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Performance Analysis of Self-Consumed Solar PV System for A Fully DC Residential House

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Abstract

Malaysia is moving forward by promoting used of renewable energy such as solar PV to the public where it is generated at the distribution voltage level. The fluctuation of fuel prices becomes main concern to the consumers since it affecting the electricity tariff. The objective of this project is to design a self-consumed DC power system for a residential house from renewable energy resource which is solar PV that it will independent from the utility grid. The methodology proposed are configuring daily load demand, sizing PV array and battery bank and simulation of the design system by using PVsyst. Based on solar energy resource, the optimum PV array size is 2.0 kWp while the battery bank size is 700 Ah at 48 V which is designated for 4 days of autonomy. The system could meet 100% of load demand throughout the year with 67.9% of performance ratio. The loss to the system is contributed by the temperature effect to the PV module, unused energy because of battery full capacity, converter and battery efficiencies. Using this concept, the proposed design set-up is expected to benefit the residential consumers in reducing utility electricity consumption up to 2,434 kWh per year and avoiding 1.7 tons of carbon emissions into the environment annually.

Keywords: *Solar PV, DC Residential House, DC Microgrids, PVsyst, Renewable Energy*

1. Introduction

Today renewable energy power system is becoming popular with the increase of energy demand and concerns on the carbon dioxide (CO2) emission to the environmental that will cause global warming [1]. Malaysia has move forward by promoting used of renewable energy such as solar PV to the public where it is generated at the distribution voltage level. The fluctuation of fuel prices become main concern to the consumers since affecting the electricity tariff because presently gas and coal are the dominant source of electricity generation [2].

Previous electricity tariff revision was conducted in 2014 where the average electricity tariff increased from 33.54 sen per kWh to 38.53 sen per kWh. All the categories have shown increment in tariff prices compared to former tariff except for two domestic customer groups. These groups are those who consumed electricity up to 200 kWh per month and also who used electricity between 201 and 300 kWh per month. Both groups represent majority of domestic users around 4.56 millions customers [3]. However, due to the nature of the fuel prices that fluctuates, there is no guarantee that the tariff for these two groups will be maintained.

Currently there are two programs of solar PV system promoted by the Sustainable Energy Development Authority of Malaysia (SEDA) to the residential customers which are Feed-in Tariff (FiT) and Net Energy Metering (NEM). For the FiT scheme, all energy generated by the PV array will be exported directly to the utility grid. The mechanism of FiT has guaranteed a fixed selling prices which has to be paid to Feed-in Approval Holder (FiAH) by a utility company, to whose grid energy is exported for 21 years of contractual periods [4].This scheme is very popular among Malaysian and received high applications demand because of its high selling rates. For the NEM scheme, the connection is through an indirect feed where the energy generated from PV array will be used by the residential load first and the surplus energy will be exported to the utility grid. Up to date, the NEM is not as popular as FiT because of the selling price is not as good as FiT.

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This paper proposed on the generation of electricity through solar PV system for the target group that consumes 200 kWh per month or below, so that they will less depending on the energy supply by the utility grid. The electricity distributed to the household loads will be totally in DC, in order to avoid the use of an inverter, hence reducing the conversion loss and increasing the efficiency. In addition, the price of inverter is relatively expensive, especially for household applications [5].

In recent years, significant improvements in efficiency and cost effectiveness of solar PV technology have been made [6]. In addition, there have been intensive efforts to utilize DC voltages at distribution system as alternative to the traditionally used of AC system [7]. Moreover, many of today's consumer loads are available at low voltage DC such as LED lightings and hand phone chargers. The advancement achieved in power electronics made the DC voltage regulation easier and more efficient [8]. Today's solid-state switching DC converters have power conversion efficiency in the range of 95% [9].Compared to AC system, the energy conversion losses of DC system is minimized [10] since there is no reactive power [11]. In addition, the use of renewable energy sources can also reduce impact of environmental pollution generated by fossil fuels [12]. According to SEDA portal, the baseline CO2 for electricity generation for Peninsular of Malaysia is 0.694 tCO2/MWh in 2014 [13].

