Science real and relevant conference 2010
Proceedings homepage://www.conference.csir.co.za/

A technical model for optimising PV/diesel/battery hybrid power systems

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Reference: EN01-PO-F

Abstract

A solar-based power supply system, such as a photovoltaic (PV)-diesel-battery system, is a particularly attractive option for decentralised power supply in southern Africa where solar radiation is ubiquitous in most countries. Such systems can make a positive contribution to the sustainability of rural communities in developing countries that do not have access to an electricity grid as they address the shortfalls of stand-alone systems. However, a lot more design effort and expertise is required for optimising the sizing and operational strategy of the PV-diesel-battery hybrid system than is required for single-source systems. Various models are available on the market and in research groups but the challenge is to customise these to suit local conditions. This paper presents the development and application of a simple spreadsheet-based mathematical model for sizing and performance prediction of a PV-diesel-battery autonomous power supply system. The model is employed to generate a set of sizing curves that define the design space for hybrid systems using dimensionless component size variables, for a specified supply reliability and diesel energy dispatch strategy. The outputs of the model reveal several important sizing and operational characteristics of the systems.

Keywords: PV-diesel hybrid systems, optimal sizing, loss of load fraction, dispatch strategy

1 Introduction

Decentralised power-generation systems based on renewable energy can play an important role in hastening the arrival of electricity to many households and commercial enterprises in the rural areas of southern Africa. This is because decentralised systems can be more cost-effective than central grid extension for supplying power to the distant, low-population-density, scattered settlements characterising most rural areas. Traditionally, diesel generators have been the favoured solution for decentralised electricity supply because of their low initial capital cost. However, apart from environmental concerns, the diesel generator has high operating costs as a result of high consumption of fuel and high maintenance costs. In diesel-only systems, these problems are exacerbated by the fact that the diesel generator necessarily has to be sized for peak power demand and has to run continuously, irrespective of diurnal load variation. During low-load periods, the peak-power-sized diesel generator operates at a low load factor, resulting in high specific fuel consumption and the problem of “wet-stacking” (Donaldson, 2005), which shortens engine life. These operational problems result in a high overall end-use energy cost for diesel-only power systems. On the other hand, the amount of power produced by renewable energy devices such as photovoltaic cells and wind turbines varies significantly on an hourly, daily and seasonal basis due to the variation in the availability of sunshine, wind and other renewable resources. This variation means that sometimes power is not available when it is required and on other occasions there is excess power.

Incorporating battery storage and a renewable energy source to form a hybrid power supply system can alleviate most of the problems mentioned for the diesel-only power system. When compared with monosourced energy systems, hybrid systems based on renewable energy sources have many advantages, including increased reliability of power supply, mitigation of environmental damage, reduced generator component sizes, increased average diesel load factor and associated benefits, and possibly lower unit energy costs. A solar-photovoltaic-based (PV-diesel-battery) system is a sustainable choice of hybrid system in many southern African countries since solar radiation is incidentally ubiquitous in abundant quantities in most of these countries.

In the design of a PV-diesel-battery hybrid system, the problem is to select a suitable size blending of generator components (PV array, diesel generator and storage battery) and an appropriate dispatch strategy for the diesel generator. This normally requires the use of sophisticated commercial computer simulation software, e.g. HYBRID2 (Baring-Gould, 1996), RAPSIM (Jennings, 1996) and others, which are ordinarily not affordable by researchers in developing countries. While some programs are freely available online, they require high expertise and the user does not gain an intuitive understanding of the system, hence the development of simplified computational methods. Compared with some previous models, the present model has the added attributes of a wider scope of parameters (different diesel dispatch strategies and variable system reliability).

This paper reports on the development and application of a simple spreadsheet-based mathematical model for sizing and performance prediction of a PV-diesel-battery autonomous power supply system. It outlines how the model is used to determine the optimum-sized hybrid system to satisfy a given load profile at a desired power supply reliability. It also forms the basis of another paper to be presented at the next CSIR conference once the system has undergone the validation process. This work is ongoing and a Memorandum of Understanding with the University of Zimbabwe is under way to enable further development and validation of the model.

