Journal of Statistics & Management Systems
ISSN 0972-0510 (Print), ISSN 2169-0014 (Online)
Vol. 29 (2026), No. 4, pp. 371–382
DOI : 10.47974/JSMS-1525

Reliability and cost analysis of hybrid solar panel system with preventive maintenance

Hemlata Thakur †
School of Mathematics
Devi Ahilya Vishwavidyalaya
Indore
Madhya Pradesh
India

Pradeep K. Joshi *
Department of Mathematics
IPS Academy
Indore
Madhya Pradesh
India

Chitaranjan Sharma §
Department of Mathematics
Prime Minister College of Excellence
Shri Atal Bihari Vajpayee Government Arts and Commerce College
Indore
Madhya Pradesh
India

Abstract

The primary aim of this study is to serve to analyze the consequences of component failure rates and the role of preventive maintenance on the overall reliability of hybrid solar panel systems. The linear differential equation technique is used to analyze various reliability measures and predict system performance by comparing the effects of preventive maintenance both theoretically and graphically. The research provides a clearer understanding of how these measures can extend system life and enhance efficiency. The study evaluates the impact of preventive maintenance on overall system efficiency, cost savings, and sustainability. The findings indicate that a well-maintained hybrid solar system

† *E-mail:* **thakur.hem78@gmail.com**
* *E-mail:* **pradeepkjoshi2@gmail.com (Corresponding Author)**
§ *E-mail:* **drcsharma3@gmail.com**

can significantly enhance energy reliability, reduce operational expenses, and improve the payback period.

Subject Classification: *90B25, 60K10, 60K20, 62NO5.*

Keywords: *Reliability, Availability, Busy period evaluation, Profit assessment, Average failure time of the system.*

1. Introduction

The increasing demand for sustainable and reliable energy solutions has led to the adoption of hybrid solar panel systems. A hybrid solar panel system combines photovoltaic (PV) solar panels with another power source, such as a solar power, battery storage, and grid or generator, to ensure a continuous and reliable energy supply. These systems are designed to maximize energy efficiency by storing excess solar energy generated during the day for use at night or during periods of low sunlight. Unlike traditional grid-tied systems that rely solely on the power grid for backup, hybrid solar systems provide greater energy independence and resilience, making them ideal for areas with frequent power outages or unreliable electricity supply. Additionally, by integrating smart inverters and energy management technology, hybrid solar panels optimize energy consumption, reduce electricity bills, and lower carbon footprints, making them a sustainable and cost -effective solution for residential and commercial application. Many authors have been investigating strategies to boost the dependability, efficiency, and cost-effectiveness of sustainable energy systems including solar. This study contributes to the larger body of knowledge on the potential of solar power and other renewable to replace or supplement traditional grid-based systems. [1] Zhang, et al. focused on assessing solar power system reliability using the Markov chain method, which enables accurate analysis of the different states and potential failures within a solar system. Mudgal, Yadav, and Mahajan [2] further explored solar energy as a viable alternative to conventional generators by combining the Markov approach with Monte Carlo simulations, providing a comprehensive look at system performance under different conditions. Acuña, Padilla, and Mercado [3] examined systems that combine solar photovoltaic (PV) and wind power, using a probabilistic approach to evaluate the reliability and effectiveness of these hybrid setups. Their study indicated that hybrid systems can enhance energy availability and reliability, making them suitable for areas with varying weather patterns. [4] Amuta, et al. developed a stochastic model for energy management, which distributes energy according to acceptable limits. This model helps improve energy allocation efficiency in unpredictable conditions, a vital aspect for off-grid systems that must meet fluctuating demands. Akinsipe, Moya, and Kaparaju [5] performed an in-depth study of PV systems, utilizing mathematical models to assess household energy requirements. This research provides insights into how off-grid systems can meet household demand, optimizing power use to ensure sustainability. [6] Rasool, et al. investigated the impact of reliability constraints on hybrid renewable energy systems, employing a techno-reliability optimization framework to examine system operation during both the planning and operational phases. Kadyan, Malik, and Gitanjali [7] analyzed a structural model resembling a household power supply system. It included a backup set of solar panels that could run concurrently if the primary power source was turned off. Khaled and El-Said [8] studied a cost analysis of renewable systems, focusing on the benefits of preventive maintenance. By applying linear differential equations, they determined how regular maintenance could reduce long-term expenses and improve system durability. Identical units were used as redundancies in most system architectures. However, keeping costly and space-consuming equipment (machines) on standby is not always practical.