2. Methodology

This project is to design a self-consumed DC power system for a residential house from renewable energy resource using solar PV. The methodology involves configuring daily load demand, sizing PV array and battery bank and then simulation of the system by using PVsyst.

PVsyst is a professional software used to design and simulate the performance of the system related to solar PV. Many researchers used PVsyst to design and simulate the performance of their PV systems either grid-connected or standalone by using PVsyst. For example PVsyst is used for simulating performance of 100 kWp grid connected Si-poly photovoltaic system to evaluate feasibility of installing a photovoltaic system to supply the electric loads of an educational institute [14]. Another researcher carried out performance analysis of a 190 kWp solar photovoltaic power plant installed at Khatkar-Kalan, India by using PVsyst [15]. Another study is based on design of solar PV system and cost analysis of 1.0 kW off-grid photovoltaic energy system installed at Jamia Millia Islamia, New Delhi, India [16].

2.1. Proposed DC Power System Architecture for Residential House

The block diagram of the solar PV system for a fully DC residential house is shown in Figure 1. The energy generated from solar array will be stored in the battery bank at 48 V DC bus voltages. The output will be distributed accordingly to load's power requirement which is 48 V DC for high power load such as refrigerator and air-conditioner unit. For low power load such as lighting, fan and charger unit, the voltage will be step down through DC converter to 12 V DC. There are 5 points for low voltage distribution that could be support loads up to 120 W each. For this project, energy generated from solar PV will be consumed totally by the residential loads while excess energy generated if any; will not be exported to the grid.

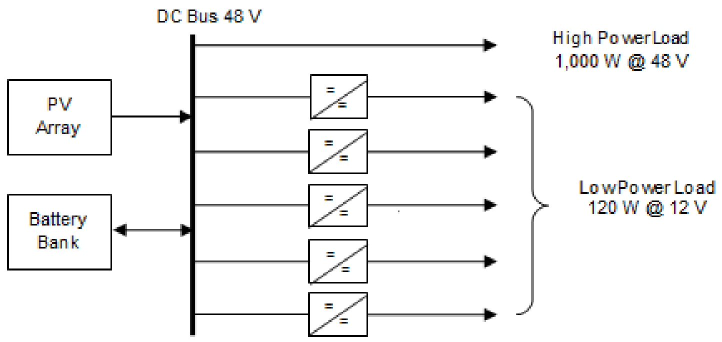

Figure 1. Block diagram of solar PV system for a proposed fully DC residential house

2.2. Solar Energy

The project site that has been chosen is Changlun (6.44 °N, 100.43 °E), which is located at the northern of Peninsular of Malaysia in the State of Kedah. Information on solar energy for Changlun is obtained from Meteonorm 7.1 which provided monthly meteorological data that has been preloaded in PVsyst. The PV array plane is placed at tilt angle of 15° facing south as shown in Figure 2. The annual global solar irradiation is 1,798 kWh/m^2 and the average ambient temperature is 27.4 °C. Figure 3 shows the monthly global solar irradiation and average ambient temperature for Changlun.

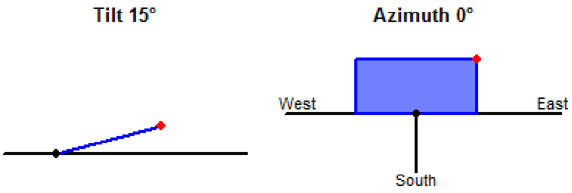

Figure 2. Tilt angle and azimuth angle of PV array plane

2.3. Residential Load Consumption

In general, a residential house will consist of basic electrical appliances such as lightings, fans, handphones charger, television, washing machine and refrigerator. The usage of these appliances is according to the needs and life style of occupants. Electricity bill payment depends on the amount of energy consumption per month as determined by the tariff. Based on the recent tariff revision in 2014, the energy consumption band has reduced from 9 bands to only 5 bands. Table 1 shows the implication of electricity tariff revision in 2014 for domestic customers in Peninsular of Malaysia [2].