2 Hybrid systems

Hybrid systems consist of combination of a PV array and a complementary means of electricity generation, such as a diesel, gas or wind generator (Suryoatmoyo, et al., 2009). Bhikabhai (2005) argues that considering the wide range of loads to be serviced, the variety of source converters available, and the type of storage and charger/inverter, there is almost an infinite variety of hybrid energy systems.

A key feature of hybrid systems is the fact that their constituent system strengths complement one another thus providing a number of advantages, which are also determined in part by the system type. These systems provide significantly greater reliability in power supply due to the use of two or more energy sources, more efficient system solutions by virtue of a high degree of flexibility during the design phase and in operation, lower overall maintenance costs due to the shorter operating cycles of the motor generator units and longer service life -time of components as a result of reduced use (Haupt, 1998). The main problem with hybrid power supply systems other than the additional investment cost of renewable energy sources, storage, power electronics and the limited experience of customers, is that they are more complex when compared with stand-alone systems in terms of system sizing and the operational strategy of components (Ashok, 2007). Karnavas and Papadopoulos (1999) highlight the main advantages of hybrid systems as reduced operational cost due to lower fuel consumption and low PV maintenance, improved reliability through diversifying power sources and continuous power supply, as well as increased operational life due to fewer generator operating hours. The system is environmentally friendly due to reduced emissions and noise pollution, and smoothes out seasonal weather fluctuations, resulting in improved energy services, reduced ‘deep-cycling’ of batteries and extended battery life.

According to a study by Phuangpornpitak and Kumar (2005), hybrid systems have been successfully implemented in countries such as Thailand. In South Africa, the Department of Minerals and Energy evaluated the Hluleka and the Lucingweni village system mini-grids for viability and replicability (Szewczuk, 2008). However, the CSIR report concluded that the Lucingweni model should not be replicated in its current form as it is not viable. It was recommended that the energy system be redesigned and optimised from a viability and replicability point of view so that it could form the basis of a distributed generation system that will contribute towards South Africa’s electricity supply.

3 PV-diesel-battery hybrid system and energy flow logic

Figure 1 shows a schematic of the PV-diesel-battery hybrid system to be analysed. The system consists of an AC load, power-generating components – solar PV array and diesel generator (DG), battery storage, and the power conditioning or regulation components – DC-AC inverter, solar controller and battery charger. Electrical energy generated by the solar PV array and the diesel generator can either be consumed by the load, supplied to the battery or wasted (dumped energy), depending on the instantaneous magnitude of the load and state of charge of the storage battery.

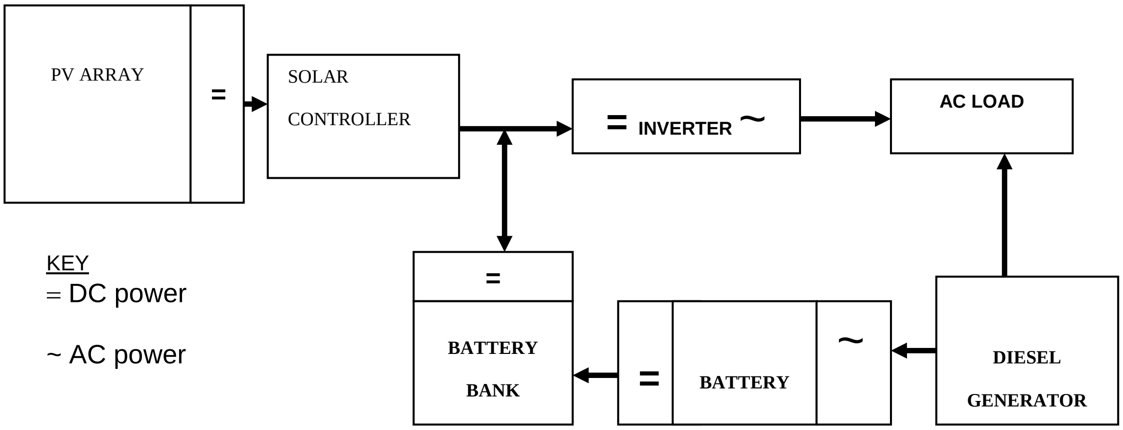

Figure 1: Schematic of a typical PV-diesel-battery hybrid power supply system

In the model, the load can take any value in the following categories, resulting in a different energy flow logic for each load category:

- If the hourly-average energy demand is less than the rated power output of the diesel generator, the diesel generator can more than satisfy the load on its own, and the excess energy goes to charging the battery. The excess diesel generator energy, over that supplied to the load and accepted by the battery, goes to waste. In this load category, the available PV energy goes to charging the battery, provided that it is not already fully charged by previous charge events, with the excess PV energy also going to waste.

- If the hourly-average energy demand is greater than or equal to the total of the rated diesel generator output and PV array output (system output), the load can be satisfied by the combined output of the diesel generator and the PV array. All of the diesel generator output is consumed by the load, with the deficit, if any, supplied by the PV array through the inverter. The excess PV energy (over that supplied to the inverter) goes to the battery and/or to waste; the amounts can go either way depending on the state of charge of the battery relative to the available excess energy.

- Finally, if the hourly-average energy demand is greater than the system output, the combined output of the diesel generator and the PV array will not be enough to satisfy the load, hence no energy is dumped. The energy deficit is provided by the battery, which can discharge energy only when its depth of discharge is less than the maximum allowed. It is possible under this load category for the combined hourly output of the battery, PV array and diesel generator to fall short of the hourly load. The system is said to experience ‘loss of load’ under these circumstances. At this point the system controller will intentionally disconnect the load from the battery, thereby avoiding a severe discharge which could damage the battery.

The hourly-average energy demand depends on the energy demand profile for the particular application. A typical load profile for residential and some institutional applications in southern Africa is the ‘double-hump’ variation shown in Figure 2.

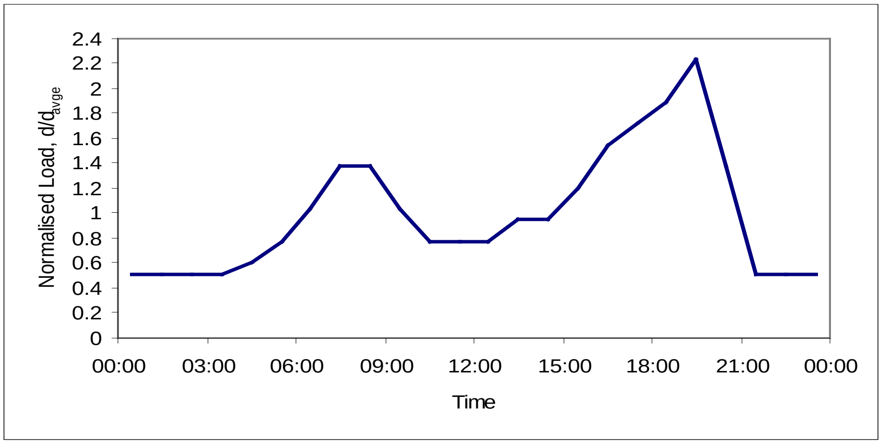

Figure 2: Load demand profile

3 Energy output of generator components

The models used for determining the diurnal variation of energy output for the two generating components of the hybrid system, PV array and diesel generator are outlined in this section.

3.1 PV array output

The PV array energy output varies with time of the day, season and weather conditions (Ashok, 2007). It is given by the product of the solar radiation received on the plane of the array, the PV solar-to-electrical efficiency and the area of the array.

In this study, the solar irradiation collected by the PV array for a given hour is calculated from measured or stochastically generated values of hourly global and diffuse irradiation, using the simplified tilted-plane model of Collares-Pereira and Rabl (1979), and assuming that the irradiation is concentrated at the middle of the hour.

