

Sizing and Cost Analysis of Self-Consumed Solar PV DC System Compared with AC System for Residential House

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ABSTRACT

The use of solar photovoltaic (PV) system has grown significantly in Malaysia after Renewable Energy Act has been gazetted in 2011. The objective of this paper is to highlight the technical and economic analysis of solar PV DC system to generate enough energy for residential customer group that consumed 200 kWh per month so that they are less dependent on energy from the utility grid. The results are then compared to the solar PV AC system with similar load setup. The methodology involves gathering solar energy resource, configuring daily load demand, sizing PV array, battery bank and inverter and lastly simulation of the design system by using Homer software. Based on Homer simulation, the solar PV AC system required slightly larger PV array sizes than the solar PV DC system to compensate losses due to the inverter efficiency which is not counted in DC system. Moreover, the solar PV AC system is almost 8.0% more expensive with 6% higher COE than the solar PV DC system due to the present of inverter. Lastly, both systems will benefit from reduction of energy consumed up to 2,434 kWh annually and to the environmental aspect, will avoid 1.7 tons of CO₂ releases into the atmosphere.

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1. INTRODUCTION

In 2011, Malaysia has gazetted Renewable Energy Act (RE Act) to catalyse energy generation from renewable resources in Malaysia. This is in line with the Government's inspiration to reduce dependency on fossil fuel based energy resources such as natural gas, petrol and coal. In addition, the use of renewable energy will reduce greenhouse gas emissions to the environment that cause global warming consistent with Malaysia's commitment to the World during the COP15 in Copenhagen in 2009.

Under RE Act 2011, the use of solar photovoltaic (PV) systems has grown significantly as a result of the Feed in Tariff (FiT) mechanism that has been introduced. Under the FiT mechanism, all energy generated by the PV array will be exported directly to the utility grid based on the dedicated selling rates for supplying renewable energy to the grid. This mechanism has guaranteed a fixed selling prices which has to be paid to Feed-in Approval Holder (FiAH) by the utility company for 21 years of contractual periods [1]. This scheme is very popular among consumers and received high applications because of its high tariff rates.

Another mechanism under RE Act 2011 is the Net Energy Metering (NEM) which has been introduced in 2016. Under NEM, an eligible consumer installs a PV system primarily for its own usage and the excess energy exported to the grid is offset through the electricity bill provided by the utility company. For residential house, the connection is through an indirect feed where the energy generated from PV array

will be used by the loads first and the surplus energy will be exported to the utility grid. Up to date, the NEM is not as popular as FiT due to the selling price which is not attractive as FiT.

Recently, connection of solar PV system for self-consumption (Selco) has been introduced. Under Selco mechanism, electricity generated from PV system is entirely for own used and in the event of excess of generation, the energy is not allowed to be exported to the grid [2]. This mechanism is to encourage individuals, commercial and industrial consumers to install PV system for their own consumptions, looking to reduce the impact of high electricity tariffs and minimizing power quality issues at the utility level. Compared with the other two mechanisms, Selco is seen to provide energy saving more effectively for the residential house especially for low monthly consumption. This is because the battery bank can be installed to store solar energy during daytime where the sun's energy peaked and supply energy at nighttime during its peaks loads. Proper system design will make the residential house fully independent from utility grid supply hence achieving energy saving. A study by Mansur, 2017 has highlighted the percentage of residential customers who consumed 300kWh or less per month is high where 50.37% consumed electricity up to 200kWh per month and 20.30% used electricity between 201 and 300kWh per month [3].

Currently there is growing interest in using DC to supply power to the load because of various advantages over AC. Moreover, the power supplied from PV array is in DC hence the system will look simpler. Therefore, the objective of this paper is to highlight the technical and economic analysis of solar PV DC system to generate enough energy for domestic customer group that consumed 200 kWh per month so that they are less dependent on energy from the utility grid. Distribution of energy to the loads will totally in DC to avoid the use of inverter. This can reduce energy loss due to inverter and increase energy efficiency. In addition, the results are then compared to the solar PV AC system with similar load setup.

