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Analysis of energy potential for grid-tied solar energy systems for medium industrial applications

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ABSTRACT

This research investigated the potential of using solar photovoltaic (PV) energy to support small-to-medium size industries without the need for energy storage. The peak industrial production hours from morning to evening were investigated and the average daily power required was compared with the available solar power, in order to determine the amount of power that can be recouped from solar-grid hybridization over one year. The available zero-upfront cost plans in Kenya were investigated and the payback rate and benefits to both the buyer and the investor were analyzed. The peak hour power demand and solar potential were compared to determine to what extent battery elimination can be used efficiently during production. The solar power without batteries was found sufficient to be used interchangeably with utility power maximizing on the times of peak solar power. The purpose of the derived report is to help in saving running costs since the cost of battery banks can be partially eliminated and reliance on grid power can be minimized. It also helps an investor to make an informed decision on the zero-upfront cost plan. It was found that, on average, a saving of 8.9% is feasible, with a potential of 23% – 30% if the maximum dependence on PV is employed. The cost of the 15kW plant was found to be recoverable in an average of 10 years for the full power uptake.

Keywords: Enabling plan, Zero-upfront cost, Power demand, Solar potential, No-batteries.

INTRODUCTION

Solar energy harnessing and research work summary

Solar radiation produces a clean source of energy that can be a substitute for environmentally unfriendly energy sources such as diesel. A solar system makes use of visible light to produce electrical energy from silicon photovoltaic (PV) cells, as explained by Goetzberger *et al.* (2003). There are different technologies used for silicon solar cells. These include: Pure silicon (Ps), crystalline silicon (Cs) and amorphous silicon (a-Si). Solar panels are made up of multiple cells, mounted in parallel arrays, which can have a fixed orientation or track the sun.

Today, many power applications make use of solar power due to its advantages. Mostly, string inverters are used, which can be on-grid or off-grid, to convert direct current into alternating current. On-grid (grid tied) systems feed into the grid, hence they need to supply a voltage waveform whose frequency is identical to that of the grid. The inverter automatically disconnects when the grid is down.

On the DC side, maximum power point tracking (MPPT) optimizes power output by varying the closed loop system voltage (Sera *et al.*, 2006). Sumathi *et al.* (2015) explain how a grid-tied DC-AC converter circuit converts direct current into an alternating current suitable for feeding into the grid. A grid-tied solar system comprises a combination of solar panel arrays, MPPTs, inverter(s), a storage system and the accessories to interconnect them (known as the Balance of System, or BoS).

The use of photovoltaic cells for power generation in Kenya is faced with a high initial cost. A lot of research has been done and is still being done to get cheaper, environmentally friendly energy. Despite this, an ideal solution has not yet been reached. The storage system typically comprises battery banks which contribute the greatest percentage of the cost. Greenlog Solutions Ltd (2021) listed their updated prices of different batteries on their website, where the average cost of a single maintenance-free 12V 200 Ah battery in Kenya is KSh. 30,000 and for a 2V 1500 Ah battery KSh. 80,000. The average battery life cycle is 1000 cycles at 60% depth of discharge (DOD). This implies that the battery will have a life span of three years. This becomes very expensive. The cost of a complete solar system big enough to power a medium-sized industry is so high that the industries may not be able to afford it. Therefore, a comprehensive enabling environment is crucial. This is the rationale for employing a grid-tied solar system and an investigation of the possibility of full operation without energy storage.

If good research on business peak hours and available solar power is done, batteries can be eliminated in the system. This research was carried out in search of information on these issues. The zero upfront cost plan can also be employed to enable easy acquisition of a solar power harnessing system, but many people do not know how much they can save on solar power so that the savings can pay for the solar system.

This research was carried out to determine how sufficient solar energy can be generated to power day-to-day production with little utilization of grid power, without any battery storage. The study also sought to educate customers on whether or not to embrace the zero upfront cost plan, and which policy terms might be preferable. Factors to consider during PV system sizing were also investigated.

Solar cell performance

Solar cell efficiency of 20 – 22 % is currently achievable, with module and plant efficiency below this due to various system losses. These losses occur in almost every component. Franklin (2019) referred to these losses as derate factors. He explained that during system sizing, the general derate factor is determined as a product of all individual derate factors.

