Optimisation of a Decentralised Photovoltaic Mini-grid, Case of Madokero Community Complex in Harare

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Abstract:
This article acknowledges and discusses the power of energy access in transforming people's way of life and as a key enabler of economic growth. A well-designed photovoltaic (PV) system should have fault-free operation, offering an attractive option to alleviate the effects of energy poverty at reasonable cost of energy. In this study, a techno-economic design of a 100 kW Solar plant was carried out for Madokero Community Complex cluster houses. Using demand matrix-based load analysis, a maximum demand of 48kW was calculated for a daily load of 565.5kWh with an annualised expected consumption of 206.4MWh for the community. For the determined hourly load profile and for a desired level of electricity supply reliability determined as 97%, a combination of solar PV array and storage battery were specified in a general way using dimensionless component size parameters, A/Ao=9 and Bcap/Lday =0.89, respectively and defined in this study. This resulted in a system with 212kWp peak panel output, 503.282kWh battery storage and 100kW inverter peak output being specified for the Madokero Community Complex cluster houses at the least levelised cost of $0.23 per kWh. Properly dimensioned PV array-battery combinations for varying reliabilities at the least levelised cost were recommended for future designs.

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INTRODUCTION

The ailing power sector in Zimbabwe is witnessed by the generation capacity persistently falling below demand resulting in insistent and massive load-shedding. The deficit was met in part by energy imports and demands side management initiatives. Energy is an essential element to economic growth and poverty eradication in developing countries. A photovoltaic (PV) mini-grid is a small-scale electricity network fed by solar energy. The generated electricity is supplied directly or indirectly, via batteries to, the end-users who mostly are connected to the mini-grid electricity network through transmission pylons. Mini-grids are ideal for dense settlements to minimise the network transmission distance, thus, cutting, on the otherwise high costs of distribution (REA, 2011). A community of people who live close to each other, for instance, in cluster houses, can be easily connected to the grid.

Madokero Community is a mixed-use and integrated housing development on 202 hectares of land. The project has a planned development of Madokero gardens, Madokero Mews and Madokero Manor that comprises 1700 housing units, 500 garden apartments, 30 industrial stands, a regional commercial centre, a medical centre, five schools and many other social amenity provisions (Exodus & Company, 2020). Madokero Gardens has a total of 106 two-bedroomed and three-bedroomed garden apartments. Madokero Manor has 12 apartments constructed at present out of a total planned 44 duplex apartments. Madokero Mews has a total of 84 garden apartments in a gated complex, comprised two-bedroomed apartment (Exodus & Company, 2020).

The community planned to use renewable sources of energy to meet the whole or part of its own energy needs. The natural plan was to install a solar power plant at an identified location within the Madokero Estate. The challenges this initiative poses on the project developers emanates from the reported unreliability and intermittence of the solar energy, given the need to maintain residential comfort to the cluster house owners. A considerable number of solar mini-grids have reported poor performance, due to known or unknown technical reasons. Hence, the Madokero Community project developers wanted to come up with a solar plant that was fit for purpose through having a well-optimised design with higher power plant performances, increased reliability and reduced downtimes.

The amount of usable energy delivered by a PV system depends on many factors, but the primary factors are:

1. The size of the PV array,
2. The amount of irradiation it receives, and
3. The total efficiency of the system.

In general, PV systems are usually exposed to a variety of major power losses, due to environmental factors, device limits and others, due to inherent manufacturing defects. The losses usually include components, such as, soiling (dust), shading, manufacturer's tolerances, temperature variations, voltage drops, inverter-battery efficiency, orientation and tilt angle of the modules, time degradation of solar modules and other location specific factors that could have impact on the PV array's performance (IEA, 2000).

A well-designed and installed PV grid-connected system should have fault free operation for many years. Poor system design can result in the PV array operating at voltages outside the inverter voltage window and consequently the inverter disconnects from the grid for long periods. Poor system design relating to the PV array and inverter also force inverters to operate very inefficiently. In many cases, the developers can overestimate unrealistically high energy yield from their designed PV system. This usually occurs, due to ignorance or poor estimation of system losses by the system designer or the consultant. Some of these losses are easy to rectify but some require in-depth understanding and testing of the system and components.

Solar PV mini-grid often faces one or more of the following constraints during their life cycle operations:

- Seamless operational constraints, i.e. load-shedding and load-weaning,
- Frequent power generation unit failure,
- Low generation capacity (Under sizing of equipment),

- Mismatching of different parameters, including components-dimensioning.

