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Design Calculation and Simulation of Photovoltaic Power Plant for Rural Electrification

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Abstract: This paper describes an energy system that is designed to meet the demands of rural population that currently have no access to grid-connected electricity. The provision of electricity to rural areas derives important social and economic benefits to remote communities throughout the world. Power supply to remote houses or villages, electrification of the health care facilities, irrigation, water supply and treatment. These papers introduce design calculation and simulation of photovoltaic power plant for rural electrification of Pwe Kyit village situated in Kyauk Padaung Township, Mandalay Region, Myanmar. This research includes sizing of photovoltaic modules, sizing of battery bank and selecting the inverter. Moreover design and calculation of total daily electrical consumption of rural area are described. The design calculation of PV power plant and simulation and analysis of the output results with Homer to achieve reliable and control the system for rural electrification is done.

Keywords: Homer, PV, Photovoltaic, Simulation, Solar Electricity, Renewable Energy.

I. INTRODUCTION

Energy consumption is one of the indices in determining the levels of development of a nation. Despite increased investment in Myanmar's electricity sector in 2013, including by international financial institutions, sustainable development remains a challenge. Only about 30 percent of the population of Myanmar has access to government electricity supply. Myanmar, developing country, is trying to get sufficient electricity from all possible energy resources to provide all parts of the nation. However, most of the remote areas away from the national grid are still facing scarcity of electricity. Myanmar is a land of plentiful sunshine, and therefore application of solar power is the only practical way to solve the insufficient electricity problem for the rural areas where the national grid cannot be extended. For those areas, solar is the fastest practical way to get electricity. The sun delivers its energy on the world in two main forms: heat and light. Solar photovoltaic system converts sunlight directly into electricity. When the PV modules are exposed to sunlight, they generate direct current electricity. An inverter then converts the dc into alternating current ac electricity. And then, it can feed for village electrification.

II. SOLAR ELECTRICITY GENERATION SYSTEM

Solar photovoltaic generation system can be classified based on the end use application of the technology. There are two main types of solar generation systems: grid-connected (or grid tied) and off-grid (or standalone) systems. Stand-alone solar systems are applicable for areas without power grid such as rural areas or off-shore islands. In order to ensure the supply of the stand-alone system with electric power also in the times without radiation (e.g., at night) or with very low radiation (e.g., at times with a strong cloud cover), stand-alone systems mostly have an integrated storage system. If the systems are only during the time when the radiation is sufficient to supply the system with electric power directly, a storage system is not necessary. This also applies to the situation in which the product delivered by the system can be stored (e.g., water) [2, 3].

A standalone solar power system consists of photovoltaic array, charge controller and batteries as well as directly connected the ac or dc appliances. In addition, a support structure for array, cable and distribution board for the appliances is needed. Mostly, the internal grid of the house works with ac power. Therefore, the solar system includes one or more inverters. Because the radiation intensity changes with the time of day as well as the season and weather conditions, a stand-alone system that is used to supply a village with electrical energy must also have storage batteries and charge controllers. An off-grid solar system needs deep cycle rechargeable batteries such as lead acid to store electricity for use under conditions where there is little or no output form the solar system, such as during the night [4] .

A. Working Process of PV Electricity Generation System

The off-grid solar electricity generation system is shown in Fig1. The modules are connected in series and parallel into a solar array that produce dc electricity when sunlight is available. The surge protector can minimize the risk of earth fault and short circuits in the array. The solar electricity produced by the solar installation is in the form of dc. In most cases, lead acid batteries are used for storing electricity. A solar battery charge controller serves generally to protect the battery against overcharging and deep discharges. It is absolutely necessary for the efficient operating conditions of the battery and of the complete solar system. The output of the solar installation is connected through the dc main cables to the terminals of the solar inverter where electricity is converted from dc to ac. After conversion, the ac current of the solar inverter is connected through disconnect switch to the model village's ac distribution panel [4,6].

B. Description of Proposed Village

The proposed village has been chosen by design calculation is Pwe Kyit.The geographical location of this village is located between NorthLatitude 20.39 degree and East Longitude 95.7 degree. This village is situated at Kyauk Padaung Township, Mandalay Division, Myanmar. There are 258 numbers of household, only one monastery, police station, hospital and Basic Education High School. The proposed village map is shown in Fig 1.The reason to choose this village is far from the national grid. Its temperature range is between 18 degree Celsius and 45 degree Celsius. The load profile of the village is 146841.6 Wh/day and its applications are ac residence only.

