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Optimal sizing of building integrated hybrid PV/diesel generator system for zero load rejection for Malaysia

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ABSTRACT

In this research, an optimisation for building integrated hybrid PV/diesel generator system for zero load rejection for Malaysia is performed. The optimisation is performed considering a loss-of-load probability (LLP) less than 0.01. However, the daily averages of solar energy for Malaysia and a mathematical model of a hybrid PV/diesel generator system are used in this optimisation. The optimisation presented in this paper aims to calculate the optimum capacities of a PV array and diesel generator, which investigate the minimum system cost. An optimisation problem in terms of system units' cost is solved graphically in this study. Moreover, the optimised system is compared to other energy source choices to highlight its feasibility. The recommended configuration of a PV/diesel system located in Malaysia is $C_A = 1.2$, $C_{DG} = 0.3$, while the optimum C_B is 0.1. The results of the optimisation show that a PV/diesel generator choice is more feasible compared to a standalone PV system or diesel generator system because it reduces the system cost by 35%.

1. Introduction

Photovoltaic (PV) system installation has played an important role in the solar industry because PV systems are clean, environment friendly and secure energy sources. However, the drawback of PV systems is their high capital cost compared to that of conventional energy sources. Therefore, many research studies have focused on the optimisation of PV systems, such as hybrid PV/diesel generator systems, so that the number of PV modules and diesel generator capacity can be optimally selected. Hybrid PV/diesel generator system size and performance strongly depend on available solar energy, and therefore, to optimise the system, extensive studies related to the solar energy at the site where the system is installed must be performed [1]. However, The utilization of PV systems compared to other renewable energy sources in green building has been investigated in many researches. In [2] the authors claimed that the least investment occurred when PV system is included in the design. In addition, the authors of [3] in a study case of Canada claimed that, solar electricity through PVs is technologically the most suitable one to meet the electricity demand. In [4], the authors studied the impact of the building integrated PV systems in Spain and concluded that this technology presents an interesting potential for decentralized generation in urban areas in sunny countries, even when considering vertical facades at low latitudes. On the other hand, the authors of [5] concluded that the integration of PV systems with other renewable systems provides a viable option for powering stand-alone greenhouses in a self-sustained manner.

Optimisation studies on hybrid PV/diesel systems size can be found in [6–12]. An hourly solar energy series, a model of hybrid PV/diesel system and an hourly load profile are used in the optimisation of PV/diesel generator system in [6]. A genetic algorithm is used to solve the optimisation problem in terms of the PV panel cost, battery cost, inverter cost, charge controller cost, diesel generator cost, fuel cost and maintenance costs. However, the optimisation problem described in this research has not been subjected to any constraint, and therefore, the availability of the designed system is not defined. In [7], the optimisation of PV-hybrid energy systems is presented. A configuration of the system and a control strategy are optimised by a genetic algorithm. The control of the system is coded as a vector whose components are five decision variables for every hour of the year. However, it is not clear how the optimal vector would be implemented physically in the system or how the variation of weather would change the operation of the system. In [8], a method for the optimal sizing of PV/diesel systems is presented. The optimisation procedure starts by modelling the diesel generator and then optimising the PV and battery sizes by determining the minimum number of storage days and the

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minimum PV array area based on a well-defined weather profile. In [9], dispatch strategies for the operation of a hybrid PV/diesel generator system set points is presented. In addition, a determination of the optimum values of set points for the starting and stopping of the diesel generator to minimise the overall system costs is presented. This optimisation is performed using a computer program for a typical dispatch strategy that predicts the long-term energy performance and the lifecycle cost of the system. In [10], a PV/diesel generator hybrid system with battery backup for a village located in Saudi Arabia is suggested. This optimisation is conducted using HOMOR software and hourly solar radiation data. The authors suggested many configurations of the desired system using four generators of different rated powers, diesel prices, different sizes of batteries and converters to find an optimal power system for the village load demand. In [11], a PV/diesel generator hybrid system for remote and rural areas is suggested to assist in expanding the electricity access in the tropical region. The authors of this paper claim that the combination of renewable energy sources such as PV or wind with diesel generator improves reliability and reduces the initial cost of the system. An optimisation study on hybrid PV/diesel system for Malaysia is presented in [12]. In this research, the importance of applying hybrid PV/diesel generator in Malaysia is highlighted. In addition, a technological feasibility study for applying such system in Sabah, Malaysia was conducted. The studied case was represented by a school load demand supplied by a 150-kW diesel generator; therefore, the authors of [12] discussed the option of applying PV system as an assistant system to reduce fuel cost and carbon emission. The authors in [12] suggested adding a 35-kWp PV array to the existing diesel generator, though this PV system is supposed to supply about 30% of the demanded energy. However, it is noted that this combination is not optimal based on the results of the proposed method.

