated capacity of solar panels levels the higher efficiency and more power generation from the solar side as well. Nevertheless, the sizing of the battery bank influenced the system efficiency and demand met, than the capacity sizing of wind turbines and solar panels, respectively [21]. Another method of optimizing the wind-solar hybrid power plant is to work on the installation ratio as well as on size of equipment. Several studies discovered how to combine wind turbines and solar panels so that to achieve the highest efficiency. For instance, Dalwadi et al. came up with the methodology for optimizing a solar-wind hybrid system for distributed generation. They used HOMER software to model and simulate the system and advised a genetic algorithm-based optimization approach for sizing the system components. The study's aim is to identify the optimal system size of renewable energy system. Their results showed that the combined solar-wind hybrid power plant could be a possible solution for distributed power generation [22]. Similarly, Mousa et al. also proposed a methodology for a hybrid solar-wind power plant. Their outcomes showed that a combination of both solar and wind power resources should offer an economically profitable solution. Both research emphasised the significance of correct sizing and implementation of hybrid machine to maximize the performance and minimize the cost. Besides, they also highlighted an advantages of using optimization techniques such as genetic algorithms in determining the optimal system design[23]. Added to this, the study by Liu et al. also focuses on optimizing the combination of wind and solar energy in order to mitigate renewable energy variability in China. The authors analyzed the complementarity of wind and solar resources and determined that the mixture of wind and solar energy in one electricity systen can appreciably lessen the range of renewable energy technology. They also recognized several areas in China in which wind and solar power structures might be optimally combined to maximize energy technology. The authors used numerical models and simulations to obtain their outcomes and supplied numerical records to support their findings [24]. Moreover, many studies proved that using energy storage can significantly improve the efficiency of wind and solar power generation. Additionally, some studies show that the use of specific storage options affects system performance differently. For example, Zhou and Sun present an optimization method for a battery-supercapacitor hybrid energy storage station (BESS) in a wind/solar generation system. The aim of the authors is to reduce the dynamics of the system and to maintain the robustness of the system. A monitoring plan for the BESS is proposed to ensure the energy balance of the wind/solar generation power system. The proposed method was implemented using a simulation model that is based on a real wind/solar power plant. The results showed that BESS can effectively reduce the power fluctuations , and the proposed optimization method can provide a balance between battery and supercapacitor energy storage between. The study shows the feasibility of using BESS to improve the efficiency of wind/solar power plants [25]. At the same time, Abbassi and Chebbi say that using battery storage helps conserve excess power and control the power output of the system. The authors also investigate the effect of various parameters on the system performance. They proposes a control scheme to maintain the battery state of charge within the desired range. Simulation results showed that the method effectively reduces the operating costs and improves the stability of the power system while providing reliable electricity to the user end [26]. In addition, several resources of a general nature in the wind-solar system optimization were identified. The article by Liu et al. provides a review of various optimization schemes of controlling wind-solar hybrid systems with new energy vehicles (NEVs). The article considers all components of hybrid systems: wind turbine, solar panel, battery, and NEV, among which the optimal characteristics should be selected to achieve maximum energy efficiency. This review outlines a wide variety of optimization schemes, from model predictive control to fuzzy logic control and artificial neural network control, and a detailed analysis of the advantages and disadvantages of each is given. Moreover, possible integration problems with NEVs are considered, and ways to solve them are proposed. This article is a comprehensive review of the optimization of wind-solar system control with NEVs. The conclusion of the authors is that the use of optimization techniques allows hybrid systems to achieve high efficiency, which will make this source of energy sustainable and more cost-effective in terms of the energetics of the future [27]. On the other hand, Lawan and Abidin considered wind-solar hybrid renewable energy systems based on the typology of these systems: modality, design, and optimization. They talk about the main advantages of combining two types of renewable energy—wind and solar, which allows compensating for the lack of one type of renewable energy with an increase in the proportion of the other. They emphasize the importance of factors such as location, consumer demand, and energy storage in the design of wind-solar systems. Various optimization techniques for the sizes of wind and solar plants and energy storage are also described [28]. However, Dagdougui et al. build mathematical models of the optimization of the design and operation of hybrid wind-solar systems, conditioned by the building. It takes into account certain restrictions on the building's energy demand, renewable energy sources: thermoelectric, solar-heated water, and the cost of electric and thermal energy. As can be seen, the optimization of the design of this type of optimal energy system is possible. The analysis of the results of the study shows that a profitable wind-solar hybrid system can fully cover the energy consumption of the building and will be more profitable from the calculation of possible greenhouse gas emissions and related costs. The authors conclude that hybrid energy systems can provide a sustainable and efficient energy solution for green buildings [29]. Scrutinizing the resources on optimization of renewable energy power plants, it could be said that there are many approaches to optimize the wind-solar power generation system. Some of them depend solely on weather conditions. Some sources suggest using energy storage elements in order to control the demand for energy. It was also found that it could be found the most suitable load configuration to optimize the system. However, it could be mentioned that the optimization results depend on the location of power plants, on the weather conditions of that place, so the approach may not be suitable or differ for different regions. Additionally, not all the methods of optimization were studied well, thus, further work is required. For this reason, it is going of be checked the already existing methods of increasing the efficiency of the system and going to be found the optimal ones. As a practical part of the work, some observations were done experimentally at the Technopark power plant. To get the relationship between the weather conditions and the work of the power plant, the corresponding data was obtained. To better understand the impact of weather conditions and different load impacts, the data was derived for summer and winter periods. The data that was obtained: were the wind speed, solar radiation, voltage level, and the power of energy generated by solar panels. Due to the breaks in the data collection systems, the data for the power of energy generated by wind turbines could not be collected. The power of energy generated by solar panels is included in the appendix.

3.2 Experimental Results

3.2.1 Obtaining wind-solar power system schemtic diagrams

In accordance with the methodology outlined, the primary objective was to develop both an electrical principle diagram (Figure 3.1) and a functional diagram(Figure 3.3) for the power system situated in close proximity to RES Technopark. This endeavor serves as a foundational step, intending to facilitate the subsequent construction of a MATLAB model tailored for system manipulation. Furthermore, to attain a comprehensive understanding of the intricacies inherent in the system, a detailed technical specification has been diligently compiled (Figure 3.2). This technical specification, a pivotal component of the project, provides a thorough delineation of the system's components, functionalities, and operational parameters. It is anticipated that this comprehensive documentation will not only bolster the construction of the MATLAB model but also serve as a valuable reference for ongoing and future analyses of the power system.

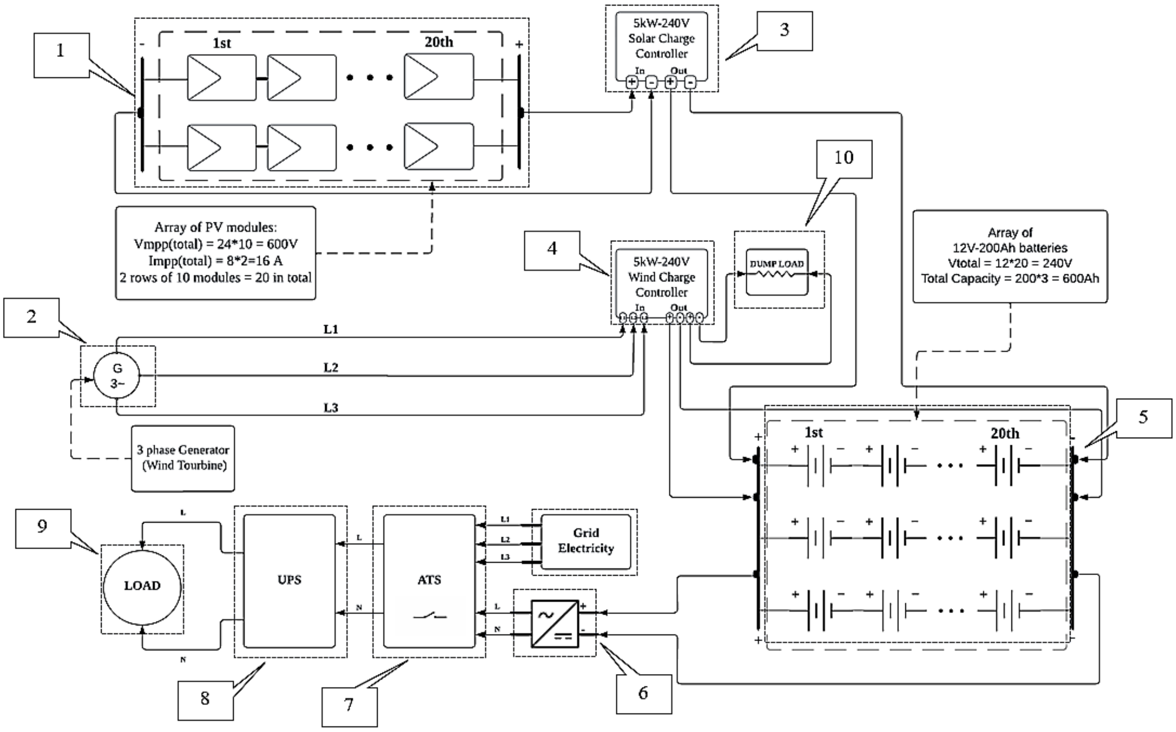
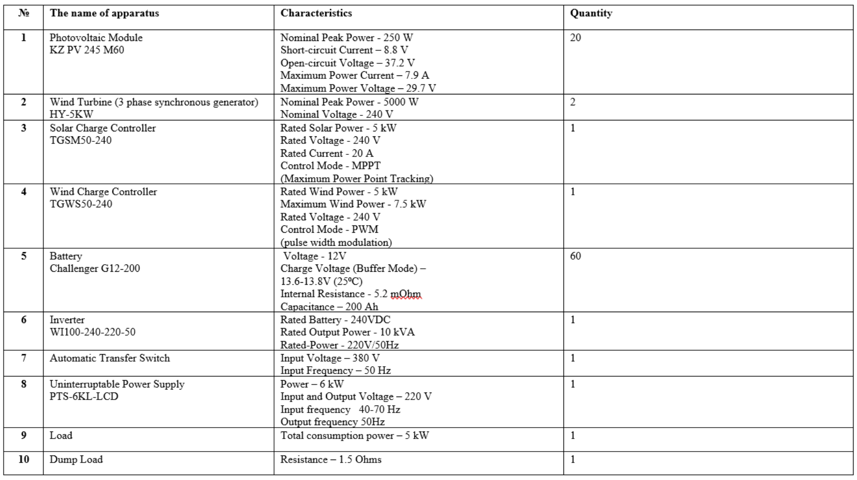


