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Optimal Sizing of Decentralized Photovoltaic Generation and Energy Storage Units for Malaysia Residential Household Using Iterative Method

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Abstract. World's fuel sources are decreasing, and global warming phenomena cause the necessity of urgent search for alternative energy sources. Photovoltaic generating system has a high potential, since it is clean, environmental friendly and secure energy sources. This paper presents an optimal sizing of decentralized photovoltaic system and electrical energy storage for a residential household using iterative method. The cost of energy, payback period, degree of autonomy and degree of own-consumption are defined as optimization parameters. A case study is conducted by employing Kuala Lumpur meteorological data, typical load profile from rural area in Malaysia, decentralized photovoltaic generation unit and electrical storage and it is analyzed in hourly basis. An iterative method is used with photovoltaic array variable from 0.1kW to 4.0kW and storage system variable from 50Ah to 400Ah was performed to determine the optimal design for the proposed system.

1 Introduction

World's electricity production is severely depending on coal, oil and natural gas as energy supply. However, fuel sources are decreasing, and global warming phenomena cause the necessity of urgent search for alternative energy sources. The use of renewable energy (RE) reduces the dependency on fossil fuels, and it is proven that RE has great potential and can be utilized to fulfill world energy demand [1].

Among other alternative energy available, photovoltaic (PV) system is the most promising RE in Malaysia. In the future, it is expected more installation of decentralized PV generation units combined with electrical storage in Malaysia's distribution network.

Grid tied decentralized PV generation system has numbers of advantages; modularity system, reduce dependency on conventional energy supply, environmental friendly [2] and the excess energy can be sold to utility [3], which entitled for bill reduction. Even though its potentials are proven, the coincidence of local load requirement with PV generation needs to be studied.

This paper introduces the new power management for interaction between electrical household demand, decentralized PV generation and electrical storage unit. This paper identifies the optimum configuration for PV array and storage capacity required to supply a specific load demand over a year. The optimization of system's parameters were performed under criteria of favoured cost of energy (COE), payback period (PP), degree of autonomy (DA) and degree of own consumption (DO).

2 System configurations

Figure 1 shows a schematic diagram for the proposed system. Referring to the figure, PV generator is used as a decentralized power source operating in grid parallel operation mode with public network. Electrical storage unit acts as the main backup power supply. Excess energy from PV plant can be sold to utility, and utility also act as backup energy when electrical storage reaches maximum depth of discharge (DOD)

The residential loads considered in the case study are only resistive loads. Figure 2 shows a typical hourly load profile for a residential house in Malaysia [4], [5] with the total daily load demand of 2.215 kWh. It is assumed that the energy requirement remains the same in each day for a year period.

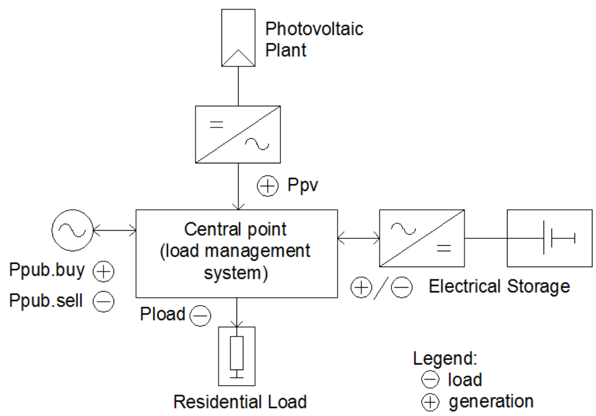

Figure 1. System configurations for a residential load in grid parallel operation mode with PV array, electrical storage and utility.

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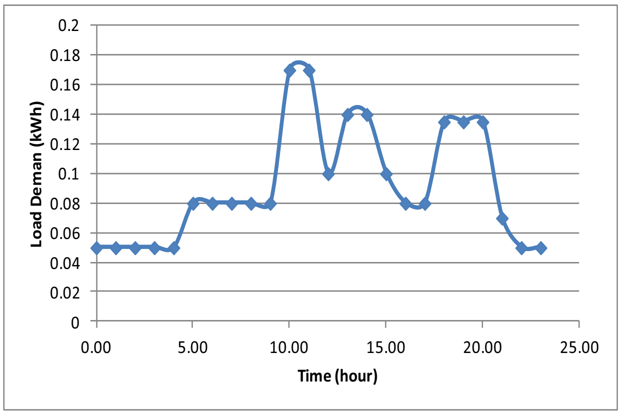

Figure 2. Hourly load profile [4], [5].

