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# Minimum cost solution of photovoltaic–diesel–battery hybrid power systems for remote consumers

Henerica Tazvinga *, Xiaohua Xia, Jiangfeng Zhang

*Centre of New Energy Systems, Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria 0002, South Africa*

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**Abstract**

Hybrid systems present a new dimension to the time correlation of intermittent renewable energy sources. The paper considers the daily energy consumption variations for winter and summer weekdays and weekends in order to compare the corresponding fuel costs and evaluate the operational efficiency of the hybrid system for a 24-h period. Previous studies have assumed a fixed load and uniform daily operational cost. A load following diesel dispatch strategy is employed in this work and the fuel costs and energy flows are analysed. The results show that the photovoltaic–diesel–battery model achieves 73% and 77% fuel savings in winter and 80.5% and 82% fuel savings in summer for days considered when compared to the case where the diesel generator satisfies the load on its own. The fuel costs obtained during both winter and summer seasons for weekdays and weekends show substantial variations which should not be neglected if accurate operation costs are to be achieved. The results indicate that the developed model can achieve a more practical estimate of the fuel costs reflecting variations of power consumption behavior patterns for any given system.

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*Keywords:* Optimisation algorithm; Hybrid system; Control strategy; Economic dispatch; Energy efficiency; Operation efficiency

## 1. Introduction

The global increase in population growth and development has led to over-dependency by many nations on energy generation from fossil fuels. At the same time, concerns about global warming and depletion of fossil fuel reserves have led many nations to turn to the exploitation of renewable energy (RE) sources. In most developing countries, the main driver for RE exploitation is access to electricity especially in remote and rural areas that are not connected to the grid. RE technologies such as solar photovoltaic (PV) generation are gaining increased importance, as they offer advantages such as little maintenance, no noise and wear owing to the absence of moving parts, absence of fuel cost, and easy expansion to meet growing energy needs (Datta et al., 2009; Hong and Lian, 2012; Agrawal and Tiwari, 2011). Solar PV generation is an established clean technology and PV-based power systems are being deployed globally to provide autonomous power for various off-grid applications (Post and Thomas, 1988; Shaahid and Elhadidy, 2008; Battisti and Corrado, 2005; Tiwari and Dubey, 2010). PV modularity is one of its major strengths as this allows the users to match PV system capacity to the desired situation. The disadvantages of PV technologies are that they are capital-cost-intensive and their sunshine-dependent output may not match the load on a daily basis. Stand-alone diesel generator (DG) sets are generally inexpensive to purchase, but expensive to operate and maintain, especially at partial loads. PV and DGs have complementary characteristics in terms of capital cost, operating cost, maintenance requirements and resource availability. In order for PV systems to meet demand completely, there is a need for backup systems

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* Corresponding author. Tel.: +27 12 420 2068.
*E-mail address:* henerica.tazvinga@up.ac.za (H. Tazvinga).

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## Nomenclature

| | |
|---|---|
| $P_1(t)$ | control variable representing energy flow from the diesel generator to the load at any hour (kW) |
| $P_2(t)$ | control variable representing energy flow from the PV array to the load at any hour (kW) |
| $P_3(t)$ | control variable representing energy flow from the PV array to battery at any hour (kW) |
| $P_4(t)$ | control variable representing energy flow from the battery to the load at any hour (kW) |
| $P_L(t)$ | control variable representing the load at any hour (kW) |
| $T_A$ | the ambient temperature (°C) |
| $NT$ | standard andnominal cell operating temperature conditions |
| $A_c$ | the PV array area (m$^2$) |
| $P_{pv}$ | the hourly energy output from a PV generator of a given array area (kW h/m$^2$) |
| $\eta_R$ | the PV generator efficiency at reference temperature |
| $T_R$ | reference cell temperature (°C) |
| $T_C$ | the cell temperature (°C) |
| $I_B$ | the hourly global irradiation (kW h/m$^2$) |
| $I_D$ | the hourly diffuse irradiation (kW h/m$^2$) |
| $R_B$ | the ratio of beam irradiance incident on a tilted plane to that incident on horizontal plane |
| SOC | the state of charge |
| $B_C(t)$ | the state of charge of the battery bank at any hour |
| $B_C(t-1)$ | the state of charge of the battery bank at the previous hour |
| $\eta_C$ | the battery charging efficiency |
| $\eta_D$ | the battery discharging efficiency |
| $B_C(0)$ | the initial state of charge of the battery |
| $B_C^{\min}$ | the minimum allowable battery bank capacity (kW h) |
| $B_C^{\max}$ | maximum allowable battery bank capacity (kW h) |
| DOD | the depth of discharge |
| $a$,$b$ | fuel cost coefficients |
| $P_{DG}$ | generator rated power output $(kVA)$ |

