Hybrid energy systems for rural communities in Zimbabwe

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Abstract. Renewable energy sources such as solar photovoltaic (PV) systems have been widely utilized as alternative energy sources to fossil fuels in residential areas in many countries. The PV cell output varies according to many factors including weather conditions, time of day, season and location. Therefore, such systems cannot meet demand at all times necessitating incorporation of backup systems to smoothen the output and to meet electricity demand. This paper presents the modeling and operational strategy of a hybrid system consisting of a PV, diesel generator and battery. If the PV output is not enough to meet the load the generator and/or battery system compensates the power imbalance. The behavior of the proposed hybrid system is verified by simulation using HOMER Software. The simulation results indicate that hybrid systems would be feasible options for distributed generation of electric power for remote locations or areas not connected to the electricity grid.

Keywords: sustainable, distributed generation, fossil based, energy access

1 Introduction

It is estimated that about 40 percent of the world's population depends on wood, charcoal or animal waste for basic energy needs such as cooking and heating [1]. Most of this population is in developing countries especially in rural areas where the communities are poor and marginalized. In Zimbabwe, just like in most developing countries, energy access is still a big challenge with an electrification rate of below 40%. There have been many initiatives to address the energy access issue by the government and donor agencies but there is still a big gap to be filled. Zimbabwe has also joined the global effort to eliminate energy poverty by 2030 under the United Nation's Sustainable Energy for All (SE4ALL) initiative [1]. The country's energy supply is mostly from hydroelectric power and also from a few thermal coal power stations. Zimbabwe has experienced power shortages in recent years and some urban households have responded by installing PV and solar water heating systems as well as diesel and petrol generators. Such systems except for the fossil fuel generators are also important demand side management measures to reduce the customer's energy bill. Innovative solar technology applications such as in street lighting and traffic lights controls have been demonstrated in some urban areas.
About 80-90 % of the rural population relies on wood fuel and kerosene for cooking and lighting [1], [2]. A high proportion of the rural population is made up of peasant

farmers who mostly grow maize. Grain milling is thus an important processing activity in most of these communities and is mostly carried out by diesel-powered mills. Renewable energy (RE) technologies can play an important role in activities such as water pumping, grain milling, cell phone charging, hair salons, battery charging and lighting thereby extending study times for learners in rural communities. Small businesses within the communities may go a long way in improving the livelihoods of the people. Access to clean and affordable energy is therefore an urgent issue as this directly benefits people's health and well-being and this fact is well documented in various literatures. Although energy access does not necessarily guarantee gender equality which is also a big challenge globally, it is a great step towards the emancipation of women by enabling them to have more time to engage in productive activities. An example of solar technology application in rural communities in Zimbabwe is the solar powered borehole water supply for Masasa Clinic, Primary and Secondary Schools donated by the Chandiwana Memorial Foundation with support from Frinton Free Church, United Kingdom and Masasa Community in Chivhu. This has benefited the community a lot as they now have access to clean water and do not have to travel long distances to fetch water.

Many rural areas of developing countries including Zimbabwe lack supply of electricity due to poor distribution of grid electricity and/or lack of financial resources for grid extension [3]. There is also relatively low energy demand in most rural areas making it uneconomic to connect them to the grid owing to the high cost of long-range transmission lines and this justifies the use of more decentralized forms of power supply systems. These decentralized systems are modular in nature and widespread in distribution as they can be built anywhere near the locations of use [4], [5]. A reliable power supply systems should be able to provide uninterrupted power at all times. Distributed generation options for providing power include stand-alone renewables, diesel generator sets or a combination of these forms of energy in a hybrid system. Because of the intermittent in nature PV supply, battery banks improve the supply reliability but sometimes they have to be over-sized to achieve the required hours or days of autonomy leading to high capital costs and they need to be replaced more times than any other component of the system. The current decrease in PV technology prices has resulted in more uptake of this technology in the residential and utility sectors. Battery bank costs are also expected go down. Diesel generators on the other hand, have been favoured options for off-grid applications for many years owing to their low initial capital costs. Their main disadvantages are the high operation and maintenance costs as well as their negative environmental impact.

