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An economic analysis of a stand-alone solar system for an off-grid village shop in Majwanaadipitse, Botswana

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Abstract
Electricity is one of the main requirements for sustainable development and the improvement of living standards for different nations. Remote areas in Botswana depend in the use of fossil fuels e.g., petrol, diesel and natural gas to produce electricity. However, the villagers encounter high fuel price from buying fossil fuels. On the other side, combustion of fuels creates air pollution that contributes to global warming which is accountable for climate change and disastrous effects. This is a study that explores replacing the fossil fuel used by a village shop in Majwanaadipitse, Botswana (22˚ 6' 50″ S, 26˚ 53 0″ E) with an off-grid PV system. This was done by designing, sizing, estimating the contribution to pollution by the fossil fuels and costing an off-grid solar PV system. The estimated energy requirement of a village shop was found to be 7.97 kWh/day. The design and sizing of the PV system equipment's depended on the estimated load. The proposed off-grid PV system required 5 PV modules each rated 330 W, 5 batteries each rated 100Ah, a charge controller and an inverter. The system capacity of an off-grid PV system to be installed was 1.6kW_p. The emitted pollution into the atmosphere to be avoided was found to be 2882 Kg of carbon dioxide per year. The payback period of the PV system was estimated to be 2 years. The NPV was also found to be favorable, showing that it is a profitable investment with a cost of P653 880. It The study revealed that an off-grid PV electricity is technically and economically feasible for electrifying a shop compared to the use of fossil fuels.

Keywords: Electricity, Majwanaadipitse shop, Botswana, off-grid photovoltaic (PV) system, pollution, net present value (NPV)

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1. Background and Motivation

The United Nations Sustainable Development Goals (SDGs) of 2015 include goal No. 7 which unequivocally recognizes how access to affordable, reliable and modern energy is central to achieving economic growth and human development while ensuring a sustainable environment. More than a billion people live without access to electricity in developing countries according to energy access outlook 2017 (1) (2). Energy has long been considered as one of the key fundamentals of modern life and if one does not have energy, then they are poor (3). Absence of energy influences individuals from numerous points of view, students have less hours to study, medical clinics and facilities have no light to see patients and independent small business cannot power electronic gadgetry (4) (5). In Botswana, there are many villages in the rural areas that are without electricity as they are located far from the national electricity grid (6) (7). Clearly not all villages will be connected to the grid in the short term as such the use of alternative energy sources such as solar PV system emerges as the best solution. Solar photovoltaic is an innovation that changes sun's radiation into usable direct current (DC) power by utilizing the use of semi-conductors. It is one of technologies that can shape a clean, reliable, and affordable electricity systems for the future (8). This alternative source of energy is well supported by the fact that Botswana has a gigantic potential to wander into the utilization of solar energy. As it encounters yearly a direct normal light equivalent to 3000 kWh/m^2/a (6). Furthermore the use of solar PV system to replace fossil fuels has a positive impact on the environment (i.e., it helps to reduce CO_2 emission, generates no noise, and has positive health benefits) .It also helps to minimize the risk of global warming which is accountable for climate change and its disastrous effects (9), as well as to reduce depletion of fossil fuel (10).

2. Description of case

As pointed out earlier, access to electricity in remote villages is a challenge. Mr. Ontireletse Rebagamang is a sole trader operating a village shop in Majwanaadipitse village. He is currently using a generator and LP gas as sources of energy for his requirements. He has to procure these sources of energy from the nearest town of Serowe and in the process incurs further transport costs. The fossil fuels he uses in the form of petrol and gas for his energy requirement poses a big threat to health and environment He is not happy with his energy expenditure and complains that his income is being eroded as a result. As such Mr. Ontireletse Rebagang is keen to switch to a stand-alone solar PV system as an alternative. A need has therefore arisen to design and cost an appropriate solar PV system for Mr. Rebagamang and carry out an economic analysis that convinces him that he is indeed better off switching to solar energy. The off-grid PV system to be designed is to be installed in Botswana, Majwanaadipitse village shop (22° 6' 50″S, 26° 53' 0″E), bearing in mind that the PV system if designed well will minimize the cost compared to the use of fuel and LPG gas. Also, PV system if installed well will provide energy requirement for Mr. Ontireletse Rebagamang's shop at a lower cost as opposed to fuel and LP gas.

