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Research paper

A study on the reliability and performance of solar powered street lighting systems

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Abstract

This paper presents the results of a study on the reliability and performance of the solar-powered street lighting systems installed at the African University of Science and Technology (AUST) in Nigeria, a hot and humid environment. The technical performance of the systems was studied using the following performance indicators: system energy yield, capture loss, as well as the system performance ratio while the reliability of the systems was examined using a model developed from the findings from the maintenance and fault diagnosis of the systems. The model was used to predict the total failure and survival probability of the systems using the Weibull distribution. The performance evaluation during the monitored period (February 2012 to January 2015) indicated that the performance ratios of the systems vary from 70% to 89% and the energy yields of the systems ranging from 2.87 h/day to 5.57 h/day. The results from the reliability analysis also showed that when the stress concentration factor around the notch between the cable terminals in the charge controller increases, the charge controller will become overheated, which in turn affected other components of the systems. The implications of this study are also discussed for the design and development of future solar-powered street lighting systems.

Keywords: *Failure; Performance; Photovoltaic; Reliability; Solar-Powered Street Lighting System.*

1. Introduction

In recent years, the increasing interest in the application of photovoltaic (PV) energy has led to the introduction of a variety of commercial products into the marketplace [1]. These applications include: solar lanterns, solar-powered traffic lights, solar-powered closed-circuit television (CCTV), solar water pumps, solar street lighting systems, mini-grid solar PV project for rural electrifications, etc. [1-11]. These products have significantly increased the quality of life of people living in the rural/urban areas, by positively impacting their social-economy, education, and health life to an appreciable level [12], [13]. The successes in the PV technology industry have stimulated the solar research community to further explore numerous efficiency enhancement techniques over the past two decade [2-11]. Today, PV research spans the full range from idealized models/experiments to realistic models/experiments across different industries, climates and geographical regions around the world [15], [16]. The motivations for this growth are traceable to technology improvement, energy efficiency, energy policies, energy security, and research and development.

Currently, silicon-based solar cells are the most widely used commercial photovoltaics (PVs) in the world [8, 9] because of the success of increased cell efficiency reports from major laboratories [10], [16]. One of the recent remarkable reports was presented in 2017 by a research group led by Yoshikawa K., where they recorded a photo-conversion efficiency of over 26% for silicon hetero junction solar cell [16]. In spite of the extensive research, PVs faces the problem of profitability, as they must compete with traditional energy sources and methods of energy conversion [11], [17]. The low efficiency-to-cost ratio of solar cells is one of the main problems that have prevented the rapid widespread use of PVs in wide-scale geographical applications [17-19]. To become competitive, however, PV modules must achieve stable conversion efficiencies more than fifteen percent; have a lifetime between twenty-five to thirty years, and cost about $US 0.3 per peak Watt or less [11].

Moreover, the reliability of PV modules and systems is critical to the commercial success of photovoltaics. This implies that, for photovoltaics to play an increased role in the future energy supply system. The reliability and long-term performance of the PV systems and modules over a period of 25 years are highly mandatory [17]. Therefore, the reliability of PV systems is a key contributing factor for cost effectiveness, and crucial to continued investor confidence, i.e. financial returns requires PV systems to reliably generate the assured electricity over the warranted period.

Within this context, increasing the reliability and the service lifetime of the PV modules represents a promising approach that can be used to engineer the reduction of the costs of photovoltaic systems. An important feature in the successful achievement of this service lifetime goal is the understanding of the failure mechanisms related to components, electrical bias, and environmental factors including the prediction of their long-term effects in different application environments [18].

Furthermore, there are a great number of existing methods that are used to characterize PV module failures, reliability and performance for outdoor [20-22] and laboratory research [17]. The most significant failure in outdoor/field PVs systems are: delamination [23], junction box failure [17], frame breakage [17], cell cracks [24], [25], burn marks [17], potential induced degradation [17], and defective bypass diodes [17]. While on the other, the common failures in laboratory PVs cells include: Interfacial and contact failure [26], delamination [27, 28], adhesion loss [29], contact degradation [26], crack due to bending and stretching of organic solar cells [26-27], [30] and cell cracks due to surface texturing [31-32]. Nevertheless, there is a need for more data on the failure, reliability and performance of PV systems that are deployed across the different terrestrial regions around the world. Monitoring and evaluation of these outdoor/fields PV systems can provide PV manufacturers and R&D institutions useful and insightful feedback on their products and thus reduce uncertainties of returns on investment.

