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Establishing the most cost effective reliability for off-grid solar systems in Zimbabwe: Trade-off, between energy supply reliability and levelised cost of energy.

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Abstract

The traditional method for designing off-grid stand-alone solar energy systems is based on a monthly-average daily energy balance approach whose only objective is to provide 100% energy supply reliability. However, such an approach tends to grossly oversize the systems thus rendering solar off-grid systems too costly for the target communities. This study has focused on designing a cost effective off-grid solar power system to ensure balancing of the trade-off between cost and reliability of power supply. Based on a time-step energy balance approach, an Excel spreadsheet-based model was developed to optimise the solar stand-alone system. Two dimensionless variables representing the size of the two main components of a solar photovoltaic off-grid system- the solar photovoltaic (PV) array and battery- were used to define the system size. For a given level of supply reliability, there is an infinite number of combinations of PV array and battery size- as the PV array size is increased, the required battery size reduces in a certain trend. However, for the given level of reliability, only one PV array-battery combination (the Optimum Design) results in the minimum Levelised Cost of Energy (LCOE), whose coordinates depend on the relative costs of the two components. The LCOE for the Optimum Design corresponding to each level of supply reliability was plotted against supply reliability. From such a plot it was observed that the LCOE increases disproportionately above a certain level of reliability. This point, which lies near the "elbow" LCOE-reliability plot, defines the most cost-effective reliability for the stand-alone solar system, and therefore the optimum combination of PV generator and battery to deploy. The results showed that sustainable cost effective off-grid systems can be operated at 98% reliability level and still satisfy the customer requirements and at the same time ensuring affordable tariffs. Increasing the PV system components beyond the optimum (98% reliability) point, in a quest to achieve 100% reliability, results in a disproportionate 22% increase in LCOE.

Key Words: Energy Systems, Optimum Design, PV array

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1. Introduction

There is a growing interest in promoting renewable energy development in Zimbabwe and the rest of all Sub-Saharan countries as a way of providing a more independent energy pathway that energy transition and clean energy access (International Renewable Energy Agency, 2019). Zimbabwe as other developing Sub Saharan countries also sees the importance of the role of distributed renewable energy solutions to provide cost effective clean energy access in remote rural areas as opposed to main grid extension (International Energy Agency, 2016). With the abundance of solar resource in sub-Saharan Africa and Zimbabwe (Avila *et al.*, 2017) in particular coupled with the falling solar Photovoltaic (PV) prices (IRENA, 2019), solar (PV) off-grid systems become the most favoured (Kavu et al., 2020). The other advantages of solar off-grid systems over other renewable include their modularity which brings flexibility and allow for ramping up approach (IEA, 2017). As long as additional hardware constraints are satisfied, PV generation and battery storage capacity can be increased to meet the growing needs of first time electricity customers (Burger, 2019).The solar PV off-grid solutions come in different packages, ranging from pico-systems for lighting only, micro-systems (solar home systems) to the mini-grids that connect a number of homes and social facilities (Moner-girona et al., 2018).

Reliability of power supply and cost of supply are two main important aspects in the design and sizing of off-grid solar power systems (Moner-Girona *et al.*, 2016). The sizing of solar PV off-grid systems are mainly anchored on the combination of storage and the generation units (Okpokam, 2021). A number of researchers have looked at optimising of PV designs aiming at achieving near 100% reliability of these systems (Alsharif, Nordin and Ismail, 2015; MacGill and Watt, 2015, 2015; Khalilpour and Vassallo, 2016; Rawat, Kaushik and Lamba, 2016; Zebra *et al.*, 2021). The issue of appropriately sizing small-scale micro-grid installations is highly pertinent to the electrification of rural locations within the developing world (Alsharif, Nordin and Ismail, 2015; Alam and Bhattacharyya, 2016; Hassan, Cipcigan and Jenkins, 2017).

This study employed an excel based spreadsheet model to develop reliability curves corresponding to levelised cost of energy (LCOE) for a set of solar generator and battery size combinations. From this exercise it was established that there exists a reliability level that is cost effective while at the same time ensuring acceptable levels of electricity supply to the consumers without causing losses. Above this reliability level, the cost of adding a small fraction of reliability becomes disproportionately too high. Thus, the trade-off between reliability of supply and cost of energy comes into play. This study was done to establish the most cost-effective reliability for a system combination that will supply electricity to the consumers who are off-grid to an extent satisfactory and at an optimum cost. The large part of an off-grid solar system costs is composed of the solar modules and the battery. These are usually imported from China and South Africa for Zimbabwe. China as the hub of mass production, has forced the PV module prices to fall significantly from 2014 to 2016 by more than half (International Renewable Energy Agency (IRENA), 2018). The fall in price is expected to continue. Searches on some of the Chinese online market, including Alibaba show that to buy solar modules at wholesale price it is on average 30UScents. Addition of shipping and clearance costs will give the average cost of acquiring solar modules per watt for Zimbabwean projects. Excise Duty is not charged on solar panels, inverters and charge controllers in Zimbabwe thus no clearance costs. The storage thus becomes the largest cost of an off-grid solar system given its short life span, thus replacements costs and also in Zimbabwe batteries are not exempted from duty, 20% is charged by the Zimbabwe Revenue Authority

(ZIMRA). This causes the landing price of good quality batteries to be on the higher side

2. Methodology

This study employed an excel based spreadsheet model to develop reliability curves corresponding to levelised cost of energy (LCOE) for a set of solar generator and battery size combinations. Energy consumption data for the loads to be supplied by the off-grid solar system was estimated from ratings of the appliances and typical consumption patterns of the randomly selected sample of houses in the villagers in the Banket area. The consumption of energy was found to vary from hour to hour, thus a load profile for the day was developed. The load profile was then standardised (normalised) to match the typical rural load profile. A normalised load profile of a typical rural load was as the model of the hourly load. The shape of the load profile is as shown in Figure 2.1.