3. Experimental description

3.1 Load assessment

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The load assessment involved finding out the daily load demand of the electrical appliances in the shop in ampere-hours (Ah). This was done through the following steps:

- All electrical appliances used at the shop (inside and outside) were listed down.
- The power ratings (wattages) of the individual appliances were noted.
- Special attention was given on whether an appliance was AC or DC.
- The hours of operation per day for each item were also noted

Table 3.2 Contains a list of electrical appliances at the shop, their daily hours of operation, rated power and the energy used by each of them on a typical day.

Table 1. Load Profile of the Appliances

Electrical Appliance	Operation Hour/day	Quantity	Rated power (W)	kW	KWh/day
Bar Fridge	6	1	320	0.32	1.92
Bar Fridge	7	1	320	0.32	2.24
Lights (CFL) indoor	5	3	15	0.045	0.225
Lights (CFL) outdoor	11	5	15	0.075	0.825
Radio	7	1	220	0.22	1.54
Tv	4	1	130	0.13	0.52
Smart Switch Machine	4	1	40	0.04	0.16
Phone Chargers	4	5	6	0.03	0.12
Long single twin tube CFL bulb	5	1	24	0.024	0.12
Small radio	6	1	50	0.05	0.30
Total	78	30	1140	1.254	7.97

Note: All electrical appliances were AC type

From the calculations of the energy load, it was found that the energy requirement of the village shop was 7.97 kWh per day.

3.2 PV system design and sizing

System sizing is a technique for determining enough voltage and current ratings for each component of the PV system, meeting the shop's electrical demand and, at the same time, calculating the total system cost from the design process to the operational of the system. The process involved calculating the system specifications e.g. battery bank, PV array, inverter etc. using the daily electrical load demand.

3.2.1 Selection of system voltage

Selecting the DC system voltage depends on different factors some of them being (11).

Peak load

- 12VDC is fine for peak loads up to 1000W
- 24VDC is good for peak loads up to 2000W
- 48VDC is best for peak loads over 2000W

The complete daily AC load is over 2000W, with 48VDC being the chosen voltage.

3.2.2 PV array sizing and selection of PV module

PV array is several PV panels electrically connected to convert sunlight rays to electricity. The size of the PV panel is calculated by considering the solar insulation available, the daily load requirement and the features of the PV modules.

The size of the PV array used for the project can be calculated as (12):

$$\text{System Capacity} = \frac{E_d}{G} \quad (1)$$

$$= \frac{7.97kwh}{6.2PSH} \times 1.25 \text{ (energy lost in the system)}$$

$$= 1.607\ kW_p$$

1607 is the minimum PV array watts. The module rated power used was 330 W

Number of needed PV module is given by:

$$\frac{System\ Capacity\ W_p}{\text{Module Rated Power } W_p} \quad (2)$$

Table 2. shows details of the PV module selected.

Table 2. Details of the PV module chosen

Brand and Model	Sunergy, SUN330-60M

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Maximum Power P_{max} (W) At STC	330
Cell type	Mono crystalline module
No of cells	60 (6×10)
Dimensions (length, width, height)	(164 × 99 × 3.5) cm
Weights	19 Kg
Short circuit current I_{sc} (A) At STC	9.35
Open circuit voltage V_{oc} (V) At STC	38.2
Maximum power current I_{mp} (A) At STC	8.72
Maximum power voltage V_{mp} (V) At STC	32.1
Module efficiency	17.25
Max system voltage	1000 V DC
Operating temperature At STC	-45℃~+ 85℃

3.2.3 Battery bank sizing and selection

During the day, batteries store energy produced by the solar array and satisfy electricity requirements during the night and after successive rainy days. Battery size is a design variable usually based on the required period of autonomy, the maximum allowable depth of release and the low operating temperature. The battery's storage capacity is displayed in ampere-hours. The battery selected must be able to achieve greater depth. The permissible discharge depth for this application is 0.8 (11).

3.2.4 Battery sizing

The following formula is used to calculate battery storage capacity requirements

The daily load demand L_d in ampere-hours (Ah) (12):

$$L_d = \frac{E_d}{DODV_{nsv}} \quad (3)$$

3.2.5 Battery bank capacity:

$$C_{batt} = \text{daily battery capacity demand} \times DOA \quad (4)$$

Specification of battery

Capacity of the battery chosen is of 100Ah and nominal voltage is 12 V.

