OPTIMUM DESIGN AND SIZING OF PHOTOVOLTAIC PANELS IN OFF-GRID PHOTOVOLTAIC SYSTEM FOR RURAL RESIDENTIAL AREA

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DECEMBER 2022

OPTIMUM DESIGN AND SIZING OF PHOTOVOLTAIC PANELS IN OFF-GRID PHOTOVOLTAIC SYSTEM FOR RURAL RESIDENTIALAREA

By

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A (dissertation/thesis) submitted to the Department of Electrical & Electronic Engineering,
Faculty of Engineering and Science,
Universiti Tunku Abdul Rahman,
in partial fulfillment of the requirements for the degree of
Master of Engineering (Electrical)
December 2022

ABSTRACT

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Low Raymond

Global energy consumption increases rapidly due to population growth, improvements in living standard and infrastructure and advancement in harnessing energy. Malaysia is one of the countries that has the advantage in generating electricity from solar energy due to its location in the equatorial zone. The electricity supply status for many rural areas and small towns in the Malaysia especially at East Malaysia is still insufficient. Utility company has the difficultly to supply a reliable power source to the remote area due to its topography and distance from the grid. Therefore, off-grid photovoltaic (PV) system or standalone PV system has become the best solution for those area far from the network grid. However, the electricity generated from the standalone PV system varies due to changing weather condition. Thus, battery energy storage system is needed to be installed and integrated with a standalone PV system to meet the demand of electricity during low irradiation days and nighttime. But high operational cost of the battery causes people less interest on investing the battery energy storage system. It is important to design an appropriate size of the PV array and battery capacity to reduce operational cost of battery. In the past, most of the researched or industrial designs focus on optimizing the battery capacity based on the number of autonomy days required for the standalone PV system. Few researchers address the importance of how fast a PV array can fully charge a battery bank to handle another subsequent long raining day after first one. In this research project, different k values and number of autonomy days were used to determine the suitable size of a PV array. k in this project defined as PV size where it means that different k value represents different PV size. k is defined as the number of days required for a PV array to fully charge a battery bank under over discharge protection state, in other words, the battery bank has reached its depth of discharge capacity after supplying electricity for the pre-designed number of autonomy days. Different k values represents different PV sizes. k in this project is simply called as charging speed. k=4,3.5,3,2.5,2 and 1.5 were used in the simulation of the appropriate size of PV panels to yield a reliable electricity supply for a period of year. An appropriate k values determine based on the criteria that the subsequent electricity been charged to a battery that just reached its over discharge protection mode, can cover energy demand of another subsequent continuously rainy days. There are two study cases were studied to determine appropriate k values for reliable supply of 2 or 3 autonomy days. The results conclude that charging speed (k) =1.5 and 2.5 are suitable for a PV capacity required to support the electricity demand for 2 and 3 autonomy days respectively. In conclusion, the required minimal charging speed (k) and PV capacity in the optimization of the PV system was determined.

ACKNOWLEDGEMENTS

The success and ultimate outcome of this final year project and dissertation required a lot of support and guidance from many people. Without the help of all these people, this final year project could not be completed within the given time frame. First and foremost, I like to express my sincere gratitude to my university, Universiti Tunku Abdul Rahman (UTAR), for giving me such as comfortable and excellent environment yet complete facilities to make my final year project and thesis workable and successful.

In addition, I would like express my deepest gratitude to my project supervisor, Ir. Assoc.Prof Dr Lim Boon Han for his extremely tolerant and encouraging during doing the final year project. Ir. Assoc.Prof Dr Lim always provides me guidance, assistance, a lot of valuable comment and helpful suggestions when I face difficulties in my final year project and thesis. He also gives me a lot of confidence when I was desperate while doing this final year project. Furthermore, I am very grateful to Ir. Assoc.Prof Dr Lim for providing me the opportunity to do this project "OPTIMUM DESIGN & SIZING OF PHOTOVOLTAIC PANELS IN OFF-GRID PHOTOVOLTAIC SYSTEM FOR RURAL RESIDENTIAL AREA". I had learnt many new knowledge that seldom teach in academic and better understanding on the solar energy system throughout this final year projects.

Lastly, I also would like thank my parents who keep supporting me along the path. My parents always give me positive energy and comfort me when I'm frustrated so that I don't give up so easily and able to complete this research project on time.

FACULTY OF ENGINEERING AND SCIENCE
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Date: 12/12/2022

PERMISSION SHEET

It is hereby certified that **Low Raymond** (ID No: **21UEM00620**) has completed this final year project entitled "OPTIMUM DESIGN AND SIZING OF PHOTOVOLTAIC PANELS IN OFF-GRID PHOTOVOLTAIC SYSTEM FOR RURAL RESIDENTIAL AREA" under the supervision of Ir Assoc.Prof. Dr.Lim Boon Han (Supervisor) from the Department of Electrical and Electronic Engineering, Faculty of Engineering and Science.

I hereby give permission to the University to upload softcopy of my final year project in pdf format into UTAR Institutional Repository, which may be made accessible to UTAR community and public.

Yours truly,

____

(Low Raymond)

APPROVAL SHEET

This dissertation/thesis entitled **"OPTIMUM DESIGN AND SIZING OF PHOTOVOLTIC PANELS IN OFF-GRID PHOTOVOLTAIC SYSTEM FOR RURAL RESIDENTIAL AREA"** was prepared by LOW RAYMOND and submitted as partial fulfillment of the requirements for the degree of Master of Engineering (Electrical) at Universiti Tunku Abdul Rahman.

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DECLARATION

I hereby declare that the dissertation is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTAR or other institutions.

Name LOW RAYMOND

Date 12/12/2022

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CHAPTER 1

1 INTRODUCTION

1.1 Introduction of Energy Resources

World's energy demand nowadays is continuously increasing due to the increase of population, improvement of living standard, enhancement of the infrastructure and advancement of the technology in harnessing energy. But, the major nonrenewable resources are rapidly depleting and these conventional energy resources will be "run out" at some time in future. Thus, renewable resources become popular and crucial in energy generation. Renewable energy has been used by human for thousands of years. Renewable industry has gradually risen during recent year. In the past 10 years, serious environmental adverse impact is noticeable by humanity. The energy that generated from solar is environmentally friendly and clean. Thus, solar energy is preferred by people nowadays because solar energy is cheaper form of energy, less depending in fossil fuels. Furthermore, world's solar energy production is substantially more than the overall global energy consumption. Besides that, the long warranties that up to 25 years for the photovoltaic system (PV) able to provide huge amount of profit and able to return the initial investment.

1.2 Solar Resources in Malaysia

Malaysia has the advantage of generating solar energy due to Malaysia is in equatorial zone. Apart from that, Malaysia has the average daily solar radiation of 1400 kWh/m^2 and plenty of sunlight for 12 hours per days. The average annual irradiation of Malaysia is 1643 kWh/m^2. The northern region of peninsular Malaysia will have the higher solar radiation. Figure 1-1 show the Malaysia's global horizontal irradiation (GTI).

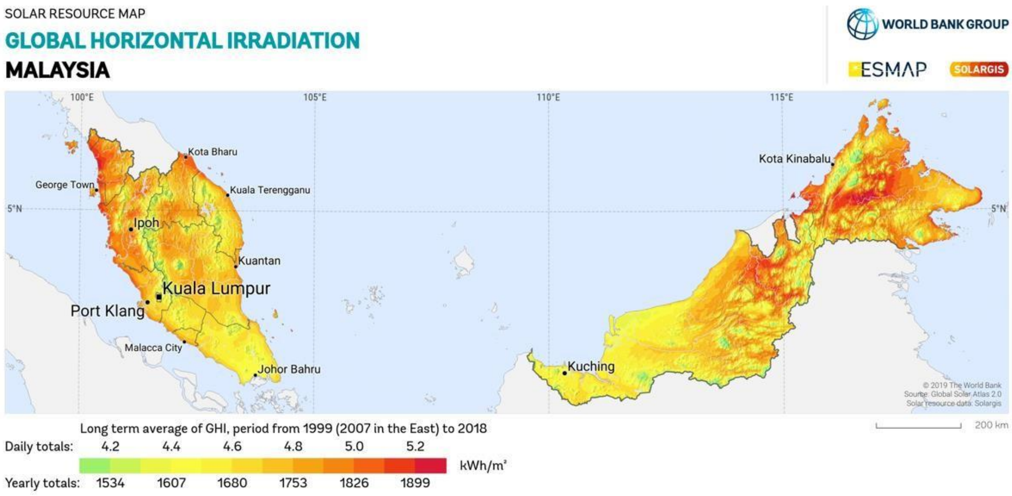

Figure 1-1 : Global Horizontal Irradiation in Malaysia

It is difficult for the electric utility company to provide reliable electricity to all areas that surrounded by mountains, hilly terrains and difficult to access for people (Yanuar Z.Areif, 20202). Therefore, electricity supply to some rural areas and small towns is still minimal. Some of the villages do using diesel generator as their power source, however generator does not provide a continuously 24/7 electricity. Thus, a reliable power supply for these rural area or villages can be achieved with renewable energy to improve their living standard and to meet ever increasing energy demand. In additional, rural electrification will eventually encourage the villager who involve in agriculture and fisheries to make use of automation technology so that it can be improve productivity, commercialization and market penetration (E.Z. Ahmad, 2015). On the other hand, massive production of agriculture and plantation industries can be boost up and become one of the main key factors in Malaysia's economy to reduce poverty rates of the country (E.Z. Ahmad, 2015).

1.3 Solar Photovoltaic (PV) System

Solar energy is easily harvested and collected from sunlight during daytime and can be used at night with the battery bank. Solar energy is divided into three type which are thermal, photovoltaic thermal, PV-T and photovoltaic, PV (electricity). For thermal system, it is using the heat energy that generated from the solar collector for drying purposes (Ag Sufiyan Abd Hamid, 2019). Photovoltaic thermal (PV-T) system involves two outputs (heat & electricity) and commonly used to study on how to obtain the best balance between both outputs.

Photovoltaic (PV) system is classified as three major categories which are grid connected PV system, standalone PV system (off-grid) and hybrid system. PV system convert solar energy into to electricity that supply to the load. Solar panel or photovoltaic (PV) module will collect the sunlight directly and convert it into DC current. The DC source is then converted to AC source via inverter and use for battery charging. The AC load will supply into the utility grid for consumptions.

1.4 Type of Photovoltaic (PV) System in Malaysia

1.4.1 Grid Connected Photovoltaic (GCPV) System

PV modules collect the sunlight and convert it into direct current (DC). The inverter converts direct current (DC) alternating current (AC) source. Power generation from PV system is measured by the PV energy meter. NEM meter indicate energy usage and excess energy produces. Any excess / balance energy after consumer consumed the energy produced from the installed PV system will be exported to the electricity grid. Figure 1-2 show the GCPV system for residential that implemented in Malaysia.

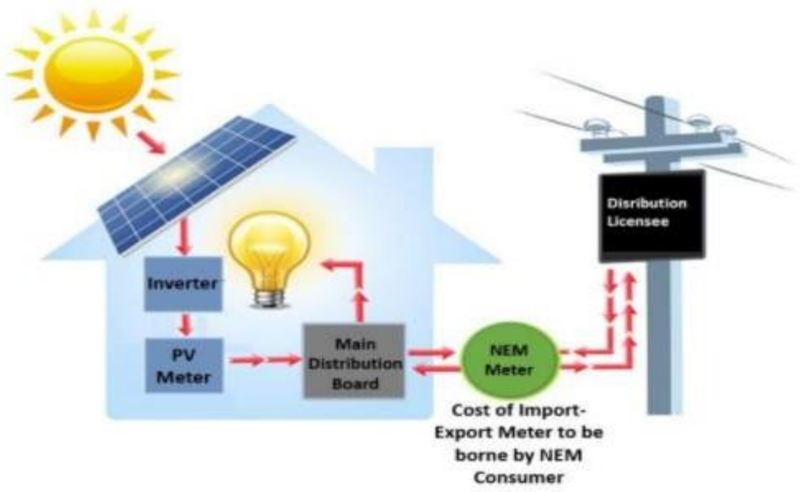

Figure 1-2: Grid Connected Photovoltaic System for Residential in Malaysia

1.4.2 Self-Consumption (SELCO)

Self-consumption is a mechanism whereby an eligible consumer installs solar photovoltaic system solely for their own us and in the event of excess of energy generation, consumer is restricted to export the energy to the grid. Figure 1-3 shows the self-consumption mechanism.

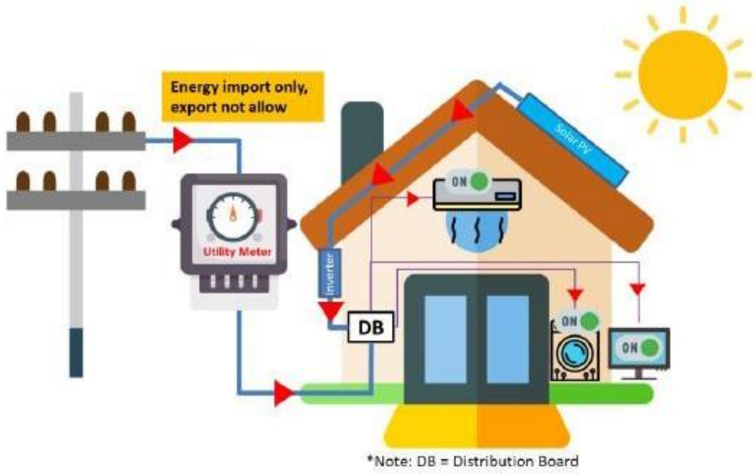

Figure 1-3: Self-Consumption Mechanism

1.4.3 Standalone / Off-Grid Photovoltaic (PV) System

Figure 1-4 shows the off-grid photovoltaic (PV) system. Standalone PV system will not connect to the electricity grid and usually is a small-scale PV system. Off-grid PV system often installed in rural area. Thus, off- grid PV system usually integrate with the battery energy storage system (BESS) to generate reliable electricity to the area that does not grid connectable. With the use of batteries in PV system, it can maintain the continuity of the power generation from the PV system and still can supply the energy demand even during low solar irradiation or raining days.

There are three major categories in off grid PV system which are system that supply DC load, system that supply DC and AC load and lastly is hybrid system. For system that supply AC & DC load, the battery charge by the battery charger that using DC power generated by the solar panel. DC load from the battery is then converter to the AC load for the end user usage trough the inverter.

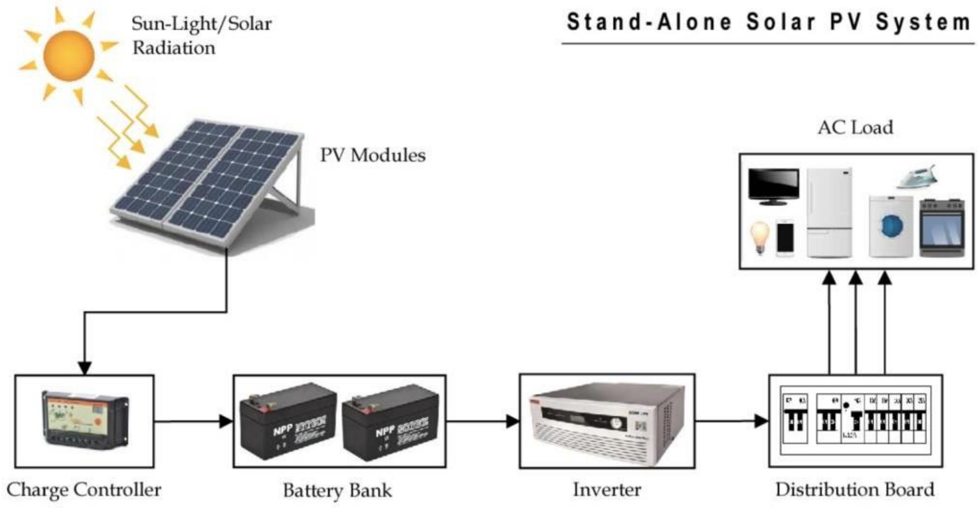

Figure 1-4: Off-Grid Photovoltaic (PV) System

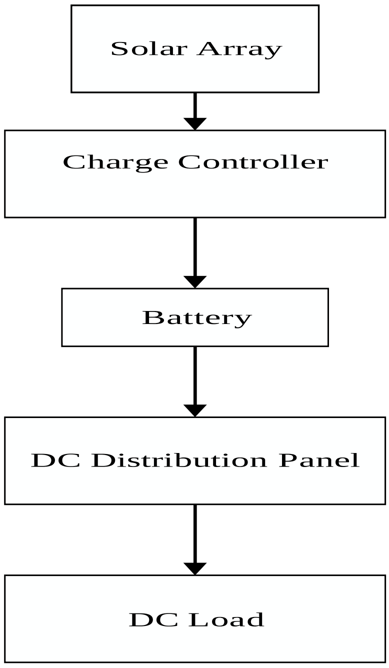

Figure 1-5: System Supply DC Load

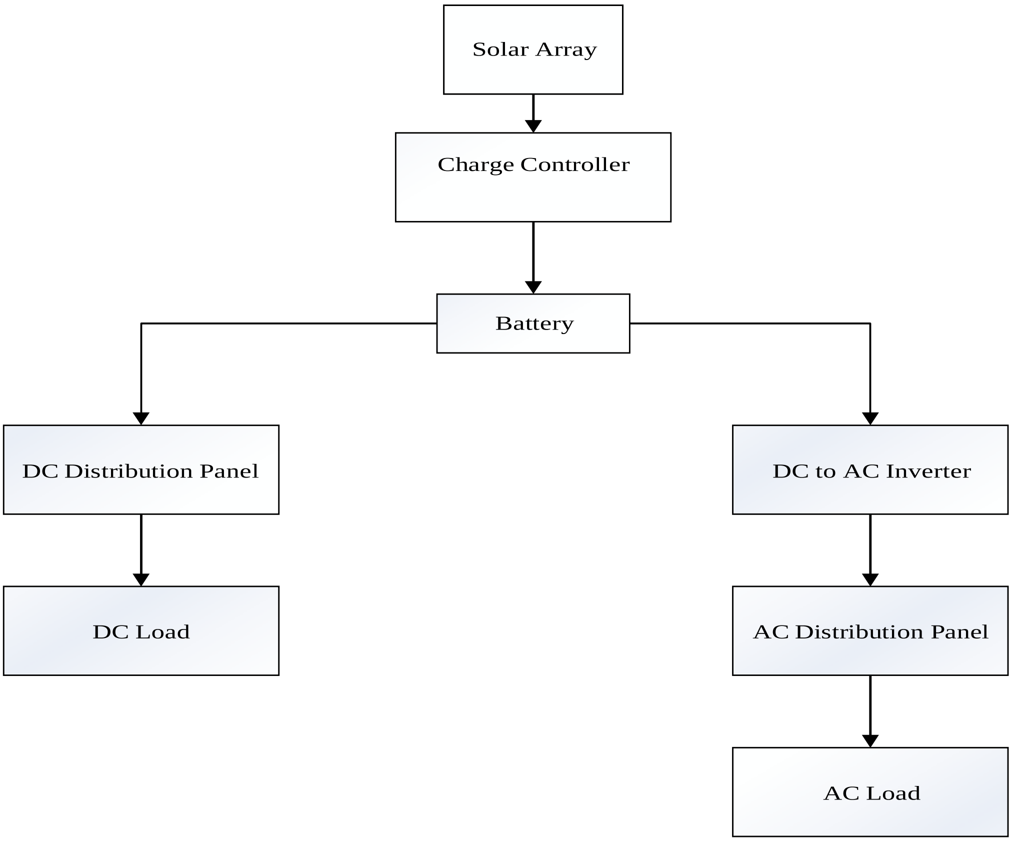

Figure 1-6: System Supply AC & DC Load

Figure 1-7: Hybrid System

1.5 Rule Based Method in Sizing of Off-Grid Photovoltaic (PV) System

$$\text{PV Capcity} = \frac{E_{demand}}{G_{PSH} \times \eta_{charge} \times \eta_{discharge}} \ldots\ldots\ldots\ldots (1.1)$$

Equation 1.1 above commonly used in sizing the PV array for the off-grid PV system. PV capacity strongly depend on the system efficiency and sunlight availability. This method is implemented to meet the daily energy demand for the month that has worst insulation across the year. By using this rule-based method, designers only consider and focus on the sunlight amount when sizing the PV array.

$$\text{No. of Battery} = \frac{(\text{no. of autonomy days}) \times E_{demand}}{Ah_{rated} \times V_{rated} \times \eta_{discharge} \times DOD} \ldots\ldots\ldots\ldots\ldots\ldots (1.2)$$

Equation 1.2 above commonly used in sizing the battery system for off-grid PV system. Battery capacity designed based on the required number of autonomy days and depth of discharge (DOD).

1.6 Optimization Method for Off-Grid Photovoltaic (PV) System

During develop an optimal off-grid photovoltaic system, most of the researchers usually focus on the optimization of battery charging control system, type of charge controller and battery used in the system and how to improve the PV cell technology to get high efficiency. Lithium ion and maximum power point (MPP) charge controller usually used in the optimization of the system. MMP charge controller used to ensure the PV arrays always operate at the maximum power point so that battery system can extract maximum available power from the PV array.

1.7 Problem Statement

In the past research, most researchers concentrate on the battery technology, battery charging technique and charger controller configuration & operating mode in optimization of the performance and efficiency of the off-grid PV system. They concentrate on how to optimize battery charging method to obtain the maximum power output from the PV array. However, they missed out the importance of how fast a PV array can fully charge a battery bank to handle another subsequent long rainy day after the first one. Without proper PV panel sizing, the amount of PV power generation is insufficient fully charge the battery to supply a reliable electricity for period of a year. In many real cases, low or no power output from battery system happen during continuous rainy days although the battery capacity determined based on the criteria can cover the energy demand of another subsequent continuous rainy days. This is because power output generated from the PV capacity determined from equation 1 is insufficient to always full charged the battery during cloudy days. For off-grid PV system, charging time is restricted by the sunlight availability. Thus, the amount of PV power generation during lack of sunlight availability is insufficient to full charge a battery bank when the battery bank has reached its depth of discharge capacity after supplying electricity for the pre-designed number of autonomy days. To ensure the stability of electricity supply to the area that is non-availability of grid power, an equation 1.3 below that involve the k values and number of autonomy days is proposed in the sizing of PV panels for the off-grid photovoltaic (PV) system. k is defined as the number of days required for a PV array to fully charge a battery bank under over discharge protection state. k in this research project is simply called as charging speed.

$$PV\ Capcity = \frac{\left(\frac{no.of\ autonomy\ days}{k}\right) \times E_{demand}}{G_{PSH} \times \eta_{charge} \times \eta_{discharge}} \ldots\ldots\ldots\ldots\ldots..(1.3)$$

1.8 Research Objectives

I. Study the effect of various of solar irradiation and PV cell temperature in term of annual, monthly and daily in sizing of photovoltaic panels for the standalone PV system.

II. Investigate the effect of different PV capacity based on the charging speed (k) of the battery to the reliability of battery supply for an off-grid system.

III. Develop an optimal standalone photovoltaic system design with suitable minimal charging speed (k) to the battery bank for different number of autonomy days.

CHAPTER 2

2 LITERATURE REVIEW

2.1 Introduction of Photovoltaic (PV) Cell Technology

Photovoltaic cells also known as PV module which are the basic component of the solar PV panel. It is a device that collects sunlight and converts it into electrical energy by using the semiconductors as a medium via photovoltaic effect. Figure 2-1 show the basic structure of a PV cell system.

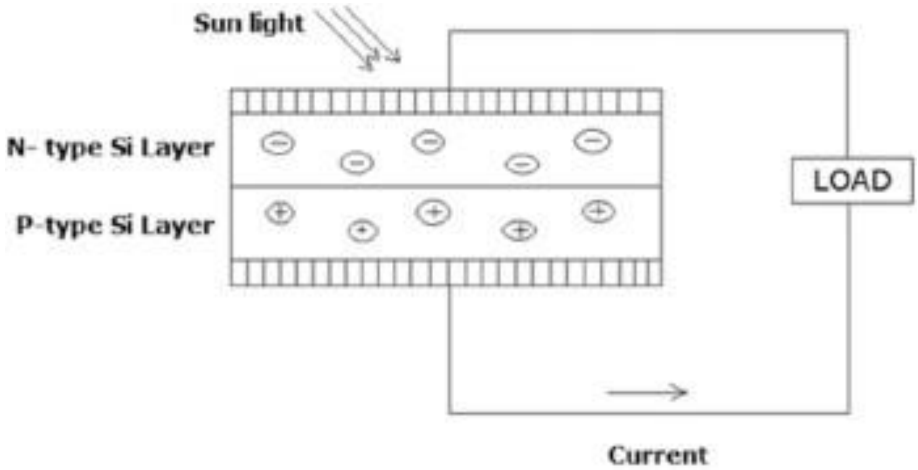

Figure 2-1:Basic Structure of PV Cell

PV cells technologies basically is divided into four categories which are multi junction, emerging technology, wafer-based PC cell technology and last but not least thin film technology (Chun Sing Lai, 2017). Wafer based PV cells is made by crystalline silicon. While thin film can be known as second generation in PV cells technology. Thin film PV cell technology now widely used by people in building integrated photovoltaic system, large scale photovoltaic system as well as small standalone photovoltaic system.

Multi-junction solar cells are built by multiple p-n junctions of different semiconductor materials. Electric current is generated through the p-junction of each material in response to different wavelengths of light, the heterojunction improves conversion efficiency by improving absorption over a broader range of wavelengths (Chun Sing Lai, 2017). As of 2016, efficiency of multi-junction technology is up to 46% which are the highest efficiency among all the PV cell technologies.

2.1.1 Crystalline Silicon (c-Si)

Crystalline silicon PV module is highly dependent on abundant silicon and high production cost. Crystalline silicon PV module are divided into 2 categories which are mono crystalline silicon and poly crystalline silicon.

2.1.2 Thin Film

Thin film solar cells can be manufacture more cheaply compared to crystalline silicon but the material that used to produce thin film solar cell has limited availability. There are few thin film technologies which are amorphous, cadmium telluride, copper indium diselenide, copper indium gallium diselenide and copper zin tin sulfide. Among all the thin film technologies, cadmium telluride is the cheapest to manufacture (Chun Sing Lai, 2017). However, there are problems with tellurium depletion and cadmium toxicity in the cadmium telluride compound (Chun Sing Lai, 2017).

Table 2-1 :Difference Between the Three Common PV Cells

PV cells	Efficiency (%)	Remarks
Mono Crystalline Silicon	17-22	High Cost High Reliability High Efficiency Low Risk
Poly Crystalline Silicon	15-17	Medium Cost High Reliability Medium Efficiency Low Risk
Thin Film	10-13	Low Cost Low Reliability Low Efficiency High Risk More space

Based on the table 2-1, crystalline silicon PV module is more beneficial compared to thin film. Mono crystalline silicon has the highest efficiency and power capacity compared to other two PV cell. Because mono crystalline solar cells are made by a single crystal of the silicon that will make electrons to flow through the cell and make the PV cell more efficient. Besides that, this high efficiency of mono crystalline solar panel requires less space only to obtain a give power capacity which can reduce the area needed for the installation of solar panel. The factors such as solar irradiation, cell temperature, tilt angle, partial shading etc. will affect the performance of the PV cell in term of power output. The most commonly used PV cell in the market which are crystalline silicon (c-Si) and thin film.