In recent years, tremendous improvements in efficiency and cost effectiveness of solar PV technology have been made [4]. In addition, there have been intensive efforts to utilize DC in distribution system to supplement the traditionally used AC system [5]. Moreover, many of today's consumer loads are available at low voltage DC such as LED lightings and hand phone chargers [6]. The advancement achieved in power electronics has made the DC voltage regulation easier and more efficient. Today's solid-state switching DC converters have power conversion efficiency in the range of 95% [7]. Compared to AC system, the energy conversion losses of DC system is minimized [8] since there is no reactive power [9]. For off-grid homes (OGH), a solar DC solution has been proposed by Kaur, 2015 where it used solar DC power to feed the loads and avoids multiple AC/DC conversions. The conclusion was, the use of DC power lines and appliances has produced higher efficiency compared to the AC lines and appliances [10]. Furthermore, a cost benefits analysis by Rajaraman, 2015 has shown the DC system can reduce costs to the consumer by eliminating the complex electronics embedded in the inversion process [11].

In addition, electricity generation from PV system will avoid the usage of conventional fossil fuels based utility grid energy, hence reduces the overall greenhouse gas emissions to the environment which is in line with Malaysia's commitment to the United Nations Framework on Climate Change Convention (UNFCCC) at the 15th Conference of the Parties (COP 15) toward reducing 40% of CO₂ emissions intensity per unit of Malaysian GDP by 2020 against a 2005 baseline [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

In this work, a self-consumed DC power system for a residential house using solar PV is proposed. In addition, the sizing and cost analysis of the system is compared with a solar PV AC system. The methodology involves gathering solar energy resource, configuring daily load demand, sizing PV array, battery bank and inverter and lastly simulation of the design system by using Homer software.

The Homer software is a powerful tool that is used for designing and analyzing the hybrid power systems, was developed by the United States (US) National Renewable Energy Laboratory (NREL) [14]. Many researchers used Homer to design and simulate the technical and economic analysis of their hybrid renewable energy system either grid-connected or off-grid system. For example, Jefry, 2017 in his work used Homer simulation to analyze the building power consumption and economic evaluation of Demand Response Program (DRP) at Universiti Tun Hussein Onn Malaysia (UTHM) [15]. Shahinzadeh, 2016 in his research used Homer as optimization tool to determine optimal sizing and energy management of a grid-connected microgrid system [16]. Study by Fazelpour, 2016 used Homer to obtain the electrical supply system requirements and the economics of the five hybrid systems which are PV-wind-diesel systems in which hydrogen is employed as a diesel generator fuel to supply the electrical requirements for a household in Tehran, Iran [17]. Another study by Haghight Mamaghani, 2016 used Homer software to perform a complete parametric analysis on system configurations of seven design cases based on combinations of diesel generator, solar panels and wind turbine units in three small rural communities in Colombia [18].

2.1. System Configuration

A solar PV system design for a fully DC residential house block diagram by Mansur, 2017 is shown in Figure 1. In general, energy generated from PV array will be stored in the battery bank at 48 V DC bus voltages. Then, the output will be distributed accordingly to loads based on to their power rating. For high power loads such as refrigerator and air-conditioner unit, will be using 48 V DC while for low power loads such as lightings, fans and phone chargers, the 48 V voltage will be step down to 12 V DC through DC-DC converter. There are 5 points for low voltage distribution that could be used inside the house which could support loads up to 120 W for each point [19]. Since this project is self-consumed, energy generated from PV array will be consumed totally by the residential loads while excess energy generated if any will not be exported to the grid.

For a solar PV AC system, the basic block diagram is shown in Figure 2. In general, energy generated from PV array will be stored in the battery bank. The typical DC bus voltage is 12 V or 24 V depending on the load. However for this work, 48 V DC is chosen. Then, the inverter will convert the output from DC to 230 V AC power for load. Since this project is self-consumed, energy generated from PV array will be consumed totally by the residential loads while excess energy generated if any will not be exported to the grid.