Fuel Cell (FC)–electrolyzer combination may be considered for backup and long-term storage system with a battery bank for short-time backup to supply transient power as proposed in [6]. However, for the system to be environment friendly, the renewable energy (RE) sources have to be sized to meet the electrolyzer's energy requirements for hydrogen production. Compared to internal combustion engines FCs operate in a silent and clean mode and also require a smaller supply of fuel, as they are more efficient. Although stationary FCs technology is near commercialization and is expected to tap into a large market in residential, commercial and industrial applications in future, currently the FC–electrolyzer system is more expensive than the diesel generator system. Another challenge associated with this technology is that the production of hydrogen (electrolysis) using renewable electricity and the conversion back into electricity (FCs) is associated with energy losses and additional costs. A combination of PV, diesel generator and battery in a hybrid system will overcome single source problems; provide environment friendly, reliable and economic systems owing to the reduced diesel generator run time, number of start/stop cycles and running costs. Use of bio diesel and biogas generators would result in the generation of cleaner energy especially at institutions like schools and rural clinics.

Hybrid energy system models have been presented by various authors in literature using various software and methodologies. A hybrid system consisting of PV, wind generator and battery storage for Yavatmal district in Maharashtra, India is presented in [7] and optimized using the HOMER software. A techno-economic analysis for powering a residential building in Iran and optimized using HOMER software is presented in [8]. There is, however no single solution to satisfy community energy requirements as each location has its own site-specific energy needs, profile and characteristics. This means that appropriate technology choices should be guided by resource availability in each location; energy needs of the community, distance from current and future planned transmission grid. It is also important to consider the cost of the current and proposed energy services for the proposed users to make informed choices.

Provision of sustainable energy service for all especially the poor communities is therefore crucial in the transition from subsistence livelihoods to increased productivity, income generation, and improved living standards. Developing economies face energy challenges in meeting the needs of billions of people who still lack access to basic, modern energy services and at the same time there is need to participate in the global transition to clean, low-carbon energy systems [9]. There is therefore a need to provide access to reliable and affordable energy services as a pre-requisite to alleviating extreme poverty and meeting other societal development goals. This paper presents a possible hybrid energy system option(s) to meet the rural energy needs in a sustainable way; and hence address energy poverty levels and improve the livelihoods of the rural population. HOMER software is used for the simulation and optimization of the system. A systems dynamics approach is used to enhance understanding of the behavior of complex systems over time (dynamics). This paper is structured as follows: introduction, hybrid energy systems, hybrid system case study, methodology, results and discussion and conclusion.

2. Renewable Energy Hybrid Systems

2.1 System benefits

Provision of renewable and affordable energy is crucial for the reduction of extreme poverty and for the attainment of the United Nations Sustainable Development Goal 7 which calls for access to affordable, reliable, sustainable and modern energy for all. Fig. 1 shows an example of environmental, economic and social benefits of RE systems [9]. The benefits can be explained using a causal relation between any two events and this exists in cases where the occurrence of the first causes the other. The first event is the cause and the second event is the effect. A positive causal link means the two events change in the same direction meaning that if the start link decreases, the end link also decreases and vice versa. A negative causal link means the two events change in opposite directions meaning that if the start link increases, the end link decreases and vice versa. A reduction in greenhouse gas emissions leads to a reduction in air pollution related health problems that are caused by the pollutants from fossil based fuels. This reduction has a positive effect on the general well-being of individuals and communities.