(i) (ii) (iii)

Figure 2-2 Mono-Crystalline Silicon (i) , Poly-Crytalline Silicon (ii) Thin Film (iii)

2.2 System Configuration of Photovoltaic (PV) System

There is various system configuration in the PV system such as DC coupled configuration, AC connected parallel configuration, series configuration and switch configuration.

2.2.1 DC Coupled Configuration

In this configuration, DC power that produced from the PV panel is supplied directly to the DC load. The maximum power point tracking (MPPT) charge controller is used to regulates the operating voltages so that the PV array can generate maximum available PV power instead of being operated in battery charging voltages (S.Y.Wong, 2012). Figure 2-3 show the DC coupled configuration.

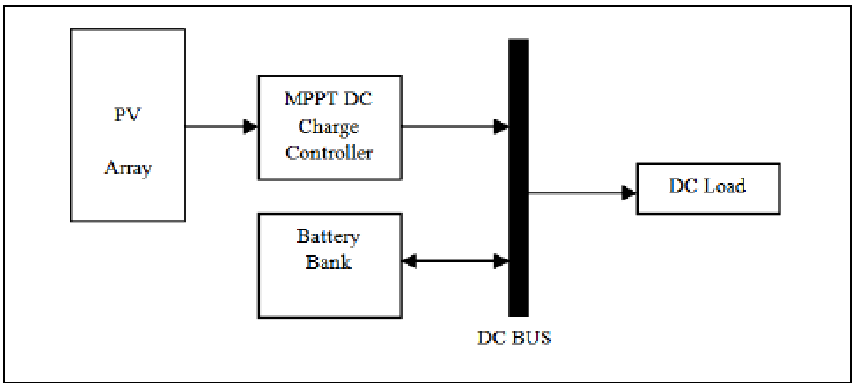

Figure 2-3: DC Coupled Configuration (S.Y.Wong, 2012)

2.2.2 Switched Configuration

In the switched configuration, the power generated from generator or utility grid will supplied to the AC bus and battery charger. But, there is a possibility that power loss will occur during the power switching (S.Y.Wong, 2012). Figure 2-4 show the switched configuration PV system.

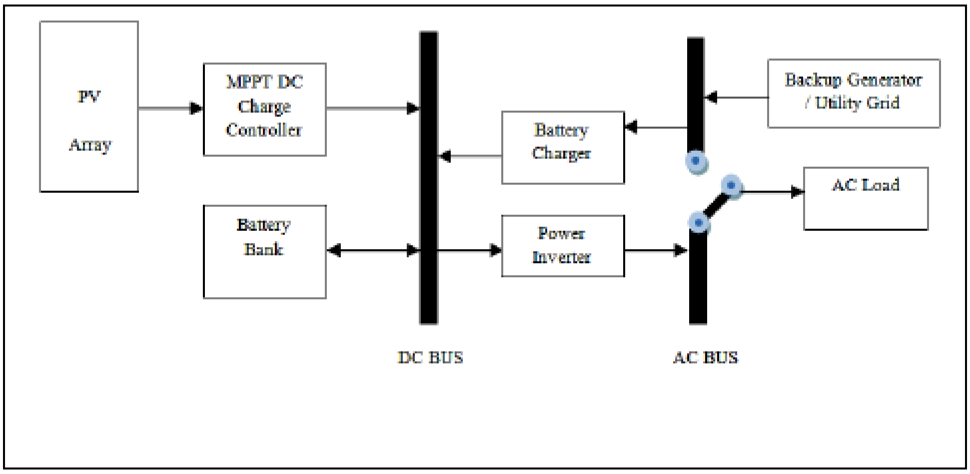

Figure 2-4: Switched Configuration (S.Y.Wong, 2012)

2.2.3 Series Configuration

In the series configuration, the inverter will convert the DC load from the solar panel into AC load. The DC load generated from genset or utility grid is supply to battery charger then is converted into AC load via the inverter. Therefore, any fault happen in the inverter will cause the total power failure of the PV system.

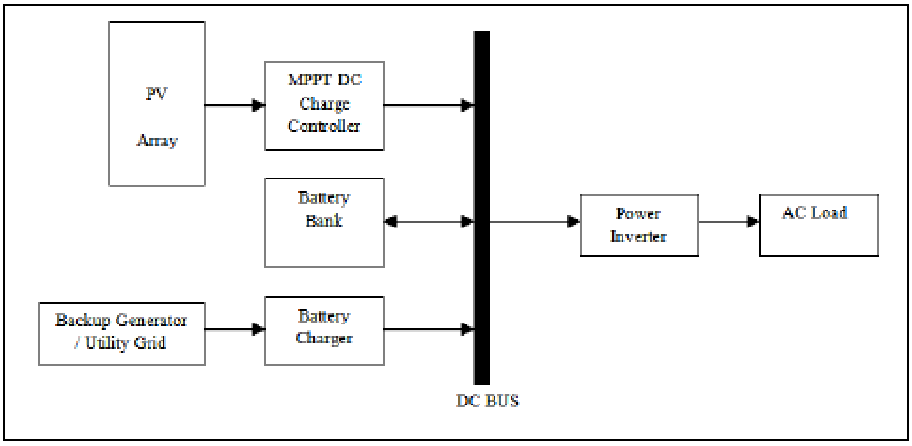

Figure 2-5: Series Configuration (S.Y.Wong, 2012)

2.2.4 Parallel Configuration

Figure 2-6 shows the parallel configuration. The bidirectional power inverter consists of the battery charger and an inverter in this configuration. The battery can be charged while both DC bus and AC bus are connected. Genset or utility grid can supply power immediately when the inverter breakdown or not functioning properly.

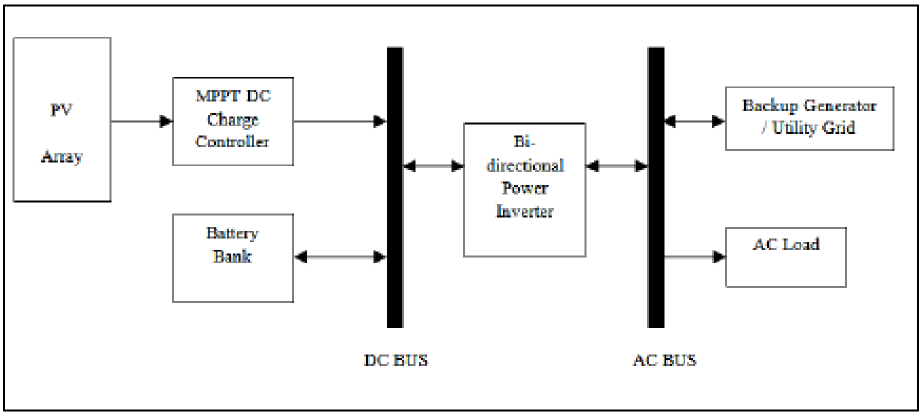

Figure 2-6: Parallel Configuration (S.Y.Wong, 2012)

2.2.5 AC Connected Parallel Configuration

Figure 2-7 shows the AC connected parallel configuration. This configuration is similar to the parallel configuration while the only things that is difference is the bi-directional power inverter is connected to the battery bank. Therefore, the bi-directional power inverter will limit the battery capacity.

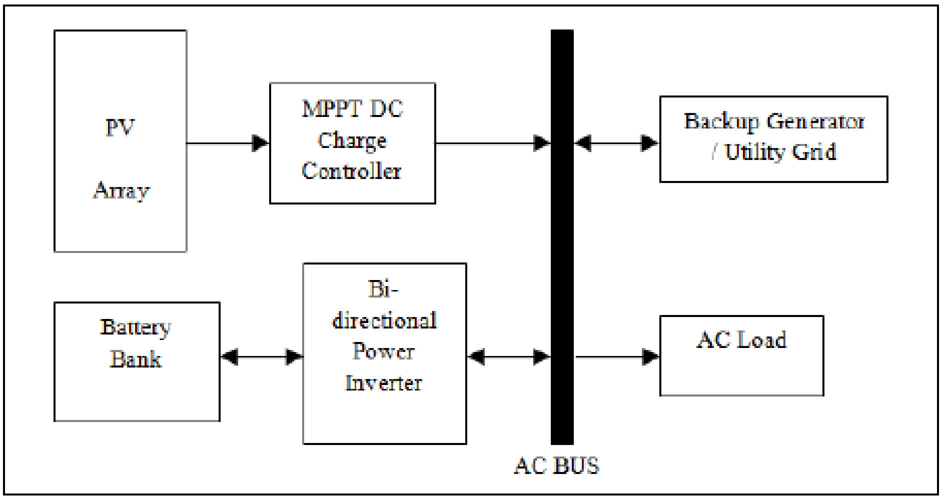

Figure 2-7: AC Connected Parallel Configuration (S.Y.Wong, 2012)

2.3 Battery Bank

There are many types of battery technologies in the market that commonly used in standalone PV system such as lithium ion, lead acid, nickel cadmium, sulphur and nickel chloride batteries (Mohamad Izdin Hlal, 2019). Lithium ion and lead acid are widely used in the market because of their low initial cost, maintenance free and high efficiency, But, these batteries degrade fast in the off-grid PV system and required replace frequently due to their short lifetime. As a result, it will lead to comparatively higher costs. Thus, it is important to perform optimization to ensure longevity of the battery. There are two key factors that affecting the battery performance which are state of energy and depth of discharge. Depth of discharge is used to determine the suitable minimum and maximum battery state of energy to make sure the battery can last longer (Yan Cao, 2022). While the amount of energy that stored inside the battery is called state of energy (SOE) (Yan Cao, 2022) .

2.4 Studied on Various Sizing and Optimization Method for Standalone Photovoltaic System

2.4.1 Sizing Method

Sizing method are closely related to reliability analysis (Hadi Nabipour Afrouzi, 2021). Solar irradiance and climate are the factor that influence the power generation, performance and reliability of the standalone photovoltaic system. There are various sizing techniques such as analytical method, probability method and simulation method etc. to design the number of PV array required for the system to minimize the system cost and ensure reliability of the system (Hadi Nabipour Afrouzi, 2021). A system can be identified as reliable if it is satisfied with the load requirement.

I. Probability method

Probability method is much less complicated and easier to implement but the result that generated from this method will not is a best solution. This technique also can be classified as monthly and annual average sizing method as well as most unfavorable month method (Hadi Nabipour Afrouzi, 2021). Average monthly solar irradiation for each year used to determine overall PV system capacity. Sizing of the PV array during month of autonomy determined by the most unfavorable month technique (Hadi Nabipour Afrouzi, 2021). It also can optimized the standalone PV system by taking into consideration of the probability function, expressed as the probability of losing load in term of energy output from solar PV system, battery capacity and load demand (Gopinath Subramani, 2017).

II. Analytical method

Analytical method is used to access system performance in terms of size of components and possible system configuration (Hadi Nabipour Afrouzi, 2021). An optimized system can be determined and selected by analyzing the system in terms of single to multiple performance indexes (Hadi Nabipour Afrouzi, 2021).

III. Simulation method

This method is used to design an optimal sizing of the off-grid PV system using clear and well- defined parameters or data. Simulation software such as PVsyst or HOMER are typically used to determine all possible hybrid combinations, carry out the PV system design and meet the reliability and load requirement.

2.4.2 Optimization Method

Optimization method used to enhance the performance of the PV system by optimized the PV sizing and cost reduction. There is various optimization method such as numerical, intuitive, iterative and artificial intelligence etc.

I. Numerical method

In (III, 2014),this method is used for optimizing the battery capacity in the PV system (Dongjin Cho, 2020). Model testing were conducted at three different locations in United States by limiting load requirement and daily solar irradiation to find out the appropriate battery capacity. Results from both cases are combined, compared and analyzed to determine the optimal battery capacity.

In (Hussein A Kazrm, 2013), this method is used to determine the sizes of the PV panels, title angle and battery capacity through MATLAB software according to the energy demand and meteorological data. Load loss probability of the system is designed by comparing the result of the proposed method with the intuitive method (Dongjin Cho, 2020).

II. Iterative method

This method can use to determine the optimal PV system configuration by repeatedly investigating the all feasible configuration of the system to get lowest levelized cost of energy (LCOE) (Hadi Nabipour Afrouzi, 2021). LCOE is known as the ratio of the total price of the system to the maximum PV power from the system. Capital recovery factor and present value is included in calculating the overall price of the photovoltaic system. Present value is the sum of the maintenance cost, replacement cost and preliminary cost. Rate of discount over the effective period of the project is taking into consideration in calculating the capital recovery factor.

III. Intuitive method

This method is used in (G.E.Ahmad, 2002) to estimate the optimal capacity of standalone PV system with energy storage system that supply the power to the residential house in Egypt (Dongjin Cho, 2020). In addition, (M. M. H. Bhuiyan, 2003) suggest an intuitive method to find the optimum capacity of the off-grid PV system with energy storage systems.

The authors used simple calculation to determine the optimal tilt angles, quantity of PV array, battery capacity and daily load requirement (M. M. H. Bhuiyan, 2003).

In (Claudia Valéria TávoraCabrala, 2010), the authors performed a stochastic method involving the Beta probability density and Markov Chain to find standalone photovoltaic system capacity (Dongjin Cho, 2020). This research determined the optimization in the configuration of batteries and PV panels according to the losses of power supply probability and total life cycle cost.

CHAPTER 3

3 METHODOLOGY

3.1 Overall Project Flow

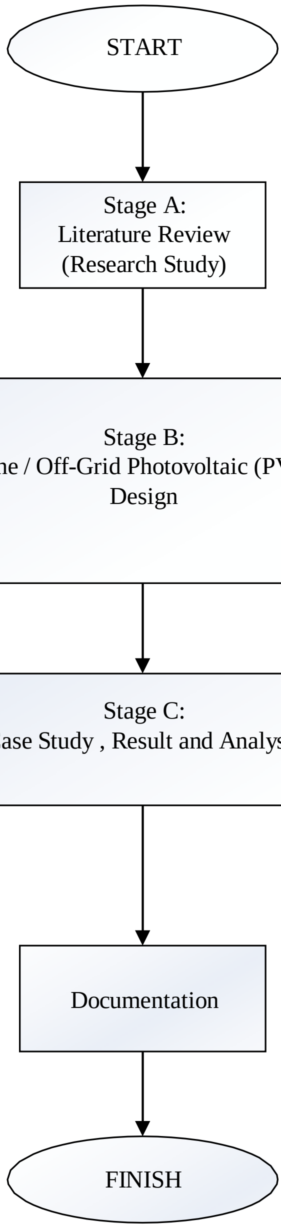

Figure 3-1: Project Flow Chart

Figure 3-1 shows the overall project flow chart. The project flow is divided into 3 mains stage which are literature review, standalone PV system design, case study, result and analysis and the final stage is documentation.

3.1.1 Design of Standalone / Off Grid Photovoltaic (PV) System

Two study cases were developed to determine the appropriate k values for reliable supply of 2 or 3 autonomy days in the research project. Before start to design the off-grid system, we study the project background of the case study such as location, longitude, latitude, altitude and time zone. All these data are important to determining the solar path, monthly meteorological value as well as the ambient temperature, solar irradiation, wind speed etc. in the project site. The proposed project site for case study in this research project is Jalan SL1, Bandar Sungai Long, 43000 Kajang, Selangor, Malaysia. All information about solar energy resources such as sun path, azimuth, solar radiation and meteorological parameters were obtained from climate database Solargis v2.2.26.

Next, daily load demand were determined by simulating the used of common electrical appliances such as light, fans, air conditioning, washing machine, refrigerator, TV and rice cooker. The required daily energy that proposed in the standalone photovoltaic (PV) system is 15,226 watt-hours.

In addition, dimensioning and optimization of the photovoltaic (PV) system is according to the case study data. Next, battery size is selected by determining the desired number of autonomy days and allowable depth of discharge. The daily, monthly and annual solar irradiation, PSH, PV cell temperature, temperature derating factor is calculated and tabulated in the Chapter 4.

The daily, monthly and annual PV power and energy generation from the PV system during different k values is calculated and discuss in the Chapter 5. The PV capacity in this research project was determined by proposed equation 3.1 below.

$$\textbf{PV Capacity} = \frac{\left(\frac{\text{no.of autonomy days}}{\text{charging speed,k}}\right) \times E_{demand}}{G_{PSH} \times \eta_{charge} \times \eta_{discharge}} \ldots \ldots \ldots (3.1)$$

Changing k values in PV power and energy generation calculation was to find the suitable number of PV panels to yield a reliable electricity supply for a period of a year.

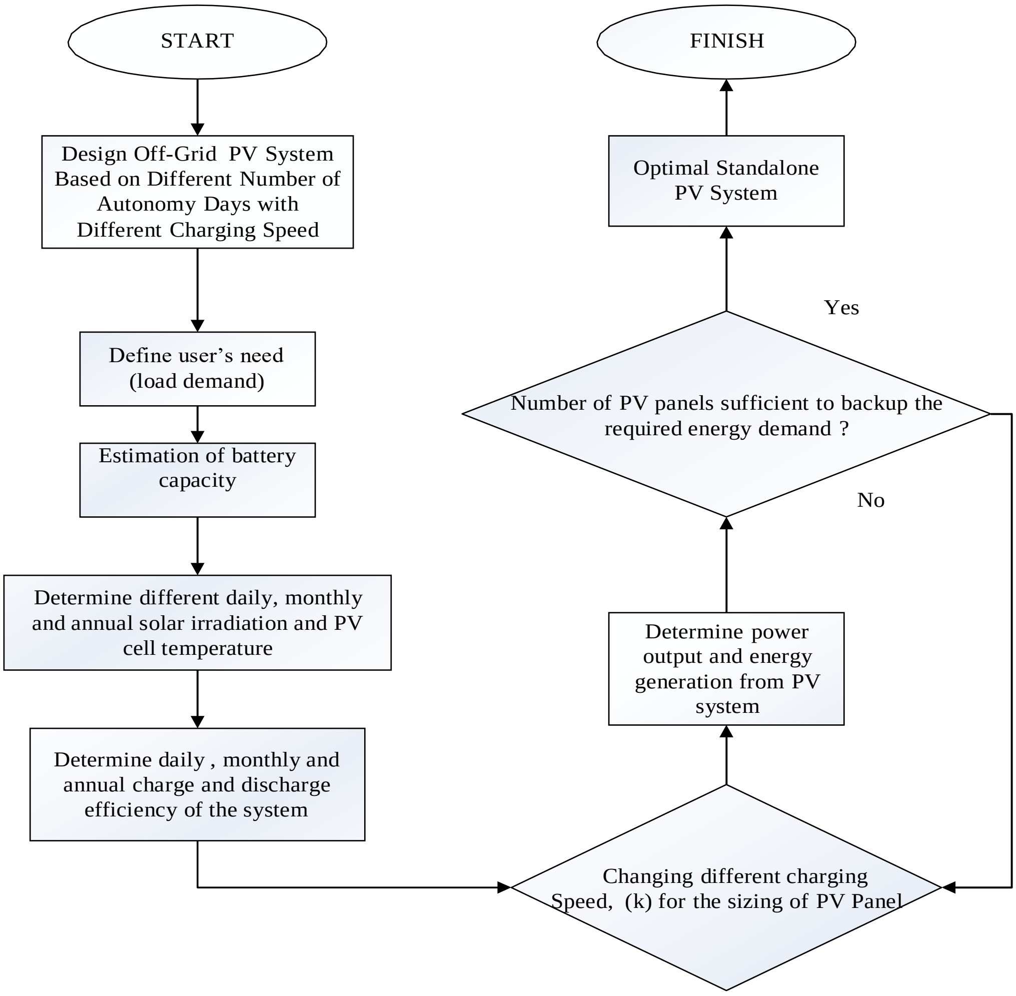

Figure 3-2 :Flow Chart of Design an Optimum Performance Standalone Photovoltaic (PV) System

3.1.2 Case Study and Result Analysis

The final stage of this project was case study and result analysis. Different case studies were carried out to study the effect of different PV capacity based on different k values of the battery to the reliability of battery supply for an off-grid system. After done all the design calculation, all the result were tabulated in the table form. Graphs were plotted to show the impact of various charging speed toward the performance and efficiency of the PV system. All the outcome for the case studies were analyzed and justified.

CHAPTER 4

4 CONCEPTUAL SYSTEM DESIGN

4.1 Design of Off-Grid Photovoltaic (PV) System

Figure 4-1 shows the proposed configuration off-grid photovoltaic (PV) system in this research project.

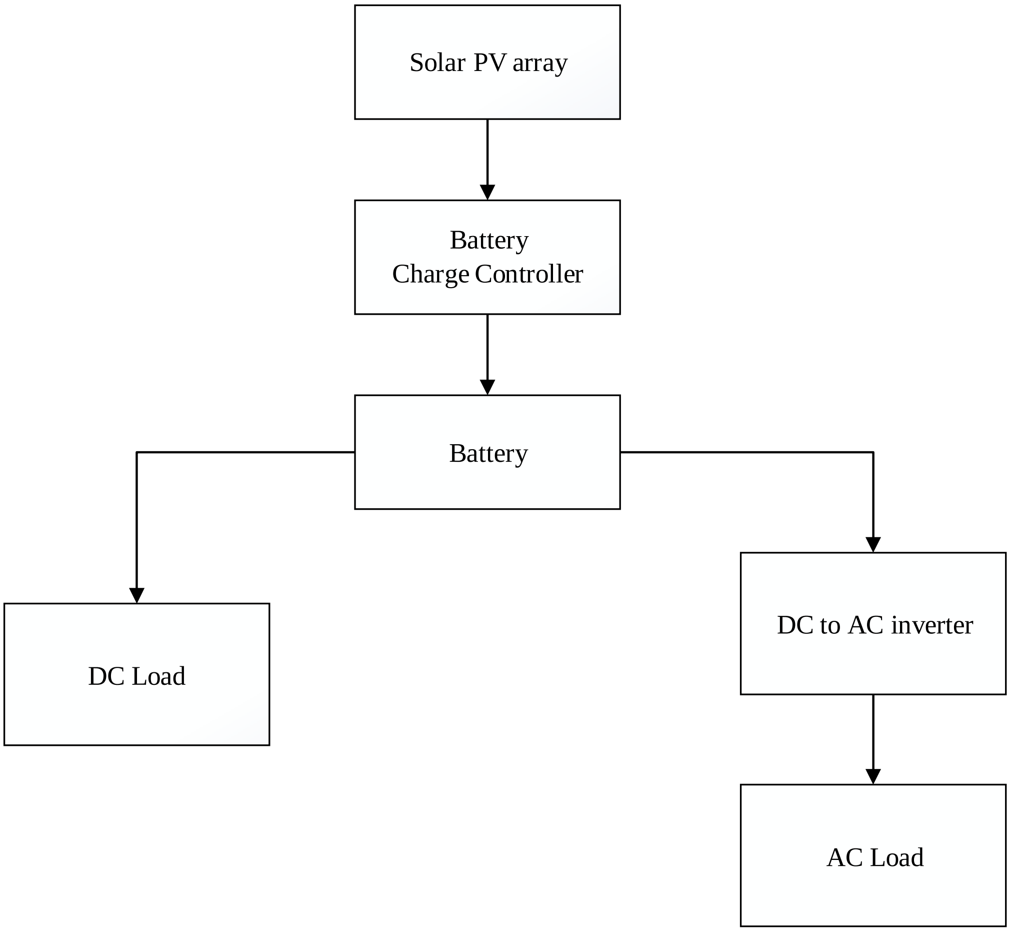

Figure 4-1: Configuration for Off-Grid Photovoltaic (PV) System

For this proposed configuration, solar PV array will collect the sunlight and generated DC current. The DC current is then supply to charge the battery via the battery charge controller. Then, DC current will discharge from the battery to supply the DC load. On the same time, DC current is then flow to the DC –AC inverter and convert into AC current. This AC current will be fed into utility grid for consumptions.

4.1.1 Proposed Project Summary

I. Location: Jalan SL1, Bandar Sungai Long, 43300 Kajang, Selangor, Malaysia

II. Latitude: 3.309514

III. Longitude: 101.794203

IV. Elevation: 81 meter above sea level

V. Time: UTC+8

4.1.2 Solar Irradiation for Year 2021

4.1.2.1 Daily Solar Irradiation

Daily solar irradiation from January 2021 to December 2021 was calculated by following formula. Figure 4-2 shows the example of daily solar irradiation for January 2021.

i. Daily Solar Irradiance, W/m^2 :

The daily irradiance is the total daily global tilted irradiance (GTI) , W/m^2 from the climate database Solargis v2.2.26.

ii. Daily Solar Irradiation, kWh/m^2 :

$= (\text{Daily Irradiance} * 0.5/1000)$

The daily irradiance in the climate database Solargis v2.2.26 is aggregated to 30 minute.

Table 4-1: Daily Solar Irradiation for January 2021

Date	Solar Irradiance (W/m^2)	Solar Irradiation (kWh/m^2)	PSH
1/1/2021	5510	2.8	2.8
2/1/2021	3280	1.6	1.6
3/1/2021	1179	0.6	0.6
4/1/2021	4347	2.2	2.2
5/1/2021	11998	6.0	6.0
6/1/2021	4691	2.3	2.3

7/1/2021	5423	2.7	2.7
8/1/2021	7146	3.6	3.6
9/1/2021	3912	2.0	2.0
10/1/2021	5542	2.8	2.8
11/1/2021	8606	4.3	4.3
12/1/2021	5703	2.9	2.9
13/1/2021	7817	3.9	3.9
14/1/2021	8332	4.2	4.2
15/1/2021	9871	4.9	4.9
16/1/2021	10554	5.3	5.3
17/1/2021	9708	4.9	4.9
18/1/2021	8143	4.1	4.1
19/1/2021	10300	5.2	5.2
20/1/2021	7121	3.6	3.6
21/1/2021	7915	4.0	4.0
22/1/2021	6198	3.1	3.1
23/1/2021	5648	2.8	2.8
24/1/2021	10072	5.0	5.0
25/1/2021	10679	5.3	5.3
26/1/2021	12148	6.1	6.1
27/1/2021	8954	4.5	4.5
28/1/2021	10334	5.2	5.2
29/1/2021	11536	5.8	5.8
30/1/2021	13497	6.7	6.7
31/1/2021	12481	6.2	6.2

4.1.2.2 Monthly Solar Irradiation

Table 4-2 shows the monthly solar irradiation of Year 2021. The annual solar irradiation is 1658.4kWh/m^2 while the daylight hour is 4.5 hour. Over the 12 months, the highest monthly solar irradiation was fall on February while January has the lowest monthly solar irradiation. The average monthly solar irradiation for year 2021 is 138.2 kWh/m^2. There is only 4 months which are February, March, May and October out of 12 months has the solar irradiation that above 138.2 kWh/m^2.