A PV module/system failure is understood as an effect that destroys the solar PV module power or an effect that creates safety issues. In general, failures of PV products are divided into three categories, namely: Infant-failures, midlife-failures, and wear-out-failures [17]. Quite a number of researches have been carried out in the past years on topics related to these failure categories in order to overcome the associated challenges. Notable works from prior work are recorded in some work presented by authors such as Wohlgemuth [20], Wohlgemuth et al. [21], [22], Zaman et al. [33], Pregeli et al. [34], Oozeki et al. [35], Voronko et al. [36], Lorenzo et al. [37], Bandou et al. [38], Ndiaye et al. [39] and Skoczek et al. [40]. The authors reviewed and explored the status duo of PV system reliability using outdoor data from fielded arrays and results from accelerated testing of components [21, 33-40]. Some authors studied the long-term outdoor performance, degradation and failure of PV systems/modules across the world [18], [22], [35-38], [40] while other explored the short-term effects (infant-failures) of these systems [33, 39]. Yet, only few reports on the degradation rates and failure mode of PV Street lighting systems (a major outdoor lighting system for roadways and streets [41-43].) have been presented in the literature [17].

The complete street lighting system can run on a highly efficient PV system to reduce power consumption [42]. As a result, PV lighting systems for cities and towns now represents one of the largest cost effective markets for PV [41-43]. The installation cost of just one or two utility power poles can justify the initial cost of a PV lighting system [20]. However, a general observation from prior reports has shown that many PV streets lighting systems have experienced a number of component failures, including premature charge controller, battery, and ballast illumination failures [41], [44-45]. This is as a result of some identified factors/challenges that are discussed in detail in Refs. [17, 20]

This paper seeks to provide an improved understanding of the reliability and performance of PV solar systems and presents results from the 36-month infant-failure assessment of 35 stand-alone solar street lighting systems installed at the African University of Science and Technology (AUST) in Nigeria.

2. Methodology

2.1. Description of Site and installation

The study site, African University of Science and Technology, lies in the tropics with latitude 9°03'36"N, longitude 7°29'24"E, and an altitude of ~520 m in Abuja, north-central Nigeria. The site consists of 35 solar powered LED street lighting systems that are installed in 2012. They were installed as part of the combined solar project between the Nelson Mandela Institute and the Department of Materials Science and Engineering at AUST. The systems were installed along walkways and strategic points around the site to initially improve security when there is a blackout and to reduce power consumption. But for a while now, it has been a medium for study and research on solar energy courses taught at the department of Materials and Engineering. In addition, considering the fact that panel orientation is one of the fundamental factors that help determine the amount of light that can be harvested from the sun daily [46], [47], the orientations of the panels are set to the south at a tilt angle of 30° to enhance the panel's performance [46], [47].

The design of the entire system comprises of a rechargeable battery (for storage/backup) and light emitting diode (LED) lamp that is sufficient to operate for 10-11 hours daily [48], interconnecting cables (for battery and lamp), a solar photovoltaic module/panel, mounting structure, and charge controller.

As estimated by the National Renewable Energy Laboratory (NREL), USA, solar panels lose up to 25% of their output electrically as a result of accretion of dirt, pollen, leaves, dust, bird droppings, and so on [49]. Within this context, comprehensive maintenance services of the solar PV systems were carried out on regular bases, prior to the measurements procedure, to eliminate the impact of dust.

2.2. Performance measurements

The systems were monitored for a period of three (3) years, from February 2012 to January 2015. Based on this, the average daily/monthly solar irradiation used as part of the tools in analyzing the technical performance of the PV systems was measured using a pyranometer (Apogee instrument USA, MP-100 integral sensor with handheld meter) and compared with those obtained by the Nigerian Meteorological Agency (NIMET). Among the other parameters monitored within this period are the DC voltages and DC power.

Furthermore, since the output and performance of the solar powered LED street lighting systems may differs appreciably with respect to the weather conditions/parameters [20], designs [50, 20], and solar PV technologies [50], it is thus, important to consider using the actual parameters in evaluating the performance trait of the systems [51, 52]. Consequently, the technical performance of the systems was evaluated based on the performance parameters and procedures recommended by the International Electrotechnical Commission under the PVPS project [51-53] and the International Energy Agency Photovoltaic Power Systems (IEA-PVPS) Programme Task 2 framework [54].

