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Original Article

Investigation of Efficiency Degradation of Solar Powered Street Lights in the Niger Delta Region of Nigeria in Sub-Saharan Africa

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Abstract- *Colossal funds have over the years been spent by the various State Governments in the Niger Delta region of the federal republic of Nigeria on the installation of solar powered Street lights to enhance the security of life and properties since grid power supply is almost non-existent in Nigeria; however, they often fail shortly after installation. This study investigated the causes of the observed failure of solar powered street lights in the Niger Delta and proffered solutions to ameliorate the ugly situation of efficiency degradation/ failure of solar powered street lights, which has negatively impacted the region over the years. From the study, the average values of the current, voltage, and power generated by the solar panels used for the study at different times of the corresponding temperature and light intensity on fifteen sunny days over the period of the study showed that the neat solar panels' performance over the period is better than the soot covered panels' performance as the values obtained for all the parameters investigated are far higher in the neat panels than the soot covered panels giving rise to an average percentage variance of 22%,41% and 80.39% in the current, voltage and power respectively of the soot covered panel from the neat panels. The calculated standard deviation and ANOVA of the power generated by the neat and soot covered panels also reinforce this result. Therefore, Soot, without doubt, is a major cause of the efficiency degradation /failure of solar powered street lights in the Niger Delta.*

Keywords *- Solar, Panel, Light, Soot, Failure.*

1. Introduction

It has been discovered that one of the more extensively utilized types of energy is renewable energy. In recent years, interest in the application of Photo-voltaic (PV) energy has culminated in the introduction of lots of commercial products [1-3]. Some of the utilizations include powering schools, hospitals, homes, and industries, as well as its use in 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 among others [4,5]. Over the years, total darkness has become a thing of serious concern for both automobiles and pedestrians at night, as vision is a major factor in many accidents involving passenger buses that occur at night [6]. In the evening and during severe weather conditions, street lights improve driving safety and reduce the incidences of criminal activities since the covered darkness would have provided for such activities, which has been overcome by light. With the rising cost of conventional energy sources and limited access to natural resources, interest in using renewable energy sources is increasing. Installing street lights is frequently a significant cost issue, particularly in regions without established grid infrastructures [6]. Environmental protection is another factor favoring the development of technologies based on renewable energy sources. Solar street lighting is a desirable substitute [7, 8]. It was mostly used in distant areas of third-world countries where electricity was non-existent or unreliable [7]. Several studies confirm that photovoltaic systems will significantly contribute in the future as solar Photovoltaic (PV) modules can extract electrical energy from the sun. Their development will accelerate due to technological innovations, improvements in the efficiency of photovoltaic panels, and support programmes from the government and the private sector [9, 10]. Solar technology has advanced, and solar projects are now being built in developed and developing nations [5]. They are advantageous due to their lower operating and maintenance costs, environmental friendliness, and ease of installation [11]. Solar panels are used to power solar streetlights. The panels transform solar energy from the sun into electrical energy stored in a storage battery during the day and are used to power streetlights at night to produce illumination [12]. However, the performance of solar panels is influenced by different variables, including solar radiation, temperature, wind speed, relative humidity and the presence of haze or dirt [13] With its location on the equator, Nigeria is within a high sunshine belt where solar irradiation is fairly well distributed [6]. Many designers have leveraged this to implement solar powered street lights. Currently, in Nigeria, numerous states and local government areas install solar street light systems in their respective areas; unfortunately, many of these solar street lights entirely malfunction or lose functionality soon after installation.

This failure could be the result of several technological issues or other issues. [14] stated that the most common cause of failure in solar-powered streetlights is the deterioration of batteries within the solar system. This is because batteries, particularly lead-acid types, have a limited lifespan and require frequent replacements. [15] further stated that although solar-powered street lights are designed to withstand outdoor conditions, extreme weather conditions such as heavy rain, snow, or high winds can cause damage to the system. Solar street lights do require regular upkeep to ensure longevity. According to [16], Street light poles and brackets incur rusting and wear due to prolonged outdoor exposure.