Figure 3.1: Electrical Principle Diagram of the wind-solar power system



№	The name of apparatus	Characteristics	Quantity
1	Photovoltaic Module KZ PV 245 M60	Nominal Peak Power - 250 W Short-circuit Current – 8.8 V Open-circuit Voltage – 37.2 V Maximum Power Current – 7.9 A Maximum Power Voltage – 29.7 V	20
2	Wind Turbine (3 phase synchronous generator) HY-5KW	Nominal Peak Power - 5000 W Nominal Voltage - 240 V	2
3	Solar Charge Controller TGSM50-240	Rated Solar Power - 5 kW Rated Voltage - 240 V Rated Current - 20 A Control Mode - MPPT (Maximum Power Point Tracking)	1
4	Wind Charge Controller TGWS50-240	Rated Wind Power - 5 kW Maximum Wind Power - 7.5 kW Rated Voltage - 240 V Control Mode - PWM (pulse width modulation)	1
5	Battery Challenger G12-200	Voltage - 12V Charge Voltage (Buffer Mode) – 13.6-13.8V (25ºC) Internal Resistance - 5.2 mOhm Capacitance – 200 Ah	60
6	Inverter WI100-240-220-50	Rated Battery - 240VDC Rated Output Power - 10 kVA Rated-Power - 220V/50Hz	1
7	Automatic Transfer Switch	Input Voltage – 380 V Input Frequency – 50 Hz	1
8	Uninterruptable Power Supply PTS-6KL-LCD	Power – 6 kW Input and Output Voltage – 220 V Input frequency 40-70 Hz Output frequency 50Hz	1
9	Load	Total consumption power – 5 kW	1
10	Dump Load	Resistance – 1.5 Ohms	1

Figure 3.2: Technical Specifications

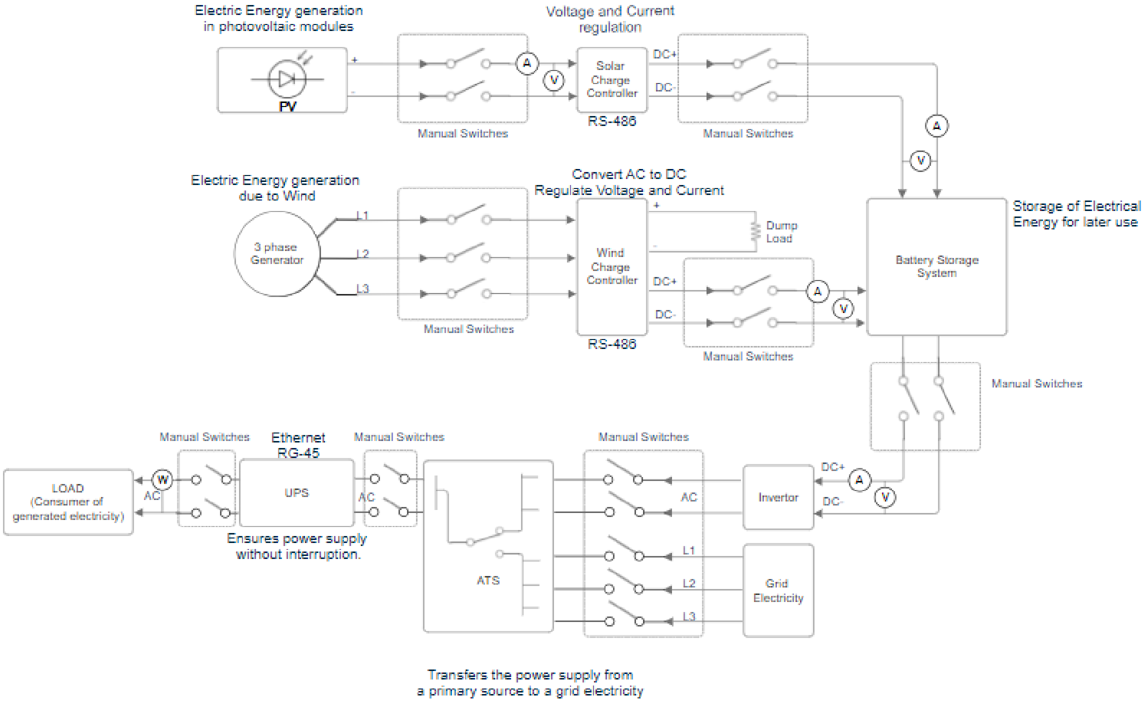


Figure 3.3: Functional Schematic Diagram

3.2.2 MATLAB Simulink

PV subsystem

As previously noted, a MATLAB model of a PV-WIND hybrid power system incorporating a battery storage unit was successfully developed. For a comprehensive analysis, the model was partitioned into distinct subsystems representing Photovoltaic (PV), Wind, and Battery Management System (BMS) components. Figure 3.4 presents a detailed depiction of the PV subsystem within the model. This particular subsystem is configured to simulate variable solar irradiation under a condition of constant temperature.

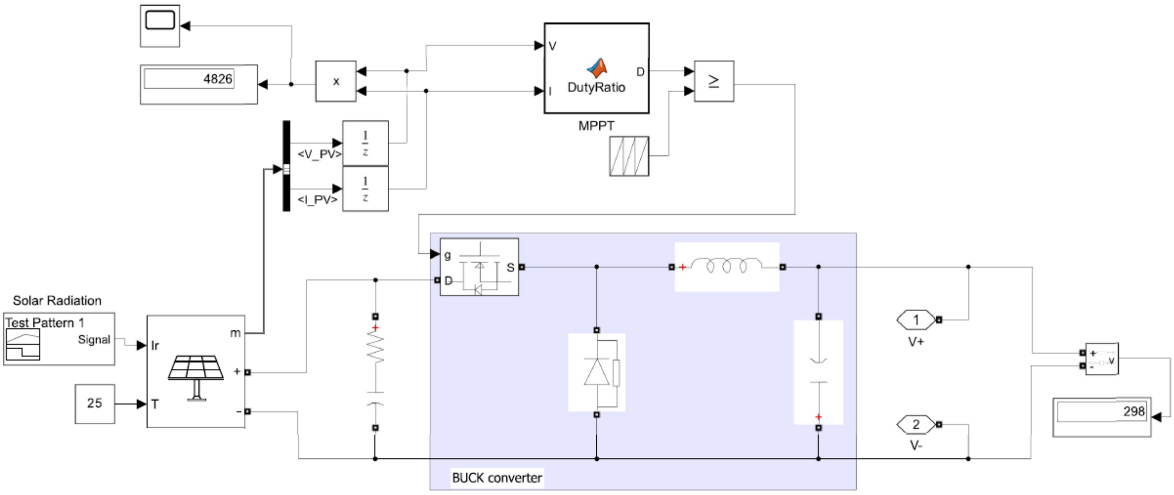


Figure 3.4: Simulink model of PV subsystem

The simulation parameters for irradiance are designed to increment in steps of 200W/m^2, starting from a baseline of 200W/m^2 and escalating to a peak of 1000W/m^2, as demonstrated in Figure 3.5.

Furthermore, the PV subsystem is realized by the buck converter whose principal function is that of regulating the voltage output from the PV cells to a suitable and steady-state level for now and future use. Lastly, the MATLAB function referred to as ‘Duty Ratio’ in this model performs the duty of the Maximum Power Point Tracking (MPPT) controller. This is critical in optimizing the power output from the PV cells, which is done by varying the duty cycle of the buck converter as solar irradiation changes to ensure that the system operates at its Maximum Power Point (MPP) regardless of the solar light intensity. This concept is well demonstrated by the I-V characteristics and the relationship between irradiation and output power that was deducted from our generated PV array model as shown in figure 3.6. It is from the figure that one can tell the specific current and voltage

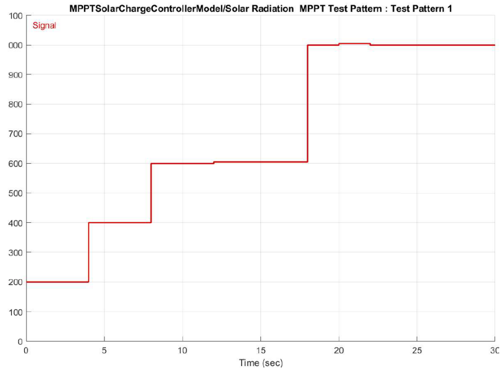


Figure 3.5: Test input for irradiation

points at which the PV array attains its maximum power as well as how this power level changes concerning the input irradiation.