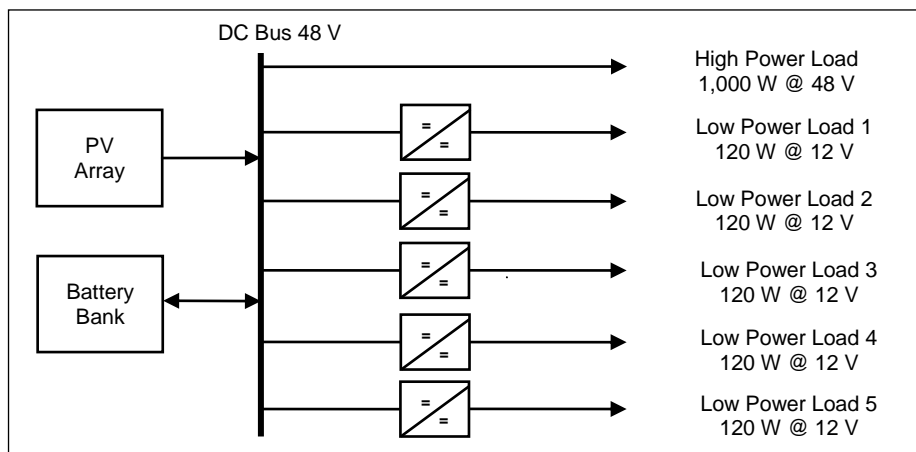


Figure 1. Basic block diagram of self-consumed solar PV DC system for a residential house [19]

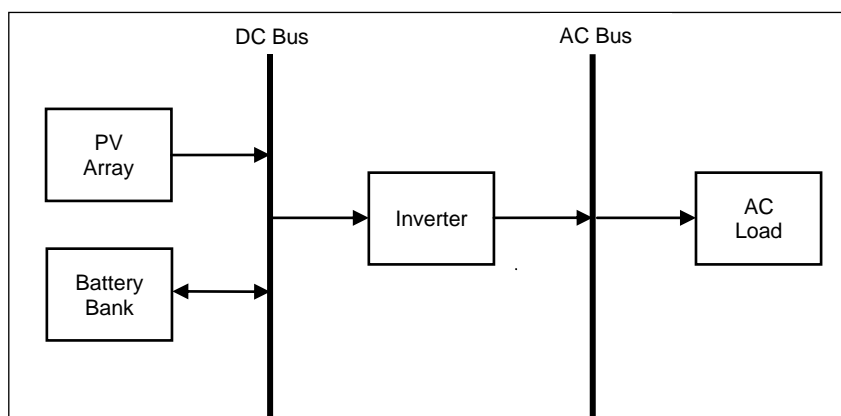


Figure 2. Basic block diagram of self-consumed solar PV AC system for a residential house

2.2. Solar Energy Resource

Changlun (6.44°N, 100.43°E), which is located at the northern of Peninsular Malaysia in the State of Kedah has been chosen as a project site. Information on solar energy is obtained from NASA Surface Meteorology and Solar Energy database which provided monthly meteorological data. These data has been

preloaded in Homer Pro software. From database, the annual average irradiation is 4.97 kWh/m² with February has the highest irradiation which is 5.86 kWh/m² per day while November has the lowest irradiation which is 4.23 kWh/m² per day. The annual average daily temperature is 26.21°C with May has the highest average daily temperature which is 26.83 °C while December has the lowest average daily temperature which is 25.21°C. Figure 3 shows the monthly global solar irradiation and average ambient temperature for Changlun.