3.2.6 Number of batteries is given by (12):

$$\text{Number of batteries} = \frac{storage\ capacity}{Capacity\ selected} \quad (5)$$

Number of batteries in series is obtained by:

$$N_s = \frac{\text{system voltage}}{\text{battery voltage}} \quad (6)$$

Number of batteries in parallel is obtained by:

$$N_p = \frac{Number\ of\ battery}{N_s} \quad (7)$$

3.2.7 Charge controller design and selection

Regulates the voltage and current from the battery-powered PV panels, prevents overloading of the battery and extends battery life (11). The voltage regulator size can be acquired by multiplying the short circuit current of the horizontally linked modules by a safety factor. It can be calculated as follows (12):

The rated current of the regulator is given by:

$$\mathrm{I_{rated}} = N_{mp} \times I_{sc} \times F_{safety} \quad (8)$$

$$= 5 \times 9.35 \times 1.25$$

$$= 58 \text{ A}$$

Number of voltage regulator is given by:

$$\text{Number of voltage regulator required} = \frac{I_{rated}}{I_{selected}} \quad (9)$$

3.2.8 Inverter design and selection

The inverter used must be capable of handling the highest anticipated energy of AC charges. It must also be at least 1.25 times the solar wattage maximum. In the scheme where AC Power is required, an inverter is used (11).

Therefore, the rated power of the inverter becomes:

= (5× 330W) × 1.25 = 2062.5 W

=2.06 kWh

The specification of required inverter will be 3000W, 12V, 100V and 50Hz

3.2.9 Determination of the system cables sizes:

Choosing the right size and sort of wire will improve a PV system's efficiency and efficiency (11).

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$$I_{rated} = N_{mp} \times I_{sc} \times F_{safety} \tag{10}$$

$$=5\times 9.35 \times 1.25$$

$$= 58 \text{ A}$$

And the cross-sectional area is given by (11):

$$A = \frac{\rho L I}{V_d} \times 2 \tag{11}$$

Where ρ = resistivity of copper wire which was taken as 1.724×10^{-8} Ωm. For Ac and Dc, the wiring for off-grid PV system the voltage drop is taken to exceed 4% value.

Determination cable size between for PV modules through the battery voltage regulator

Maximum voltage drop

$$V_d = \frac{4}{100} \times 48 = 1.92v$$

Let the length of the cable (L) = 1m

Therefore $A = \frac{\rho L I}{V_d} \times 2$

$$A = \frac{1.724 \times 10{-}8 \times 1 \times 58}{1.92V} \times 2$$

$$= 2.08 \text{ mm}^2$$

Determination of cable size between battery bank and inverter

Let length of cable (L) = 3.5m, therefore maximum current from battery is given by (11)

$$I_{max} = \frac{inverter\ capacity}{\eta_{\text{inverter}} \times V_{system}} \tag{12}$$

$$= \frac{1000}{0.95 \times 48}$$

$$= 21.9 \text{ A}$$

Maximum voltage drop $V_d = \frac{4}{100} \times 24$

$$= 0.96\text{v}$$

$$A = \frac{1.724 \times 10{-}8 \times 3.5 \times 21.9}{0.96} \times 2$$

$$=2.75 \text{ mm}^2$$

Table 3.7 below shows a summary of the proposed sizing of an off-grid system

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Table 3. Summary of the proposed sizing of an off-grid PV system

Components	Description	Results	Cost (Pula)
Load estimation	Total estimated load	7.97 kWh/day	
PV array Model: Renewsys Solar panels	Capacity of PV array	1.6 kW	11 500
	Number of modules in series	3	
	Number of modules in parallel	2	
	Total number of modules	5	
Battery Bank Model: freedom Battery	Battery bank capacity	416 Ah	41 290
	Number of batteries in series	4	
	Number of batteries in parallel	1	
	Total number of batteries required	5	
Victron Energy Voltage Regulator	Capacity of voltage regulator	58A	2 300
	Number of voltage regulator required	1	
1.5kVA Victron Energy Inverter	Capacity of the inverter	2.06 kW	6 003
Wire	Between PV modules and batteries through the voltage regulator	2.08 mm^2,58A	2000

	Between battery and inverter	2.75 $mm^{2,}$ 21.9A	
Balance of system			3 400
Labour			1 800
		Total Cost	68 093

3.3 Cost benefit analysis of the solar PV system

Table 1. shows that in a day a village shop requires 7.97 kWh per day of energy. Thus, for a year the solar PV system will provide 95.64 kWh of energy. The working life span of a solar PV systems averages between 20 to 25 years. The average value of 25 years working life span was used in this project. The cost of fossil fuel used in a village shop was P28 500. The energy efficiency factor for a standard petrol generator was found to be 0.935. The cost of fossil fuel was adjusted using the efficiency factor of 0.935 and recorded in **Table 4.** The following **Table 4** shows the cost involved in using fossil fuels to provide a village shop with electricity.