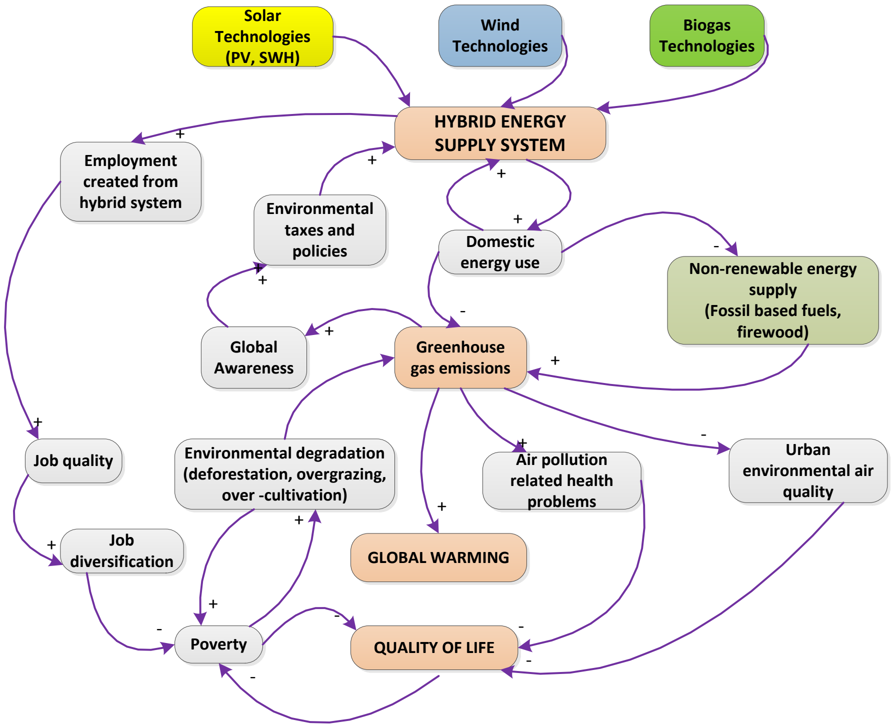

Fig. 1 Environmental, economic and social benefits of renewable energy systems

For instance, in Fig. 1, a decrease in fossil based fuel usage leads to a decrease in greenhouse gases especially carbon dioxide build-up in the atmosphere. A reduction in the amount of carbon dioxide in the atmosphere in turn reduces the effect of global warming. Implementation of RE technologies has great potential of creating income through job diversification and this can lead to small enterprises development which will in turn reduce poverty and promote sustainable rural livelihoods. Reduction in poverty in turn will decrease the traditional use of biomass (wood) and related activities such as deforestation, overgrazing and over-cultivation as there is a correlation between poverty and environmental degradation.

2.2 Implementation models

Innovative RE implementation models have been developed in [10] and used in order to encourage widespread affordability and acceptance of RE technologies. When developing a new RE market, it is important to make informed choices of the most appropriate implementation models. It is critical to note that the local conditions require tailored solutions and approaches, or perhaps combinations of the models described here. The three generic models are [10]:

Model 1- Cash Sales: the RE supplier sells the RE system directly or through a dealer to the end-user who immediately becomes the owner of the system.

Model 2- Credit sales: the end-user acquires the RE system on credit. The credit sales are divided into three categories:

- Dealer Credit: the RE supplier/dealer sells the RE system to the end-user, who also enters into a credit arrangement with the RE supplier/dealer. Depending on the arrangements, the end-user immediately becomes the owner of the system, or when all payments are made.
- End-user Credit: the RE supplier/dealer sells the RE system to the end-user, who obtains consumer credit from a third party credit institution. The end-user usually becomes the owner of the system immediately, but this can be delayed until all payments are made.
- Lease/Hire purchase: the RE supplier/dealer or a financial intermediary leases the RE system to the end-user: At the end of the lease period, ownership may or may not be transferred to the end-user, depending on the arrangements. During the lease period, the lessor remains owner of the system and is responsible for its maintenance and repair.