These performance indicators include: system energy output, system energy yield, reference yield, capture loss, as well as system performance ratio. These parameters are briefly defined below.

2.2.1. System energy yield

System energy yield, Y_A (h/day), is the ratio of the system's DC energy output (kWh/m^2) per installed capacity per unit area of the PV solar panel (kWp/m^2) which is given by [55]:

$$Y_A = \frac{E_{DC}}{P_0} \tag{1}$$

where, E_{DC} is the system's DC energy output (kWh/m^2) and P_0 is the PV system's output power at STC (Peak capacity), kW$_P$.

2.2.2. Reference yield

Reference yield, Y_R (h/day) is the ratio of the total daily in-plane radiation on the PV solar panel to the reference in plane radiation [55]. Hence,

$$Y_R = \frac{H}{G} \quad (2)$$

Where, H is the total daily in-plane radiation on the solar panel (kWh/m^2), and G is the reference radiation taken as 1 kWh/ m^2.

2.2.3. Capture loss

Panel capture loss L_C is the difference between the reference yield and the system energy yield [55]. Thus,

$$L_C = Y_R - Y_A \quad (3)$$

where, Y_R is the reference yield while Y_A are the system energy yield.

2.2.4. Performance ratio

Performance ratio, P_R, is generally used to measure the quality of the solar PV system (street lighting system) and it is the ratio of system energy yield and reference yield. This can be obtained by the following expression [55]:

$$P_R = \frac{Y_R}{Y_A} \quad (4)$$

2.3. Reliability model

Following the completion of the maintenance service and fault diagnosis of 35 solar street lighting systems at AUST (See Fig. 1), 24 systems (68.57%) were found to be working properly, 10 systems (28.57%) were faulty due to some damaged components and 1 system (2.86%) was totally damaged by thunder strike (See Table 1). The faulty systems were diagnosed to troubleshoot the possible causes of their failures.

Fig. 1: A Photograph Some of the Solar Powered LED Street Lighting Systems at AUST.

The fault diagnosis involved several technical tests of the components of the systems, such as, the functional tests of the solar panels, charge controllers, batteries, cables etc. The fault diagnosis however, revealed a number of salient issues that are summarized in Table 1 below.

Table 1: Description of the Damaged Components in the 11 Faulty Solar PV Systems, As Revealed By the Fault Diagnosis

System Components	Charge Controllers	Light Emitting Diodes	Batteries	Cables	Solar Panels
No of systems with issues	10	1	5	10	1

Furthermore, using the information from the fault diagnosis, the reliability of solar street lighting systems can be characterized by the Normal distribution. The statistical variations in the strengths of these solar street lighting systems could also be characterized by Weibull distribution [56], [58]. Weibull distribution is commonly used for reliability modelling approach in reliability engineering [56], [58]. To estimate the future performance of the system, the parameters of the underlying distribution must be determined. So, we assume that the failure frequency, $f(x)$ for such systems can be traceable to the stress level (x) in the systems' charge controller as shown in Table 1. This can thus, be represented by the expression [56, 59]:

$$f_{\bar{x},\sigma}(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\left[-\frac{1}{2}\left(\frac{x-\bar{x}}{\sigma}\right)^2\right]} \quad (5)$$

Where $\bar{x}$ is the mean stress, and σ is the standard deviation.

Also, the probability of failure, $P_f(x)$, in the charge controller of the solar street lighting systems at a given stress level (x) is given by [56], [59]:

$$P_f(x) = \int_{-\infty}^{\sigma} f(x)dx \quad (6)$$

Where $P_f(x)$ represents the cumulative density function and $f(x)$ corresponds to the probability density function.
Conversely, the probability of survival $P_s(x)$ can be determined from the following expression [46], [47]:

$$P_s(x) = 1 - P_f(x) = \int_{x}^{\infty} f(x)dx \quad (7)$$

This gives the probability of survival, $P_s(V)$, of a stressed volume, V, subjected to a stress level, x, by the following expression [56]:

$$P_s(V) = e^{\left\{\frac{-V}{V_o}\left(\frac{X-X_0}{X_\sigma}\right)^m\right\}} \quad (8)$$