The main objective of this paper is to determine the optimum configuration of PV/diesel generator system for Malaysia. The optimum configuration indicates the optimum PV array and diesel generator capacities that lead to minimum system cost. Moreover, a system cost comparison between hybrid PV/diesel system, PV system and diesel generator is discussed to highlight the feasibility of the proposed system. Finally, daily averages of solar energy for Malaysia are used in the optimisation. These data were provided by the Solar Energy Research Center (SERI), Universiti Kebangsaan Malaysia.

2. Building's load demand and its possible power supplies

In this research, the building load demand was supposed to be 100 kWh/day with 8.3 kW as a peak demand at a 400-V line voltage. In this section, the feasibility of supplying this load demand by PV system and diesel generator as individual systems is discussed.

2.1. Sizing of the PV system for supplying the considered load demand

In general, the sizing of the PV system is represented by calculating the number of needed PV modules and storage battery capacity. However, to achieve a zero load rejection, the loss of load probability (LLP) of the designed system must be less than 0.01. The loss of load probability is given by

$$\mathrm{LLP} = \frac{\sum_{i=1}^{366} \mathrm{Energy\ deficits}_i}{\sum_{j=1}^{366} \mathrm{Energy\ demand}_j} \tag{1}$$

The required PV modules and battery capacity can be calculated using some of the formulas below

$$P_{PV} = \frac{E_L}{\eta_s \eta_{inv} PSH} S_f \tag{2}$$

where E_L is daily energy consumption, PSH is the peak sun hours, η_s and η_{inv} are the efficiencies of the system components and S_f is the safety factor that represents the compensation of resistive losses and PV-cell temperature losses. On the other hand, the battery capacity can be calculated by,

$$C_{Wh} = \frac{E_L * \mathrm{Number\ of\ autonomous\ days}}{V_B \mathrm{DOD} \eta_B} \tag{3}$$

where V_B and η_B are the voltage and efficiency of the battery block, respectively, while DOD is the permissible depth of discharge rate of a cell [13]. Using Eqs. (2) and (3), the required PV power is 16.2 kWp and 207.6 kWh, respectively. These results do not investigate a zero load rejection (LLP < 0.01) because the LLP of such system is around 0.08, which is very high. In [14], the optimisation of a PV system at certain LLP for Malaysia is proposed. Based on [14], the required PV system ratings for supplying 100 kWh/day at LLP = 0.01 is 32.7-kWp and a 6.6-KAh storage battery. Table 1 shows the cost of the designed PV system.

2.2. Sizing of the diesel generator for supplying the considered load demand

To supply the considered load demand using a diesel generator, an 11 kVA diesel generator at a 0.85 power factor is required. Table 2 shows the cost of this system.

From Tables 1 and 2, the PV system choice is less expensive than the diesel generator choice. However, a more feasible choice can be achieved by combining the two energy sources in a hybrid PV/diesel generator system based on the results is shown in Section 4.

3. Modelling of the hybrid PV/diesel system

Fig. 1 shows the proposed hybrid PV/diesel system. The proposed system consists of a PV array, battery, diesel generator, DC–DC and AC–DC converters. The main load of the proposed system is represented by a building that consumes 100 kWh/day with an 8.3 kW peak load demand. Meanwhile, the system is connected to the main grid to inject the excess energy in case any exists. The system in Fig. 1 is supposed to have the PV array as a main source with a backup battery while the diesel generator is operated in deficit times. The deficit time is defined as the time in which the instantaneous produced energy form the PV array is not enough to cover the load demand. However, the operation of the PV array, the battery and the diesel generator is organised by an automatic transfer switch (ATS).