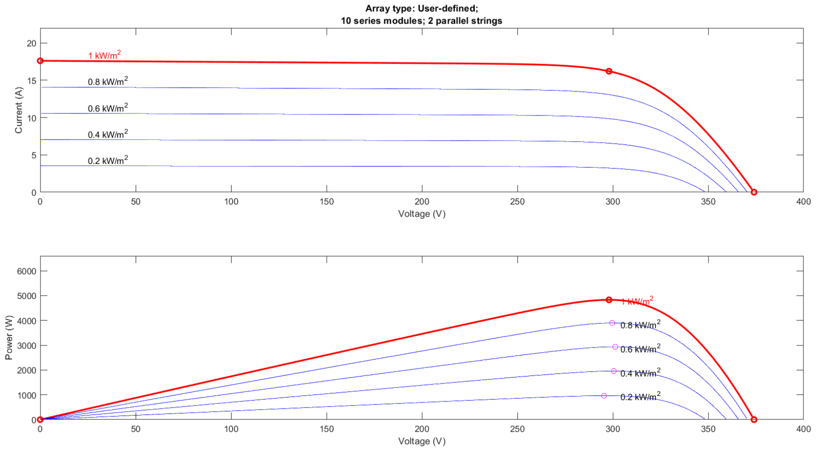


Figure 3.6: PV array characteristic curves

Subsequent to the simulation run, the output power corresponding to various levels of irradiation was derived (figure 3.7). This data served to confirm the efficacy of the MPPT controller, as it indicated that for each increment in irradiation, the controller successfully adjusted the operational parameters to ensure that the PV array consistently produced the maximum possible power (ex. 4827W at 1000 W/m2 irradiation). The results validate the MPPT controller's critical role in optimizing the energy harvest from the PV array, effectively adapting to changes in environmental conditions to maintain peak performance.

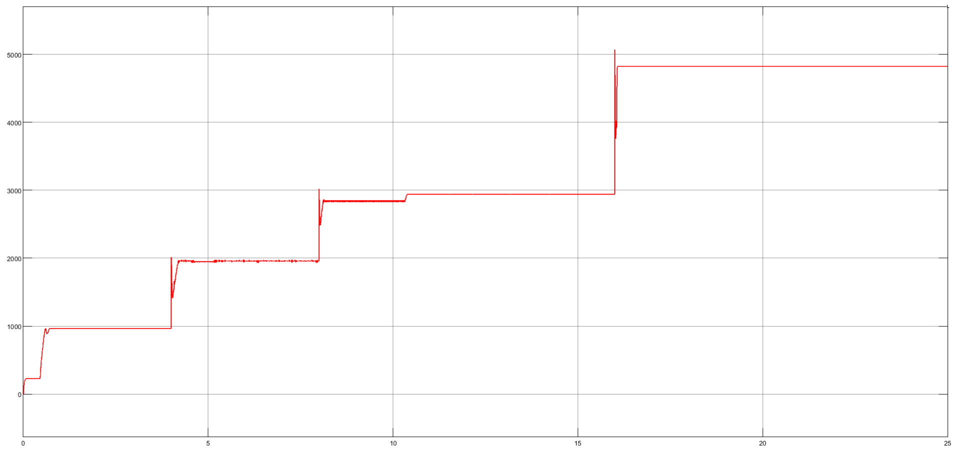


Figure 3.7: PV array output generated power at different irradiation levels

Wind Energy Generation

The Wind Energy Generation within the hybrid system was simulated through a combination of a wind turbine and a Permanent Magnet Synchronous Generator (PMSG). Accompanying these elements, a two-mass drive train was incorporated to realistically model the mechanical dynamics between the rotor and the generator. Additionally, this subsystem includes an MPPT (Maximum Power Point Tracking) controller paired with a boost converter, integral for optimizing the energy capture from wind (figure 3.8).

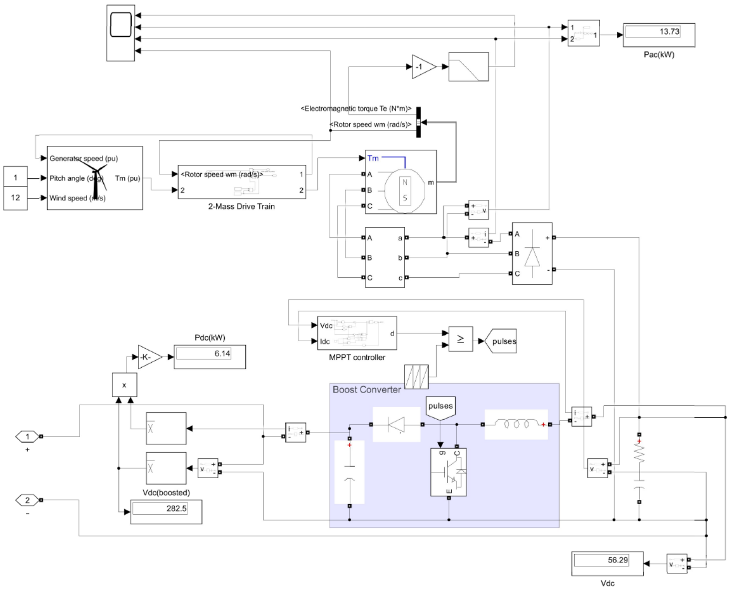


Figure 3.8: Wind Energy generation subsystem

While the photovoltaic (PV) subsystem utilizes a MATLAB function specifically for the Perturb & Observe (P&O) algorithm to achieve MPPT, the wind energy subsystem employs the same algorithm but represented as a distinct subsystem model (figure 3.9).

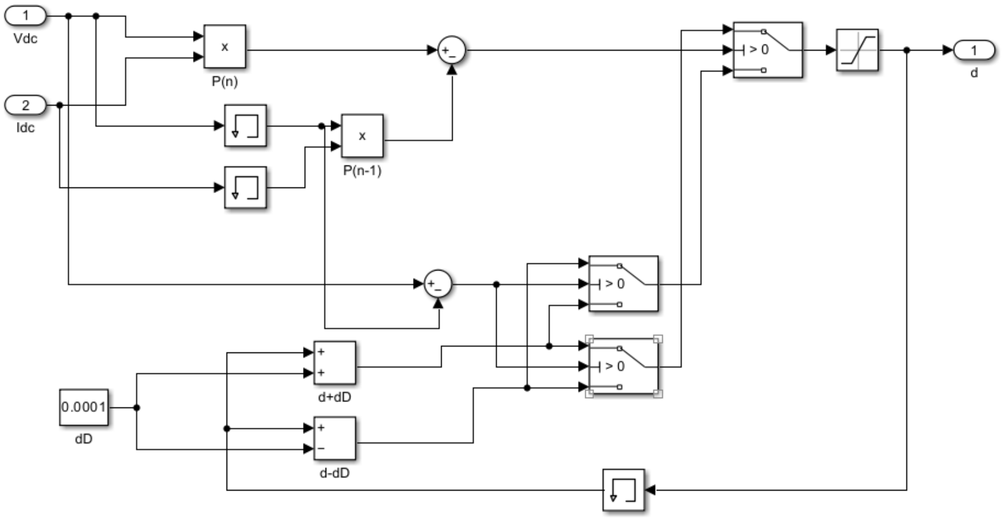


Figure 3.9: P&O MPPT algorithm as a subsystem

The simulation results demonstrate that the boost converter is performing efficiently, attaining the desired voltage level at the output, which is 282.5 V. This verifies that the integration of the MPPT with the boost converter is successful in maintaining the optimal operational point for the wind turbine, ensuring maximum energy conversion irrespective of varying wind conditions. The use of the P&O algorithm within both the PV and wind subsystems highlights the versatility of this method in enhancing the overall efficiency of hybrid renewable energy systems.

Battery Management System (BMS)

The Battery Management System (BMS) implemented within this project utilizes a passive cell balancing approach, as depicted in model screen in figure 3.10. Each row of battery cells is managed by a dedicated control block, designed to uniformly maintain the charge levels across the entire array. This system operates on a state-of-charge (SOC)-based control algorithm, encapsulated within a MATLAB function that is meticulously crafted to promote equalization among the cells. The control algorithm embarks on a comparative loop, scrutinizing the SOC of each individual cell against its counterparts. Should the SOC of any particular cell surpass that of the others, the algorithm assigns a binary high signal (1) to that cell's corresponding element within the output array; otherwise, the element retains a binary low signal (0). Upon activation, where a specific battery's signal 's' is set to one, the respective MOSFET is triggered, facilitating the flow of current between its drain and source terminals. This activation allows for the passage of current through an associated resistor, consequently converting the excess electrical energy into heat. This process effectively reduces the cell's voltage, thereby decrementing its SOC until it aligns with the lower SOC levels of the other cells in the system. The control block eventually ensures that all battery cells converge to a uniform SOC. Through this algorithm, the BMS effectively mitigates the risks of overcharging or undercharging, thereby optimizing the operational harmony and durability of the battery array.