This can result in bent poles, warped fittings, or mounting bracket failure, leading to the system's collapse. Also, the quality of wiring used during installations greatly affects the functionality and durability of the system [17]. Faulty wiring resulting from incorrect installation or low-quality wire can lead to disrupted battery charging and system failure. The investigation by [18] found that neglecting the required maintenance of solar-powered streetlights can lead to various problems, such as battery failure, wiring issues, and component damage. The solar panel size is also an important factor in the effectiveness of solar-powered streetlights. If the panel is too small, it may not be able to generate enough energy to power the streetlight, especially during periods of low sunlight. This can result in dim or non-functioning streetlights.

All the previous works cited did not contemplate coating the solar panels with soot resulting from oil exploration and exploitation as one of the causes of the efficiency degradation of solar powered street lights. This forms the crux of this investigation. Colossal sum of money has over the years been spent by the various State Governments in the Niger Delta region of the federal republic of Nigeria on the installation of solar powered street lights to enhance the security of life and properties since grid power supply is almost non-existent in Nigeria; however, they often fail shortly after installation, thereby rendering the effort of the various governments ineffective as well as resulting in a colossal waste of funds, and failing to ameliorate/enhance the security of life and properties. This study, therefore, investigates the immediate and obscure causes of the observed failure of solar powered street lights in the Niger Delta region of Nigeria in sub-Saharan Africa and also proffers solutions to mitigate the failure critically.

2. Materials and Method

The materials and methods employed in this investigation are stated as follows:

i) The comparative analytical method was employed in this investigation
ii) The following materials were used:
    - Ten (10) complete solar-powered street light systems with 140W panels, five systems with clean surfaces, and five with soot over the panels.
    - Multimeter for voltage and current measurements.
    - Microsoft Excel software is used for computing and plotting graphs.

Ten pieces of 140W monocrystalline solar panels are more efficient than polycrystalline panels [19]. Five neat and five soot covered solar panels, having the exact specifications (Table 1) without cracks and other defects, were employed for the study. The panels were placed directly under sunlight to receive the same temperature and same level of irradiation during the study, which spanned three months.

2.1. The Structure and Composition of Solar Powered Street Light

The structure and composition of solar powered streetlights are as shown in the block diagram below.

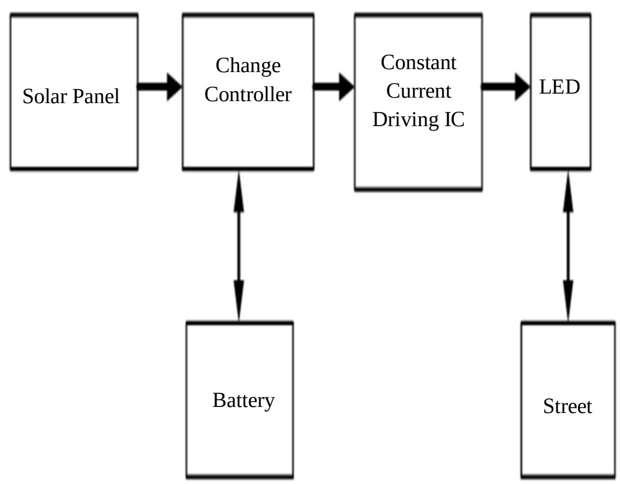

Fig. 1 Diagram of the structure and composition of solar powered streetlight

2.2. Test and Observation

Various tests were conducted on many functional and non-functional solar powered streetlights to arrive at empirical conclusions. For the conduct of the test for the causes of solar powered street light failure, the following steps were taken:

a) Visual Inspection: This involves examining the solar panels for any visible damage, such as cracks, scratches, or discoloration. The wiring and connectors were also inspected for signs of wear or corrosion.

b) Voltage Measurement: Here, a multimeter was employed to measure the voltage output of the solar panels; after that, the measured voltages were compared with the expected voltage specified by the manufacturer. This was done to ensure no significant deviation from the expected voltage specified by the manufacturer, as a significant deviation may indicate a problem with the panel's performance.

c) Current Measurement: A multimeter was also employed in measuring the current output of the solar panels; thereafter, the measured currents were compared with the anticipated current stipulated by the manufacturer. This was done to ensure no significant deviation from the expected current specified by the manufacturer, as a significant deviation may indicate a problem with the panel's performance.

d) Shading Analysis: The solar panels were observed throughout the day to identify any shading issues. Shadows from nearby objects, such as trees or buildings, can reduce the panel's efficiency. The panel's position was adjusted whenever shading was observed, and the shading objects were sometimes removed.

e) Inverter Testing: The purpose of the inverter is to convert the DC power generated by the solar panel into AC power to illuminate the street light. The inverter's performance is tested by monitoring its output voltage and current. If the inverter is not functioning correctly, it can lead to solar panel failure.