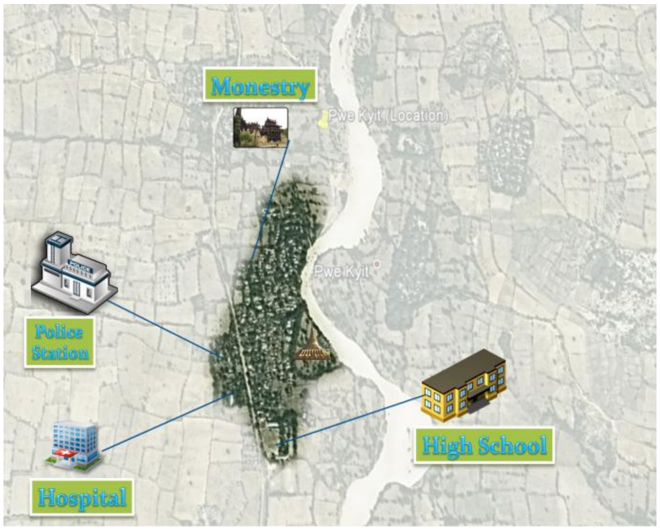


Fig.1.Maps of Pwe Kyit Village and it's Public Buildings.

C. Load Side Estimation

The felicitous loads are 84 numbers of single phase pumping motors, 531 numbers of fluorescence lamp, 75 numbers of LED street lamps, 7 numbers of four feet fluorescent lamps and 102 numbers of televisions. The total power consumption of load is 146,841.6 watts. However, in this project, there are three period to supply loads, Period A (00:00 to 06:00), Period B (06:00 to 15:00) and Period C (15:00to 24:00). Hospital has access electricity a whole day. In Period A, there will be supplied monastery, hospital, police station and street light. In Period B, there will be supplied high school and one hour for the running motor. At the rest Period, there will be supplied all the load except motors. Period Load consumptions of Pwe Kyit Village with period time separation are shown in Table 1. The estimated hourly load consumption and chart for one day is shown in Fig 2.

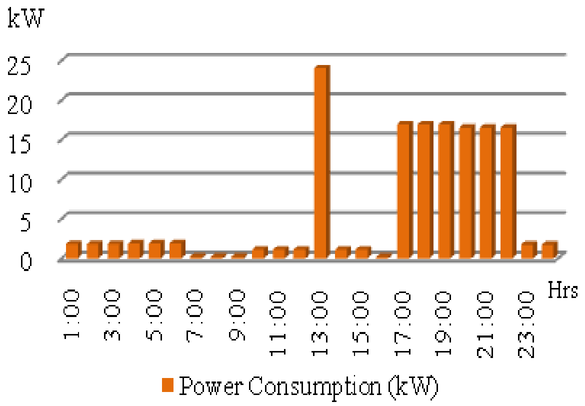
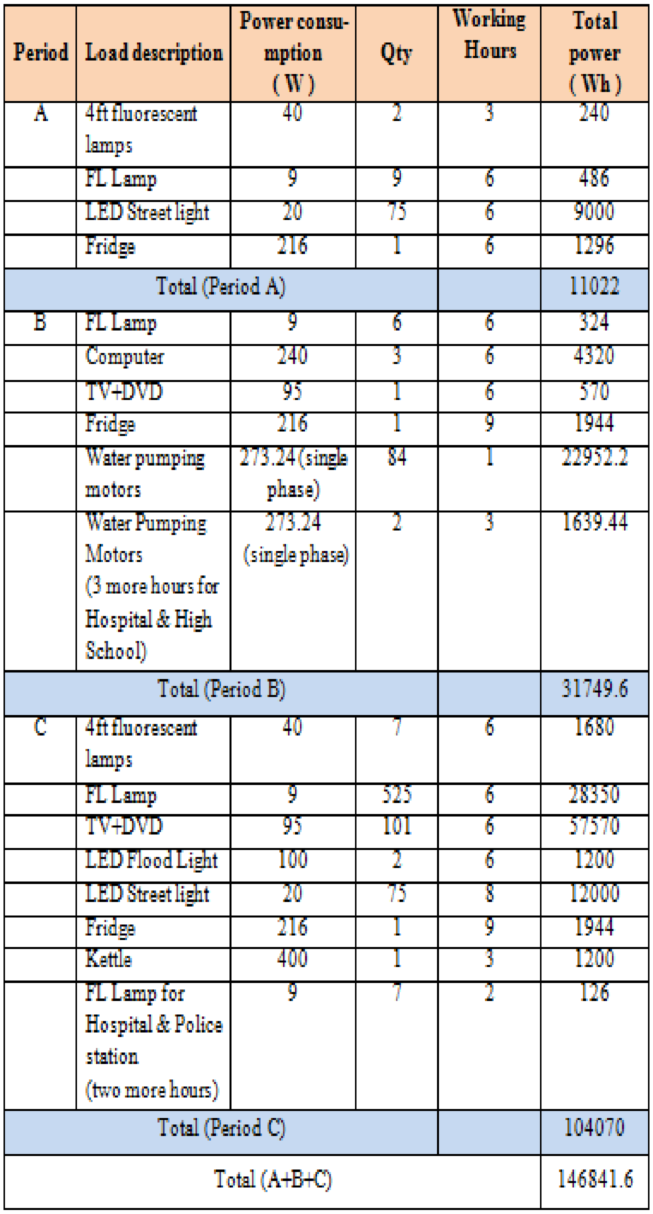