3 System design

In this paper, the proposed power management strategies algorithm is summarized in Figure 3. The simulation is performed by iterating the PV array variable (0.1kW - 4.0kW) and also the storage system variable (50Ah - 400Ah). The priority of the management strategies is to optimize all PV energy output to supply demand. When PV output is higher than load demand, it is used to charge the battery and sell the surplus power to public network. However, when PV energy generation is not enough to supply the household load, battery will be discharge. If battery reaches lowest DOD, the additional energy for the load is supply or bought from utility.

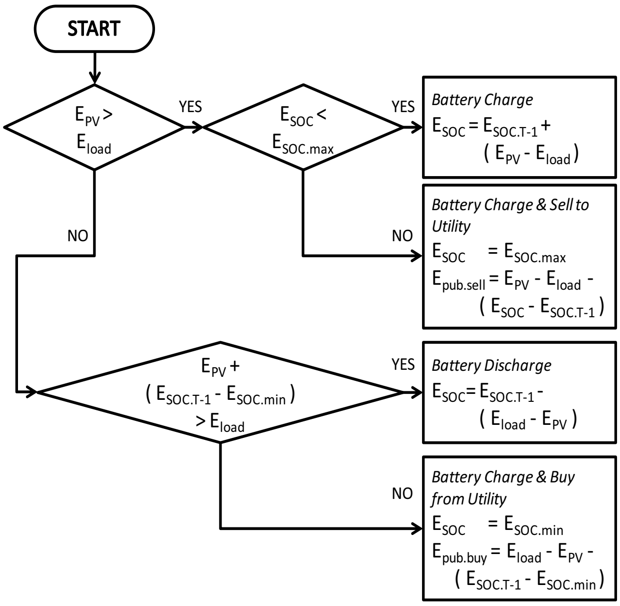

Figure 3. Power management strategies algorithm.

3.1 PV array modeling

PV output size must able to fulfill load demand with extra energy to cover system losses. In the analysis, Kuala Lumpur's hourly climate data is used. The hourly energy generated by PV array, E_{pv} is calculated using Equation (1) [3], [6]. *PSH* is peak sun hour over the period of interest (one hour), P_{mp_stc} is PV's maximum power output in standard test condition, *STC*, N_{pv} is number of PV module in the array, η_{temp} is temperature de-rating factor, η_{wire} is cable efficiency, η_{inv} is inverter efficiency, η_{mm} is module mismatch, and η_{dirt} is dirt derating factor.

$$E_{pv}(t) = PSH(t) * P_{mp\_stc} * N_{pv} * \eta_{temp} * \eta_{wire} * \eta_{inv} * \eta_{mm} * \eta_{dirt} \quad (1)$$

3.2 Battery modeling

Estimation of battery state of charge (SOC), E_{bat} analysis is shown as Equation (2) [4], [7] (charging/discharging and self discharge efficiency is ignored). I_{bat} is battery capacity in Ah, and V_{bat} is battery's nominal voltage. Minimum SOC, $E_{SOC.min}$ is 50% of its full capacity.

$$E_{bat}(t) = Q_{bat}(t) * V_{bat} \quad (2)$$

3.3 Inverter size selection

Inverter is expected to deliver maximum AC load in household. Hence, inverter's power rating for battery system, P_{inv_bat} is selected using Equation (3), where P_{ACload} is total power from AC load demand and 1.25 is set as oversized factor [2].

$$P_{inv\_bat} = P_{ACload} * 1.25 \quad (3)$$

Inverter's power rating for PV array, P_{inv_pv} is selected using Equation 4:

$$P_{inv\_pv} = SF_{inv\_pv} * P_{mp\_stc} * N_{pv} \quad (4)$$

where SF_{inv_pv} is inverter-to-PV sizing factor (0.80) [2], and N_{pv} is quantity of PV modules in the system.

4 System optimization criteria

In order to select an optimum combination, four analyses were used to determine the ideal parameters for PV plant and electrical storage unit. To find optimum configuration with the lowest investment possible, it is inevitable to use economic analysis. Therefore, Cost of Energy (COE) and Payback period (PP) is used. Meanwhile, Degree of Autonomy (DA) and Degree of own-much energy generated from PV plant are used in residential household.