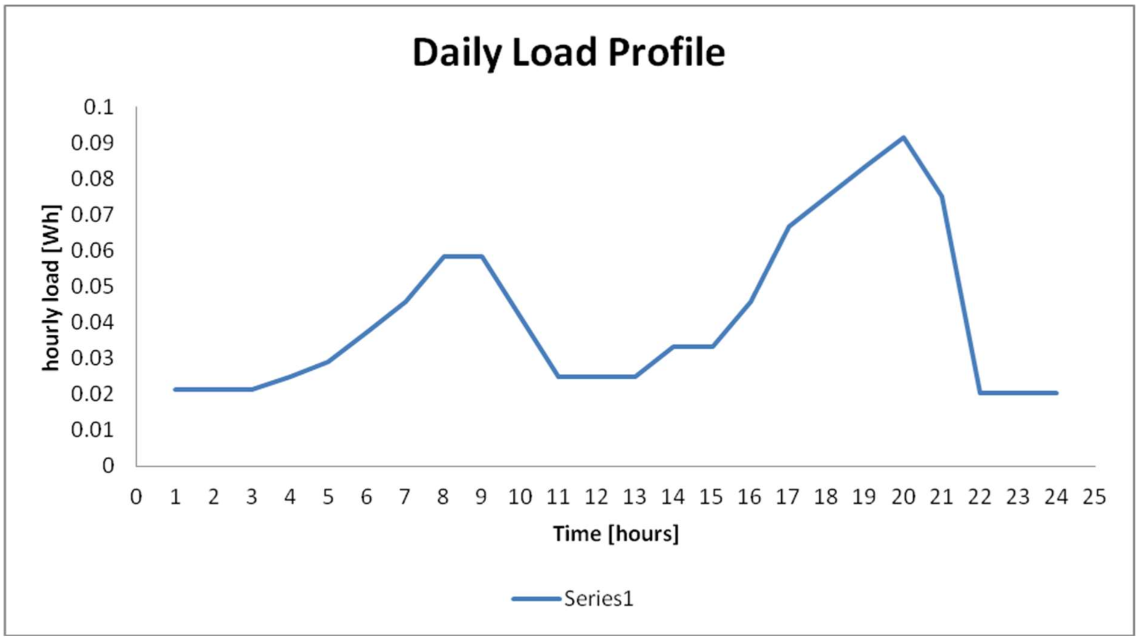

Figure 2.1: Load profile of a typical rural settlement in Zimbabwe

Typical Meteorological Year (TMY) data was downloaded for a location in Banket, Mashonaland West Province of Zimbabwe. The TMY shows hourly daily data for the whole year of 2009. The modelled yearly radiation data for the place is as shown in Figure2.2.

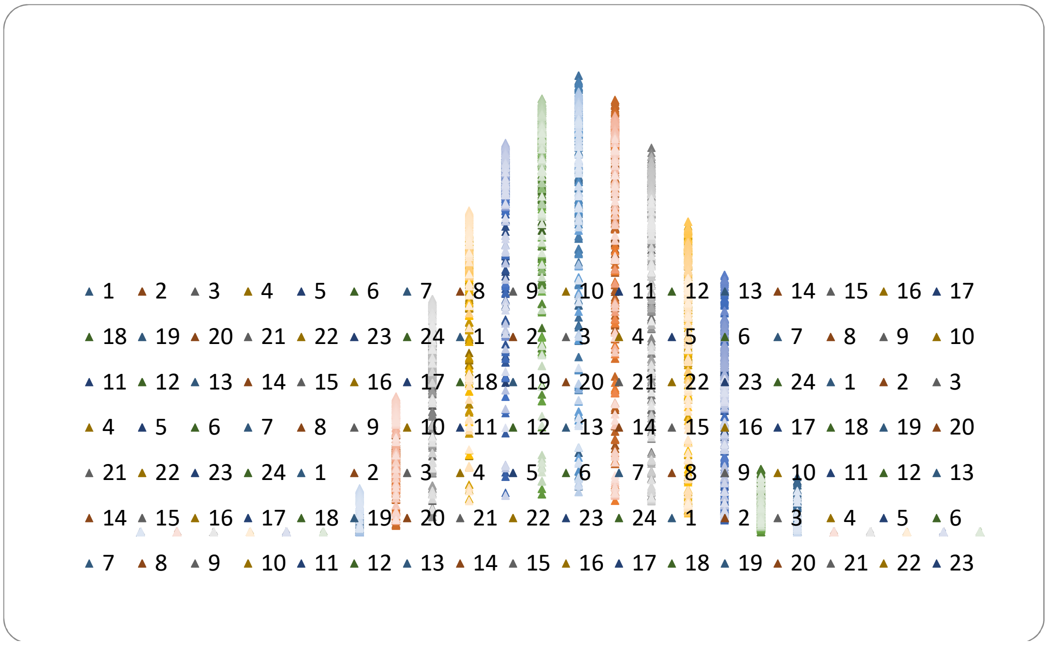

Figure 2.2: Year 2009 hourly radiation on a tilted surface for a location in Banket, Zimbabwe

The hourly daily load was replicated for the whole year, 2009 to match the hourly solar radiation. The model allows for analysis of energy balance of each hour, day, month and year. The hourly radiation on a tilted surface is modelled by adopting the Collares – Pereira and Rabl Sky Model (Duffie and Beckman, 2013) and making some assumptions so that the instantaneous radiation incident on the array, I_{array} can be estimated by

$$\boldsymbol{I_{array} = (I_h - I_d)\frac{Cos\theta_{array}}{Cos\theta_z} + I_d/c} \qquad \textbf{Equation 2.1}$$

Where I_h is the global horizontal hourly radiation, θ array is the angle of incidence of direct irradiance on the array, c is the concentration ratio which is equal to unit for flat-plate array and I_d is the diffuse irradiance. R_b , the geometric ratio. This represents the ratio of beam radiation on the tilted surface to that on a horizontal surface at any given time and is given as $\frac{Cos\theta}{Cos\theta_z}$ where , θ_z is the zenith angle. **Zenith angle**, θ_z is the angle between the vertical and the line to the sun, that is, the angle of incidence of beam radiation on a horizontal surface.

2.1 PV Generator-Battery and energy flow logic

Figure 2.3 shows the layout of the solar off-grid system to be analysed in this paper. The power will be supplied from a solar PV array supplying power to AC loads and charge the battery bank with any power in excess of the load at any given time. Any power in excess of the load and battery charging at any given time is dumped. A standby load can be designated to use this power.

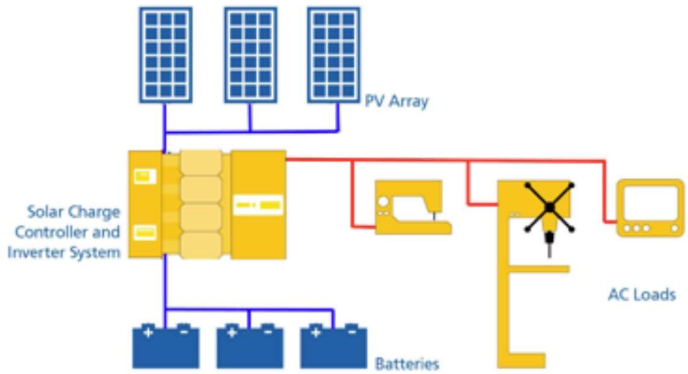

Figure 2.3: Layout of a PV - battery off-grid system
Source: adopted from Alsharif, Nordin and Ismail, (2015)

The model used in this study, for simulating the performance of the PV-Battery power supply system, is an improvement of an earlier model by (Hove and Tazvinga, 2012)The main improvements of the present model, over the earlier model, include; the use of normalized power P_o, to size the PV array instead of the normalized area A_o used in the earlier version and that this is applied to a solar PV-battery system without diesel. The model makes an hourly-hour audit of the energy flows in the system, taking into account the variability of the load; the environmental driving forces (solar radiation and ambient temperature) and the battery state of charge (Hove and Tazvinga, 2012). Different hourly performance characteristics of the power supply system can be calculated by the model, such as the PV generator energy output; the hourly battery energy gain (charge or discharge); the hourly solar contribution to the load; the fraction of the battery charge life spent in the hour in question; and other performance characteristics. The salient features of the model are outlined below.