Fig.2.Estimated hourly load consumption of a day.

TABLE I: Daily Load Duty Cycle of Pwe Kyit Village With Period Time Seperation



Period	Load description	Power consu-mption (W)	Qty	Working Hours	Total power (Wh)
A	4ft fluorescent lamps	40	2	3	240
	FL Lamp	9	9	6	486
	LED Street light	20	75	6	9000
	Fridge	216	1	6	1296
Total (Period A)					11022
B	FL Lamp	9	6	6	324
	Computer	240	3	6	4320
	TV+DVD	95	1	6	570
	Fridge	216	1	9	1944
	Water pumping motors	273.24 (single phase)	84	1	22952.2
	Water Pumping Motors (3 more hours for Hospital & High School)	273.24 (single phase)	2	3	1639.44
Total (Period B)					31749.6
C	4ft fluorescent lamps	40	7	6	1680
	FL Lamp	9	525	6	28350
	TV+DVD	95	101	6	57570
	LED Flood Light	100	2	6	1200
	LED Street light	20	75	8	12000
	Fridge	216	1	9	1944
	Kettle	400	1	3	1200
	FL Lamp for Hospital & Police station (two more hours)	9	7	2	126
Total (Period C)					104070
Total (A+B+C)					146841.6

III. DESIGN CALCULATIONS OF SOLAR PHOTOVOLTAIC POWER PLANT

The design calculation steps are described in the Fig4. The schematics diagram of solar photovoltaic power plant shown in Fig 3.

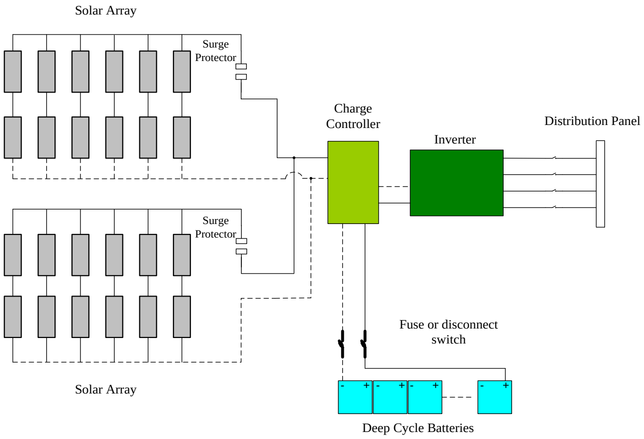


Fig.3.Schematics of solar photovoltaic generation system.