The daily energy produced by a PV module/array is given by

$$E_{PV} = A_{PV} * E_{sun} * \eta_{PV} * \eta_{inv} * \eta_{wire} \tag{4}$$

where A_{PV} is the area of the PV module/array and E_{sun} is daily solar irradiation. η_{PV}, η_{inv}, and η_{wire} are efficiencies of PV module, inverter and wires, respectively.

The energy at the front end of a hybrid PV/diesel system or at the load side is given by

$$\mathrm{Energy\ difference} = \sum_{i=1}^{366} (E_{PV} - E_L) \tag{5}$$

where E_L is the load daily energy demand.

The result of Eq. (5) is that it may be either positive ($E_{PV} > E_L$) or negative ($E_{PV} < E_L$). If the energy difference is positive, then there is an excess in energy (EE), while if it is negative, there will be an energy deficit (ED). The excess energy is stored in batteries to be

Table 1
PV system cost for zero load rejection.

No.	Item	Unit price (USD)	Quantity	Price (USD)	Life time years
1	PV modules	3.71/Wp	38.5 kWp	142,835	20
2	Support structure	50	80	4000	20
3	Storage battery	2/Ah	6.6 kAh*2	26,400	20
4	Charge regulator	12,000	1	12,000	20
5	Inverter	6000	1	16,000	20
6	Circuit breakers	200	2	400	20
7	Installation materials	–	–	500	–
8	Civil work	–	–	3000	–
	Total			205,135	20

Table 2
Diesel generator cost for zero load rejection.

No.	Item	Unit price (USD)	Quantity	Consumption	Price (USD)	Life time years/h
1	DG capital cost	6000/DG	2	–	12,000	13 years
2	Diesel	0.6/L	350, 400 L	3.5 L/h	183,960	–
3	Engine oil	1.4/L	2920 L	5 L/150 h	4088	–
4	Diesel filter	4.5	117	–	525	750 h
5	Air filter	35	29	–	1022	3000 h
6	Overhaul	1500	3	–	4500	26,280 h
	Total				206,095	20

used in case of energy deficit. Meanwhile, the energy deficit can be defined as the inability of the PV array to provide power to the load at a specific time. At this time, the diesel generator will be operated in case the PV array cannot cover the load demand. Moreover, the storage battery will operate in the cases where the PV array and the diesel generator cannot cover the load demand. However, the annual energy amount supposed to be stored in the storage battery is given by

$$E_B = \left(\sum_{i=1}^{366} \text{Energy excess}\right) \eta_{\text{charge}} \tag{6}$$

where η_{charge} is the charging efficiency of a storage battery. The expected daily storage battery capacity can be calculated by dividing the result of Eq. (6) by the number of days in a year.

4. Optimisation of hybrid PV/diesel generator system

In this section, the optimum combination of PV array and diesel generator is chosen first, and then the optimum capacity of the storage battery is calculated. However, to generalise the obtained results, the following assumptions must be considered:

$$C_A = \frac{E_{PV}}{E_L} \tag{7}$$

$$C_{DG} = \frac{E_{DG}}{E_L} \tag{8}$$

$$C_B = \frac{E_B}{E_L} \tag{9}$$

Fig. 2 shows the optimisation algorithm for the proposed hybrid PV/diesel generator system for zero load rejection. The algorithm starts by obtaining the PV module and diesel generator specifications. These specifications include the following: PV module