2.3. Comparative Study of Neat and Soot Covered Solar Panels

Even if all other factors that could cause a solar powered street light to fail are put right, the system's efficiency may still be very low if there is an accumulation of soot on the panels as the photovoltaic cells may be covered and, as such, prevented from receiving the radiation from the sun to function properly. There is prevalence of soot in the Niger Delta region because of Oil exploration and exploitation activities.

Table 1. Specifications of the panels

Open Circuit Current ($V_{OC)}$	21.6V
Short-Circuit Current (I_{SC})	8.63A
Voltage at P_{MAX} (V_{MP})	17.2V
Current at P_{MAX} (I_{MP})	8.14A
Maximum System Voltage	1000VDC
Operating Temperature	-40 to +85C
Tolerance	±3%

For the study, ten pieces of solar panels, five neat and five soot covered, having the exact specifications as depicted in Table 1, were employed for the study, which spanned three months. Data generated from the study were analyzed and graphed.

3. Result and Discussion

Average values of the current, voltage, and power generated by the solar panels used for the study at different times- 9 AM, 11 AM, 1 PM and 3 PM of corresponding temperature and light intensity on fifteen sunny days over the period of the study are here presented.

3.1. Results for the Neat Solar Panel

Results obtained from the study carried out on the neat solar panel over the period of the study are as tabulated below: The graph clearly separates data obtained from the neat solar panel for each month (December, January, and February) using red, green, and blue lines. From the graph, there is a positive correlation between current and voltage.

Table 2. Data for December 2023 (neat and soot covered solar panels)

Time	Current(A)	Voltage(V)	Power(W)
9:00 AM	3.57	17.84	63.69
11:00 AM	4.55	18.23	82.95
1:00 PM	5.7	18.7	106.59
3:00 PM	6.2	19.6	121.52

Table 3. Data for January 2024 (neat and soot covered solar panels)

Time	Current(A)	Voltage(V)	Power(W)
9:00 AM	3.8	17.5	66.50
11:00AM	4.8	18	86.40
1:00 PM	6.0	18.4	113.40
3:00 PM	6.5	18.9	122.85

Table 4. Data for February 2024 (neat and soot covered solar panels)

Time	Current(A)	Voltage(V)	Power(W)
9:00 AM	4.0	17.2	68.80
11:00 AM	5.0	17.8	89.0
1:00 PM	6.2	18.2	112.84
3:00 PM	6.7	18.7	125.29

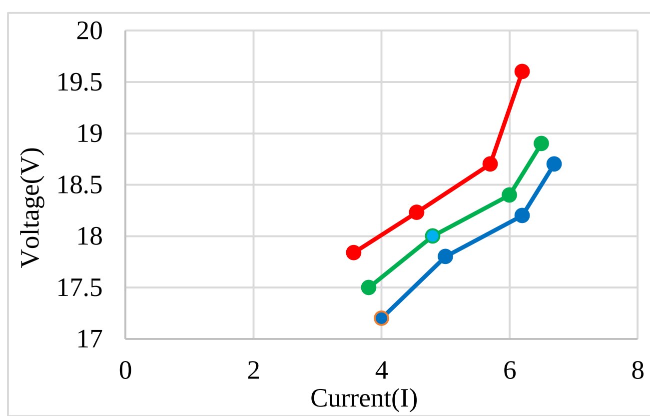

Fig. 2 Graph of voltage and current of the neat solar panels for 3 months

As current increases, voltage also increases. It has differences in line slopes that suggest variation in the solar panel's performance across months. Individual data points represent measured current and voltage values for each month, offering an insight into the solar panel's behavior that an increase in the sun's intensity will increase power.

3.2. Results of the Soot Covered Solar Panel

Results obtained from the study carried out on the soot covered solar panel throughout the study are as tabulated below:

Data for each month (December, January, and February) are distinctively marked in red, green, and blue. The graph illustrates a positive correlation between current and voltage, indicating that a current increase results in a higher voltage.