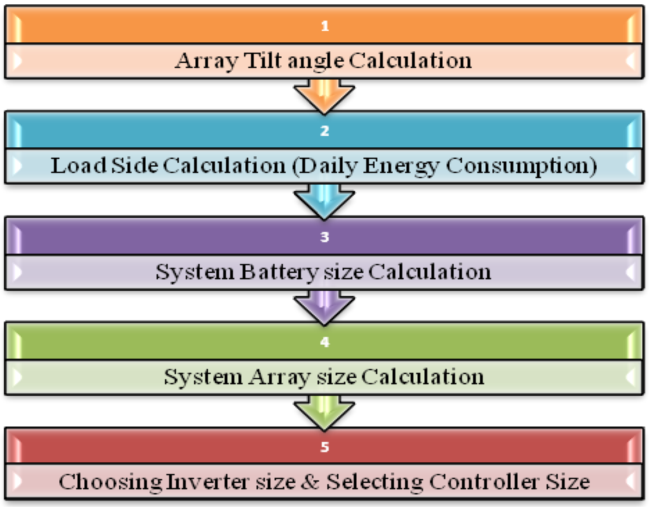


Fig.4. Design calculation process in solar generation system.

A. Calculation of Array Tilt Angle

The earth revolves around the sun in an elliptical orbit, making one revolution every 365.25 days. The related angles between the sun and the earth are as shown in Fig 5.

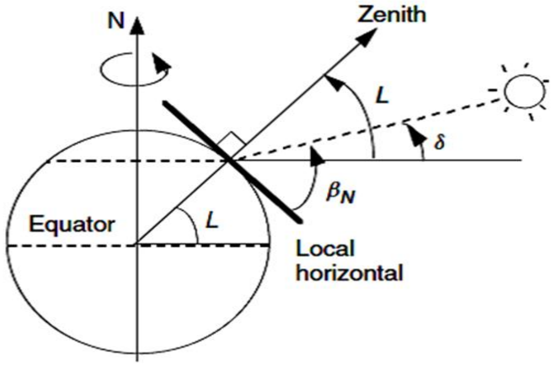


Fig.5. Related angles between the sun and the earth.

TABLE II: The Day Numbers for The First Day Of Each Month

Months	Number (n)
January	1
February	32
March	60
April	91
May	121
June	152
July	182
August	213
September	244
October	274
November	305
December	335

$$\text{Array tilt angle for selected location} = 90 - \beta_N \tag{1}$$

$$\beta_N = 90 - L + \delta \tag{2}$$

$$\delta = 23.45^\circ \sin \frac{360}{365}(n - 81) \tag{3}$$

Where,

δ = the angle between the plane of the equator and a line drawn from the centre of the sun and centre of the earth (varies between extremes of $\pm 23.45^0$).

n = day number for the first day of each months (the spring equinox condition is 81 that is day number).

β_N = altitude angle of the sun at noon.

L = latitude angle of the selected location [12].

According to eqn: (3)

$\delta = 23.45^0 \sin [(360/365)(60\text{-}81)]$

$= -8.29^0$

By using eqn:(2),

$\beta_N = 90^0 - 20.39^0 + (-8.29^0) = 61.32^0$

At last,

According to eqn:(1),

Array tilt angle for selected location = 28.68^0

B. Load Side Calculation

$$\text{Daily load consumption (Ahrs/day)} = \frac{\text{daily load consumption (Whrs/day)}}{\text{power conversion efficiency} \times \text{nominal system voltage}} \tag{4}$$

Where,

power conversion efficiency = 0.95

nominal system voltage = 240 V ($P_{gen} > 5000W$)

TABLE III: Calculation Results of Daily Load Consumption

Period	Daily load consumption (Whrs/day)	Calculated load consumption (Ahrs/day)
Period A+C	115092	504.79
Period B	31749.6	139.25

$$\text{Corrected Ahr load consumption} = \frac{\text{daily load consumption (Ahrs/day)}}{\text{wire efficiency factor} \times \text{battery efficiency factor}} \quad (5)$$

Where,
Wire efficiency factor = 0.98
Battery efficiency factor = 0.9

TABLE IV: Calculation Results Of Corrected Ampere Hour Load Consumption

Period	Corrected load consumption (Ahrs/day)	Total (Ahrs/day)
A+C	572.32	730.2
B	157.88	

C. Calculation of System Battery Size

Sizing a storage system to meet the demand 99% of the time can easily cost triple that of one that meets demand only 95% of the time. As a starting point for estimating the number of days of storage to be provided, Fig. 6 gives an estimate for days of battery storage needed to supply a load as a function of the peak sun hours per day. For the proposed village, August is the least peak sunshine hours, 5.4 shown in Table V. So storage day numbers is chosen 3.