Model 3: Fee for service: an electricity supply company (ESCO) owns the system, and provides an energy service to the end-user, who pays a periodic fee (e.g., monthly) to the ESCO. The end-user is not responsible for the maintenance of the renewable energy system and never becomes the owner, although the end-user may own for example the battery and lamps/radio or gas stove.

Another concept linked to hybrid systems is the mini- grids concept and mini-grids can be made of single or multiple generation sources. The business models for mini-grids may include but are not limited to the following categories [11]:

- Community-based model: the community owns and operates the mini-grid, with a cooperative often established to own and manage the system. This model usually relies on initial capital support from governments or philanthropic organizations, as well as technical support for project implementation;
- Private sector-based model: a private organization(s) manages the construction and operation of the mini-grid, with varying levels of external financial support depending on the level of government involvement and type of subsidies available;
- Utility-based model: the national utility is responsible for the construction and operation of the mini-grid;
- Hybrid model: Involves various combinations, such as public-private partnerships where the government finances the construction of a mini-grid

that is then managed by a private organization, or a privately owned mini-grid that is maintained by the community that it serves.

3. Hybrid system case study

The considered system configuration is as shown in Fig. 2 below. The hybrid energy system is made up of a PV generator, diesel generator and battery storage. The dispatch strategy is such that the PV generator must supply the load whenever there is PV output, otherwise the battery storage comes in to meet the imbalance between the PV output and the load provided it is within its operating limits. If both PV and battery cannot meet the load, the diesel generator comes in to ensure that the load is fully satisfied and also to charge the battery. The PV generator should also charge the battery whenever there is excess power. The idea is to minimize use of the diesel generator due to its high operating cost in terms of both fuel and maintenance costs.

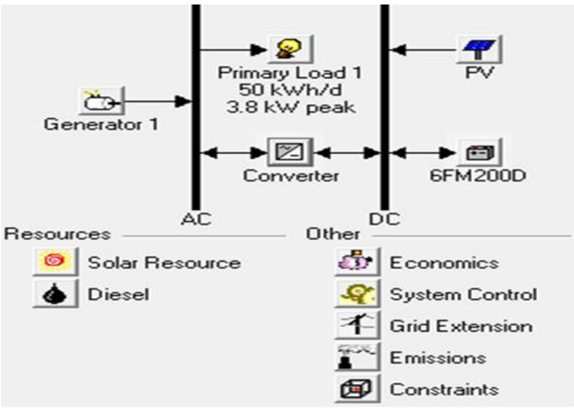

Fig 2. Hybrid energy system configuration

3 Methodology

The HOMER Hybrid Optimization Modeling Software developed by National Renewable Energy Laboratory, USA is used for the design, optimization and analyses of hybrid power systems. These hybrid systems may contain two or more of the following: conventional generators, cogeneration, wind turbines, solar photovoltaics, hydropower, batteries, fuel cells, hydropower, biomass and other inputs. The software can analyze either grid tied or standalone systems as well as perform greenhouse gas calculations for the measures being considered [12]. HOMER allows the user to input hourly power consumption profiles and match renewable energy generation to the required load. Additionally, HOMER contains a powerful optimizing function that is useful in determining the cost of various energy project scenarios which allows for minimization of cost and optimization of scenarios based on various factors (e.g., CO_2 minimization). The working principle is as shown in Figure 3.

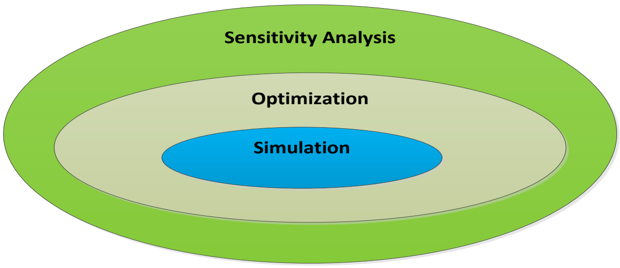

Fig. 3. Conceptual relationship between simulation, optimization, and sensitivity analysis

The software simulates a viable system for all possible combinations of the components considered. The simulated systems are optimized according to the user defined criteria so that the best possible solution is obtained. Besides economic optimization model, the user can minimize fuel usage. Sensitivity analysis may be done to observe the impact of variables, such as fuel costs, wind speed, etc., on the optimal system.