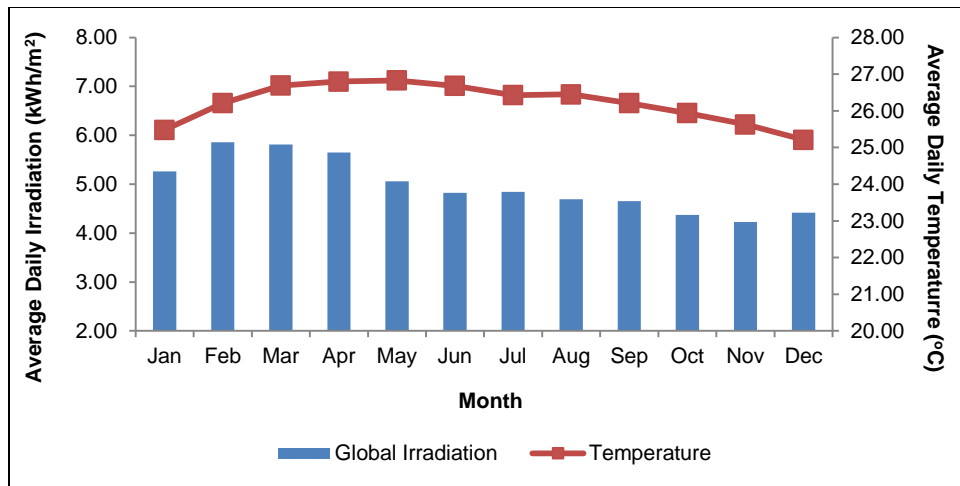


Figure 3. Average daily solar irradiation and average daily temperature for Changlun, Malaysia

2.3. Residential Load Profile

Generally, a residential house will consist of basic electrical appliances such as lightings, fans, phone’s charger, television, washing machine and refrigerator. The usage of these appliances is according to the lifestyles of residents. A study has been made to obtain an hourly load profile for a residential house, where a power monitoring device has been installed to monitor power consumption for a week at several houses in Changlun that used in average 200 kWh per month [19].

The average daily load profile is shown in Figure 4 where the average daily consumption is 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 until 9.00 am and between 7.00 pm until 11.00 pm daily. The annual load demand will be 2,434 kWh, assuming this daily load is constant throughout a year.

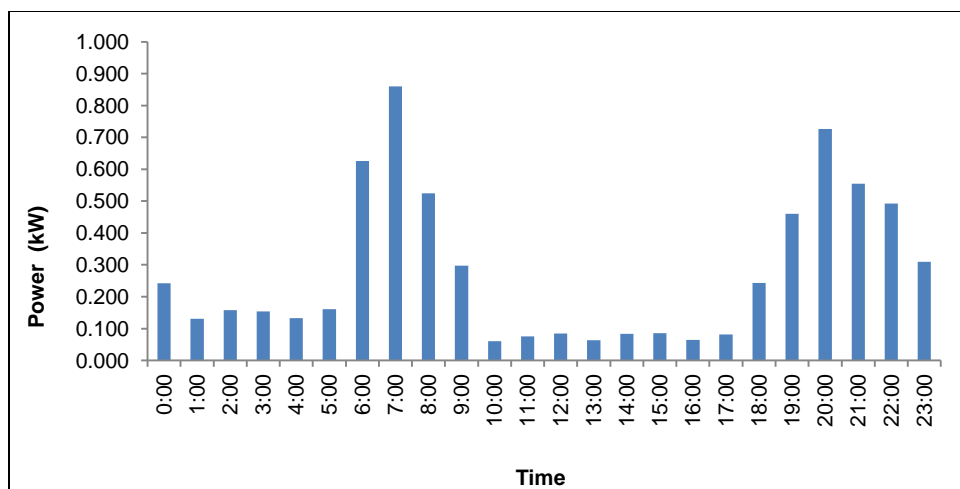


Figure 4. Average daily load profile for residential house in Changlun, Malaysia

2.4. PV 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) [20].

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

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

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

where γ_{pmp} is temperature coefficient for P_{mp} in % per °C, T_{cell_ave} is average daily maximum cell temperature and T_{stc} is cell temperature at standard test condition which is 25°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 °C, NOCT is nominal operation cell temperature in °C, $G_{amb_ave_max}$ is average daily maximum solar irradiance in W per m².