This study aimed at contributing to knowledge on the use of solar PV mini-grids by examining and assessing the design, dimensioning and fitness for purpose of solar mini-grids to support target local socio-economic activities in a sustainable manner. The study focused on formulating an optimised design at the least-cost per derived benefit that is viable, reliable, effective and efficient. The power plant audit aimed at identifying the root causes of potential losses, generation unit failure, inconsistence in power supply and reported grid failure. The study also aimed at techno-economically providing an answer to the usual constraints experienced at a typical PV power plant to maximise the plant's energy performance.

LITERATURE REVIEW

The average solar insulation in Zimbabwe is approximately 5.7kWh/m2/day (USEIA, 2010). Thus, there is an enormous potential for use of solar resource as PV and solar water heaters in Zimbabwe that has not yet been fully exploited. Solar PV has a potential of around 300 MW of electricity. At present, only about 1% of the technical potential for solar water heaters has been exploited (REA, 2011). Solar power is mostly installed in new settlement locations in urban areas, in peri-urban locations and in rural areas of Zimbabwe at service centres, such as schools, clinics, police stations and hospitals (cf. NASA, 2008; SMA, 2016; SNV, 2017). However, currently, the private home market for solar is growing. Solar-powered 'base stations' for charging electrical appliances have also been installed through telecommunications companies in Zimbabwe (MoEPD, 2015).

Solar PV is essentially a semi-conductor-based technology that converts radiation energy from the sun to electrical energy. It is remarked as the only known source of electrical energy where there are no moving parts, noise or emissions (Power for All, 2016). Solar PV systems are used in applications where conventional electricity was previously used. When the sun shines on a PV panel, the PV panel produces direct current. The most common forms of PV devices have been the polycrystalline, mono-crystalline and amorphous (thin film) modules. Solar mini-grid systems have been successfully installed all over the world. A mini-grid connects several households to one or more sources of electric power. The conventional sources of power in existing mini-grids are diesel generators. There are many examples around the world of diesel-based mini-grids where PV is used as a supplementary source of energy. One of the aims of these solar mini-grid projects is often tied to design the system so that the need for a large battery-capacity is avoided, to keep system costs down (Civic Solar, 2017).

In a small, but growing number of mini-grids, the PV generators now make out the prime source of energy, either in combination solely with battery storage or in combination with other energy sources. Benefits of mini-grids include, but not limited to, the following:

- Independent of national electricity changes and price rises.
- Scalable – can be designed for a wide range of power requirements.
- Centralised – convenient control and maintenance.
- Fast deployment – ready to work within hours or days.
- Reliable – designed to work for at least 20 years and low operational and maintenance costs.

Mini-grids offer the easiest, fast, reliable and cost-effective way to improve rural energy access to the remote areas, through meeting the energy needs of communities and reducing energy poverty.

Solar system designers now use a wide range of approaches to mini-grid development today. These are classified in terms of technologies involved, desired level of operational reliability and the institutional and financial arrangements (Practical Action, 2011). Mini-grids can include single generation technologies, such as diesel, solar PV, wind, hydropower or biomass power generation, or a hybrid system that includes two or more technologies. Hybrid systems have generated most interest because they mix dispatchable power sources (e.g. diesel generation which can be delivered on demand) with non-dispatchable power sources, so increasing reliability and load matching.

Despite the various low-lying opportunities, penetration of mini-grid systems remains low in most developing countries (Bank, 2015). Their development has been greatest in Asia. China has an estimated 60,000 schemes and Nepal, India, Vietnam and Sri Lanka, each have 100–1000 mini-grids. Most schemes use Solar PV, diesel or hydro power generation and they are government-run (IEA, 2000). Building sustainable solar mini-grid financing structures can be challenging, despite a growing understanding of financial barriers in project development and an increasing number of financial tools to be used (Bank, 2015). While they may be more economically attractive than grid connection in remote areas, mini-grid systems can have high upfront costs. This is particularly the case for certain renewable generation technologies, compared to more conventional options, such as diesel and conventional electricity.

Around the world, the successful mini-grid schemes have been developed where their design carefully considered prevailing and expected local economic, social and environmental conditions; where sustainable financial business models have been developed and where the national policy and regulatory context are sensitive to the requirements for building mini-grids. Many of these factors are very context specific (Bank, 2015). Situation based site selection is important to ensure that solar mini-grids are not developed so close to grid systems that they are quickly superseded by conventional grid power supply. Detailed site analysis also helps with appropriate technology selection that will provide some estimate of projected output. For renewable energy promotion, this includes an understanding of hydrology, wind speeds and solar insulation, depending on the technology. In the case with diesel generation, a clear understanding of current and future fuel availability and price at the location are important. When appropriate sites are identified, it is also important to develop mini-grids along other initiatives that may help to increase demand and people‘s ability to pay (Practical Action, 2011). Having a good understanding of the energy demand through field studies and demand analysis is another pre-requisite for designing sustainable systems, economically viable. However, future demand growth also needs to be kept in mind. For example, one method would be to over-size some components of the solar plant where appropriate, but this should be done in a way that does not increase the overall cost of energy delivery (SNV, 2017).