such as DGs and battery storage in a hybrid system. Hybrid systems present a resolution to the time correlation of intermittent RE sources (Muselli et al., 1999; Belfkira et al., 2011; Tiwari and Dubey, 2010). The fact that the hourly solar radiation incident on the PV module at a given location is a function of the day and time of the year means that the fraction of the load supplied by PV is not constant. This implies that in the hybrid system considered in this paper, the solar fraction and battery bank capacity are expected to have a great impact on the DG fuel consumption, depending on the day, season and load profile. A high solar resource output will result in reduced fuel consumption, as the PV will be able to generate enough power to serve the load and/or charge the battery.

Various authors have proposed hybrid PV-diesel- battery systems for off-grid applications in which the cost of energy is the main criterion used to select the optimal power system (Shaahid and Elhadidy, 2008; Dufo-Lopez and Bernal-Augustin, 2005). The selection and sizing of components of a hybrid power system in Shaahid and Elhadidy (2008) are done using the Hybrid Optimisation Model for Electric Renewables (HOMER) software developed by the National Renewable Energy Laboratory, USA. HOMER is a simplified optimization model that can perform many hourly simulations in order to come up with the best possible matching between supply and demand to design the optimum system. It uses life cycle cost to rank different systems and also calculates the annual diesel costs. The main algorithm used by Dufo-Lopez and Bernal-Augustin (2005) obtains the optimal configuration of PV panels, batteries and DG, minimizing the total net present cost of the system, which includes all the life cycle costs throughout the useful lifetime of the system. It is shown in this work that the minimum output power of the DG and the minimum state of charge (SOC) of the batteries have an influence on the total net present cost and the optimal dispatch strategy. The PV-diesel-battery systems are found to be economically better than PV or diesel stand-alone systems for peak load profiles.

An economic analysis and environmental impact model of a PV with a diesel–battery system is proposed by Wies et al. (2005), in which the fuel cost is calculated over a one-year period and simple payback is worked out for the PV module. The electric power sources in the hybrid system consist of a PV array, a battery bank, a DG, and a wind generator. The model calculates the annual cost of electricity for different systems and also the annual cost of fuel. The results show that the PV–diesel–battery hybrid power system reduces the operating costs and the greenhouse gases, as well as the amount of particulate matter emitted to the atmosphere. However, the work done by Shaahid and Elhadidy (2008); Dufo-Lopez and Bernal-Augustin (2005); Wies et al. (2005) assumes a constant load and also a uniform daily operational cost, which does not reflect the variation of radiation output throughout the year and also the varying consumption patterns.

In contrast to the above-mentioned work on hybrid systems, the current work focuses on the minimization of the

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operational cost during a 24-h period for a chosen diesel dispatch strategy. The work looks at the optimization of the operation cost of the PV–diesel–battery power supply system from an energy efficiency perspective, as one of the key characteristics of energy efficiency is the search for optimality. Energy efficiency is defined as the ratio of energy output and input and is summarized as having the following components (Xia and Zhang, 2011; Xia et al., 2012): performance efficiency (P), operation efficiency (O), equipment efficiency (E), and technology efficiency (T) (POET). Operation efficiency is a system-wide measure, which is evaluated by considering the proper sizing and matching of different system components, time control and human coordination (Xia and Zhang, 2011). Operation efficiency can be improved through mathematical optimisation and optimal control approaches, for instance, pump operations (Zhang et al., 2012) and conveyor belt systems (Zhang and Xia, 2011) are investigated in literature. In the current study the operation efficiency is measured in monetary terms so as to minimize the fuel cost during a 24-h period. The objective of this work is also to illustrate the daily variation of demand and supply, as well as real operational issues in improving efficiency.

