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# On the policy of photovoltaic and diesel generation mix for an off-grid site: East Malaysian perspectives

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**Abstract**

The recent policy of the Malaysian government to promote use of renewable, especially photovoltaic, energy has warranted a feasibility study on supplementing diesel generation in off-grid sites by solar (photovoltaic) electricity to be done in the Malaysian context. This paper addresses the technical viability and economy of using a photovoltaic (PV) system to supplement an existing diesel generator-based supply in a typical secondary school located at an interior, off-grid and rural site of Sarawak state in East Malaysia. The findings of the present study, would therefore, help the Government with a realistic picture of the techno-economic aspects in implementing its vision regarding renewable energy. Presently, a 150 kW diesel generator supplies electricity to the considered school. The study required simulation of the load sharing pattern of the PV–diesel hybrid system taking into account varied weather and insolation conditions of the chosen site. Also, the purchase price as well as the size of the supplementing PV system that would give the lowest life cycle cost have been determined. The PV system was considered in both forms, i.e. with and without battery back-up. It has been found that if the market price for purchasing a PV system would drop to RM 11.02/$W_P$ (Ringgit Malaysia; US\$1.00=RM 3.80) i.e. US\$2.90/$W_P$, a 35 k$W_P$ PV system without battery back-up in conjunction with the diesel generator would be able to supply the selected school's demand at a marginally lower energy cost than the existing diesel-only system. With continuous research and developments, PV price would keep falling in the near future so that a PV–diesel hybrid system with a higher sized PV is expected to be economically more viable. The reported feasibility study can serve as a guideline for making similar studies in the context of another off-grid site.

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## 1. Introduction

In developing countries a significant percentage of populations are living in remote areas without having any access to grid connected power supply. The remote and interior parts of the Sarawak state in East Malaysia are good examples of this. It is not economically viable to extend the existing grid line to the hundreds of scattered settlements in the interior of Sarawak. Usually electricity is supplied over there by small local diesel generators. But the price of diesel fuel for this purpose is much higher than that of normal market price mainly due to the expensive transportation cost. These problems have contributed to uneven developments in remote settlements compared to those in the urban areas. This can be mitigated to some extent by supplementing the diesel-based electricity with the energy from sunshine which usually abounds in equatorial countries like Malaysia. However, a complete replacement of diesel generation by a photovoltaic (PV) system is not realistic as sunshine is subject to the vagaries of nature and it would require a huge battery back-up for night-time or low insolation (incoming solar radiation) periods. The Government of Malaysia is keen to maximize the use of photovoltaic energy. But the technical and financial implications of a plan for use of photovoltaic

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electricity have not yet been systematically studied in the context of the off-grid locations of Malaysia.

A review of the literature shows that stand alone or grid interfaced hybrid systems in various forms such as PV–diesel (Vera, 1992; Hoff and Iannucci, 1990), wind–diesel (Dokopoulos et al., 1996; Saramourtsis et al., 1994), PV–wind–diesel (Vera, 1994), grid–PV–wind (Giraud and Salameh, 2001; Chedid et al., 1998), grid–PV–diesel (Nayar et al., 2000) have been studied in the context of some specific sites. However, most of the studies addressed the technical performance of an already installed prototype. A few that addressed the feasibility study at planning stage had either very broad objectives with diverse data requirements (that are difficult to be applied at any site in general) or no details on the principles for choosing component size and control configuration, life cycle costing etc.

This paper presents a study on the technical aspects and life cycle costs of using a PV system to supplement an existing diesel generator at an off-grid site with the example of a typical remote school named Sekolah Menengah Kerajaan Balleh (SMK Balleh). This secondary level boarding school with a population size of 600 is located in Nanga Gaat in Kapit Division of Sarawak of East Malaysia. Its distance from Kapit township is ~80 km southeast and can only be reached by river transport. Presently a 150 kW diesel generator unit provides electricity to the school. Apart from the cost of diesel purchase and transportation, the diesel generator also requires frequent maintenance, which costs about RM 40,000 or US$10,500 per year (US$1.00=RM 3.80). Moreover, due to lack of spare units, the school suffers from blackout during the maintenance period. Consequently, the cost of diesel generation-based electricity supply in the remote habitats/schools of Sarawak similar to SMK Balleh is very high. In this paper, several options for catering to the example school's electricity requirement viz. (i) only the diesel generator as exists now, (ii) the diesel generator plus a PV system, and (iii) the diesel generator combined with a PV system and a battery back-up, have been studied in detail.

## 2. Methodology

The method for conducting a techno-economic study uses the following algorithm. The final output of the algorithm will be the optimum size of the PV system that will supplement the existing diesel-based supply with and without a battery back-up.

1. Obtain the selected site's (school) average daily load profile.
2. Decide the load sharing pattern of the diesel generator and the PV system.
3. Synthesize daily generation profiles for the diesel generator and the PV system.
4. Construct daily generation duration curves, i.e. cumulative distribution function based on the daily generation profiles.
5. Calculate the daily energy generation from the profiles of step 4 using numerical integration technique, e.g. trapezoidal rule of integration.
6. Calculate daily operating (fuel) generation cost for the diesel generator.
7. Calculate and compare total life cycle cost for:
   (i) Diesel system only.
   (ii) Diesel plus PV system.
8. Repeat steps 2 to 7 by varying the size of the PV system (capacity at peak insolation) to arrive at an optimum size.
9. Repeat steps 2 to 8, considering a battery back-up with suitable capacity.

Since all the data needed for such a study are seldom available irrespective of the site location, the following assumptions have been made to make the study as realistic as possible.

1. In the hybrid system operation a load equal to or less than a threshold is supplied only by the diesel generator.
2. Available PV generation is proportional to insolation profile (Williams, 1986; Chedid et al., 1998).
3. Daily PV generation has been classified in terms of five typical weather conditions such as sunny, partly sunny, partly cloudy, cloudy and rainy day. The corresponding meteorological and insolation data available for the nearest locations are used.
4. The PV conversion efficiency is theoretically 11% to 13% (EUREC Agency, 1996) but is taken as 10% to be realistic.
5. Efficiency for the PV inverter was taken as 90% (Winter et al., 1990; Bose, 2000).
6. The PV's balance of system (BOS) excluding battery back-up cost is assumed to be 30% of the PV panels cost (Williams, 1986).
7. The site's energy demand is constant throughout the life cycle.
8. Interest and escalation rates in Malaysia are considered as 8% and 4%, respectively.

### 2.1. Diesel generator's operating cost

The diesel generator's fuel consumption (litres) is determined by the electrical power output it has to provide. The daily operation cost for a thermal power plant (Wood and Wollenberg, 1984) can be adapted for a diesel generator as follows:

$$OC_{\mathrm{D}} = (H_{\mathrm{D}} \times NL_{\mathrm{D}}) + (E_{\mathrm{D}} \times IN_{\mathrm{D}}) \quad (1)$$

where $OC_{\mathrm{D}}$ is daily operation cost ($), $H_{\mathrm{D}}$ is hours of operation over a day, $NL_{\mathrm{D}}$ is no load fixed cost rate ($/h),

$E_D$ is energy generated in a day (kWh) and $IN_D$ is incremental fuel cost rate ($/kWh).