Where V is the sample volume, V_0 is a reference volume, X is the applied stress, X_0 is the stress corresponding to zero probability of failure, X_σ is the mean strength and m is the Weibull modulus. Conversely, the probability of failure may be obtained from the following expression [56]:

$$P_f(V) = 1 - P_s(V) = 1 - e^{\left\{\frac{-V}{V_o}\left(\frac{X-X_0}{X_\sigma}\right)^m\right\}} \quad (9)$$

By taking double natural logarithms of Equation (8), we obtain the following expression:

$$ln\left(ln\frac{1}{P_s(V)}\right) = m \, ln \, X + C_1 \quad (10)$$

Where X is the applied stress and $C_1 = ln\,V - ln\,V_0 - m\,ln\,X_0$.
The value of m can be determined by plotting $lnln\frac{1}{P_s(V)}$ versus $ln\,X$ on Weibull paper. The Weibull modulus may thus be determined from the slope of the Weibull plot.
By taking into consideration the linear elastic fracture mechanics conditions, the weediest link statistics can be used to determine the failure or survival probability within the fracture process zone

in the charge controller. The total survival probability can then be expressed in integral form to be:

$$P_s(r) = \exp\left[-2B\beta fN \int_0^{\pi}\int_{r_o}^{r_p}\left(\frac{\sigma-\sigma_u}{\sigma_o}\right)^m rdrd\theta\right] \quad (11)$$

This implies that, the total failure probability, Φ, can then be obtained by the expression:

$$\Phi = 1 - P_s(r) = 1 - \exp\left[-2B\beta fN \int_0^{\pi}\int_{r_o}^{r^p}\left(\frac{\sigma-\sigma_u}{\sigma_o}\right)^m rdrd\theta\right] \quad (12)$$

where B is the thickness of the positive terminal port of the charge controller, β is the distance behind crack tip, σ is the maximum stress, σ_u is the mean stress, σ_0 is the stress at zero, r_0 is the radial distance at which Hutchinson-Rice-Rosengreen (HRR) stresses are truncated by crack-tip blunting and r_p is the plastic zone size respectively for total survival and failure probabilities as:

$$r_p = \lambda\left(\frac{K_I}{\sigma_{ys}}\right)^2 \quad (13)$$

$$r_p = \lambda\frac{E\delta}{d_n(1-\nu)\sigma_{ys}} \quad (14)$$

Where K_I is the stress intensity factor, σ_{ys} is the yield stress and v is the poison ratio.

3. Results and discussion

3.1. Average daily irradiation for Abuja

Fig. 2 presents the values of the monthly average daily irradiation for the study site from February 2012 to January 2015. The irradiation in terms of daily averages during the monitored period is 5.49 kWh/m^2. Furthermore, the monthly average daily irradiation ranges from 4.10 to 6.51 kWh/m^2 during the monitored period, as shown in Fig. 2. It can also be deduced from Fig. 2 that the monthly average daily irradiation dropped dramatically between June and September, due to the rainy season. The two highest peak irradiation periods transpired around February and March respectively, while the two lowest radiation peaks occurred around July and August respectively.

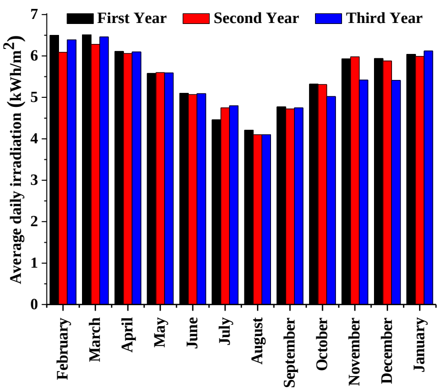

Fig. 2: The Monthly Average Daily Irradiation from February 2012 to January 2015.

3.2. System energy yield and capture loss

The monthly averaged daily energy yield and capture loses for the monitored period (February 2012 to January 2015) is presented in Figs. 3 – 5. Comparing Figs 3, 4 and 5, it can be deduced that the variation of the energy yield is attributed to the changes in solar irradiation of the study site, as shown in Fig. 2.