In the analysis of a PV power generation plant, a PV system is documented by a capacity test that quantifies the power output of the system at set conditions, such as an irradiance of 1000 W/m^2, an ambient temperature of 20°C and a wind speed of 1 m/s. For accurate results, a longer test period will be used to verify the system performance under a wide range of conditions. A long test period samples weather and shading associated with all seasons. Shorter tests use less time, but are susceptible to seasonal bias, especially, if the model is inconsistent in accuracy percentage throughout the year (for example, if the shading is incorrectly estimated). The documentation of energy yields might appear to be straightforward, but, in practice, there are many issues and subtitles that complicate the performance analysis associated with variations in weather and imperfect data collection (Hottel and Woertz, 1942).

Performance of a PV mini-grid during a year varies, depending on factors, such as:

- Seasonal shading issues and array soiling
- Sensitivity of modules to high temperatures
- Sensitivity of the model to weather – for example, if performance ratio is used as the metric, the measured performance will vary strongly with temperature.
- Early system degradation and clipping or intentional curtailment.

There is general international agreement that an energy test completed over a full year provides greater confidence for a PV system that was correctly designed and installed, compared with a shorter test (NREL, 2012). Energy performance analysis of a PV solar plant depends on the details of the test and its implementation.

METHODOLOGY

Quantitative data analysis was used as a means of inspecting, cleansing, transforming and modelling energy-related data with the goal of discovering useful information, critical evaluating, suggesting energy efficiency conclusions and supporting solar grid design decision-making. Three levels of data analysis were performed on the number of connected/expected loads, solar resource and predicted PV system energy yields. Load analysis was used to evaluate a variety of parameters (load behaviour) for each potential appliance/equipment to be connected on the solar PV grid. A demand matrix, that was a convenient method for computation of the different type of loads to make up a load profile, was used. It showed the time of day and the appliance in use for that hour. The resulting load profile was obtained from plotting instantaneous hourly power demand against time. Expected and future-growth loads were estimated as accurately as possible through trying to be realistic about the levels of lifestyle and energy usage habits.

Solar resource and meteorological data sets were available for the project location through a variety of public and private measurement sites. Although the periods of record vary for these softwares, most included data up to the present day with some records extending back to the mid-1970's. PVsyst obtains its data from more widely known networks including the National Oceanic and Atmospheric Administration's (NOAA), Integrated Surface Irradiance Study (ISIS) and Surface Radiation (SURFRAD) networks, Meteo Norm and NREL's Measurement and Instrumentation Data Centre (MIDC). An evaluation of these reference data sets was done through using PVsyst software to check for the proximity to the project site, period of record and data quality and accuracy protocols (Mermoud, 2012). The three most common measurements of solar radiation that were of interest during the assessment are Global Horizontal Irradiance (GHI), Diffuse Horizontal Irradiance (DHI) and Direct Normal Irradiance (DNI) since PV plants utilise both direct and diffuse radiation in the project's plane of the array. Other meteorological parameters that were typically obtained from PVsyst software with the irradiance values include temperature, precipitation, relative humidity, wind speed, wind direction and barometric pressure.

Having realised that data from the above sources vary over a wide range of collection points (from monitoring stations, extrapolated, or derived from satellite information), they were further analysed using software Meteo Norm and RET-Screen platforms. This facilitated easy comparisons of irradiation levels from different sources and power output from the solar panels, with variation in type and make of panel used, the angle of tilt, local weather conditions, such as temperature and losses, such as panel degradation, inverter losses and so on. PV plant design was developed basing more on the results of the load forecasting, expected future developments, preliminary energy resource and yield estimates which can easily be obtained from prefeasibility studies done during project conceptualisation.

The power plant system was dimensioned by way of simulating the hourly power supply flows and matching it with the hourly load profile until a desired level of energy supply reliability was achieved using a home-made Microsoft Excel program (Hove and Tazvinga, 2000). The study further aimed at improving the energy performance of the plant by addressing other site-specific requirements and constraints through considerations of site measurements, site topography, performance issues and environmental and social considerations. The major aim was to come up with a technically reliable design at the least-cost (levelised cost of energy). Design context entitled the use of only renewable sources of energy in coming up with an optimised power plant that would be able to meet the power requirements for the chosen community. Thus, fossil fuel sources, such as generator, gas turbines, were excluded from the design owing to the green nature or the project. The system is supposed to operate as a solar stand-alone with battery storage for autonomous days and night time energy supply. It should be able to supply enough power to critical loads even during cloudy periods using the battery-based storage. It was, therefore, critical to come up with a minimum battery size to cater for the worst case when environmental conditions are not suitable.