Table 4-2: Monthly Solar Irradiation

Month	Solar Irradiation (kWh/m^2)	PSH
Jan	124.3	4.0
Feb	165.0	5.9
Mar	157.5	5.1
Apr	136.9	4.4
May	139.9	4.5
Jun	130.3	4.3
Jul	130.9	4.2
Aug	127.9	4.1
Sep	136.5	4.6
Oct	149.5	4.8
Nov	128.1	4.3
Dec	131.5	4.2

4.1.3 Ambient & PV Cell Temperature for Year 2021

4.1.3.1 Daily Ambient & PV Cell Temperature

Daily average ambient and cell temperature from January 2021 to December 2021 was calculated by following formula. Figure 4-3 shows the example of daily average ambient and cell temperature for January 2021.

i. Daily Average Ambient Temperature, °C:

$= (\text{Daily Ambient Temperature}/\text{N})$

Where:

- Daily ambient temperature = sum of all ambient temperature within 1 days during day time (GTI >0)
- N= total number of day time (GTI>0)

The daily ambient temperature in the climate database Solargis v2.2.26 is aggregated to 30 minute.

ii. Daily Average Cell Temperature (T_{cell_avg}), °C:

= (R x Daily Average Irradiance) + Daily Average Ambient

Temperature

Where:

- R = 0.026 °C/(W/m2) - Time Specific Ross Coefficient

Table 4-3: Daily Average Ambient & Cell Temperature for January 2021

Date	Average Ambient Temp.(°C)	Average Cell Temp.(°C)
1/1/2021	27.1	33.0
2/1/2021	26.5	29.9
3/1/2021	24.1	25.5
4/1/2021	26.4	31.1
5/1/2021	28.5	41.5
6/1/2021	26.3	31.3
7/1/2021	27.2	33.0
8/1/2021	28.7	36.5
9/1/2021	27.6	31.8
10/1/2021	27.5	33.5
11/1/2021	27.4	36.7
12/1/2021	27.8	33.9
13/1/2021	27.6	36.0
14/1/2021	27.6	36.6
15/1/2021	28.7	39.4
16/1/2021	29.2	40.6
17/1/2021	29.5	40.0
18/1/2021	28.0	36.8
19/1/2021	27.9	39.1
20/1/2021	28.1	36.2
21/1/2021	28.0	36.6
22/1/2021	27.2	34.0
23/1/2021	27.2	33.3
24/1/2021	29.0	39.9
25/1/2021	28.6	40.1
26/1/2021	29.1	42.2
27/1/2021	28.4	38.1
28/1/2021	28.1	39.3
29/1/2021	28.4	40.9
30/1/2021	29.0	43.6
31/1/2021	28.8	42.3

4.1.3.2 Monthly Average Cell Temperature , T_{cell_avg}

Table 4-4 shows the monthly average cell temperature of Year 2021. The annual average cell temperature, T_{cell_avg} is 38.7 ℃ . Over the 12 months, the highest monthly average cell temperature was fall on February while January has the lowest monthly average cell temperature. There is only 4 months which are February, March, May and October out of 12 months has the average cell temperature that is above 38.7 ℃.

Table 4-4: Monthly Average Cell Temperature

Month	Average Cell Temp.(℃)
Jan	36.6
Feb	42.8
Mar	40.3
Apr	38.6
May	38.8
Jun	38.2
Jul	37.8
Aug	37.3
Sep	38.3
Oct	40.1
Nov	38.0
Dec	38.0

4.1.4 Estimation of Daily Load Demand

Table 4-5: Estimation of Daily Load Demand

Daily Load/Consumption					Total Energy
Description	**Quantity**	**Watt**	**Hours**	**Total Watt**	**Watt Hour/Day**
LED Light	10	20	6	200	1,200
Fan	3	100	6	300	1,800
Plug Point	5	200	2	1000	2,000

Refrigerator	1	400	12	400	4,800
Air Conditioner	1	1500	2	1500	3,000
Computer	1	270	5	270	1,350
Laptop	1	50	5	50	250
TV	1	17	3	17	51
Washing Machine	1	1150	0.5	1150	575
Rice Cooker	1	200	1	200	200
			Total:	**5,087**	**15,226**

The estimation of daily load demand in this research project is 15,226Wh.

4.1.5 Battery Sizing

i. Battery bus voltage: 48V

ii. Allowable depth of discharge: 0.9

iii. Total required amp-hour demand per day:

$= \text{Total watt} - \text{hours per day}/\text{Battery bus voltage}$

iv. Required battery capacity:

$$= \frac{(\text{Number of Autonomy Days} \times \text{Total Amp}-\text{Hour Demand per day})}{\text{Allowable Depth of Discharge}}$$

v. Amp-Hour Capacity of Selected Battery:

= 53.3 amp-hour (Battery Box- Pro 2.5 is selected in this project)

	Battery-Box Pro 2.5	Battery-Box Pro 5.0	Battery-Box Pro 7.5	Battery-Box Pro 10.0	Battery-Box Pro 13.8
Battery module	B-Plus L 2.5 (2.56 kWh)				GBSSB
	1 module	2 modules	3 modules	4 modules	2 modules
Usable Energy [1]	2.56 kWh	5.12 kWh	7.68 kWh	10.24 kWh	13.8 kWh
Max Output Power	2.56 kW	5.12 kW	7.68 kW	10.24 kW	12.8 kW
Peak Output Power	5.12 kW, 30 s	10.24 kW, 30 s	15.36 kW, 30 s	20.48 kW, 30 s	13.3 kW, 60 s
Round-Trip Efficiency	≥95.3 % [1]				≥95.3 % [1]
Nominal Voltage	51.2 V				51.2 V
Operating Voltage Range	43.2~56.4 V				40~59.2 V
Communication	RS485 / CAN				RS485 / CAN
Dimensions (W/H/D)	600 x 883 x 510 mm				650 x 800 x 550 mm
Weight	79 kg	113 kg	146 kg	180 kg	181 kg
Enclosure Protection Rating	IP20				IP20
Warranty	10 years				10 years
Operating temperature [2]	-10 °C to +50°C				-10 °C to +50°C
Certification & Safety Standard	TUV (IEC62619 / CE / UN38.3 / Sicherheitsleitfaden Li-Ionen-Hausspeicher				TUV / CE / UN38.3
Scalability	Max. 32 B-Plus 2.5 in parallel / 81.92 kWh				Max. 32 systems in parallel / 441.6 kWh
Compatible Inverters	SMA / GOODWE / SOLAX / Victron / Sungrow / Selectronic, more brands to be announced				
Application	ON Grid / ON Grid + Backup / OFF Grid (Refer to BYD Minimum Configuration List)				

Figure 4-2: Battery-Box Pro

vi. Required number of batteries in parallel:

=Require battery capacity/Amp − Hour Capacity

vii. Required number of batteries in series:

=Battery Bus Voltage/Selected Battery Voltage

viii. Total required battery amp-hour capacity:

= Amp-Hour Capacity of Selected Battery x Number of Batteries in Parallel

ix. Total required battery kilowatt-hour capacity:

= Total battery amp-hour capacity x battery bus voltage

4.1.6 Temperature Deration Factors, f_{temp}

$$= 1 + \gamma \times (T_{cell\_avg} - T_{STC})$$

Where

i. γ = temperature coefficients of P_{max}

= -0.0035 %/°C (from Jinko Solar Datasheet)

ii. T_{STC} = standard cell temperature

= 25°C (from Jinko Solar Datasheet)

iii. T_{cell_avg} = average cell temperature

4.1.6.1 Daily Temperature Derating Factor, f_{temp}

Table 4-6 shows the example of daily temperature derating factor for January 2021.

Table 4-6: Daily Temperature Derating Factor for January 2021

Date	f_{temp}
1/1/2021	0.97
2/1/2021	0.98
3/1/2021	1.00
4/1/2021	0.98
5/1/2021	0.94
6/1/2021	0.98
7/1/2021	0.97
8/1/2021	0.96
9/1/2021	0.98
10/1/2021	0.97
11/1/2021	0.96
12/1/2021	0.97
13/1/2021	0.96
14/1/2021	0.96
15/1/2021	0.95
16/1/2021	0.95
17/1/2021	0.95
18/1/2021	0.96
19/1/2021	0.95
20/1/2021	0.96
21/1/2021	0.96
22/1/2021	0.97
23/1/2021	0.97
24/1/2021	0.95
25/1/2021	0.95
26/1/2021	0.94
27/1/2021	0.95
28/1/2021	0.95

29/1/2021	0.94
30/1/2021	0.93
31/1/2021	0.94

4.1.6.2 Monthly Temperature Derating Factor, f_{temp}

Table 4-7 shows the monthly temperature derating factor of Year 2021.

The annual average temperature derating factor will be 0.95.

Table 4-7:Monthly Temperature Derating Factor

Month	f_{temp}
Jan	0.96
Feb	0.94
Mar	0.95
Apr	0.95
May	0.95
Jun	0.95
Jul	0.96
Aug	0.96
Sep	0.95
Oct	0.95
Nov	0.95
Dec	0.95

4.1.7 Charge Efficiency, η_{charge}

$$= f_{mm} \times f_{low\_irr} \times f_{cable\_ac} \times f_{cable\_ac} \times f_{inv} \times f_{dirt} \times f_{temp}$$

Where

i. Mismatch, f_{mm} = 0.95

ii. Non-usable irradiance, f_{low_irr} = 0.98

iii. AC cable power drop, f_{cable_ac} = 0.98

iv. DC cable power drop, f_{cable_dc} = 0.98

v. Inverter efficiency, f_{inv} = 0.958 (from inverter datasheet)

vi. Soiling, f_{dirt} = 0.97

vii. Temperature, f_{temp} = value from Table 4-28 to Table 4-39

4.1.8 Discharge Efficiency, $\eta_{disharge}$

The discharge efficiency in this research project is 0.9.

4.1.9 PV Power Generation from Standalone PV System, W

$$= \frac{\left(\frac{no.of\ autonomy\ days}{charging\ speed,\ k}\right) \times E_{demand}}{G_{PSH} \times y_{charge} \times y_{discharge}}$$

4.1.10 Energy Generation from Standalone PV System, Wh

$$= PV\ Power\ Generation \times PSH$$

CHAPTER 5

5 RESULT AND ANALYSIS

5.1 Case Study 1: Number of Autonomy Days Required = 2 Days

In case study 1, PV capacity and battery capacity of the off-grid PV system were designed to support the electricity demand for 2 autonomy days. Different charging speed (k) values used in the simulation of the suitable size of PV panels to provide a reliable electricity supply. If proposed energy storage capacity in the PV system exceeded 1 days of the energy demand, then proposed PV capacity consider good and can be used support load demand for 2 autonomy days. The proposed charging speed (k) value for a PV capacity also will selected because it can ensure at least the off –grid PV system have enough battery capacity for covering 2 autonomy days. The proposed PV capacity also determined by using annual, monthly and daily info as it will have discrepancies in the results between the annual, monthly and daily case.

5.1.1 Daily Case

The PV capacity in the daily case was calculated based on daily info. The daily PV energy generation and energy storage capacity was determined and tabulated in the table form. The condition of the battery system and PV system for each day shows in the table.

Table 5-1: Daily Energy Generation in January during k=4

Date	PV Power Generation (W)	Energy Generation (Wh)	Initial Battery Energy (Wh)	Balance Energy (Wh)	Remark	Battery System Condition
1/1/2021	2402.7	6619.4	33259.2	24652.6	GOOD	OK
2/1/2021	2429.7	3984.8	24652.6	13411.3	BAD	OK
3/1/2021	2468.1	1454.9	13411.3	0.0	BAD	CUT OFF

4/1/2021	2419.1	5258.0	0.0	0.0	BAD	CUT OFF
5/1/2021	2329.3	13973.7	0.0	0.0	BAD	CUT OFF
6/1/2021	2417.4	5670.1	0.0	0.0	BAD	CUT OFF
7/1/2021	2402.7	6514.9	0.0	0.0	BAD	CUT OFF
8/1/2021	2373.1	8479.1	0.0	0.0	BAD	CUT OFF
9/1/2021	2413.0	4719.9	0.0	0.0	BAD	CUT OFF
10/1/2021	2398.6	6646.5	0.0	0.0	BAD	CUT OFF
11/1/2021	2370.6	10200.6	0.0	0.0	BAD	CUT OFF
12/1/2021	2394.9	6829.0	0.0	0.0	BAD	CUT OFF
13/1/2021	2376.8	9289.8	0.0	0.0	BAD	CUT OFF
14/1/2021	2371.7	9880.4	0.0	0.0	BAD	CUT OFF
15/1/2021	2347.3	11585.1	0.0	0.0	BAD	CUT OFF
16/1/2021	2337.1	12332.9	0.0	0.0	BAD	CUT OFF
17/1/2021	2342.4	11370.0	0.0	0.0	BAD	CUT OFF
18/1/2021	2370.1	9650.0	0.0	0.0	BAD	CUT OFF
19/1/2021	2350.5	12105.0	0.0	0.0	BAD	CUT OFF
20/1/2021	2375.6	8458.5	0.0	0.0	BAD	CUT OFF
21/1/2021	2371.8	9386.2	0.0	0.0	BAD	CUT OFF
22/1/2021	2394.7	7421.3	0.0	0.0	BAD	CUT OFF
23/1/2021	2400.7	6779.6	0.0	0.0	BAD	CUT OFF
24/1/2021	2342.9	11799.0	0.0	0.0	BAD	CUT OFF
25/1/2021	2341.3	12501.6	0.0	0.0	BAD	CUT OFF
26/1/2021	2323.0	14110.1	0.0	0.0	BAD	CUT OFF
27/1/2021	2359.3	10562.5	0.0	0.0	BAD	CUT OFF
28/1/2021	2348.2	12133.1	0.0	0.0	BAD	CUT OFF
29/1/2021	2334.9	13467.5	0.0	0.0	BAD	CUT OFF
30/1/2021	2311.0	15595.5	0.0	369.5	BAD	CUT OFF
31/1/2021	2322.2	14491.6	0.0	0.0	BAD	CUT OFF

Table 5-2: Daily Energy Generation in January during k=3.5

Date	PV Power Generation (W)	Energy Generation (Wh)	Initial Battery Energy (Wh)	Balance Energy (Wh)	Remark	Battery System Condition
1/1/2021	2745.9	7565.0	33259.2	25598.2	GOOD	OK
2/1/2021	2776.8	4554.0	25598.2	14926.2	BAD	OK
3/1/2021	2820.7	1662.8	14926.2	1363.0	BAD	CUT OFF
4/1/2021	2764.7	6009.1	0.0	0.0	BAD	CUT OFF
5/1/2021	2662.1	15970.0	0.0	744.0	BAD	CUT OFF
6/1/2021	2762.8	6480.1	0.0	0.0	BAD	CUT OFF
7/1/2021	2745.9	7445.6	0.0	0.0	BAD	CUT OFF
8/1/2021	2712.1	9690.4	0.0	0.0	BAD	CUT OFF
9/1/2021	2757.8	5394.2	0.0	0.0	BAD	CUT OFF
10/1/2021	2741.2	7596.0	0.0	0.0	BAD	CUT OFF
11/1/2021	2709.2	11657.9	0.0	0.0	BAD	CUT OFF
12/1/2021	2737.0	7804.6	0.0	0.0	BAD	CUT OFF
13/1/2021	2716.4	10616.9	0.0	0.0	BAD	CUT OFF

14/1/2021	2710.5	11291.9	0.0	0.0	BAD	CUT OFF
15/1/2021	2682.6	13240.1	0.0	0.0	BAD	CUT OFF
16/1/2021	2671.0	14094.8	0.0	0.0	BAD	CUT OFF
17/1/2021	2677.0	12994.3	0.0	0.0	BAD	CUT OFF
18/1/2021	2708.7	11028.5	0.0	0.0	BAD	CUT OFF
19/1/2021	2686.3	13834.3	0.0	0.0	BAD	CUT OFF
20/1/2021	2715.0	9666.9	0.0	0.0	BAD	CUT OFF
21/1/2021	2710.6	10727.1	0.0	0.0	BAD	CUT OFF
22/1/2021	2736.8	8481.5	0.0	0.0	BAD	CUT OFF
23/1/2021	2743.6	7748.1	0.0	0.0	BAD	CUT OFF
24/1/2021	2677.6	13484.5	0.0	0.0	BAD	CUT OFF
25/1/2021	2675.8	14287.6	0.0	0.0	BAD	CUT OFF
26/1/2021	2654.9	16125.8	0.0	899.8	BAD	CUT OFF
27/1/2021	2696.3	12071.4	0.0	0.0	BAD	CUT OFF
28/1/2021	2683.6	13866.4	0.0	0.0	BAD	CUT OFF
29/1/2021	2668.4	15391.4	0.0	165.4	BAD	CUT OFF
30/1/2021	2641.1	17823.5	0.0	2597.5	BAD	CUT OFF
31/1/2021	2653.9	16561.8	0.0	1335.8	BAD	CUT OFF

Table 5-3: Daily Energy Generation in January during k=3

Date	PV Power Generation (W)	Energy Generation (Wh)	Initial Battery Energy (Wh)	Balance Energy (Wh)	Remark	Battery System Condition
1/1/2021	3203.6	8825.8	33259.2	26859.0	GOOD	OK
2/1/2021	3239.7	5313.0	26859.0	16946.0	GOOD	OK
3/1/2021	3290.8	1939.9	16946.0	3660.0	BAD	CUT OFF
4/1/2021	3225.5	7010.6	0.0	0.0	BAD	CUT OFF
5/1/2021	3105.8	18631.6	0.0	3405.6	BAD	CUT OFF
6/1/2021	3223.3	7560.2	0.0	0.0	BAD	CUT OFF
7/1/2021	3203.6	8686.5	0.0	0.0	BAD	CUT OFF
8/1/2021	3164.1	11305.4	0.0	0.0	BAD	CUT OFF
9/1/2021	3217.4	6293.2	0.0	0.0	BAD	CUT OFF
10/1/2021	3198.1	8862.0	0.0	0.0	BAD	CUT OFF
11/1/2021	3160.8	13600.8	0.0	0.0	BAD	CUT OFF
12/1/2021	3193.2	9105.3	0.0	0.0	BAD	CUT OFF
13/1/2021	3169.1	12386.4	0.0	0.0	BAD	CUT OFF
14/1/2021	3162.2	13173.9	0.0	0.0	BAD	CUT OFF
15/1/2021	3129.7	15446.8	0.0	220.8	BAD	CUT OFF
16/1/2021	3116.1	16443.9	0.0	1217.9	BAD	CUT OFF
17/1/2021	3123.2	15160.1	0.0	0.0	BAD	CUT OFF
18/1/2021	3160.2	12866.6	0.0	0.0	BAD	CUT OFF
19/1/2021	3134.0	16140.0	0.0	914.0	BAD	CUT OFF
20/1/2021	3167.5	11278.0	0.0	0.0	BAD	CUT OFF
21/1/2021	3162.3	12515.0	0.0	0.0	BAD	CUT OFF
22/1/2021	3193.0	9895.1	0.0	0.0	BAD	CUT OFF
23/1/2021	3200.9	9039.4	0.0	0.0	BAD	CUT OFF

24/1/2021	3123.9	15732.0	0.0	506.0	BAD	CUT OFF
25/1/2021	3121.8	16668.8	0.0	1442.8	BAD	CUT OFF
26/1/2021	3097.4	18813.5	0.0	3587.5	BAD	CUT OFF
27/1/2021	3145.7	14083.3	0.0	0.0	BAD	CUT OFF
28/1/2021	3130.9	16177.4	0.0	951.4	BAD	CUT OFF
29/1/2021	3113.1	17956.6	0.0	2730.6	BAD	CUT OFF
30/1/2021	3081.3	20794.1	0.0	5568.1	BAD	CUT OFF
31/1/2021	3096.2	19322.1	0.0	4096.1	BAD	CUT OFF

Table 5-4: Daily Energy Generation in January during k=2.5

Date	PV Power Generation (W)	Energy Generation (Wh)	Initial Battery Energy (Wh)	Balance Energy (Wh)	Remark	Battery System Condition
1/1/2021	3844.3	10591.0	33259.2	28624.2	GOOD	OK
2/1/2021	3887.6	6375.6	28624.2	19773.8	GOOD	OK
3/1/2021	3948.9	2327.9	19773.8	6875.7	BAD	OK
4/1/2021	3870.6	8412.7	6875.7	62.5	BAD	CUT OFF
5/1/2021	3726.9	22358.0	0.0	7132.0	BAD	OK
6/1/2021	3867.9	9072.2	7132.0	978.2	BAD	CUT OFF
7/1/2021	3844.3	10423.8	0.0	0.0	BAD	CUT OFF
8/1/2021	3796.9	13566.5	0.0	0.0	BAD	CUT OFF
9/1/2021	3860.9	7551.8	0.0	0.0	BAD	CUT OFF
10/1/2021	3837.7	10634.4	0.0	0.0	BAD	CUT OFF
11/1/2021	3792.9	16321.0	0.0	1095.0	BAD	CUT OFF
12/1/2021	3831.8	10926.4	0.0	0.0	BAD	CUT OFF
13/1/2021	3802.9	14863.7	0.0	0.0	BAD	CUT OFF
14/1/2021	3794.7	15808.6	0.0	582.6	BAD	CUT OFF
15/1/2021	3755.7	18536.1	0.0	3310.1	BAD	CUT OFF
16/1/2021	3739.4	19732.7	0.0	4506.7	BAD	CUT OFF
17/1/2021	3747.9	18192.1	0.0	2966.1	BAD	CUT OFF
18/1/2021	3792.2	15440.0	0.0	214.0	BAD	CUT OFF
19/1/2021	3760.8	19368.0	0.0	4142.0	BAD	CUT OFF
20/1/2021	3801.0	13533.6	0.0	0.0	BAD	CUT OFF
21/1/2021	3794.8	15018.0	0.0	0.0	BAD	CUT OFF
22/1/2021	3831.6	11874.1	0.0	0.0	BAD	CUT OFF
23/1/2021	3841.1	10847.3	0.0	0.0	BAD	CUT OFF
24/1/2021	3748.7	18878.4	0.0	3652.4	BAD	CUT OFF
25/1/2021	3746.2	20002.6	0.0	4776.6	BAD	CUT OFF
26/1/2021	3716.9	22576.2	0.0	7350.2	BAD	OK
27/1/2021	3774.9	16900.0	7350.2	9024.2	BAD	OK
28/1/2021	3757.1	19412.9	9024.2	13211.1	BAD	OK
29/1/2021	3735.8	21548.0	13211.1	19533.0	GOOD	OK
30/1/2021	3697.5	24952.9	19533.0	29259.9	GOOD	OK
31/1/2021	3715.5	23186.5	29259.9	33259.2	GOOD	OK

Table 5-5: Daily Energy Generation in January during k=2

Date	PV Power Generation (W)	Energy Generation (Wh)	Initial Battery Energy (Wh)	Balance Energy (Wh)	Remark	Battery System Condition
1/1/2021	4805.3	13238.7	33259.2	31271.9	GOOD	OK
2/1/2021	4859.5	7969.6	31271.9	24015.5	GOOD	OK
3/1/2021	4936.2	2909.9	24015.5	11699.3	BAD	OK
4/1/2021	4838.2	10515.9	11699.3	6989.3	BAD	OK
5/1/2021	4658.7	27947.4	6989.3	19710.7	GOOD	OK
6/1/2021	4834.9	11340.3	19710.7	15825.0	GOOD	OK
7/1/2021	4805.4	13029.8	15825.0	13628.8	BAD	OK
8/1/2021	4746.2	16958.1	13628.8	15360.9	GOOD	OK
9/1/2021	4826.1	9439.8	15360.9	9574.7	BAD	OK
10/1/2021	4797.2	13293.0	9574.7	7641.6	BAD	OK
11/1/2021	4741.2	20401.2	7641.6	12816.9	BAD	OK
12/1/2021	4789.8	13658.0	12816.9	11248.9	BAD	OK
13/1/2021	4753.7	18579.6	11248.9	14602.5	BAD	OK
14/1/2021	4743.3	19760.8	14602.5	19137.3	GOOD	OK
15/1/2021	4694.6	23170.2	19137.3	27081.5	GOOD	OK
16/1/2021	4674.2	24665.8	27081.5	33259.2	GOOD	OK
17/1/2021	4684.8	22740.1	33259.2	33259.2	GOOD	OK
18/1/2021	4740.3	19300.0	33259.2	33259.2	GOOD	OK
19/1/2021	4701.0	24210.0	33259.2	33259.2	GOOD	OK
20/1/2021	4751.3	16917.0	33259.2	33259.2	GOOD	OK
21/1/2021	4743.5	18772.5	33259.2	33259.2	GOOD	OK
22/1/2021	4789.5	14842.6	33259.2	32875.8	GOOD	OK
23/1/2021	4801.4	13559.1	32875.8	31208.9	GOOD	OK
24/1/2021	4685.9	23597.9	31208.9	33259.2	GOOD	OK
25/1/2021	4682.7	25003.2	33259.2	33259.2	GOOD	OK
26/1/2021	4646.1	28220.2	33259.2	33259.2	GOOD	OK
27/1/2021	4718.6	21125.0	33259.2	33259.2	GOOD	OK
28/1/2021	4696.4	24266.1	33259.2	33259.2	GOOD	OK
29/1/2021	4669.7	26935.0	33259.2	33259.2	GOOD	OK
30/1/2021	4621.9	31191.1	33259.2	33259.2	GOOD	OK
31/1/2021	4644.4	28983.2	33259.2	33259.2	GOOD	OK

Table 5-6: Daily Energy Generation in January during k=1.5

Date	PV Power Generation (W)	Energy Generation (Wh)	Initial Battery Energy (Wh)	Balance Energy (Wh)	Remark	Battery System Condition
1/1/2021	6407.1	17651.6	33259.2	33259.2	GOOD	OK
2/1/2021	6479.3	10626.1	33259.2	28659.3	GOOD	OK
3/1/2021	6581.5	3879.8	28659.3	17313.1	GOOD	OK
4/1/2021	6451.0	14021.2	17313.1	16108.3	GOOD	OK

5/1/2021	6211.6	37263.3	16108.3	33259.2	GOOD	OK
6/1/2021	6446.5	15120.3	33259.2	33153.5	GOOD	OK
7/1/2021	6407.2	17373.1	33153.5	33259.2	GOOD	OK
8/1/2021	6328.2	22610.8	33259.2	33259.2	GOOD	OK
9/1/2021	6434.8	12586.4	33259.2	30619.6	GOOD	OK
10/1/2021	6396.2	17723.9	30619.6	33117.5	GOOD	OK
11/1/2021	6321.6	27201.7	33117.5	33259.2	GOOD	OK
12/1/2021	6386.3	18210.6	33259.2	33259.2	GOOD	OK
13/1/2021	6338.2	24772.9	33259.2	33259.2	GOOD	OK
14/1/2021	6324.5	26347.7	33259.2	33259.2	GOOD	OK
15/1/2021	6259.5	30893.6	33259.2	33259.2	GOOD	OK
16/1/2021	6232.3	32887.8	33259.2	33259.2	GOOD	OK
17/1/2021	6246.4	30320.1	33259.2	33259.2	GOOD	OK
18/1/2021	6320.3	25733.3	33259.2	33259.2	GOOD	OK
19/1/2021	6268.0	32280.0	33259.2	33259.2	GOOD	OK
20/1/2021	6335.1	22556.0	33259.2	33259.2	GOOD	OK
21/1/2021	6324.7	25030.0	33259.2	33259.2	GOOD	OK
22/1/2021	6386.0	19790.2	33259.2	33259.2	GOOD	OK
23/1/2021	6401.8	18078.8	33259.2	33259.2	GOOD	OK
24/1/2021	6247.8	31463.9	33259.2	33259.2	GOOD	OK
25/1/2021	6243.6	33337.6	33259.2	33259.2	GOOD	OK
26/1/2021	6194.8	37626.9	33259.2	33259.2	GOOD	OK
27/1/2021	6291.4	28166.7	33259.2	33259.2	GOOD	OK
28/1/2021	6261.8	32354.9	33259.2	33259.2	GOOD	OK
29/1/2021	6226.3	35913.3	33259.2	33259.2	GOOD	OK
30/1/2021	6162.6	41588.1	33259.2	33259.2	GOOD	OK
31/1/2021	6192.5	38644.2	33259.2	33259.2	GOOD	OK

Table 5-3 to Table 5-6 shows the example result of daily energy generation for January 2021 during charging speed (k) =4, k=3.5, k=3, k=2.5, k=2, k1.5).