### 2.2. Photovoltaic system output

The sunlight impinging on PV panels, i.e. irradiance or insolation (incoming solar radiation), is measured in units of watts per square meter (W/m$^2$). The PV system power output (DC) has approximately a linear relationship to the insolation (Williams, 1986; Chedid et al., 1998).

$$P_{PV,DC} = C_{PV} \times I_{PV} \quad (2)$$

where $P_{PV,DC}$ is the available PV power output (DC), $C_{PV}$ is the PV conversion factor and $I_{PV}$ is the insolation impinging on the total area of the PV array.

The balance of system (BOS) refers to the components of the PV system other than the PV panels. BOS usually includes the support structure, foundations, wiring, control equipment and power conditioner (inverter). The available PV power output after inversion (AC) is dependent on the inverter efficiency.

$$P_{PV,AC} = \eta_{inv} \times P_{PV,DC} \quad (3)$$

where $P_{PV,AC}$ is the available PV power output (AC) and $\eta_{inv}$ is the inversion efficiency.

### 2.3. Battery back-up capacity

The battery capacity is often expressed (Nayar et al., 2000) in ampere-hour (Ah). The total capacity required for the assembly of batteries in a PV system can be computed as follows (Robert, 1991):

$$TC_B = (E_B \times S_B)/V_{DC} \quad (4)$$

where $TC_B$ is the capacity (Ah) needed, $E_B$ is the energy (Wh) available for storage for 1 day, $S_B$ is the period (in days) of storage required and $V_{DC}$ is the required output DC voltage of the system.

The number of batteries connected in parallel $N_{B,P}$ and in series $N_{B,S}$ is calculated as follows:

$$N_{B,P} = (TC_B \times 100\%)/(C_B \times D_B) \quad (5)$$

$$N_{B,S} = V_{DC}/V_B \quad (6)$$

$$N_{TB} = N_{B,P} \times N_{B,S} \quad (7)$$

where $C_B$ is the full capacity (Ah) specified for one battery, $D_B$ is the maximum depth (in %) of charging and discharging cycles, $V_B$ is the nominal battery voltage and $N_{TB}$ is the total number of batteries needed.

### 2.4. Load sharing between PV and diesel generator

The load sharing pattern determines which part of the hybrid system is to share how much load and when. The sharing mechanism is supposed to utilize the PV energy (availability is subject to insolation) for meeting the demand as much as possible. On the other hand, since a diesel generator can provide a guaranteed supply (so long as it does not malfunction) it should operate continuously during the operation time.

If the diesel generator operates near full load then the fuel consumption rate will be less compared to that for operation at a small fraction of the full load. In order to achieve an acceptable fuel consumption rate for the generator in the hybrid mode, only the generator should run when the load does not exceed a threshold, i.e. $P_{D,min}$ (kW). This will lead to a compromise between reliability and fuel economy, and a few more benefits depending upon the generator and resulting hybrid system. As for instance, use of diesel generation may be unavoidable for low load in the early hours of the day in certain situations. These are (i) available PV power is less than the system load but more suitable for charging back-up battery, and/or (ii) the discharge limit of battery back-up is less than the system load etc., as in the site and case presented in this paper. So when load exceeds $P_{D,min}$, generation priority is to be given to the PV system only subject to the availability of the required insolation.

The PV power to be used $P_{PV,U}$ is decided by the load $P_{Load}$, diesel generator preferable minimum loading requirement $P_{D,min}$ and the available PV power output $P_{PV,AC}$

$$P_{PV,U} = P_{Load} - P_{D,min}; \quad (8)$$

when $P_{Load} > P_{D,min}$ and $P_{PV,U} < P_{PV,AC}$.

For this, there will be excess PV power, i.e. ($P_{PV,AC} - P_{PV,U}$) kW which is not utilized.

In the special case when $P_{Load} - P_{D,min}$ is greater than $P_{PV,AC}$ then

$$P_{PV,U} = P_{PV,AC}. \quad (9)$$

The diesel generator's share, $P_{D,hybrid}$ is as follows:

$$P_{D,hybrid} = P_{Load} - P_{PV,U}; \quad (10)$$

when $P_{Load} > P_{D,min}$, $P_{PV,U}$ is as in (8) or (9)

$$P_{D,hybrid} = P_{Load}; \quad (11)$$

when $P_{Load} \leq P_{D,min}$, $P_{PV,U} = 0$.

### 2.5. Load sharing between PV, diesel generator and battery back-up

The load sharing mechanism for diesel generator and PV for the hybrid system with battery back-up considers the contribution from the battery back-up. When there is excess (unutilized) PV power as stated in Section 2.4 the corresponding energy will be stored by the battery back-up and will be discharged after sunset. The diesel generator's share in the PV–diesel hybrid system with battery back-up is as follows:

$$P_{D,hybrid} = P_{Load} - P_{PV,U} - P_{B,discharge}; \tag{12}$$

when $P_{Load} > P_{D,min}$, $P_{PV,U}$ is as in (8) and (9)

$$P_{D,hybrid} = P_{Load}; \tag{13}$$

when $P_{Load} \leq P_{D,min}$, $P_{PV,U} = 0$ and $P_{B,discharge} = 0$ where $P_{B,discharge}$ is the power discharged from battery back-up (kW).

### 2.6. Life cycle costing

Life cycle cost (LCC) analysis is an economic assessment of the cost for a number of alternatives considering all significant costs over the life span of each alternative, adding each option's costs for every year and discounting them back to a common base (present worth). These costs can be categorized into two types: (i) recurring cost, e.g. operation cost and fuel transportation cost for diesel generator and maintenance cost for diesel and PV system, and (ii) non-recurring cost, e.g. battery replacement cost.

The conversion of recurring costs to present worth is as follows (Brown and Yanuck, 1985):

$$PW_R = R\frac{\left[\frac{1+e}{1+i}\right]\left\{\left[\frac{1+e}{1+i}\right]^n - 1\right\}}{\left[\frac{1+e}{1+i}\right] - 1} \tag{14}$$

where $i$ and $e$ are the interest and escalation rate, respectively. $R$ is the recurring cost and $n$ is the life span of the whole system.

The conversion of non-recurring cost to present worth is as follows:

$$PW_{NR} = NR\frac{\left[\frac{1+e}{1+i_{adj}}\right]\left\{\left[\frac{1+e}{1+i_{adj}}\right]^n - 1\right\}}{\left[\frac{1+e}{1+i_{adj}}\right] - 1} \tag{15}$$

where $i_{adj}$ is the adjusted interest rate given as follows, $P$ is number of years between two successive payments for nonrecurring costs and $NR$ is the non-recurring costs

$$i_{adj} = \frac{(1+i)^P}{(1+e)^{P-1}} - 1. \tag{16}$$

The salvage value, $S$ expressed in present worth is given as follows:

$$PW_S = S\frac{1}{(1+i)^n}. \tag{17}$$

The total LCC may then be expressed as follows:

$$TLCC = C + PW_R + PW_{NR} - PW_S \tag{18}$$

where $TLCC$ is the total life cycle cost and $C$ is the initial (purchase and installation) cost. All the components in the above equation are expressed in their present worth.

## 3. Results and discussion

The methodology shown in Section 2 has been computer coded and run using MATLAB 5.3.