The inputs used in the model included the PV array and battery size dimensionless parameters (Hove and Tazvinga, 2000) as **A/A_0** and **B_{cap}/L_{day}**, respectively. **A_0** defined as a hypothetical PV array area that would be required to satisfy the daily load if the irradiance was the standard $1000W/m^2$ and the PV efficiency was the reference value over all 24 hours of the day; such that:

$$A_0 = \frac{L_{day}(Wh)}{\eta_r * 24hr * 1000W/m^2} \qquad (1)$$

Where **L_{day}** (Wh) was the daily electrical load. Such that A, the actual installed PV area, divided by **A_0**; $\left({}^{\boldsymbol{A}}/_{\boldsymbol{A_0}}\right)$ was dimensionless. The battery size was similarly represented by the dimensionless parameter $\left({}^{\boldsymbol{B_{cap}}}/_{\boldsymbol{L_{day}}}\right)$ where **B_{cap}** was the installed battery capacity (Hove and Tazvinga, 2000). Power is generated by the PV array. A battery bank is used to store excess power from the PV generator for use to augment low PV generation during the night and cloudy autonomous days. To determine the relationships between individually sized components, a model was used to simulate various operating parameters. The major constraint was the uncertainty of solar irradiation. This was overcome by using simulation software designed to predict monthly averages of hourly radiation.

The latitude of the site determined the angle of tilt in which panels were to be set. The zenith angle was, in this case, chosen to be 180 (north facing) for maximising the year-round radiation income. The reference efficiency of the PV arrays and temperature coefficient was considered when selecting an array. The area **A** was obtained by inputting the standard area (**A/A_o**) that was found by dividing the area by **A_o** which refers to the array that would be required to satisfy the daily load if the array delivered a constant power throughout the day at the reference efficiency and reference radiation conditions. The tilt angle in degrees represents array tilt angle from the horizontal while the angle of latitude referred to the location of the site, positive North and negative south.

The effective battery capacity was normalised by dividing by the daily load, giving the standard battery capacity, **B_{cap}/L_{day}**. The allowable depth of discharge (DOD) limited the amount of battery discharges, **$B_{gain.}$** Other input parameters included the battery charge-discharge efficiency, the solar PV reference and inverter efficiency, the maximum battery charging current and the maximum depth of discharge (DOD_{max}). The daily load, L_{day} together with its hourly distribution was also an input and load-shedding schedule for the project area (Hove and Tazvinga, 2000). Economic parameters, such as the lifespan of system components, their initial costs, the maintenance costs relative to capital costs, the fuel and electricity price and the discount rate were entered.

Project capital costs, including cost of system components and their replacement period, maintenance parameters, project running costs and economical parameters, were obtained from feasibility studies (Practical Action, 2011) and online platforms, such as Civic Solar (Civic Solar, 2017).

Battery storage was required to smoother the high fluctuation of the discrepancy between the supply and demand, the worst case being the time in which irrigation pumps would be on in a cloudy autonomous day. To size the battery storage capacity, graphs of cumulative consumptions against time and cumulative solar PV generation against day time were plotted, superimposed and analysed to get the maximum deficit and maximum surplus power. The total maximum deficit and surplus provides the storage that was divided by the allowable depth of discharge (obtainable form the battery manufacturer). The result was further divided by battery discharge efficiency (0.85) and multiplied by the daily critical load to provide the minimum required battery storage.

The size combinations of PV array and battery capacity achieving different levels of power supply reliability were determined. Systems achieving higher levels of reliability required larger battery sizes for the same PV area size than those achieving lower reliability. The required battery capacity ($\mathbf{B_{cap}/L_{day}}$) achieving a given level of reliability generally reduces with the PV array area ($\mathbf{A/A_o}$) provided, but marginal reduction reduces as the PV array area is increased.

Certain combinations of battery capacity and solar array size resulted in the least LCOE. This was taken as the optimum system design of the solar-battery system for the load profile, the given load shape, economic parameters and solar and ambient temperature climate. The LCOE was used as the objective function to select among systems obtaining the same level of reliability, i.e. the system with the least LCOE was selected that achieved a given level of supply reliability. Comparisons were made on the dimensionless size of battery and PV array required achieving a desired level of reliability at minimum LCOE together with the corresponding LCOE, for the reliabilities ranging from 90% to 100%. From this, a decision was then made of which system to invest in at a certain level of reliability and the implying levelised cost of energy from that system.