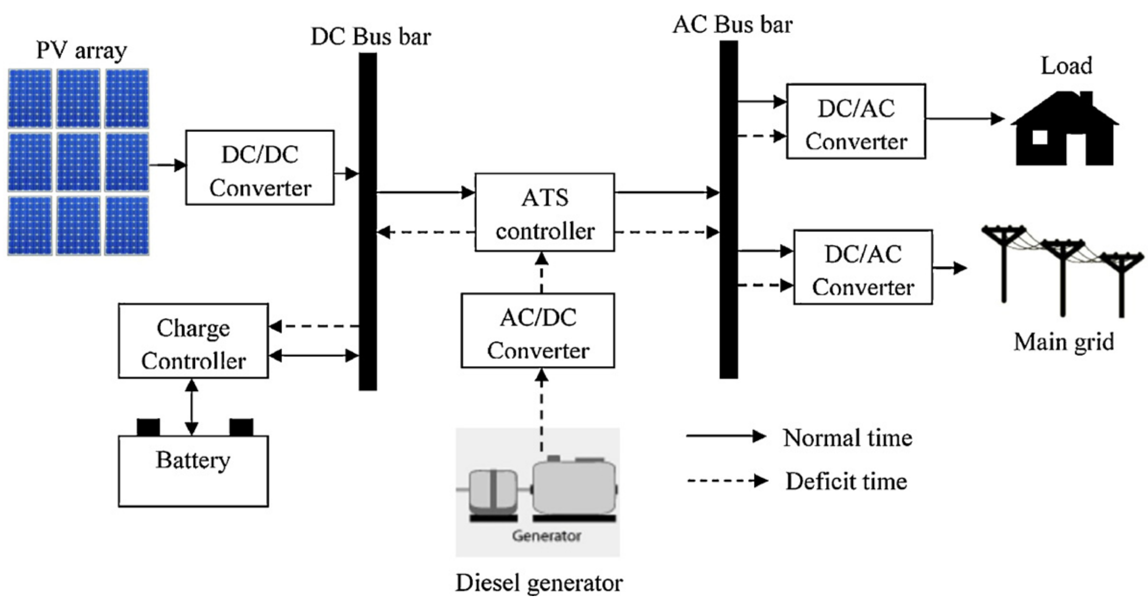

Fig. 1. Proposed hybrid PV/diesel system configuration.

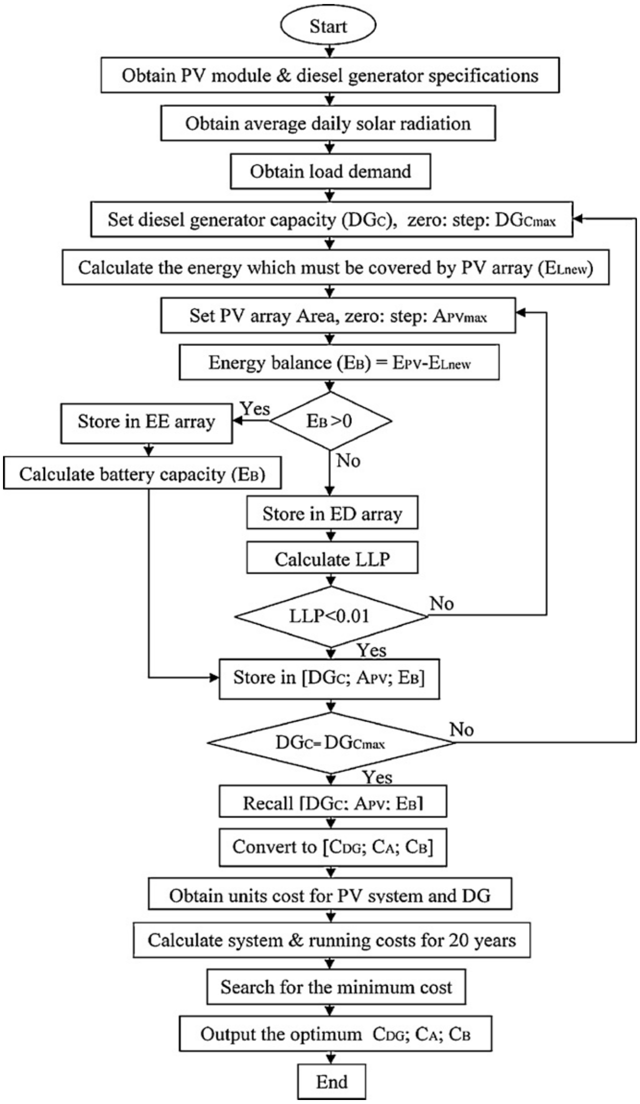

Fig. 2. Optimisation algorithm.