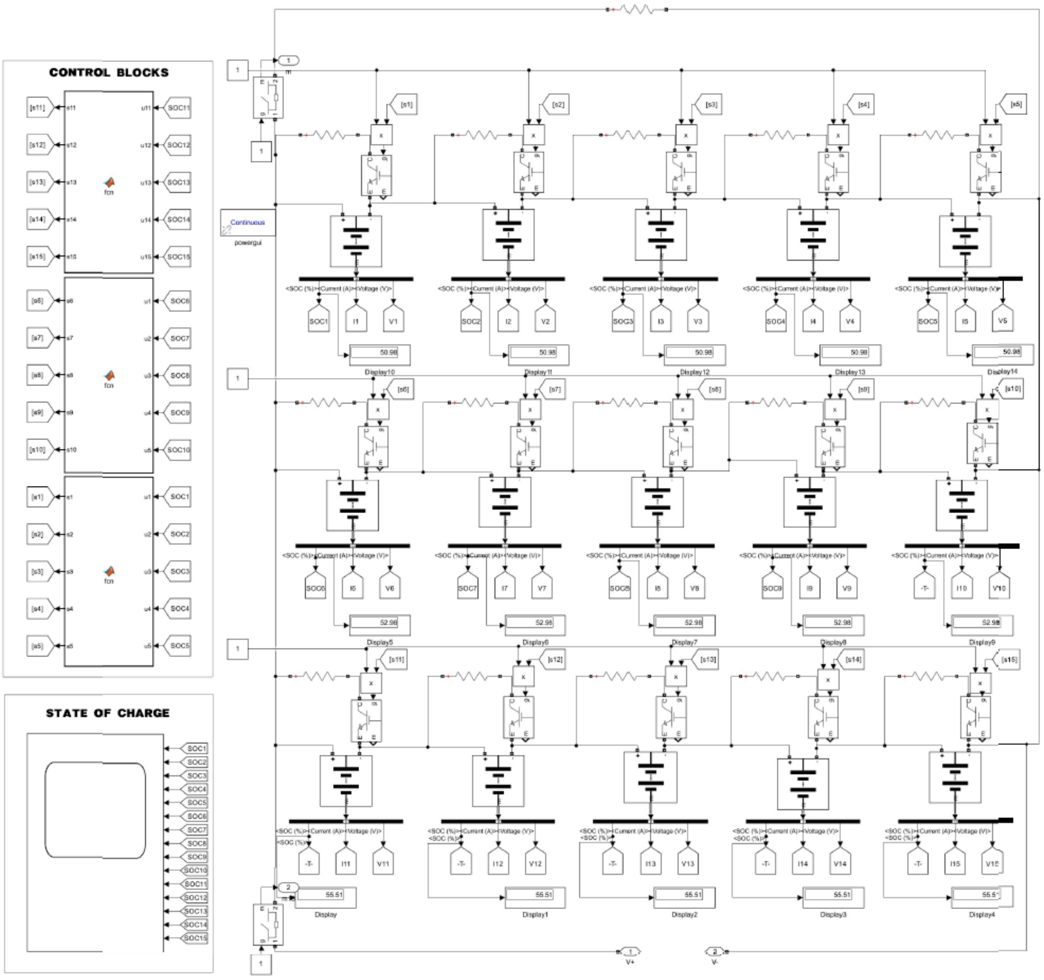
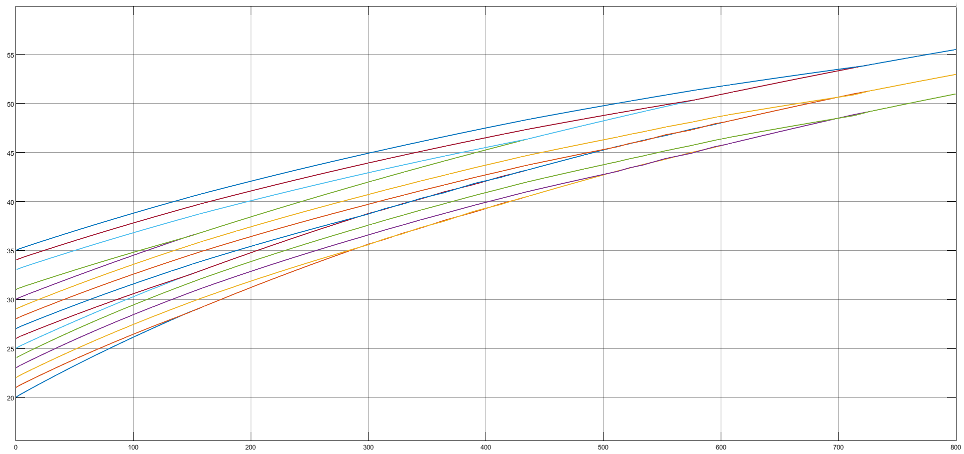
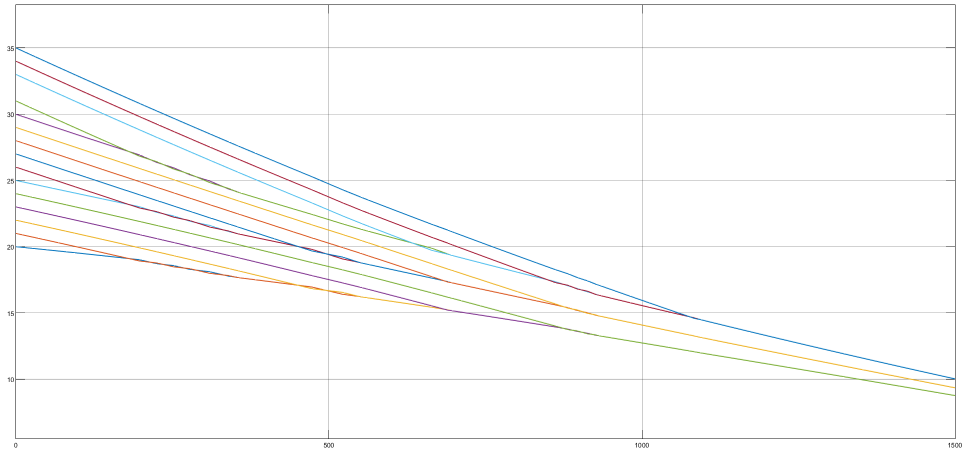


Figure 3.10: Battery Management system model

To validate the efficacy of the control algorithm within the battery management system, the initial State of Charge (SOC) for each battery in the array was deliberately set to varying levels. Subsequent graphical representations were generated to visualize the performance of the algorithm (figure 3.11).



(a) Output voltage level of the batteries in charging mode



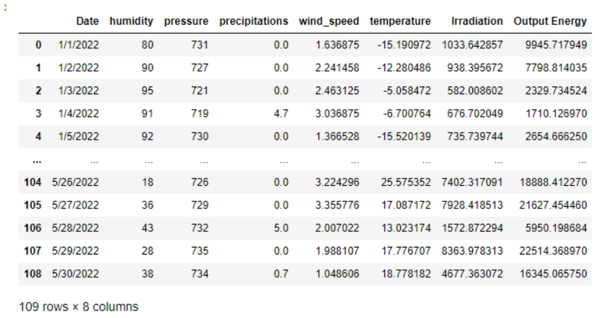
(b) Output voltage level of the batteries in discharging mode

Figure 3.11: Battery System operataing in charging and discharging modes

An examination of the graphs, as depicted above, reveals a convergence of the voltage levels of the individual batteries over time, both during the charging and discharging cycles. This convergence is indicative of the algorithm's capability to mitigate the discrepancies in SOC among the cells, ensuring a uniform charge distribution throughout the array. Moreover, it can be observed that the passive cell balancing mechanism operates on the principle of equalizing the cells' voltage levels by sequentially discharging cells with higher voltages down to the level of the cells with the lowest voltages. This systematic approach underscores the efficiency of the passive cell balancing method in stabilizing the battery array, thus enhancing the overall reliability and longevity of the energy storage system.

3.2.3 Data Evaluation

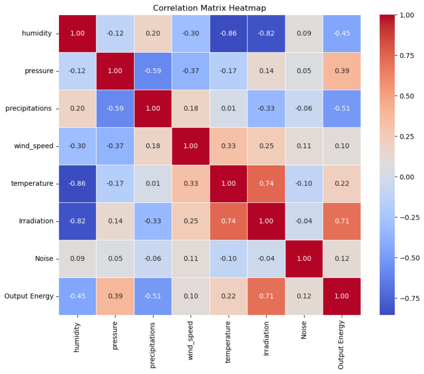
As highlighted earlier, preceding the construction of the prediction model, a comprehensive evaluation of the data is imperative to ensure its compatibility with the intended model. Following a meticulous analysis and the amalgamation of essential features, the resultant data frame is presented as Figure 3.12. After doing a thorough data analysis, the next stage was to carefully choose features that fit the needs of the model. The results of this method of selection are explained in Figures 3.13 and 3.14. All features show notable relationships when the correlation matrix is examined, with the exception of wind speed, temperature, and noise. The selection of features is based on the degree to which the absolute values are close to one; this makes the features more desirable to include in the model. Moreover, the importance chart supports our hypotheses by showing that temperature, precipitation, and radiation have leading positions. The validity of the feature selection process used is reinforced by the congruence between the expected and observed findings.