2.2 Determination of the Photovoltaic Generator Output

The hourly energy output from the PV generator of given power rating, $P_{\_rated}$, is given by:

$$\boldsymbol{P_{PV}} = \frac{\boldsymbol{\eta_{pv}\,(Ta,I)}}{\boldsymbol{\eta_{ref}}} * \frac{\boldsymbol{I_{pv}}}{\boldsymbol{I_{ref}}} * \boldsymbol{P_{rated}} \qquad \text{Equation 2.2}$$

In Equation (2.2),η_{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}(kWh/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 (NOCT) conditions. The expression for η_{PV} derived by Hove, (2000) was used:

$$\boldsymbol{\eta_{pv} = \eta_r[1 - 0.9\beta\left(\frac{I_{PV}}{I_{PV-NOCT}}\right)\left(T_{PV,NOCT} - T_{a,NOCT}\right) - \beta(T_a - T_r)} \qquad \text{Equation 2.3}$$

η_r is the PV generator efficiency measured at reference cell temperature, T_r, i.e. under Standard test conditions (25^{0}C). β is a temperature coefficient for cell efficiency (typically 0.004 to 0.005/^{0}C), $I_{PV,NOCT}$ is the average hourly solar irradiation incident on the array at Nominal Operating Cell Temperature (NOCT) test conditions (0.8 kWh/m^2), $T_{c,NOCT}$ (typically 45^{o}C), $T_{a,NOCT}$ (20^{o}C), are respectively, the cell and ambient temperatures at NOCT test conditions.

In this study, the simplified isotropic diffuse formula suggested by Collares-Pereira and Rabl (1979) was used because it can be applied with a simple data set that is easily obtainable in Zimbabwe (Hove and Tazvinga, 2012).

$$I_{PV} = (I_h - I_d)R_b + I_d \qquad \text{Equation 2.4}$$

In Equation (2.4), I_h and I_d are, respectively, the hourly global and diffuse irradiation in W/m^2. R_b is geometric factor representing the ratio of beam irradiance incident on a tilted plane to that incident on horizontal plane.

Hourly average meteorological data, global irradiation, diffuse irradiation and ambient temperature were used as inputs in evaluating Equations (2.2), (2.3) and (2.4) of the performance of the simulation model for the whole year. The evaluation was performed at the mid-point of each hour of the day, on every day of each month.

2.3 Battery Energy

The battery is charged by the PV generator and is discharged to make good supply deficit by the PV generators. The hourly battery charge or discharge depends on the size of the hourly load, Lo, relative to PV- generated (P_{PV}) power, and the battery state of charge.

2.3.1. Battery Charge

The battery was designed to charge if the PV output is greater than the load and if there is space in the battery to take up the charge (when the battery is not full). The actual battery charge, B_{charge} is the minimum between the excess energy that is available and was not used by the load, and the battery space available, and the maximum charge rate of the battery.

Maximum charging power = Battery capacity/minimum charging hours.

Battery space = Battery Capacity-Battery state

Excess power = PV power (P_{pv}) –Load (L)/Inveter efficiency (η_{INV})

Therefore,

B_{charge} = IF (AND (P_{pv}>L/η_{INV},Bstate<Bcap),MIN(Ppv-L/η_{INV},Bcap-Bstate,Bcap/min charging hours),0) **Equation 2.5**

The operation of the system modelled for discrete hourly periods is as shown in table 2.1.

Table 2.1: Tabular Summary of the Model

Energy flow parameter	Conditions for the parameter	Excel function
Radiation incident on the array, I_{pv}	If there is radiation incident on the PV array	$I_{PV} = (I_h\text{-}I_d)\ Rb + I_d$
Photovoltaic Generator Output, P_{pv} $\infty P_{\_rated}$	If there is radiation incident on the PV array and if the PV array is connected to the system components to allow flow of energy	$P_{PV} = \frac{\eta_{pv}\,(Ta, I)}{\eta_{ref}} * \frac{I_{pv}}{I_{ref}} * P_{rated}$
Battery charge by PV array at a charging rate of $\frac{B_{cap}}{hrs}$	If the PV output is greater than load and if battery state is lower the maximum charge rate (there is space to take the charge) $P_{pv} > L$ AND $B_{cap} > B_{state}$	B_{charge}=[IF(AND(P_{pv}>L/η_{inv},B_{state},<B_{cap}),MIN(P_{pv}-L/η_{inv},B_{cap}-B_{state},B_{cap}/hrs),0)]η_{bat}
Battery discharge	If PV output is less than the load and if the battery state is greater than minimum allowed state of charge. If, L>η_{inv}xP_{pv} and if B_{state} >SOC_{min}xB_{cap}	$B_{discharge}$=IF(AND(L>η_{inv}xP_{pv},B_{state}>SOC_{min}xB_{cap}),MIN(L- ($\frac{\eta inv x Ppv}{\eta_{inv}}$),$B_{state}$-$SOC_{min}xB_{cap}$),0)
Hourly load met	Actual load met by the energy supplied via the inverter	=MIN($B_{discharge}$ x η_{inv}+ η_{inv}xP_{pv},Load)
% of load met	Fraction of load met over the load demanded as a percentage	=[MIN($B_{discharge}$ x η_{inv}+ η_{inv}xP_{pv})/Load]x100
Excess PV energy dumped	P_{pv}>L and energy to charge the battery	$PV_{dumped} = P_{pv} - \frac{Bcharge}{\eta bat} - Load/\eta_{inv}$
Solar contribution	Actual energy from the PV generator supplied to the load	SC = MAX($B_{discharge}$ x η_{inv}+ η_{inv}xP_{pv},Load)
Solar fraction	Fraction of the load met from energy supplied by power generated by PV array	SF=SUM(Load met)/SUM(Annual load)
Strict Reliability	Fraction of load met which is fully satisfied	Re_{strict}=1-countif(load met,"<1")/count(load met)
Partial reliability	Fraction of total load met even not fully met	$Re_{partial=}$SUM(annual load met)/SUM(annual load demanded)

And the battery discharges if the PV output is less than the load and there is charge in the battery to cover for the deficit. It is given by;

$B_{discharge}$=IF(AND(L> η_{INV}Ppv,B_{state}>SOC_{min}*B_{cap}),MIN($\frac{L-\eta INVPpv}{\eta IN}Bstate - SOCmin * Bcap$),0)*$\eta_{bat}$ Equation 2.6

The amount of battery discharge is limited, by the charge regulator, to the maximum allowable rate of discharge. DOD_{max} = maximum allowable depth of discharge.