The PV power generation shows is Table 5-3 to Table 5-6 was calculated by the equation 5.1 below.

$$\frac{\left(\frac{no.of\ autonomy\ days}{charging\ speed,\ k}\right)\times E_{demand}}{G_{PSH}\times y_{charge}\times y_{discharge}} \quad (5.1)$$

When calculating PV power generation, the variable such as energy demand, number of autonomy days, and discharge efficiency will be constant. Charging speed (k) value that used in this project is 4, 3.5, 3, 2.5, 2 and 1.5. All the derating factor in charge efficiency will be constant except temperature derating factor will be changing all the time due to different PV cell temperature for each day. The peak sun hour value also will be different for each day.

The energy generation shows in the Table 5-3 to Table 5-6 was calculated by the equation 5.2 below.

$$PV\ Power\ Generation \times PSH \ \ldots\ldots\ldots\ldots\ldots.. \ (5.2)$$

The initial battery energy in the first day of the year’s shows in Table 5-3 to Table 5-6 represent the newly battery capacity which is 33,259 watt-hours. Then, initial battery energy for the next days is refer to the balance energy stored in the battery on previous days. The balance energy refers to the unused energy that stored in the battery after supply power to the load for consumptions. Balance energy also known as energy storage capacity. Balance energy is calculated by equation 5.3 below.

Balance Energy (Wh) = (Energy Generation + Initial Battery Energy) – Energy Demand ....(5.3)

“GOOD” will shows in the remark if the daily balance energy is more than the 1 days of the energy demand. It means that balance energy stored inside the battery system enough to support the energy demand for 1 autonomy days. If “BAD” show in the remark, it meant that the balance energy stored in the battery are not capable to support energy demand for 1 day. If there is low power output or no power output generated from the PV system and battery bank is under over discharge protection, then people will be facing shortage of electricity supply.

“CUT OFF” will be show under the battery system condition when balance energy less than the allowable depth of discharge of the battery.

When this condition occurs, it will shut down the energy storage system and stop supply the energy to the load. This is to protect the battery from over discharge to ensure longer lifetime of the battery system.

Based on the result obtained, daily PV power generation is inversely proportional to the charging speed (k) value. When charging speed (k) value is reduced, the required number of photovoltaic panels for the PV system is more. Thus, more PV power will generate from the system when the charging speed (k) reduces.

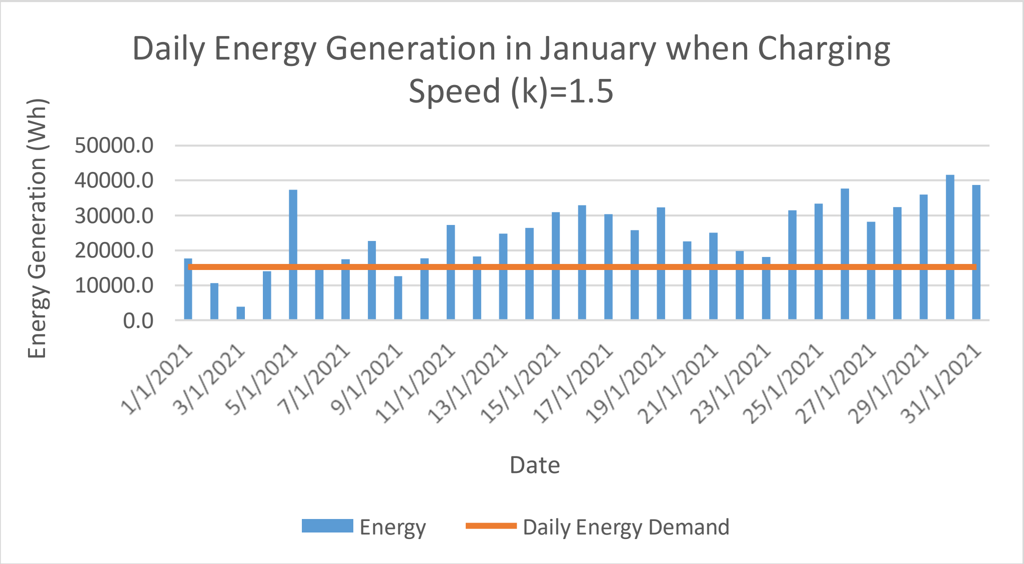

Figure 5-1:Daily Energy Generation in January during Charging Speed (k)=1.5

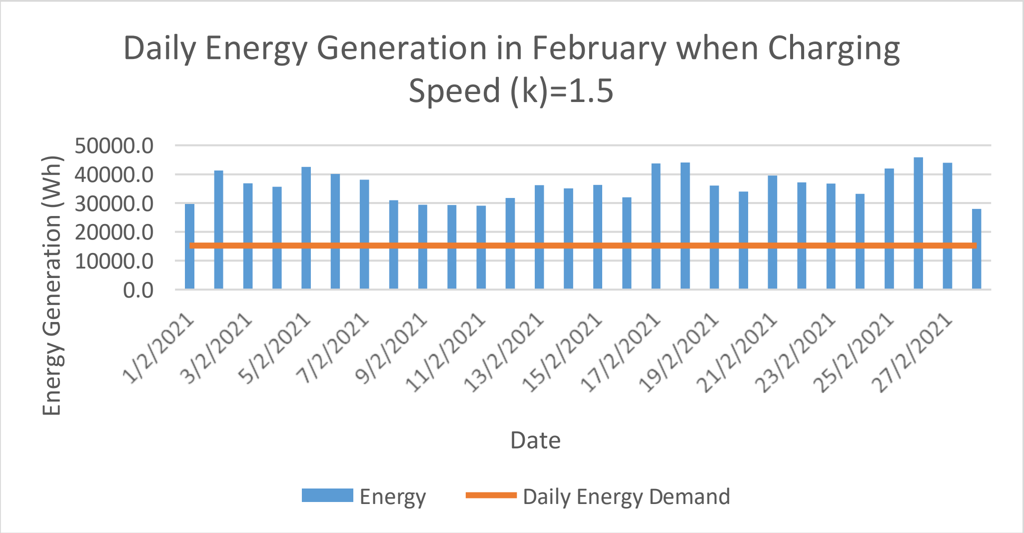

Figure 5-2:Daily Energy Generation in February during Charging Speed (k)=1.5

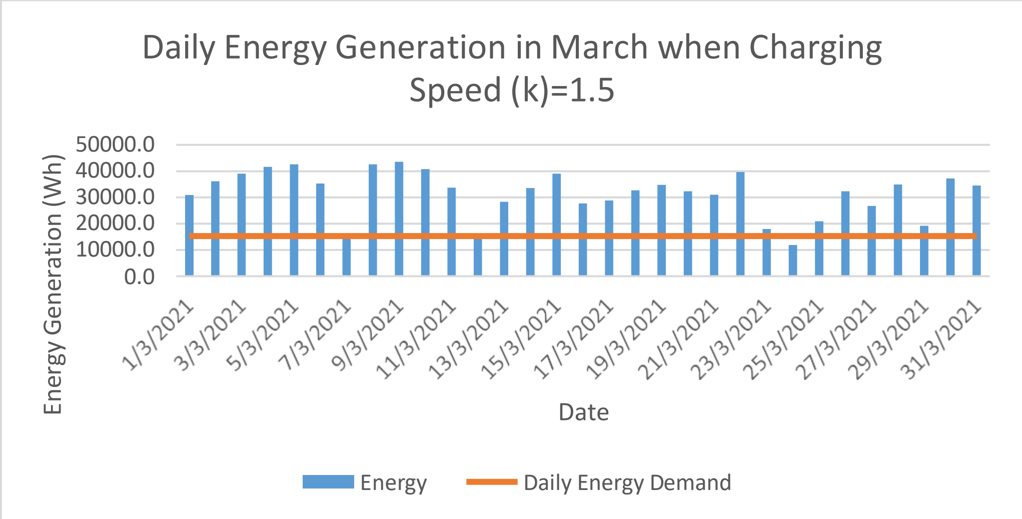

Figure 5-3:Daily Energy Generation at March during Charging Speed (k)=1.5

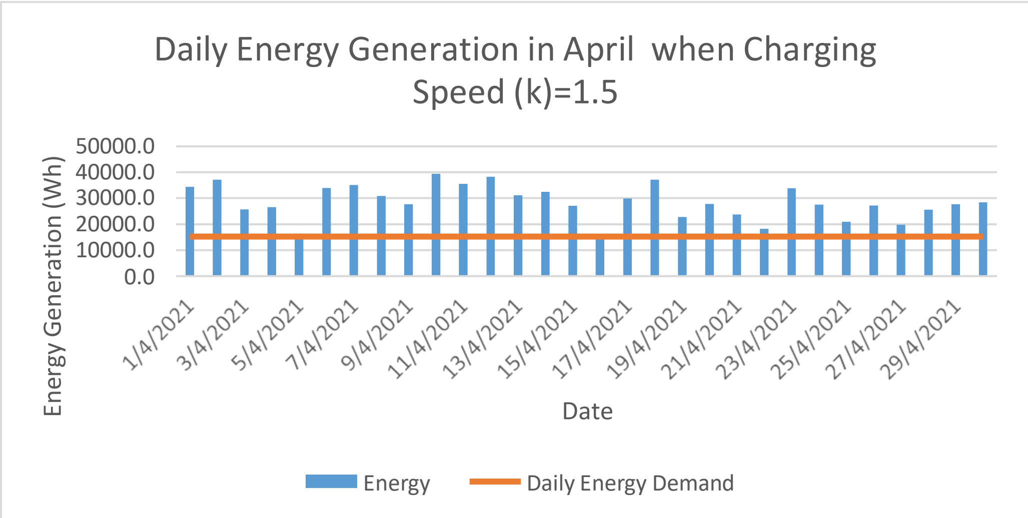

Figure 5-4:Daily Energy Generation in April during Charging Speed (k)=1.5

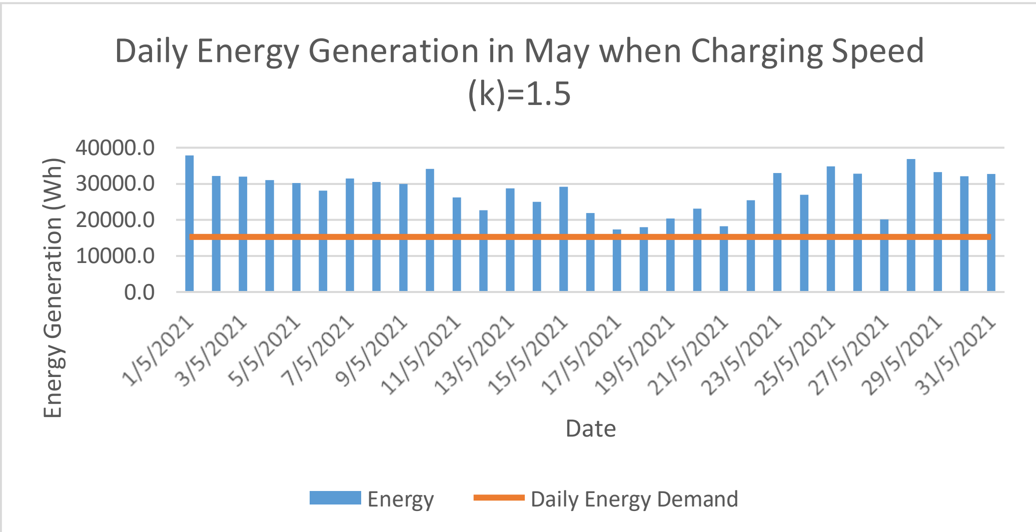

Figure 5-5:Daily Energy Generation in May during Charging Speed (k)=1.5

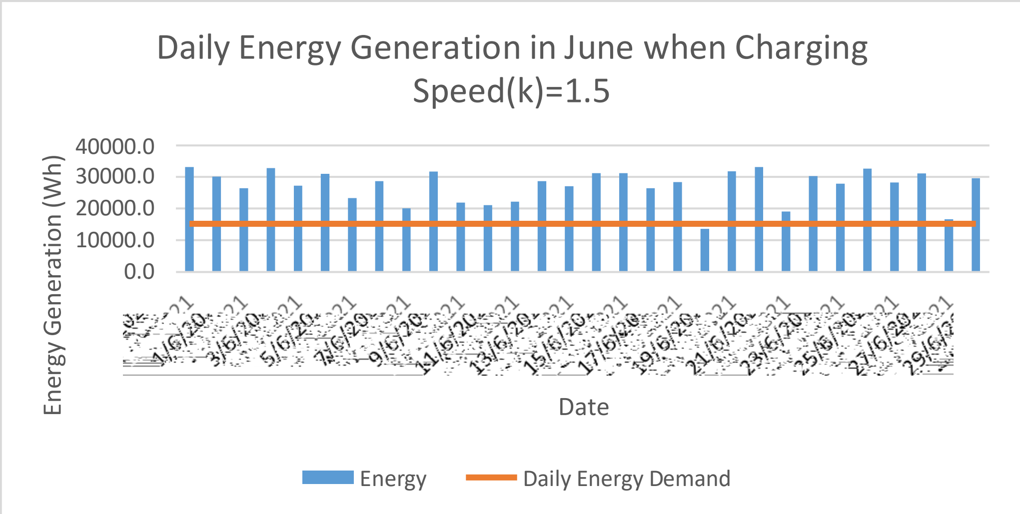

Figure 5-6:Daily Energy Generation in June during Charging Speed (k)=1.5

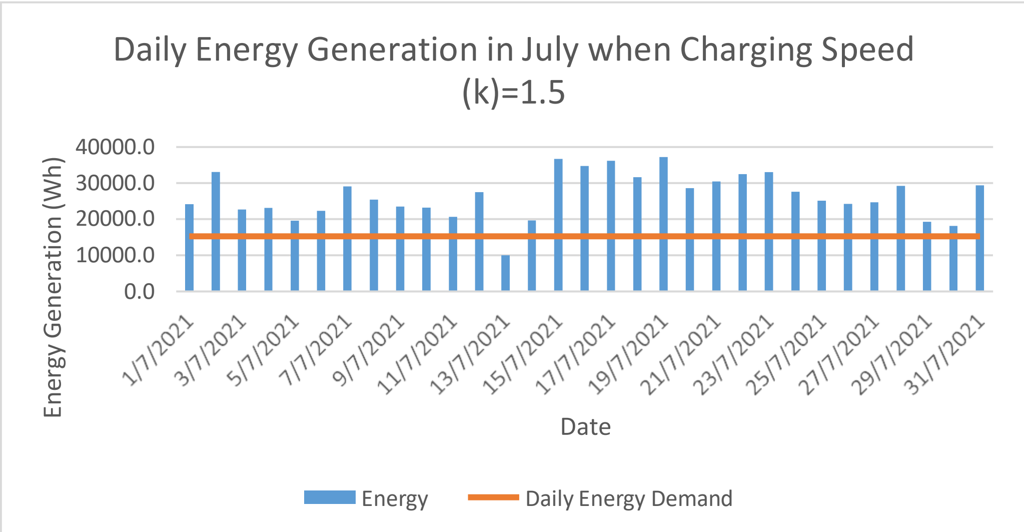

Figure 5-7:Daily Energy Generation in July during Charging Speed (k)=1.5

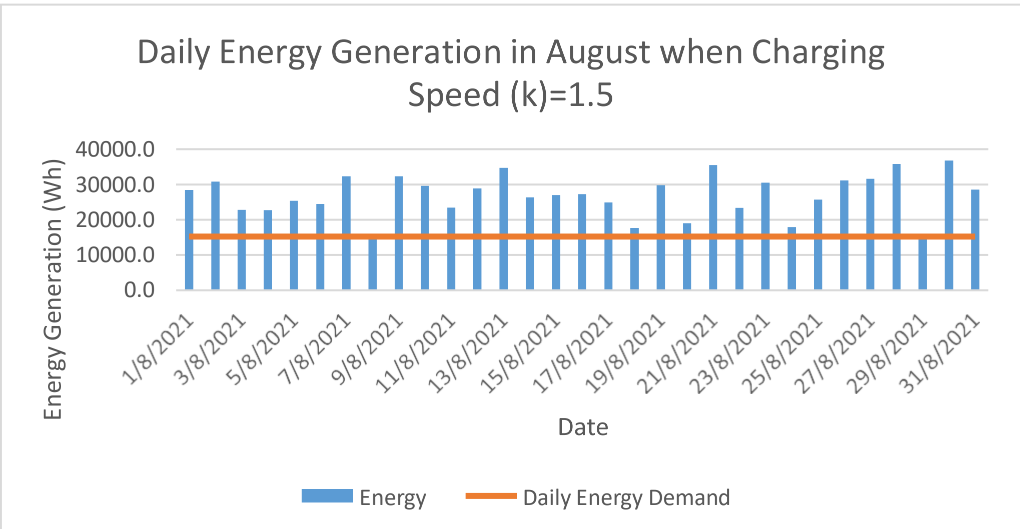

Figure 5-8:Daily Energy Generation in August during Charging Speed (k)=1.5

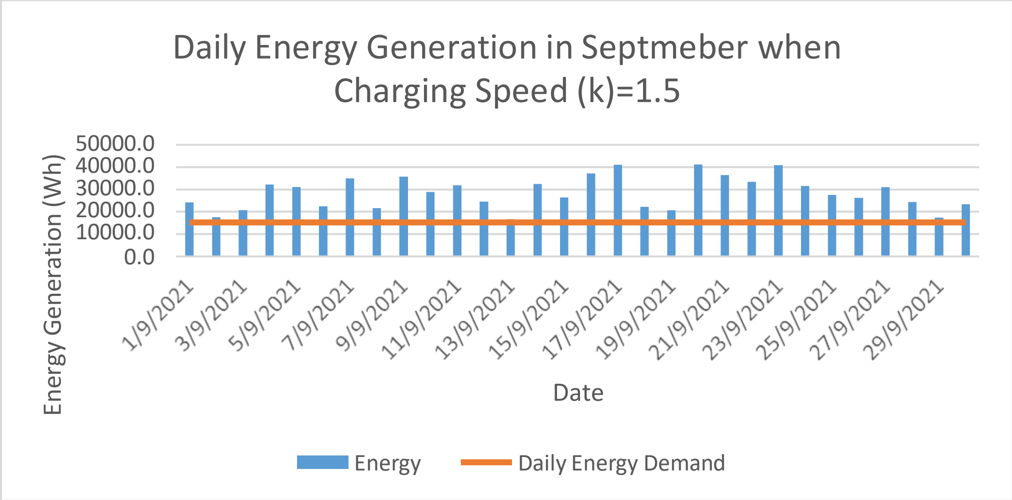

Figure 5-9:Daily Energy Generation in September during Charging Speed (k)=1.5

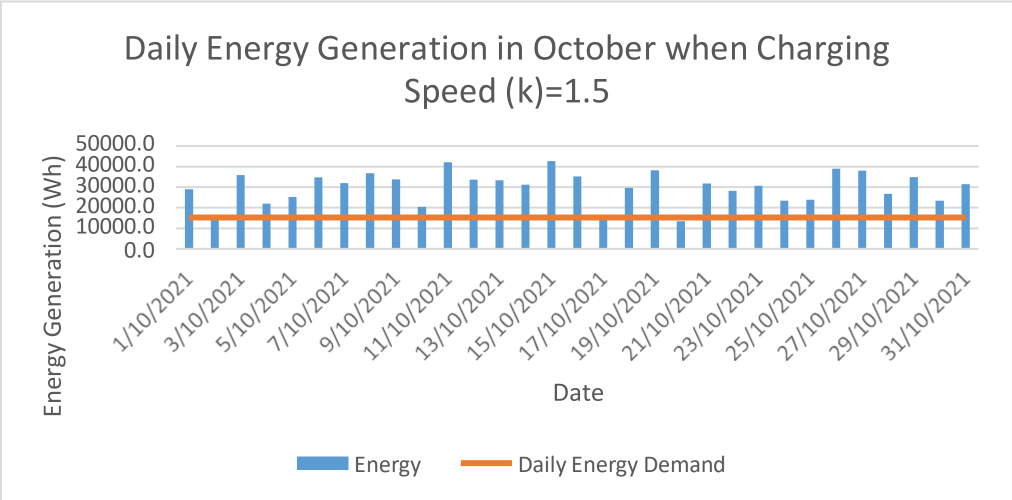

Figure 5-10:Daily Energy Generation in October during Charging Speed (k)=1.5

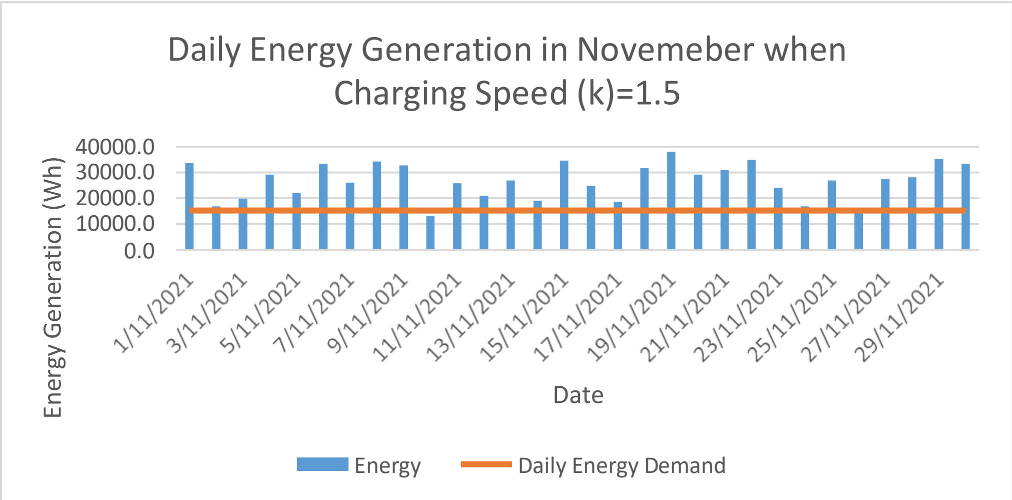

Figure 5-11: Daily Energy Generation in November during Charging Speed (k)=1.5

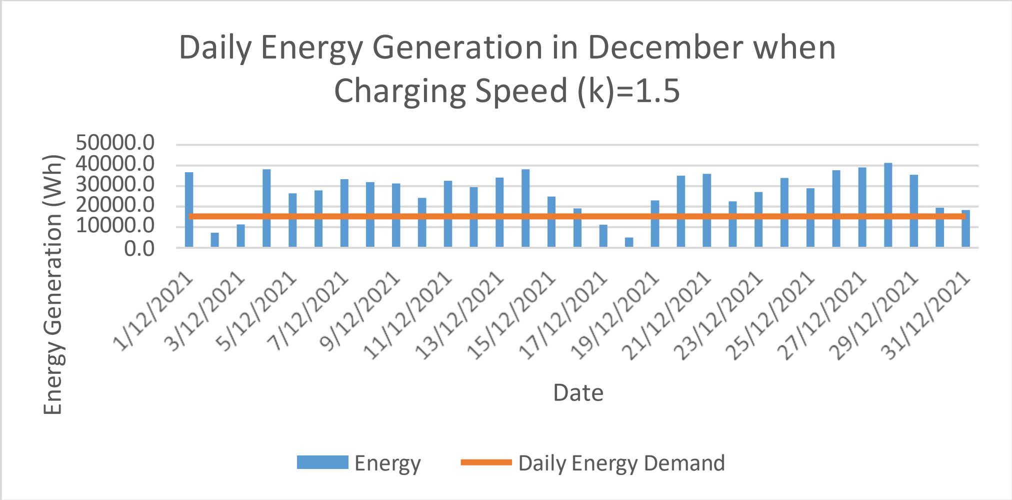

Figure 5-12:Daily Energy Generation in December during Charging Speed (k)=1.5

Figure 5-1 to Figure 5-12 shows the different graph of daily energy generation during charging speed (k) =1.5. All the graph in Figure 5-1 to Figure 5-12 was plotted based on the daily energy generation for 365 days. Based on the graph above, all daily energy generation in February, April, May, August, September and October was higher than the required energy demand.