The PV electrical efficiency is a function of collected solar radiation, I_{PV}, and ambient temperature, T_a, as given by Hove (2000).

$$\eta_{PV} = \eta_r \left[1 - 0.9 \frac{I_{PV}}{I_{PV,NOCT}} (T_{C,NOCT} - T_{a,NOCT}) - \beta (T_a - T_r) \right] \quad (1)$$

In Equation (1), η_r is the manufacturer-rated efficiency of the modules making up the PV array and T_r is the reference cell temperature at which η_r is measured; $T_{C,NOCT}$ and $T_{a,NOCT}$ are respectively the PV cell temperature and ambient temperature at nominal operating cell temperature (NOCT) conditions (i.e. when $\eta_{PV} = 0$, $I_{PV} = 800$ W/m^2, $T_a = 20^{o}$C and wind speed = 1 m/s); and β is a temperature coefficient for cell efficiency which is also provided by the PV manufacturer.

3.2 Diesel generator output

For any given hour, the diesel generator output is either zero or the rated diesel generator power, depending on whether the diesel generator is switched off or on, respectively, for the hour in question. The conditions for switching on or off depend on the diesel generator energy dispatch strategy adopted by the system designers and/or operators. In the present study, two different dispatch strategies are analysed.

(1) The Night Dispatch Strategy assumes that the diesel generator will be switched on only at night (when there is no solar radiation). This strategy allows a simple operation that can be done manually without the need for sophisticated electronic control, but might be wasteful for load profiles exhibiting low night energy usage.

(2) In the Load-following Strategy, the diesel generator is switched on when the load equals or exceeds a certain prescribed threshold. This strategy, depending on the correct choice of threshold load, may result in a more economical usage of diesel generator energy since it is dispatched only when really needed, and the diesel generator is likely to operate at high load factors, resulting in low specific fuel consumption and longer diesel generator lifespan. However, its implementation entails the use of electronic controls that may be costly to acquire and maintain, increase system sophistication, and hence be less appropriate for the rural setting in most developing countries.

The switch-on load value can take any value prescribed by the system designer and/or operator, between zero and peak demand. For a varying load, the higher the prescribed value of threshold load, the lower the diesel generator runtime.

4 System sizing

For a given load and diurnal profile, the principal variables controlling the energy performance of the system are the PV array size, the diesel generator rated power, the battery capacity and the strategy employed for dispatching diesel generator energy. The main constraint is that the chosen combination of component sizes should always be able to deliver enough energy to attain a certain prescribed degree of supply reliability. The degree of supply reliability is measured in this study by the loss of load fraction (LLF). The LLF is defined here as the fraction of annual hours when the power supply system fails to completely satisfy the load. A prescribed LLF can be attained by any of an infinite number of combinations of system component sizes (PV array, battery and diesel generator size) and diesel generator dispatch strategies. The combination resulting in the least energy cost is the optimum system.

4.1 System sizing curves

The procedure used is to define the hybrid system design space by generating a family of system sizing curves, then to plot the PV array size required to attain a prescribed LLF, against battery size, for different discrete values of diesel generator size. To generalise the sizing curves for all magnitudes of daily loads with the same diurnal profile, the hybrid system component sizes are represented by dimensionless variables. The PV array size is characterised by the normalised variable A/A_o, where A is the actual installed PV array area (m^2) and A_o is a hypothetical area conceptualised by Hove (2000) as the PV array area required for satisfying a daily electrical load, D, if the array is operated at reference efficiency, η_r, and reference solar irradiance (1 kW/m^2) constantly throughout the day. Hence

$$A_o[m^2] = \frac{D}{24\eta_r} \tag{2}$$

The diesel generator size is characterised by the normalised variable, $Q_{DG}/\bar{d}$, where $\bar{d}$ is the daily average load, equal to $D/24$; and the battery size is represented by the variable B_{cap}/D.