### 3.1. General features of the site

Presently a 150 kW diesel generator meets the electricity demand of the selected site (school). The peak demand of the school during a weekday is about 85 kW while during holidays/weekend is about 70 kW. In the proposed PV–diesel hybrid system, the PV system will supplement the existing diesel generator in the way shown in Fig. 1.

The number of days for each of the five weather conditions, i.e. sunny, partly sunny, partly cloudy, cloudy and rainy at the school site have been estimated. For this categorisation, daily total sunshine hours and rainfall for the nearest site of Sibu Airport weather station in Sarawak (latitude: 2° 15′ North, longitude: 111° 58′ East and altitude: 38 m above mean sea level) recorded in the year 2000 have been used. The distribution of days for each weather condition is given in Table 1.

For the diesel only system, the average load profiles are also the generation profiles. These are shown in Figs. 2 and 3 for both cases, respectively, (i) weekdays and (ii) weekends/holidays. The generator is run for 18 h during weekdays while 14 h during weekends/holidays. The corresponding generation duration curves are shown in Figs. 4 and 5. It is noteworthy that the generator at the studied site is presently operating at any load in non-hybrid mode, and accelerated wear (if any) arising from low load is well accounted by the annual maintenance cost.

However, in hybrid mode the threshold loading requirement of the diesel generator $P_{D,min}$ will be considered as 20 kW, i.e. any load less or equal to 20 kW will only be fed by the diesel generator. It should be noted that the same load profiles as in Figs. 2 and 3 are considered also for the hybrid system.

### 3.2. Cost related data

Table 2 shows the typical data on cost, life and size of the diesel generator, PV and battery units as used in the present study. Some of the data were taken from EUREC Agency (1996), Winter et al. (1990) and Bose (2000).

### 3.3. Life cycle costing of diesel only system

From Figs. 4 and 5, the daily energy produced by the diesel generator for weekdays and weekends/holidays were obtained using numerical integration technique. Those are ~990 kWh and 800 kWh, respectively. The

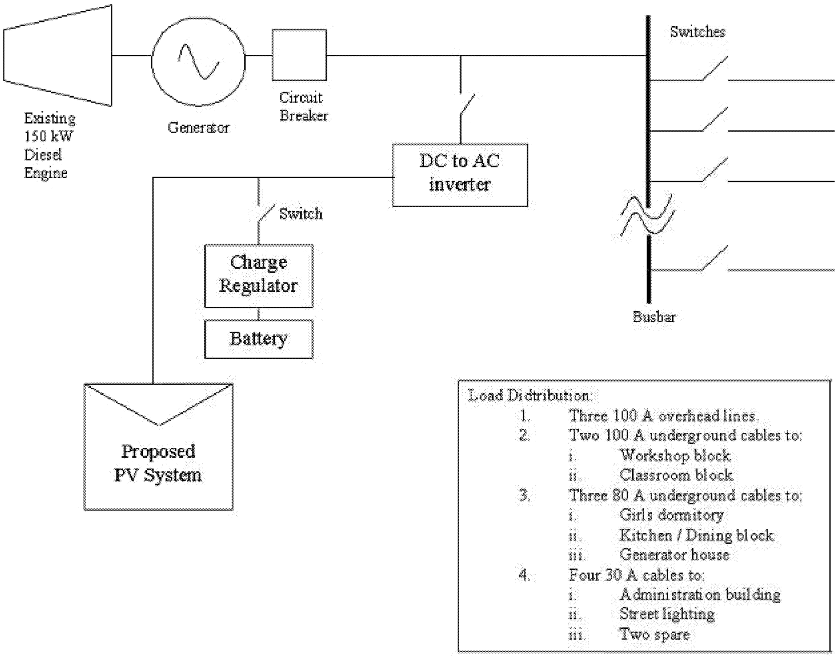


Fig. 1. Proposed PV–diesel hybrid system.

effect of this difference is significant over a 1-year period, i.e. in relation to computing the annual cost. The daily operation cost for the diesel generator is obtained using Eq. (1) while the annual fuel transportation cost is obtained using data from Table 2. The diesel generator operation cost in 365 days is obtained by considering the weekday and the weekend operation costs, the numbers of weekdays in 1 year, i.e. 193, and the number of weekends/holidays, i.e. 172, as mentioned in Table 1. The diesel generator maintenance cost is RM 40,000 (≅ US$10,500) as given in Table 2.

The present worth recurring costs, $PW_R$ such as the diesel generator operation, maintenance and fuel transportation costs are obtained using Eq. (14). The present worth for salvage value is obtained using Eq. (17). Total life cycle cost is obtained using Eq. (18). The detailed results of LCC analysis for the diesel only system are shown in Table 3.

Table 1
Distribution of days according to typical weather conditions at the studied site in the year 2000

| Weather categories | Number of days | |
|---|---|---|
| | Weekdays | Weekends/holidays |
| Sunny day | 45 | 41 |
| Partly sunny day | 50 | 44 |
| Partly cloudy day | 39 | 34 |
| Cloudy day | 37 | 33 |
| Rainy day | 22 | 20 |
| Total | 193 | 172 |

### *3.4. Life cycle costing of PV–diesel hybrid without battery back-up*

The insolation data for the selected location (SMK Balleh site) or Sibu Airport was not available. Moreover, minimum information such as clearness index was also not available for use by synthetic insolation data generator over a year. So for the sake of a realistic study, actual hourly insolation data available for the nearest possible site, i.e. the Pacific Ocean island of Guam (latitude: 13° 33′ North, longitude: 144° 50′ East and altitude: 110 m above mean sea level) is used as a reference. These data were obtained from the United States National Renewable Energy Laboratory's website. The insolation data for each of the five weather conditions (as mentioned in Table 1) are a steady reduction of the maximum insolation, i.e. 100% for sunny day, 80% for a partly sunny day, 60% for a partly cloudy day, 40% for a cloudy day, and 20% for a rainy day.

The irradiance ($W/m^2$), i.e. insolation data, was converted into available AC power from PV using total surface area of the PV array for the chosen size, and Eqs. (2) and (3) with $C_{PV} = 10\%$ and $\eta_{inv} = 90\%$. As this pair of equations is linear, the irradiance patterns are of the same shape as the obtained available PV power profiles for the corresponding days.

For the PV–diesel hybrid system without battery back-

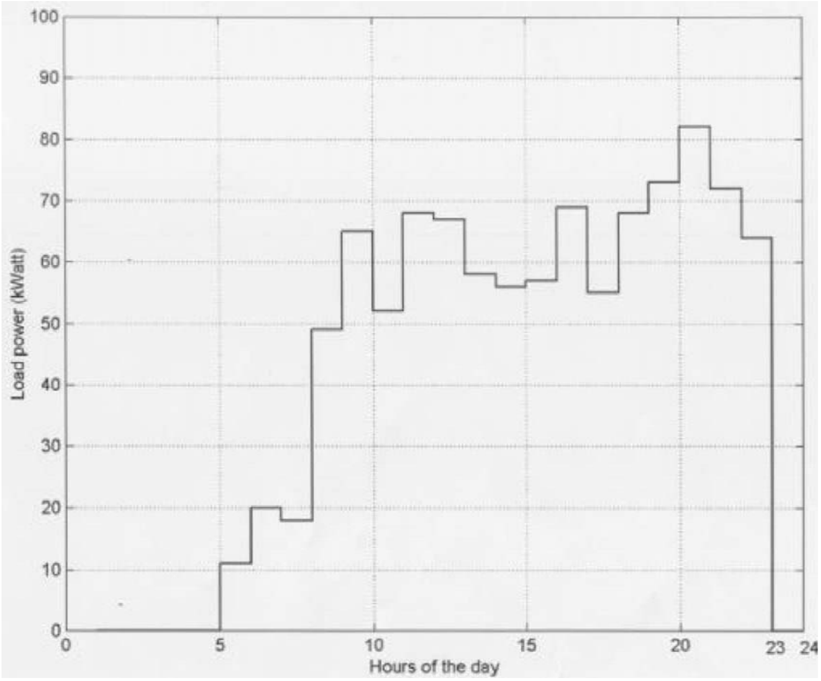


Fig. 2. Load profile (weekdays).