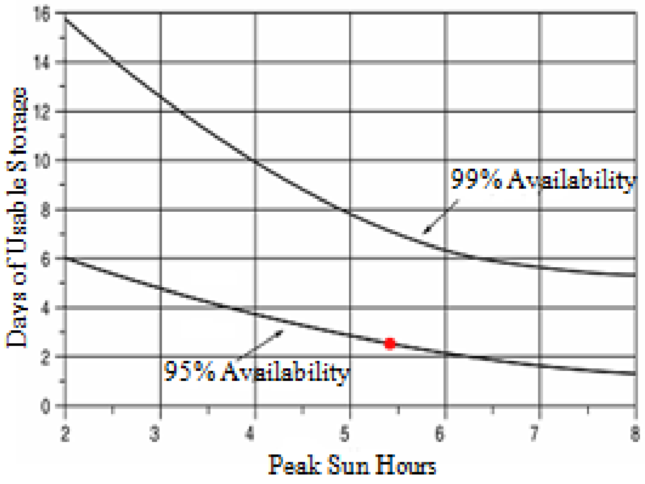


Fig.6.Days of battery storage needed for a stand-alone system with 95% and 99% system availability.

$$\text{Required battery capacity} = \frac{\max : \text{corrected Ahrs} \times \text{storage days}}{\max : \text{depth of discharge} \times \text{derate factor}} \quad (6)$$

Where,
maximum corrected Ahr load = 572.32 Ahrs/day
storage day numbers = 3
maximum depth of discharge = 80%
derate factor for temperature = 1
(local temperature>-8^{0}C)

TABLE V: Peak Sun Hours of Each Months

Months	Peak sun hours (hrs/day)
January	10
February	9.9
March	9.7
April	9.7
May	8.6
June	6.9
July	5.9
August	5.4
September	7.1
October	7.2
November	9
December	9

So, Required Battery capacity = 2146.21 Ahrs

Therefore, the selected battery should be rated at 700 Ahrs and 12V or greater and 80% discharging cycle.

$$\text{Number of parallel batteries} = \frac{\text{required battery capacity}}{\text{selected battery capacity}} \quad (7)$$

= 2146.21/700

= 3.07 ≈ 3 number

$$\text{Number of series batteries} = \frac{\text{nomial system voltage}}{\text{nominal battery voltage}} \quad (8)$$

= 20 numbers

$$\text{Number of total batteries} = \text{number of parallel batteries} \times \text{number of series batteries} \quad (9)$$

= 60 numbers

$$\text{System battery capacity} = \text{number of parallel batteries} \times \text{capacity of selected batteries} \quad (10)$$

= 2100 Ahrs

$$\text{Usable battery capacity} = \text{system battery capacity} \times \text{maximum depth of discharge} \quad (11)$$

= 1680 Ahrs

The maximum Ahr load is 572.32 Ahrs per day. Therefore, the usable battery capacity 1680 Ahrs is adequate for the generation system.

$$\text{No. of days that battery can be used} = \frac{\text{usable battery capacity}}{\text{maximum corrected Ahr load capacity}} \quad (12)$$

= 1680/5732.32

=2.94 days

D. Calculation of System Array Size

When calculating the system array size, the size depends on the load consumption and battery storage capacity. The battery charging current depend on parallel module of the array. And also consider least peak sun hours months of the years. The batteries that was very heavily charged, this causes severe stresses within the battery which seriously shorten it's life. Most of the manufacturer recommended the charging current should have 10 percent and 25 percent of the battery size. But solar installation should use the charging current between 10% and 30% of the battery capacity tend to seem reasonably happy with the compromise they have of the battery life versus recharge time. [15]

$$\text{Number of parallel modules} = \frac{15\%\text{ of usable battery capacity}}{\text{module derate factor} \times \text{rated module current}} \quad \textbf{(13)}$$