In such circumstances, we may develop a few alternative units that will take over in case the main unit fails.In this article, various dependability measures have been evaluated in order to analyze hybrid solar panel systems. The system's main component is a solar panel, and its two separate components are a transformer and an inverter that runs on batteries. Depending on the demands of the home, the transformer and inverter function simultaneously if the solar panel fails. This study involves the use of solar panels while the transformer is operational. The effect of the solar panels' failure rate on key system reliability metrics is examined using a linear differential equation technique. If the inverter fails after the transformer has already failed, the household power supply will be completely disrupted. Theoretical and pictorial comparisons are used to demonstrate how preventive maintenance affects system performance.

2. System Description and Representation

This study evaluates a three-component maintenance system with a primary unit (the solar panel) and two independent components (the transformer and inverter). The main unit is more cost-effective and efficient, while two other units are different from one another and work on the main unit's failure at the same time. Three units with varying failure rates can be repaired instantly by a single server. It is assumed that there is an exponential distribution between the breakdown and restoration rates. When the core unit fails, the model fails together with the other two units. When the system is in state S0, when every unit is operational, preventive maintenance (inspection, minor repair, etc.) is provided at random intervals.

The system's states are

S_0: An operational condition in which the primary unit is running and the backup units arein standby.

S_1: A functioning condition where other units operate simultaneously while the main unit is malfunctioning and being repaired.

S_2: An operational state in which the transformer and the main unit are being repaired.

S_3: An operational state in which the main unit and other units are running while one unit transformer is being repaired.

S_3: An operational state in which the main unit and other units are running while one unit transformer is being repaired.

S_4: A failed state in which the inverter is the other cold standby unit that failed and the main unit and one cold standby unit (Transformer) are already being repaired.

S_5: Preventive maintenance is being performed on the standby unit.

Representation and Notations

S_i : State of transition, where i = 0, 1, 2, 3, 4, 5,

$\lambda/\ \lambda_1/\ \lambda_2$	Failure rate of Transformer /Solar panel / Inverter.
$\mu/\ \mu_1/\ \mu_2$	Repair rate of Transformer /Solar panel / Inverter
$M_0/\ T_0/\ I_0$	The main unit Solar panel /Transformer/ Inverter areoperative
$MU_r/\ TU_r/\ IU_r$	The Failed main unit Solar panel /Transformer/ Invertor is under repair
$M_p/\ T_p/\ I_p$	The main unit Solar panel /Transformer/ Inverter are under preventive maintenance
α :	A fixed rate for scheduling preventive maintenance on a unit
β	Completion of preventive maintenance at a steady pace

3.State Transition Diagram

Up State

$S_0 \equiv (M_0, T_0, I_0)$, $S_1 \equiv (MU_r, T_0, I_0)$ $S_2 \equiv (MU_r, TU_r, I_0)$

$S_3 \equiv (M_0, TU_r, I_0)$ $S_5 \equiv (M_p, T_p, I_p)$

Down State

$S_4 \equiv (MU_r, TU_r, IU_r)$

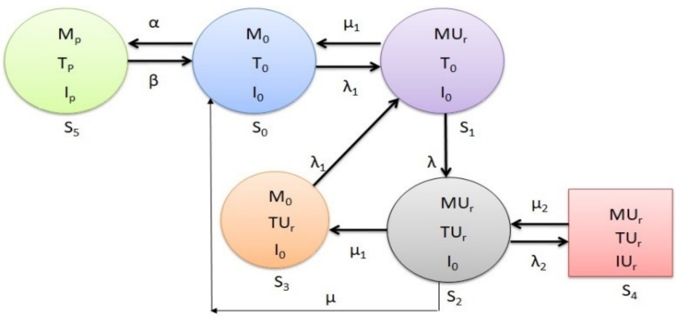

Figure 1
State transition diagram for the system

4. Average Failure Time of the System

In figure 1, suppose P(t) represents the probability vector representing the state distribution at instant t. $P_{i(t)}$ denotes the chance of occupying state S_i at time t, wherein t is a non-negative value ($t \geq 0$).