The hybrid system considered in this paper is made up of PV modules with battery storage and a DG set. The hybrid operation costs are the costs incurred after installation in order to run the system. These costs are usually determined on an annual basis or any other time interval and then discounted for the project life. The long-term operation costs of a project include maintenance, fuel, component overhaul and replacement costs. These costs are estimated for the future and are therefore more difficult to determine than the initial costs. In the short term, the operation costs of the battery and PV are negligible during the time interval considered, so only the fuel cost of the DG is taken into account. The PV–diesel–battery hybrid system operation costs are generally non-linear, as they depend on the component size and type, and the dispatch strategy (Seeling-Hochmuth, 1997).

The various optimisation approaches used in literature such as probabilistic, iterative and other classical approaches described above do not consider the weekday, weekend and seasonal changes in demand. The optimisation model proposed in this work takes into account the non-linearity of the operation costs associated with the PV–diesel–battery hybrid systems and this necessitates the use of quadratic programming. Heuristic techniques such as the one employed in this study are more efficient than classical techniques in terms of their ability to handle complex non-linear problems with many decision variables without extending computing time (Koutroulis et al., 2006). The approach used in this work also has low computational requirements achieving results in reasonable time, thus a faster and more accurate approach is developed. The fuel costs and energy flows are analysed taking into account weekday, weekend and seasonal changes in demand. The paper considers the daily energy consumption variations for weekdays and weekends in order to compare the corresponding fuel costs and evaluate the operational efficiency of the PV–diesel–battery hybrid system. Previous studies have assumed a fixed load and uniform daily operational cost, which can be extrapolated to get the monthly or yearly cost. However, the assumption is not accurate because of variations of consumer behavior patterns, hence a more practical daily operational cost is considered in this paper. The PV–diesel–battery hybrid system is found to achieve substantial savings when compared to that of a case where the DG only supplies the load. The model can assist solar energy practitioners or companies to give consumers accurate estimates of fuel costs they will expect to incur daily, seasonally or yearly. The remaining sections will look at the proposed hybrid system and the sub-models, namely the photovoltaic system, battery bank and DG. The optimisation model, which includes the objective function, constraints and model parameters, is examined, followed by the analysis of results, discussion and conclusion.

## 2. The hybrid system

The PV–diesel–battery hybrid power supply system proposed in this study is made up of three main sub-systems, the PV system, the battery storage system and the DG. The load is met by the PV array and the battery comes in and discharges when the PV output is not enough to meet the load if it is within its operating limits. If PV output is above the load requirements, the battery is charged by the PV array. The DG comes in when the PV and/or the battery cannot meet the load but does not charge the battery. Fig. 1 shows the proposed simulation process in terms of the input or database, the data base support and the output.

### 2.1. Photovoltaic system model

The hourly energy output from the PV generator of a given area is written as:

$$P_{pv} = \eta_{pv} A_c I_{pv}. \tag{1}$$

In Eq. (1), $\eta_{pv}$ is the efficiency of the PV generator, which can be expressed as a function of the hourly solar irradiation incident on the PV array, $I_{pv}$ ($kW\,h/m^2$), and the ambient temperature, $T_A$, as well as the test parameters of the PV generator at standard and nominal cell operating temperature (NT) conditions. $A_c$ is the PV array area and

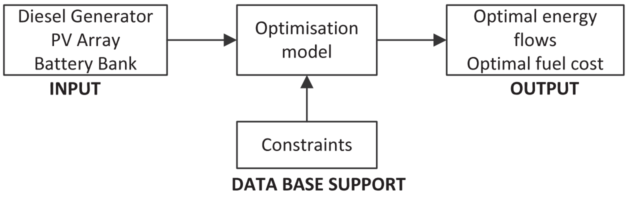

Fig. 1. Simulation of a PV-diesel-battery hybrid power supply system.

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$P_{pv}$ is the hourly energy output from a PV generator of a given array area. The efficiency of the PV generator is given by:

$$\eta_{pv} = \eta_R\left[1 - 0.9\beta\left(\frac{I_{pv}}{I_{pv,NT}}\right)(T_{c,NT} - T_{A,NT}) - \beta(T_A - T_R)\right], \tag{2}$$