2.4 Solar Fraction

The hourly solar fraction which is referred in this study as the fraction of the hourly load contributed by solar energy was calculated as follows: The hourly energy contributed to the load by solar energy, L_s, is the sum of the PV hourly output and the battery discharge attributable to solar energy, B_{gain}-PV.

The daily solar contribution to the load is the sum of the hourly contributions, and the daily solar fraction is the ratio of the daily solar contribution to the daily load. The monthly solar fraction is equal to the daily solar fraction for the average day, and the annual solar fraction is the weighted average (according to number of days in each month) of the monthly solar fractions.

2.5 Economic Model

The economic parameters used in the model are as shown in the table 2.2.

Table 2.2: System Economic Parameters

Parameter	**Quantity**	**Unit**
PV Array lifespan	25	Years
Battery lifespan	5	Years
Inverter lifespan	10	Years
PV Capital Cost	0.25	$/W
Battery Cost	0.5	$/Wh
Inverter Cost	0.2	$/W
PV Array Maintenance Cost	3%	of capital cost
Inverter Maintenance Cost	3%	of capital cost
Battery Maintenance Cost	1%	of capital cost
Electricity Price (domestic)	0.11	$/kWh
Discount Rate	10%	
Cable cost%	2%	
Installation	30%	

The economic model here was limited to computation of levelised cost of a number of possible system combinations for different reliability levels of supply. The LCOE was here used and the system optimisation tool with reliability level of supply as constraint. From the studied market information, the above general market parameters were derived. These were then used to determine capital and maintenance costs of equipment for the project life. These became the inputs to the calculations of the levelised cost of energy. The Levelised Cost of Energy is given by, LCOE = Total Energy Delivered Annually/Total cost of delivering the energy.

2.6 Life span of equipment

The life span of a solar PV off-grid system was pegged on the life span on the photovoltaic modules which ranges between 20-25 years at an output of at least 80% of rated capacity. Thus the life span of the PV modules in this study was pegged on 25 years.

Lead-acid gel-type batteries with the life span pegged on 5 years were used in this current study because of their abundant availability on the local market. The lifespan of inverters in the current study was pegged on 10 years basing on a market survey done by the researcher.

2.7 Determination of the System Costs

The system costs were being determined through averages obtained from a random market survey of prices.

Table 2.3: Determination of system costs

CAPITAL COSTS +maintenance	**Cost**
Item	$
PV Array	6314.847
Inverter	1029.086
Battery	9470.587
Cables	336.2904
Installation	3430.162
Charge controller	84.0726
Total capital costs	20665.04
PV maintenance	189.4454
Inverter maintenance	30.87259
Battery maintenance	94.70587
Grand Total Costs	**20980.07**

The unit cost of energy was reached by calculating the total energy produced per year and divide it by an annual cost. The annual cost was determined through the multiplication of a capital recovery factor with the total present value annualised cost. Once the annualized cost was computed then it was divided by the annual energy produced to give the levelised cost of energy (LCOE).

2.8 Determination of Optimum system combination with least cost reliability

Reliability of supply is measured as one minus loss of load fraction (1-LLF) which also can be expressed as a percentage of load met. In this case reliability is also equal to corresponding solar fraction since all the power is generated from solar generator only. To determine optimum system combination a number of curves of $P_{\_rated}/P_o$ against B_{cap}/L_{day} were plotted for different reliability levels. For each reliability level the most optimum system is at the point where a change in rate of increase in size of power required from PV array rises at a faster rate for a slight decrease in battery capacity.

The optimum system combinations for each reliability level are also confirmed by a PV array size corresponding to the least levelised cost of energy (LCOE). The minima of the levelised costs of system combinations at different reliabilities are then plotted against the corresponding reliabilities to determine the overall least cost optimum system reliability. This is somewhere at the elbow of the graph when the rate of increase of the cost to add a small fraction of reliability becomes too high, just before the steep gradient is the most cost effective reliability for a system. The graphs plotted are shown in the results section.

2.9 Determination of LCOE for the traditional sizing method

To validate the design model developed in this current study, it was compared with the LCOE for a system designed using the traditional method which uses total daily consumption as load. This method assumes a constant demand and irradiation throughout the day. Using the same economic parameters of the components as used in the optimising model designed in this study, capital and maintenance costs of the system were determined. The calculated capital and maintenance costs were brought to the present value of the life cost cash flows of the system. The total present value costs were then annualized by multiplying with the Capital Recovery Factor (CRF) which is the same as calculated in the optimised model. With the total annual energy produced, the cost per unit of energy was determined; this is the levelised cost of energy.

2.10 Determination of LCOE for the grid extension option

An option of electrifying the community with the grid was also explored and LCOE calculated.

Table 2.3: Economic parameters for the grid project option

Grid capacity		length	1% of capital cost		Cost
33	kV	20	20000.00	$/km	400000
11	kV	15	16000.00	$/km	240000
380	V	5	8000.00	$/km	40000
240	V	5	5000.00	$/km	25000
25	kVA	1	4500.00	$	4500
			10% of capital cost		70950
			30% of capital cost		212850
					709500
					922350

Assuming the above parameters from the Zimbabwe Electricity Transmission and Distribution Company (ZETDC) and ZERA draft mini-grids code, a life span equal to that of the solar project was also assumed to allow for comparison.

3. Results and discussion

3.1 System sizing and Reliability curves

A number of curves were produced to determine most optimum system PV-battery combinations corresponding to given reliability levels. Figure 3.1shows the curves.