A plot of LCOE/Reliability against Reliability gave the optimum point with coordinates, giving a system that meets the constraints at the minimum cost. This was the point were much benefits (high reliability) were derived from the power system at the least-cost. The dimensionless parameters from the model were then used to calculate the actual system parameters; required PV array area, array peak power, battery capacity and inverter size.

Given the daily load L_{day}, required reliability and PV module reference efficiency, the PV array size was obtained as required component dimensionless sizes:

$$A/A_O = xx; \quad AND \quad B_{cap}/L_{day} = xx \tag{2}$$

Given the daily load L_{day}, required reliability and PV module reference efficiency, the PV array size was obtained as required component dimensionless sizes:

$$A_O = \frac{L_{day}[Wh]}{\eta_{ref} \times 1000 \left[\frac{W}{m2}\right] \times 24[hour]} \tag{3}$$

The number of modules required were found by dividing the total power output by the chosen PV module as:

$$Peak\ Power_{total}/Module\ W_p \qquad 4)$$

The number of modules in series were found by dividing the system voltage by the module voltage at maximum power:

$$System_{voltage}/Module\ Peak_{voltage} \tag{5}$$

The number of modules in series were calculated. However, these were dependent on the type and specifications (number of strings input the invert can accommodate per string) of the PV inverters to be used. The dimensionless battery size parameter, B_{cap}/L_{day}, which were equal to the ratio of battery energy capacity, B_{cap} [Wh], to the stated daily load, L_{day} [Wh] were used to calculate the actual required battery size as:

$$B_{cap}/L_{day} = xxWh \tag{6}$$

Batteries required by the systems were given as;

$$\text{xx}\ (2V \times 1000\ AH)\ Batteries \tag{7}$$

The inverter was sized according to the obtaining peak power as demanded by the loads. To obtain the power rating that can be matched with the inverter capacity, the peak power demand from the loads was multiplied by a factor of 1.2 to account for system losses and unplanned surges.
Therefore, the rated inverter power was found by:

$$= \quad Peak\ power \times 1.2 \qquad (8)$$

RESULTS AND DISCUSSION

Load forecasting technique was used to predict the instantaneous power and energy requirements for a typical urban settlement known as Madokero Community cluster houses for possible power supply from the solar power plant under consideration. Using shared resource data, the expected and planned loads where assessed using the planned number of apartments and economic activities with the bulk of the information coming from Madokero Community cluster houses project developers. The accuracy of forecasting, basing on the expected apartments and economic activities, was of great significance for the operational planning and designing of the power plant.

Table 1: Load Matrix of Madokero Community Complex

Call #	Equipment	Quantity	Power Rating (W)	Total Power (W)
A	Energy saver lights	168	5	840
B	Refrigerators	32	250	8000
C	Security flood Lights	20	18	360
D	Fluorescent lights	28	12	336
E	DVD/decoder	30	20	600
F	LED TV	22	80	1760
G	Cathode Ray TV	15	150	2250
H	Low power radio	30	5	150
I	High power radio	10	80	800
J	Latten Charging	280	5	1400
K	Computer	12	120	1440
M	Other Equipment	20	200	4000
N	Auxiliary Usage	4	1200	4800
O	Business	4	4000	16000
P	Amenities	4	4000	16000

A prediction of future demand for energy by the load centres was carried out using a demand matrix. The forecasting referred to the prediction of probable energy demand for services based on the observed and past events trends. The task of predicting future time series from random past observations and experience is ubiquitous in energy systems.