3.1 Load profile

Fig. 4 shows the average daily load profile for the rural based institution considered in this paper. The daily load profile is based on a survey conducted in rural communities in Zimbabwe [2].

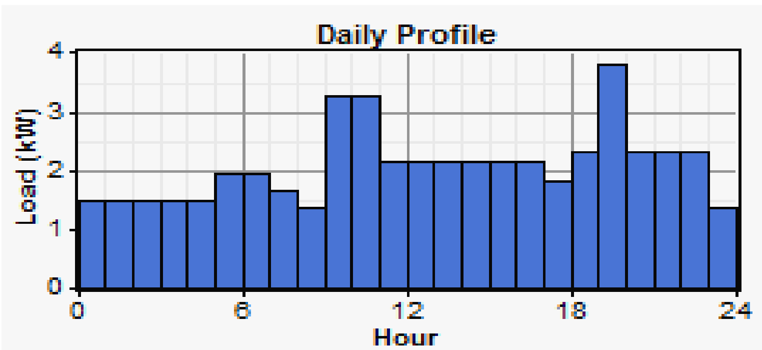

Fig. 4. Load profile [2]

An appliance usage matrix was developed for the convenient computation of the load data. It shows the time of the day and the appliance in use for each hour. This represents a *24* number of appliance (NA) matrix* which when multiplied by the NA *1 matrix give a 1*24 matrix that represents the load as shown in Table 1. In Table 2 the data characteristics are shown.

Table 1. Appliance Usage Matrix

Time	Appliance in Use								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1:00	1	1	0	0	0	0	1	0	0
2:00	1	1	0	0	0	0	1	0	0
3:00	1	1	0	0	0	0	1	0	0
4:00	1	1	0	0	0	0	1	0	0
5:00	1	1	0	0	0	0	1	0	1

Table 2: **Data Characteristics**

	Baseline	Scaled
Average (kWh/d)	50.0	50.0
Average (kW)	2.08	2.08
Peak (kW)	3.81	3.81

3.2 Solar resource

The solar resource data used for Masvingo rural area at location -20.079 latitude and 30.838 longitude was taken from NASA Surface Meteorology and Solar Energy website [12]. The annual average solar radiation is 5.427 kWh/m^2/day and the average clearness index is 0.542. Fig. 5 below shows the annual radiation and clearness Index for Masvingo.