conversion efficiency, PV module peak power, PV module area, PV module standard operation conditions, diesel generator fuel and oil consumption, diesel generator operation power factor and diesel generator. Furthermore, battery specifications such as charging efficiency, allowable depth of charge (DOD) and battery nominal voltage are required. In the second phase of the optimisation, a time series of daily solar energy records for the targeted site is needed. These data are used in modelling the PV array based on the fact that the PV array output energy depends on the available solar energy. However, the proposed optimisation technique aims to find the least expensive configuration of a PV array and diesel generator at LLP less than 0.01; therefore, an array containing a PV array capacity, storage battery capacity and diesel generator capacity at certain LLPs is required. To do so, a range of diesel generator capacities is set. The initial value of this range is supposed to be zero (i.e., there is no existence of the diesel generator and the load is supplied by the PV array only), while the maximum value of the range is supposed to be equal to the load demand (i.e., the load is fully supplied by the diesel generator). When a diesel generator capacity value is set, the PV array must cover the remaining load demand. Therefore, the value of the load that must be covered by the PV array after setting the diesel generator capacity is given by

$$E_{new} = E_{DG} - E_L \tag{10}$$

After setting the diesel generator capacity and calculating the load that must be supplied by the PV array, an iterative loop is applied to calculate the LLP and battery capacity at different values of PV array area and diesel generator capacities. The range of PV array area is also set from zero to the capacity of PV area that can produce daily energy covers the daily load demand. However, during this loop, only the values of PV array capacity that produce an LLP less than 0.01 are stored in an array. This iterative loop is repeated until reaching the maximum value of the PV array area, and then a new diesel generator capacity is set and the previous loop is repeated until the maximum value of the diesel generator is reached. After constructing the desired array, a conversion of this array value using Eqs. (7–9) is performed to generalise the obtained results. Here, the optimal choice is begun after obtaining units cost of PV system and diesel generator. The unit cost includes the cost of Wp per PV module, Ah per battery, charge controller, inverters, diesel per litre, oil per litre, support structures, maintains and installation. Eventually, the optimal choice can be found by a graphical solution for the resulting sizing curve. The optimisation problem of this paper is presented in Eq. (11). The objective function of the optimisation problem is in terms of a unit cost equation that describes the capital cost of a hybrid PV/diesel generator system in terms of PV module, battery, PV module support structures (ST), power electronic devices (PE), diesel generator capital cost (DG_{kVA}), diesel generator running, system maintaining (DG_{run}) and system installation as follows:

$$\left\{\begin{array}{l}\text{Minimise}: \ \text{SYSTEM}_{\text{cost}} = \alpha PV_{Wp} + \beta B_{Ah} + \Phi ST + \xi PE + \delta DG_{KVA} + \mu DG_{run} + \rho \\ \text{Subject to}: E_L(t) \le E_B(t)\cdot B_{Ah} + E_{PV}(t)\cdot PV_{Wp} + E_{DG}(t).DG_{kVA}\end{array}\right\} \tag{11}$$

where α, β, Φ, ξ, δ, and μ are the costs of ($/Wp) of the PV array, ($/Ah) of storage, ($/unit) of sport structure, ($/kWp) of the power electronic converters (DC-DC, AC-DC and DC-AC converters), ($/KVA) of the diesel generator and ($/kWh) of the diesel generator, respectively. Meanwhile, ρ contains the other costs such maintenance, installation and commissioning and is considered to be constant. $E_L(t)$ is the average daily load demand at t, while $E_B(t)$, $E_{PV}(t)$ and E_{DG} are the average daily output energy of the storage battery, PV array and diesel generator, respectively.