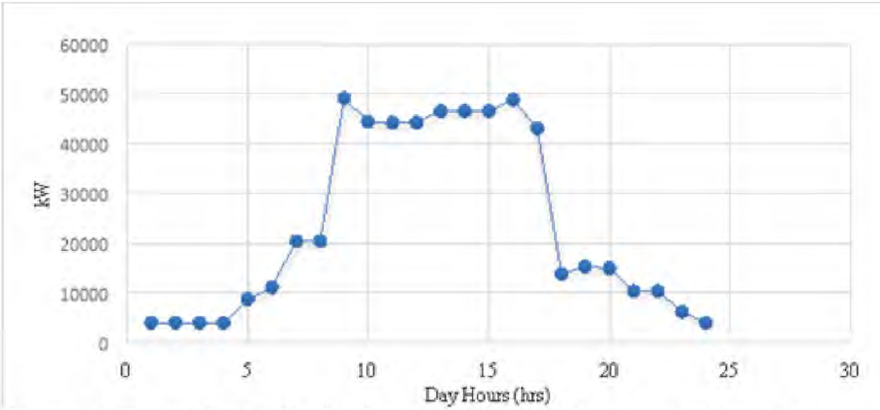

Figure 1: Typical Load Profile for the Madokero Community Complex

Despite their ubiquity and complexity, a demand matrix for the expected loads for the Madokero cluster houses was ultimately employed as "point forecast" in determining the specific maximum demand at each hourly interval, thus, leading to a daily load profile as shown in Figure 1. Care was taken to predict the usage behaviours basing on past referenced studies. The maximum demand for the community was estimated to be approximately 50 kW (shown by the peak on the graph) that was projected to occur mostly during mid-morning and mid-afternoon.

The load analysis provided an opportunity to proffer system design dimensions that aimed at providing dependable and reliable energy supply at the least-cost. Ideally, a system with 100% reliability would meet the needs of the urban settlement regardless of the extenuating weather conditions. Such a system would require to be grossly oversized, hence, the capital cost required to achieve such a fit will be enormous. The sheer sizes of the equipment and materials for such a system will be so much that much land clearing and civil works would be required. Internationally, 100% reliability is reserved for telecommunication installations and critical infrastructure that require a constant and reliable power supply. Considering the nature of the Madokero cluster house loads potentially under power supply from the PV generator, the benefit offered by the 100% reliability system was far outweighed by the capital costs required to achieve such a feat, hence, in determining the optimum system that was able to meet the energy constraints at the least-cost, the following stages were carried out.

To determine the size of the solar generator components, a design space was created. In the design space, different systems were dimensioned by way of simulating the hourly power supply flows and matching them with the hourly load profiles until a desired level of energy supply reliability was achieved. A plot of iso-reliability curves gave out the detailed design space. Each curve showed the design space (array and battery size) by use of dimensionless parameters which achieved the given reliability.

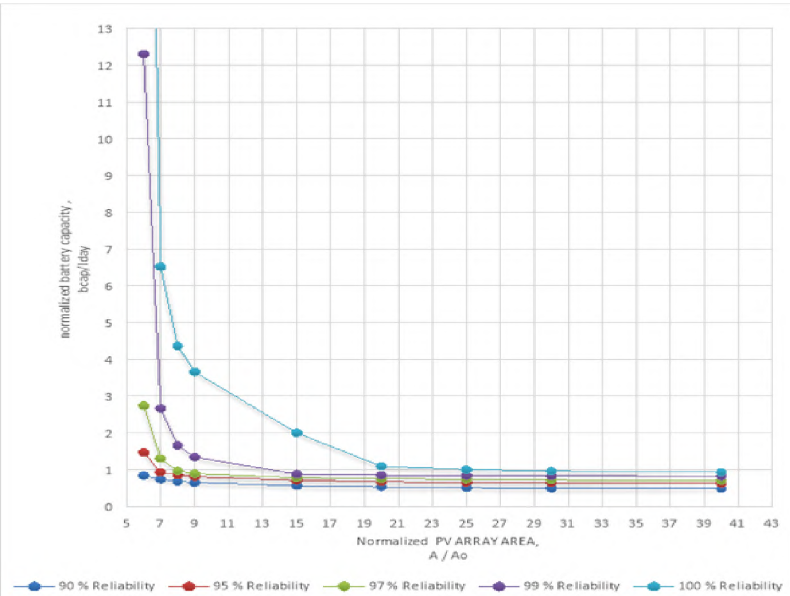

Figure 2: Design Space for different PV-Battery Configurations with respective reliability percentage

Using the Excel-generated model, the solar generator inputs included the PV array and battery size dimensionless parameters, A/A_0 and B_{cap}/L_{day}, respectively. The different size combinations of PV array and battery capacity which achieved given levels of power supply reliability are shown on in Figure 2. The figure showed the locus of points representing the dimensionless PV array and battery capacity obtaining from given supply reliability. A decision could not be made solemnly on the combinations that gave the desired reliability and power output without factoring in and considering the cost of the energy. To consider the cost impact on the design, a design space for different array area combinations with respective LCOE at different PV system reliability was carried out, with the results presented in Figure 3.