Table 4. Shows annual energy requirement for a village shop with respective bills for using fossil fuels.

Village shop Annual energy (kWh)	Annual bill (P)	Inefficiency factored annual bill (P)
95.64	28 400	30 246

A cost-benefit analysis of a village shop in Majwanaadipitse to switch from using fossil fuels to using solar PV system is performed here. The maintenance costs for the system in this project was P700 for a year. The Net Present Value (NPV) and internal rate of return (IRR) were computed utilizing the aggregate money streams for the 25 years. Annual inflation rate in Botswana arrived at the midpoint of 4.3 percent from 2013 until 2016 (13) and this is the rate utilized as a part of this investigation. Avoided electricity costs of the year under consideration year (C_{av}) are calculated by applying the annual inflation rate to the previous year's avoided electric bill (C_{py}) as captured in the formula:

$$C_{av} = C_{py}(1 + i_{an}) \quad (13)$$

Where i_{an} is annual inflation?

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Fossil Fuel	Quantity	Total Pollution of carbon dioxide
Petrol	960 litres	2208 kg
LP gas	228 kg	674 kg
	Total Pollution from fossil fuel	2882 kg

The annual cash flow is the energy cost that a shop is avoiding paying every year by having invested in the use of solar PV system; it is essentially the avoided electricity costs. The NPV (PV_n) of an annual cash flow is calculated using the formula:

$$PV_n = \frac{C_{av}}{[1+i_n]^n} \tag{14}$$

Where i_n the interest rate is for the period n, the interest rate in Botswana is 5.5 percent and this rate is used in the study.

3.4 Fossil fuel cost of petrol for a shop and litres used

The following table shows the cost of fossil fuel used by a village shop, it also shows amount of fossil fuel used per year and total emission of carbon dioxide.

Total cost of fossil fuels per year is given by:

Cost of petrol per year + Cost of LP gas per year

P 24 000 + P 4400 = P 28 440

3.5 Results

The cost benefit analysis was done using P 68 293 as the system cost and P 30 246 as the annual bill for a village shop. The results were presented in **Table 5.**

Table 5. Shows annual energy demand for solar PV system and the respective bill for a village shop in Majwanaadipitse.

Year(n)	System Cost (P)	Avoided Bill (P)	Annual Cash-Flow (P)	NPV of Annual Cash-Flow (P)	Cumulative NPV (P)
0	68293.67	0	68293.00	68293.67	68293.67
1	0	31546.58	31546.58	29901.97	38391.70
2	0	32903.08	32903.08	29561.85	8829.85
3	0	34317.91	34317.91	29225.60	-20395.76
4	0	35793.58	35793.58	28893.18	-49288.94
5	0	37332.71	37332.71	28564.54	-77853.47
6	0	38938.01	38938.01	28239.63	-106093.11

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7	0	40612.35	40612.35	27918.42	-134011.53
HIDDEN CALCULATIONS					
20	0	70202.75	70202.75	24060.52	-469328.04
21	0	73221.47	73221.47	23786.84	-493114.89
22	0	76369.99	76369.99	23516.28	-516631.17
23	0	79653.9	79653.90	23248.80	-539879.96
24	0	83079.02	83079.02	22984.35	-562864.32
25	0	86651.41	86651.41	22722.92	-585587.24
Totals	68293.67	1368159		653 880	

Table notes

Annual Inflation	4.3 %		NPV	P 653 880
Interest Rate	5.5 %		Payback Period	2 Years
Base Annual bill	P 30 246		Avoided Bill	P 1 368 159
IRR	50.49			

3.6 Estimation of pollution caused by fossil fuels

3.6.1 For Petrol

The complete combustion of hydrocarbon fuel is given by the equation below (14):

$$\text{Fuel } (C_xH_y) + O_2 + \text{Spark} \longrightarrow H_2O + CO_2 + \text{Heat} \quad (15)$$