where $\eta_R$ is the PV generator efficiency measured at reference cell temperature $T_R$, i.e., under standard test conditions (25 °C). $\beta$ is the temperature coefficient for cell efficiency (typically 0.004–0.005/°C); $I_{pv,\ NT}$ is the average hourly solar irradiation incident on the array at $NT$ (0.8 kW h/m$^2$); $T_{C,NT}$ (typically 45 °C) and $T_{A,NT}$ (20 °C) are, respectively, the cell and ambient temperatures at $NT$ test conditions. The hourly solar irradiation incident on the PV array is a function of time of day, expressed by the hour angle, the day of the year, the tilt and azimuth of the PV array, the location of the PV array site as expressed by the latitude, as well as the hourly global solar irradiation and its diffuse fraction (Duffie and Beckman, 2006; Collares-Pereira and Rabl, 1979; Agrawal, 2012). The actual expression relies on the sky model, which is a mathematical representation of the distribution of diffuse radiation over the sky dome presented in Duffie and Beckman (2006). In the study, the simplified isotropic diffuse formula suggested in Collares-Pereira and Rabl (1979) is used. The hourly solar irradiation incident on the PV array is given by:

$$I_{pv} = (I_B + I_D)R_B + I_D. \tag{3}$$

In (3), $I_B$ and $I_D$ are respectively the hourly global and diffuse irradiation in kW h/m$^2$. $R_B$ is a geometric factor representing the ratio of beam irradiance incident on a tilted plane to that incident on a horizontal plane. Monthly average hourly meteorological data, global irradiation, diffuse irradiation and ambient temperature are used as inputs in evaluating (1)–(3) of the performance simulation model. The evaluation is performed at the mid-point of each hour of the day, on the "average day" of each month as defined in Duffie and Beckman (2006). For any energy supply system, the hourly average energy demand depends on the energy demand profile for the particular application. Typical load profiles for summer and winter seasons for rural community clinics in Zimbabwe are shown in Table 1. The load profile is for the clinic and nurses houses. The methodology for calculating the load demand developed in Tazvinga and Hove (2010) and in Tazvinga et al. (2010) is used to obtain the weekday and weekend demand profiles based on an energy demand survey carried out in rural communities by the same authors.

Table 1
Weekday and weekend demand profiles.

| Time | Winter load (kW) | | Summer load (kW) | |
|---|---|---|---|---|
| | Weekend | Weekday | Weekend | Weekday |
| 00:30 | 1.5 | 1.5 | 1.5 | 1.5 |
| 01:30 | 1.5 | 1.5 | 1.5 | 1.5 |
| 02:30 | 1.5 | 1.5 | 1.85 | 1.85 |
| 03:30 | 1.5 | 1.5 | 1.95 | 1.95 |
| 04:30 | 1.5 | 1.5 | 1.85 | 1.85 |
| 05:30 | 1.95 | 1.65 | 1.5 | 1.5 |
| 06:30 | 1.95 | 1.65 | 1.65 | 1.15 |
| 07:30 | 1.65 | 1.35 | 1.65 | 1.25 |
| 08:30 | 1.35 | 1.35 | 1.7 | 1.3 |
| 09:30 | 3.25 | 3.0 | 1.75 | 1.32 |
| 10:30 | 3.25 | 3.0 | 1.75 | 1.35 |
| 11:30 | 2.15 | 1.95 | 1.75 | 1.32 |
| 12:30 | 2.15 | 1.95 | 1.25 | 1.25 |
| 13:30 | 2.15 | 1.95 | 1.32 | 1.32 |
| 14:30 | 2.15 | 1.95 | 1.35 | 1.35 |
| 15:30 | 2.15 | 1.95 | 1.35 | 1.35 |
| 16:30 | 2.15 | 1.65 | 1.45 | 1.45 |
| 17:30 | 1.8 | 1.65 | 2.1 | 2.15 |
| 18:30 | 2.31 | 3.25 | 2.4 | 2.31 |
| 19:30 | 3.81 | 3.25 | 3.8 | 3.25 |
| 20:30 | 2.31 | 2.31 | 3.8 | 3.25 |
| 21:30 | 2.31 | 2.15 | 2.0 | 2.0 |
| 22:30 | 2.31 | 2.15 | 1.95 | 1.95 |
| 23:30 | 1.35 | 1.35 | 1.65 | 1.65 |

## 2.2. Battery bank model

The power output from the PV and the load demand at given an hour $t$, determine the charge or discharge power into and out of the battery bank. $t$ is an integer representing the $t$th hour interval. The SOC of the battery bank at any hour $t$, $B_C(t)$, depends on the SOC at the previous hour $B_C(t-1)$. The following conditions need to be taken into consideration for energy flows from $t-1$ to $t$:

At any given hour the battery SOC will be given by the expression:

$$B_C(t) = B_C(t-1) + \eta_C P_3(t) - \eta_D P_4(t), \tag{4}$$

in which, $\eta_C$ is the battery charging efficiency, and $\eta_D$ is the battery discharging efficiency. The following general expression derived from (4) applies to the battery dynamics:

$$B_C(t) = B_C(0) + \eta_C \sum_{\tau=1}^{t} P_3(\tau) - \eta_D \sum_{\tau=1}^{t} P_4(\tau), \tag{5}$$

where $B_C(0)$ is considered as the initial SOC of the battery.