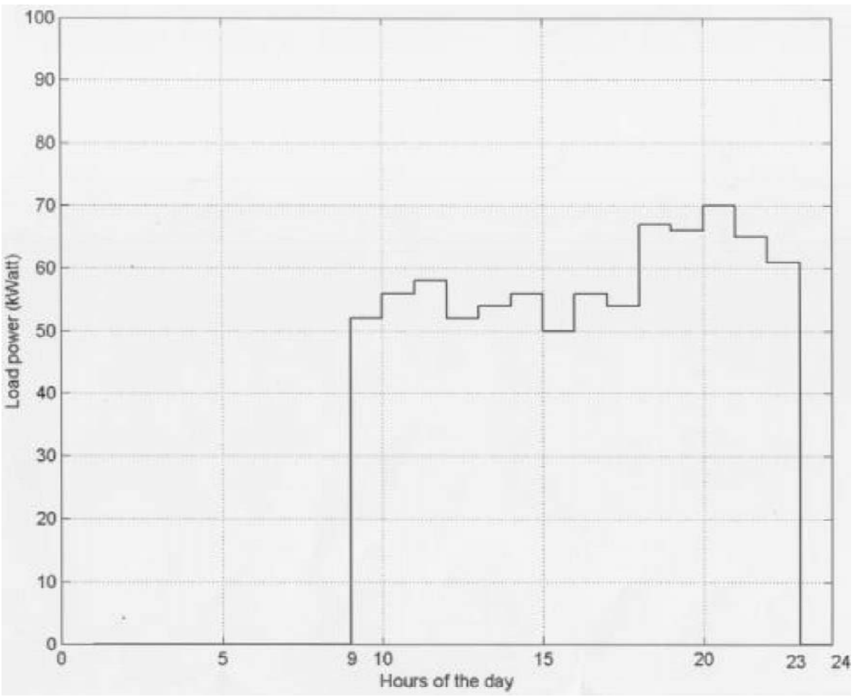


Fig. 3. Load profile (weekends/holidays).

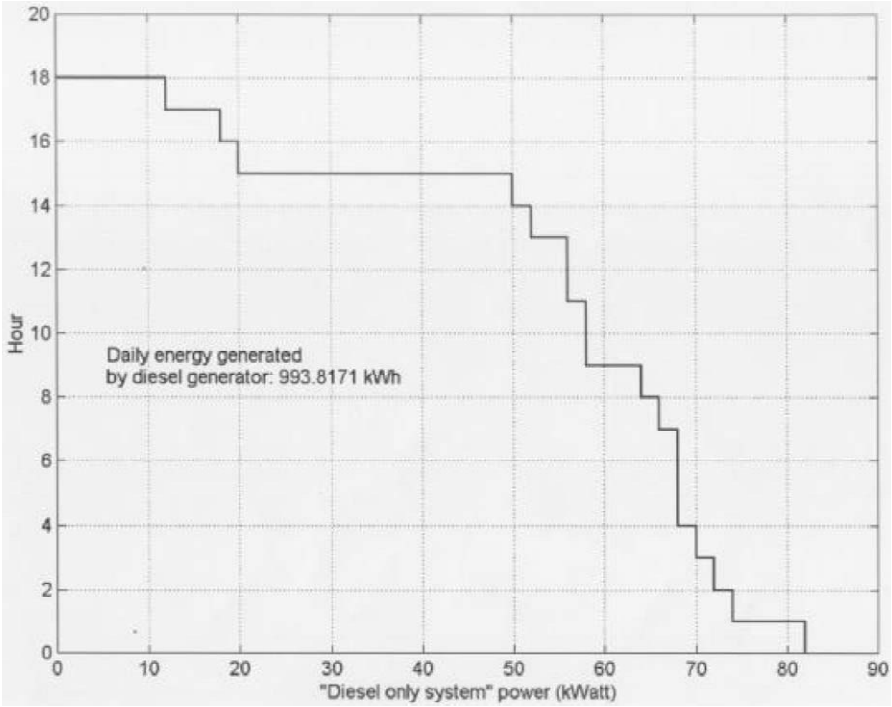


Fig. 4. Generation duration curve (weekdays) for existing diesel only system.

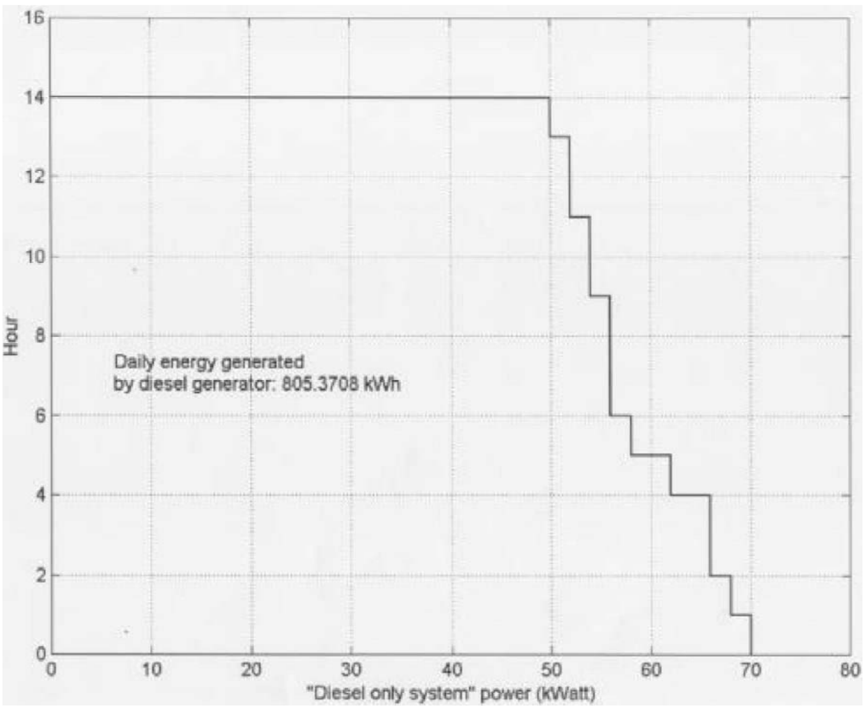


Fig. 5. Generation duration curve (weekends/holidays) for existing diesel only system.