	Date	humidity	pressure	precipitations	wind_speed	temperature	Irradiation	Output Energy
0	1/1/2022	80	731	0.0	1.636875	-15.190972	1033.642857	9945.717949
1	1/2/2022	90	727	0.0	2.241458	-12.280486	938.395672	7798.814035
2	1/3/2022	95	721	0.0	2.463125	-5.058472	582.008602	2329.734524
3	1/4/2022	91	719	4.7	3.036875	-6.700764	676.702049	1710.126970
4	1/5/2022	92	730	0.0	1.366528	-15.520139	735.739744	2654.666250
...	...	...	...	...	...	...	...	...
104	5/26/2022	18	726	0.0	3.224296	25.575352	7402.317091	18888.412270
105	5/27/2022	36	729	0.0	3.355776	17.087172	7928.418513	21627.454460
106	5/28/2022	43	732	5.0	2.007022	13.023174	1572.872294	5950.198684
107	5/29/2022	28	735	0.0	1.988107	17.776707	8363.978313	22514.368970
108	5/30/2022	38	734	0.7	1.048606	18.778182	4677.363072	16345.065750

109 rows × 8 columns

Figure 3.12: Dataframe of features



Correlation Matrix Heatmap

	humidity	pressure	precipitations	wind_speed	temperature	Irradiation	Noise	Output Energy
humidity	1.00	-0.12	0.20	-0.30	-0.86	-0.82	0.09	-0.45
pressure	-0.12	1.00	-0.59	-0.37	-0.17	0.14	0.05	0.39
precipitations	0.20	-0.59	1.00	0.18	0.01	-0.33	-0.06	-0.51
wind_speed	-0.30	-0.37	0.18	1.00	0.33	0.25	0.11	0.10
temperature	-0.86	-0.17	0.01	0.33	1.00	0.74	-0.10	0.22
Irradiation	-0.82	0.14	-0.33	0.25	0.74	1.00	-0.04	0.71
Noise	0.09	0.05	-0.06	0.11	-0.10	-0.04	1.00	0.12
Output Energy	-0.45	0.39	-0.51	0.10	0.22	0.71	0.12	1.00

Figure 3.13: Covariance Matrix

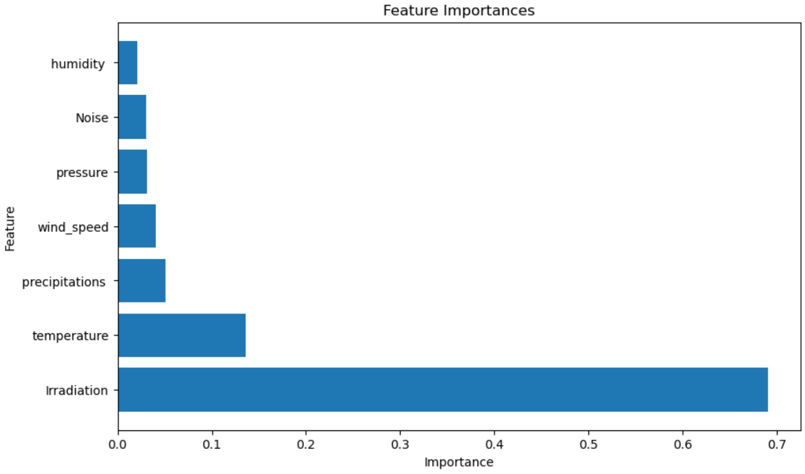


Figure 3.14: Importance Chart

3.2.4 Prediction Model Constuction

Upon obtaining the dataframe for model construction, various prediction models were systematically developed and evaluated using the $R\hat{2}$ scorer, chosen for its interpretable percentage representation. The performance results for different models were as follows:

- KNeighborsRegressor: 76%
- DecisionTreeRegressor: 29%
- Linear Regression: 67%
- K-fold CV with KNN: 53%
- K-fold CV with CART: 44.5%
- RandomForestRegressor: 92%

Notably, the KNeighborsRegressor with a hyperparameter K value of 7 exhibited the highest performance among the initial models. However, recognizing the need for enhanced results, a decision was made to implement another model with an expanded set of hyperparameters for fine-tuning. A distinctive aspect of this approach involved utilizing minute-level recordings from RES Technopark to augment the dataframe, thereby increasing its size. The rationale behind this strategic choice was the assumption that a bigger dataset has a favorable influence on the model's performance. As a result, the final model used, RandomForestRegressor, had an accuracy measure of 92%, a significant improvement. Thus, this result signalizes the efficiency of the chosen model and proves that the prediction it creates is accurate in the given setting.

3.3 Discussion

3.3.1 Matlab Model Analysis

The examination of the experimental results obtained for the MATLAB model of the PV-WIND hybrid power system, with a focus on the Battery Management System (BMS), provides essential information regarding the system response under different operational conditions. In addition to that, the performance of the system design component, particularly in the context of the utilization and operation of the Maximum Power Point Tracking (MPPT) systems, and several passive configurations for cell balancing present within BMS in response to changing external factors will be evaluated. Indeed, this model demonstrates that the PV system varies its response based on the sunlight exposition level. Additionally, the critical role of the MPPT controller is also outlined—it allows altering the buck converter's duty cycle for maximum power output. As sunlight increased from 200W/m^2 to 1000W/m^2, Figures 3.5 and 3.6 depict the controller adjusting the duty cycle for optimal power at each light level. This robust design demonstrates the controller precisely tracking the Maximum Power Point despite fluctuations. Figure 3.7 confirms consistent maximum power output, proving the MPPT controller's effectiveness. The data showing a peak output of 4827W at the highest irradiance underscores the system's capacity to leverage increased solar irradiation effectively. The integration of a wind turbine with a PMSG and a two-mass drive train within the Wind Energy Generation subsystem introduces additional complexities due to the mechanical-to-electrical energy conversion process. The subsystem's performance, depicted in Figure 3.8, highlights how the MPPT controller and a boost converter, successfully manages the variability of wind speeds. The effectiveness of this setup is important in maintaining consistent energy output, that is achieved by optimizing the turbine's operational point continuously. The obtained results confirm the MPPT's role in reducing energy loss and enhancing the efficiency of wind power conversion, adapting to environmental dynamics. This not only stabilizes the power output but also extends the turbine's operational lifespan by mitigating stress on mechanical components. The BMS's passive cell balancing mechanism control blocks and operational data offer insight into the system's ability to maintain battery "health" and system stability. The SOC-based control algorithm's effectiveness in managing the charge levels across multiple battery cells reveals its capability to mitigate the risks associated with differential charging. The experimental results that portray the converging voltage levels during charging and discharging cycles are clear evidence that the algorithm worked in equalizing charge between the batteries. It is pertinent to be noted that the above stability prevents the conditions that promote battery degradation, such as overcharging and deep discharging. The fact that high voltage cells could be brought down to match the lowest voltage cells extends the overall durability and performance of the battery pack. This confirms that the design managed the variable input from the environmental parameters while optimizing the energy conversion processes. The MPPT controllers in both the PV and wind subsystems exhibit exemplary performance in maximizing energy harvest, which is critical for the sustainability and efficiency of renewable energy systems. Meanwhile, the BMS's passive balancing enhances the reliability and longevity of the battery storage, ensuring that the hybrid system remains a viable solution for continuous and efficient energy supply.

3.3.2 Machine Learning

In comparison to the winter period from the data obtained, the assumption regarding the energy generation could be made. First, due to the high level of radiation that can reach up to 1200 kW/m$\hat{2}$ in July in comparison with the winter level, which is only around 350 kW/m$\hat{2}$, the energy level produced by the wind-solar system can totally provide the electricity necessary for the work of the yurt. This can be seen in Figure A.4; here 300 V voltage level means that the inverter is working, which inverts the DC from batteries to AC. While for the winter period, the inverter is turned off for some duration of time. This happens because of a lack of energy to meet load demand and the system automatically switches to city electricity. Regarding the voltage at batteries, this depends on both the connected load and energy generated rate. The system is not perfect, and further experiments are going to be done on power plants. First, by looking into it in detail, the voltage level of batteries may vary from each other, which negatively affects their life. Moreover, the test on the working mode of batteries should be done to choose the most optimal. For instance, either choose to work in buffer mode or not. Additionally, several tests could be done to obtain the most suitable load configuration. One suggestion to improve the system that was only recently discovered is to use a battery balancer. From the literature review, we could say that optimization of the wind-solar system is a wide range study to work on it. Although there are common methods of optimizing the systems, every country and cities there have different conditions and power consumption levels, which is why it is crucial to conduct an experiment and research on local wind-solar power systems to optimize the level of operation of wind-solar systems.

Predictive and tested modeling of a hybrid wind and solar energy system near RES Technopark yielded remarkable insights and improvements. The model was rigorously tested, using different frameworks and techniques to find the most effective strategy . The results measured by the R$\hat{2}$ scorer showed different levels of performance among the samples. Notably, KNeighborsRegressor with a hyperparameter K value of 7 emerged as the most performant of the first set of models, with an appreciable accuracy of 76% obtained This is in line with expectations, due to how the algorithm is sensitive to local patterns. A more sophisticated model was introduced using the RandomForestRegressor algorithm to achieve higher accuracy. This decision resulted in a significant improvement, with an accuracy of 92% in the final sample. The group learning approach of RandomForestRegressor, which aggregates predictions from multiple decision trees, contributed to its efficiency. A unique feature of the prototyping process was the use of a few minutes of recordings from the RES Technopark. The purpose of this selection process was to improve the quality of the data set, recognizing the possibility of improving model performance through extended and more diverse data sets However, it is important to acknowledge some limitations and areas for improvement. The very low specificity of some basic models, such as the DecisionTreeRegressor and the K-fold CV of CART, highlight the sensitivity of model performance to algorithm selection and parameter tuning Further research on hyperparameter-alternative algorithms may be a possible avenue for future research.Importantly, it should be noted that the performance of the final model can be enhanced by incorporating large data sets. In particular, augmenting the data with more observations and different scenarios can further refine the model's predictive capabilities so that future efforts can focus on obtaining additional data to examine model performance in a wider range of scenarios. In conclusion, the research process of model building, feature selection, and data enhancement has culminated in robust predictive models with an accuracy of 92%. The strategic choices made throughout this process, informed by data analysis and evaluation, contribute to the model's reliability and effectiveness in forecasting the daily output of the wind-solar hybrid power system.

Chapter 4

Conclusion

This capstone project has successfully demonstrated the potential and effectiveness of a hybrid wind-solar power system, with a particular focus on optimizing the efficiency and longevity of battery usage within these systems. Through multiple simulations and experimental setups, this research has revealed significant improvements in the operational strategies of hybrid renewable energy systems. These improvements contribute valuable insights into their practical applications and affirm the viability of such systems in real-world settings.

The proven success of implementing the Maximum Power Point Tracking (MPPT) controller and the passive cell balancing concept within the Battery Management System (BMS) has been instrumental in improving the system's overall performance. Not only have these technologies enabled more efficient utilization of energy, but they have also ensured the systems' general stability and durability. The experimental outcomes clearly show that these systems are capable of adapting to varying environmental conditions, hence maximizing the utilization of renewable energy.