P (0) be characterized as initial condition

$$P(0) = [P_0(0), P_1(0), P_2(0), P_3(0), P_4(0), P_5(0)]$$

Given initial value

$$P(0)=[1,0,0,0,0,0] \tag{1}$$

A mathematical relationship, expressed as a differential equation,

$$\frac{dp_0(t)}{dt} = -(\lambda_1+\alpha)P_0(t)+\mu_1 P_1(t)+\mu P_2(t)+\beta P_5(t)$$

$$\frac{dp_1(t)}{dt} = -(\mu_1+\lambda)P_1(t)+\lambda_1 P_0(t) + \lambda_1 P_3(t)$$

$$\frac{dp_2(t)}{dt} = -(\lambda_1+\mu_1+\lambda_2)P_2(t)+\lambda P_1(t)+\mu_2 P_4(t)$$

$$\frac{dp_3(t)}{dt} = -\lambda_1 P_3(t) + \mu_1 P_2(t)$$

$$\frac{dP_4(t)}{dt} = -\mu_2 P_4(t) + \lambda_2 P_2(t)$$

$$\frac{dP_5(t)}{dt} = -\beta P_5(t) + \alpha P_0(t) \tag{2}$$

The following is a matrix representation of the differential equation mentioned above.

$$\frac{dp(t)}{dt} = MP$$

$$M=\begin{bmatrix} -(\lambda_1+\alpha) & \mu_1 & \mu & 0 & 0 & \beta \\ \lambda_1 & -(\mu_1+\lambda) & 0 & \lambda_1 & 0 & 0 \\ 0 & \lambda & -(\lambda_1+\mu_1+\lambda_2) & 0 & \mu_2 & 0 \\ 0 & 0 & \mu_1 & -\lambda_1 & 0 & 0 \\ 0 & 0 & \lambda_2 & 0 & \mu_2 & 0 \\ \alpha & 0 & 0 & 0 & 0 & -\beta \end{bmatrix} \tag{3}$$

To avoid complexity, a simplified method is employed to determine the MTSF because it is extremely difficult to find the precise, time-dependent behavior of the system (the "transient solution"). This approach involves manipulating the system's transition rate matrix, denoted as "M." Following that, the vertical and horizontal components that represent the terminal state are eliminated. The new matrix "A," which is created by this operation, contains the transition rates between the non-absorbing phases. The MTSF is then determined using this matrix A.

The MTSF has an explicit expression provided by

$$\text{MTSF} = E[TP(0) \rightarrow (absorbing)] = P(0)(-A^{-1})\begin{bmatrix}1\\1\\1\\1\\1\end{bmatrix} \tag{4}$$

where

$$A = \begin{bmatrix} -(\lambda_1+\alpha) & \lambda_1 & 0 & 0 & \alpha \\ \mu_1 & -(\mu_1+\lambda) & \lambda & 0 & 0 \\ \mu & 0 & -(\lambda_1+\mu_1+\lambda_2) & \mu_1 & 0 \\ 0 & \lambda_1 & 0 & -\lambda_1 & 0 \\ \beta & 0 & 0 & 0 & -\beta \end{bmatrix}$$

$$\text{MTSF} = \frac{((\lambda_1+\lambda_2-\mu)\,[(\alpha+\beta)(\lambda\lambda_1+\lambda\lambda_2+\mu_1^2\lambda_1\ \mu_1+\lambda_2\mu_1)+\beta\lambda_1(\lambda_1+\lambda_2+\mu_1+\lambda)+\beta\lambda\mu_1]}{\beta\lambda\lambda_1(\lambda_1+\lambda_2-\mu)^2} \quad (5)$$

5. Availability of Steady -State

Starting probabilities of being in each state are identical to those used in the system's reliability analysis (time to failure). This typically implies that at t=0, the system is considered to be fully functional.