Table 2
Costing data considered in the study (1 US$ = 3.80 RM)

| | |
|---|---|
| Diesel generator | |
| 150 kW diesel generator capital cost | RM 125,000.00 |
| Fuel cost | RM 0.85/l |
| Fuel consumption rate | 0.3633 l/kWh |
| No load fixed cost rate | RM 5.95/h |
| Annual diesel maintenance cost | RM 40,000.00 |
| Fuel transportation cost | RM 0.3/l |
| Diesel salvage value | 10% of diesel generator capital cost |
| Diesel life | 30 years |
| PV panels | |
| PV size | Various peak capacity ($kW_P$) |
| PV capital cost | Various PV prices are considered[a] |
| PV balance of system (excluding battery back-up) cost | 30% of PV capital cost |
| Annual PV maintenance cost | 3% of annualized PV capital cost |
| PV salvage value | 10% of PV capital cost |
| PV life | 30 years |
| Battery back-up | |
| Battery capital cost for 12 V unit | RM 0.317/Wh |
| Battery savage value | Nil |
| Nominal system voltage | 240 V |
| Battery size for each unit | 200 Ah, 12 V |
| Annual battery maintenance cost | 15% of annualized battery capital cost |
| Battery life | 5 years |
| Financial indicators | |
| Interest or discount rate, *i* | 8% |
| Price escalation rate, *e* | 4% |

[a] The current market price of PV panels is RM 13.30/$W_P$ (US$3.50/$W_P$).

up, the generation profiles for PV panels and diesel generator as decided by Eqs. (8)–(11) are shown in Figs. 6 and 7, respectively. The figures represent the load being shared by PV and diesel generator for a typical weekday with sunny weather. The preferable minimum loading requirement for the diesel generator $P_{D,min}$ is set to 20 kW as mentioned in Section 3.1. Similarly PV panels' generation profiles for other weather conditions and weekdays and weekends were also taken into account. A PV array size of 60 $kW_P$ (i.e. DC output kilowatt corresponding to the peak insolation is 60 kW) has been used as an example in these figures. For other sizes of PV arrays, similar profiles were obtained by the developed computer program.

For the diesel generator in hybrid mode, the total energy produced by it in 365 days is less than that for the diesel only system due to the energy contribution from the PV system. The annual maintenance cost for the diesel generator in hybrid mode, $D_{M,hybrid}$, is obtained using the following equation:

Table 3
Life cycle cost for existing diesel only system (1 US$ = 3.80 RM)

| Diesel generator only system | |
|---|---|
| Initial cost (RM) | 125,000.00 |
| Operation cost (RM) | 2,412,900.00 |
| Fuel transportation cost (RM) | 634,310.00 |
| Maintenance cost (RM) | 704,790.00 |
| Salvage value (RM) | 1242.00 |
| Total life cycle cost (RM) | 3,876,700.00 |
| Total energy generated by the diesel generator over its life span (kWh) | 9,909,900 |
| Energy cost (RM/kWh) = Total LCC/Total Energy | 0.3912 |

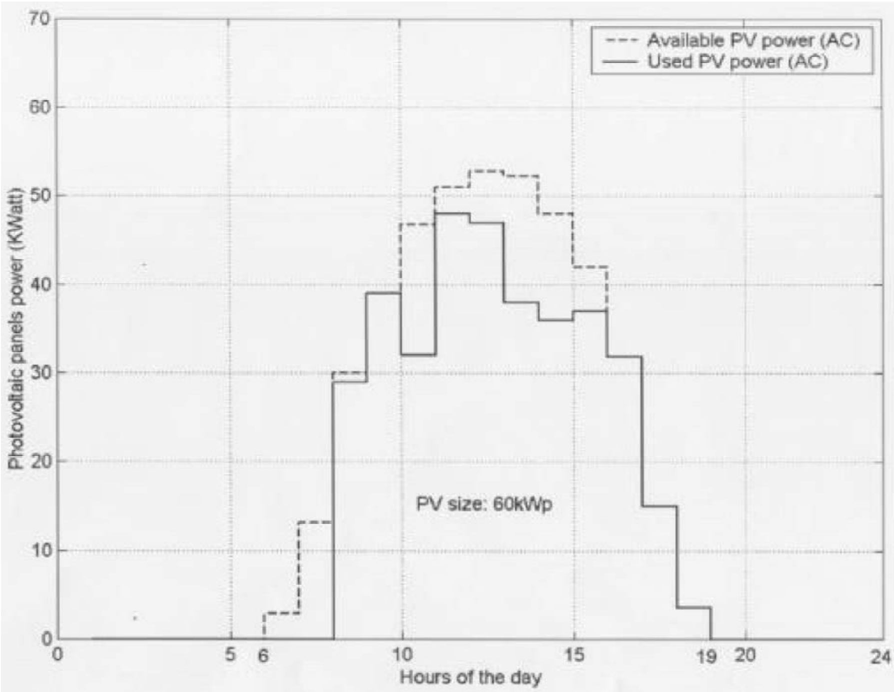


Fig. 6. PV panels generation profile for a sunny day (60 $kW_P$ PV–diesel hybrid system without battery back-up).

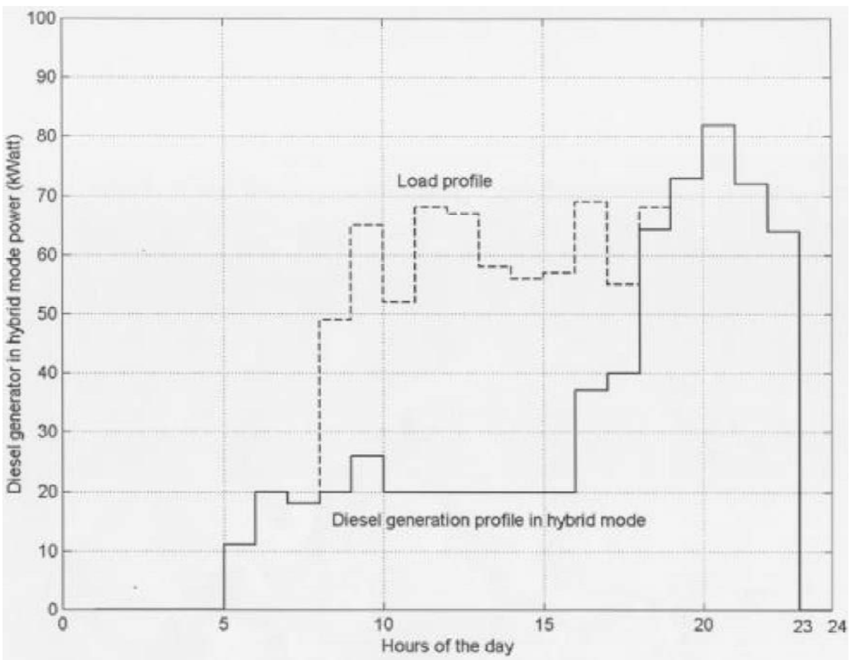


Fig. 7. Diesel generator generation profile in hybrid mode on a sunny day (60 $kW_P$ PV–diesel hybrid system without battery back-up).

$$D_{\mathrm{M,hybrid}} = D_{\mathrm{M}} - D_{\mathrm{M}}\left(\frac{PV_{\mathrm{E}}}{D_{\mathrm{E}}}\right) \quad (19)$$

where $D_M$ is the existing diesel only system's annual maintenance cost (RM 40,000 for this specific case), $PV_E$ is the energy used from PV panels in 365 days and $D_E$ is the annual energy generated by the diesel only system.