The PV module used in the simulation is a generic flat plat PV which is preloaded in the HOMER database. The efficiency of the module is 13% while the temperature coefficient -0.5 % / °C. The capital cost for the PV array per kW is RM 5,000 while replacement cost is RM 4,000 with 25 years of lifetime.

2.5. Battery 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 lead acid battery with 1 kWh capacity. The capital cost for a unit of battery is RM 800 while replacement cost is RM 700 with 10 years of lifetime.

2.6. Inverter

Inverter is a device used to convert DC input to AC output. In this simulation, the inverter is used in solar PV AC system to convert DC power from PV array to AC power for its load. The inverter efficiency is set to 95%. The capital cost for a kW of inverter is RM 300 with 15 years of lifetime

2.7. Economic Aspect

Economic aspect of the system is calculated and optimized by using HOMER Pro. The total net present cost (NPC) is the main economic output of the HOMER. This value will rank all system configurations in the optimization results. In addition, it will be the basis to calculate the total annualized cost and the levelized cost of energy. The total annualized cost is the annualized value of the total NPC which is calculated by using Equation (5).

$$C_{ann,tot} = CRF(i, R_{proj}) C_{NPC,tot} \quad (5)$$

where $C_{NPC,tot}$ is the total net present cost, i is the annual real discount rate, R_{proj} is the project lifetime and $CRF()$ is a function returning the capital recovery factor

The levelized cost of energy (COE) is the average cost per kWh of useful electrical energy produced by the system and is calculated by using Equation (6).

$$COE = \frac{C_{ann,tot}}{E_{served}} \tag{6}$$

where $C_{ann,tot}$ is total annualized cost of the system and E_{served} is total electrical load served per year.

3. RESULTS AND DISCUSSION

Homer Pro is used to simulate and produced optimization result for the system based on sensitivity input parameter. The results are divided into two parts which are solar PV DC system and solar PV AC system. Figure 4 and Figure 5 showed the Homer Pro schematic diagram for both systems. The sensitivity input parameters considered for this simulation are the renewable fraction of the energy delivered to the load and capacity shortage. 100% renewable fraction means the energy supplied to load is totally from solar PV while reduction of the fractional percentage value will increase the dependency to the utility grid supply. Capacity shortage means annual shortfall of the energy capacity of the system than the required value by the load. The capacity shortage could occur from downsizing the system to get lower initial capital cost and COE. Similarly, the utility grid energy will be used to accomodate the shortage of energy.

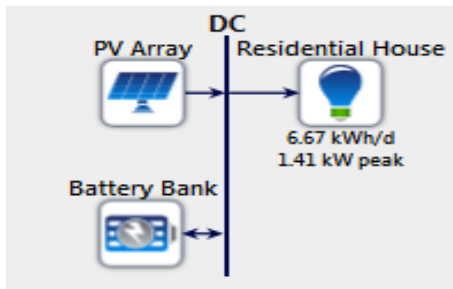


Figure 4. Homer Pro schematic diagram for solar PV DC system

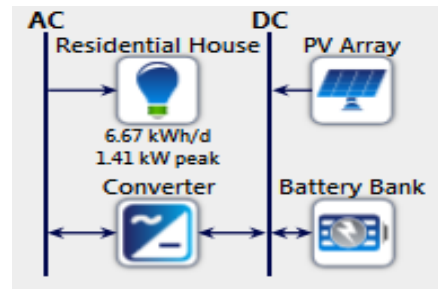


Figure 5. Homer Pro schematic diagram for solar PV AC system

3.1. Solar PV DC System

Figure 6 summarized the sensitivity result for the solar PV DC system. In order to obtain a system with totally independent from grid, it must be 100% renewable fraction with 0% capacity shortage in electricity supply throughout the year. Based on simulation, the PV array size required is 3.5 kW while the battery bank needs 32 units of batteries which are 4 units in series at 48V DC bus and 8 parallel strings. This configuration will have 69.1 hours of autonomy which is almost 3 days. However this setup required high initial capital cost which is RM 43,100 hence the COE will be RM 1.91 per kWh. Even though all loads demand will be met all over the year, it will have 37.1% of excess electricity produced by the PV array. In addition, the simulation also shows with increasing the energy shortage, the system sizing will reduced. This condition leads to a decrease in initial capital cost and COE values. However this situation is contrary to the objective of totally independent from the utility grid.