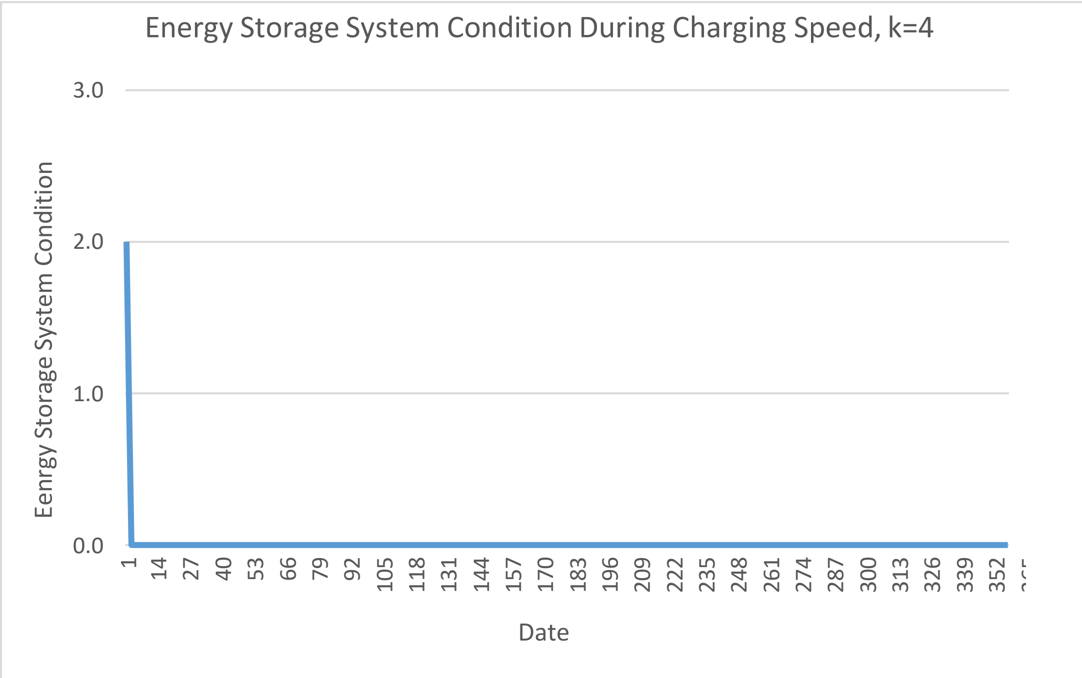

Figure 5-13: Graph of Energy Storage System Condition during Charging Speed (k)=4

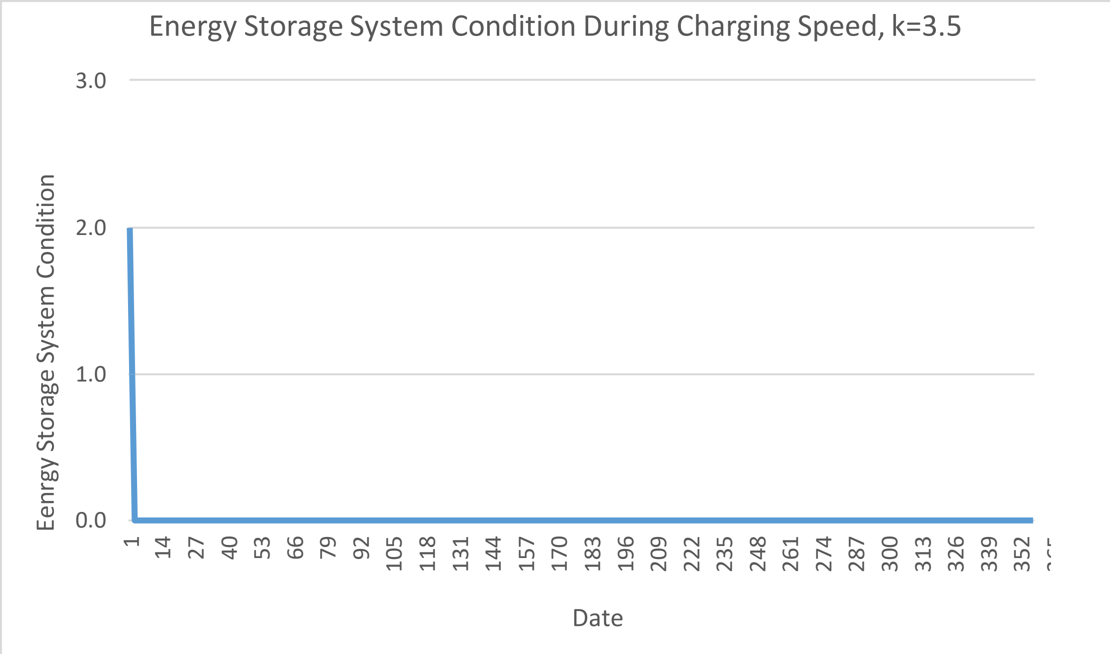

Figure 5-14: Graph of Energy Storage System Condition during Charging Speed (k)=3.5

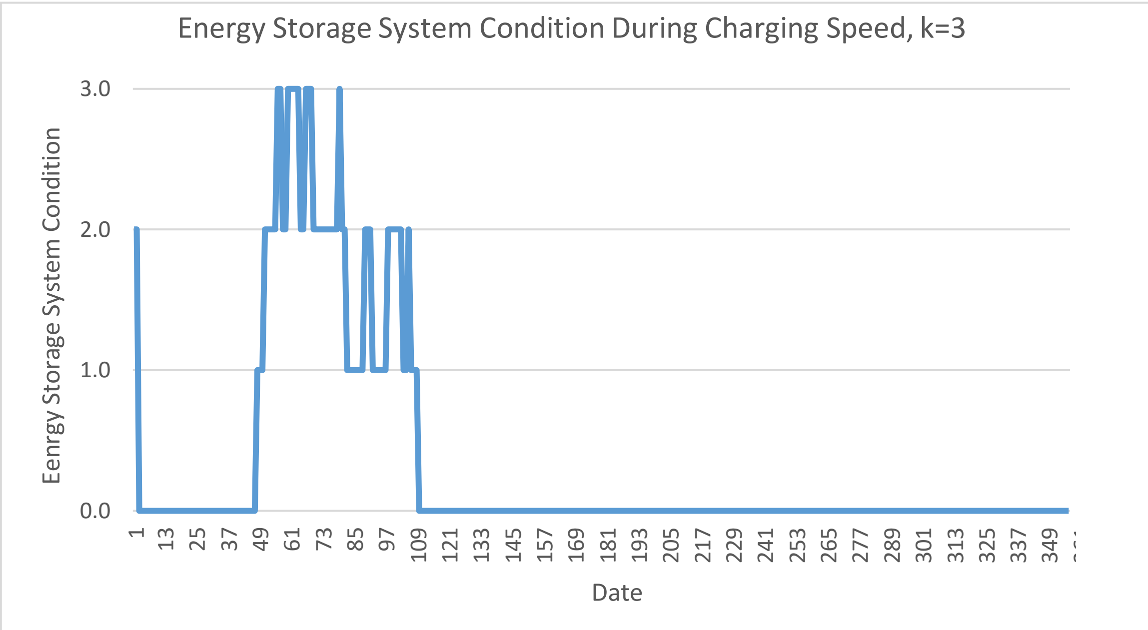

Figure 5-15: Graph of Energy Storage System Condition during Charging Speed (k)=3

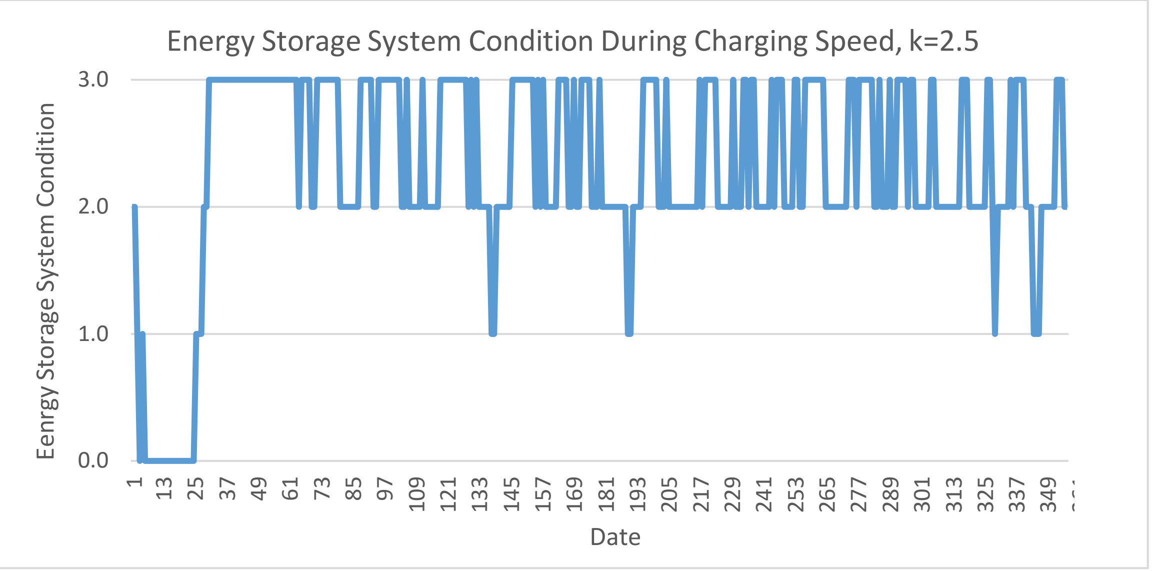

Figure 5-16: Graph of Energy Storage System Condition during Charging Speed (k)=2.5

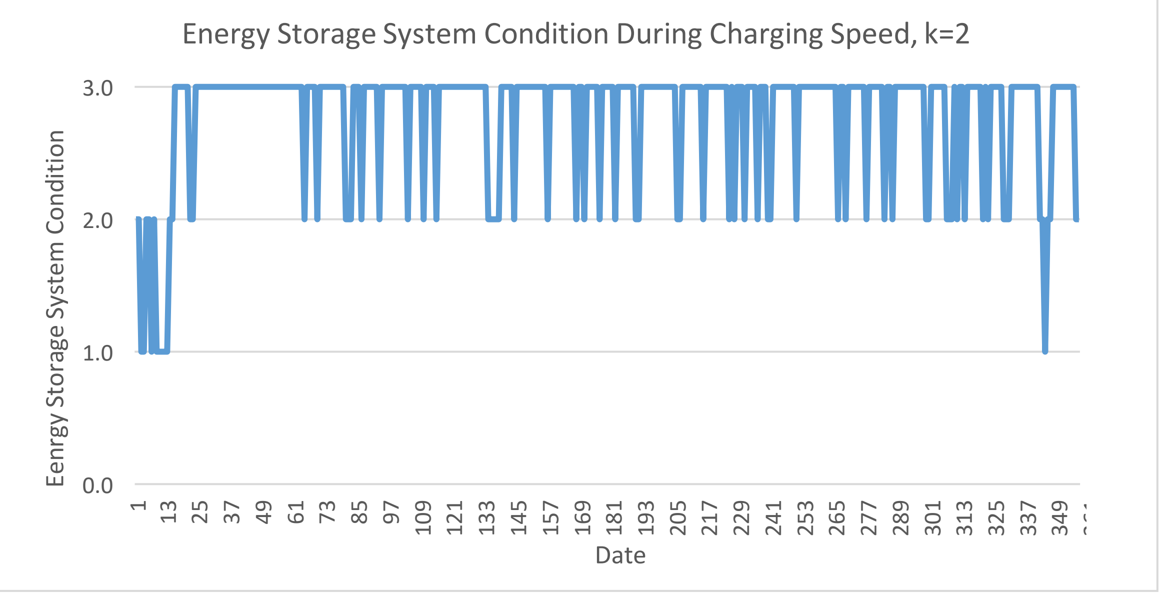

Figure 5-17: Graph of Energy Storage System Condition during Charging Speed (k)=2

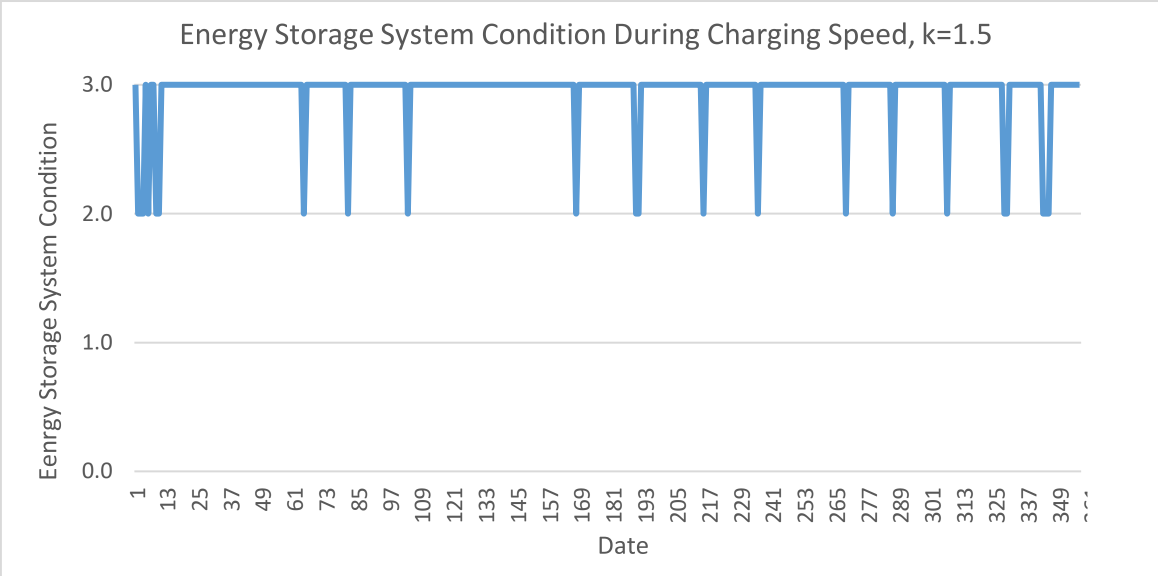

Figure 5-18: Graph of Energy Storage System Condition during Charging Speed (k)=1.5

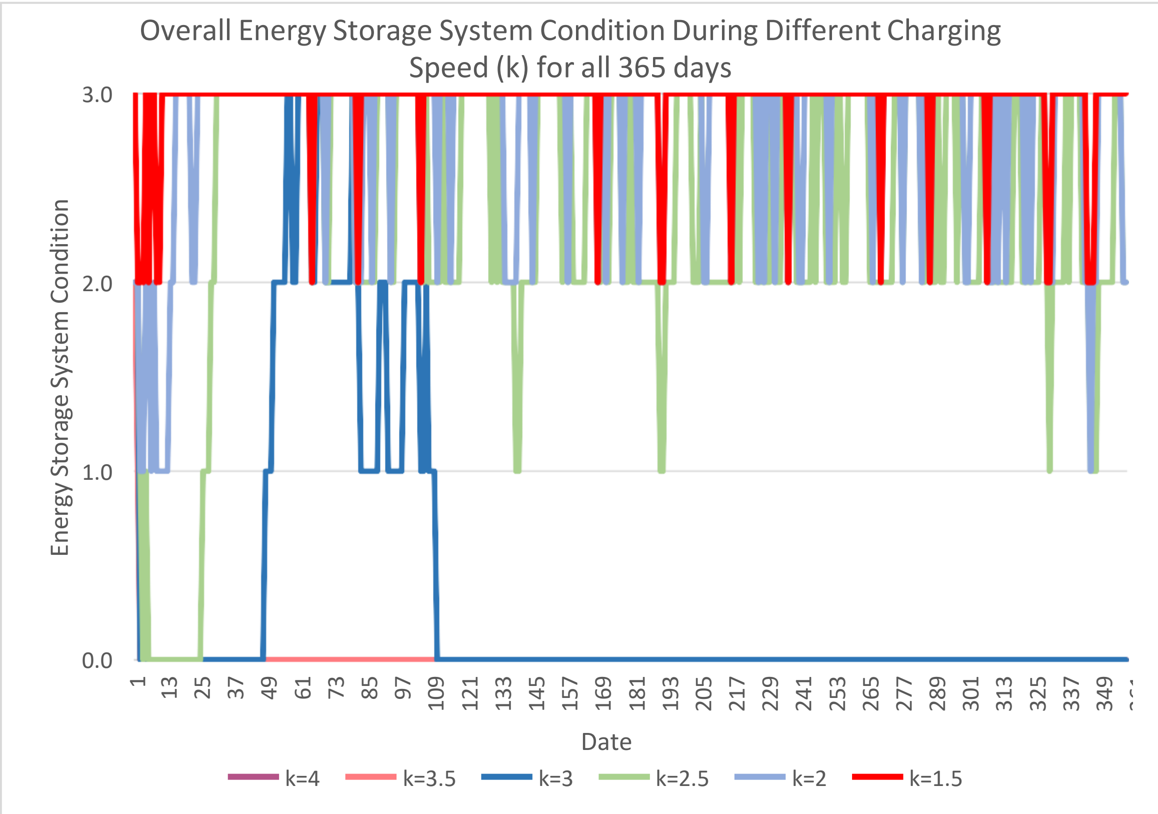

Figure 5-19: Graph of Overall Energy Storage System Condition during Different Charging Speed for all 365 days

Legend:
"0" is represent cut off condition for energy storage system (when energy storage capacity < 6651.85Wh).
"1" is represent the stored energy in the battery less than the daily energy demand (15,225Wh).
"2" is represent the store energy in the battery more than the daily energy demand (15,226Wh).
"3" is represent the battery system is in 100% capacity condition (100% condition = when energy storage capacity = 33259.2Wh).

Figure 5-13 to Figure 5-18 shows different graph of energy storage system condition during different charging speed (k) values. Figure 5-19 shows graph of overall energy storage system along the 365 days during different charging speed (k) values. Graph shows in figure 5-7 was the combination of all energy storage system condition under different charging speed (k) values used in the sizing of PV array.

For charging speed (k) value =4, the PV capacity is not enough to supply the daily energy demand. Only few days' energy generation in the January, February, March and October sufficient to meet the required energy demand. For case that used charging speed (k)=4 and 3.5 in the sizing of PV array, the standalone PV system is failed to generate enough energy to meet the required daily energy demand and the energy storage system will need to cut off from over discharge the energy to the load for all the times.

For charging speed (k) value =3, only energy storage capacity in February and March able to cover 2 autonomy days. For the rest of others month, the energy generation is not sufficient to meet the required daily energy demand. And the energy storage system also needs to cut off for all the times except February and March.

For charging speed (k) values =2.5, only energy generation in January is less than required energy demand. The energy storage capacity for all days over the years is more than the energy demand for 1 days except May, July and Dec. There is 2 days continuously where energy storage capacity in May and July is less than the daily energy demand. While for December, there is continuously 3 days where energy storage capacity is less than the daily energy demand. If continuously raining more than 1 days and when battery bank has reached its depth discharge capacity after supplying electricity for the pre-designed number of autonomy days, then there will be no power supply for the specific 2 or 3 days in May, July, and December.

During charging speed (k) values = 2, the energy generation from the PV system in every month can meet the required energy demand. The energy storage capacity for all days along the year is more than the energy demand for 1 days except January and December. There are 4 consecutive days in December where the energy storage capacity less than the daily energy demand. While in January, there is only 1 day where the energy storage capacity is less than the daily energy demand. Thus, power shortage will occur at the specific 1 days in January. While for December, there is no disruption of the electricity supply if there is raining continuously for 1 days because the energy storage capacity enough to backup for 1 day's energy demand.

Lastly, the energy storage capacity in each day over the year during charging speed (k) values = 1.5 can cover the energy demand of another subsequent 1 days continuously raining. Thus, PV capacity with charging speed (k) value =1.5 can ensure there is reliable electricity supply to the load for period of a year.

5.1.2 Monthly Case

The PV capacity in the monthly case was calculated based on monthly info. The monthly average PV energy generation and energy storage capacity was determined and tabulated in the table form. The condition of the battery system and PV system for each month shows in the table. Table 5-7 to Table 5-12 shows the result of monthly average energy generation during different charging speed (k) values.

Table 5-7: Monthly Energy Generation during Charging Speed (k) =4

Date	PV Power Generation (W)	Energy Generation (Wh)	Initial Battery Energy (Wh)	Balance Energy (Wh)	Remark	Battery System Condition
Jan	2372.3	9513.8	33259.2	27547.0	GOOD	OK
Feb	2317.9	13655.7	27547.0	25976.7	GOOD	OK
Mar	2340.2	11890.7	25976.7	22641.4	GOOD	OK
Apr	2354.8	10402.1	22641.4	17817.5	GOOD	OK
May	2353.2	10621.3	17817.5	13212.8	BAD	OK
June	2358.4	10242.3	13212.8	8229.2	BAD	OK
July	2361.8	9976.5	8229.2	2979.7	BAD	CUT OFF
Aug	2366.1	9763.8	0.0	0.0	BAD	CUT OFF
Sep	2357.4	10728.5	6651.8	2154.3	BAD	CUT OFF
Oct	2341.6	11290.3	6651.8	2716.2	BAD	CUT OFF
Nov	2360.0	10078.6	6651.8	1504.4	BAD	CUT OFF
Dec	2360.0	10007.1	6651.8	1433.0	BAD	CUT OFF

Table 5-8: Monthly Energy Generation during Charging Speed (k) =3.5

Date	PV Power Generation (W)	Energy Generation (Wh)	Initial Battery Energy (Wh)	Balance Energy (Wh)	Remark	Battery System Condition
Jan	2711.2	10872.9	33259.2	28906.1	GOOD	OK
Feb	2649.0	15606.5	28906.1	29286.6	GOOD	OK
Mar	2674.5	13589.3	29286.6	27649.9	GOOD	OK
Apr	2691.2	11888.2	27649.9	24312.1	GOOD	OK
May	2689.4	12138.7	24312.1	21224.8	GOOD	OK
June	2695.3	11705.5	21224.8	17704.3	GOOD	OK
July	2699.2	11401.7	17704.3	13880.0	BAD	OK
Aug	2704.1	11158.6	13880.0	9812.6	BAD	OK
Sep	2694.2	12261.1	9812.6	6847.7	BAD	OK
Oct	2676.1	12903.2	6847.7	4524.9	BAD	CUT OFF

Nov	2697.1	11518.4	4524.9	817.3	BAD	CUT OFF
Dec	2696.9	11435.9	817.3	0.0	BAD	CUT OFF

Table 5-9: Monthly Energy Generation during Charging Speed (k) =3

Date	PV Power Generation (W)	Energy Generation (Wh)	Initial Battery Energy (Wh)	Balance Energy (Wh)	Remark	Battery System Condition
Jan	3163.0	12685.1	33259.2	30718.3	GOOD	OK
Feb	3090.6	18207.6	30718.3	33259.2	GOOD	OK
Mar	3120.3	15854.2	33259.2	33259.2	GOOD	OK
Apr	3139.7	13869.5	33259.2	31902.7	GOOD	OK
May	3137.7	14161.8	31902.7	30838.5	GOOD	OK
June	3144.6	13656.4	30838.5	29269.0	GOOD	OK
July	3149.0	13302.0	29269.0	27344.9	GOOD	OK
Aug	3154.8	13018.3	27344.9	25137.3	GOOD	OK
Sep	3143.2	14304.6	25137.3	24215.9	GOOD	OK
Oct	3122.1	15053.8	24215.9	24043.7	GOOD	OK
Nov	3146.6	13438.1	24043.7	22255.8	GOOD	OK
Dec	3146.4	13341.8	22255.8	20371.6	GOOD	OK

Table 5-10: Monthly Energy Generation during Charging Speed (k) =2.5

Date	PV Power Generation (W)	Energy Generation (Wh)	Initial Battery Energy (Wh)	Balance Energy (Wh)	Remark	Battery System Condition
Jan	3795.7	15222.1	33259.2	33255.3	GOOD	OK
Feb	3708.7	21849.1	33255.3	33259.2	GOOD	OK
Mar	3744.3	19025.1	33259.2	33259.2	GOOD	OK
Apr	3767.7	16643.4	33259.2	33259.2	GOOD	OK
May	3765.2	16994.2	33259.2	33259.2	GOOD	OK
June	3773.5	16387.7	33259.2	33259.2	GOOD	OK
July	3778.8	15962.4	33259.2	33259.2	GOOD	OK
Aug	3785.7	15622.0	33259.2	33259.2	GOOD	OK
Sep	3771.8	17165.6	33259.2	33259.2	GOOD	OK
Oct	3746.5	18064.5	33259.2	33259.2	GOOD	OK
Nov	3776.0	16125.7	33259.2	33259.2	GOOD	OK
Dec	3775.7	16010.2	33259.2	33259.2	GOOD	OK

Table 5-11: Monthly Energy Generation during Charging Speed (k) =2

Date	PV Power Generation (W)	Energy Generation (Wh)	Initial Battery Energy (Wh)	Balance Energy (Wh)	Remark	Battery System Condition
Jan	4744.6	19027.6	33259.2	33259.2	GOOD	OK
Feb	4635.8	27311.3	33259.2	33259.2	GOOD	OK

Mar	4680.4	23781.3	33259.2	33259.2	GOOD	OK
Apr	4709.6	20804.3	33259.2	33259.2	GOOD	OK
May	4706.5	21242.7	33259.2	33259.2	GOOD	OK
June	4716.8	20484.6	33259.2	33259.2	GOOD	OK
July	4723.5	19953.0	33259.2	33259.2	GOOD	OK
Aug	4732.1	19527.5	33259.2	33259.2	GOOD	OK
Sep	4714.8	21457.0	33259.2	33259.2	GOOD	OK
Oct	4683.2	22580.6	33259.2	33259.2	GOOD	OK
Nov	4720.0	20157.1	33259.2	33259.2	GOOD	OK
Dec	4719.6	20012.8	33259.2	33259.2	GOOD	OK

Table 5-12: Monthly Energy Generation during Charging Speed (k) =1.5

Date	PV Power Generation (W)	Energy Generation (Wh)	Initial Battery Energy (Wh)	Balance Energy (Wh)	Remark	Battery System Condition
Jan	6326.1	25370.2	33259.2	33259.2	GOOD	OK
Feb	6181.1	36415.1	33259.2	33259.2	GOOD	OK
Mar	6240.5	31708.4	33259.2	33259.2	GOOD	OK
Apr	6279.4	27739.1	33259.2	33259.2	GOOD	OK
May	6275.3	28323.6	33259.2	33259.2	GOOD	OK
June	6289.1	27312.9	33259.2	33259.2	GOOD	OK
July	6298.1	26604.0	33259.2	33259.2	GOOD	OK
Aug	6309.5	26036.7	33259.2	33259.2	GOOD	OK
Sep	6286.4	28609.3	33259.2	33259.2	GOOD	OK
Oct	6244.2	30107.5	33259.2	33259.2	GOOD	OK
Nov	6293.3	26876.2	33259.2	33259.2	GOOD	OK
Dec	6292.8	26683.7	33259.2	33259.2	GOOD	OK

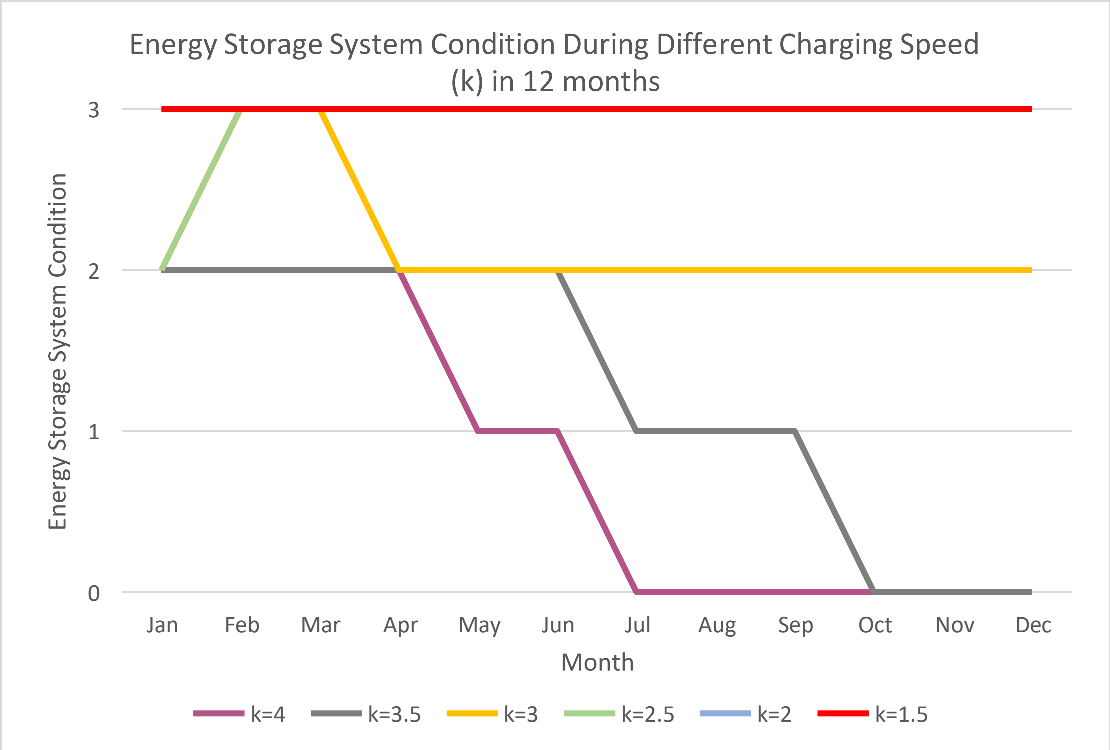

Figure 5-20: Overall Energy Storage System Condition During Different Charging Speed (k) in 12 months

Legend: "0" is represent cut off condition for energy storage system (when energy storage capacity less than 6651.85Wh). "1" is represent the stored energy in the battery is less than the daily energy demand (15,225Wh). "2" is represent the store energy in the battery is more than the daily energy demand (15,226Wh). "3" is represent the battery system is in 100% capacity condition (100% condition = when energy storage capacity equal to 33259.2Wh).