Table 5. Data for December 2023 (soot covered solar panels)

Time	Current(A)	Voltage(V)	Power(W)
9:00 AM	4.0	16	64.0
11:00 AM	2.7	14.56	39.32
1:00 PM	3.2	15.2	48.64
3:00 PM	3.5	15.5	54.25

Table 6. Data for January 2024 (soot covered solar panels)

Time	Current(A)	Voltage(V)	Power(W)
9:00 AM	4.2	15.7	65.94
11:00AM	2.9	14.2	41.18
1:00 PM	3.4	14.8	50.32
3:00 PM	3.8	15.2	57.76

Table 7. Data for February 2024 (soot covered solar panels)

Time	Current(A)	Voltage(V)	Power(W)
9:00 AM	3.0	13.8	41.40
11:00 AM	3.6	14.4	51.84
1:00 PM	4.0	14.9	59.60
3:00 PM	4.5	15.3	68.85

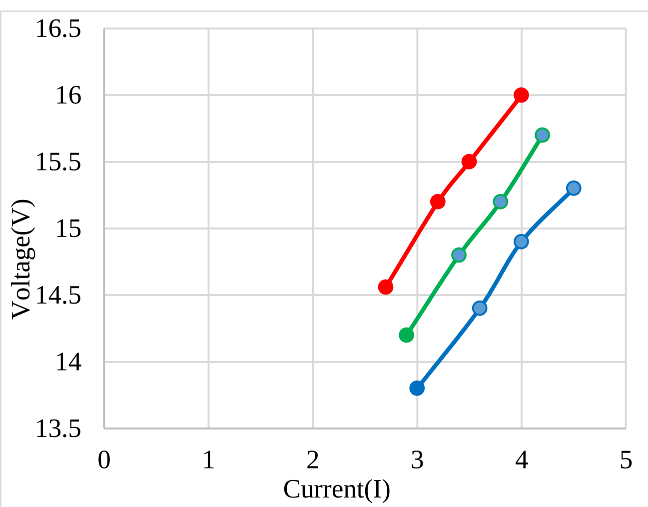

Fig. 3 Graph of voltage and current of the soot covered solar panel for 3 months

The graph depicts that an increase in the sun's intensity will increase the power produced by the solar panel. Each specific data point representing measured current and voltage values for each month helps us understand how the solar panel behaves when covered with soot.

It can be seen from the plot that the solar panel that soot covered generated lower voltages and currents, hence lower power throughout the period of the study compared with the neat solar panel.

3.3. Percentage Variance

Percentage variance in the current, voltage and power of the soot covered solar panel from the neat solar panel was obtained by applying the formula:

a) Percentage variance in voltage (V) =

$$\frac{\bar{x}\text{V neat} - \bar{x}\text{V soot covered}}{\bar{x}\text{V soot covered}} \times 100 \quad (1)$$

where: x̄-mean, V-voltage

b) Percentage variance in current (I) =

$$\frac{\bar{x}\text{I neat} - \bar{x}\text{I soot covered}}{\bar{x}\text{I soot covered}} \times 100 \quad (2)$$

where: x̄-mean, I-current

c) Percentage variance in power (W) =

$$\frac{\bar{x}\text{W neat} - \bar{x}\text{W soot covered}}{\bar{x}\text{W soot covered}} \times 100 \quad (3)$$

Where: x̄-mean,w-power

Table 8. Percentage variance in voltage (V)

Months	Neat panel (mean)	Soot covered panel (mean)	Percentage variance
December	17.98	15.32	17%
January	18.59	14.98	24%
February	18.20	14.60	25%

Table 9. Percentage variance in current (I)

Months	Neat panel (mean)	Soot covered panel (mean)	Percentage variance
December	5.48	3.83	43%
January	5.00	3.58	40%
February	5.28	3.78	40%

Table 10. Percentage variance in Power (W)

Months	Neat panel (mean)	Soot covered panel (mean)	Percentage variance
December	93.69	51.55	81.74%
January	97.29	53.80	80.84%
February	98.98	55.42	78.60%