$\eta_C\sum_{\tau=1}^{t}P_3(\tau)$ is the power accepted by the battery at time $t$, and $\eta_D\sum_{\tau=1}^{t}P_4(\tau)$ is the power discharged by the battery at time $t$.

The available battery bank capacity must not be less than the minimum allowable capacity $B_C^{\min}$ and must not be higher than the maximum allowable capacity $B_C^{\max}$ (Vosen and Keller, 1999):

$$B_C^{\min} \leqslant B_C(t) \leqslant B_C^{\max},$$

and

$$B_C^{\min} = (1 - \mathrm{DOD})B_C^{\max},$$

where DOD is the depth of discharge expressed as a percentage.

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### 2.3. Diesel generator model

DGs are incorporated in hybrid power supply systems as back-up and are usually required to cover the load at times when the PV and the battery cannot meet the load (Koutroulis et al., 2006). The manufacturer of the DG usually recommends the minimum diesel operation. The maximum efficiency of a DG corresponds to the rated power of the DG, therefore the DG has to be operated between the rated power and specified minimum value (Dufo-Lopez and Bernal-Augustin, 2005; Fulzele and Dutt, 2012; Zhou et al., 2007) as represented by the following constraint:

$$P_1^{\min} \leqslant P_1(t) \leqslant P_1^{\max}.$$

The conditions for switching on or off depend on the DG energy dispatch strategy. In the present study, a load-following strategy is employed in which the DG is switched on when the PV and/or the battery is unable to meet the load. This strategy promises to be more economical in terms of usage of DG energy, as the generator is dispatched only when required. Under the load-following strategy, the diesel generator produces only enough power to meet the load demand and is not used as a battery charger. The DG is more likely to operate at high load factors, resulting in low specific fuel consumption and longer DG life (Muselli et al., 1999; Tina et al., 2006). In this work a 5 kVA Power Rush generator type is employed in which an electronic control system is used to vary the output by sensing the load and sending an electrical signal to the fuel injection system to adjust the fuel supply and engine revolutions in response to the load. The advantage of this type of generator is its ability to supply the required power output at any given time.

## 3. Optimization model

The PV module is modeled as a variable power source controllable in the range of zero to the maximum available PV power for the 24-h interval. No PV operating costs are incorporated. The battery is modeled as a storage entity with minimum and maximum available capacity levels. No battery operating costs are incorporated. The DG is modeled as a controllable variable power source with minimum and maximum output power as indicated at the end of the previous section. Fuel consumption costs are modeled as a non-linear function of generator output power (Seeling-Hochmuth, 1997). The non-linear optimisation programming is solved using the “quadprog” function in MATLAB. This function solves problems in the form:

$$\min \frac{1}{2} x^T H x + f^T x,$$

subject to:

$$\begin{aligned} Ax &\leqslant b, \\ A_{eq}x &= b_{eq}, \\ lb \leqslant x &\leqslant ub. \end{aligned}$$

The load demand is to be met by the PV generator. If the PV output is not enough to satisfy the load demand, the battery discharges to satisfy the load requirement. If the PV output is above the load requirement, the excess energy from the PV is stored in the battery until full capacity of the batteries is reached. In some instances the solar PV power and/or battery bank power available is supplied to the load and the DG supplies the deficit in order to satisfy the load completely. The DG switches off when the PV and/or the battery bank can fully satisfy the load. The economic dispatch problem is to determine the optimum scheduling of generation at any given time that minimizes the fuel cost while completely satisfying the demand and operating limits. The objective function is given by the following expression:

$$\min C_f \sum_{t=1}^{N} (aP_1^2(t) + bP_1(t)), \tag{6}$$

subject to the following constraints:

$$P_2(t) + P_3(t) \leqslant P_{pv}(t), \tag{7}$$

$$P_1(t) + P_2(t) + P_4(t) = P_L(t), \tag{8}$$

$$P_1(t) \geqslant 0, P_2(t) \geqslant 0, P_3(t) \geqslant 0, P_4(t) \geqslant 0, \tag{9}$$

$$P_i^{\min} \leqslant P_i(t) \leqslant P_i^{\max}, \tag{10}$$

$$B_C^{\min} \leqslant B_C(0) + \eta_C \sum_{\tau=1}^{t} P_3(\tau) - \eta_D \sum_{\tau=1}^{t} P_4(\tau) \leqslant B_C^{\max}, \tag{11}$$

for all $t = 1, \cdots, N$, where $N$ is 24 and $C_f$ is the fuel price. $B_C(t)$ is equal to the sum of and the power accepted or discharged by the battery. $P_1(t)$,$P_2(t)$ and $P_4(t)$ are the control variables representing energy flows from the DG, PV and battery to the load at any time ($t$) respectively and $P_3(t)$ represents the energy flow to the battery during the 24-h period. The first constraint (7) implies that the sum of the charging power and power supplied directly to the load from the PV array is less than or equal to the total power from the PV array. Constraint (8) ensures that the power supplied by the DG, PV array and battery at any hour equals to the demand at the same hour. Constraint (9) ensures that the charging power, power supplied directly to the load from the PV array and power supplied by the battery to the load is each greater than or equal to zero. Each energy source $i$ is constrained by minimum and maximum values as specified by constraint (10).

### 3.1. Model parameters

The generator cost coefficients $a$ and $b$ are specified by the manufacturer while the DG, PV and battery bank capacities are chosen based on a sizing model in Hove and Tazvinga (2012). The system sizing is such that demand will be met at any given time. A small system means demand will not always be met while an oversized system means the demand will be met but the system will be unnecessarily costly and energy will be wasted, hence the need for an optimally sized system. In this work, the

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focus is mainly on the optimal energy management of any given system. The sizing is also within “Rule of thumb” provisions, for example PV array area for 1 kWp varies from 7 $m^2$ to 20 $m^2$ depending on cell material used. The energy generated by the PV array and the DG is consumed by the load and the PV generator also charges the battery, depending on the instantaneous magnitude of the load and SOC of the storage battery. The switching on or off times of the DG depend on the DG energy dispatch strategy employed which is herein referred to as the load following strategy. The DG switches on when the PV hourly output is lower than the hourly load and the combined battery output and PV output cannot meet the load. The parameters used in this model are shown in Table 2.

## 4. Results and discussion

Figs. 2–5 show the energy flow during the 24-h period. During the night and early morning the load is either met by the battery if the SOC is within limits and can satisfy the load or by the DG or by a combination of the two sources. PV output supplies the load and charges the battery. The first constraint (7) means that for PV array output to be able to satisfy the load or satisfy the load and charge the battery, it must be equal or greater than the load. The DG switches on when the PV and battery cannot satisfy the load. The charge and discharge processes of the battery are shown in Figs. 2–5 as $P_3(t)$ and $P_4(t)$ respectively. Generally the battery bank is charged during the day and supplies the load mostly during the night when there is no power from the PV. During the early hours of the day after sunrise and towards sunset the load is met by the DG, PV and battery bank. The DG turns off when the PV produces enough power to meet the load or when the combined power from the PV and battery can satisfy the load. In Figs. 2–5, it is shown that power from the PV to the load $P_2(t)$ is not enough to meet the load just after sunrise and just before sunset. The PV output continues to increase up to point when it produces more than the load and is able to charge the battery bank. At that same point the diesel generator switches off until the point when the PV cannot produce enough power to meet the load and charge the battery as shown in Figs. 2–5 in $P_1(t)$. The DG running time and amount of power supplied by the DG depends on the SOC of the battery and the amount of power from the PV array. It therefore follows that the DG runs for more hours and generates more power if the output from the PV and/or battery is low.