The operation and fuel transportation costs were calculated considering the energy output of the diesel generator in hybrid mode in 365 days.

Then for the diesel generator, Eq. (14) is used to calculate the present worth for operation, maintenance and fuel transportation costs. Similarly the diesel generator's salvage value is obtained using Eq. (17).

For the PV panel, the costs involved are initial cost and maintenance cost. Eq. (14) is used to calculate the present worth maintenance cost while salvage value is obtained using Eq. (17).

Table 4 shows the LCC for all significant costs and the energy cost expressed in present worth. It is found that the LCC for the PV–diesel hybrid system with PV size at 60 $kW_P$ (RM 3,936,700.00 ≅ US$1,035,900.00) is larger than LCC for the existing diesel only system (RM 3,876,700.00 ≅ US$1,020,100.00). Thus a PV–diesel hybrid system with PV size at 60 $kW_P$ is more expensive than the existing diesel only system.

The LCC analyses were repeated considering various PV peak capacities ranging from 5 to 70 $kW_P$. The life cycle costs and energy costs expressed in present worth for various PV sizes ($kW_P$) and purchase prices (RM/Watt peak or RM/$W_P$) are shown in Fig. 8. The figure shows that for a PV panel price equal to or above RM 11.40/$W_P$ (US$3.00/$W_P$), the PV system is not a viable option for the selected school. For PV panel price equal to RM 11.02/$W_P$ (US$2.90/$W_P$) or less, the PV system of different sizes (depending upon the price) looks viable. This is also evident from curves E to J being below the 'diesel only' line (K) up to a certain PV capacity size.

The economic viability of the PV system as a supplement to the diesel generator depends on the life cycle saving achieved from the reduced diesel system costs (i.e. operation, maintenance and fuel transportation costs) against the life cycle cost of the PV system (i.e. capital and maintenance cost). To determine the size of the supplementing PV system for the selected school, the highest viable PV purchase price of RM 11.02/$W_P$ (curve E of Fig. 8) is considered. It is found that a PV size of 35 $kW_P$ produces the lowest LCC, which is RM 3,866,100.00 (≅US$1,017,390.00) against the diesel only LCC of RM 3,876,700.00 (≅US$1,020,100.00), while the present worth energy cost is 0.3901 RM/kWh (0.1027 US$/kWh) against 0.3912 RM/kWh (0.1029 US$/kWh) for the diesel only system. The detailed results of LCC analysis for the 35 $kW_P$ PV–diesel hybrid system are shown in Table 5.

### 3.5. Life cycle costing of PV–diesel hybrid with battery back-up

Using the 35 $kW_P$ PV size (found as the viable size without battery back-up) and a price of RM 11.02/$W_P$ (US$2.90/$W_P$), a study has been done on the PV–diesel hybrid system with battery back-up. The PV generation profile is shown in Fig. 9. The generation profiles for battery back-up and diesel generator as decided by Eqs. (8), (9), (12) and (13) are shown in Figs. 10 and 11, respectively. The figures represent the load of a weekday being shared by PV and diesel generator for a typical weekday with sunny weather. The preferable minimum loading requirement for the diesel generator $P_{\mathrm{D,min}}$ is set to 20 kW. Similarly, the generation profiles for all five weather conditions and weekdays/weekends were also taken into account.

Using Eqs. (4)–(7), the battery back-up size is obtained (20 units of 200 Ah, 12 V battery). The energy to be stored, i.e. $E_B$ in Eq. (4), is set as the maximum unutilized energy of the PV panels in a typical sunny day. This is

Table 4
Life cycle cost for 60 $kW_P$ PV–diesel hybrid system without battery back-up (1 US$ = 3.80 RM)

| Costs in present worth | Diesel generator | PV system |
|---|---|---|
| Initial cost (RM) | 125,000.00 | 859,560.00<br>(at RM 11.02/$W_P$) |
| Operation cost (RM) | 1,937,500.00 | – |
| Fuel transportation cost (RM) | 466,170.00 | – |
| Maintenance cost (RM) | 517,970.00 | 40,359.00 |
| Salvage value (RM) | 1242.20 | 8542.10 |
| Total life cycle cost (RM) | 3,045,400.00<br>3,936,700.00 | 891,380.00 |
| Total energy over system's life span (kWh) | 7,283,100<br>9,909,930 | 2,626,830 |
| Energy cost (RM/kWh) = Total LCC/Total Energy | 0.3973 | |

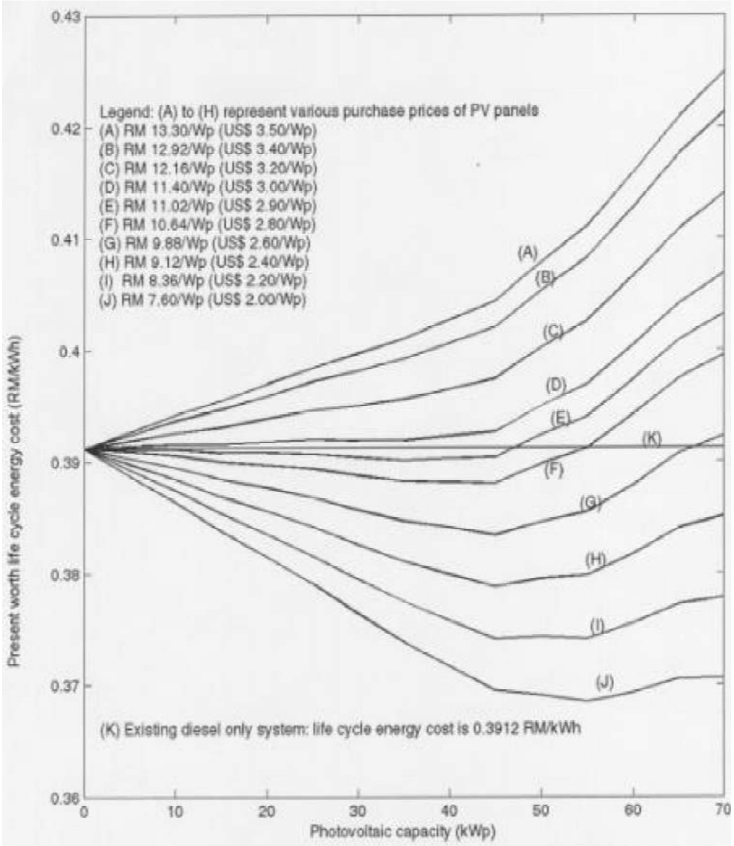


Fig. 8. Energy cost vs. PV size for various PV price (PV–diesel hybrid system without battery back-up).