Since group of 200 kWh or below represents majority of the domestic consumers, hence it is important to study their daily energy usage patterns. In relation to that, a power monitoring device has been installed to monitor power consumption for a week at several houses in Changlun that used in average of 200 kWh per month. The average daily load profile is shown in Figure 4 where the average daily consumption in 6.67 kWh and maximum power demand is 0.86 kW. The hourly trend shows that the peak demand occurs twice a day which is between 6.00 am to 9.00 am in the morning and between 7.00 pm until 11.00 pm in the evening. Assuming this daily load is constant throughout a year, then the annual energy demand is 2,434 kWh.

Table 1. Implication of electricity tariff revision in 2014 for domestic customer in Peninsular of Malaysia [3]

Consumption Band (kWh)	Tariff Rates 2011 (sen / kWh)	Tariff Rates 2014 (sen / kWh)	Difference (sen / kWh)	Number of Customers (millions)
0 - 200	21.80	21.80	No difference	3.25
201 – 300	33.40	33.40	No difference	1.31
301 – 400	40.00			
401 – 500	40.20	51.60	10.00 - 11.60	1.39
501 – 600	41.60			
601 – 700	42.60			
701 – 800	43.70	54.60	9.30 - 12.00	
801 – 900	45.30			0.5
901 and above	45.40	57.10	11.70	

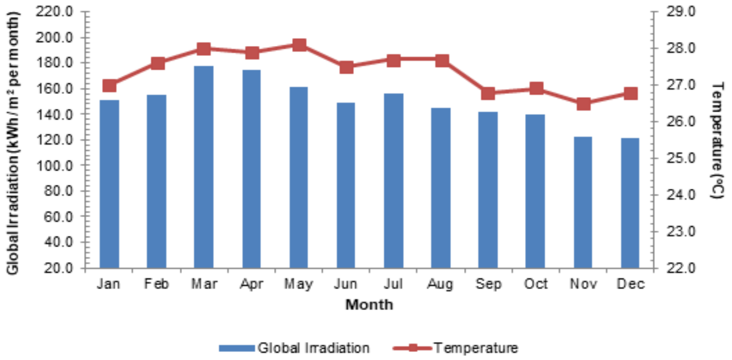

Figure 3. Monthly global solar irradiation and average ambient temperature for Changlun

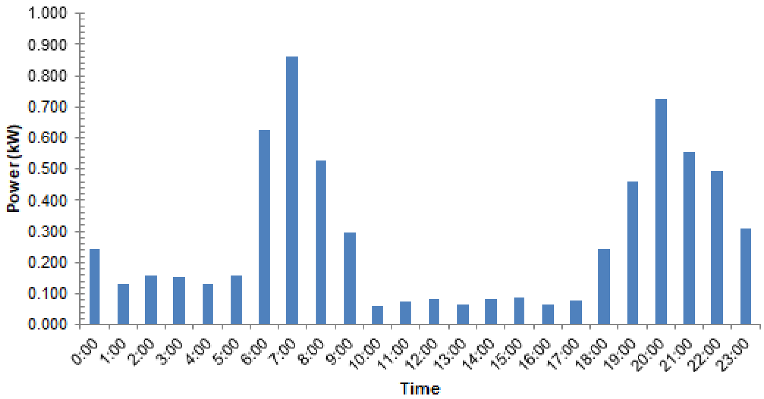

Figure 4. Average hourly load profiling for a residential house using 200 kWh per month

2.4. Solar Array Sizing

Solar PV array is sized to meet the required energy demand. The output energy of PV array is a function of peak sun shine hours and temperature. The estimation of energy generated from PV array is simplified and calculated based on Equation (1) below [17].