The differential equation can be expressed as

$$\dot{P} = \text{M P}$$

$$\begin{bmatrix} \dot{p}_0 \\ \dot{p}_1 \\ \dot{p}_2 \\ \dot{p}_3 \\ \dot{p}_4 \\ \dot{p}_5 \end{bmatrix} = \begin{bmatrix} -(\lambda_1+\alpha) & \mu_1 & \mu & 0 & 0 & \beta \\ \lambda_1 & -(\mu_1+\lambda) & 0 & \lambda_1 & 0 & 0 \\ 0 & \lambda & -(\lambda_1+\mu_1+\lambda_2 P_1) & 0 & \mu_2 & 0 \\ 0 & 0 & \mu_1 & -\lambda_1 & 0 & 0 \\ 0 & 0 & \lambda_2 & 0 & \mu_2 & 0 \\ \alpha & 0 & 0 & 0 & 0 & -\beta \end{bmatrix} \begin{bmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \end{bmatrix}$$

Availability is obtained from

$$A(\infty) = 1 - P_4(\infty) \quad (6)$$

In a steady state, since the probabilities are no longer changing, these rates of change become zero.

$$A\,P(\infty) = 0 \quad (7)$$

The representation of the matrix is provided by

$$\begin{bmatrix} -(\lambda_1+\alpha) & \mu_1 & \mu & 0 & 0 & \beta \\ \lambda_1 & -(\mu_1+\lambda) & 0 & \lambda_1 & 0 & 0 \\ 0 & \lambda & -(\lambda_1+\mu_1+\lambda_2 P_1) & 0 & \mu_2 & 0 \\ 0 & 0 & \mu_1 & -\lambda_1 & 0 & 0 \\ 0 & 0 & \lambda_2 & 0 & \mu_2 & 0 \\ \alpha & 0 & 0 & 0 & 0 & -\beta \end{bmatrix} \begin{bmatrix} P_0(\infty) \\ P_1(\infty) \\ P_2(\infty) \\ P_3(\infty) \\ P_4(\infty) \\ P_5(\infty) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (8)$$

$$P_0(\infty) + p_1(\infty) + P_2(\infty) + p_3(\infty) + p_4(\infty) + p_5(\infty) = 1 \quad (9)$$

Equation (9) is replaced into one of equation (8)'s redundant rows to find $P_4(\infty)$. The matrix equivalent of the linear equations.

$$\begin{bmatrix} -(\lambda_1+\alpha) & \mu_1 & \mu & 0 & 0 & \beta \\ \lambda_1 & -(\mu_1+\lambda) & 0 & \lambda_1 & 0 & 0 \\ 0 & \lambda & -(\lambda_1+\mu_1+\lambda_2 P_1) & 0 & \mu_2 & 0 \\ 0 & 0 & \mu_1 & -\lambda_1 & 0 & 0 \\ 0 & 0 & \lambda_2 & 0 & \mu_2 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} P_0(\infty) \\ P_1(\infty) \\ P_2(\infty) \\ P_3(\infty) \\ P_4(\infty) \\ P_5(\infty) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \tag{10}$$

For fig.1,the solution of (10) can be used to determine the steady state availability.

The precise expression for $A(\infty)$

$$A(\infty) = \frac{N}{D} \tag{11}$$

where

N = $\lambda_1\mu_2\,[\lambda_1\,(\beta+\lambda)+2\,\beta(\mu_1+\lambda)]+\mu_1\mu_2[\mu_1(\alpha+\beta)+\beta\lambda+\alpha\lambda_1]+\lambda\lambda_1\,\mu_2(\alpha-\mu)$

D = $\lambda_1\mu_2[\lambda_1\,(\beta+\lambda)+2\,\beta(\mu_1+\lambda)]+\mu_1\mu_2[\mu_1(\alpha+\beta)+\beta\lambda+\alpha\lambda_1]+\lambda\lambda_1\mu_2(\alpha-\mu)+\beta\lambda\lambda_1\lambda_2$

6. Busy Period Analysis

The differential equations used to model this problem contain the same mathematical structure as the ones used to analyze availability.The initial value herein is consistent with those of the reliability case. The busy period B(∞) is computed through

$$B(\infty) = 1-[p_0(\infty)+p_5(\infty)] = 1-\frac{N}{D} \tag{12}$$

Where, N = $\beta\lambda\,(\lambda_1\,\lambda_2+\mu_1\mu_2)+\beta\,\lambda_1\mu_2(\lambda_1+\lambda+\mu_1)$