Figure 5-20 shows the graph of overall energy storage system condition for 12 months during different charging speed (k) values. The graph was plotted based on the result obtained from Table 5-7 to Figure 5-12. Based on the graph shows in figure 5-20, we observed that the monthly average energy storage capacity during charging speed (k) values = 3, 2.5 ,2 and 1.5 was higher than the required energy demand for each month. When charging speed (k) values = 4, the monthly average energy storage capacity starts from May until December less than the energy demand for 1 days. While during charging speed (k) values =3.5, the monthly energy storage capacity starts from July until December is less than the required energy demand.

5.1.3 Annual Case

The PV capacity in the annual case was calculated based on annual info. The annual average PV energy generation and energy storage capacity was determined and tabulated in the table form. The annual condition of the battery system and PV system shows in the table. Table 5-13 shows the result of annual average energy generation during different charging speed (k) values.

Table 5-13: Annual Energy Generation for Different Charging Speed (k)

k	**PV Power Generation (W)**	**Energy Generation (Wh)**	**Initial Battery Energy (Wh)**	**Balance Energy (Wh)**	**Remark**	**Battery System Condition**
4	2353.6	10693.7	33259.2	28726.9	GOOD	OK
3.5	2689.9	12221.4	33259.2	30254.6	GOOD	OK
3	3138.2	14258.3	33259.2	32291.5	GOOD	OK
2.5	3765.8	17109.9	33259.2	33259.2	GOOD	OK
2	4707.2	21387.4	33259.2	33259.2	GOOD	OK
1.5	6276.3	28516.5	33259.2	33259.2	GOOD	OK

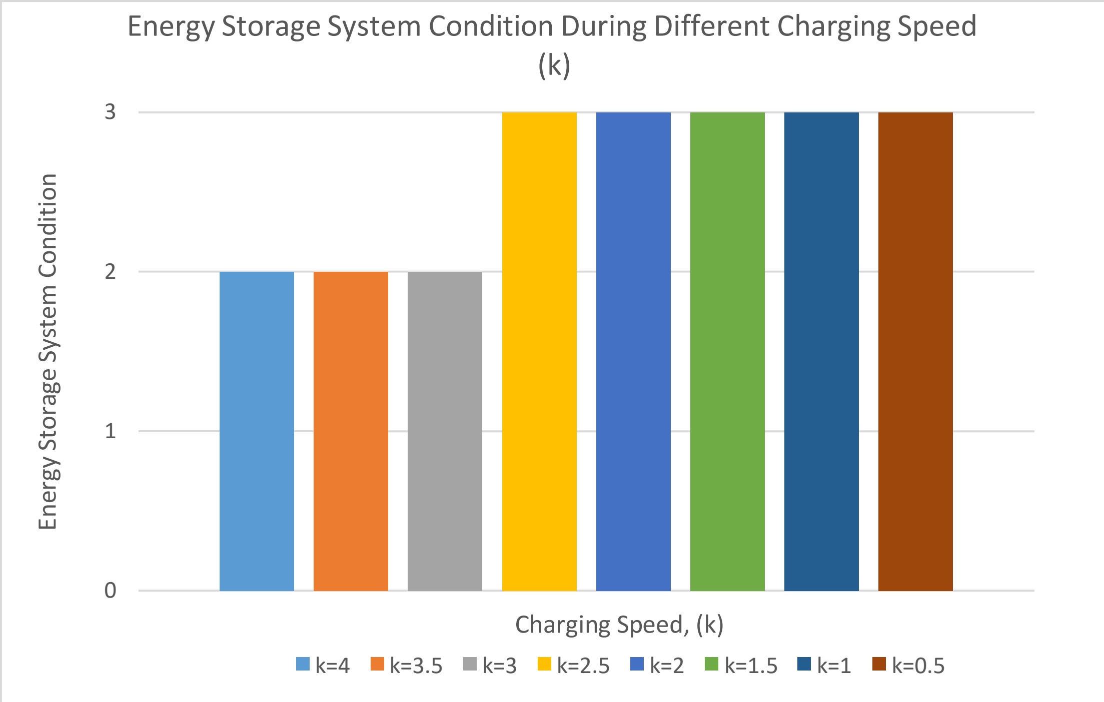

Figure 5-21: Overall Energy Storage System Condition During Different Charging Speed (k) for Annual Case

Legend:
"0" is represent cut off condition for energy storage system (when energy storage capacity less than 6651.85Wh).
"1" is represent the stored energy in the battery is less than the daily energy demand (15,225Wh).
"2" is represent the store energy in the battery is more than the daily energy demand (15,226Wh).
"3" is represent the battery system is in 100% capacity condition (100% condition = when energy storage capacity equal to 33259.2Wh).

Figure 5-21 shows the graph of overall energy storage system condition during different charging speed (k) values for annual case. Based on the graph, we observed that the energy storage capacity during all charging speed (k) values for annual case is higher than the required energy demand. It indicated that even charging speed (k) values =4 was proposed and used in the sizing of the PV panels for the system, the energy storage capacity seem to have sufficient battery to support the electricity demand for 2 days over the years.

5.1.4 Discussion on Case Study 1

By comparing the result obtained from daily case, monthly case and annual case with using the same sets of 30-minute values of solar radiation and meteorological parameter, the PV power generation and energy generation were different among all three cases. This is because the result calculated for monthly and annual case is based on average function. The average in the statistical analysis also knows as arithmetic mean. The average value can be influenced by the outliers. The outliers can be known as unusual value that is different from other data point which can cause problems in statistical analysis. In this research project, the accuracy of the output generated from monthly and annual case will lower than output generated from daily case. Therefore, suitable proposed charging speed should choose based on the result generated from daily case so that the standalone PV system can deliver the optimum performance and efficiency.

For case study 1, charging speed (k) value = 1.5 was selected and proposed in the sizing of the PV panels for the off-grid PV system. Because PV capacity with the charging speed (k) values = 1.5 meet the criteria where the battery for the PV capacity enough for covering 2 days of autonomy. Based on the result generated from the design when charging speed (k) values =1.5, it proven that the energy storage capacity on everyday can be backup 1 days of the energy demand. Charging speed (k) value = 1.5 is suitable for a PV capacity that required to support the electricity demand for hospital that located in rural area and data center. Because, those application is crucial and required 100% availability of the electricity for every day. They cannot afford any downtime or any interruption of the electricity supply.

If for those application that does not required high reliability of the electricity supply or rely on generator such as housing or school, then charging speed (k) value =2 can be choose in the sizing of the PV panels. Because low energy storage capacity only happens at few days in December. Thus, there is not a major challenge to have the reliable power supply along the years.

5.2 Case Study 2: Number of Autonomy Days Required = 3 Days

For case study 2, PV system capacity and battery capacity were design to supply energy demand for 3 autonomy days. Different charging speed (k) values were used in the appropriate sizing of PV array to yield a reliable electricity supply. If proposed energy storage capacity in the PV system exceeded 2 days of the energy demand, then the proposed PV capacity consider good and can be used to supply electricity demand for 3 autonomy days. The proposed charging speed (k) value for a PV capacity also will selected because it can ensure at least the off –grid PV system have enough battery capacity to support electricity demand for 3 autonomy days. The proposed PV capacity also determined by using annual, monthly and daily info as it will have discrepancies in the results between the annual, monthly and daily case.

5.2.1 Daily Case

Table 5-14: Daily Energy Generation in January during k=4

Date	PV Power Generation (W)	Energy Generation (Wh)	Initial Battery Energy (Wh)	Balance Energy (Wh)	Remark	Battery System Condition
1/1/2021	3604.0	9929.0	51168	45871.0	GOOD	OK

2/1/2021	3644.6	5977.2	45871.0	36622.2	GOOD	OK
3/1/2021	3702.1	2182.4	36622.2	23578.6	BAD	OK
4/1/2021	3628.7	7886.9	23578.6	16239.6	BAD	OK
5/1/2021	3494.0	20960.6	16239.6	21974.1	BAD	OK
6/1/2021	3626.2	8505.2	21974.1	15253.3	BAD	OK
7/1/2021	3604.0	9772.4	15253.3	9799.7	BAD	CUT OFF
8/1/2021	3559.6	12718.6	0.0	0.0	BAD	CUT OFF
9/1/2021	3619.6	7079.8	0.0	0.0	BAD	CUT OFF
10/1/2021	3597.9	9969.7	0.0	0.0	BAD	CUT OFF
11/1/2021	3555.9	15300.9	0.0	74.9	BAD	CUT OFF
12/1/2021	3592.3	10243.5	0.0	0.0	BAD	CUT OFF
13/1/2021	3565.2	13934.7	0.0	0.0	BAD	CUT OFF
14/1/2021	3557.5	14820.6	0.0	0.0	BAD	CUT OFF
15/1/2021	3520.9	17377.6	0.0	2151.6	BAD	CUT OFF
16/1/2021	3505.7	18499.4	0.0	3273.4	BAD	CUT OFF
17/1/2021	3513.6	17055.1	0.0	1829.1	BAD	CUT OFF
18/1/2021	3555.2	14475.0	0.0	0.0	BAD	CUT OFF
19/1/2021	3525.7	18157.5	0.0	2931.5	BAD	CUT OFF
20/1/2021	3563.5	12687.7	0.0	0.0	BAD	CUT OFF
21/1/2021	3557.6	14079.4	0.0	0.0	BAD	CUT OFF
22/1/2021	3592.1	11132.0	0.0	0.0	BAD	CUT OFF
23/1/2021	3601.0	10169.3	0.0	0.0	BAD	CUT OFF
24/1/2021	3514.4	17698.5	0.0	2472.5	BAD	CUT OFF
25/1/2021	3512.0	18752.4	0.0	3526.4	BAD	CUT OFF
26/1/2021	3484.5	21165.1	0.0	5939.1	BAD	CUT OFF
27/1/2021	3538.9	15843.8	0.0	617.8	BAD	CUT OFF
28/1/2021	3522.3	18199.6	0.0	2973.6	BAD	CUT OFF
29/1/2021	3502.3	20201.2	0.0	4975.2	BAD	CUT OFF
30/1/2021	3466.4	23393.3	0.0	8167.3	BAD	CUT OFF
31/1/2021	3483.3	21737.4	0.0	6511.4	BAD	CUT OFF

Table 5-15: Daily Energy Generation in January during k=3.5

Date	PV Power Generation (W)	Energy Generation (Wh)	Initial Battery Energy (Wh)	Balance Energy (Wh)	Remark	Battery System Condition
1/1/2021	4118.9	11347.5	51168	47289.5	GOOD	OK
2/1/2021	4165.3	6831.0	47289.5	38894.5	GOOD	OK
3/1/2021	4231.0	2494.2	38894.5	26162.7	BAD	OK
4/1/2021	4147.1	9013.7	26162.7	19950.3	BAD	OK
5/1/2021	3993.2	23954.9	19950.3	28679.3	BAD	OK
6/1/2021	4144.2	9720.2	28679.3	23173.5	BAD	OK
7/1/2021	4118.9	11168.4	23173.5	19115.9	BAD	OK
8/1/2021	4068.2	14535.5	19115.9	18425.4	BAD	OK
9/1/2021	4136.6	8091.2	18425.4	11290.7	BAD	OK
10/1/2021	4111.9	11394.0	11290.7	7458.7	BAD	CUT OFF
11/1/2021	4063.9	17486.8	0.0	2260.8	BAD	CUT OFF
12/1/2021	4105.5	11706.8	0.0	0.0	BAD	CUT OFF

13/1/2021	4074.6	15925.4	0.0	699.4	BAD	CUT OFF
14/1/2021	4065.7	16937.8	0.0	1711.8	BAD	CUT OFF
15/1/2021	4023.9	19860.1	0.0	4634.1	BAD	CUT OFF
16/1/2021	4006.5	21142.2	0.0	5916.2	BAD	CUT OFF
17/1/2021	4015.6	19491.5	0.0	4265.5	BAD	CUT OFF
18/1/2021	4063.1	16542.8	0.0	1316.8	BAD	CUT OFF
19/1/2021	4029.4	20751.4	0.0	5525.4	BAD	CUT OFF
20/1/2021	4072.5	14500.3	0.0	0.0	BAD	CUT OFF
21/1/2021	4065.9	16090.7	0.0	864.7	BAD	CUT OFF
22/1/2021	4105.3	12722.2	0.0	0.0	BAD	CUT OFF
23/1/2021	4115.5	11622.1	0.0	0.0	BAD	CUT OFF
24/1/2021	4016.4	20226.8	0.0	5000.8	BAD	CUT OFF
25/1/2021	4013.7	21431.3	0.0	6205.3	BAD	CUT OFF
26/1/2021	3982.3	24188.7	0.0	8962.7	BAD	CUT OFF
27/1/2021	4044.5	18107.2	0.0	2881.2	BAD	CUT OFF
28/1/2021	4025.5	20799.5	0.0	5573.5	BAD	CUT OFF
29/1/2021	4002.6	23087.1	0.0	7861.1	BAD	CUT OFF
30/1/2021	3961.7	26735.2	0.0	11509.2	BAD	OK
31/1/2021	3980.9	24842.7	11509.2	21125.9	BAD	OK

Table 5-16: Daily Energy Generation in January during k=3

Date	PV Power Generation (W)	Energy Generation (Wh)	Initial Battery Energy (Wh)	Balance Energy (Wh)	Remark	Battery System Condition
1/1/2021	4805.3	13238.7	51168	49180.7	GOOD	OK
2/1/2021	4859.5	7969.6	49180.7	41924.3	GOOD	OK
3/1/2021	4936.2	2909.9	41924.3	29608.1	BAD	OK
4/1/2021	4838.2	10515.9	29608.1	24898.1	BAD	OK
5/1/2021	4658.7	27947.4	24898.1	37619.5	GOOD	OK
6/1/2021	4834.9	11340.3	37619.5	33733.8	GOOD	OK
7/1/2021	4805.4	13029.8	33733.8	31537.6	GOOD	OK
8/1/2021	4746.2	16958.1	31537.6	33269.7	GOOD	OK
9/1/2021	4826.1	9439.8	33269.7	27483.5	BAD	OK
10/1/2021	4797.2	13293.0	27483.5	25550.4	BAD	OK
11/1/2021	4741.2	20401.2	25550.4	30725.7	GOOD	OK
12/1/2021	4789.8	13658.0	30725.7	29157.7	BAD	OK
13/1/2021	4753.7	18579.6	29157.7	32511.3	GOOD	OK
14/1/2021	4743.3	19760.8	32511.3	37046.1	GOOD	OK
15/1/2021	4694.6	23170.2	37046.1	44990.3	GOOD	OK
16/1/2021	4674.2	24665.8	44990.3	51168.0	GOOD	OK
17/1/2021	4684.8	22740.1	51168.0	51168.0	GOOD	OK
18/1/2021	4740.3	19300.0	51168.0	51168.0	GOOD	OK
19/1/2021	4701.0	24210.0	51168.0	51168.0	GOOD	OK
20/1/2021	4751.3	16917.0	51168.0	51168.0	GOOD	OK
21/1/2021	4743.5	18772.5	51168.0	51168.0	GOOD	OK

22/1/2021	4789.5	14842.6	51168.0	50784.6	GOOD	OK
23/1/2021	4801.4	13559.1	50784.6	49117.7	GOOD	OK
24/1/2021	4685.9	23597.9	49117.7	51168.0	GOOD	OK
25/1/2021	4682.7	25003.2	51168.0	51168.0	GOOD	OK
26/1/2021	4646.1	28220.2	51168.0	51168.0	GOOD	OK
27/1/2021	4718.6	21125.0	51168.0	51168.0	GOOD	OK
28/1/2021	4696.4	24266.1	51168.0	51168.0	GOOD	OK
29/1/2021	4669.7	26935.0	51168.0	51168.0	GOOD	OK
30/1/2021	4621.9	31191.1	51168.0	51168.0	GOOD	OK
31/1/2021	4644.4	28983.2	51168.0	51168.0	GOOD	OK

Table 5-17: Daily Energy Generation in January during k=2.5

Date	PV Power Generation (W)	Energy Generation (Wh)	Initial Battery Energy (Wh)	Balance Energy (Wh)	Remark	Battery System Condition
1/1/2021	5766.4	15886.5	51168	51168.0	GOOD	OK
2/1/2021	5831.4	9563.5	51168.0	45505.5	GOOD	OK
3/1/2021	5923.4	3491.8	45505.5	33771.3	GOOD	OK
4/1/2021	5805.9	12619.1	33771.3	31164.4	GOOD	OK
5/1/2021	5590.4	33536.9	31164.4	49475.4	GOOD	OK
6/1/2021	5801.9	13608.3	49475.4	47857.7	GOOD	OK
7/1/2021	5766.5	15635.8	47857.7	48267.4	GOOD	OK
8/1/2021	5695.4	20349.7	48267.4	51168.0	GOOD	OK
9/1/2021	5791.3	11327.7	51168.0	47269.7	GOOD	OK
10/1/2021	5756.6	15951.5	47269.7	47995.3	GOOD	OK
11/1/2021	5689.4	24481.5	47995.3	51168.0	GOOD	OK
12/1/2021	5747.7	16389.6	51168.0	51168.0	GOOD	OK
13/1/2021	5704.4	22295.6	51168.0	51168.0	GOOD	OK
14/1/2021	5692.0	23712.9	51168.0	51168.0	GOOD	OK
15/1/2021	5633.5	27804.2	51168.0	51168.0	GOOD	OK
16/1/2021	5609.1	29599.0	51168.0	51168.0	GOOD	OK
17/1/2021	5621.8	27288.1	51168.0	51168.0	GOOD	OK
18/1/2021	5688.3	23160.0	51168.0	51168.0	GOOD	OK
19/1/2021	5641.2	29052.0	51168.0	51168.0	GOOD	OK
20/1/2021	5701.6	20300.4	51168.0	51168.0	GOOD	OK
21/1/2021	5692.2	22527.0	51168.0	51168.0	GOOD	OK
22/1/2021	5747.4	17811.1	51168.0	51168.0	GOOD	OK
23/1/2021	5761.7	16270.9	51168.0	51168.0	GOOD	OK
24/1/2021	5623.0	28317.5	51168.0	51168.0	GOOD	OK
25/1/2021	5619.2	30003.9	51168.0	51168.0	GOOD	OK
26/1/2021	5575.3	33864.2	51168.0	51168.0	GOOD	OK
27/1/2021	5662.3	25350.0	51168.0	51168.0	GOOD	OK
28/1/2021	5635.6	29119.4	51168.0	51168.0	GOOD	OK
29/1/2021	5603.7	32322.0	51168.0	51168.0	GOOD	OK
30/1/2021	5546.3	37429.3	51168.0	51168.0	GOOD	OK
31/1/2021	5573.2	34779.8	51168.0	51168.0	GOOD	OK

Table 5-18: Daily Energy Generation in January during k=2

Date	PV Power Generation (W)	Energy Generation (Wh)	Initial Battery Energy (Wh)	Balance Energy (Wh)	Remark	Battery System Condition
1/1/2021	7208.0	19858.1	51168	51168.0	GOOD	OK
2/1/2021	7289.2	11954.3	51168.0	47896.3	GOOD	OK
3/1/2021	7404.2	4364.8	47896.3	37035.1	GOOD	OK
4/1/2021	7257.4	15773.9	37035.1	37583.0	GOOD	OK
5/1/2021	6988.0	41921.2	37583.0	51168.0	GOOD	OK
6/1/2021	7252.3	17010.4	51168.0	51168.0	GOOD	OK
7/1/2021	7208.1	19544.7	51168.0	51168.0	GOOD	OK
8/1/2021	7119.3	25437.2	51168.0	51168.0	GOOD	OK
9/1/2021	7239.1	14159.7	51168.0	50101.7	GOOD	OK
10/1/2021	7195.8	19939.4	50101.7	51168.0	GOOD	OK
11/1/2021	7111.8	30601.9	51168.0	51168.0	GOOD	OK
12/1/2021	7184.6	20487.0	51168.0	51168.0	GOOD	OK
13/1/2021	7130.5	27869.5	51168.0	51168.0	GOOD	OK
14/1/2021	7115.0	29641.2	51168.0	51168.0	GOOD	OK
15/1/2021	7041.9	34755.3	51168.0	51168.0	GOOD	OK
16/1/2021	7011.3	36998.8	51168.0	51168.0	GOOD	OK
17/1/2021	7027.2	34110.1	51168.0	51168.0	GOOD	OK
18/1/2021	7110.4	28949.9	51168.0	51168.0	GOOD	OK
19/1/2021	7051.5	36315.0	51168.0	51168.0	GOOD	OK
20/1/2021	7126.9	25375.5	51168.0	51168.0	GOOD	OK
21/1/2021	7115.3	28158.7	51168.0	51168.0	GOOD	OK
22/1/2021	7184.2	22263.9	51168.0	51168.0	GOOD	OK
23/1/2021	7202.1	20338.7	51168.0	51168.0	GOOD	OK
24/1/2021	7028.8	35396.9	51168.0	51168.0	GOOD	OK
25/1/2021	7024.0	37504.8	51168.0	51168.0	GOOD	OK
26/1/2021	6969.1	42330.3	51168.0	51168.0	GOOD	OK
27/1/2021	7077.8	31687.5	51168.0	51168.0	GOOD	OK
28/1/2021	7044.6	36399.2	51168.0	51168.0	GOOD	OK
29/1/2021	7004.6	40402.5	51168.0	51168.0	GOOD	OK
30/1/2021	6932.9	46786.6	51168.0	51168.0	GOOD	OK
31/1/2021	6966.5	43474.7	51168.0	51168.0	GOOD	OK

Table 5-19: Daily Energy Generation in January during k=1.5

Date	PV Power Generation (W)	Energy Generation (Wh)	Initial Battery Energy (Wh)	Balance Energy (Wh)	Remark	Battery System Condition
1/1/2021	9610.7	26477.4	51168	51168.0	GOOD	OK
2/1/2021	9719.0	15939.1	51168.0	51168.0	GOOD	OK
3/1/2021	9872.3	5819.7	51168.0	41761.7	GOOD	OK

4/1/2021	9676.5	21031.9	41761.7	47567.6	GOOD	OK
5/1/2021	9317.4	55894.9	47567.6	51168.0	GOOD	OK
6/1/2021	9669.8	22680.5	51168.0	51168.0	GOOD	OK
7/1/2021	9610.8	26059.6	51168.0	51168.0	GOOD	OK
8/1/2021	9492.4	33916.2	51168.0	51168.0	GOOD	OK
9/1/2021	9652.1	18879.6	51168.0	51168.0	GOOD	OK
10/1/2021	9594.3	26585.9	51168.0	51168.0	GOOD	OK
11/1/2021	9482.3	40802.5	51168.0	51168.0	GOOD	OK
12/1/2021	9579.5	27316.0	51168.0	51168.0	GOOD	OK
13/1/2021	9507.3	37159.3	51168.0	51168.0	GOOD	OK
14/1/2021	9486.7	39521.6	51168.0	51168.0	GOOD	OK
15/1/2021	9389.2	46340.3	51168.0	51168.0	GOOD	OK
16/1/2021	9348.4	49331.7	51168.0	51168.0	GOOD	OK
17/1/2021	9369.6	45480.2	51168.0	51168.0	GOOD	OK
18/1/2021	9480.5	38599.9	51168.0	51168.0	GOOD	OK
19/1/2021	9401.9	48420.0	51168.0	51168.0	GOOD	OK
20/1/2021	9502.6	33834.0	51168.0	51168.0	GOOD	OK
21/1/2021	9487.0	37545.0	51168.0	51168.0	GOOD	OK
22/1/2021	9579.0	29685.2	51168.0	51168.0	GOOD	OK
23/1/2021	9602.8	27118.2	51168.0	51168.0	GOOD	OK
24/1/2021	9371.7	47195.9	51168.0	51168.0	GOOD	OK
25/1/2021	9365.4	50006.5	51168.0	51168.0	GOOD	OK
26/1/2021	9292.1	56440.4	51168.0	51168.0	GOOD	OK
27/1/2021	9437.1	42250.0	51168.0	51168.0	GOOD	OK
28/1/2021	9392.7	48532.3	51168.0	51168.0	GOOD	OK
29/1/2021	9339.4	53869.9	51168.0	51168.0	GOOD	OK
30/1/2021	9243.9	62382.2	51168.0	51168.0	GOOD	OK
31/1/2021	9288.7	57966.3	51168.0	51168.0	GOOD	OK

Table 5-14 to Table 5-19 shows the result of daily energy generation for January during different charging speed (k) values.