Comparing the results from the three years study, the results show that the peak average energy yield occurred in February for the three years in a roll. This is traceable to the solar irradiation for February, which has the highest value for the three years of study. The annual averaged daily energy yield for the first year of study (February 2012 to January 2015) is found to be 4.52 h/day, which was followed by the second year of study (4.48 h/day). The lowest annual averaged daily energy yield of 4.44 h/day was recorded in the third year of the study.

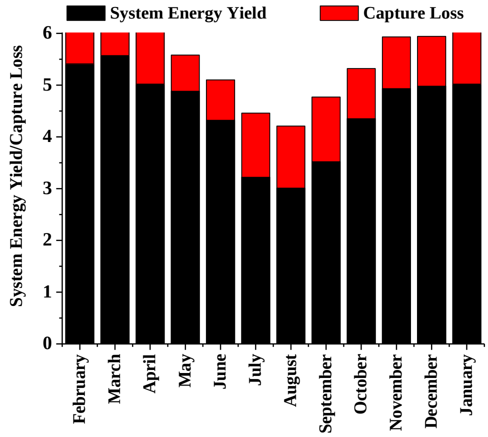

Fig. 3: The Annual Averaged Daily Energy Yield and Capture Losses for the First Year (Feb. 2012 - Jan. 2013).

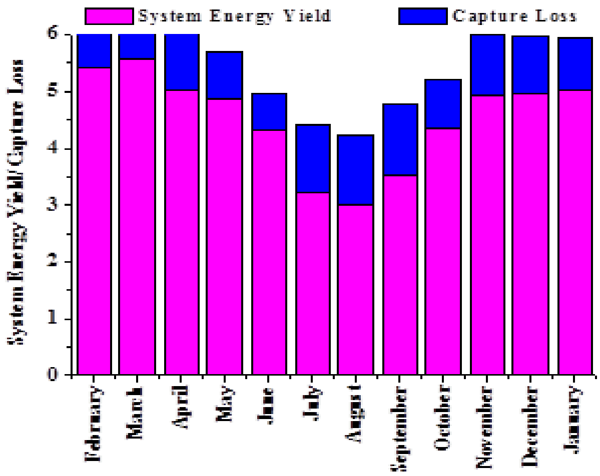

Fig. 4: The Annual Averaged Daily Energy Yield and Capture Losses for the Second Year (Feb. 2013 - Jan. 2014).

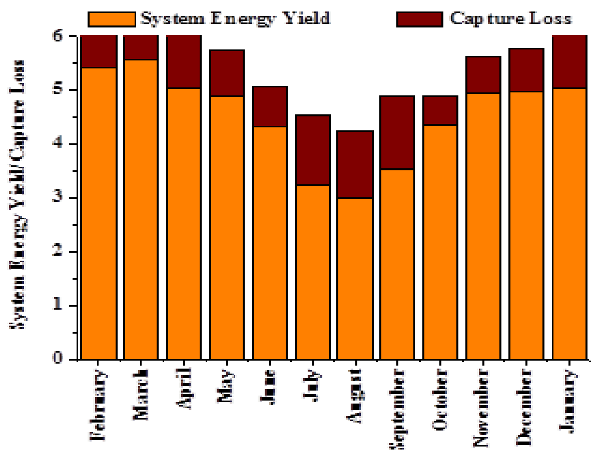

Fig. 5: The Annual Averaged Daily Energy Yield and Capture Losses for the Third Year (Feb. 2014 - Jan. 2015).

3.3. System performance ratio

The performance of the solar street lighting system is described by the system's performance ratio (PR) that is obtained using Equation (4). The monthly averaged daily performance ratios for the solar street lighting systems is calculated and presented in Fig. 6. The performance ratio measures how effectively the solar street lighting systems interact with the solar radiation available at the study site. It is noticeable from Fig. 6 that the system performance ratios range from 71% to 87%, 70% to 87%, and 70% to 89%, respectively, for the first, second and third years of study. However, following the study period, all the months except for July, August and September have a PR value greater than 83%. The poor performance of the solar street lighting systems during this three-month period can be traceable to little or no solar irradiation available at the study site as a result of the rainy season.