Where,

module derate factor = 0.85 (depends on temperature)

rated module current = 17.14 A

Number of parallel modules = 17.29 ≈ 17 numbers

$$\text{Number of series modules} = \frac{\text{battery loss factor} \times \text{battery voltage} \times \text{series batteries}}{\text{highest temperature module voltage}} \quad \textbf{(14)}$$

$$= 14.4 \approx 14 \text{ numbers}$$

$$\text{Total modules} = \text{number of parallel modules} \times \text{number of series modules} \quad \textbf{(15)}$$

$$= 238 \text{ numbers}$$

$$\text{Rated array current} = \text{number of parallel modules} \times \text{rated module current} \quad \textbf{(16)}$$

$$= 291.38 \text{ A}$$

$$\text{Array short} = \text{number of parallel modules} \times \text{circuit current module short circuit current} \quad \textbf{(17)}$$

$$= 311.44 \text{ A}$$

$$\text{Rated array voltage} = \text{number of series modules} \times \text{rated module voltage} \quad \textbf{(18)}$$

$$= 245 \text{ V}$$

$$\text{Array open circuit voltage} = \text{number of series modules} \times \text{module open circuit voltage} \quad \textbf{(19)}$$

$$= 308 \text{ V}$$

$$\text{Charging time to full battery} = \frac{\text{system battery capacity}}{\text{rated array current}} \quad \textbf{(20)}$$

$$= 5.765 \text{ hrs}$$

The peak sun hours of August are at least and have only 5.4 hrs. So it comparing with the least peak sun hours month with the charging time to full battery. The charging time to full battery is 5.765 hrs. So array size is suitable with the least charging time. If the charging time is much more than least peak sun hour's month, charging current must be increase. But the design should take account other peak sun hours months.

$$\text{Total generated power} = \text{total modules} \times \text{of modules power of module} \quad \textbf{(21)}$$

$$= 71400\text{W}$$

E. Choosing Inverter Size

Since the generated power of the array is greater than 6kW, the usable inverter should be three phases.

Total capacity of all loads = 40.737 kW

So, the suitable inverter for the system will have to be 45 kW and three phases. For safely, the inverter size should be more than 25 to 30 percents of load consumption power. Therefore, 25% of output power 40,737 W is 10,184.25W. Thereafter, the inverter, 50,000 W, is accommodated with solar generation system.

F. Selected Controller Size

According to standard practice,

$$I_{min}\,(\text{controller}) = 1.25 \times \text{array short circuit current} \quad \textbf{(22)}$$

$$= 1.25 \times 311.44$$

$$= 389.3 \text{ A}$$

So, the specifications of charge controllers in the available market are 100A, 120A, 200A and etc. So, 240V, 200A size charge controller is appropriate for this village.

$$\text{No. of controllers} = \frac{I_{min}}{I_{rated}} \quad \textbf{(23)}$$

$$= 389.3/200$$

$$= 1.95 \approx 2 \text{ nos}$$

IV. SIMULATION OF PHOTOVOLTAIC POWER PLANT

Sizing approaches for PV power plant system in above section is ampere hour method. The ampere hour method is useful in that it is relatively simple. But solar radiation from the sun on the earth changes time by time. The above calculation is only based on average solar radiation and average peak sun hours. Ampere hour method is not absolutely reliable to manage the whole system. For that, it is needed to simulate the paper base method result to the PV simulation software, Homer, using the proposed site hourly solar resources. Homer can optimized the system configuration and perform sensitivity analyses and therefor, the designer can make the right decision when the supplying load is needed to optimized and adjust the system components.

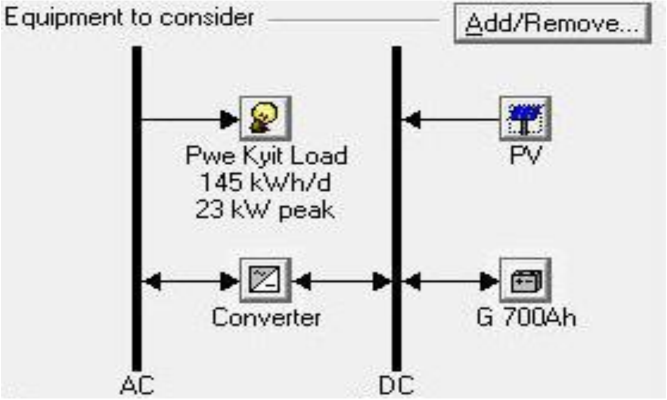


Fig.7. System Configuration of PV Power Plant in Homer Simulation Software.

When using the Homer simulation software, it may need to enter base data of the proposed site village. The system is simulated with 60 minutes time steps and global horizontal irradiation is get from NASA by inputting the latitude and longitude of the site. For PV modules, slope angle is inputted the above calculation result as shown in Fig.7, 28.68 degree and 20% ground reflectance. The variable sizes of PV to consider in kW are 58.8, 63, 67.2, 71.4, 75.6 and 79.8. For battery, GNB 6-90G13 battery with 12V, 700 Ah is used and the variable sizes of battery to consider per string for 240V DC bus are 2, 3, 4, 5 and even 8.