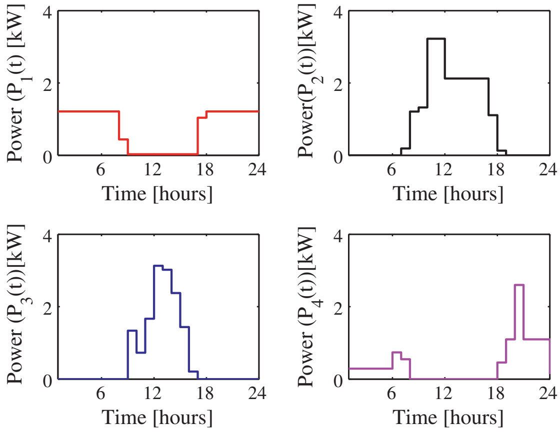

Fig. 2. June weekend power flow.

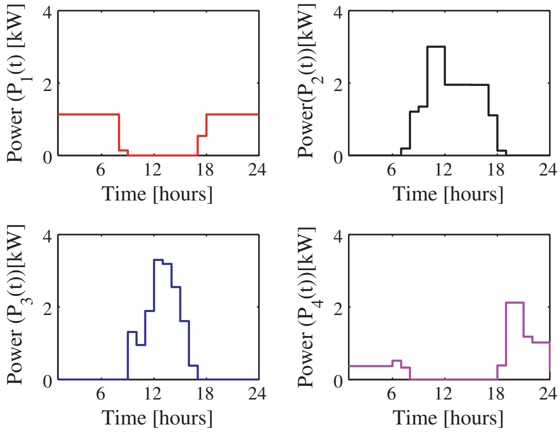

Fig. 3. June weekday power flow.

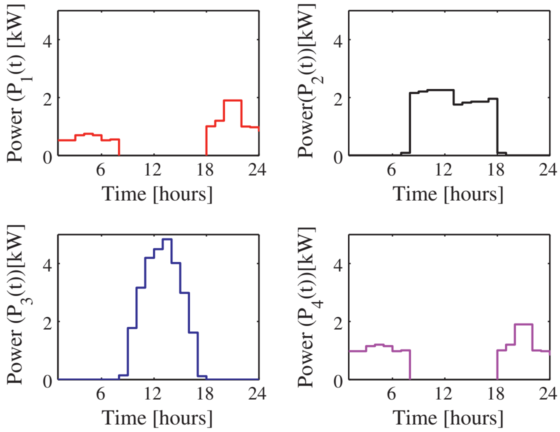

Fig. 4. December weekend power flow.

Table 2
Parameters.

| | |
|---|---|
| Nominal battery capacity | 54.5 kW h |
| Battery charge efficiency | 85% |
| Battery discharge efficiency | 100% |
| Battery allowable depth of discharge | 50% |
| PV array capacity | 4 kW |
| DG capacity | 5 kVA |
| a | US\$0.246/h |
| b | US\$0.1/kW h |
| Fuel Cost | US\$1.2/l |

Fig. 2 and 3 show the weekend and weekday power flows during winter while Fig. 4 and 5 show the weekend and weekday power flows during summer. The graphs

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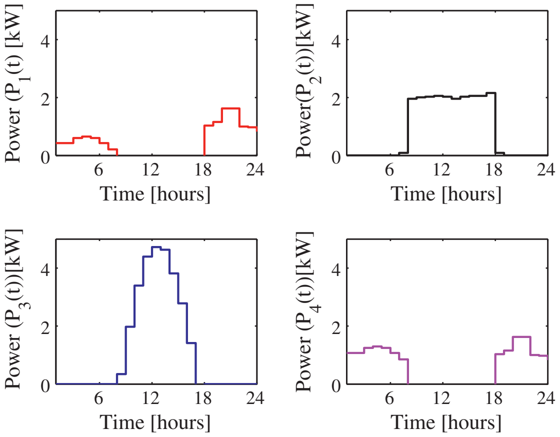

Fig. 5. December weekday power flow.

Table 3
Fuel cost savings.

| | Winter weekend | Winter weekday | Summer weekend | Summer weekday |
|---|---|---|---|---|
| Diesel only scenario | US$51.4 | US$46.5 | US$43.7 | US$37.8 |
| Hybrid model | US$13.2 | US$11.3 | US$8.4 | US$6.80 |
| Savings | US$38.2 | US$35.2 | US$35.3 | US$31 |

show how seasonal variations in PV output and change in demand affect the diesel dispatch strategy. In summer the PV supplies more power than it does in winter. Figs. 2–5 generally show that the DG switches off earlier and switches on later in summer than in winter. The longer summer day-times, shorter winter day-times and the corresponding high and low radiation levels mean that the battery is charged more in summer than in winter. The DG also supplies more power in winter than in summer especially during the early hours of the day and this is attributed to higher PV output and higher SOC of the battery bank in summer than in winter.