4.1. Cost of energy

COE (RM/kWh) is defined as the average cost per kWh of electrical energy produced by the system when a lifetime, investment cost, replacing, operation & maintenance, and capital cost is considered [8]. Based on technical datasheet, the batteries need to be replaced for every 5 years and inverter need to be replaced every 10 years [5]. Lower COE is desirable and it is calculated by dividing producing electricity annualized life cycle cost, LCC_{1year} with E_{PV} [9]. The market price for system components is summarized as in Table 1 [9], [10].

$$LCC = C_{pv} + C_{controller} + C_{bat} + C_{inv} + C_{install} + C_{batrep} + C_{invrep} + C_{O\&M\_25years} - C_{salvage} \quad (5)$$

$$LCC_{1year} = \frac{LCC}{\left[\frac{(1+i)^N}{i(1+i)^N}\right]} \quad (6)$$

$$COE = \frac{LCC_{1year}}{E_{PV}} \quad (7)$$

4.2. Payback period

PP is used to determine the time it would take to recover or break even on initial investment cost and ongoing O&M cost [11]. E_{sell} is energy fed back to utility during surplus energy from PV and E_{buy} is energy bought from utility during lack of PV output. Meanwhile, feed in tariff, *FIT* is different for each country, and for Malaysia, it is RM 1.35/kWh in 2015 [10]. Each energy unit bought from utility is provided by Tenaga Nasional Berhad, *TNB* [12]. Shorter payback period are more desirable.

$$PP = \frac{LCC}{\left(\sum_{365}^{T} E_{sell} * FIT\right) - \left(\sum_{365}^{T} E_{buy} * TNB\right)} \quad (8)$$

Table 1. Components' pricing.

Component		Unit	Price
Module		RM/Wp	5.000000
Battery		RM/Output Watt Hour	0.041667
Inverter		RM/Continuous Watt	1.000000
Support Structure & Installation cost		RM/Wp	4.000000
FIT	Basic FiT rates up to and including 4kW	RM/Wh	0.000917
	Use as installation in buildings or building structures	RM/Wh	0.000172
	Use as building materials	RM/Wh	0.000166
	Use of locally manufactured or assembled solar PV modules	RM/Wh	0.000050
	Use of locally manufactured or assembled solar inverters	RM/Wh	0.000050
TNB Bill pricing tariff		RM/Wh	0.000218

4.3. Degree of autonomy

DA shows how much energy provided from decentralized PV generator and directly used in residential household compared to the whole energy demand. It is calculated using Equation (9) [13]:

$$DA = \frac{\sum_{365}^{T} E_{pv} - \sum_{365}^{T} E_{sell}}{\sum_{365}^{T} E_{pv} - \sum_{365}^{T} E_{sell} + \sum_{365}^{T} E_{buy} - E_{bat\_start} + E_{bat\_end}} \quad (9)$$

where E_{bat_start} is initial battery's energy and E_{bat_end} is battery's energy at the end of the period. Higher DA is desirable for optimum configuration.

4.4. Degree of own-consumption

Meanwhile, DO shows how much energy is provided from decentralized PV plant that is directly used by the residential household compared to the provided power by PV generator. It is calculated as Equation 10 [13]. However, contrast with DA, optimum design tends to have lower DO.

$$DO = \frac{\sum_{365}^{T} E_{pv} - \sum_{365}^{T} E_{sell}}{\sum_{365}^{T} E_{pv} - E_{bat\_start} + E_{bat\_end}} \quad (10)$$

5 Results and discussion

Figure 4, 5, 6 and 7 show the analyses results based on the optimization criteria as stated in equations 7, 8, 9 and 10. Referring to Figure 4, it shows the results from COE analysis as the optimization criteria. It can be seen that when battery capacity ranged from 50Ah to 100Ah is paired with PV capacity from 3kW to 4kW, the system obtained the lowest COE of RM 0.57/kWh.

Figure 5 is obtained after payback period analysis was performed; it is observed that for all combination of battery capacity at the PV ranged from 0.3kW to 0.9kW gives the payback period more than 20 years. Hence, it can be concluded that any configuration within the specified range of PV capacity is not feasible. This is due to insufficient PV output, which causes the total benefit obtained from selling energy to utility is inadequate to break-even on LCC system. However, for all pairs of battery capacity at the PV ranged from 3.45kW to 4kW gives PP lower than 8 years.