The output voltage of every solar cell is temperature-dependent. During array sizing, care is taken to ensure that the voltage variation with temperature change does not exceed the system. The temperature corrected maximum open circuit voltage, $Mod\ V_{oc\ max}$, for a single module is calculated using

$$Mod\ V_{oc\,max} = V_{oc} \times [1 + (T_{min} - T_{stc}) \times TKV_{oc}] \quad (1)$$

where T_{min} is the area minimum expected ambient temperature, T_{stc} is the standard temperature condition, TKV_{oc} is the temperature coefficient of V_{oc}.

The minimum temperature corrected voltage, $Mod\ V_{mp\ min}$, is calculated using

$$Mod\ V_{mp\,min} = V_{mp} \times [1 + (T_{add} + T_{max} - T_{sc}) \times TKV_{mp}] \quad (2)$$

where T_{add} is the temperature adder specific to the mounting system, T_{max} is the maximum expected ambient temperature, and TKV_{mp} is the temperature coefficient of V_{mp}.

Power purchase agreement (PPA) plans

The following options are available under Kenya's PPAs: The costing is dependent upon the plant output and the capacity charge, whereby the charge amount and period of payment is agreed upon by the seller and the policy buyer according to The World Bank Group (2021). The pay to own agreements of periods from 3 to 20 years and the full power uptake agreements were investigated. The findings for one year were speculated to develop a full time report as presented. The full power uptake was either in 10-years or 20-years period.

Table 1: Some of the available power purchase agreement plans.

DURATION (years)	3	5	7	10	20
Full uptake policy average kWh % saved	-	-	-	23.01	30.32
70/30%	4.89	5.50	4.87	5.68	10.77
60/40%	30.55	45.50	63.43	89.66	94.50
50/50%	30.45	31.01	29.66	31.32	30.21

Related Research

Shi (2017) investigated a data-driven approach to the projection of solar energy generation. He compared a Beta distribution, Weibull distribution, Log-normal distribution and Normal distribution. In the study, he found that Beta (a_1, b_1) distribution is the most accurate forecasting method. It is given by

$$f_{\tilde{a}}(\tilde{a}) = \frac{\tilde{A}(a+b)}{\tilde{A}(a)\tilde{A}(b)}\left(\frac{\tilde{a}}{\tilde{a}_{max}}\right)^{a-1}\left(1-\frac{\tilde{a}}{\tilde{a}_{max}}\right)^{b-1}$$

where γ denotes solar irradiance and γ_{max} is its maximum value, the beta parameters a_1 and b_1 are

$$a_1 = \mu\left[\frac{\mu(1-\mu)}{\sigma^2}\right]a_1 = \mu\left[\frac{\mu(1-\mu)}{\sigma^2}\right]$$

and

$$b_1 = (1-\mu)\left[\frac{\mu(1-\mu)}{\sigma^2} - 1\right]$$

where, μ is the mean value and σ is the standard deviation of solar irradiance.

Energysage (2009) they clarified the understanding of "free solar energy." The company explained that the term is used sometimes to advertise solar lease or solar power purchase agreements (PPAs).

Wasike (2015) studied the assessment of solar radiation potential of the Thika-Nairobi area, panel sizing and analyzed the system cost. From his study, he was able to show that Thika-Nairobi region has plentiful solar energy.

Kariuki (2018) investigated the obstructions to the development of clean energy technologies and found that a great distortion of the renewable energy market has been experienced in sub-Saharan Africa due to poor economic conditions. Initial capital, inadequate credit facilities and high transaction costs for renewable energy were concluded as the major challenges.

METHODS

- Data for solar radiation from the Global Solar Atlas for the geographical location of Fortis Industrial Park, Syokimau was used in the determination of the annual solar potential of that area.
- An energy audit, which entails power and energy data analysis, was conducted at the premises to examine the instantaneous energy demand for the institution and its possible energy savings through solar-grid power hybridization while prioritizing solar power. Comparative data was gathered through an examination of previous energy records.
- A selection of the available zero-upfront cost plans was investigated by visiting companies offering the plans and requesting plant quotations on the best terms they could offer. Energy generated and conserved data was also collected and analysed. Some of the already existing plans adopted by some companies were investigated as well. These costs were compared with the up-front acquisition and associated bank financing costs.
- The amount of energy saved by solar power generation was investigated to see if it could pay for the plant under the available policies.

Global solar atlas

This research was carried out at Solutions General Ltd which is found in Fortis Industrial Park, Syokimau, geographically located at -1.362872, 36.920109.