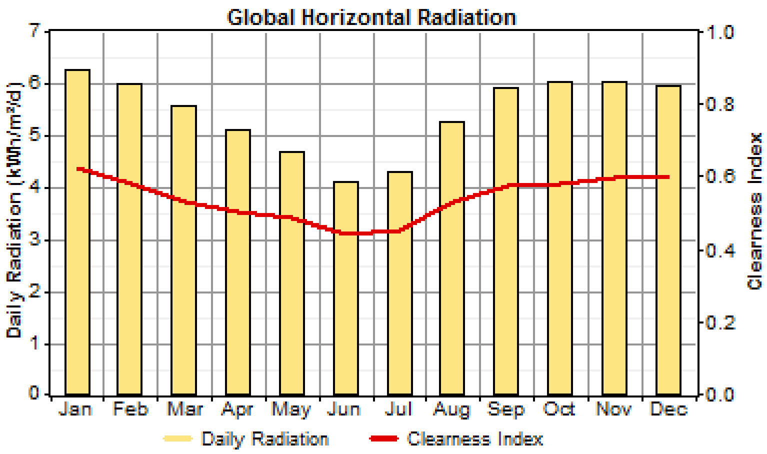

Fig. 5. Average daily radiation and Clearness Index

3.3 Model components

For Solar PV, the following module sizes are considered: 100W, 250W and 300W solar panels from Enersol. The solar PV capacities considered in the model are 0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5 and 5 kW. The cost of the solar PV panels was pegged at $1.50/W in Zimbabwe. The rated power of the inverter is determined using the peak load. However, since it will get power from both solar PV panels and diesel generator, sometimes it does not need to be equal or above the peak load. The cost of a 1.5kW converter is set at $900. The replacement cost is 80% of the capital cost and the efficiency of the converter is set at 90%. Its lifetime is set at 15 years. Converter sizes considered in this research paper are 0, 1, 1.5, 2, 3, 4.5 and 6 kW.

The diesel generator is not allowed to run at less than the minimum load ratio of 30%. The maximum power rating of the diesel generator is 5.5 kW. The cost of the diesel generator is $1500. Lifetime of the generator is about 15000 hr. Diesel generator capacities considered in the study are 0, 2.5, 4, 5.5 kW. The price of diesel in Zimbabwe is around $1.20/Litre. The storage battery considered in this paper is the Vision 6FM200D from Vision Battery. The nominal capacity of the battery is 200Ah (2.4kWh) with a nominal voltage of 12V for a single battery. The battery efficiency is set at 80% with a minimum state of charge of 40%. The cost of one battery is $400 in Zimbabwe. Quantities of batteries considered are 0, 1, 2 and 3.

4. Results and discussion

The optimized results are shown in Table 3 and the combination with the lowest cost of energy (COE) is shown to be the best option. The strategy chosen by the software is the load following one. The cash flow summary and net present cost of each component are also shown. Table 4 shows the annualized costs of the system and also that the load is met 100%. The PV array's annual energy production is 7925 kWh/yr while that for the diesel generator is 11784 kWh/yr giving a total of 19710 kWh/yr. Fig. 6 shows monthly average electric production from the PV and diesel generators.

Table 3: Optimized results

Sensitivity Results | Optimization Results

Double click on a system below for simulation results.

PV (kW)	Label (kW)	6FM200D	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Label (hrs)
5.0	2.5	1	3.0	LF	$ 11,538	6,764	$ 98,001	0.428	0.34	0.02	4,967	7,161
5.0	2.5		3.0	CC	$ 11,138	6,830	$ 98,444	0.434	0.32	0.03	5,137	7,553
	2.5	1	1.0	CC	$ 2,238	9,773	$ 127,172	0.553	0.00	0.01	7,277	8,760
	4.0			CC	$ 1,500	10,896	$ 140,785	0.603	0.00	0.00	8,278	8,760

Table 4: Annualized costs

Annualized Costs					
Component	**Capital ($/yr.)**	**Replacement ($/yr.)**	**O&M ($/yr.)**	**Fuel ($/yr.)**	**Total ($/yr.)**
PV	587	0	75	0	662
Generator	73	418	64	5961	6515
Vision 6FM200D	31	162	4	0	198
Converter	211	71	23	0	292
System	903	650	166	5961	7666