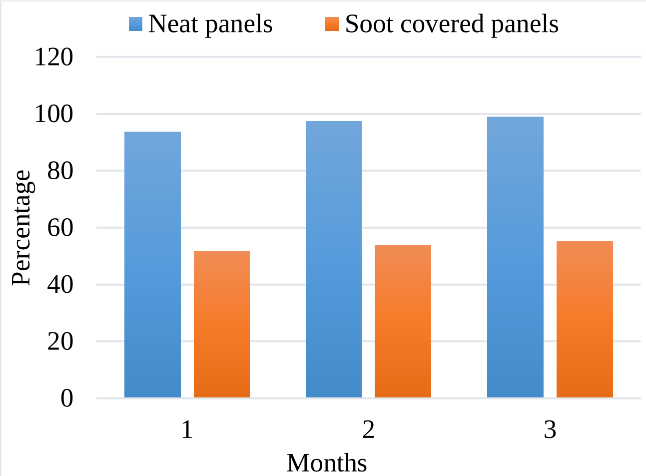

Fig. 4 Graph of power of the neat solar panels versus power of the soot covered solar panels for 3 months

The values of current and voltage obtained from the neat solar panels were within and sometimes above the data stipulated by the manufacturer (Table 1), considering the specified tolerance value of ±3%. This is not the case for the soot-covered solar panel, where the data obtained are lower than the neat solar panels and, thus, not near the data specified by the manufacturer. This clearly shows that the solar panel covered by the soot will fail to generate adequate power for the effective operation of the street light to which it is connected. Tables 8 and 9 depict the percentage by which the soot covered solar panels' current and voltage vary from the current and voltage of the neat panel.

The percentage variance shows a radical departure of the current and voltage of the soot covered panel from the neat panels' current and voltage, whose data are approximately the same as the manufacturer's specification. This obviously impacted the power generated by the panels within the study period, as shown in Figure 4. From the graph in Figure 4, it can be seen that the power generated by the soot covered panel (orange bars) per month within the period of the study is just a little above 50% of the power generated by the neat panel (blue bars) within the same month; meaning that soot adversely affected the efficiency of the solar panel thus the functioning of the solar powered street light.

3.4. Standard Deviation in Power Generated

The standard deviation in the power generated by the neat and soot covered panels during the study duration (3 months) was calculated using the Microsoft Excel Spread Sheet. The results obtained are briefly presented as follows:

a) Neat solar panel

Table 11. Standard deviation in the power of neat panels

Total Power Generated (Neat)	Mean of Power Generated	Standard Deviation (σ)
1159.83	96.65	23.14

b) Soot covered solar panel

Table 12. Standard deviation in power of soot covered panels

Total Power Generated (Soot covered)	Mean of Power Generated	Standard Deviation (σ)
643.1	53.59	9.96

3.5. Analysis of Variance (ANOVA) Test

To further strengthen the result obtained from the comparison of the power generated by both neat and soot covered panels throughout the study, an analysis of variance (single factor) test was done in Microsoft Excel as presented in this subsection as follows:

Table 13. Summary (ANOVA)

Anova: Single Factor				
Summary				
Group	**Count**	**Sum**	**Average**	**Variance**
Neat Panels	11	1034.54	94.04909	499.4309
Soot Covered Panels	11	574.25	52.20455	83.82159

Table14. Statistical Analysis (ANOVA)

ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	9630.31	1	9630.31	33.02279	1.27E-05	4.351244
Within Groups	5832.52	20	291.626			
Total	15462.8	21				

3.6. Suggested Solutions

Some measures obtained from the study that can enhance the performance and hence prevent the failure of solar powered street lights are suggested here:

i) Check the Connections: Ensure all connections between the solar panel and the inverter are secured and properly seated. Loose or faulty connections can disrupt the induction function. Inspect the wiring and connectors for any signs of damage or corrosion. If necessary, clean or replace the connectors to establish a reliable connection.

ii) Evaluate Environmental Factors: Environmental conditions can impact the performance of solar panels. Verify that any shading objects, such as trees, buildings, or debris, do not obstruct the solar panel. Ensure the solar panel is positioned at an optimal angle to maximize sunlight exposure. Consider relocating or adjusting the panel's orientation for better performance if necessary.

iii) Isolate Power Supply Problems: If there are issues with the solar panel or battery, such as insufficient charge or damage, it can lead to improper functioning. The damaged panel or battery should be promptly replaced.
iv) Replace Faulty Components: The effective performance of the solar powered street light relies on various components. If any of these components, like the induction coil or control circuitry, are faulty, they could fail to function, and they should be promptly replaced for proper functioning to be achieved.
v) Soot covered panels: Panels should be routinely cleaned with soap and water to reduce/eliminate the presence of soot on them, as this can drastically reduce the panel's efficiency.