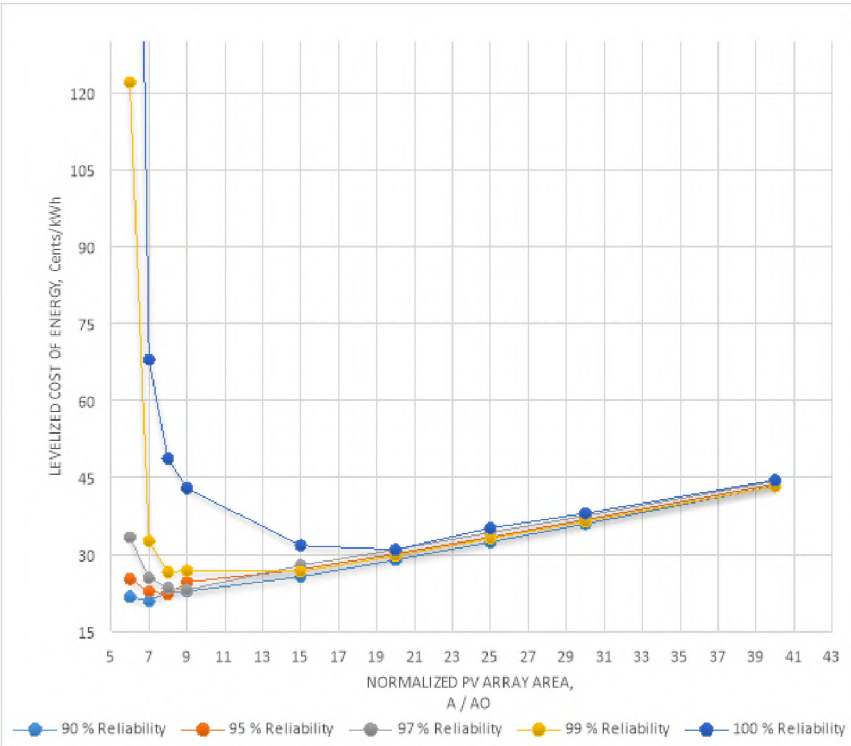

Figure 3: Design Space for different Array Area combinations with respective LCOE at different PV system reliability

It was observed that systems achieving higher level of reliability required larger battery capacities for the same dimensionless area size as compared to those achieving lower reliability. Thus, the required normalised battery capacity (B_{cap}/L_{day}) that achieved a given level of reliability was observed to generally reduce with the PV array area (A/A o) provided. Marginal reduction of the battery capacity reduced as the PV array area was increased.

From the discussion and plot in Figure 3, the levelised cost of energy for system designs achieving the same level of reliability were observed to vary with PV array-battery size combinations. The relationship (design space) between the dimensionless PV array area and the respective levelised cost of energy are also shown in Figure 3. It was deduced from the graph in Figure 3 that certain combinations of battery capacity-solar array area results in the least LCOE. Using engineering institution and by direct observation, values at the elbow of the graph for each reliability were taken as the optimum design parameters as presented in Table 2. The dimensionless sizes of battery and PV array required to achieve a desired level of reliability with a minimum levelised cost of energy are shown in Table 2.

Table 2: Design Space

Reliability	A/A_o	B/B_{cap}	LCOE
90%	7	0.74	0.2087
95%	8	0.85	0.2227
97%	9	0.89	0.2314
99%	8	1.66	0.2653
100%	20	1.09	0.3094

A plot of (LCOE/Reliability) against (Reliability) as shown in Figure 4, gave the optimum point with coordinates, giving a system that meets the design constraints at the least-cost. This was the point were much benefits (high reliability) can be derived from the power system at the least-cost.

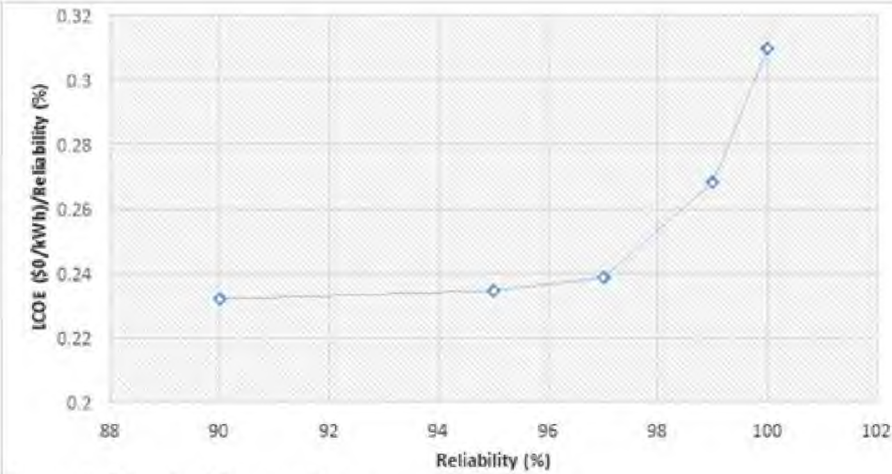

Figure 4: Marginal Return Curve

The graph was used as a decision matrix in deciding a system combination that would offer the most benefits at the least-cost. As discussed before, the study demonstrated that reliability usually increases with the cost of energy delivery , however this relationship was found not to be perfectly symmetric, that is, sometimes, the magnitude of the increment in reliability as a percentage does not correspond to the magnitude of increment in the cost of energy delivery (LCOE).The graph shows that as reliability increases from 90% to 97%, the LCOE (as represented by the ordinate (LCOE/Reliability)) does not increase much (same as reliability as a percentage), however, from the ordinate where reliability is 98% there was a marked increase in LCOE (not symmetric) as reliability level was increased. Thus, it can be concluded that 97% offers the most benefits at the least-cost.