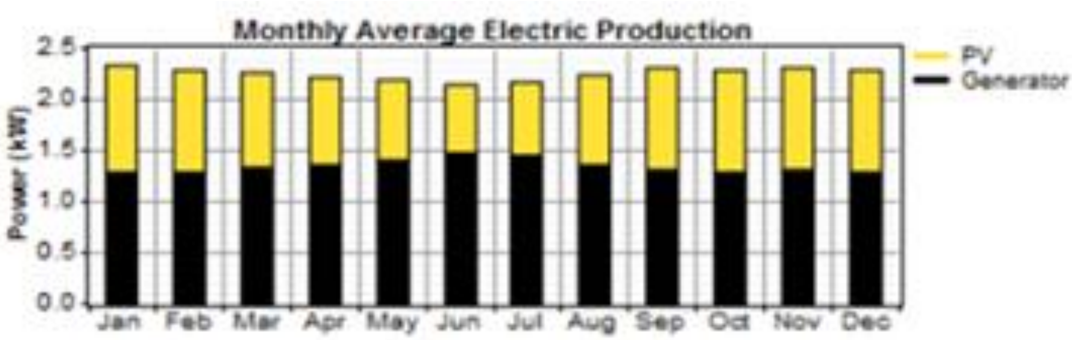

Fig. 6. Monthly average electric production

Table 5 shows PV only parameters and performance reflecting a capacity shortage as PV alone can only meet the load during the day. In Fig. 7, PV array monthly hourly performances are shown and the corresponding PV generation outputs in each are as displayed. PV penetration is refers to the ratio of total peak PV power to peak load apparent power and the renewable fraction is the fraction of the energy delivered to the load that originated from renewable power sources.

Table 5: PV array performance

Quantity	Value	Units	Quantity	Value	Units
Rated capacity	5	kW	**Hours of operation**	4360	hr/yr.
Mean output	0.905	kW	**Levelized cost**	0.0835	$/kWh
Mean output	21.7	kWh/d	**Excess electricity**	1025	kWh/yr.
Capacity factor	18.1	%	**Unmet load**	335	kWh/yr.
Total production	7925	kWh/yr.	**Capacity shortage**	335	kWh/yr.
Min. output	0	kW	**Renewable fraction**	0.342	
Max, output	4.83	kW	**PV penetration**	43.4	%

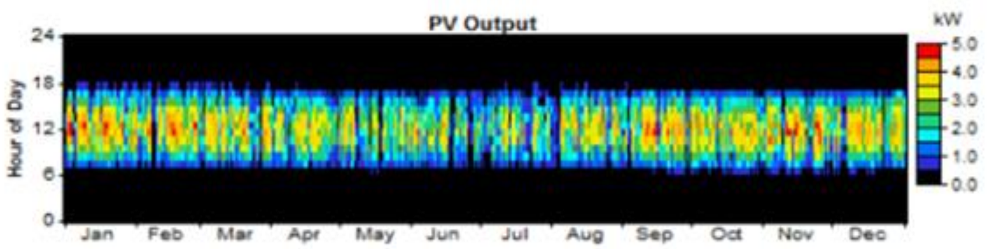

Fig. 7. PV array monthly performances

The diesel generator and battery parameters as well as the performance summaries are shown in Tables 6 and 7 and in Fig. 8. It is shown that the diesel generator operates mainly during night times and also during times when PV cannot meet the demand. It is important to take note of the expected battery life, which is very short tough there are other battery technologies with longer life periods. The life span of the battery also depends on how the battery is used amongst other factors. Because of the short life span, the user(s) will have to replace this component of the hybrid system quite often during the life time of the system and this makes the system expensive.

Table 6: Diesel generator performance

Quantity	Value	Units	Quantity	Value	Units
Electrical energy production	11784	kWh/yr.	**Fuel consumption**	4967	L/yr.
Mean electrical output	1.65	kW	**Specific fuel consumption**	0.422	L/kWh

Min. electrical output	0.75	kW	**Fuel energy input**	48880	kWh/yr.
Max. electrical output	2.5	kW	**Mean electrical efficiency**	24.1	%