Solar resource data from the Global Solar Atlas as presented by Solargis (2020) were used to determine the solar energy potential. The monthly insolation data was retrieved from the live site data streaming using the geographical coordinates, time, duration of data required and filtered out the times the company had no much works going on. The solar potential for the plant installed was estimated by keying in the plant size in to the Solargis and selecting the required time and duration of data required. These data were tabled in figures 1 and 2.

Actual measurements

An Elspec G4500 portable power quality meter was used for power measurements on a mono-crystalline silicon solar module farm, with an SMA Sunny Tri-power 15 kW grid-tied string inverter, a clamp meter for control and data logger. The data logger was hooked to the main three-phase power intake in the whole building for effective data recording. The measurement assured that accurate in-depth data was captured both with and without the solar system. The installed solar plant was connected to supply power to the whole premises, prioritizing solar power use over grid power. The data logger was connected to record the generated and consumed power measurements. The resolution of the meter was set to 10 mins so as to be able to tabulate a wide enough report. The current sensing probes were the open type current transformers. Time-stamped data was stored in the meter which was used in all manner of sizing calculations.

Power utility bills audit

The power bills for the last three years were used to calculate the energy demand for the farm. The bills were picked randomly for some months before and after the company had installed the solar plant, and the averages were calculated and compared to the actual measurements.

The coefficient of variation

The coefficient of variation (σ_v) is important in cases where the obtainable solar energy resource should be efficiently harvested for uninterrupted applications and forecasting of auxiliary energy sources. The coefficient of variation was determined using

$$\sigma_v = \frac{\sigma}{\bar{x}} \times 100 \tag{3}$$

where $\acute{o}$ is the radiation data standard deviation given by

$$\sigma = \sqrt{\frac{\Sigma(x-\bar{x})^2}{N}}$$

and N is the sample size and $\bar{x}$ the mean

Measurement of derate factors

Various factors affect the efficiency of the array. High temperatures cause voltage losses in an array. Dust on the array leads to energy absorption loss. System wiring poses copper losses. As a result, every element of a solar system has efficiency losses. These factors are referred to as derate factors. The general derate factor was obtained by multiplying all the distinct derate values as expressed by Boxwell (2012).

The derate factor due to soiling/ dirt was determined using two similar solar modules. Both were selected from an installation that had been used for 4 months without cleaning. One of the modules was cleaned while the other one was not. A multi-meter was used to measure V_{oc} and I_{sc} and the results were recorded. The measurements were done at full-clear sunlight, the modules placed perpendicular to the Sun and at the best solar condition available. The results were used to determine how much energy was lost due to soiling. The derate due to shading was investigated and found to be near negligible because there was no obscuring object of much concern near the array. The only shade was due to moving clouds, which was brief. However, this derate could not be eliminated since it was noted that during some months given under the results, the climatic change affects solar yield to some degree, as expressed on average by the derate factor due to cloud cover. The time for the partially obscuring clouds was recorded and tabulated. The other derate factors considered were assumed to be equivalent to the values given by Franklin (2019), because the equipment used was similar to those used elsewhere.

The company operating hours

Many small-scale and medium-sized companies' staff, just like those at Solutions General Ltd., work from 08:00 to 17:00. Using a staff attendance register, the exact working time was recorded and power demand variation was recorded to investigate the demand at peak and off peak. It was assumed that the higher the power demand, the greater the work load since other duties like office work consumed little power.

Backup requirements

Two to three backup days were considered since the demand for essential power was not expected to change. The backup was aimed at sustaining only the essential load, which was for the alarm system, server, and some security lights. The required demand per hour was determined by considering the report from the analyzer on the amount of energy needed from 19:00. to 07:00. for a period of one day. The backup size estimate model used as subsequently expressed by Wasike (2015) as

$$E_s(\text{kWh}) = \text{Hours} \times E_d \tag{4}$$

where, E_d is the continuous essential power size in kW.

Estimation of Investment and Maintenance costs

The cost of the investment, running costs, and the expected lifespan were estimated. For easy and reasonable evaluation, an overall yearly cost was calculated, which was comprised of the cost of the investment and the maintenance costs. The yearly investment was calculated according to (Wasike, 2015) as

$$\text{Investment cost} = \frac{\text{I} \times \frac{\text{d}}{100}}{1 - \left(1 + \frac{\text{d}}{100}\right)^{-\text{N}}} \tag{5}$$

where I is the total asset cost (KSh), N the period the system has served, and d is the percentage rate of discount.