It is observed that demand is generally lower in summer than in winter. Weekday and weekend fuel consumption value differences are attributed to differences in consumption patterns as shown in Table 1. Generally the weekend demand is higher than weekday demand due to the fact that during the week in most rural communities people will be busy with activities outside the home but during weekends they will be at home making more use of the various appliances. Also the number of people who visit the clinic is higher during weekends. The results show that more fuel is used in winter than in summer and also more is used during the weekends than during weekdays. The fuel cost for winter weekends is found to be 15% more than that for the weekdays. The fuel cost for summer weekends is 19% more than that for the weekdays. The fuel cost for winter weekends is found to be 36% more than that for summer weekends while that for winter weekdays is 39% more than that for summer weekdays.These results show that it is very important to consider seasonal demand changes when calculating operation costs. The results thus show how demand is optimally satisfied by the DG, PV array and battery bank and the corresponding energy flows during the 24-h interval.

In the model configuration employed in this work, the battery is charged by the PV array only and the DG supplies the load when it is switched on. This configuration ensures maximum use of PV output and no energy is wasted when the DG runs since the output matches the demand. The objective function is to minimise fuel costs while satisfying demand and other constraints using quadratic programming as stated in preceding sections. No similar optimisation model for PV–diesel–battery hybrid system is found in literature that minimises fuel costs taking into account variations in demand. Closer to this work is work done by Suryoatmojo et al. (2010) who use genetic algorithm to solve an economic model in which the annual cost of the system is minimised. The battery is utilised when both the DG and the PV cannot meet the load while in the model developed in this study it is utilised when PV output cannot meet the load but before the DG comes in depending on its SOC. Barley and Winn (1996) look at various dispatch strategies for various combinations of wind turbine generators, diesel generators, PV arrays and batteries using an analysis of cost trade-offs,a simple quasi-steady-state time-series model, and HYBRID2. However, there is no basis for comparing the corresponding fuel costs as the system configurations are different. The system configurations and the operational strategies employed are different from the optimisation model developed in this work making it difficult to compare the daily fuel costs.

Table 3 shows how the diesel fuel costs for typical weekdays and weekends in both summer and winter seasons compare to the diesel only scenario. The fuel savings are obtained by finding the difference between the fuel cost values for the diesel only scenario in which the load is met completely by the DG, and the PV–diesel–battery model for the days and consumption patterns considered. The results show that the PV–diesel–battery model achieves 73% and 77% fuel savings in winter, and 80.5% and 82% fuel savings in summer on weekends and weekdays respectively when compared to the diesel only scenario. The differences in fuel cost obtained indicate the potential of the optimisation model to reduce fuel costs for the DG dispatch strategy employed compared to the diesel only scenario. As already mentioned, most of the work done so far assume a load that does not change and also a uniform daily operational cost, which do not reflect the variation of consumption patterns. The current study results indicate that by making use of the described methodology and considering daily and seasonal variations in demand, more accurate costs can be obtained.

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## 5. Conclusion

An optimal energy dispatch model of a PV–diesel–battery hybrid system is presented and the optimal energy flows are analysed. The optimisation model developed is shown to achieve more savings than the diesel only scenario. The results show how daily and seasonal variations in demand variations affect the operational cost of the PV–diesel–battery power supply system. For both summer and winter seasons, the weekend fuel costs are higher than weekday costs. Winter fuel costs are found to be higher than the summer fuel cost due to higher demand in winter and also the lower winter radiation levels mean more use of supplementary sources. This shows that the daily and seasonal demand changes are important aspects to be considered as they considerably affect the operation cost and the energy flows. It has been shown that the developed optimisation model achieves optimal fuel costs and can be used in the analysis of the energy flows in any given system. A more practical estimate of the fuel costs reflecting variations of power consumption behavior patterns is thus presented in this paper, which can be extrapolated to give an accurate estimate of the daily diesel fuel cost. Further development of the model will include optimization of the various components of the hybrid system, incorporating on/off switching of the DG, use of more generators and carrying out a life cycle cost analysis of the whole system in longer term by taking into consideration the variations of the daily operational costs. A validation for the present model is planned and will be the subject of future publications.

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