$$E_{array} = P_{array} \times PSH_{period} \times f_{temp} \quad (1)$$

where E_{array} is PV array yield in kWh, PSH_{period} is Peak Sun Hour and f_{temp} is temperature de-rating factor. The temperature de-rating factor, f_{temp} is given by the Equation (2)

$$f_{temp} = 1 + \left[\left(\frac{\gamma_{pmp}}{100} \right) \times \left(T_{cell\_ave} \times T_{stc} \right) \right] \quad (2)$$

where γ_{pmp} is temperature coefficient for P_{mp} in % per ^{o}C, T_{cell_ave} is average daily maximum cell temperature and T_{stc} is cell temperature at standard test condition which is 25 ^{o}C . The average cell temperature, T_{cell_ave} is given by Equation (3)

$$T_{cell\_ave} = T_{amb\_ave\_\max} + \left[\left(\frac{NOCT - 20}{800} \right) \times G_{amb\_ave\_\max} \right] \quad (3)$$

where $T_{amb\_ave\_max}$ is average daily maximum ambient temperature in ^{o}C, NOCT is nominal operation cell temperature in ^{o}C, $G_{amb\_ave\_max}$ is average daily maximum solar irradiance in Wm^{-2}. The PV module used is Yingli Solar YL250P-29b which is preloaded in the PVsyst database. Selected parameter and their value for the PV module is shown in Table 2.

Table 2. PV module specification

Parameter	Value at Standard Test Condition (STC)
Power output, P_{max}	250.0 Wp
Voltage at Pmax, V_{mpp}	30.23 V
Current at Pmax, I_{mpp}	8.27 A
Open-circuit voltage, V_{oc}	37.73 V
Short-circuit current, I_{sc}	8.83 A
Module efficiency	15.40 %
Temperature coefficient at Pmax, γ_{mpp}	-0.42 % / ^{o}C

2.5. Battery Storage Sizing

The amount of charge required for battery bank is based on Equation (4):

$$C_{Ah\_req} = \frac{E_{req}}{V_{sys}} \times \frac{k_{storage}}{DOD_{max}} \times T_{aut} \quad (4)$$

where C_{Ah_req} is charge storage capacity required in Ah, V_{sys} is the system voltage, $k_{storage}$ is the battery efficiency, DOD_{max} is maximum depth of discharge allowed and T_{aut} is number of autonomy days.

The system voltage is set to 48 V, battery efficiency is set to 97%, number of autonomy days is set to 4 days and maximum depth of discharge is set to 80%. The battery used in this simulation is a generic 12 V battery with 100 Ah capacity.

3. Results and Discussion

Summary of the system configuration is shown in Figure 5. In general, 2.0 kWp of PV array and 700 Ah of battery bank are required to meet the annual load demand. The 250 Wp PV module is arranged 4 in parallel strings with 2 modules in series for each string. For the battery bank, a 12 V 100 Ah battery is arranged 4 in series to make up 48 V with 7 in parallel. The charge controller with rating 1.8 kW is used to regulate the input from PV array, to the battery bank and ouput to the load.

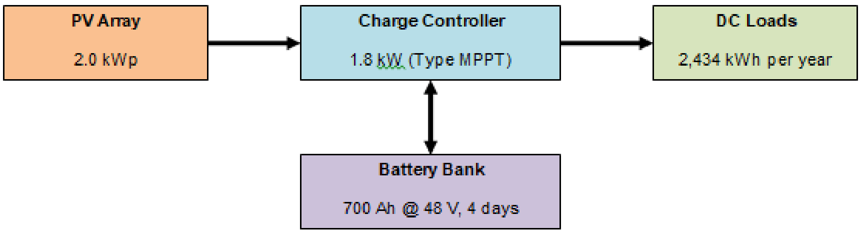

Figure 5. Summary of the system configuration

Table 3 summarized the system performance throughout the year. The annual Global Horizontal Irradiation available is 1,798 kWh/m^2 but only 1,735 kWh/m^2 is effectively available at PV array plane. Generally, the system is capable of meeting the yearly loads demand which is 2,434 kWh. However, there is 211 kWh of excess energy generated due to the design criteria which is to meet the monthly demand with lowest solar irradiation. This leads to the no excessive energy in December which has the lowest solar irradiation but excessive energy generated in the first 4 months because of high solar irradiation.