Table 5
Life cycle cost for 35 $kW_P$ PV–diesel hybrid system without battery back-up (1 US$ = 3.80 RM)

| Costs in present worth | Diesel generator | PV system |
|---|---|---|
| Initial cost (RM) | 125,000.00 | 501,410.00 (at RM 11.02/$W_P$) |
| Operation cost (RM) | 2,109,800.00 | – |
| Fuel transportation cost (RM) | 527,000.00 | – |
| Maintenance cost (RM) | 585,550.00 | 235,430.00 |
| Salvage value (RM) | 1242.20 | 4982.90 |
| Total life cycle cost (RM) | 3,346,100.00<br>3,866,100.00 | 519,970.00 |
| Total energy over system's life span (kWh) | 8,233,200<br>9,909,780 | 1,676,580 |
| Energy cost (RM/kWh) = Total LCC/Total Energy | 0.3901 | |
| Life cycle saving (RM/kWh) = TLCC (diesel only system) − TLCC (PV–diesel hybrid system) | 3,876,700.00 − 3,866,100.00 = 10,600.00 | |

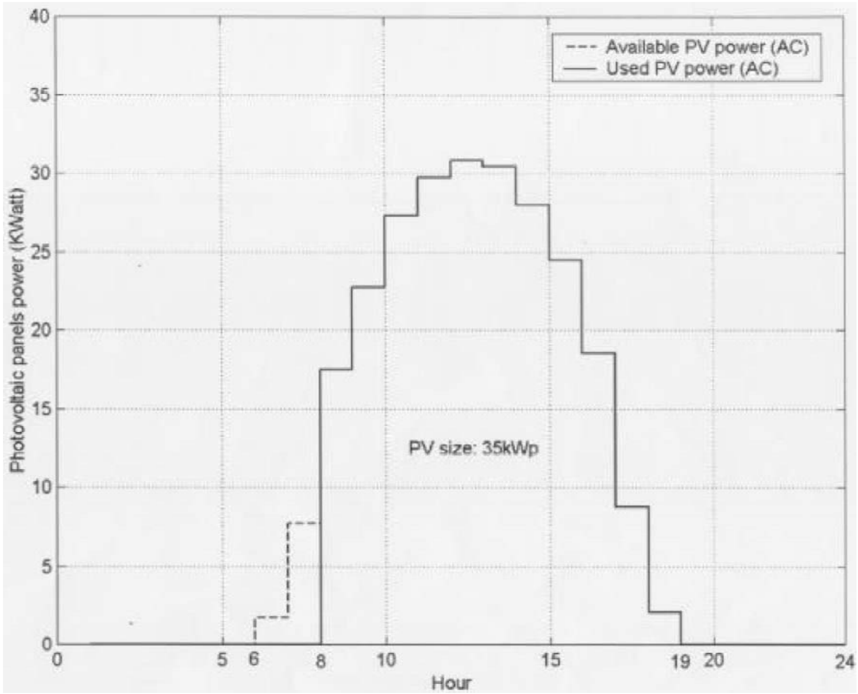


Fig. 9. PV panels generation profile on a sunny day (35 $kW_P$ PV–diesel hybrid system with battery back-up).

because battery size should be with respect to the maximum energy it is supposed to store. The period of storage required ($S_B$) is set as 1 day, the DC system voltage is 240 V (i.e. 12×20) and the battery depth of discharge $D_B$ is 80%.

It should be noted that the total battery purchase cost is

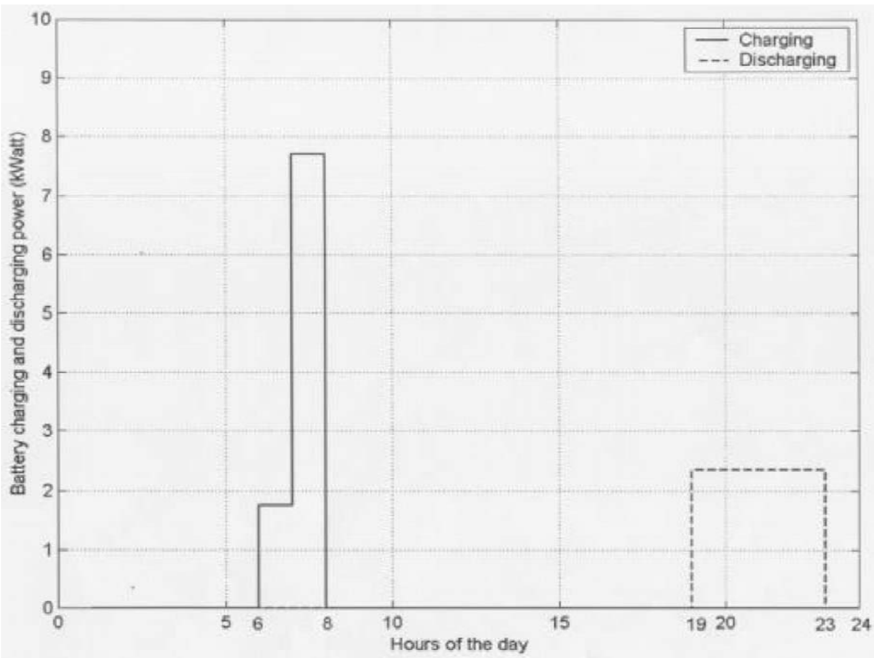


Fig. 10. Battery back-up generation profile on a sunny day (35 $kW_P$ PV–diesel hybrid system with battery back-up).

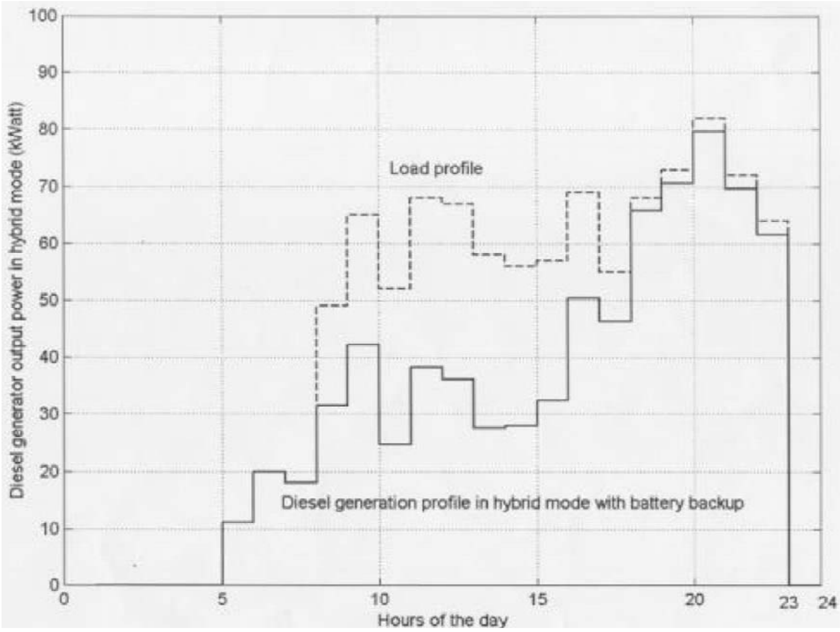


Fig. 11. Diesel generator generation profile in hybrid mode on a sunny day (35 $kW_P$ PV–diesel hybrid system with battery back-up).

20 times the cost of each unit (12 V, 200 Ah) and it turns out to be the same if the unit capacity is expressed in Wh by multiplying the Ah (200) with each unit's voltage, i.e. 12.

The annual maintenance cost for the diesel generator in hybrid mode with battery back-up is obtained using the following equation:

$$D_{\mathrm{M,hybrid}} = D_{\mathrm{M}} - D_{\mathrm{M}}\left(\frac{PV_{\mathrm{E}} + B_{\mathrm{E}}}{D_{\mathrm{E}}}\right) \tag{20}$$

where $D_{\mathrm{M}}$ is the existing diesel only system annual maintenance cost, $PV_{\mathrm{E}}$ is the used energy from the PV panels in 365 days, $B_{\mathrm{E}}$ is the energy discharged from the battery back-up's stored energy in 365 days and $D_{\mathrm{E}}$ is the annual energy generated by the diesel only system.