Dimensionless size of battery and PV array required to achieve desired reliability of 97% at minimum LCOE were chosen from the "elbow" values as discussed from Figure 2 and Figure 3. For values of array normalised area to the left of the elbow, there was a marginal increase in the levelised cost while for values right of the elbow there was relatively lower LCOE costs and hence, the most optimum design parameter A/A_o was obtained at the "elbow" that was then matched to the corresponding dimensionless parameter $B_{cap}/Lday$.

Table 3: Dimensioning Decision

Reliability	A/A_o	B/B_{cap}	LCOE ($/kWh)	Capital Cost
97%	9	0.89	0.2314	**$225 506**

The dimensionless size of battery and PV array required to achieve a desired 97% level of reliability at minimum LCOE is shown in Table 3. The table was used to make a design decision that was used to then specify the system for bidding.

The dimensionless parameters from the model were then used to calculate the actual system parameters; required PV array area, array peak power, battery capacity and inverter size. The general observation made was that as battery size increases, the initial system capital cost increases but the life of the battery also increases. Therefore, the battery will be replaced less frequently. For a smaller battery size, the initial capital cost was usually lower but the battery would be replaced more frequently (Hove, 1999; Hove and Tazvinga, 2000; Hove and Mushiri, 2016), and, therefore, the size can be best analysed and determined through economic analysis beyond the scope of this study.

The sizing and operational parameters that can be adopted for a specific level of PV system reliability, load shape and prevailing economic parameters for a plant within the solar resource contour as put forward is suggested as in Table 4.

Table 4: Design Space for different Combinations

	Reliability	Current	90%	95%	97%	100%
Sizing Parameters	**Units**					
PV Array Power	kW	102.000	164.934	188.495	212.057	471.239
Battery Size	kWh	287.833	418.460	480.663	503.283	616.380
Inverter Size	kW	100	58.848	58.848	58.848	58.848
Operational Parameters						
Solar Fraction	%	74	90%	95%	97%	100%
Battery Life	Years	5.000	5.000	5.000	5.000	6.000
Dumped PV Energy	%	10%	31%	36%	42%	73%
Economic Parameters						
Capital Cost	$	132890	187336	210380	225506	364757
LCOE	Cents/kWh	18.2	20.9	22.3	23.1	30.9

Table 4 provides an understanding of the different system combinations that achieved different levels of reliability with the associated economic and operational parameters. To achieve 90% system reliability for the Madokero Community cluster houses, an initial capital of $187 336 was required with the resultant energy having a levelised cost of $0.209/kWh. More than 30% of the energy will be dumped (not useful for the system) that is a remarkably high percentage. As demonstrated in Table 4, it followed that, to achieve higher levels of reliability the system needed to be seemingly oversized to cater for the variability of the solar resource and load conditions.

CONCLUSION

The study demonstrated a reliable method for designing and sizing community type Solar PV plants with battery storage. Different systems component matching relationships were analysed and the most economical and feasible way of determining the right combinations was proposed. From the discussions, the solar array power for 100% system reliability was approximately twice that for the 97% reliability system. It, thus, showed that as the level of reliability reaches unit factor, high component sizes were required to achieve optimum levels of reliability, as opposed to when reliability levels were nominal. As expected, the investment cost for systems with different reliabilities went up with the increase in the level of reliability desired. Thus, the relative sizes of components were found to have an implication on the capital costs of the systems. Capital cost was very high for the 100% reliability system though it was found more satisfying. In the Zimbabwean urban context, since the capital and operational items are important, it was difficult to judge which of the systems presented would be better from an economical point of view at the study stage as other issues to do with the proposed use of the energy, business models, agricultural commodity prices were beyond the scope of this research. However, from a technical point of view, designing a 97% reliability system would offer unmatched benefits for the Madokero Community cluster houses. From an environment point of view, the design, regardless of which level of reliability that may eventually be chosen, appeared to offer immense environmental related benefits that aid to address energy access issues, whilst at the same time, mitigating climate-related issues.

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