Figure 6 shows the normalized production per installed kWp. The daily energy supplied to the user is 3.33 kWh/kWp while daily unused energy due to battery full is 0.29 kWh/kWp. The PV array loses is 0.91 kWh/kWp per day while system losses and battery charging is 0.37 kWh/kWp per day. The overall performance ratio as shown in Figure 7 is 67.9%.

Table 3. Balance and main result

	GlobHor kWh/m²	GlobEff kWh/m²	E Avail kWh	EUnused kWh	E Miss kWh	E User kWh	E Load kWh	SolFrac
January	151.0	160.9	254.8	24.79	0.000	206.7	206.7	1.000
February	155.0	159.9	251.5	53.84	0.000	186.7	186.7	1.000
March	178.0	174.4	273.6	54.96	0.000	206.7	206.7	1.000
April	174.9	162.6	256.6	45.46	0.000	200.1	200.1	1.000
May	161.8	144.2	229.0	18.93	0.000	206.7	206.7	1.000
June	149.5	130.6	209.0	0.01	0.000	200.1	200.1	1.000
July	156.6	137.3	219.4	8.51	0.000	206.7	206.7	1.000
August	145.3	132.9	211.6	0.02	0.000	206.7	206.7	1.000
September	142.3	136.0	215.4	0.03	0.000	200.1	200.1	1.000
October	139.5	139.8	221.0	4.07	0.000	206.7	206.7	1.000
November	122.8	127.1	201.4	0.01	0.000	200.1	200.1	1.000
December	121.6	129.5	203.8	0.00	0.000	206.7	206.7	1.000
Year	1798.4	1735.2	2747.2	210.64	0.000	2434.2	2434.2	1.000