D =$\lambda_1\mu_2[\lambda_1\,(\beta+\lambda)+2\,\beta(\mu_1+\lambda)]+\mu_1\mu_2[\mu_1(\alpha+\beta)+\beta\lambda+\alpha\lambda_1]+\lambda\lambda_1\mu_2(\alpha-\mu)+\beta\lambda\lambda_1\lambda_2$

7.Preventive Maintenance's Anticipated Frequency

Using the conditions from the reliability example, the steady state is applied to determine the Preventive maintenance frequency per time interval, K(∞).

$$K(\infty) = p_5(\infty) = \lambda\lambda_1^2\mu_2+\alpha\lambda\lambda_1\,\mu_2 - \lambda\lambda_1\mu\mu_2+\alpha\mu_1^2\mu_2+\alpha\lambda_1\mu_1\mu_2/\,D$$

8. Cost Analysis

The predicted cumulative gain over a period invested in the state's system is given by the estimated total benefit within a time frame sustained under steady conditions, characterized by

Profit = Revenue –Expenses

$$PF(\infty) = R\,A(\infty) - C_0\,B(\infty) - C_1\,K(\infty)$$

Where;

PF(∞)= Reflects the system's profitability

R = Revenue generated per unit of operational time
C_0 = Expenses incurred during repairs
C_1 = The expense per preventive maintenance service

9. Special Case:

If preventive maintenance cannot be performed, failure of the system is determined by

$$\text{MTSF} = \frac{a_1}{a_3}$$

Where

$$a_1 = \lambda(\lambda_1 + \lambda_2) + (\lambda_1 + \mu_1)(\lambda_1 + \lambda_2 + \mu_1 + \lambda)$$

$$a_2 = \lambda\lambda_1(\lambda_1 + \lambda_2 - \mu)$$

The availability of the system is given by;

$$A_1(\infty) = 1 - P_4(\infty) = \frac{N_1}{D_1}$$

Where;

$$N_1 = \lambda\lambda_1\mu_2 + \mu\mu_2(\lambda+\lambda_1) + \mu_1\mu_2(\lambda_1 + \mu_1+\lambda+\mu)$$

$$D_1 = \lambda\lambda_1(\lambda_1 + \lambda_2 - \mu + \mu_2) + \mu\mu_2(\lambda+\lambda_1)+\mu_1\mu_2(\lambda_1 + \mu_1+\lambda+\mu)$$

The system's steady state busy time is determined by

$$B_1(\infty) = \frac{N_2}{D_1}$$

Where;

$$N_2 = \lambda\lambda_1(\lambda_1 + \lambda_2 - \mu + \mu_2) + \lambda_1\mu_2\,\mu+\mu_1\mu_2(\lambda+\lambda_1)$$

The total profit expected from the system is ascertained by

$$\text{Profit} = R\,A_1(\infty) - C_0\,B_1(\infty)$$

10. Graphical and Numerical Analysis of Various Reliability Measures

In tables 1 and 2, the system's failure rate λ_1 is compared with the characteristics MTSF, $A(\infty)$, $B(\infty)$, and $PF(\infty)$ for fixed values of $\lambda = 0.2$, $\beta = 0.6$, $\lambda_2 = 0.3$, $\mu = 0.2$, $\mu_1 = 0.5$, $\mu_2 = 0.4$, $\alpha = 0.3$, η $C_0 = 1000$, and $C_1 = 100$.

Table 1

Failure rate in relation to MTSF (with and without PM) and System Availability

λ_1 (Failure rate)	The system's MTSF with PM	The system's MTSF without PM	The system's Availability with PM	The system's Availability without PM
0.1	251.2500000	185.0000000	0.977667494	0.983050847
0.2	103.3333333	78.33333333	0.966480447	0.957142857
0.3	62.29166667	48.33333333	0.96069869	0.926829268
0.4	44.25000000	35.00000000	0.957796014	0.894736842
0.5	34.41666667	27.66666667	0.956521739	0.862385321

0.6	28.33333333	23.09523810	0.95620438	0.830645161
0.7	24.24107143	20.00000000	0.956461645	0.800000000
0.8	21.31944444	17.77777778	0.95706619	0.770700637
0.9	19.13888889	16.11111111	0.957878315	0.742857143
1.0	17.45454545	14.81818182	0.958810069	0.716494845