The running cost is difficult to evaluate for green energy systems, but an estimated value of 3% of the total initial investment was found to be reserved every year for maintenance and degradation costs.

No-upfront cost policy plan samples analysis

Using zero-upfront cost plans, clients' site proposals and embraced plans from different policy sellers, different power purchase agreements (PPAs) were evaluated. The amounts paid annually to the seller companies were investigated using policy consumer interrogation and trying to bargain on the proposal agreements.

The considered plant sizes were 10 kWp, 20 kWp, 60 kWp and 220 kWp all in 10 years and 20 year plans. The estimated savings on kWh was considered at the steps of 3, 5, 7 and 10 years where the amount saved were also estimated at the same span. Agreements whereby the share on the kWh saved between the investor and the consumer was 70% to 30% and 60% to 40% were analyzed. A 20 kWp plant on 20 years' full power uptake policy was also investigated. Care was taken to ensure that the investor company was still making some reasonable margins and was not exploiting the consumer company by ensuring that the minimum premium summed throughout the policy period was at least 130% of the plant total cost, and that the monthly cost of kWh was below KSh 22.

The cost of system degradation was taken into consideration. The factor used was 0.3% per annum. For the onsite installed plant, the total saving on kWh cost was monitored and the amount paid back was estimated, considering the system degradation to estimate the total amount that should have been paid for the system in the zero-upfront plan, as well as the amount paid for other systems mentioned above. The total amount paid monthly for each plan was estimated as

$$X_1 = \frac{X_0 \times \left(1 + \frac{9.2}{100} n_i\right) \frac{0.3}{100}}{3 \times 12} \qquad (6)$$

where, X_0 is the one-off total plant cost, X_1 is the total amount payable every month for a period of three years, n_i is the policy period in years and 0.3% is the system degradation per annum. Amounts for 3, 5, 7, and 10 year plans were calculated.

RESULTS AND DISCUSSION

Trend of solar radiation at Syokimau area

Syokimau lies in a region where the daily average is 4.6 kW h^{-1} kWp and 1607 kW h^{-1} kWp yearly according to Solargis (2020).

Our key interest was the total amount of solar radiation reaching the Earth's surface. The extracted data is shown in figure 1.

From the data used in figure 1, an average insolation of 4.174 kW h^{-1} m^{-2} d^{-1} was recorded. From the records, diffuse horizontal irradiation (DIF) of 2.338 kW h^{-1} m^{-2} d^{-1} was also recorded. This forms a significant percentage of the required insolation. It was found that the radiation reaching the study area every year rose during the month of January, attaining its maximum value in the month of February. Regardless of the highest intensity in March, a drop was noted which continued until the lowest in the month of July. Then the value began to peak intensity, then started rising again in the month of August throughout September, reaching another peak in October. The October peak was inferior to the February one. Once more, it was detected that the intensity to some extent dropped in November and then rose through December. The peak that was noted in February was credited to dryness and fewer winds during the period of December up to February, which is normally dry and with fewer winds. March is the beginning of the long rainy season, and as a result, the declining tendency of the insolation also begins. The rains again commence around the middle of March through May, with April being the high point of plentiful downpour. This lengthy rain period is characterized by dense clouds that attenuate the solar radiation in that period. The cold season starts in June and extends to August. During the month of June, it was found to experience less radiation potential due to low-lying clouds that are stable with low temperatures. As a result, July has the lowest level of insolation. Short rains begin in September and last until November. This season is accompanied by plenty of humidity, heavy clouds, and rainfall. Consequently, low insolation is experienced in October and November. Comparing the data for previous years, the effect of gradual uneven climatic change had not much effect on the energy potential of the study area. The derate factor contributed by cloud cover in that region was determined, which had significant impact on the energy produced. During the month of June, the factor is likely to increase since the weather kept on fluctuating, hence we relied on the averaged factor.

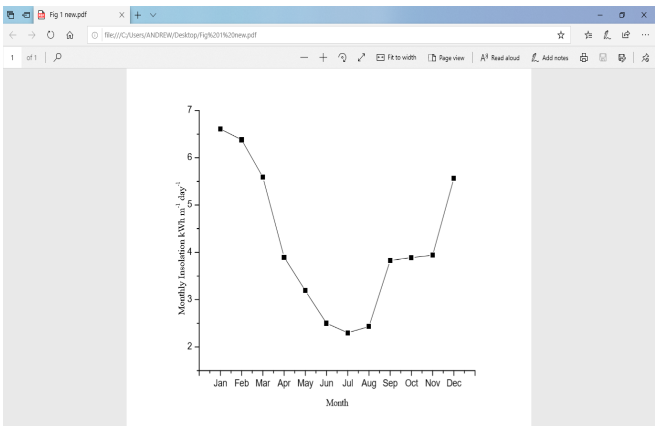

Figure 1: Mean monthly insolation plotted from Global solar Atlas data for the Syokimau area.