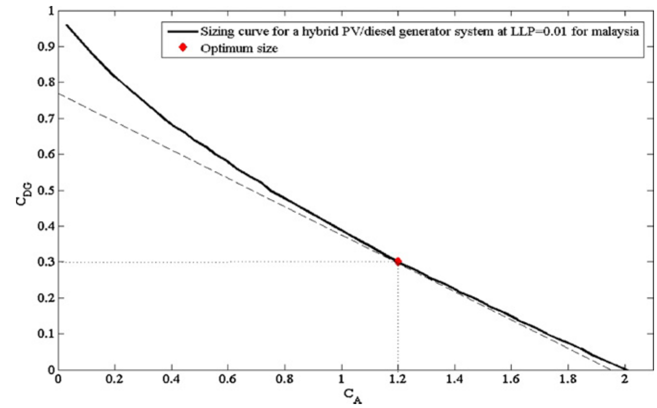

Fig. 3. Solution of the optimisation problem described in Eq. (11).

Fig. 3 shows the sizing curve for the PV/diesel generator at LLP < 0.01 for Malaysia. The tangent point between the sizing curve and the linear line represents the optimum solution of the optimisation problems described in Eq. (11). Based on Fig. 3, the optimum

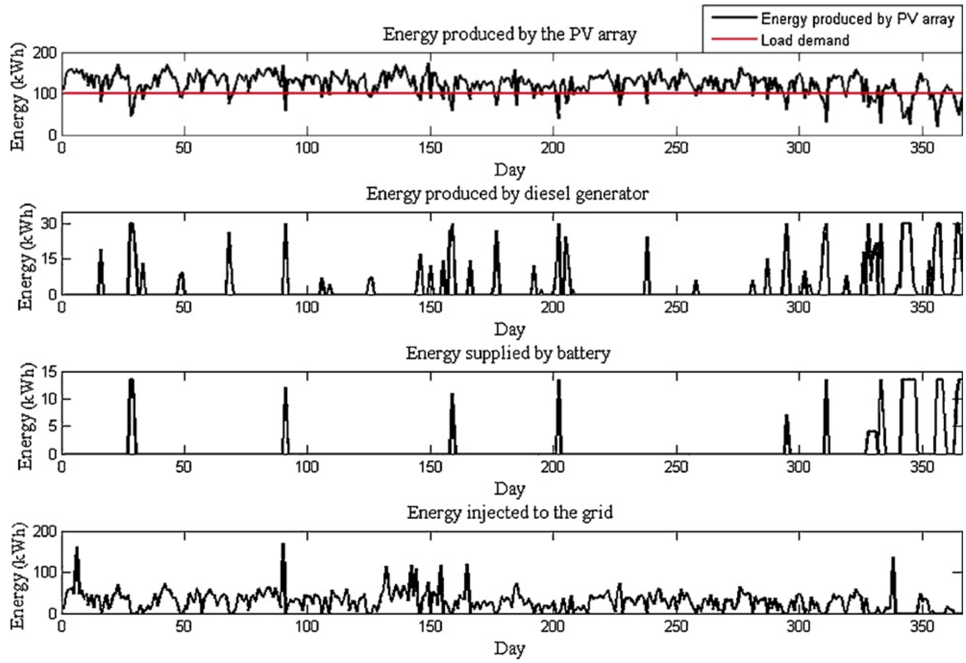

Fig. 4. Energy production and flow in the proposed system.