A. Simulation Results of PV arrays

It is clearly that the most electric production months are in the hot season. The first month of the hot season, February, is the best month of the electric production. The simulation result of PV electric production of the whole year is shown in Appendix A1. When the time of changing to rainy season, the last month of the hot season, May, the production of electricity of PV has been gradually decrease. In the rainy season, the electric production of PV cell decreases because it contains the cloudy and raining day. The least and worst month of the year is August. The starting month of the winter season, October, there are increase electric production can be seen in Fig 8. And the last three months also has the good electric production than October. Because the winter season in Myanmar, is not fallen much of snow and will get the plenty of sunshine at this season. So, when comparing and checking with paper base methods and data of least peak sunshine hours of August is appropriate with the selection of the system design calculation.

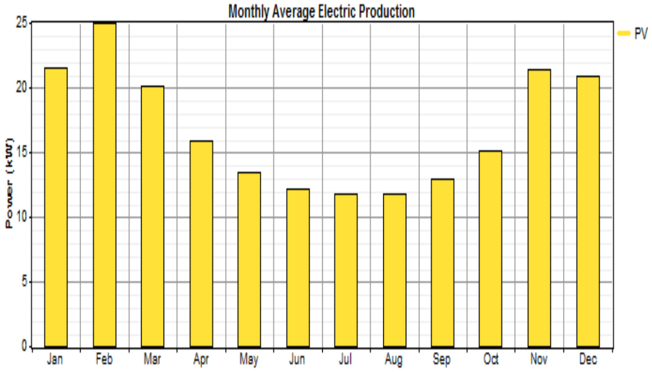


Fig.8. Simulation Result of Monthly Average PV Electric Production of PV Arrays.

B. Simulation Results of Battery Bank

Battery is important for the PV standalone system. When analyzing the simulation results of battery bank. The annual throughput of the battery is about 42,000 kWh per year. Fig 9 shows the monthly statics of battery state of chart. In this, it shows the maximum, minimum, and mean daily state of charge of battery. It depends on the PV electric production. So state of charge of battery is best level at hot season and also in cold season. The minimum daily state of charge of battery is also found in August like PV production. The minimum state of charge is 30 percent shown in Appendix A2. But in August, daily low level is about 70 percent state of charge. So it will provide the battery for longest life. According to the results, battery state of charge will be minimum condition of 30 percent at some days of the rainy season. But it will not need other backup generation (eg, Diesel generator) because the battery used in this system serve to 20 percent state of charge and the proposed site is also at the dry climate.

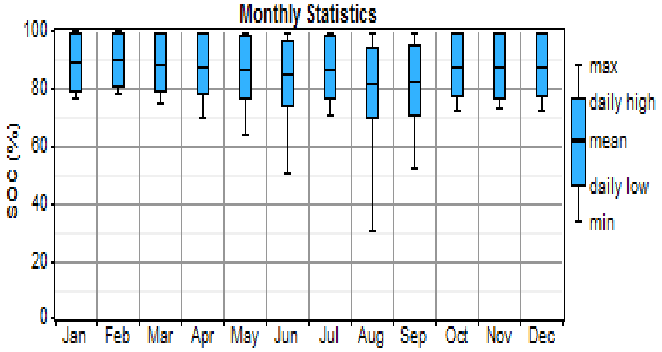


Fig.9. Monthly Statics of Maximum, Minimum and Mean Daily State of Charge of Battery.

C. Comparision of Load, PV Electric Production and Battery for System Control Management

When comparing simulation results (Figs.10 and 11) of AC load, PV electric production and battery state of charge, there are much excess electricity except in the rainy season. So the system can supply more electricity in the hot season and cold season. The system supply more electricity about 76 kWh/day. The load dispatch has been done by seeing the battery state of charge. The battery state of charge must not less than 50 percent and it will lead to the blackout day. To prevent the blackout day, the control supervisor should follow the weather forecasting and watching the battery state of charge not less than 50 percent. According to the results, the least PV production month is the August and the highest PV production month is February. In August, the state of charge of battery reached the lowest point of 30 percent but it is not exceed the maximum depth of discharge 80 percent. After simulation, the design calculation method of Ampere hour method results is appropriate with the simulation results.