From the data in figure 2, it can be seen that from around 18:00 every day of every year up to around 07:00, there is zero to insignificant yield. Significant yield is evident from 08:00, which rises to its peak at noon. This is because the sun is directly overhead at that time, with much of the radiation perpendicular to the PV modules. The month of February was found to attain the highest hourly peak, with July being the lowest in terms of solar potential.

The daily average power that was actually generated per unit of the installed plant capacity in (kW h^{-1} kWp), was found to be between 3.84.5 $kWh^{-1}kWp$ and 5.5 4.5 $kWh^{-1}kWp$ with an average of 4.5 kW h^{-1} kWp and 1643.375 kW h^{-1} kWp yearly.

The dust effect was evaluated and added to the derate factors in determination of the practical PV yield.

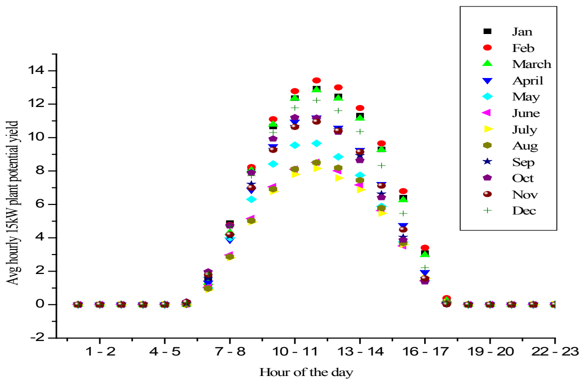

Figure 2: PV average annual potential round the clock.

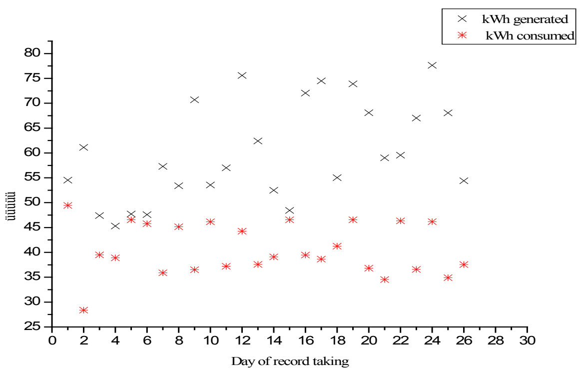

Figure 3: Instantaneous kWh generated compared to kWh demand.

Coefficient of variation of solar power generated

The coefficient of variation, which is defined as a statistical concept for relative variability in a data set, indicates the magnitude of standard deviation from the mean.

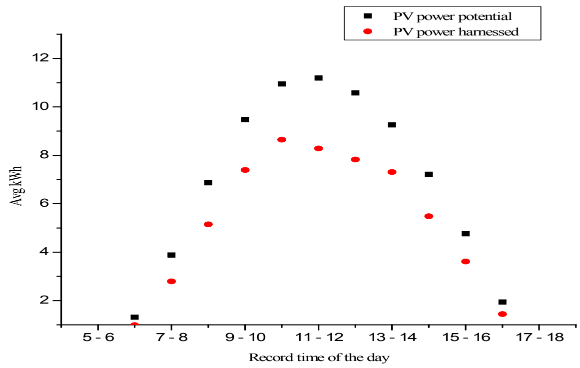

Figure 4: PV power potential for 15kW plant compared to the actual power harnessed.

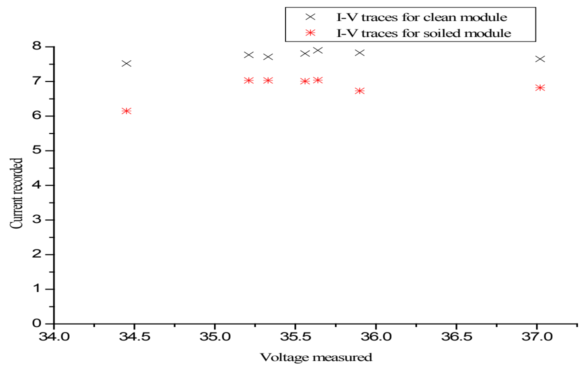

Figure 5: I-V relation for the measured module characteristics for clean and soiled outputs.