An Excel spreadsheet calculator was developed for computing, among other things, the LLF from inputs of the three dimensionless variables (normalised array area, battery capacity and diesel generator size), as well as inputs defining the diesel generator dispatch strategy. For a chosen dispatch strategy, each sizing curve is generated by fixing the diesel generator size, and the combinations of battery capacity and array area that just yield the prescribed LLF are the required coordinates of the sizing curve. The diesel generator size is then varied in discrete increments, say, from average daily power to peak load power, to generate the complete family of sizing curves.

Examples of sizing curves generated this way, using meteorological data for a chosen site in southern Africa and the load profile in Figure 2, are shown in Figures 3 and 4 for different dispatch strategies and levels of supply reliability. A number of observations can be made from the sizing curves. The PV array area required to achieve a chosen level of reliability decreases with increases in the battery size (along each sizing curve), and with increases in diesel generator size (among different sizing curves). Of course, greater supply reliability (decreased LLF) calls for larger sizes of the hybrid system components and a correspondingly larger system cost. The prescribed system component size combinations differ from one diesel generator dispatch strategy to another.

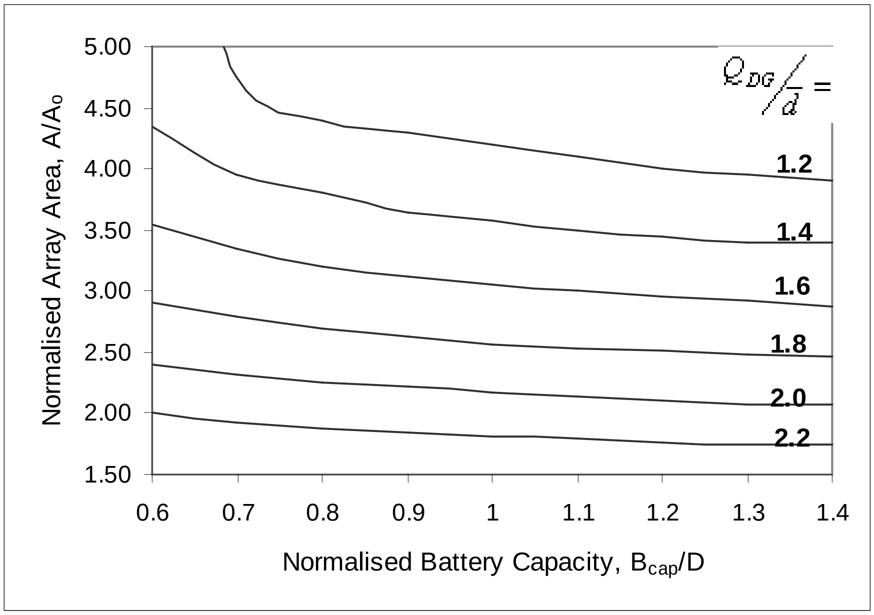

Figure 3: Sizing curves for system on load-following dispatch strategy, for LLF = 1%