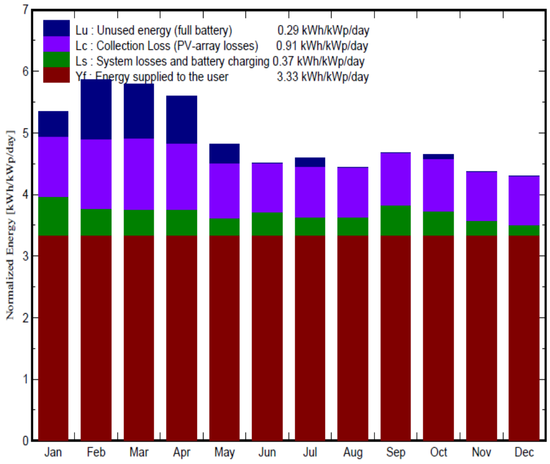

Figure 6. Normalized production per installed kWp

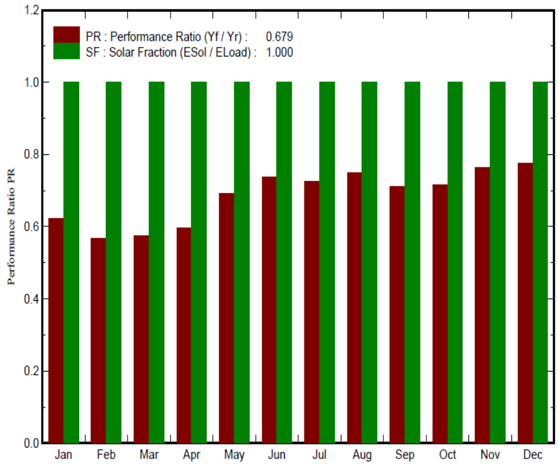

Figure 7. Performance ratio and solar fraction

Figure 8 summarized the system's energy loss throughout the year. The nominal PV array energy at STC is 3,471 kWh but only 2,707 kWh is available as output from it. The losses are due to the PV array (15.9%) and unused energy because of battery full (7.2%). From PV array output, only 2,434 kWh has been supplied to the users where the main losses are from converter efficiency (6.3%) and battery efficiency (4.1%). The total cost of the project is estimated around RM 46,000 with cost of energy (COE) is RM 1.62 per kWh.This COE level is high compared to the monthly grid energy price at 200 kWh or below which is RM 0.218 per kWh. Despite drawback in COE level, this project has shown positive aspect in environmental conservation where the 2,434 kWh energy generated from renewable resources annually and used by the system has replaced the fossil fuel based power from grid. This value is equivalent to almost 1.7 tons of CO_2 avoidance to the environment.

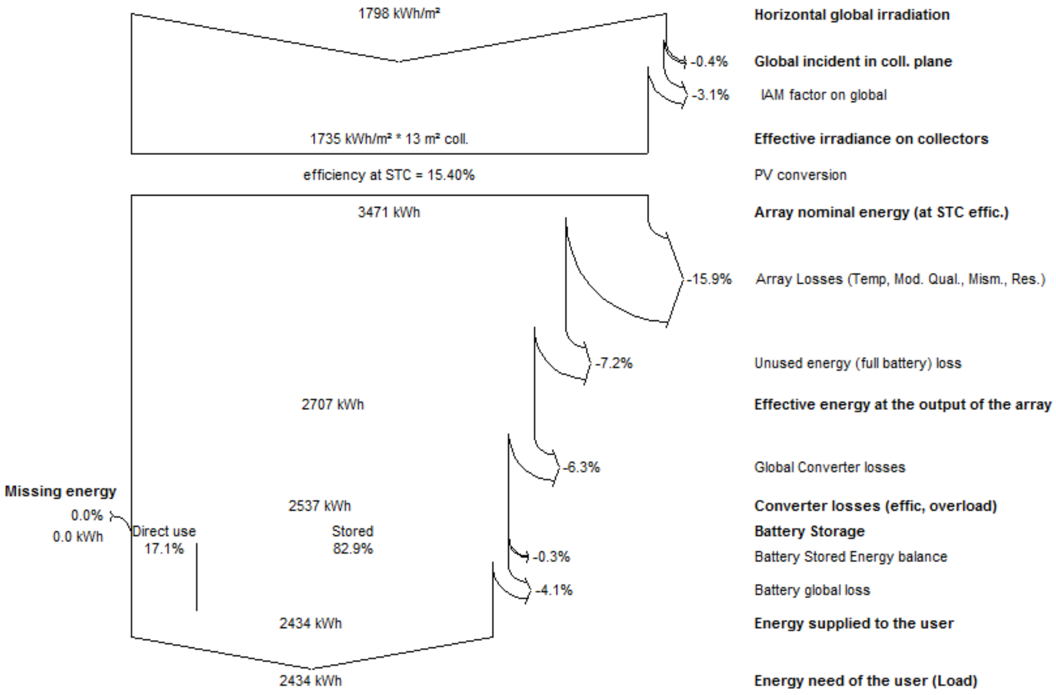

Figure 8. Loss diagram

4. Conclusion

The design and performance analysis of a solar PV system for a fully DC residential house in Changlun, Malaysia has been proposed in this paper. The amount of user's energy demand is 2,434 kWh per year. Based on solar energy resource, the optimum PV array size is 2.0 kWp while the battery bank size is 700 Ah at 48 V which is designated for 4 days of autonomy. The system could meet 100% of load demand throughout the year with 67.9% of performance ratio. The loss to the system is contributed by the temperature effect to the PV module, unused energy because of battery full, converter efficiency and battery efficiency. The cost of energy is RM 1.62 per kWh which is high compared to the monthly grid energy price at 200 kWh or below which is RM 0.218 per kWh. By using this concept, the proposed design set-up is expected to benefit the residential consumers in reducing utility electricity consumption up to 2,434 kWh per year and avoiding 1.7 tons of carbon emissions into the environment annually.

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