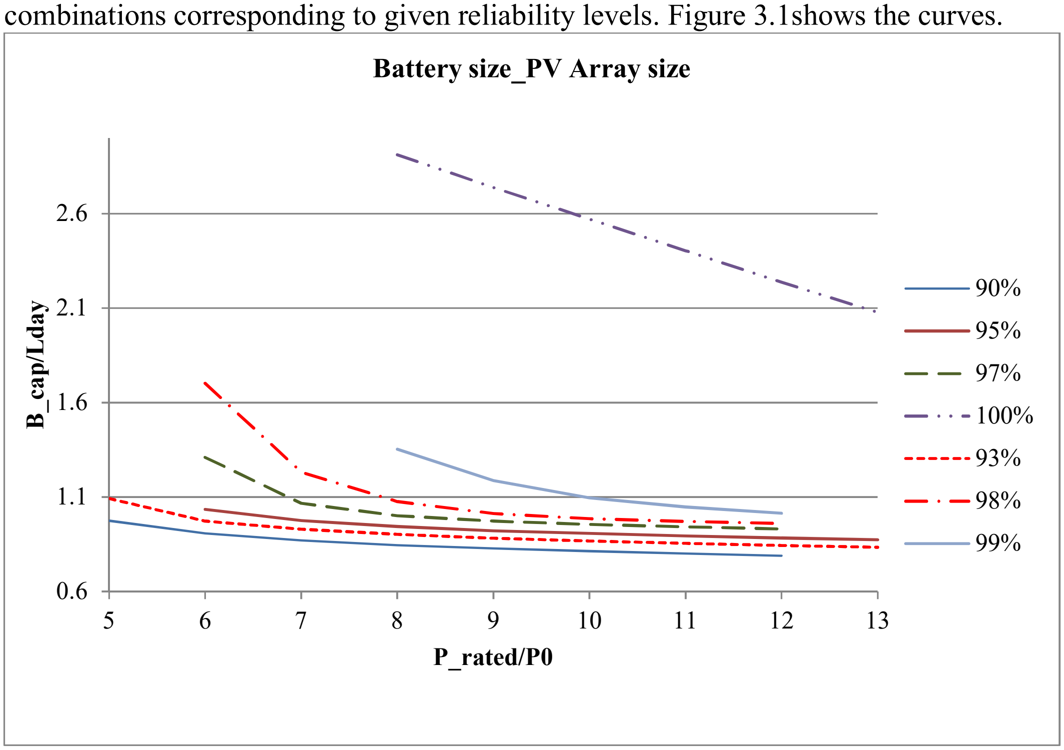

Figure 3.1: System combination curves PV array size and the corresponding battery size

Figure 3.1 is a set of curves showing possible system combinations for the PV array and battery corresponding to different reliability of supply levels. The reliability of supply here is referred to as 1-LLF, where LLF is the fraction of the unmet load over the total yearly load. The graph above shows that for a given reliability level there are infinite system combinations that can be installed. However, since the system design is anchored on least cost design then the system with least levelised cost of energy is chosen per each reliability level for further analysis. (Magnor and Sauer, 2016; Mundada, Shah and Pearce, 2016) concluded that the best system combination to achieve a chosen reliability is somewhere along the elbow of the curve corresponding to that reliability. Basing on the same premises, then from the curves in figure 3.1, the system combinations in the table below can be read from the graph as the optimum combinations to meet a given reliability of supply level.

Table 3.1: Optimum system combinations corresponding to given reliability level

Reliability	**$PV_{\_rated}/P_o$**	**B_{cap}/L_{day}**
0.9	6	0.90748
0.93	6	0.97199
0.95	7	0.97514
0.97	8	1.00051
0.98	9	1.01232
0.99	11	1.0475
1	27	1.0479

3.2 Cost versus PV array size for different reliability levels

Levelised costs of energy of different system combinations to give certain reliability levels were plotted. For each reliability level of supply, a locus of results were partially plotted to determine the system combination that corresponds to the minimum LCOE (Lee, Soto and Modi, 2014).

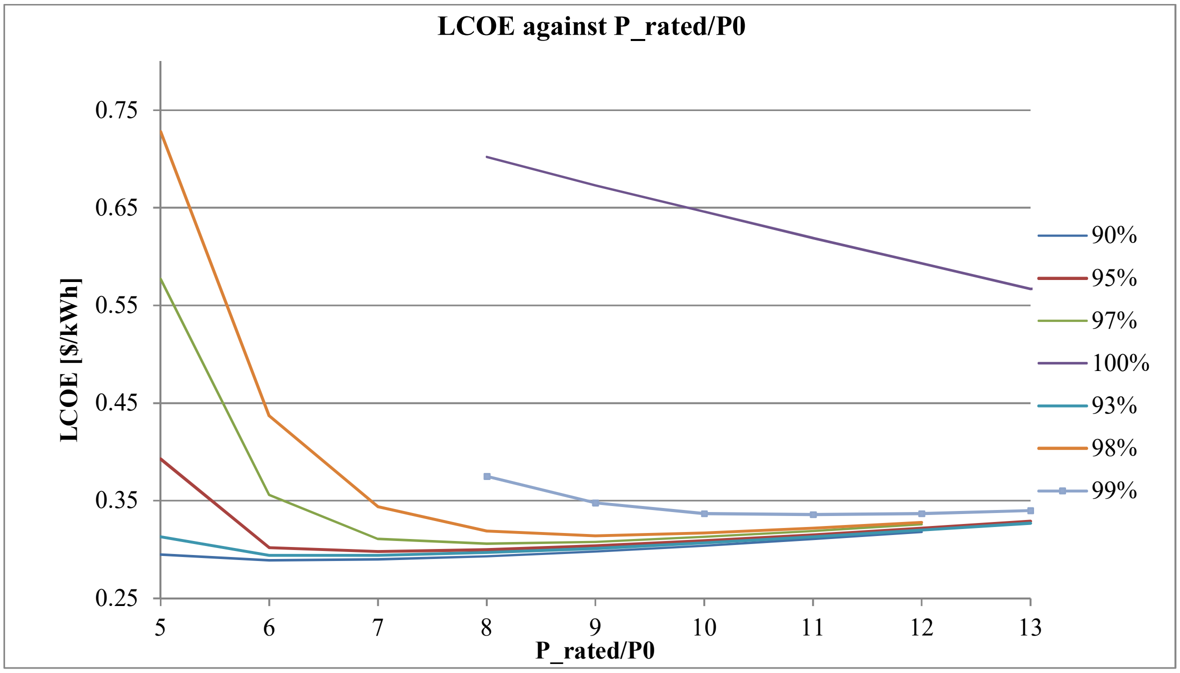

Figure 3.2: LCOE versus P_rated/P0

As depicted in the curves in Figure 3.2, the LCOE of the systems fall rapidly with the initial increases of PV generator size after reaching a minimum, the LCOE starts rising though with low gradient. According to (Hove and Tazvinga, 2012), the least cost system for a given reliability level corresponds to a point on the elbow of the curve. Minimum LCOE for given reliability level is read from figure 3.2. Beyond an optimum array size the larger the array size, the higher the cost of supplying energy at any level of reliability.

Table 3.2: Minimum LCOE per given reliability level of supply

$LCOE_{min}$	**Reliability**
0.289	0.9
0.294	0.93
0.298	0.95
0.306	0.97
0.314	0.98
0.336	0.99
0.467	1

3.3. Determination of an optimum reliability

The optimum reliability level of a system is the level of supply which supplies critical load cost effectively.