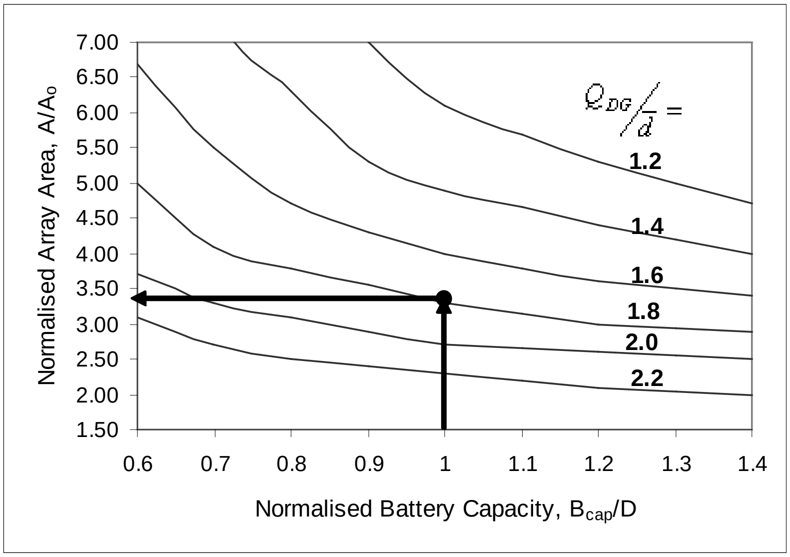

Figure 4: Same as Figure 3 but for LLF = 0%

Once constructed, the sizing curve can be used as a design tool for the system. First, it can be used to determine all possible combinations of component size variables normalised array area, battery capacity and diesel generator size that satisfy a given load and diurnal profile to a desired degree of reliability. The compliant size combinations can then be scrutinised to select the optimum combination. Secondly, given any two of the size variables, one can fix the third variable. The actual values are calculated in the model via given equations.

For example, suppose that an existing diesel generator-battery system, with B_{cap}/D = 1.0 and $Q_{DG}/\bar{d}$ = 1.8, and supplying a load of 42 kWh/day, is to be upgraded to a PV-diesel-battery system in order to reduce fuel costs. The required PV array can be easily determined from the sizing curves. Assuming that a load-following strategy is adopted and that a 100% supply reliability is desired, A/A_o can be read from Figure 4, i.e. $A/A_o = 3.4$. The reader can confirm that the required array area, calculated via Equation (2) and assuming 14% PV efficiency, is 42.5 m^2.

5 Battery life model

The battery life prediction model used in this paper is similar to the one described by Drouilhet and Johnson (1997). The battery cell is assumed to have a finite life (charge life) as measured by the sum of the effective ampere-hours throughput during its useful life. The battery's rated charge life is defined as the product of the rated ampere-hour capacity at rated discharge current, the depth of discharge for which rated cycle life was determined, and the battery cycle life at rated depth of discharge and discharge current.

However, under actual operation, the battery is often discharged to varying depths and at varying discharge rates, different from the rated values, resulting in an increased or decreased charge life. This fact is modelled by adjusting the battery charge life expended on each discharge event with respect to the actual periodic discharge depth and rate.

Figure 5 shows typical values of battery life calculated by this battery-life sub-model. As can be observed, the battery life consistently increases with increase in battery size. This is expected since, for a given load, the battery discharge stress reduces with increase in battery size, resulting in a healthier battery. This fact has important implications for the optimisation of the battery size. A large battery costs more to purchase, house and possibly to maintain than a smaller battery but, because of its longer life, it will have to be replaced less frequently and hence the replacement costs are lower. Therefore there exists an optimum battery size, resulting in the least battery life-cycle cost.

For a given battery size, the battery life increases to a maximum, then decreases, as diesel generator size is increased. This pattern of variation can be explained from the sizing curves, which dictate that a small diesel generator is sized with a large PV array. For very small diesel generator sizes (very large PV array sizes), the battery is kept at a healthy state of charge during the day as it receives abundant PV charge, but not so during the night when it can receive only a limited amount of charging by the small diesel generator. The reverse is true for very large diesel generator sizes and very small PV array sizes. Between these two extremes, there is an optimum combination of diesel generator and PV array size, which results in the healthiest battery.