The coefficient of variation of solar energy harnessed was calculated. The standard deviation was found to be 9.73, while the mean was 60.15. These values were used to determine the coefficient of variation. A value of 0.16 which is 16.17% was obtained.

From the investigations, the general value of the coefficient of variation that was obtained confirmed that there was some degree of variability in the solar power harnessed during the period of study. However, the main reason for the variation was that the solar plant was switched off from time to time. Taking the maximum values of the generated power for each day and calculating the coefficient of deviation using the maximum daily values, the range was found to be from 0.16 to 0.24. This variability is less than one, showing that the solar power in that area is sufficiently reliable. The value of the coefficient of variation was within the acceptable limit. However, the value showed that the actual power harvested had some variance attributed to derate factors, and that the plant was not working all the times.

Most of the time, during the company working period, the amount of power generated at any given time was greater than the amount of power demanded. This was due to the fact that we had oversized the plant at Solutions General Ltd, and that there was minimal activity during the study period. The focus of this study was on how sufficient this generated power was and how stable the sufficiency was. It was found that on average from 9:00 to 17:00 the power generated was 151% of the power demanded, hence 51% of the power generated was fed back into the grid. The excess generation was attributed to oversizing of the solar system and reduced plant activity due to COVID-19's impact on industries in the country. Since a number of machines were idle at times, the fed back power which they could have consumed was recorded contributing to 51% of the total generated power on average. As expected from figure 1, the amount of solar power generated during the months of June, July and August dropped significantly. There was little impact on the power bill paid for utility power since the power demand had also dropped.

Utility power bills paid extract

It was found that the average power bill paid without solar power was KSh 17,772.83 per month and KSh 4,638.42 with solar power. It was also noted that during the month of May 2021, the bill shot up by 14.6%. This was as a result of solar power being fed back to the grid, whose metering was found not to offer a selling back policy. The generalized cost per kWh for grid power, inclusive of all deductions and taxes, was on average KSh 22.00.

Power generated from the installed solar system

A sample of data for the energy generated in September was recorded and is presented in figure 3. The harvested solar power was found to be sufficient for running the industry from 10:00 to 16:00, with only a minor reliance on grid power. Therefore, the solar power potential from the data captured in the area was sufficient to power the plant's day-to-day operation.

The generated power was subsequently compared to the potential data for the plant from the Global Solar Atlas. It was found that from January to March, the solar potential for the plant was on average 165% of the required load from 06:00 to 17:00. Considering the kWh generated, this could not be achieved due to low system efficiency and the derating factors, among other unquantified losses. However, an average of 115% of the required load was recorded and presented in figure 3. The total power harnessed as measured in a span of an hour was compared to the regional average hourly potential from Global Atlas data for the same installed capacity. The data is presented in figure 4, showing that our system yield was always lower than the Global Atlas potential yield.

System Design

It was found that the total power demand was 11.5 kW. The reactive total load was found to be, on average, 4.5 kVAR, which was less than one third of the inverter size, indicating a safe load for the inverter. The total continuous load measured on average was 7 kW. This was found to be safe for the 15 kW inverter used. The continuous load was found to be about 50% of the rated inverter size, hence the inverter was concluded to operate at the highest rated efficiency possible as stated by Holmes *et al.* (2006). Using equations (1) and (2), the maximum and minimum number of 345 W panels that needed to be connected in series was found to be from 16 to 22. Therefore, it was concluded that since the inverter input was from 600 – 1000 V DC, 22 panels were appropriate. The plant was therefore reduced to two strings of 22 panels each.

The average essential power load was found to be 200 W. Using equation (4) and at a DOD of 50%, a 24 V, 400 AH backup was found to be enough for the system's essential power. This back up was found to be enough for at least two days in the cases the charging power was not available.

System derate factors results

The overall derate factor was found to be 0.74. This factor was included in solar system sizing**.** Hence**,** the system efficiency was 73.68%, resulting from environmental factors and system limitations which could not be easily avoided. From the shading result, it was found that 3% of a year's time, the system was shaded, resulting in an equivalent energy loss fraction.