Furthermore, the integration of a Machine Learning algorithm for forecasting energy generation has introduced a sophisticated tool that significantly enhances the predictive capabilities of the system. This tool offers a strategic advantage in managing and distributing energy resources efficiently. The innovative approach to predictive modeling underscores the potential of integrating advanced data analytics into renewable energy management, paving the way for smarter, more responsive energy systems.

This project lays a solid ground for further research on hybrid renewable energy systems. Subsequent research may focus on further integrating different types of renewable sources and modern battery solutions to improve the systems' reliability and sustainability. Real-time data processing and a real-time adaptive control strategy may also be studied to get more insight into how the systems can be optimized dynamically.

In summary, the findings obtained in this project show that the use of hybrid wind-solar systems is sufficient to meet energy needs in a renewable and sustainable way. The methodologies applied in this project not only contribute to the academic and practical realms of learning but also provide a basis for future research on the systems. The success of this project proves the viability of this hybrid system in improving energy production. Further research is expected to yield even greater discoveries. The results obtained in this project give a strong rationale for expanded use and support of hybrid renewable energy systems globally. As the world moves towards cleaner and more sustainable energy sources, the data from this study can be employed in the development of better energy systems.

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Appendix A

Appendix

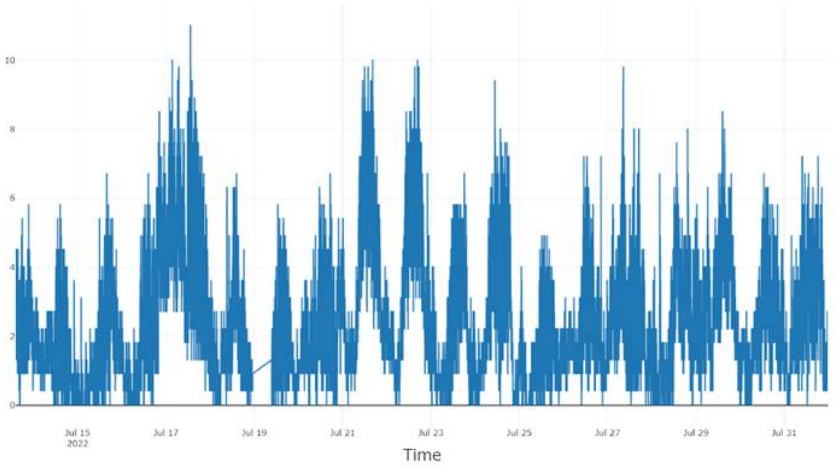


Figure A.1: Wind Speed for July

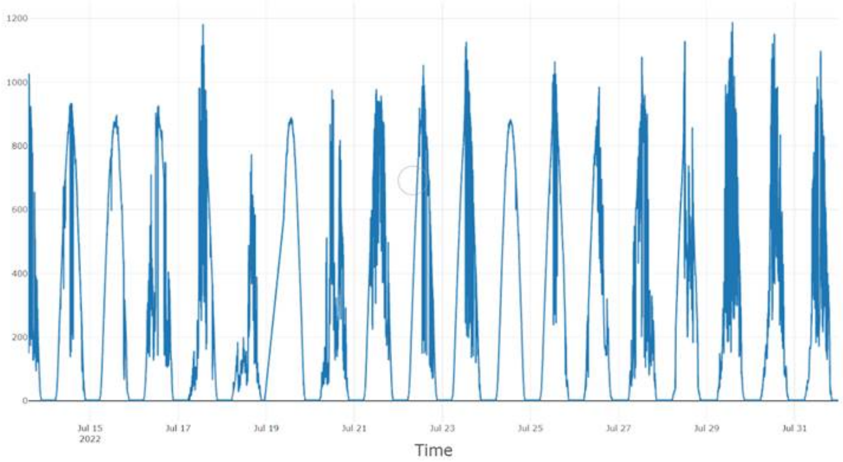


Figure A.2: Solar Radiation for July

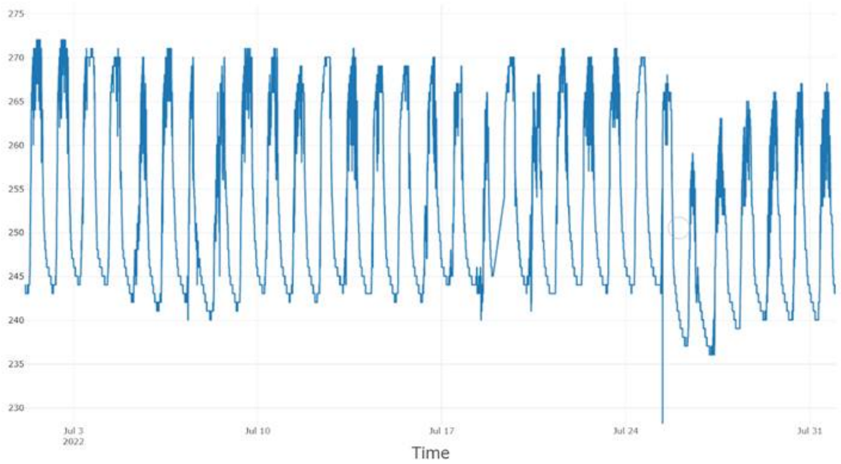


Figure A.3: The Voltage of the Battery System for July

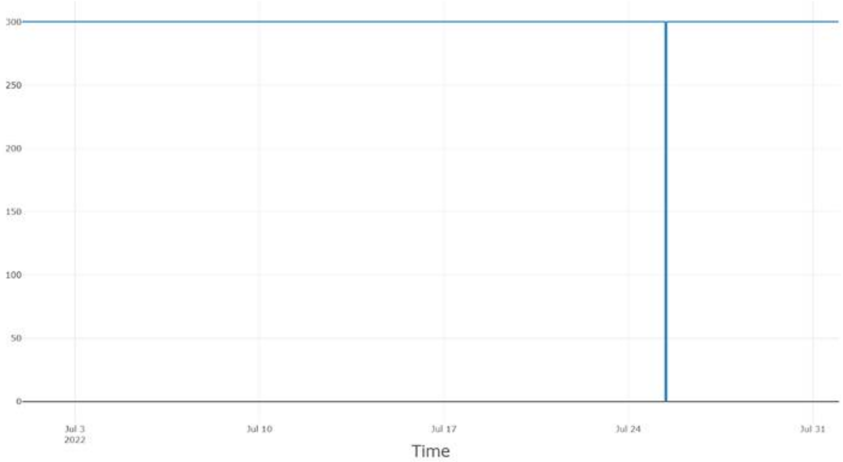


Figure A.4: The voltage at Inverter for July

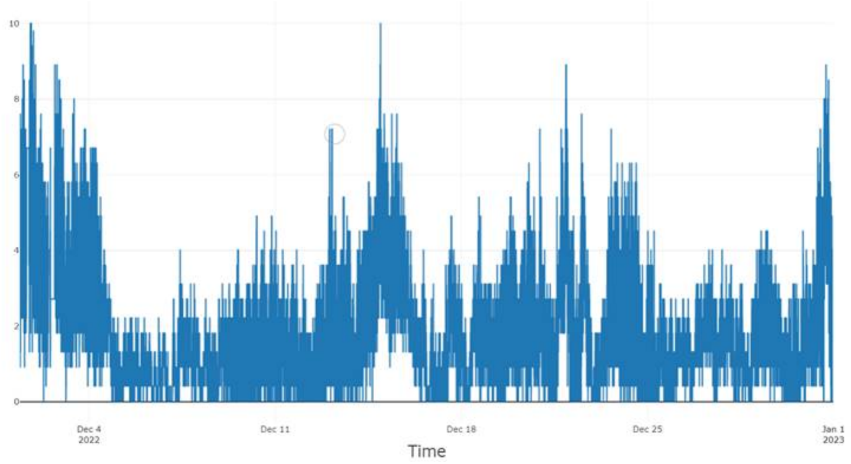


Figure A.5: Wind Speed for December

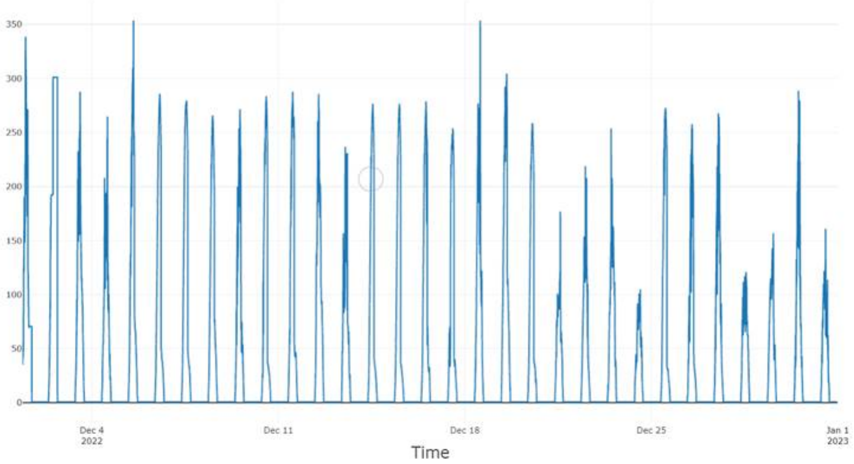


Figure A.6: Solar Radiation for December

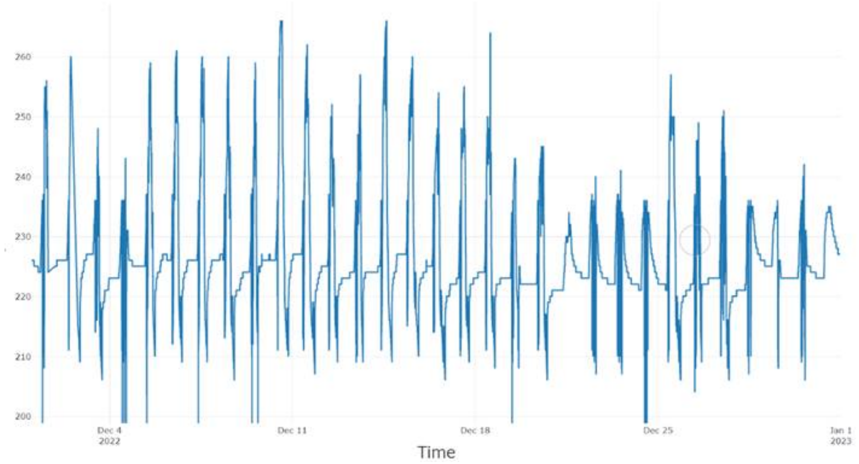


Figure A.7: The Voltage of the Battery System for December

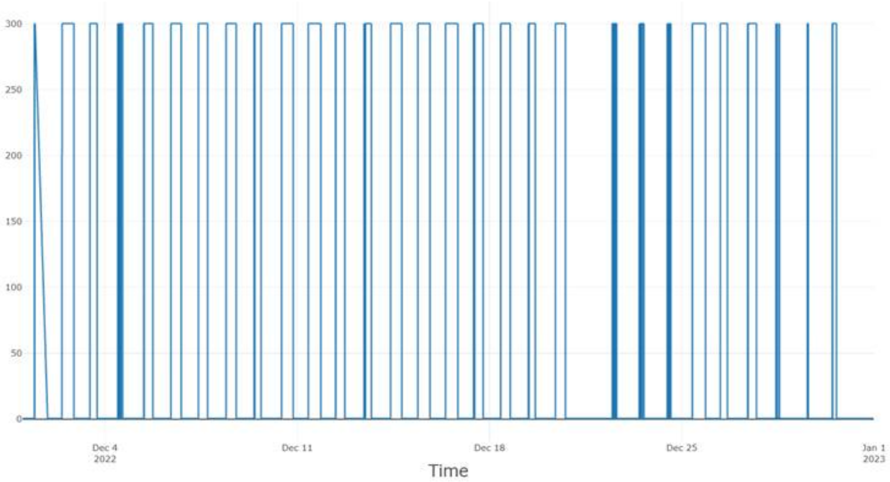


Figure A.8: The voltage at Inverter for July

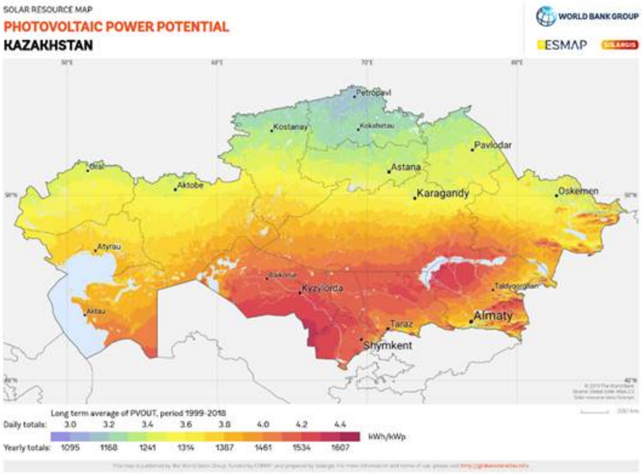


Figure A.9: The photovoltaic potential map of Kazakhstan [30]

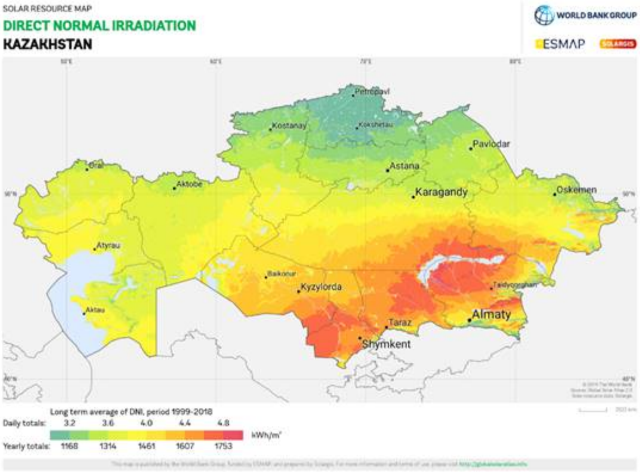
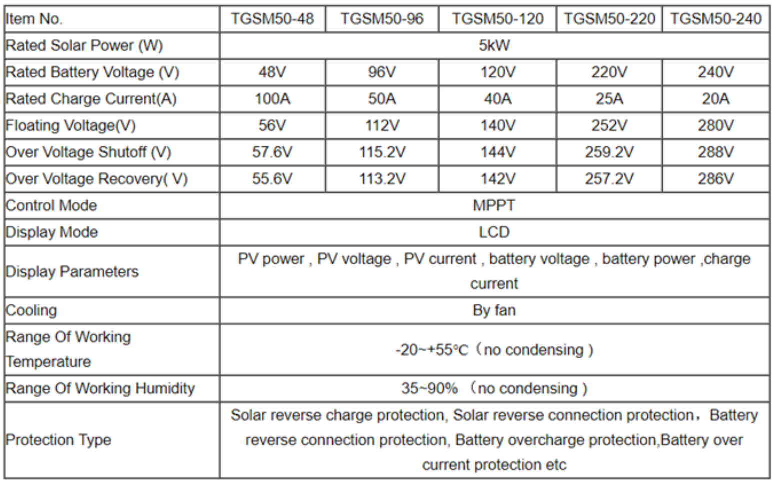
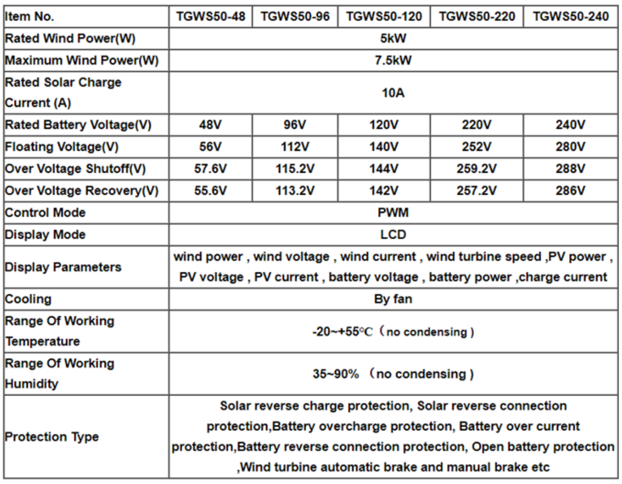


Figure A.10: The irradiation map of Kazakhstan



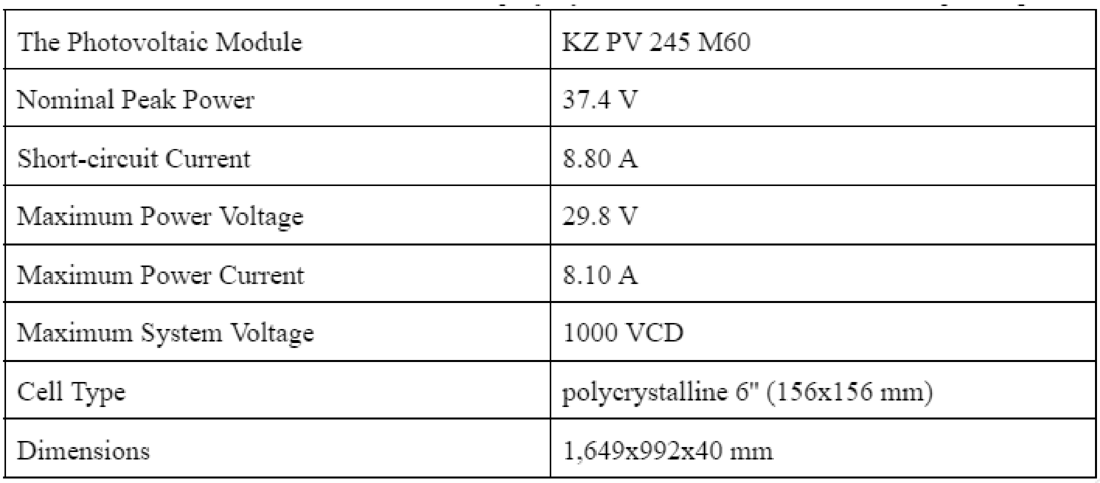
Item No.	TGSM50-48	TGSM50-96	TGSM50-120	TGSM50-220	TGSM50-240
Rated Solar Power (W)	5kW				
Rated Battery Voltage (V)	48V	96V	120V	220V	240V
Rated Charge Current(A)	100A	50A	40A	25A	20A
Floating Voltage(V)	56V	112V	140V	252V	280V
Over Voltage Shutoff (V)	57.6V	115.2V	144V	259.2V	288V
Over Voltage Recovery(V)	55.6V	113.2V	142V	257.2V	286V
Control Mode	MPPT				
Display Mode	LCD				
Display Parameters	PV power , PV voltage , PV current , battery voltage , battery power ,charge current				
Cooling	By fan				
Range Of Working Temperature	-20~+55℃（no condensing)				
Range Of Working Humidity	35~90% （no condensing)				
Protection Type	Solar reverse charge protection, Solar reverse connection protection，Battery reverse connection protection, Battery overcharge protection,Battery over current protection etc				