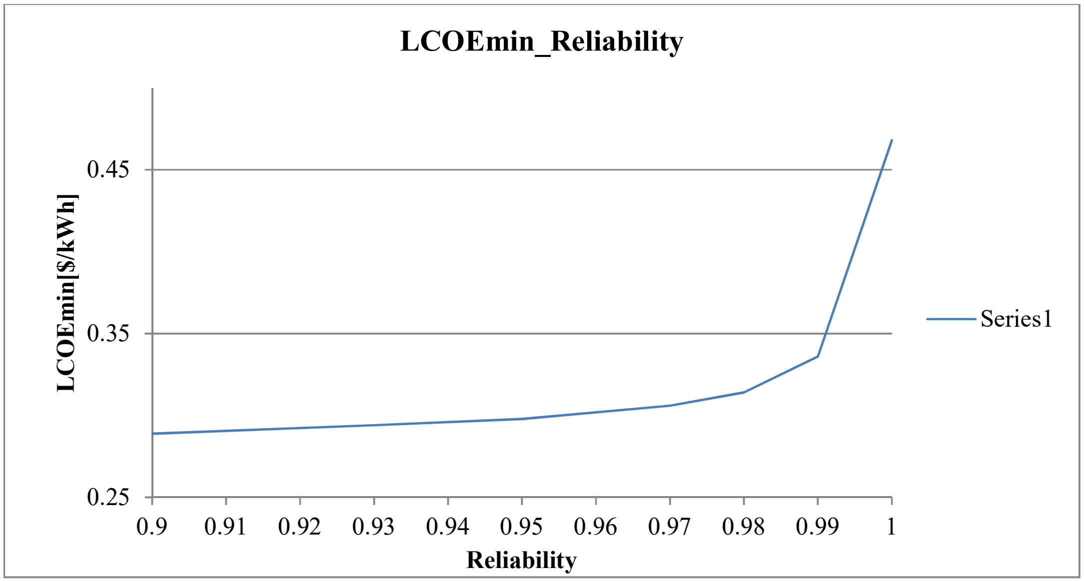

Figure 3.3: LCOE$_{min}$ versus Reliability

This is determined by considering the least cost system combinations for each reliability level and plotting them against the reliability levels. The cost effective system is the one which corresponds to the point at the elbow of the graph in figure 3.3. This is a point beyond which the cost of increasing system supply reliability rises sharply for a very small increase in reliability. $\frac{\Delta LCOE}{\Delta Reliabilit} = \frac{0.668-0.448}{1-0.98} = \frac{0.220}{0.02} = 11$ In this case the cost of increasing reliability becomes economically not viable if the load in question can be managed through intelligent energy management tools. The high cost of reliability becomes justifiable only when the load in question is so critical that it requires 100% reliability otherwise a trade-off between reliability level of supply and cost of supply is needed. In addition, at 98% reliability load management is a better solution than striving to bear the cost of achieving 100% reliability.

3.4 Determination of system sizes corresponding to optimum reliability

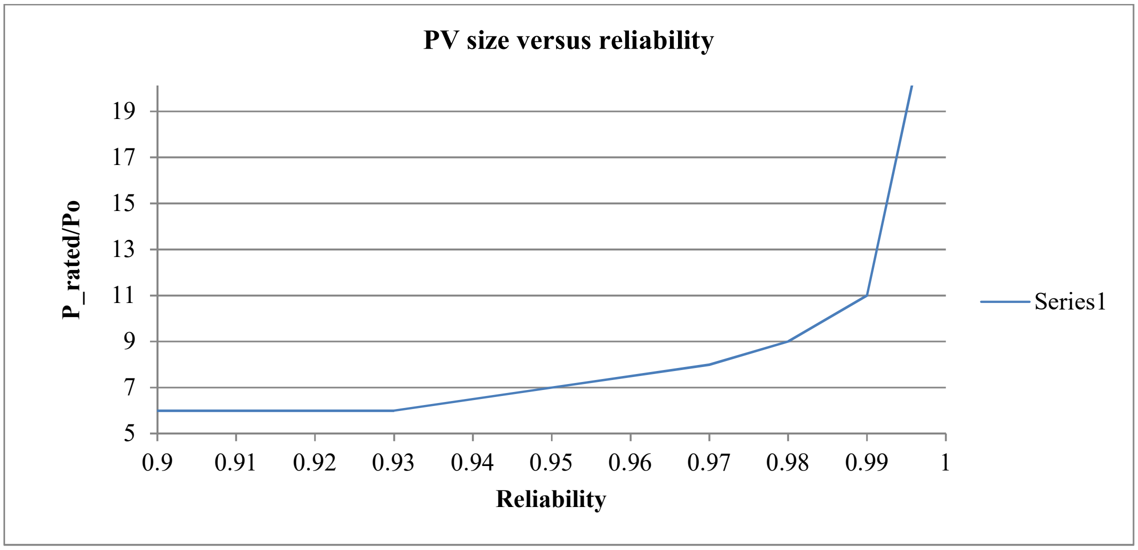

Figure 3.4: Normalised PV power versus reliability

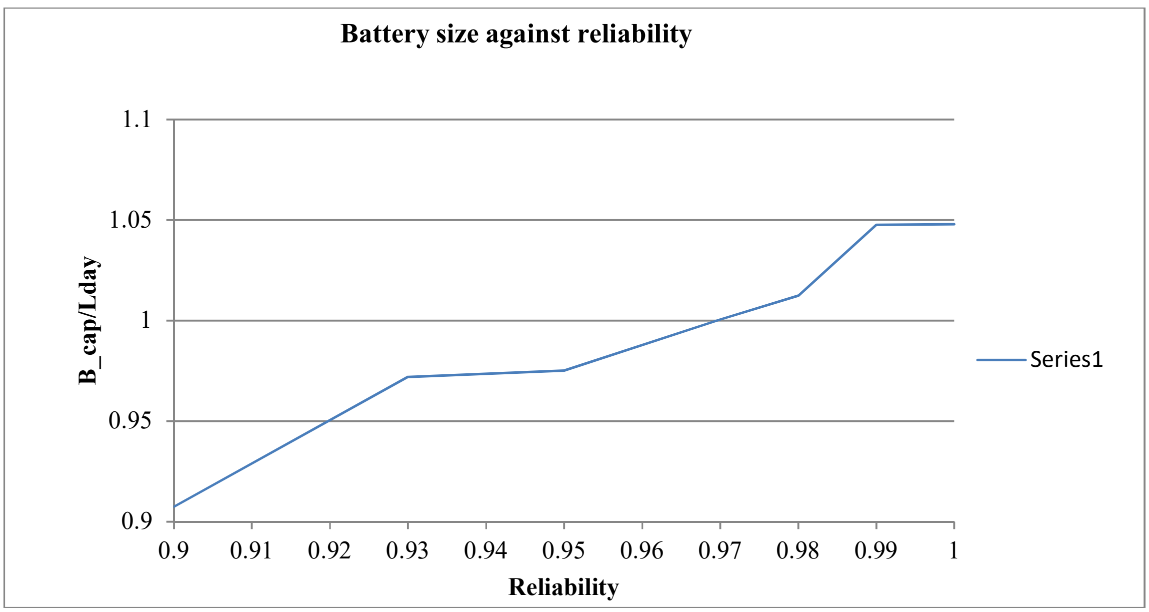

Figure 3.5: Normalised battery capacity against Reliability

The sizing graphs, in figure 4.4 and 4.5 helps to determine the normalized PV power and battery capacity that corresponds to the optimum system reliability. The elbow of each corresponds to the optimum reliability above which the sizes of PV array and battery capacity required increases sharply disproportionate to the corresponding gain in reliability.