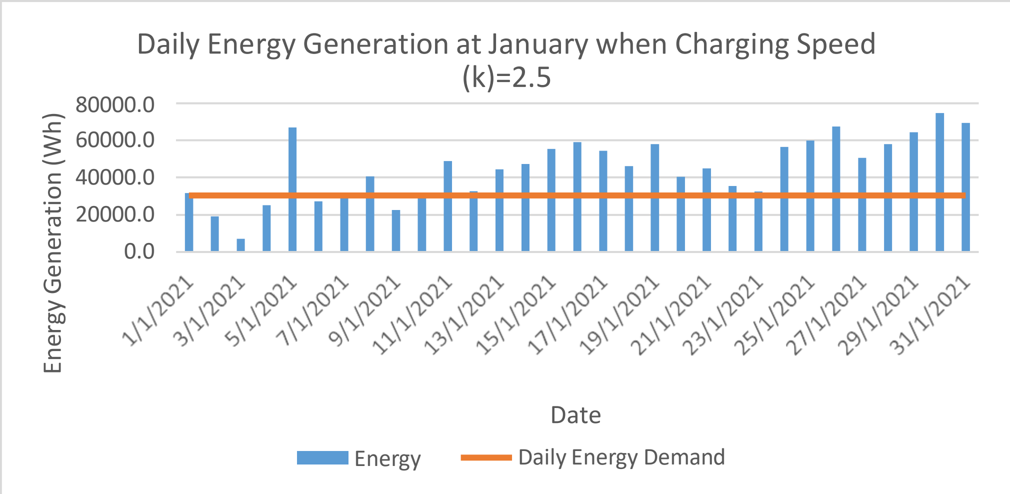

Figure 5-22:Daily Energy Generation in January during Charging Speed (k)=2.5

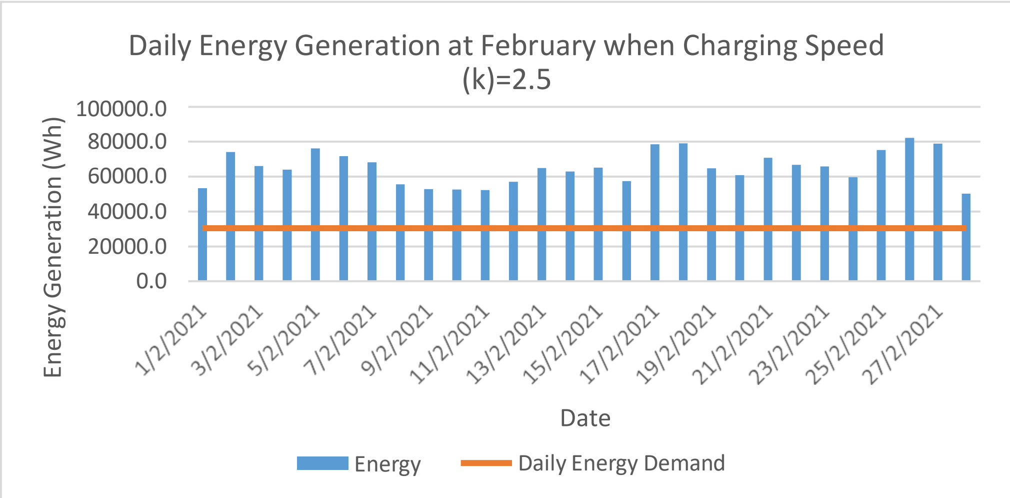

Figure 5-23:Daily Energy Generation in February during Charging Speed (k)=2.5

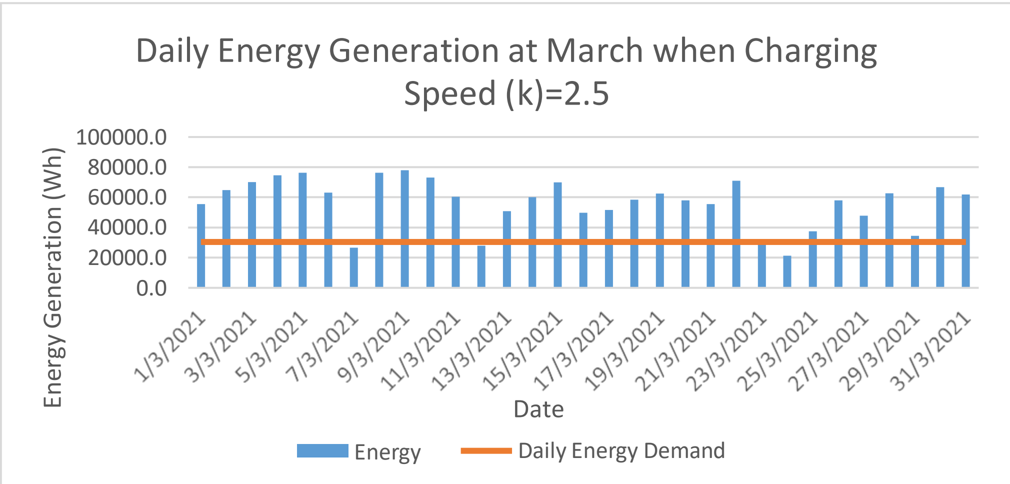

Figure 5-24:Daily Energy Generation in March during Charging Speed (k)=2.5

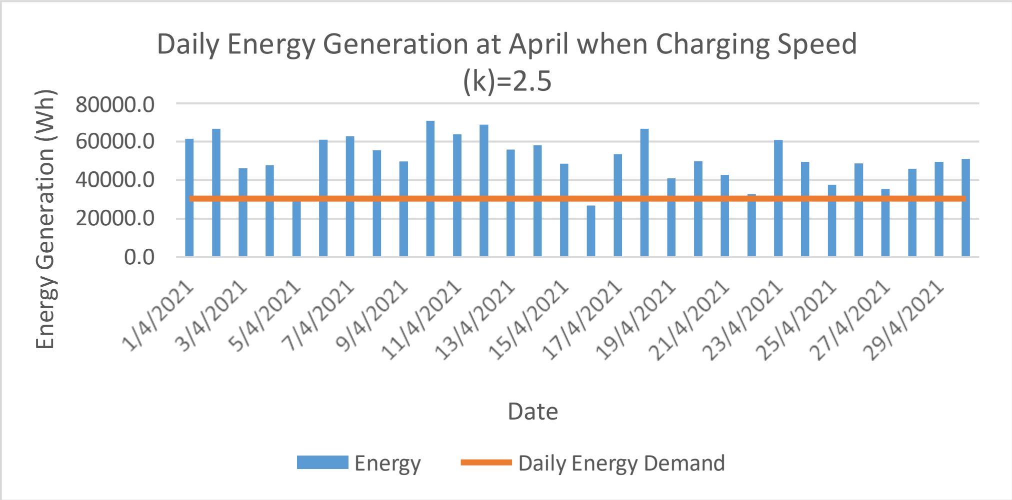

Figure 5-25:Daily Energy Generation in April during Charging Speed (k)=2.5

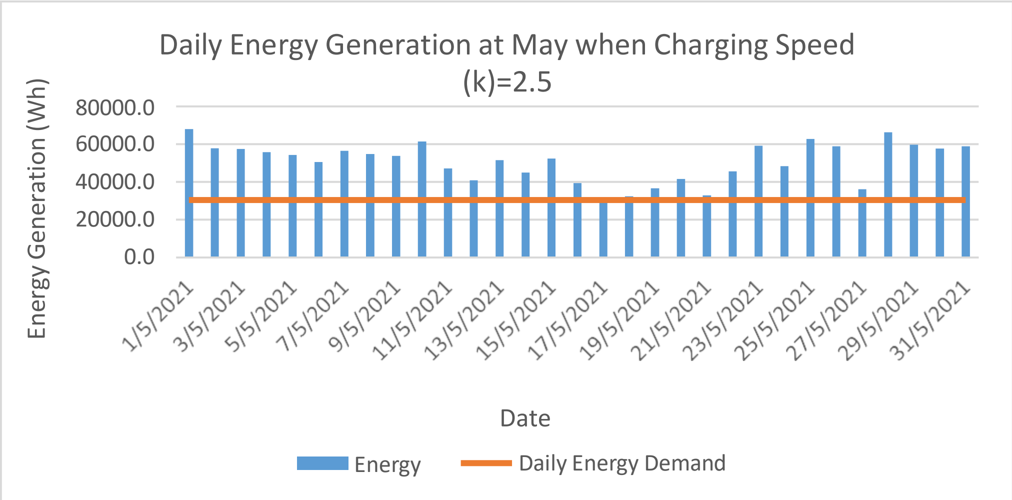

Figure 5-26:Daily Energy Generation in May during Charging Speed (k)=2.5

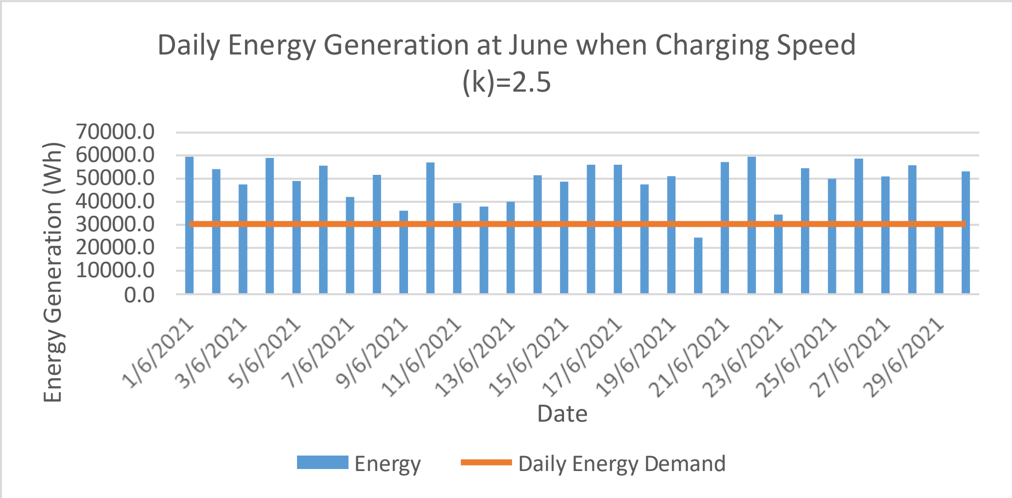

Figure 5-27:Daily Energy Generation in June during Charging Speed (k)=2.5

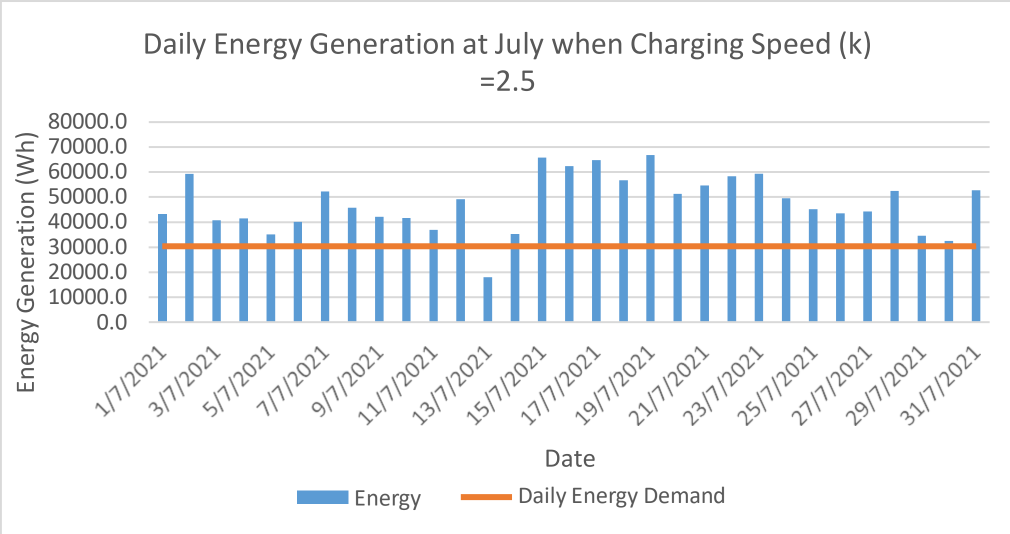

Figure 5-28:Daily Energy Generation in July during Charging Speed (k)=2.5

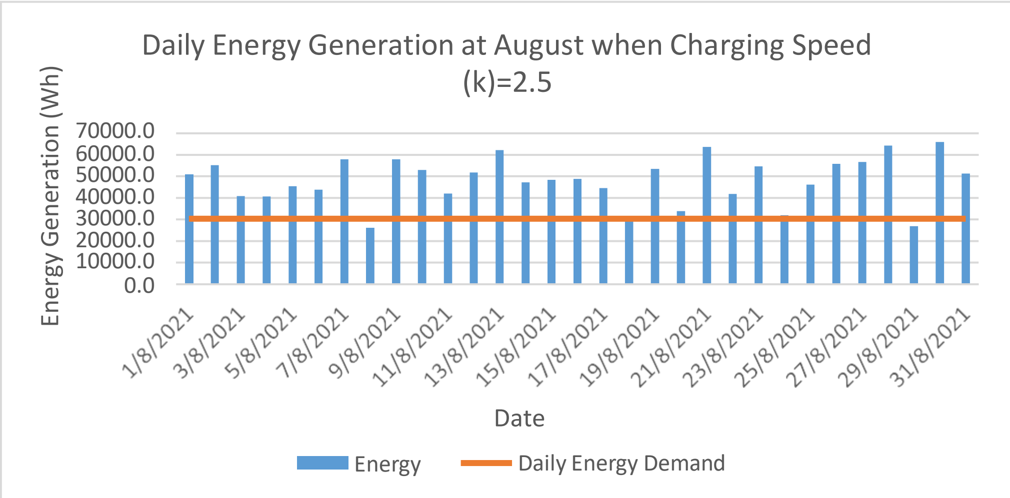

Figure 5-29: Daily Energy Generation in August during Charging Speed (k)=2.5

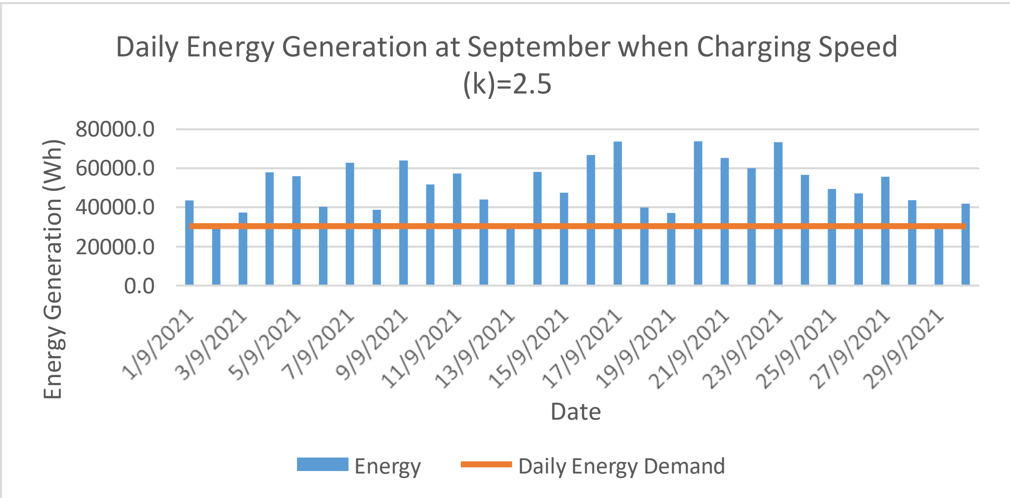

Figure 5-30:Daily Energy Generation in September during Charging Speed (k)=2.5

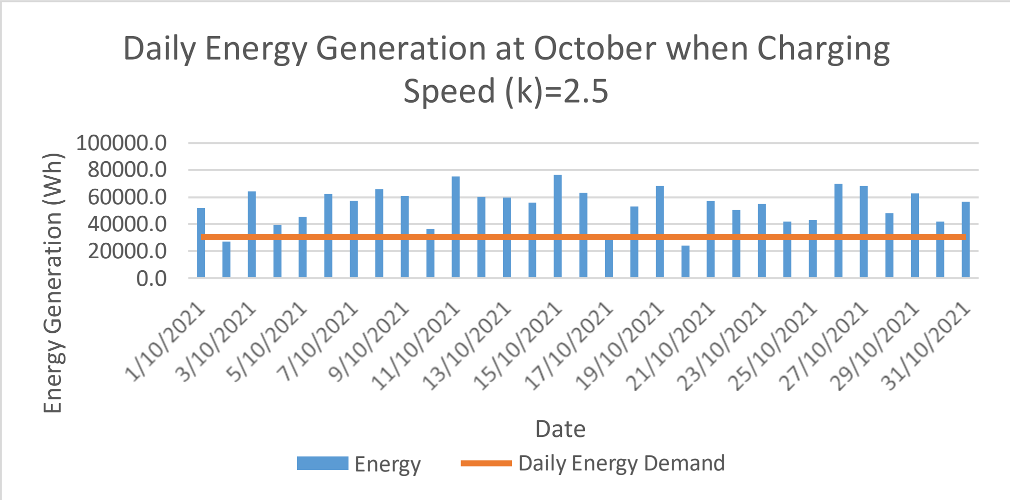

Figure 5-31:Daily Energy Generation in October during Charging Speed (k)=2.5

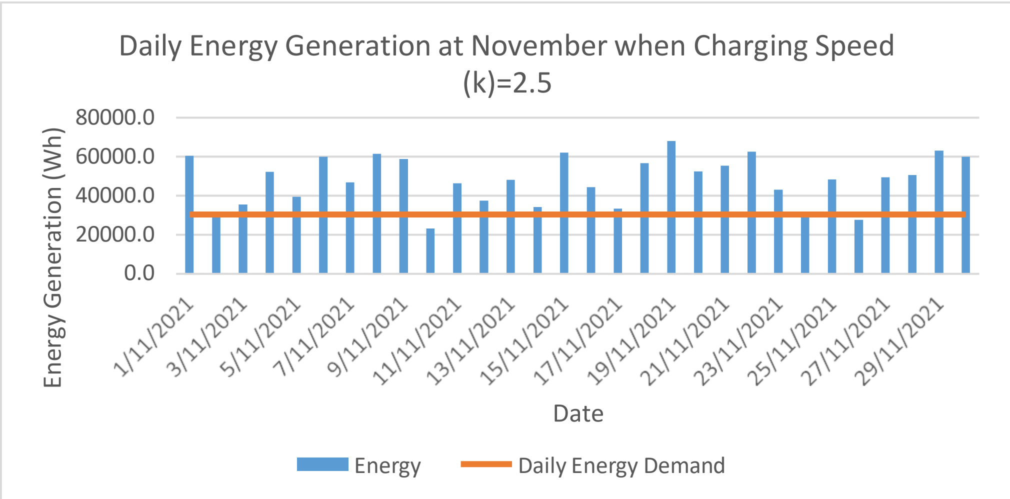

Figure 5-32:Daily Energy Generation in November during Charging Speed (k)=2.5

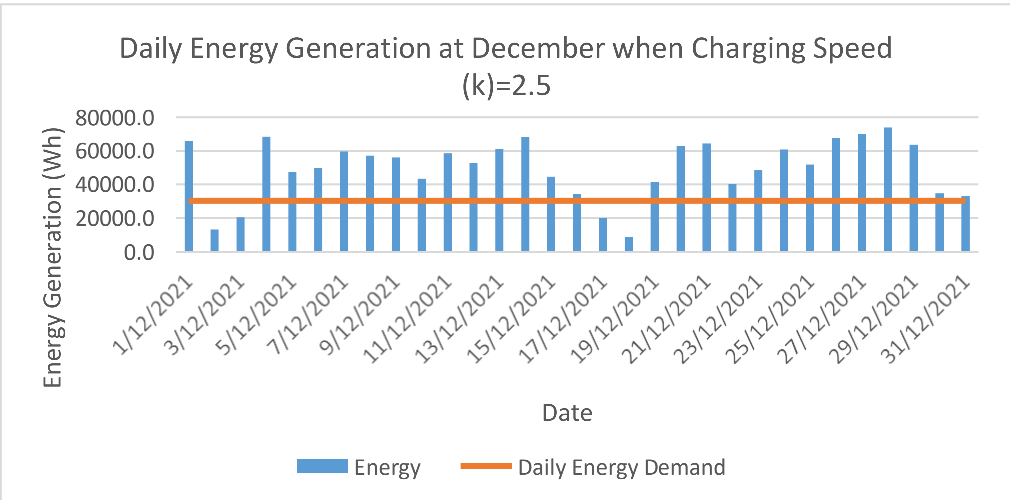

Figure 5-33:Daily Energy Generation in December during Charging Speed (k)=2.5

Figure 5-22 to Figure 5-33 shows the different graph of daily energy generation during charging speed (k) values =2.5 . All the graph shows in Figure 5-22 to Figure 5-33 was plotted based on the daily energy generation for all 365 days.

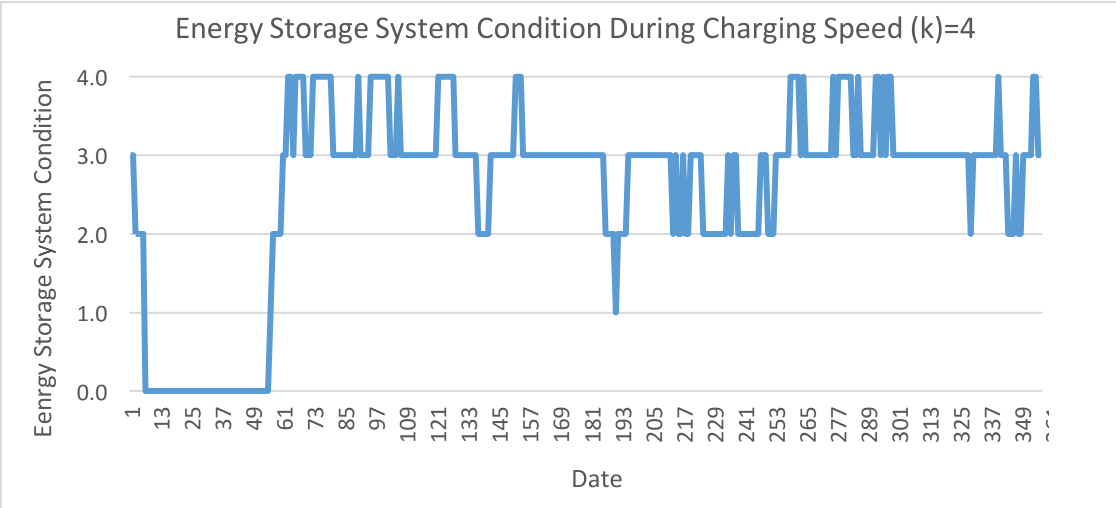

Figure 5-34:Graph of Energy Storage System Condition during Charging Speed (k)=4

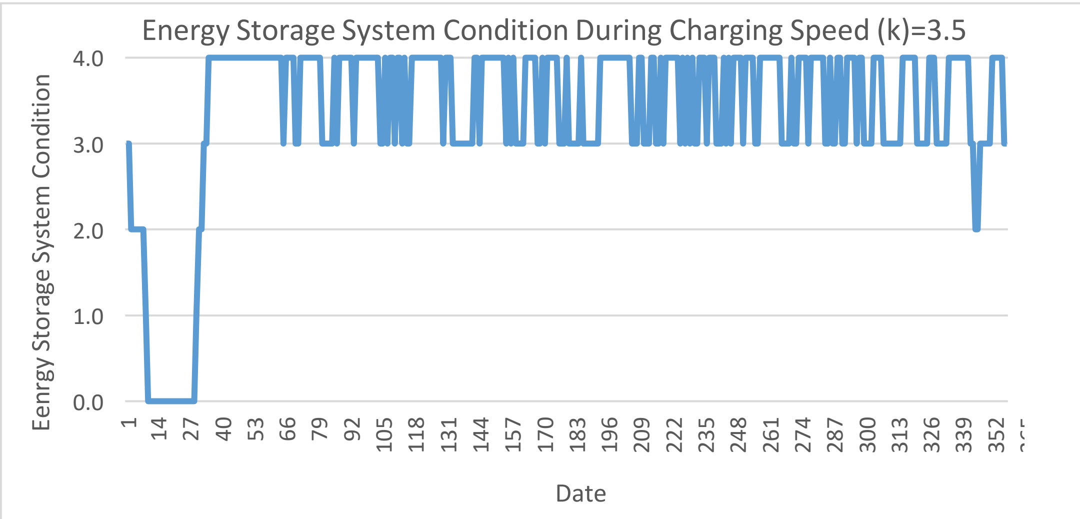

Figure 5-35:Graph of Energy Storage System Condition during Charging Speed (k)=3.5

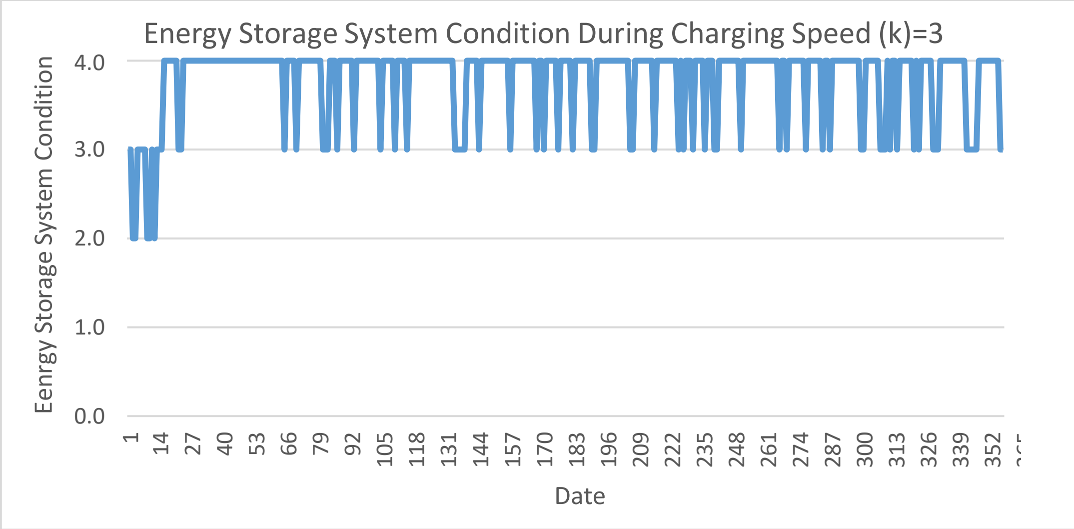

Figure 5-36:Graph of Energy Storage System Condition during Charging Speed (k)=3

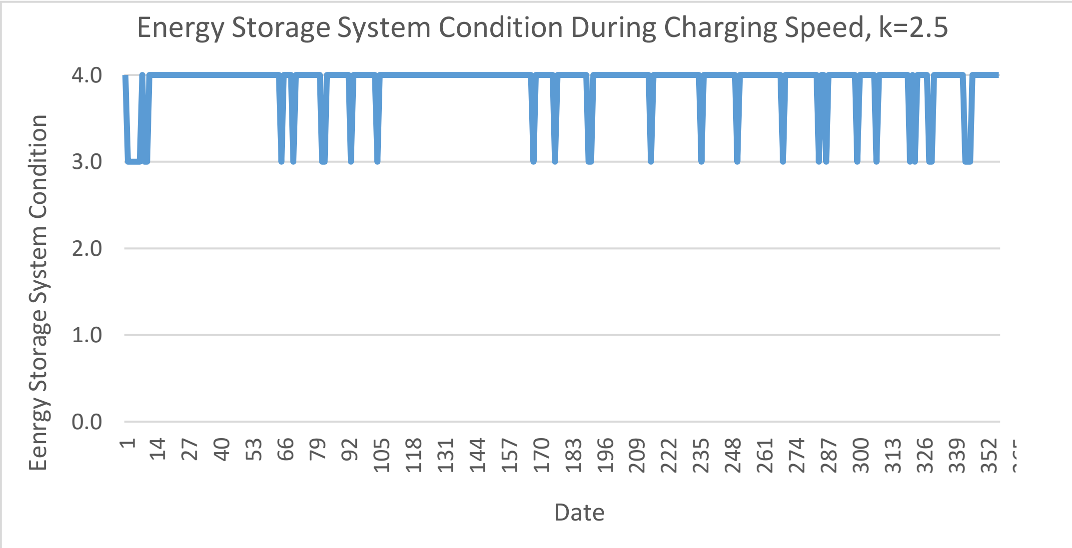

Figure 5-37:Graph of Energy Storage System Condition during Charging Speed (k)=2.5