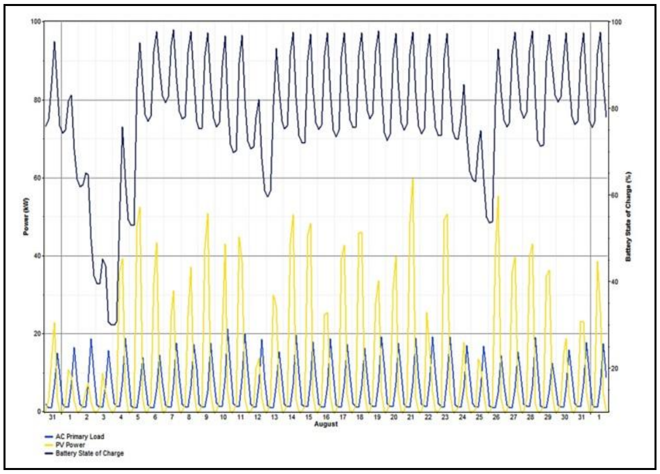


Fig.10. Comparision of Simulation Results of AC Primary Load, PV Output and Battery State of Charge for the Least PV Production Month (August).

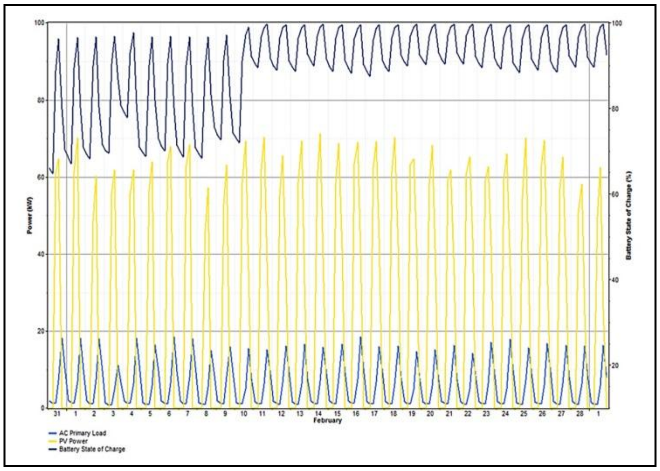


Fig.11. Comparision of Simulation Results of AC Primary Load, PV Output and Battery State of Charge for the Highest PV Production Month (February).

V. CONCLUSIONS

The proposed site, Pwe Kyit is a large village in Kyauk Pahtaung township. According to the results obtained in this research, off grid standalone PV power plant can supply the whole village without other backup sources. The simulations are computed using one year of hourly global solar irradiations on tilted plane 28.69˚. This analysis investigates the providing electricity to the village only using one power source, solar PV. The results show the impact of different assumptions about solar resource and load profile applying a simulation software tools HOMER. When calculating using ampere hour method, the number of storage days has been chosen by using 95 percent demand availability. But when selecting the stand-alone PV power system without other backup generation system, number of storage days should be used 99 percent demand availability. Because the larger the battery capacity size that it is followed by higher cost of energy. It will cost triple that of one that meets demand only 95 percent of the time. Although not considered in ampere hour method, it should account in simulation.

So when input data of solar PV energy are entered in the simulation software, variable size of 33.6,42, 50.4, 58.8, 63, 67.2, 71.4, 75.6, 79.8, 193.2 in kW are inputted. So it is simulated using different energy production and which is more feasible and economy for the system. And also inputting the battery bank string size, variable size of batteryper string 2, 3, 4, 5, and even 8 strings are added and investigated. An important conclusion is that the choosing system devices represent an important step in the optimal sizing of the PV system so that the system operation will meet the demand load with improving system reliability. Including economical consideration, more electricity of about 76kW per day can supply in industrial and households load at the day time. The second conclusion that can be withdrawn from this work is the possibility to create a typical design for PV energy systems to supply energy in remote area wherever the site or location has a favourable solar radiation. According to the current cost of PV module, Battery and the cost of energy ($/kWh) is still high, the initial cost is expected to decrease in the near future. Even though, using renewable energy sources is far more popular than the past while the cost of the components are decreasing. The proposed system is intended for not only to optimize the solar PV power system but also to decrease the air pollution which effects the environment.

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