Sensitivity		Architecture			Cost		System				Battery Bank	
Renew	Cap.	⚠️	🔌	PV Array (kW)	Battery	COE (RM)	Initial capital (RM)	Excess Elec (%)	Excess Elec (kWh/yr)	Unmet load (%)	Unmet load (kWh/yr)	Autonomy (hr)
100	0			3.50	32	RM1.91	RM43,100	37.1	1,701	0.0398	0.969	69.1
100	10.0			2.50	16	RM1.40	RM25,300	17.8	584	6.68	163	34.6
100	15.0			2.50	16	RM1.40	RM25,300	17.8	584	6.68	163	34.6
100	20.0			2.00	16	RM1.36	RM22,800	4.78	125	13.5	328	34.6
100	5.00			3.00	16	RM1.46	RM27,800	29.6	1,165	4.05	98.5	34.6

Figure 6. Homer Pro sensitivity result for solar PV DC system

3.2. Solar PV AC System

Figure 7 summarized the sensitivity result for the solar PV AC system. In order to obtain a system with totally independent from grid, it must be 100% renewable fraction with 0% capacity shortage in electricity supply throughout the year. Based on simulation, the PV array size required is 4.0 kW, 1.5 kW inverter and 32 units of batteries which are 4 units in series at 48V DC bus and 8 parallel strings. This configuration will have 69.1 hours of autonomy which is almost 3 days. However this setup required high initial capital cost which is RM 46,500 hence the COE will be RM 2.03 per kWh. Even though all loads demand will be met all over the year, it will have 42.1% of excess electricity produced by the PV array. In addition, the simulation also shows with increasing the energy shortage, the system sizing will reduced. This condition leads to a decrease in initial capital cost and COE values. However this situation is contrary to the objective of totally independent from the utility grid.

Sensitivity		Architecture				Cost		System				Battery Bank
Rene	Capac		PV Arra (kW)	Batte	Conv (kl)	COE (RM)	Initial ca (RM)	Excess (%)	Excess (kWh)	Unmet (%)	Unmet (kWh)	Autonomy (hr)
100	0		4.00	32	1.50	RM2.03	RM46,500	42.1	2,206	0.0367	0.893	69.1
100	10.0		2.50	16	1.50	RM1.49	RM26,200	14.9	489	8.25	201	34.6
100	15.0		2.50	16	1.00	RM1.48	RM25,900	15.1	496	8.45	206	34.6
100	20.0		2.00	16	1.00	RM1.45	RM23,400	3.25	85.1	16.4	399	34.6
100	5.00		3.50	16	1.00	RM1.60	RM30,900	36.3	1,666	3.73	90.8	34.6

Figure 7. Homer Pro sensitivity result for solar PV AC system

3.3. Analysis

Based on the simulation results in 4.1 and 4.2, the solar PV AC system have shown almost 8.0% increased in initial capital cost and 6% higher COE than the solar PV DC system. This is due to the fact that solar PV AC system required additional equipment which is inverter to convert DC power from PV array into AC power for its load. In addition, it also required slightly larger PV array sizes to compensate losses due to the inverter efficiency which is not counted in DC system.

Despite the differences, both systems have shown positive aspect in environmental conservation where the 2,434 kWh energy generated from renewable resource annually and consumed by the loads has replaced the fossil fuel based power from grid. This value is equivalent to almost 1.7 tons of CO₂ avoidance to the environment.