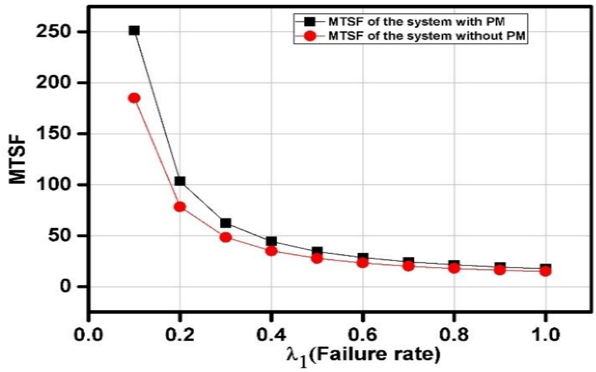

Figure 2
Mean failure time against failure rate

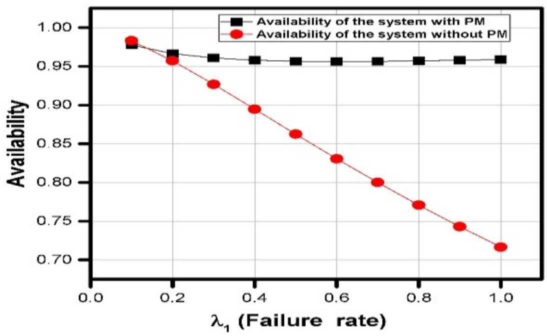

Figure 3
Availability against Failure Rate

Table 2
Failure rate in concerning the busy period (with and without PM) and Profit

λ_1 (Failure rate)	The model Busy time with the PM	The model Busy time without PM	The model profit with PM	The model profit without PM
0.1	0.290322581	0.618247299	923.0221567	883.0508475
0.2	0.346368715	0.642201835	906.6822851	857.1428571
0.3	0.388646288	0.660102115	896.9635948	826.8292683
0.4	0.422039859	0.674224344	890.9093765	794.7368421
0.5	0.449275362	0.685785536	887.0327994	762.3853211

0.6	0.472019465	0.695504665	884.5186573	730.6451613
0.7	0.491361437	0.703839122	882.8903546	700.0000000
0.8	0.508050089	0.711096939	881.8551332	670.7006369
0.9	0.522620905	0.717495086	881.2259807	642.8571429
1.0	0.535469108	0.723192020	880.8795963	616.4948454