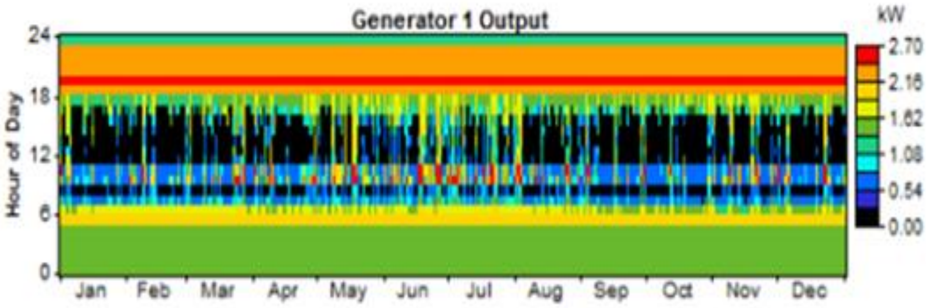

Fig. 8. Diesel generator performance

In Table 7, throughput refers to the change in energy level of the storage bank measured after charging losses and before discharging losses or simply the sum of the discharge energy. The battery wear cost on the other hand defined as the cost of cycling energy through the battery bank while the battery depletion is the difference between the state of charge of the battery at the beginning and at the end of the year.

Table 7: **Battery parameters and performance**

Quantity	Value	Units	Quantity	Value	Units
Nominal capacity	2.4	kWh	**Energy in**	450	kWh/yr.
Usable Nominal capacity	1.44	kWh	**Energy out**	361	kWh/yr.
Autonomy	0.691	hr	**Storage depletion**	1.47	kWh/yr.
Lifetime throughput	917	kWh	**Annual throughput**	404	kWh/yr.
Battery wear cost	0.488	$/kWh	**Expected life**	2.27	Yr.

In Fig. 9 it is shown that the breakeven grid extension distance is 7.15 kilometres. The break-even grid extension distance is the distance from the grid which makes the net present cost of extending the grid equal to the net present cost of the stand-alone system. The net present cost or life-cycle cost of a system is the present value of all the costs of installing and operating that system over the project lifetime, minus the present value of all the revenues that it earns over the project lifetime [13]. Further away from the grid, the stand-alone system is optimal. Nearer to the grid, grid extension is optimal. This means that in terms of cost, it is only economical to connect the grid for distances less than 7.15km, and for any distance beyond the 7.15 km it does not make any economic sense. For the site considered the grid is very far away so prospects of being connected are next to none as it will be very expensive.

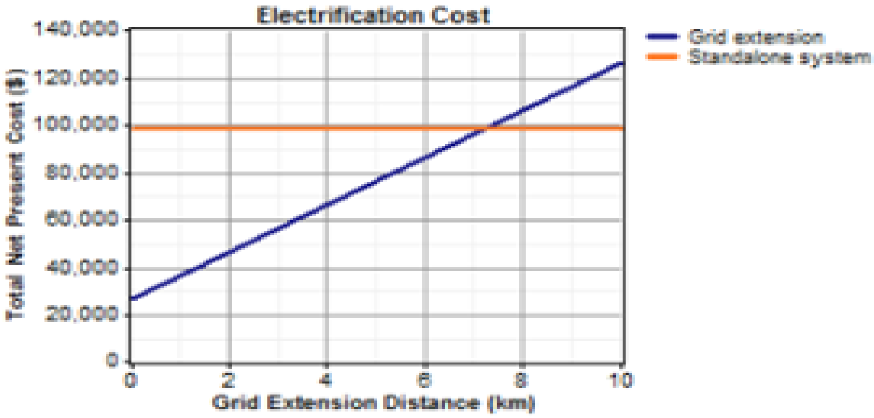

Fig. 9. Break even grid extension distance

5 Conclusion

It has been shown that solar PV alone even on a high power production day cannot meet the load as it is only available during the day. For the diesel generator to meet the load there are considerable costs involved in terms of fuel and maintenance costs. Combining PV and diesel generator systems results in fuel savings and reduced air pollution. It is observed that it is beneficial for the communities to use clean energy for especially for their day activities when sunshine is available. Such a hybrid energy system is shown to be a feasible solution for reducing energy poverty and the livelihoods of many rural communities. Use of fossil fuel based options and batteries in rural communities especially at household level remain a big challenge due the high operational and maintenance costs and replacement costs.

Acknowledgements. The authors acknowledge the support for this work provided by the Council for Scientific and Industrial Research and the University of Johannesburg, South Africa.

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