From the above equation, carbon dioxide is the waste produced

Carbon dioxide waste equation is given by:

$$C + O_2 \longrightarrow CO_2 \quad (16)$$

Carbon has an atomic weight of 12 while oxygen has 16 (14). The molecular weight of carbon dioxide is given by:

= (1 Carbon atom + 2 Oxygen atom)

= 12 + (2×16)

= 44

Therefore:

1 litre of gasoline produces 2.3 kg of carbon dioxide (14). As such 960 liters of petrol used for a village shop will give:

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= 2.3 of carbon dioxide × 960 litres of petrol

= 2208 kg for a year into the atmosphere

3.6.2 For LP gas

Emission factor for LP gas is given by 1.51

LP gas Unit Conversion Formulas (Metric): (LP gas unit conversion of kg to litres is 1kg = 1.96L). Therefore 228 kg gives us 446.88 litres. We then multiply the emission factor by litres used

= 1.51 × 446.88 L

= 674 kg emission into the atmosphere for a year.

3.6.3 Total emission caused by fossil fuels is given by:

Petrol emission + LP gas emission

=2208 kg + 674 kg

= 2882 Kg of carbon dioxide is caused by fossil fuel used in a village shop into the atmosphere per year

4. Discussion

The purpose of this thesis was to provide a village shop in Majwanaadipitse, Botswana (22˚ 6 ' 50˝ S, 26˚ 53' 0˝E) with an energy throughout the whole year by designing, sizing and costing an off-grid solar PV system to replace fossil fuels.

In **Table 1.** the estimated energy requirement of a village shop was found to be 7.97 kWh/day.

The proposed off-grid PV system required 5 PV module rated 330 W, 5 batteries of 100Ah 12V nominal voltage, charge controller and inverter to power a village shop in Majwanaadipitse. The system capacity of a stand-alone PV system to be installed was 1.6 kWp.

Table 3. shows PV system components required for a proposed stand-alone system it also includes installation cost, maintenance cost, accessories, and total cost of P68 093. The total cost of the system is affordable if Mr. Ontireletse Rebagamang saved money for a year from fossil fuels.

In section 3.6 the amount of emitted pollution into atmosphere was found to be 2882 Kg of carbon dioxide per year. This implies that by installing stand–alone PV system the risk caused by pollution will be minimized.

The Net Present Value was also found to be favorable, showing that it is a profitable investment with a cost of about P653 880. This shows that the costs of the project are outweighed by the benefits because after 2 years, the project will have paid itself back and up to the 25^{th} year shop owner Mr. Ontireletse Rebagamang will enjoy free energy for the shop. The shop owner avoids paying an electric bill of P 1 368 159 over the 25 years by installing a solar PV system.

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The payback period of the PV system was estimated to be 2 years, which is shorter than the life span of selected PV modules which is 25 years. The Net Present Value was also found to be positive, showing it's a profitable investment with a value of about P653 880. This is indicated by the fact that the Botswana interest rates fluctuate at around 5.5%, which is always lower than the internal rate of return of the system valued at 50.49%.

5. Conclusion

Compared to the use of fossil fuels, it is concluded that stand-alone PV electricity is technically and economically viable to electrify a store. Majwanaadipitse stand as a best place for installing a PV system, to produce electricity for daily requirements. This is well supported by the fact that it gets plenty of solar energy around 6,211 kWh / kWp per day, making the PV system efficient. The installation of a solar photovoltaic system will therefore go a long way in eliminating the risk of pollution caused by fossil fuels, as it will not release any dangerous gas. By replacing fossil fuel with off-grid PV system after 2 years, the project will have paid itself back and up to the 25th year shop owner Mr. Ontireletse Rebagamang will enjoy free energy. The shop owner will avoid paying an electric bill of P 1 368 159 over the 25 years by installing a solar PV system.

5.1 Future Work

It is recommended that the proposed off-grid PV system to be installed in Majwanaadipitse to open access to others to venture into the use of solar energy. A PV simulator software may be used for verification of results before installing.

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Nomenclature

PV = Photovoltaic

E_d = Electrical load

G = Solar irradiation

W_p= Watts peak

DOD= Depth of discharge

DOA = Days of Autonomy

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