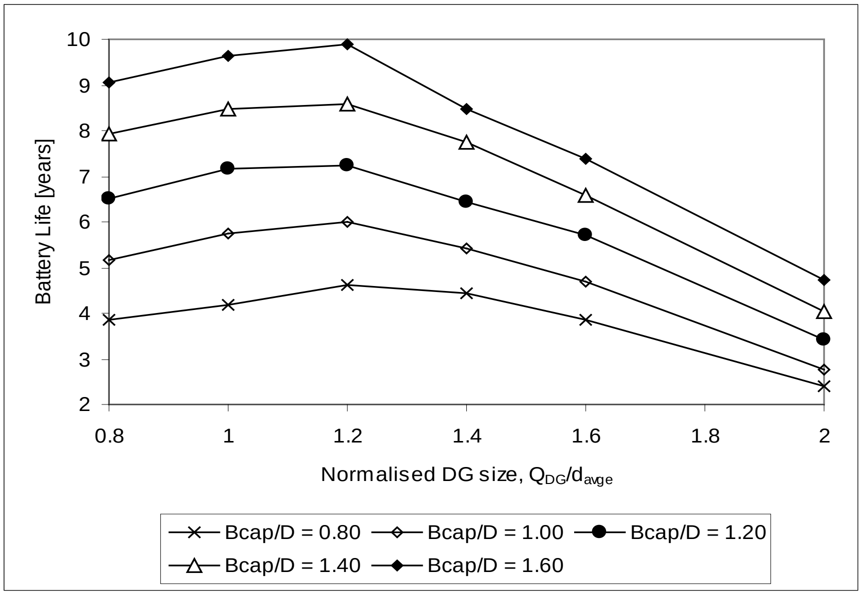

Figure 5: Battery life against diesel generator (DG) size for different battery sizes for Night Dispatch Strategy and LLF = 1%

In practice, the battery may require decommissioning well before its charge life is finished because of physical deterioration caused by aging effects such as corrosion of plates or contamination of electrolytes (Suryoatmoyo et al., 2009; Akyuz, et al., 2009). With respect to this consideration, a maximum battery life of 10 years, representing the warranty life given by some manufacturers, is used in this study.

6 Summary and Conclusion

The paper has described the elements and application of a technical model for the optimal design and performance analysis of hybrid power supply systems based on solar and/or diesel energy, with or without battery storage. The model can simulate the time-series energy flow in a hybrid system of any selected combination of system component sizes and mode of operation, as characterised by the strategy of dispatching diesel energy.

The importance of diesel generator energy dispatch strategy in influencing system component sizing and operational parameters is well illustrated. For instance, it can be observed that, compared with its Load-following counterpart, the hybrid system employing a Night diesel generator Dispatch Strategy required smaller battery and diesel generator components, was able to achieve a higher solar fraction, operated with a higher diesel generator load factor and resulted in a slightly longer battery life. However, on a negative note, this dispatch strategy required a larger PV array, had a higher average specific fuel consumption, dumped more PV energy and operated with longer diesel generator runtime. Comparing the two hybrid PV-diesel systems without economics, the Load-following diesel generator energy Dispatch Strategy shows superiority over the Night Dispatch Strategy for the load profile considered, though the former goes with greater control-system sophistication.

The model was used to compute the energy performance of systems with different combinations of component sizes, for two different diesel generator dispatch strategies (Load-following and Night Dispatch Strategies). The model also has scope to evaluate autonomous power supply options falling outside the domain of strictly ‘PV-diesel-battery’, such as diesel-only, diesel-battery-inverter and PV-battery-inverter systems. These systems can be treated by the model as PV-diesel-battery systems with some missing components.

The model could be useful in the upgrading of the PV systems that have been rolled out in South Africa in rural and peri-urban areas where there is no access to grid electricity, as well as where there are diesel generator systems only. Hybrid systems can also be sized to supply whole villages, schools and clinics in remotely located rural areas where there is no access to grid electricity, as well as to feed into the national grid. These can go a long way in satisfying both electrical and thermal needs, thus improving the livelihoods of the South African population. The use of biodiesel could also help in decarbonising the environment.

The model, as described so far, is able to evaluate the technical energy performance of the hybrid PV-diesel-battery power system and hence enable the definition of the loci of possible generator component size combinations (system sizing curves) that result in a chosen supply reliability (LLF). To select the optimum combination of generator components, an economic model is also required. The cost of energy per unit output can then be used as the criterion for selecting among the many possible combinations. This aspect, together with the validation of the model itself, will form the basis of follow-up work to this paper.

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