The I-V characteristic relationship for the measured output for the dirty PV module is plotted in figure 5. The curve was compared to the manufacturer's I-V curve and found to differ. This was due to the fact that the data was taken on different days that had different solar conditions and that the soil particles were not evenly distributed. The data captured were not absolute but taken at a 0.5% instrument error.

Dusting contributed to a greater fraction of energy loss of 12% in a year. These factors are unique for different places but the other factors are valid anywhere since copper in Africa is the same as copper in Australia.

Table 2 shows the derate factors and the allowable ranges. It was found that much of the concern was the dust derate since the area at times is very dusty. Many enterprises who have installed PV modules take more than a year before cleaning the modules, thereby losing a significant amount of power. It was noted that after cleaning the modules, it takes an average of four months of no rain for them to get dusty enough to start having significant power loss due to dirt. The shading factor was found to account for about 0.97 factor.

Table 2: Individual and the general derate factor results.

Derate factor	value	Allowable range
Soiling	0.88	0.30 - 0.995
Shading	0.97	0.00 - 1.0
System downtime	0.98	0.00 – 0.995
AC wiring	0.99	0.98 – 0.993
DC wiring	0.98	0. 97- 0.99
Module power tolerance	0.95	0.88 – 1.05
Diodes and connections	0.995	0.99 – 0.997
Module mismatch	0.98	0.97 – 0.995
Inverter efficiency	0.98	0.88 – 0.98
General derate factor	0.7368	

Consequently, the equation for PV array size is

$$PV\ (\text{arraysize}) = \frac{\text{maximum power demand}(\text{kWh})}{\text{avrg P.S.H} \times 0.7368} \quad (7)$$

Energy saved and some power purchase agreements

From the bills paid for the grid power with and without a solar system the average amount of energy saved was calculated. Analysis using average data measured was emphasized during data presentation. The practical yield was measured and presented for different plant sizes.

The harnessed averaged energy for the down sized 15kW$_p$ plant was found to be 597.02 kWh, which is about 73.90% of the total energy demand every month. This was found to be an encouraging fraction of the available potential.

Some extract power output and demand data for 20, 30, 60, and 220 kW$_p$ plants was analysed. It was found that, on average, some plants consumed efficiently 60% of the generated energy in a year, hence the amount payable for the ownership of the plant should be well agreed upon.

For the 30 kW$_p$ plant, we found that in a lease period of 10 years it could generate approximately 46,452 kWh every year, resulting in KSh. 218,700 saving on kWh in the first year and KSh. 837,800 in the eleventh year. It was found that the average annual plant output (kWh) could be estimated as

$$\frac{\text{plantsize} \times 365 \times PSH_{aveg} \times 0.7}{1 + \left(\frac{0.3}{100}\right) N} \quad (8)$$

where N is the age of the modules in years, and PSH_{aveg} is the peak solar hours for that particular region under consideration, which is 6.9 hours in Kenya according to Onyango and Ongoma (2015).

Considering the 220 kW$_p$ plant, the available plans were 3, 5, 7, and 10 years. The cost of the plant, monthly rental fees, total cost, power generated, speculated amount saved, and grid power bills were tabulated. It was found that the average annual bill paid for utility power was KSh. 14,945,000 for this plant without solar power installed. The average daily power demand at KSh. 22 per kWh was 1,860 kWh. The average percentage amount of kWh saved on-grid solar hybridization was calculated for all the policy terms. The amount of mean interest percentage payable out for each plant and for each policy period was also evaluated and the findings are presented in table 3. However, the savings for the 60kWp plant were lower than those from the other plants. This was attributed to the fact that the location of this plant has very low solar radiation reaching the Earth due to being misty and foggy most of the time of the year. As a result, much dependency was on the grid power for this plant.

Table 3: Mean savings on kWh and the amount of interest paid out during the plan periods.

Plant size (kWp)	Policy period (years)	220	60	20	% Averages saved
% (kWp) saved	3	31.46	19.99	30.55	27.33
	5	31.46	19.99	45.50	32.32
	7	31.33	19.91	63.43	38.22
	10	31.00	19.71	89.66	46.79
% Averages of interest paid	3	27.56	27.53	33.28	29.46
	5	47.02	46.74	45.53	46.43
	7	60.04	59.90	58.30	59.41
	10	75.04	74.31	68.51	72.62

As expected, the interest paid for a three-year policy is the lowest. As the policy term increases, the interest amount also increases. From 7 to 10 years, the interest is slightly beyond the average bank loan interest of an average of 14% p.a. For any plant size and at any policy period, it was found that the percentage kWh of the demand saved was an average of 36.17. Therefore, we decided to consider a full power uptake policy with the above savings and cost data.