In addition, sensitivity analysis has been done together with the simulation to investigate the effect of small capacity shortages which are 5%, 10%, 15% and 20%. The results shown that PV array and battery bank sizes will decreased that will lead to the reduction of initial capital cost, COE and the percentage excess energy produced. However, the percentage of not fulfilling to total load demand will increase hence relying more on fossil fuel based grid electricity.

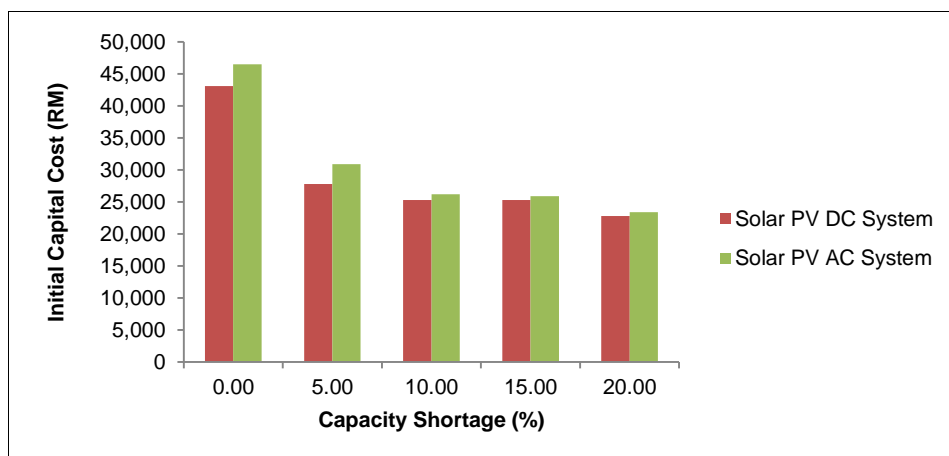


Figure 8. Comparison between Initial Capital Costs of Solar PV DC System and Solar PV AC System