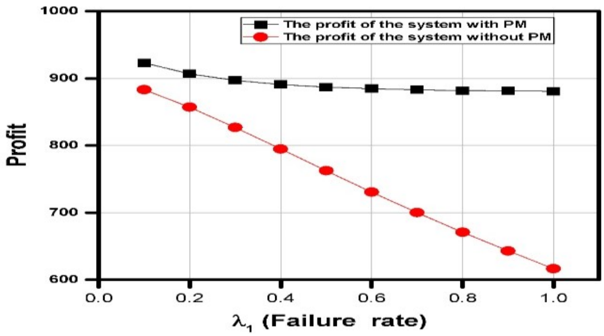

Figure 4
Profit against Failure Rate

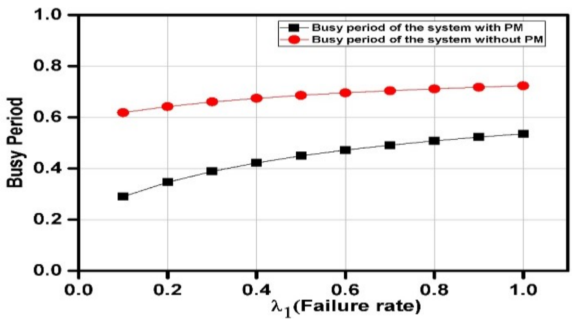

Figure 5
Busy Period against Failure Rate

11. Results and Discussion

The study evaluates the reliability of hybrid solar panel systems by analyzing Table 1 and Table 2 performance metrics. The impact of preventive maintenance is also assessed by comparing system performance with and without preventive maintenance. The results show how preventive maintenance strategies influence system reliability and efficiency**.** The analysis shows a clear inverse relationship between failure rate and MTSF, as depicted in Figure 2. As foreseen, an increase in failure rate directly correlates with a decrease in MTSF, indicating more frequent system breakdowns. Notably, the implementation of preventive maintenance (PM) significantly elevates MTSF across all failure rates. Similarly, Figure 3 illustrates that system availability declines as the failure rate increases. However, the system employing PM consistently maintains higher availability. Without PM, a substantial drop in availability occurs at higher failure rates. Furthermore, Figure 5 demonstrates that the busy period of repair service increases as the failure rate rises. Without maintenance, the busy period is higher, indicating more frequent and longer repair times. With preventive maintenance, the busy period remains comparatively lower, suggesting that maintenance interventions reduce the downtime of the system. Finally, Figure 4 shows that earnings diminish with growth in breakdown rate for both scenarios, but the system with PM consistently yields higher profits. At $\lambda_1 = 0.1$, the profit with PM is 923.02, compared to 883.05 without PM. This disparity widens at higher failure rates, with profits dropping to 880.87 with PM and 616.49 without PM at $\lambda_1 = 1.0$. This highlights that preventive maintenance enhances reliability and availability and significantly improves financial performance by reducing operational delays and maintenance expenses.

12. Conclusion

This study considers the outcome regarding the component failure rates and preventive maintenance concerning the reliability of hybrid solar panel systems using linear differential equations techniques. The analysis demonstrates that preventive maintenance significantly enhances system performance by increasing MTSF, improving operational reliability, and ensuring better overall efficiency. Graphical and theoretical comparisons reveal that systems with preventive maintenance maintain higher reliability and profitability than those without maintenance. Findings indicate that as the failure rate increases, system availability and profit decrease, emphasizing the need for regular maintenance to sustain optimal operation. With the rising demand for sustainable and efficient energy solutions, hybrid solar panel systems are becoming a popular choice for homes and businesses. They offer an eco-friendly and financially viable alternative to traditional electricity sources. By understanding the potential benefits and challenges associated with hybrid solar systems, stakeholders can effectively strategize their energy solutions and contribute to a more sustainable future. Moreover, the findings encourage collaboration among various sectors to enhance the adoption of renewable energy technologies.

References

[1] P. Zhang, W. Li, S. Li, Y. Wang, and W. Xiao, “Reliability assessment of photovoltaic power systems: Review of current status and future perspectives,” *Applied Energy*, vol. 104, pp. 822–833 (2013).

[2] S. M. Mudgal, A. K. Yadav, and V. Mahajan, “Reliability evaluation of power system network with solar energy,” in Proceedings of the 8th International Conference on Power Systems (ICPS), *IEEE* (2019), pp. 1–6.

[3] L. G. Acuña, R. V. Padilla, and A. S. Mercado, "Measuring reliability of hybrid photovoltaic–wind energy systems: A new indicator," *Renewable Energy,* vol. 106, pp. 68–77 (2017).

[4] E. O. Amuta, S. T. Wara, A. F. Agbetuyi, U. A. Adoghe, and A. Olajube, "Reliability assessment of an off-grid hybrid micro-grid power system (HMPS) for a remote community in Nigeria," *IOP Conference Series: Earth and Environmental Science,* vol. 655, no. 1, p. 012053 (2021).

[5] O. C. Akinsipe, D. Moya, and P. Kaparaju, "Design and economic analysis of an off-grid solar PV system in Jos, Nigeria," *Journal of Cleaner Production*, vol. 287, p. 125055 (2021), doi: 10.1016/j.jclepro.2020.125055.

[6] M. H. Rasool, U. Perwez, Z. Qadir, and S. M. H. Ali, "Scenario-based techno-reliability optimization of an off-grid hybrid renewable energy system: A multi-city study framework," *Sustainable Energy Technologies and Assessments*, vol. 53, p. 102411 (2022), doi: 10.1016/j.seta.2022.102411.

[7] S. Kadyan, S. C. Malik, and Gitanjali, "Stochastic analysis of a three-unit non-identical repairable system with priority to main unit for operation and repair," *International Journal of Reliability and Safety*, vol. 14, no. 2–3, pp. 182–198 (2020).

[8] M. Khaled and El-Said, "Cost analysis of a system with preventive maintenance using the Kolmogorov forward differential equation method," *American Journal of Applied Sciences*, vol. 5, no. 4, pp. 405–410 (2008).

Received April, 2025