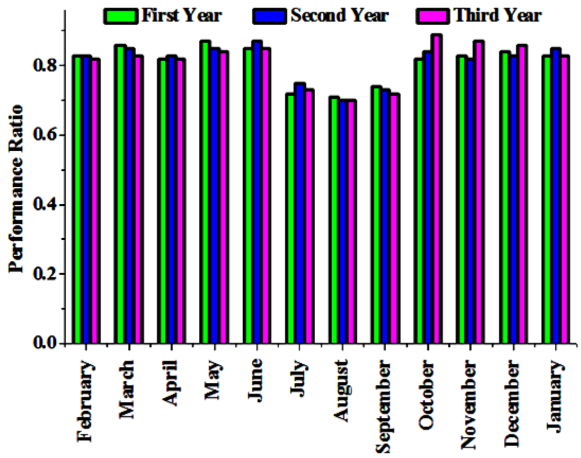

Fig. 6: The Monthly Averaged Performance Ratios (February 2012 – January 2015).

3.4. Reliability analysis

The failures of PV systems are majorly ascribed to inverter failures [61-63]. However, some case may be attributed to various sources such a human and natural cause, batteries [50, 60, 64], and charge controller as in the case of the solar PV street lighting systems [17], [64].Thus, considering the reliability of the systems from Table 1, it can be deduced that 2.86% of the LED, 2.86% of the panels, 14.29% of the batteries and 28.6% of the charge controllers failed to meet the minimum required lifespan (LED: 6-8 years, solar panel: 20-25 years, battery: 4-6 years and charge controller: 5-15 years) respectively. The above analysis shows that a high percentage of the charge controllers did not meet the minimum lifespan required.
A summary of the reliability analysis of the solar PV street lighting systems is presented in Fig. 7. It can be deduced from the reliability analysis that the charge controllers of the faulty PV systems were damage as a result of the accumulation of stress around the notch between the cable terminals in the charge controller. This shows that when the stress concentration factor around the notch between the cable terminals in the charge controller increases, there will be overheating of the charge controller which can thus lead to the damage in the system.
Furthermore, Fig. 7 also shows that the total survival probability of the charge controller is 0.5, covering a distance of 3 mm behind the crack tip around the cable terminals. This implies that, the solar PV street lighting systems can function effectively with a survival probability of 0.6, covering approximately 2 mm behind the crack tip around the cable terminals. The probability of failure, $P_f(x)$, of the charge controller in the solar street lighting systems at the same stress concentration around the cable terminals is also obtained to be 0.4.

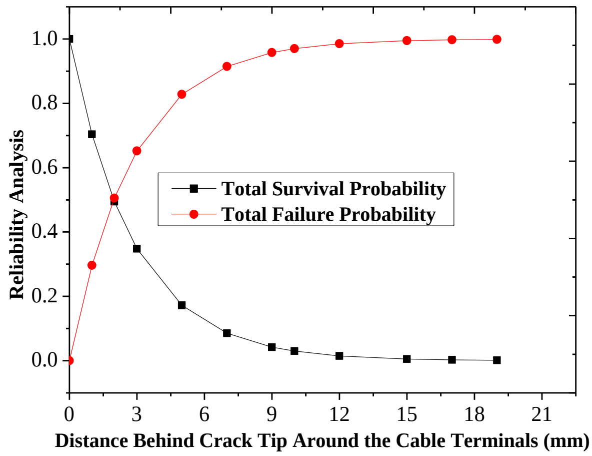

Fig. 7: Reliability Analysis of Solar PV Street Lighting Systems.

4. Conclusion

The reliability and performance of solar-powered street lighting systems are explored throughout this study. Following the guidelines lay down by IEA and IEC, the energy yield, capture losses, and performance ratio are considered as the benchmark for the performance evaluation. First, the results show that the performance ratios of the solar-powered street lighting systems vary from 70% to 89% and the energy yields of the systems ranging from 2.87 h/day to 5.57 h/day for the monitored period. The best performance in terms of the peak average energy yield and performance ratio occurred in February 2013. The capture loss for the same month was also the lowest for the monitored period.
Furthermore, the results from the reliability analysis showed that the charge controllers of the faulty PV systems were damage as a result of the accumulation of stress around the notch between the cable terminals in the charge controller, which in turn affected some other components within the PV system (such as cable, battery, etc.). Without any doubt, the use of a quality charge controller can protect and increase the life cycle of the PV system's battery and also support monitoring and quick troubleshooting of the systems.

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