The 70/30% 10-year policy and 60/40% 20-year policy

Savings of a 20 kWp plant on this policy were investigated and data presented in table 4.

Table 4: Results for a 70/30% and 60/40% 10 and 20-year policy.

20kWp plant yield and savings		
	10 years	**20 years**
Power generated (kWh)	276,500	553,000
Power saved (kWh)	204,333	408,667
Cost of the power saved	4,495,326	8,990,674
70% of the saved amount	3,146,728.20	5,394,404.40
30% average saved	944,018.46	3,596,269.60
Cost of kWh over the period	20.75	19.63

The actual savings of the 15 kWp plant over three months was evaluated for comparison. The average monthly power bill without a solar power plant was found to be KSh. 19,533.69 and the average bill with a solar power plant was KSh. 4,440.81. This was found to be a 77.27% saving on the power bill. The cost of the plant was about KSh. 1,500,000. When the seller and the buyer share the saved amount, the plant seller receives KSh 13,134.44 monthly, which means that the plant cost can be recovered in 10 years generating KSh. 1,576,132.80. The PV modules used had a 25-year warranty. Therefore, during the remaining years of the system life, factoring the 0.3% degradation, the investor will have gotten at least 204% of the investment amount. The speculated total plant paid back amount was estimated as

$$\text{Total paid back (KSh)} = 11.964x\left(\frac{0.997^{n} - 1}{-0.003}\right) \quad (9)$$

where x is the calculated agreed first year monthly payment, and n the final year or the year of cumulated amount determination.

The full power uptake was found to be effective since the investor transfers all the power responsibilities to the power provider. Including the monthly average 55.51 kWh, which is in general 8.93% of the generated power that was fed back, it was found that a saving of 23 – 30% on kWh was possible, such that the cost per kWh can drop by 30% with maximum reliance on solar power of at least 80%.

CONCLUSION

The PV power potential, industrial power demand, and PV system adoption plans were investigated. The region studied was found to have an annual PV potential of 1607 kWh/kW$_p$. The available solar power was found to be sufficient to power the operations of a medium-sized industry.

The daily insolation PV potential was found to be between 2.4 and 6.5 kW h^{-1} m^2 d^{-1}. This minimum was found to be enough to power 65% of the plant on average for the installation studied. It was found that the PV daily energy variation coefficient varied from 0.16 to 0.24, which was concluded to be reliable.

The amount of energy harnessed at any instance was 14.64% more than the energy needed from 09:00 to 17:00. The surplus energy was automatically fed back to the grid power system.

The maximum plant demand at any given time was found to be less than the average PV generated power. The 15 kW inverter used was found to be enough for the 11.5 kW continuous load. It was noticed that during motor start events, about three times the rated power was drawn.

The grid power was essential for sequencing reasons and to augment the PV source whenever needed. The instances of working time without sufficient PV power were minimal with negligible power outage cases. The averaged practical lifespan of the batteries used was found to be 3 years.

The general efficiency factor was found to be 0.74, with the greatest derating factor contributed by dust. This factor was included in the array sizing, and the maximum and minimum modules that could be connected in series were determined.

It was found that, on average, an energy saving of 27.3 – 72.6% from 3 years to 10 years was possible for different consumers. This percentage was found to depend on the region, climate and the energy source prioritized.

When the 3, 5, 7 and 10 year plans were investigated, it was found that the average interest paid during these periods was higher than the local banks' lending rates. However, depending on what policy is available, suitable, and affordable for a given industry, the plans investigated were still found to be more beneficial in the long run once the system is paid off. The shorter the plan payment period, the higher the monthly paid premiums: as a result, the plan is less affordable but more beneficial after the policy lapses.

A full power uptake policy was found to be the most affordable for medium-scale industries. The plant's cost was found to be recoverable in the first 10 years, and the remaining 10 warranty years were found to be of profit to the investor. Theoretically, it was found that the cost of kWh could be reduced by 23 – 30% but, experimentally this was only 8.9%. The theoretical value could not be achieved due to the fact that some generated energy was fed back to the grid and that during some working times the plant relied on grid power when the PV system was switched off for modifications and comparison purposes.

Effective maximization on the utilization of the generated solar power by industry is essential so as to save on grid energy costs with an environmentally friendly alternative.

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