Hence, the lowest PP and DO values obtained are 7.333 years and 0.1436p.u respectively at the combination of 4kW PV array and 50Ah battery capacity. Meanwhile, the highest DA obtained using the configuration of 4kW PV capacity and 100Ah is 0.9998p.u.

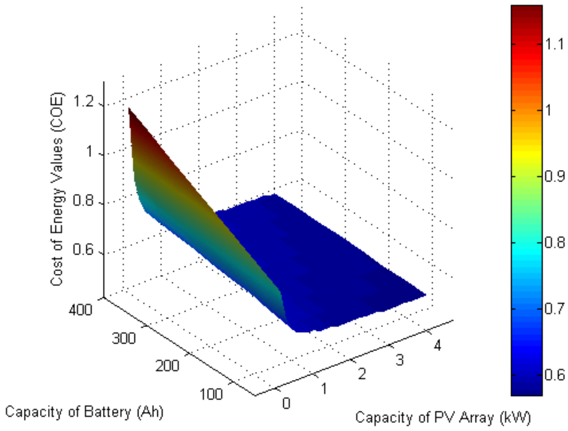

Figure 4. Results of COE analysis.

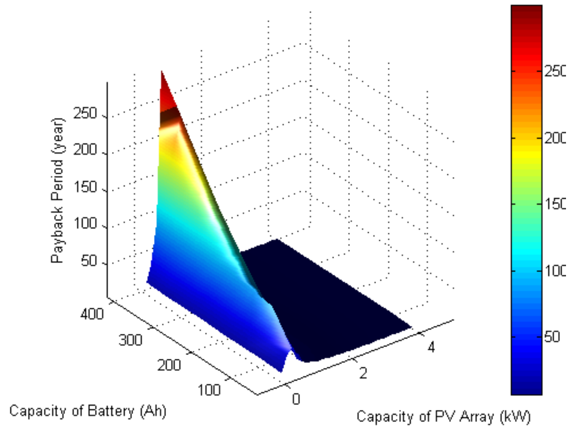

Figure 5. Results of PP analysis.

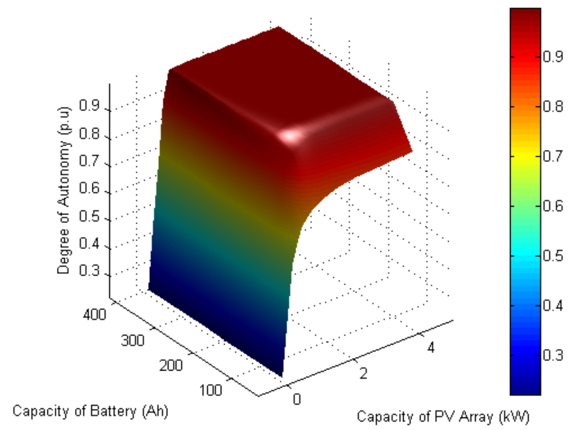

Figure 6. Results of DA analysis.

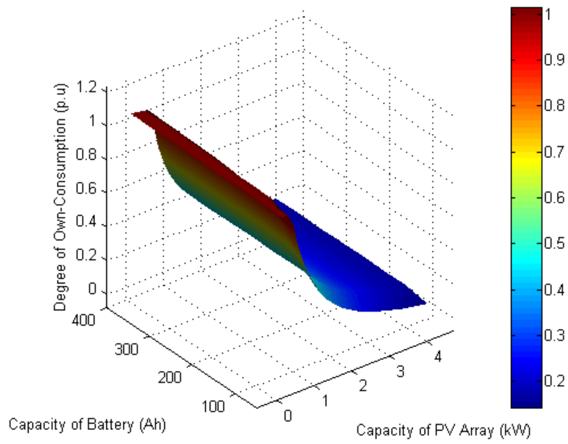

Figure 7. Results of DO analysis.

6 Conclusions

The optimal sizing of decentralized photovoltaic generation and energy storage units for Malaysia residential household has been presented. From the results obtained, the most favorable design is either a system of PV capacity 4kW and 50Ah or 100Ah battery capacity, which is obtained from the lowest DO or the highest DA value. However, based on the observation, it is wiser to select the best combination parameters using DA analysis. It is because DA indicates which design has high degree of energy independence from local utility with lowest COE and low PP. The selected parameter pair is able to use most energy from PV generator directly in residential household, with low energy need to be bought from utility and has small changes between initial and ending battery's capacity.

This has proven that it is possible to effectively use RE sources and storage that allows the system to be independent from utility, and gain profit from solar FIT.

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