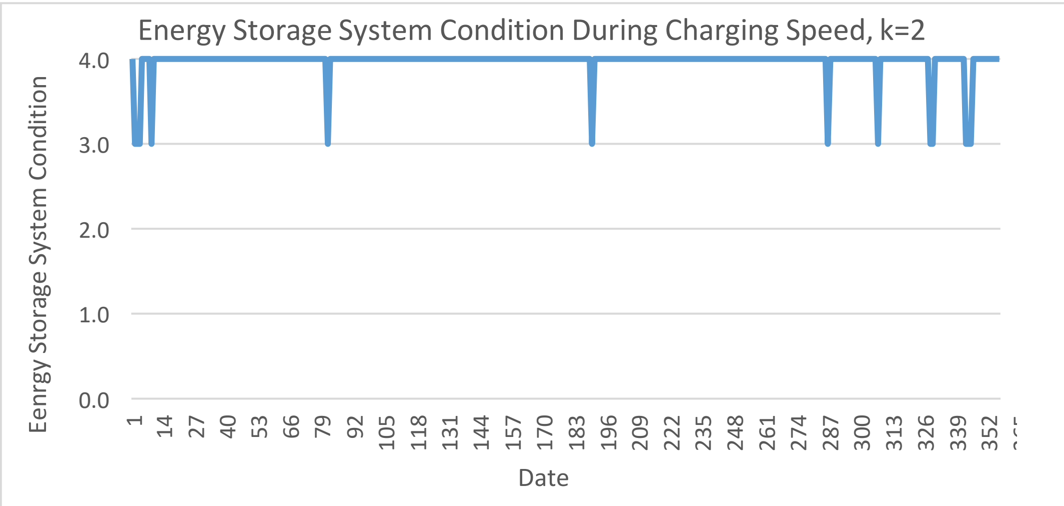

Figure 5-38:Graph of Energy Storage System Condition during Charging Speed (k)=2

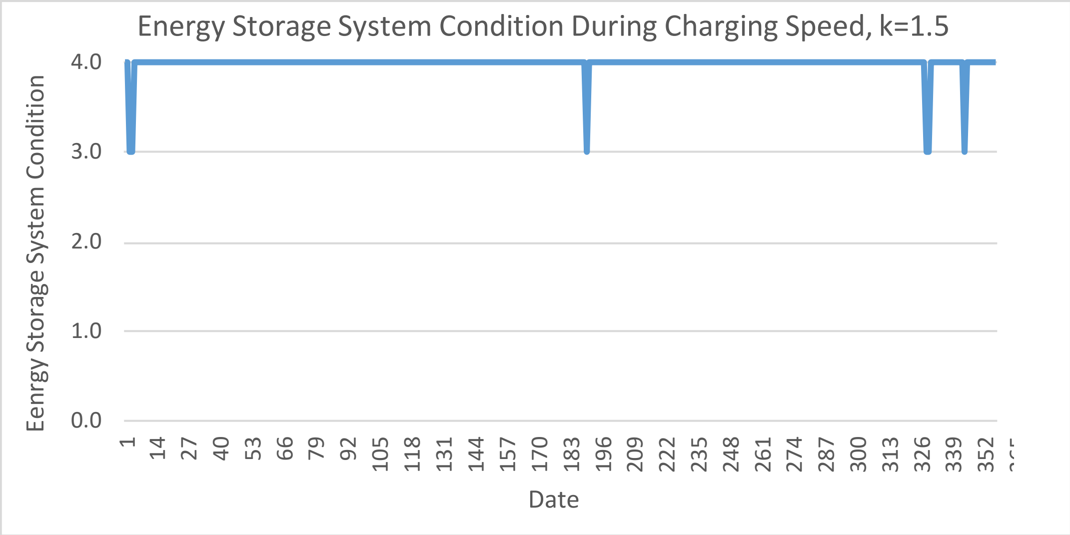

Figure 5-39:Graph of Energy Storage System Condition during Charging Speed (k)=1.5

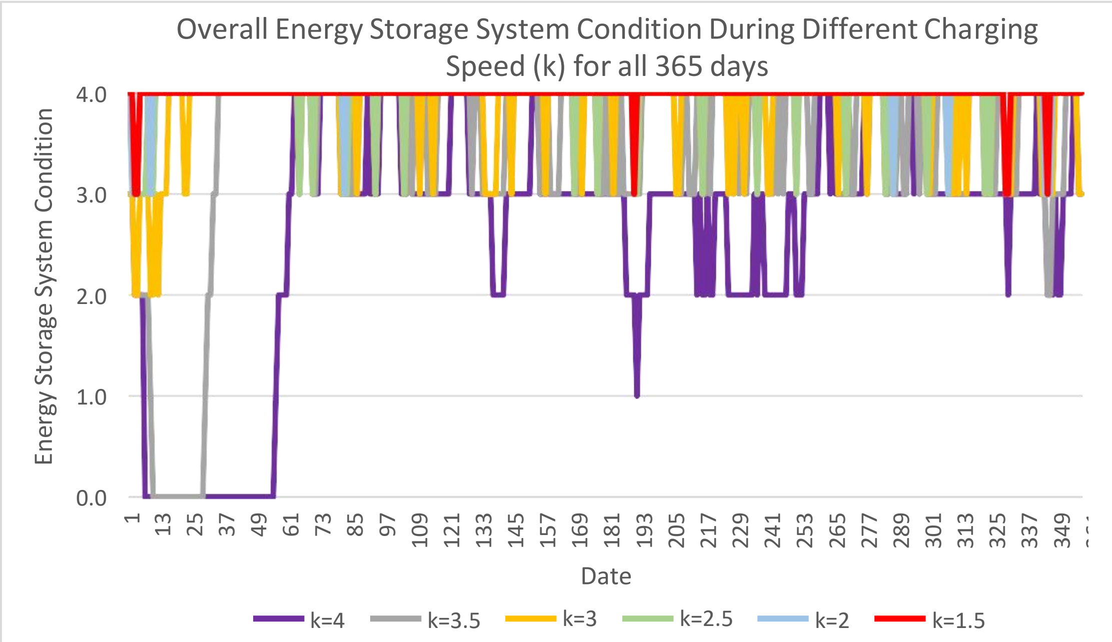

Figure 5-40:Overall Energy Storage System Condition During Different Charging Speed (k) for all 365 days

Legend:
"0" is represent cut off condition for energy storage system (when energy storage capacity less than 10,233.6Wh).
"1" is represent the stored energy in the battery is less than the daily energy demand (15,225Wh).
"2" is represent the store energy in the battery is more than the 1 day's energy demand (15,226Wh) but less than 2 days' energy demand (30,452Wh).
"3" is represent the store energy in the battery is more than the 2 day's energy demand (30,452Wh).
"4" is represent the battery system is in 100% capacity condition (100% condition = when energy storage capacity equal to 51,168Wh).

Figure 5-34 to Figure 5-39 show different graph of energy storage system condition during different charging speed (k) value =4. Figure 5-40 shows the graph of overall energy storage system for all 365 days. This graph was the combination of all energy storage system condition during different proposed charging speed.

Based on the graph shown in Figure 5-40, the energy storage capacity for the PV system that able to support the energy demand after subsequent 2 days continuously raining along the years is during charging speed (k) value below 3 which is (k=2.5, 2 & 1.5).

During charging speed (k) values = 3, the battery capacity of the PV system along the year almost more than 2 days of the required energy demand. However, the energy storage capacity for certain period in January only can backup for 1 days of the require energy demand.

During charging speed (k) value = 3.5, only daily energy storage capacity for certain date in December can support 1 days of the load demand. Then, energy storage system is needed to cut off for a certain period in January and February due to the energy storage capacity under the depth of discharge capacity.

For charging speed (k) value =4, energy storage capacity is fluctuating and not constant over the years. Thus, it cannot guarantee a reliable power output generated from the battery system.

Lastly, energy storage capacity during charging speed (k) values = 2.5 is enough used for backup energy demand for 2 days. The energy storage system condition for all 365 days show in Figure 5-31 was plotted between level 3 and level 4. It represents that the energy storage capacity for everyday along the year can support energy demand for 2 days and the battery system is almost in fully charged condition for each days. Thus, PV system design with charging speed (k) values =2.5 can ensure a continuous electricity supply to the load despite continuously raining for 2 days due to the PV system have enough battery for covering 3 days of autonomy.

5.2.2 Monthly Case

The PV capacity in the monthly case was calculated based on monthly info. The monthly average PV energy generation and energy storage capacity was determined and tabulated in the table form. The condition of the battery system and PV system for each month shows in the table. Table 5-20 to Table 5-25 shows the result of monthly average energy generation during different proposed charging speed (k).

Table 5-20: Monthly Energy Generation during Charging Speed (k) =4

Date	PV Power Generation (W)	Energy Generation (Wh)	Initial Battery Energy (Wh)	Balance Energy (Wh)	Remark	Battery System Condition
Jan	3558.4	14270.7	51168	50212.7	GOOD	OK
Feb	3476.9	20483.5	50212.7	51168.0	GOOD	OK
Mar	3510.3	17836.0	51168.0	51168.0	GOOD	OK
Apr	3532.2	15603.2	51168.0	51168.0	GOOD	OK
May	3529.9	15932.0	51168.0	51168.0	GOOD	OK
June	3537.6	15363.5	51168.0	51168.0	GOOD	OK
July	3542.7	14964.7	51168.0	50906.7	GOOD	OK
Aug	3549.1	14645.6	50906.7	50326.4	GOOD	OK
Sep	3536.1	16092.7	50326.4	51168.0	GOOD	OK
Oct	3512.4	16935.5	51168.0	51168.0	GOOD	OK
Nov	3540.0	15117.9	51168.0	51059.9	GOOD	OK
Dec	3540.0	15010.7	51059.9	50844.5	GOOD	OK

Table 5-21: Monthly Energy Generation during Charging Speed (k) =3.5

Date	PV Power Generation (W)	Energy Generation (Wh)	Initial Battery Energy (Wh)	Balance Energy (Wh)	Remark	Battery System Condition

Jan	4066.8	16309.4	51168	51168.0	GOOD	OK
Feb	3973.6	23409.7	51168.0	51168.0	GOOD	OK
Mar	4011.8	20384.0	51168.0	51168.0	GOOD	OK
Apr	4036.8	17832.3	51168.0	51168.0	GOOD	OK
May	4034.1	18208.0	51168.0	51168.0	GOOD	OK
June	4043.0	17558.3	51168.0	51168.0	GOOD	OK
July	4048.7	17102.6	51168.0	51168.0	GOOD	OK
Aug	4056.1	16737.9	51168.0	51168.0	GOOD	OK
Sep	4041.3	18391.7	51168.0	51168.0	GOOD	OK
Oct	4014.2	19354.8	51168.0	51168.0	GOOD	OK
Nov	4045.7	17277.5	51168.0	51168.0	GOOD	OK
Dec	4045.4	17153.8	51168.0	51168.0	GOOD	OK

Table 5-22: Monthly Energy Generation during Charging Speed (k) =3

Date	PV Power Generation (W)	Energy Generation (Wh)	Initial Battery Energy (Wh)	Balance Energy (Wh)	Remark	Battery System Condition
Jan	4744.6	19027.6	51168	51168.0	GOOD	OK
Feb	4635.8	27311.3	51168.0	51168.0	GOOD	OK
Mar	4680.4	23781.3	51168.0	51168.0	GOOD	OK
Apr	4709.6	20804.3	51168.0	51168.0	GOOD	OK
May	4706.5	21242.7	51168.0	51168.0	GOOD	OK
June	4716.8	20484.6	51168.0	51168.0	GOOD	OK
July	4723.5	19953.0	51168.0	51168.0	GOOD	OK
Aug	4732.1	19527.5	51168.0	51168.0	GOOD	OK
Sep	4714.8	21457.0	51168.0	51168.0	GOOD	OK
Oct	4683.2	22580.6	51168.0	51168.0	GOOD	OK
Nov	4720.0	20157.1	51168.0	51168.0	GOOD	OK
Dec	4719.6	20012.8	51168.0	51168.0	GOOD	OK

Table 5-23: Monthly Energy Generation during Charging Speed (k) =2.5

Date	PV Power Generation (W)	Energy Generation (Wh)	Initial Battery Energy (Wh)	Balance Energy (Wh)	Remark	Battery System Condition
Jan	5693.5	22833.2	51168	51168.0	GOOD	OK
Feb	5563.0	32773.6	51168.0	51168.0	GOOD	OK
Mar	5616.5	28537.6	51168.0	51168.0	GOOD	OK
Apr	5651.5	24965.2	51168.0	51168.0	GOOD	OK
May	5647.8	25491.2	51168.0	51168.0	GOOD	OK
June	5660.2	24581.6	51168.0	51168.0	GOOD	OK
July	5668.2	23943.6	51168.0	51168.0	GOOD	OK
Aug	5678.6	23433.0	51168.0	51168.0	GOOD	OK
Sep	5657.8	25748.3	51168.0	51168.0	GOOD	OK
Oct	5619.8	27096.8	51168.0	51168.0	GOOD	OK

Nov	5664.0	24188.6	51168.0	51168.0	GOOD	OK
Dec	5663.5	24015.3	51168.0	51168.0	GOOD	OK

Table 5-24: Monthly Energy Generation during Charging Speed (k) =2

Date	PV Power Generation (W)	Energy Generation (Wh)	Initial Battery Energy (Wh)	Balance Energy (Wh)	Remark	Battery System Condition
Jan	7116.9	28541.5	51168	51168.0	GOOD	OK
Feb	6953.7	40967.0	51168.0	51168.0	GOOD	OK
Mar	7020.6	35672.0	51168.0	51168.0	GOOD	OK
Apr	7064.4	31206.4	51168.0	51168.0	GOOD	OK
May	7059.7	31864.0	51168.0	51168.0	GOOD	OK
June	7075.2	30727.0	51168.0	51168.0	GOOD	OK
July	7085.3	29929.5	51168.0	51168.0	GOOD	OK
Aug	7098.2	29291.3	51168.0	51168.0	GOOD	OK
Sep	7072.2	32185.4	51168.0	51168.0	GOOD	OK
Oct	7024.8	33871.0	51168.0	51168.0	GOOD	OK
Nov	7079.9	30235.7	51168.0	51168.0	GOOD	OK
Dec	7079.4	30019.1	51168.0	51168.0	GOOD	OK

Table 5-25: Monthly Energy Generation during Charging Speed (k) =1.5

Date	PV Power Generation (W)	Energy Generation (Wh)	Initial Battery Energy (Wh)	Balance Energy (Wh)	Remark	Battery System Condition
Jan	9489.1	38055.3	51168	51168.0	GOOD	OK
Feb	9271.7	54622.7	51168.0	51168.0	GOOD	OK
Mar	9360.8	47562.7	51168.0	51168.0	GOOD	OK
Apr	9419.2	41608.6	51168.0	51168.0	GOOD	OK
May	9413.0	42485.4	51168.0	51168.0	GOOD	OK
June	9433.7	40969.3	51168.0	51168.0	GOOD	OK
July	9447.1	39906.0	51168.0	51168.0	GOOD	OK
Aug	9464.3	39055.0	51168.0	51168.0	GOOD	OK
Sep	9429.6	42913.9	51168.0	51168.0	GOOD	OK
Oct	9366.4	45161.3	51168.0	51168.0	GOOD	OK
Nov	9439.9	40314.3	51168.0	51168.0	GOOD	OK
Dec	9439.2	40025.5	51168.0	51168.0	GOOD	OK

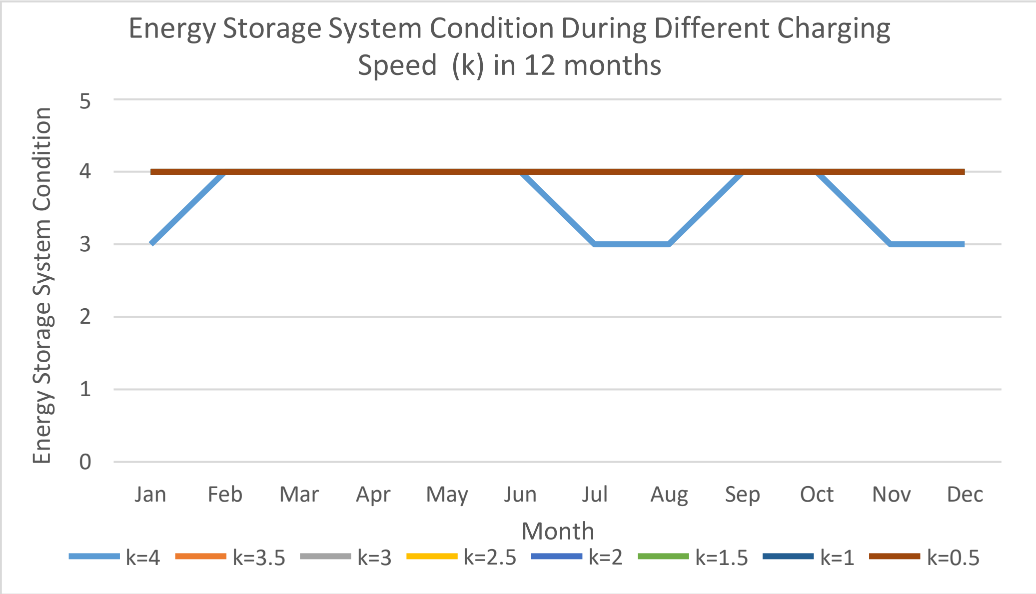

Figure 5-41:Overall Energy Storage System Condition During Different Charging Speed (k) in 12 months

Legend: “0” is represent cut off condition for energy storage system (when energy storage capacity less than 10,233.6Wh). “1” is represent the stored energy in the battery is less than the daily energy demand (15,225Wh). “2” is represent the store energy in the battery is more than the 1 day’s energy demand (15,226Wh) but less than 2 days’ energy demand (30,452Wh). “3” is represent the store energy in the battery is more than the 2 day’s energy demand (30,452Wh). “4” is represent the battery system is in 100% capacity condition (100% condition = when energy storage capacity equal to 51,168Wh).

Figure 5-41 shows the graph of overall energy storage system condition during different proposed charging speed (k) in 12 months. The graph is plotted based on the result obtained from Table 5-20 to Figure 5-25. Based on graph, we observed that the monthly average energy storage capacity during all charging speed (k) values is higher than 2 days of the required energy demand in every month. It means that the all the charging speed (k) values used in the sizing of PV panels for the PV system with have enough battery to support 2 days’ energy demand even though there is low solar irradiation or continuous raining for 2 days.

5.2.3 Annual Case

The PV capacity in the annual case was calculated based on annual info. The annual average PV energy generation and energy storage capacity was determined and tabulated in the table form. The annual condition of the battery system and PV system shows in the table. Table 5-26 shows the result of annual average energy generation during different charging speed (k) values.

Table 5-26: Annual Energy Generation for Different Charging Speed (k)

k	PV Power Generation (W)	Energy Generation (Wh)	Initial Battery Energy (Wh)	Balance Energy (Wh)	Remark	Battery System Condition
4	3530.4	16040.6	51168	51168.0	GOOD	OK
3.5	4034.8	18332.1	51168	51168.0	GOOD	OK
3	4707.2	21387.4	51168	51168.0	GOOD	OK
2.5	5648.7	25664.9	51168	51168.0	GOOD	OK
2	7060.9	32081.1	51168	51168.0	GOOD	OK
1.5	9414.5	42774.8	51168	51168.0	GOOD	OK

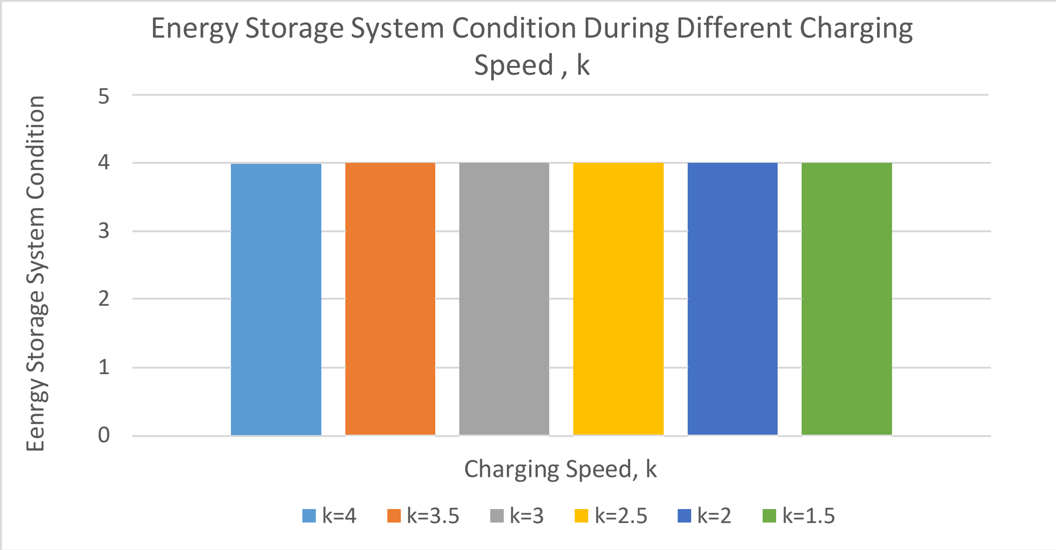

Figure 5-42:Overall Energy Storage System Condition During Different Charging Speed (k) for Annual Case

Legend:
"0" is represent cut off condition for energy storage system (when energy storage capacity less than 10,233.6Wh).
"1" is represent the stored energy in the battery is less than the daily energy demand (15,225Wh).
"2" is represent the store energy in the battery is more than the 1 day's energy demand (15,226Wh) but less than 2 days energy demand (30,452Wh).
"3" is represent the store energy in the battery is more than the 2 day's energy demand (30,452Wh).
"4" is represent the battery system is in 100% capacity condition (100% condition = when energy storage capacity equal to 51,168Wh).

Figure 5-42 shows the overall energy storage system condition during different charging speed (k) values for annual case. Based on the graph, we observed that the energy storage capacity during all different proposed charging speed (k) scenario has more than 2 days of required energy demand for annual case. It means that even using charging speed (k) =4 in the sizing of the PV panels for the PV system, the energy storage capacity is sufficient to supply the energy demand for 2 days when there is no power output from the PV system for consecutive 2 days.

5.2.4 Discussion on Case Study 2

There are discrepancies in the result between daily case, monthly case and annual case. The results show the PV power generation and energy generation will be different among all 3 cases with using the same sets of 30-minute values of solar radiation and meteorological parameter. This is because the result calculated for monthly and annual case is based on average function. The average in the statistical analysis also knows as arithmetic mean. The average value can be influenced by the outliers. The outliers can be known as unusual value that is different from other data point which can cause problems in statistical analysis. In this research project, the output generated from monthly and annual case will less accurate than the output generated from daily case. Therefore, suitable proposed charging speed should choose based on the result generated from daily case to determine the PV capacity so that people won't miss out any days that has issues run out of electricity.

For case study 2, charging speed (k) value= 2.5 was selected and proposed in the sizing of the PV panels for the PV system. Because result generated from the design had proven that the PV system can supply a reliable electricity supply for 3 autonomy days. This result had met the criteria for case study 2 where the PV system required sufficient battery for covering 3 autonomy days. PV system design with charging speed (k) values = 2.5 is suitable for the application such as hospital and data center that required a reliable electricity supply especially located at area that are not grid connectable. They are not allowing downtime happen even single minute because electricity supply is very crucial for them.

If for those application that does not required high reliability of the electricity supply or got the backup generator such as housing or school, then charging speed (k) values =3 can be choose in the simulation of the appropriate size of PV panel. Because low energy storage capacity only occurs 4 consecutive days in January while battery capacity on other days along the year able to support 2 days of energy demand. Therefore, it will not create a major issue to have the reliable and continuous power supply during charging speed (k) value =3 for all 365 days.

CHAPTER 6

6 CONCLUSION

In conclusion, the objectives of this research project were accomplished and achieved. It is important to ensure the amount of energy generation to meet the required energy demand in designing the standalone photovoltaic system. Various solar irradiation and PV module temperature will influence the PV power generation from system. The PV power produced from the standalone photovoltaic system is fluctuated due to the regularly changing weather condition and solar availability. Therefore, an energy storage system required installed and integrate with the off grid photovoltaic system to ensure the continuity of electricity supply to the house. However, an off grid photovoltaic system with battery energy storage always has the problem of run out of electricity for fully off load area although the battery energy storage designed to backup the autonomy that people claim. This is due to the current PV capacity design in the market only capable to meet the load demand, but it cannot guarantee the PV power generation is always enough to fully charge a battery bank under over discharge protection state. The industrial designers had miss out the importance of how fast a PV array can fully charge a battery bank to handle another subsequent long rainy day after the first one as they only concentrate on optimization of charging control method for off-grid PV system. Therefore, it is crucial to optimize the size of PV panel.

In this research project, charging speed (k) value and number of autonomy days included in the calculation of PV capacity to provide a reliable electricity supply for a period of a year. Charging speed (k) value play an important role in optimization and sizing of PV panels for off-grid photovoltaic system. In this research project, the sizing of PV panel will keep increase as the charging speed (k) reduce. The PV capacity is inversely proportional to the charging speed (k) value. Two study cases were conducted to determine suitable minimal charging speed (k) to the battery bank for different number of autonomy days. An appropriate charging speed (k) value was determined based on the criteria where that the subsequent energy electricity stored been charged to a battery that has just reached its over discharge protection mode, can cover the daily energy demand when of another subsequent continuously rainy days. The outcome of this research project was to develop and optimal off-grid photovoltaic system design with suitable minimal charging speed (k) for 2 and 3 days of autonomy. Charging speed (k) values =1.5 was proposed in the sizing of PV panels for a PV capacity required to support the load demand for 2 autonomy days. The PV system able to generate about 6276.3 W power output when charging speed (k) values =1.5 used in the sizing of PV panels. While charging speed (k)= 2.5 was proposed and choose for PV system design when number of autonomy days=3. PV system with charging speed (k) value = 2.5 able to generate 5648.7 W power output.

However, there are few limitations were found in this research project. First, the solar radiation data and meteorological parameters that used in the design of off –grid PV system in this research project is based on the location that located in Malaysia. Thus, results and findings from this project maybe not a best solution for the people who want to install the standalone PV system outside of Malaysia. Because different location will have different solar radiation and meteorological values where all these parameters wills strongly affect the sizing of the standalone PV system. Next, only one type of PV system configuration was proposed in the design and sizing of the standalone PV system in this research project. Thus, different configuration for the PV system required to study and find out the suitable charging speed (k) and PV capacity that needed.

In conclusion, we advise the industrial designers to include charging speed (k) value and number of autonomy days in determine the PV capacity for the off-grid photovoltaic system. Besides that, we suggest people to use daily information rather than annual or monthly average value to determine the suitable charging speed (k) in the simulation of the appropriate size of PV panels to ensure a reliable electricity supply in one year period. Because we found that people prefer use annual or monthly average info to determine PV capacity in the past. The results in this research project show that if the PV system designed based on the k value that determined by annual or monthly average value, the PV array is not fast enough to charge the battery to handle another subsequent long rainy day after the first one.

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