4. Conclusion

The causes of failure and efficiency degradation of solar powered street lights in the Niger Delta region of Nigeria were investigated and discussed in the paper. While many of the causes which include power supply issues, environmental factors like shading, faulty/loose connections, and faulty components may be seen as general causes of failure and efficiency degradation of solar powered street lights, soot has been identified as a major cause of failure/ reduced efficiency of solar powered street lights in the Niger Delta region as the average values of the current, voltage, and power generated by the solar panels utilized for the study at different times- 9 AM, 11 AM, 1 PM and 3 PM of corresponding temperature and light intensity on fifteen sunny days over the period of the study show that the neat solar panels' performance over the period is better than the soot covered panels' performance as the values obtained for all the parameters investigated are far higher in the neat panels than the soot covered panels giving rise to an average percentage variance of 22%,41% and 80.39% in the current, voltage and power respectively of the soot covered panel from the neat panels.

This implies that over 80% of the power needed to charge the solar street light battery whose panels are soot covered is absent; the result is that the battery will be charged below its capacity, and the energy stored will be insufficient when required to power the street light. This, without doubt, is the major cause of the efficiency degradation of solar powered street lights in the Niger Delta Region of Nigeria. The value of the standard deviation in the power generated by the neat panels (Tables11) indicates that there is a high variability in the power generated throughout the study; therefore, the power generated by the neat panels was not only high (as indicated by the mean) but was more spread out throughout the span of the study. This is in contrast to the standard deviation of the soot covered panel (Tables12) which indicates a low variability in power generated throughout the study; therefore, the power generated by the soot covered panels was not only low (as indicated by the mean) but was clustered around the mean, signifying that the generation of power by the soot covered panels was not throughout the study but for only a limited period. This again shows that soot on panels impedes their power generation ability. Also, from the statistical analysis table obtained from the ANOVA (Table 14), it can be seen that the F value is higher than the F-critical. This indicates that the difference between the power generated by the neat and soot covered panels is significant. This signifies that the higher average of power generated by the neat panels (Table 13) compared with the lower average of the power generated by the soot covered panels was not coincidental, thus indicating that the neat panels generated high power throughout the study. The P-value of 1.2×10^{-5} which is less than the alpha, 0.05. (P-value ≤ 0.05) further shows a significant difference between the power generated by the neat panels and the soot covered panels within the study. From the suggested solutions, a routine check carried out on solar street light installations will prevent failure and improve the effectiveness of solar street light installations. This will result in the early detection of faults and other factors that may impede the efficiency of the installations, thereby enabling preventive maintenance. However, the challenge of adequate manpower and technical know-how may frustrate the implementation of the suggested measures as the companies that carry out these installations never return to the installations for routine checks/preventive maintenance after the installations are commissioned. The consequence of this challenge is the complete failure/reduced efficiency of the installations as faults that develop over time are not cleared.

To address this anomaly, governments in the Niger Delta and other regions of the country should engage companies to carry out routine checks to engender preventive maintenance of solar street light installations to sustain their efficiencies. In addition, communities where solar streetlights are installed should also be involved in sustaining the installations. They could constitute monitoring committees to regularly monitor the installations' performance and promptly report malfunction cases to designated authorities for immediate checks and possible repairs to be effected. This will greatly enhance the performance of solar street light installations in the region. Communities with efficient street light installations have nightlife, as the sustained presence of light drastically reduces the rate of criminality. This means economic activities will still occur even at night, thus undoubtedly boosting the economy of such communities and engendering local development. This will not be possible if solar streetlights fail. The darkness that will result from the failure can fester insecurity and criminality. This will negatively impact nightlife and the local economy, as security and safety cannot be guaranteed in darkness.

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