3.5 Yearly Energy Sharing Scenarios for the optimum system

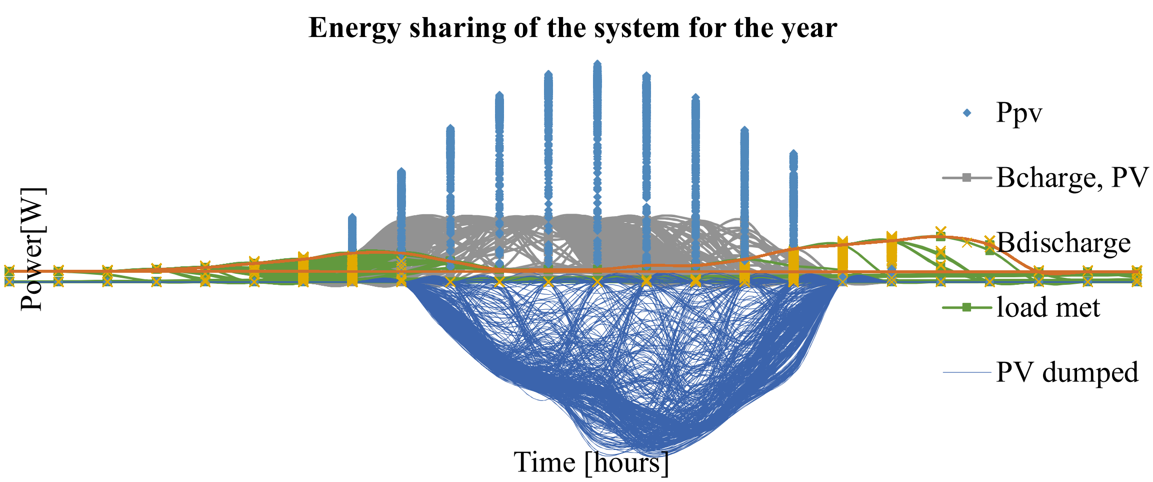

Figure 3.6: Energy sharing scenarios of system in a year

Figure 3.6 shows how the load is shared between the direct PV supply and the battery discharge. It also shows how the system dumps excess PV power and when the load is met or not. The instance when the load is not met is when the battery has discharged to its rated minimum state of charge and there is no PV to supply the load and recharge the battery. Battery charging is done during peak hours of PV supply, between 0900 and 1500 being hourly when solar insolation is at peak supply and dumping happens when the battery is fully charged and the load is lower than the power supplied from the PV array. The optimum sized system should be designed that it minimizes dumping and maximizes load met. There is more energy dumping during the day also because the typical rural load profile peaks in the morning and evening when there is more cooking activities and heating of water. The dumped energy can be diverted for use by direct coupling gadgets like water pumps, etc.

3.6. Comparison of the results of the Model and the Traditional sizing method

The results of the sizing methods used in this study are compared as in table 3.3.

Table 3.3: Comparison of system parameters obtained during sizing

Parameter	**Business as usual method/Simple method**	**Optimised model [100% reliability]**	**Optimised system [98% reliability]**	**Grid extension option**
PV power [W]	8859.842	42098.98	14032.99	
Battery Capacity [Wh]	205097.6	39213.80	37882.35	
Inverter power [W]	56131.97	5145.43	5145.43	

LCOE [$/kWh]	1.39	0.468	0.314	0.533

Table 3.3 gives a comparison of four systems, that were designed through the simple technician/ business as usual method, the one designed through the optimising model developed in this study ensuring 100% reliability of supply and the optimised design at 98% reliability of supply plus the grid extension option.

We can see that the optimised system is the most cost effective of option 4 with LCOE of 31.4UScents/kWh compared to 46.8UScents/kWh of the 100% reliability and 139UScents/kWh for the business-as-usual model. All these systems presented to the same community; I believe the community will go for the optimised system. Even though with some hours of unmet load the community will still be comfortable and reliably supplied with the energy management system in place. The levelised cost of energy of the grid extension scenario was also calculated and found to be 0.53US$/kWh which is higher than the solar PV optimised system, thus rendering the optimised model the most cost-effective means of electrifying areas 20km and above from the grid connection point.

The business as usual or the simple technician method is too costly for the community in question and more so the economy at large. If more of these systems are installed in rural areas, it means the Government will have to highly subsidise to ensure affordability of the power and thus the whole economy will be prejudiced of large sums of money which could be used for productive sectors.

4. Model output

The resultant system sizing parameters, energy generation and demand characteristics and economic performance characteristics of the optimally-reliable system are shown table 4.1.

Table 4.1 System Sizing, Energy and Economic Performance Characteristics

SYSTEM SIZING, ENERGY AND ECONOMIC PERFORMANCE CHARACTERISTICS		
Daily Load Demand	37421.32	Wh
P_{-rated}/P_0	9.00	
$B_{\_capacity}/L_{day}$	1.01	
PV Array Power	14032.99	W
Battery capacity	37882.35	Wh
Inverter Power	5145.43	W
annual load met	13385553.76	Wh
annual PV generated	33190370.10	Wh
annual load	13658780.34	Wh

Strict reliability	0.97	
partial reliability	0.98	
Solar Fraction	0.98	
Dumped PV energy	0.49	
Total Capital costs	20665.04	$
levelised cost of energy (LCOE)	0.31	$/kWh

4.1. Sizing and operating parameters of the optimally-reliable system

Operating parameters of the optimally-reliable solar PV-battery electricity off-grid system are shown in table 4.3 below.