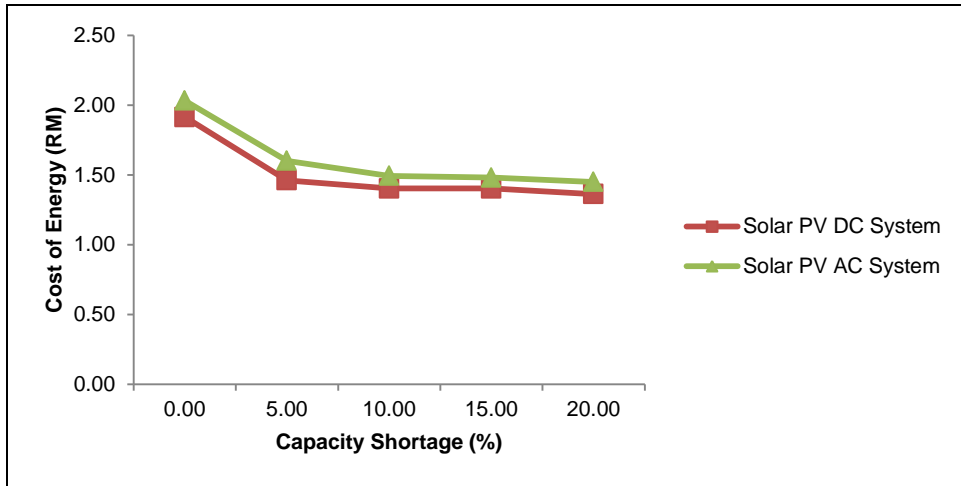


Figure 9. Comparison between COE of Solar PV DC System and Solar PV AC System

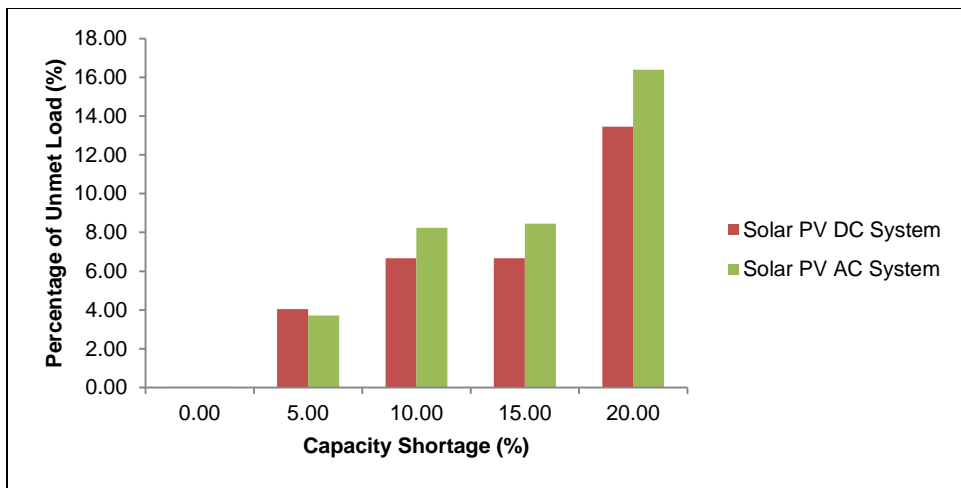


Figure 10. Comparison between Percentages of Unmet Load of Solar PV DC System and Solar PV AC System

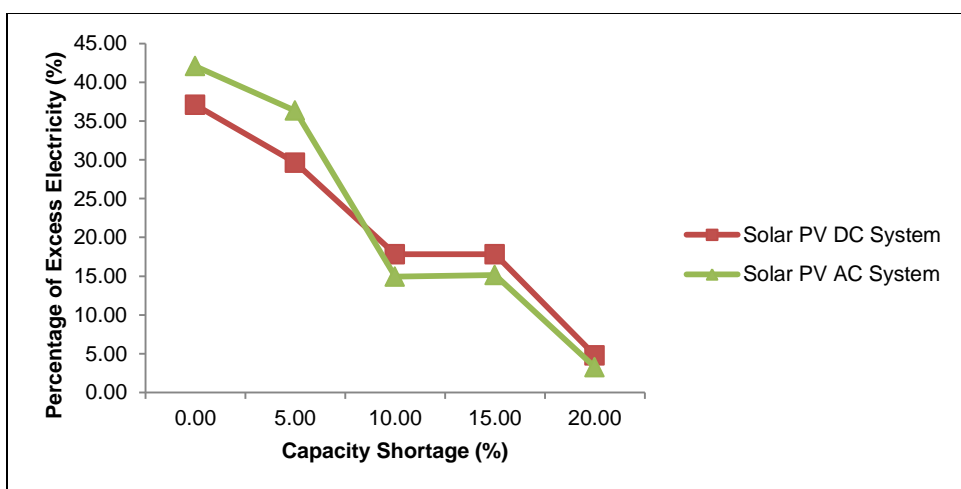


Figure 11. Comparison between Percentages of Excess Energy of Solar PV DC System and Solar PV AC System

4. CONCLUSION

Sizing and cost analysis of self-consumed solar PV DC system compared with AC system for residential house in Changlun, Malaysia has been presented in this paper. The analysis has been carried out by using Homer Pro software simulation. Based on the results obtained, the conclusions were:

- a. From design aspect, solar PV AC system required slightly larger PV array sizes than the solar PV DC system. This is to compensate losses due to the inverter efficiency which is not counted in DC system.
- b. From economic aspect, the solar PV AC system is almost 8.0% more expensive in initial capital cost than the solar PV DC system. In addition, the COE for the solar PV AC system is 6% higher the solar PV DC system. This is due to the additional equipment which is inverter to convert DC power from PV array into AC power for its load.
- c. From the environmental aspect, both the systems show positive aspect for the environmental conservation where 2,434 kWh of annual load demand are totally supplied from solar PV, has replaced the fossil fuel based power from grid equivalent to almost 1.7 tons of CO₂ avoidance to the environment annually.

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