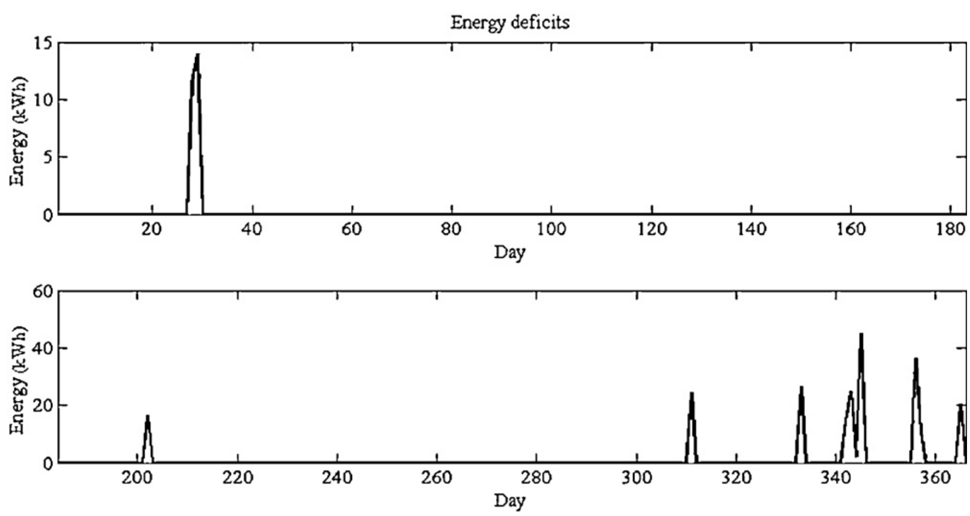

Fig. 5. Energy deficits for the proposed system throughout one year.

Table 3
Proposed system cost.

Item	Unit price ($)	Quantity	Consumption	Price ($)	Life time years/h
PV system					
PV modules	3.71/Wp	22.9 kWp	–	84,959	20
Support structure	50	28	–	1400	20
Storage battery	2/Ah	1.4 kAh*2	–	5600	20
Charge regulator	7000	1	–	7000	20
Inverter	10,000	1	–	10,000	20
Circuit breakers and installation materials	200	2	–	400	20
Civil and installation work	–	–	–	300	–
Diesel generator	–	–	–	2000	–
Generator capital cost	1800/DG	2	–	3600	13 years
Diesel	0.6/L	23,220 L	2.7 L/h	13,932	–
Engine oil	1.4/L	201 L	3.5 L/150 h	281	–
Diesel filter	4.5	12	–	52	750 h
Air filter	35	3	–	105	3000 h
Overhaul	1500	1	–	1500	26,280 h
Total				131,129	20

configuration of a PV/diesel system located in Malaysia is (C_A = 1.2, C_{DG} = 0.3), while the optimum C_B is 0.17.

Fig. 4 shows the operation analysis of the designed system through one year, considering Kuala Lumpur as the system's location. The first part of the figure shows the energy produced by the PV array and the load demand, which is supposed to be constant. However, the total energy produced by the PV array through a year is 44.7 MWh (122 kWh as a daily average of production). On the other hand, the second part shows the energy produced by the diesel generator through a year. The total energy produced by the diesel generator is 1.1 MWh, which is approximately 430 operation hours. The third part of Fig. 4 shows that 285.5 kWh are supplied by the storage battery over a year. Finally, the fourth part shows the total energy injected the grid (excess energy). Over one year, 1.04 MWh is injected to grid (28.4 kWh as an average daily amount).

Fig. 5 shows the energy deficits during one year, which are about 247.5 kWh/year. Based on Fig. 5, most of the energy deficits occurred in December. Using Eq. (1), the LLP for the proposed system is calculated to be 0.0068. The LLP of the proposed system is not equal to zero but is very low and acceptable. As a fact, designing PV systems at high availability rate (LLP = 0.0) is not feasible; therefore, most of the designers recommend designing PV systems with LLP in the range of 0.05–0.01 [15].

Table 3 shows the cost of the optimised system; the capital cost of the proposed hybrid PV/diesel generator system is less than the option of supplying the desired load demand by a stand-alone PV system by $74,000. Meanwhile, the optimised hybrid PV/diesel system option has a reduced system cost of $75,000 compared to the option of supplying the desired load demand by a diesel generator.

5. Conclusion

The optimisation of a hybrid PV/diesel generator system was performed in this research. The optimised system exhibits a minimum system cost with an LLP less than 0.01. A graphical solution is used to solve the optimisation problem in this study. This optimisation problem is stated in terms of the system unit cost and subjected to zero load rejection condition. Finally, recommendations for the optimum sizes of a PV array and diesel generator are given for a hybrid PV/diesel generator system in Malaysia. Moreover, a system-cost-based comparison is made between the proposed system and two other choices to show the system's feasibility. The results of the optimisation show that the PV/diesel generator is more feasible than a stand-alone PV system or diesel generator. The recommended configuration of a PV/diesel system located in Malaysia is C_A = 1.2, C_{DG} = 0.3, while the optimum C_B is 0.17. Such optimisation provides optimal sizes for hybrid PV/diesel generator system for Malaysia.

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