Table 4.2: Operating parameters of the optimum system

Energy Source	**-**	**Solar PV+Battery**
Daily load demand	kWh	37421.32
$PV_{\_rated}/P_o$	-	9.00
B_{cap}/L_{day}	-	1.01
PV array power	kW	14032.99
Batter capacity	kWh	37.88
Inverter power	kW	5.15
Solar fraction	-	0.98
Dumped PV energy	-	0.49
Total capital cost	$	20665.04
Operating costs	$/Annum	315.02
Levelized cost of energy	Cents/kWh	31.40
Reliability	%	0.98

5. Conclusion

It can be deduced that the optimally-reliable cost effective off-grid solar PV-battery system does not necessarily need to be 100% reliable. For a cost-effective system, there is always trade-off between cost and reliability because as shown in graphs in figures 3.3-3.5, there is a level of reliability to which a system can be optimised without compromising on cost of energy beyond which a slight increment in reliability attracts a cost which is not justifiable for it. In this case the ratio of increase in LCOE to the increase in reliability from 98% to 100% is 11

times which results in a huge investment not justifiable of the gain. One needs to install more PV modules and batteries to meet 100% of the load all year round thus a very high cost which can inhibit investment in off-grid systems due to the huge initial capital outlay.
In addition, when comparing the system sizing method of the model developed in this study and the system common solar off-grid sizing method referred here as the common basic technician method, there is great optimization of resources and thus costs can be reduced when the proposed optimization model is adopted. This is so because there is generally oversizing of system components in the common basic technician method than when sizing for hourly demand as in the model developed in this study.
Partial reliability is opted for in these systems because there now exist on the market energy management systems that can ensure that even at 98% reliability, the customers will still be comfortable.

5.1. Recommendations

It is recommended that in Zimbabwe designing solar PV-battery of grid systems, this model can be used as long as the load profile in question is similar to the typical rural one with a peak in the morning and evening.

Further studies should include calculations of greenhouse gas emissions avoided or reduced by extending this model as it is now the global trend to ensure accountability and sustainability. Inclusion of these environmental and climate issues in designs will make the projects more bankable for funding from the international world. It is recommended that off-grid systems in Zimbabwe designed for similar load profile, be optimised to minimize cost of energy supply and increase affordability.

References

Alam, M. and Bhattacharyya, S. (2016) Decentralized renewable hybrid mini-grids for sustainable electrification of the off-grid coastal areas of Bangladesh, *Energies*, 9(4). doi: 10.3390/en9040268.

Alsharif, M. H., Nordin, R. and Ismail, M. (2015) Energy optimisation of hybrid off-grid system for remote telecommunication base station deployment in Malaysia, *Eurasip Journal on Wireless Communications and Networking*, 2015(1), pp. 1–15. doi: 10.1186/s13638-015-0284-7.

Avila, N., Carvallo, J.P., Shaw, B. and Kammen, D.M. (2017) The energy challenge in sub-Saharan Africa: A guide for advocates and policy makers. Generating Energy for Sustainable and Equitable Development, Part, 1, pp.1-79.. doi: 10.13140/RG.2.2.25037.44001.

Burger, A. (2019) Zimbabweans Turn to Minigrids in Droves Amid Chronic Blackouts, pp. 1–2.

Duffie, J. A. and Beckman, W. A. (2013) *Solar Engineering of Thermal Processes Solar Engineering*. doi: 10.1002/9781118671603.fmatter.

Hassan, A.S., Cipcigan, L. and Jenkins, N. (2017) Optimal battery storage operation for PV systems with tariff incentives. Applied Energy, 203, pp.422-441. doi: 10.1016/j.apenergy.2017.06.043.

Hove, T. and Tazvinga, H. (2012) A techno-economic model for optimising component sizing and energy dispatch strategy for PV-diesel-battery hybrid power systems, *Journal of Energy in Southern Africa*, 23(4), pp. 18–28.

International Energy Agency. (2016) Rural Electrification with Renewable Energy Technologies, quality standards and business models, *International off-grid Renewable energy Conference*, 40(1), pp. 11, 26. doi: 10.1016/j.rser.2014.07.161

International Energy Agency. (2017) Energy Access Outlook 2017: From Poverty to Prosperity, IEA, Paris, https://doi.org/10.1787/9789264285569-en

International Renewable Energy Agency. (2018) *Policies and regulations for renewable mini-grids*. Available at: https://irena.org/-/media/Files/IRENA/Agency/Publication/2018/Oct/IRENA_mini-grid_policies_2018.pdf.

International Renewable Energy Agency. (2019) *Future of solar photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation: paper)*, *International Renewable Energy Agency*. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Oct/IRENA_Future_of_wind_2019.pdf.

Kavu, S., Mashungu, L., Kajongwe, C. and Chigerwe, J.(2020) Modelling an hourly load profile for an archetypal load rural community in Zimbabwe. J*ournal of African Interdisciplinary Studies*, 4(5), pp.104-118.

Khalilpour, R. and Vassallo, A. (2016) Planning and operation scheduling of PV-battery systems: A novel methodology, *Renewable and Sustainable Energy Reviews*, 53, pp. 194–208. doi: 10.1016/j.rser.2015.08.015.

Lee, M., Soto, D. and Modi, V. (2014) Cost versus reliability sizing strategy for isolated photovoltaic micro-grids in the developing world. *Renewable Energy*, 69, pp.16-24. doi: 10.1016/j.renene.2014.03.019.

Magnor, D. and Sauer, D.U. (2016) Optimization of PV battery systems using genetic algorithms. *Energy Procedia*, 99, pp.332-340. doi: 10.1016/j.egypro.2016.10.123

MacGill, I. and Watt, M. (2015) *Economics of solar PV systems with storage, in main grid and mini-grid settings. In Solar Energy Storage* (pp. 225-244). Academic Press.

Moner-Girona, M., Solano-Peralta, M., Lazopoulou, M., Ackom, E.K., Vallve, X. and Szabó, S. (2018) Electrification of Sub-Saharan Africa through PV/hybrid mini-grids: Reducing the gap between current business models and on-site experience. Renewable and Sustainable '*Energy Reviews*, 91, pp.1148-1161.

Moner-Girona, M., Ghanadan, R., Solano-Peralta, M., Kougias, I., Bódis, K., Huld, T. and Szabó, S. (2016) Adaptation of Feed-in Tariff for remote mini-grids: Tanzania as an illustrative case. *Renewable and Sustainable Energy Reviews*, 53, pp.306-318. doi: 10.1016/j.rser.2015.08.055.

Mundada, A.S., Shah, K.K. and Pearce, J.M. (20160) Levelized cost of electricity for solar photovoltaic, battery and cogen hybrid systems. *Renewable and Sustainable Energy Reviews*, 57, pp.692-703. doi: 10.1016/j.rser.2015.12.084

Okpokam, E.A. (2021). Small and Medium Enterprises Green Energy Strategies for Profitability (Doctoral dissertation, Walden University).

Rawat, R., Kaushik, S.C. and Lamba, R. (2016) A review on modeling, design methodology and size optimization of photovoltaic based water pumping, standalone and grid connected system. *Renewable and Sustainable Energy Reviews*, 57, pp.1506-1519. doi: 10.1016/j.rser.2015.12.228

Zebra, E.I.C., van der Windt, H.J., Nhumaio, G. and Faaij, A.P. (2021) A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries. *Renewable and Sustainable Energy Reviews*, 144, p.111036.). doi: 10.1016/j.rser.2021.111036.