Figure A.11: Technical parameters of 5kW MPPT Solar Charge Controller



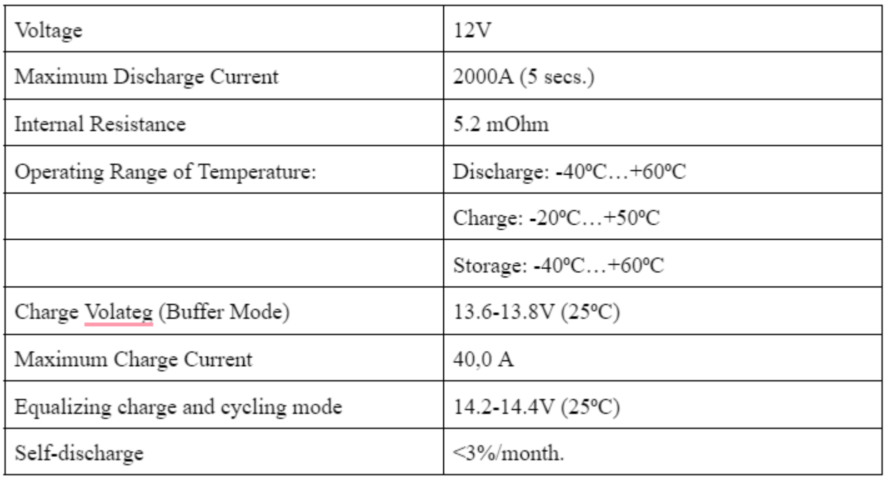
Item No.	TGWS50-48	TGWS50-96	TGWS50-120	TGWS50-220	TGWS50-240
Rated Wind Power(W)	5kW				
Maximum Wind Power(W)	7.5kW				
Rated Solar Charge Current (A)	10A				
Rated Battery Voltage(V)	48V	96V	120V	220V	240V
Floating Voltage(V)	56V	112V	140V	252V	280V
Over Voltage Shutoff(V)	57.6V	115.2V	144V	259.2V	288V
Over Voltage Recovery(V)	55.6V	113.2V	142V	257.2V	286V
Control Mode	PWM				
Display Mode	LCD				
Display Parameters	wind power , wind voltage , wind current , wind turbine speed ,PV power , PV voltage , PV current , battery voltage , battery power ,charge current				
Cooling	By fan				
Range Of Working Temperature	-20~+55℃（no condensing)				
Range Of Working Humidity	35~90% （no condensing)				
Protection Type	Solar reverse charge protection, Solar reverse connection protection,Battery overcharge protection, Battery over current protection,Battery reverse connection protection, Open battery protection ,Wind turbine automatic brake and manual brake etc				

Figure A.12: Technical parameters of 5kW Wind/Solar Hybrid Controller



The Photovoltaic Module	KZ PV 245 M60
Nominal Peak Power	37.4 V
Short-circuit Current	8.80 A
Maximum Power Voltage	29.8 V
Maximum Power Current	8.10 A
Maximum System Voltage	1000 VCD
Cell Type	polycrystalline 6" (156x156 mm)
Dimensions	1,649x992x40 mm

Figure A.13: The technical characteristics of the polycrystalline module installed on the power plant



Voltage	12V
Maximum Discharge Current	2000A (5 secs.)
Internal Resistance	5.2 mOhm
Operating Range of Temperature:	Discharge: -40°C…+60°C
	Charge: -20°C…+50°C
	Storage: -40°C…+60°C
Charge Volateg (Buffer Mode)	13.6-13.8V (25°C)
Maximum Charge Current	40,0 A
Equalizing charge and cycling mode	14.2-14.4V (25°C)
Self-discharge	<3%/month.

Figure A.14: The technical characteristics of the Challenger G12-200 battery

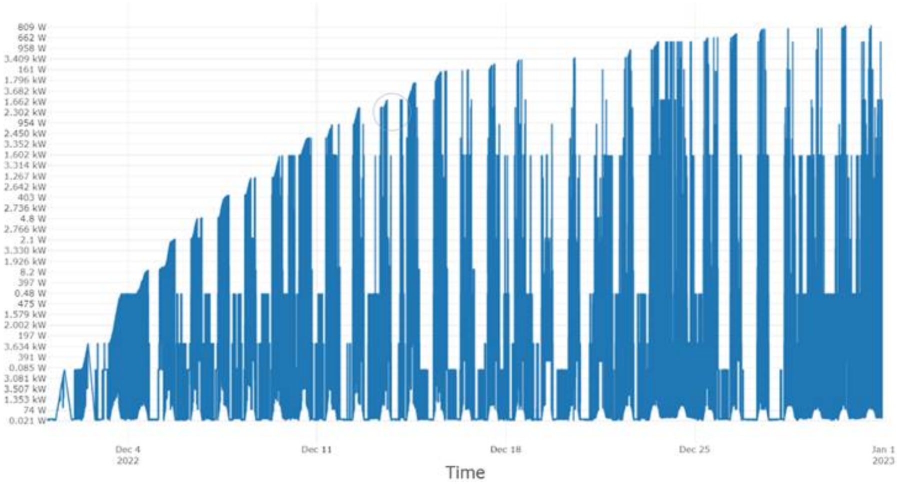


Figure A.15: The power of energy generated by solar panel 1 for December

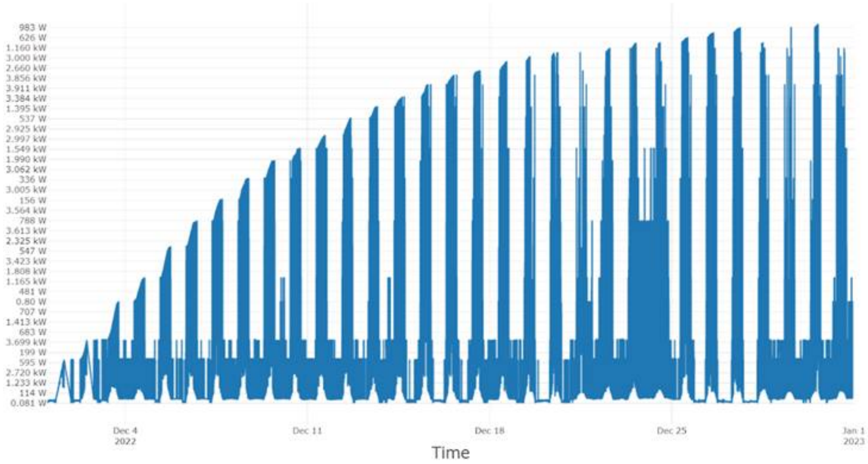


Figure A.16: The power of energy generated by solar panel 2 for December

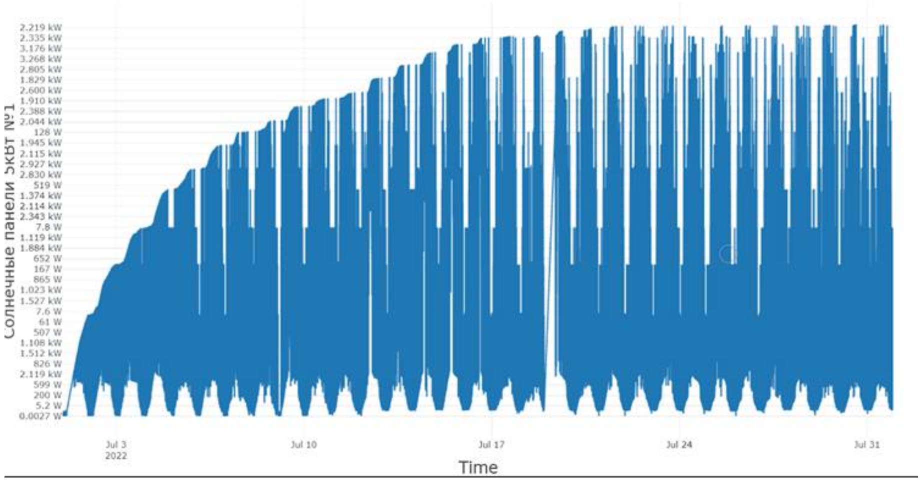


Figure A.17: The power of energy generated by solar panel 1 for July

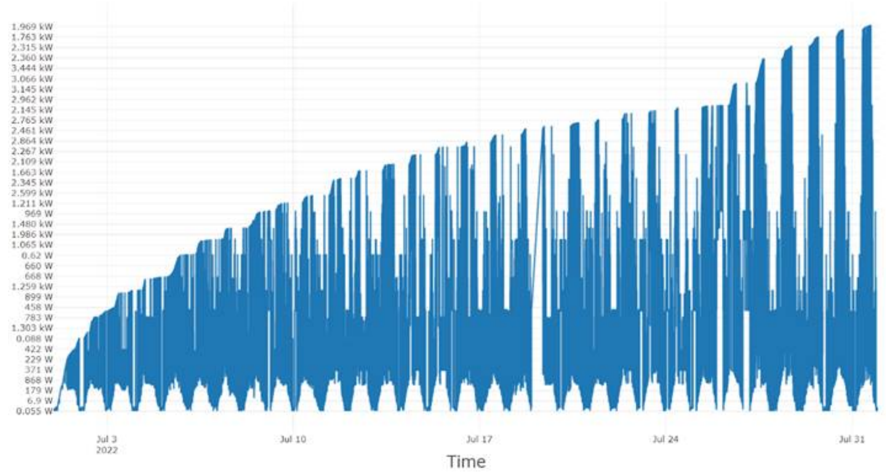


Figure A.18: The power of energy generated by solar panel 2 for July