The operation and fuel transportation costs for the diesel generator were calculated considering its output energy in 365 days in hybrid mode with battery back-up.

Eq. (14) is used to calculate the LCC for recurring costs, i.e. operation, fuel transportation and maintenance costs for the diesel generator in hybrid mode and maintenance cost for the PV system and battery back-up. Eqs. (15) and (16) are used to calculate nonrecurring cost, i.e. battery replacement cost. Table 6 shows the LCC for all significant costs and the energy cost expressed in present worth. Comparing

Table 6
Life cycle cost analysis for 35 $kW_P$ PV–diesel hybrid system with battery back-up (1 US\$ = 3.80 RM)

| Costs in present worth | Diesel generator | PV system | Battery back-up (20 units of 12 V, 200Ah) |
|---|---|---|---|
| Initial cost (RM) | 125,000.00 | 501,410.00<br>(at RM 11.02/$kW_P$) | 15,200.00<br>(at RM 0.317/Wh) |
| Operation cost (RM) | 2,086,800.00 | – | – |
| Fuel transportation cost (RM) | 518,870.00 | – | – |
| Maintenance cost (RM) | 576,520.00 | 23,543.00 | 10,062.00 |
| Replacement cost (RM) | – | – | 72,935.00 |
| Salvage value (RM) | 1242.20 | 4982.90 | – |
| Total life cycle cost (RM) | 3,305,900.00<br>3,924,100.00 | 519,970.00 | 98,196.00 |
| Total energy over system's life span (kWh) | 8,106,300<br>9,909,819 | 1,676,100 | 127,419 |
| Energy cost (RM/kWh) = Total LCC/Total Energy | 0.3978 | | |

LCC for the PV–diesel hybrid system with battery back-up with those in Table 5 without battery back-up, it is found that LCC for the former (RM 3,924,100.00 ≅ US$1,032,650.00) is larger than the latter (RM 3,866,100.00 ≅ US$1,017,390.00). So a PV–diesel hybrid system with a battery back-up and a PV size of 35 $kW_P$ does not look more promising than the same system without battery back-up.

The LCC analyses were repeated considering various PV peak capacities ranging from 5 to 70 $kW_P$. The life cycle costs and energy costs expressed in present worth for various PV sizes ($kW_P$) and PV panel purchase prices ($RM/W_P$) are shown in Fig. 12. This figure shows that for PV panel price equal to or above RM 10.64/$W_P$ (US$2.80/$W_P$), the hybrid system with battery back-up is not a viable option for the selected school for any PV sizes. For PV panel price at RM 9.88/$W_P$ (US$2.60/$W_P$) and below, the hybrid system with battery back-up is viable for different PV sizes depending upon PV price. Comparing Fig. 12 with Fig. 8, it is found that the PV–diesel hybrid system without battery back-up is less expensive than with battery back-up. The higher LCC for the latter is mainly due to the high capital, maintenance and replacement costs for battery back-up.

## 4. Conclusions

The Government of Malaysia is keen to maximize the use of photovoltaic energy. But the technical and financial implications of a plan for use of photovoltaic electricity has not yet been systematically studied in the context of the off-grid locations of Malaysia. This paper presents a study on the technical aspects and life cycle costs of using a PV system to supplement an existing diesel generator for a typical remote school premises with the example of SMK Balleh in Sarawak of East Malaysia. The selected site is presently supplied from a 150 kW diesel generator.

At current market price of PV panels, which is RM 13.30/$W_P$ (US$3.50/$W_P$), the hybrid system may not be a viable option for the selected school. An extensive study has shown that at a PV purchase price of RM 11.02/$W_P$ (US$2.90/Wp), a 35 $kW_P$ sized PV system without battery back-up can be the optimum choice to supplement the diesel system of the selected school. The saving from this supplement for the whole life span is RM 10,600.00 (≅ US$2,780.00). This means it is only marginally viable. Use of higher than 35 $kW_P$ PV systems at the price of RM 11.02/$W_P$ (US$2.90/Wp) are not viable options to supplement the diesel supply of the selected site.

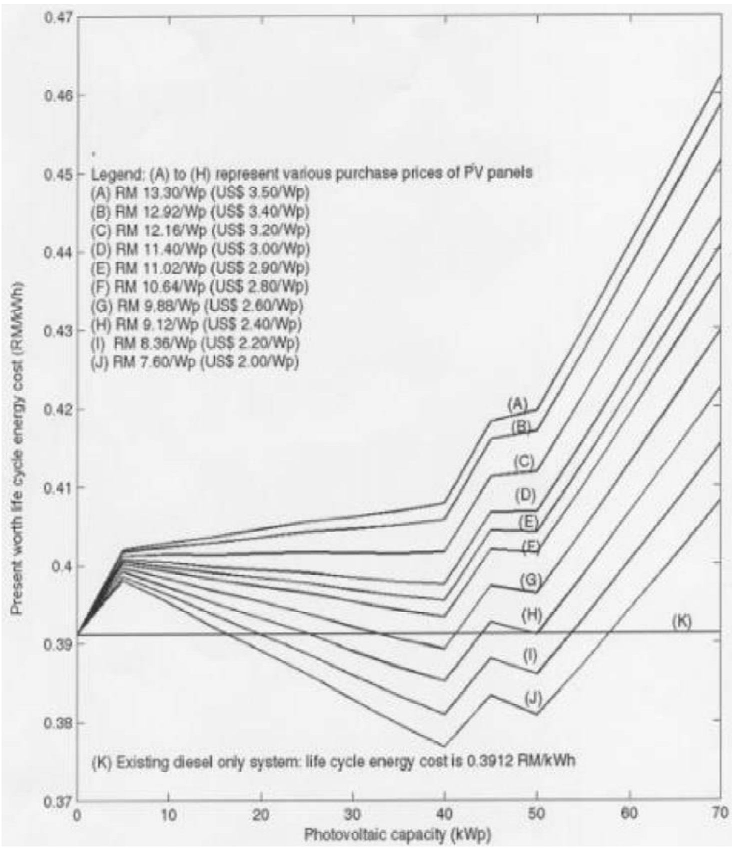


Fig. 12. Energy cost vs. PV size for various PV price (PV–diesel hybrid system with battery back-up).

A study has also been made on supplementing the diesel generator with a 35 $kW_P$ PV plus a battery back-up. The total LCC of a PV–diesel hybrid system without battery back-up is found less than that of the PV–diesel hybrid system with battery. The saving obtained from excess energy utilized by the battery is outweighed by the high costs for battery back-up.

This study has also shown that in the near future, when with continuing development PV panel price would reduce to RM 11.02/$W_P$ (US$2.90/$W_P$) or lower, the potentials of installing a PV–diesel hybrid system with higher sized PV especially in remote sites of Sarawak will greatly be enhanced. The total saving that would be achieved by adopting this supplement technology for all such remote sites represents a substantial amount. The way the study has been done does not lack in generality, and can serve as a guideline for assessing techno-economic aspects of a PV supplement at an off-grid site of any other country.

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