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Evaluation of PV Module Reliability Across A Temperature Range, Spanning A Period of 0 and 35 Years

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Abstract Solar energy, being both abundant and environmentally friendly, holds great promise as a renewable energy source. It can be converted into electricity through photovoltaic (PV) modules, which are crucial in the shift towards renewable energy. While PV modules are typically designed for a 25-year lifespan, their performance is significantly affected by environmental factors, especially ambient temperature. PV modules are normally tested under standardized conditions (25°C, 1000 W/m², AM1.5), that differ from real-world outdoor environments. However, temperature fluctuations can reduce their efficiency and accelerate material degradation, potentially undermining the reliability of these PV modules. This study aims to analyze the reliability of PV modules in Burkina Faso, employing Weibull's law and the Arrhenius model to evaluate the impact of temperature fluctuations. A mathematical model was developed and implemented in Matlab/Simulink, with simulations conducted at 25°C to 40°C. This methodology allows for examining PV module durability and reliability under local conditions. The study results show that a 1°C rise in ambient temperature causes a 0.5% drop in PV module efficiency. Lifespan and average lifespan (MTTF) are reduced by around 1.8% for each additional degree and by 0.06% with each 1W/m² in solar irradiation. The failure probability density peaks after 7 years at 40°C and 11 years at 25°C, then decreases until it disappears after 20 years. Meanwhile, the failure rate continues to rise throughout the life of the PV module. These results highlight the importance of considering thermal conditions when using PV modules, as high temperature can adversely affect their long-term performance. To enhance the durability and reliability of these modules, limiting their exposure to heat is essential.

Keywords: *Reliability, Photovoltaics, temperature, Weibull, Arrhenius*

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1. Introduction

Solar energy is abundant, environmentally friendly, and non-polluting, making it a highly attractive energy source, especially through photovoltaic (PV) modules that convert sunlight into electricity [1,2]. These PV modules, which are crucial components of photovoltaic systems, come with warranties of up to 25 years, depending on the manufacturer [3,4]. However, manufacturers often lack reliable data to validate this longevity. Most provide a warranty that guarantees less than a 20% loss in the nominal power of their PV modules over 25 years [5]. To rapidly evaluate the reliability of PV modules before deployment, various tests are conducted according to IEC standards. Typically, these PV modules are tested under standardized conditions (25°C, 1000 W/m², AM1.5) [6,7], which do not represent actual operating conditions, where ambient temperature in Burkina Faso can reach up to 40°C in April and May. Temperature fluctuations can reduce energy performance and accelerate the aging of materials like solar cells and encapsulants used in PV modules, potentially compromising their long-term reliability. The reliability of PV modules is a well-researched field, as evidenced by the work of Tsuda and al. [8], Vázquez and Rey-Stolle [9], and Laronde et al. [10], who developed accelerated tests for assessing crystalline silicon modules following IEC 61215 [8]. However, these studies often overlook the actual conditions of accelerated tests and their inherent random, limiting the applicability of the results to real-world scenarios. In contrast, Voiculescu et al [11] have introduced more nuanced approaches that account for the variability of environmental conditions, using statistical analysis to improve predictions of PV module reliability. Our research stands out by developing a model that accurately simulates the impact of environmental factors, particularly ambient temperature fluctuations, on PV module reliability. By using the Arrhenius acceleration law and the Weibull distribution, our approach provides a more comprehensive and realistic understanding of PV module lifespan under various conditions. This study aims to evaluate the reliability of a PV module over a span of 0 to 35 years. Several lifetime distributions are cited t in the literature, with the exponential, the Weibull, and the log-normal distributions being commonly used in PV module reliability analysis [5]. The Weibull distribution is particularly significant for practical applications, as it is widely used for reliability, lifetime, and survival analyses [5,10]. In this article, we employ this distribution to propose a mathematical model of PV module lifespan that incorporates a correction factor related to ambient and PV module temperatures and implement it in Matlab/Simulink. Our approach combines Weibull's law for modeling PV module lifespan and failures with the Arrhenius model to assess the impact of ambient temperature on the degradation of materials and encapsulants used in PV modules. This study addresses the reliability of PV modules in the context of climate change, particularly focusing on temperature variations in Burkina Faso. To gain a deeper understanding of PV modules' behavior, we analyze their reliability and estimate their average lifespan (MTTF) over a period ranging from 0 to 35 years. Simulations will be conducted by varying the ambient temperature from 25°C to 40°C, with a constant solar irradiation of 1000 W/m². The remainder of this study includes PV module reliability analysis in section 2. In section 3, we apply a mathematical model to assess PV module reliability, examining the effect of ambient temperature on PV module temperature and performance. Results and discussions are presented in section 4. The conclusion is given in section 5.

2. PV Module Reliability Analysis

PV module reliability analysis and lifespan estimation are complementary processes aimed at ensuring the PV module's performance and longevity. Reliability analysis assesses the PV module's ability to function correctly over a specific period by identifying potential failures and predicting their occurrence through stress tests, aging simulations, and statistical studies. Lifespan estimation, on the other hand, forecasts how long the PV module will operate efficiently before its performance begins to degrade, utilizing mathematical models and tools such as Arrhenius law and Weibull distribution [5]. Together, these analyses are essential for ensuring that the PV module delivers the expected energy output throughout its lifespan while also facilitating efficient planning of costs, replacement, and maintenance.

2.1. Weibull Distribution

Distributions commonly used for assessing component reliability include the exponential, the Weibull, and the lognormal distributions [5]. Among these, the Weibull distribution has gained particular significance in practical applications, such as reliability analysis and lifetime and survival studies [12]. It is distinguished by its simplicity and its ability to model a component's behavior across all three phases of its lifespan: youth period, useful life period, and aging period [5,13]. The Weibull distribution is especially versatile for modeling the reliability and lifespan of components with variable failure rates [5], including PV modules. In its most general form, it is defined by three parameters (β, η, and γ) and is characterized by the following equation (1) [14]:

$$R(t) = \exp\left(-\left(\frac{t-\gamma}{\eta}\right)^{\beta}\right) \tag{1}$$

where η is the scale parameter of the Weibull distribution in hours (h), β is the shape parameter of the Weibull distribution, which we consider to be constant whatever the test conditions, and γ is the position parameter of the Weibull distribution. Due to the adjustable parameters of the Weibull distribution, it can describe various scenarios, making it adaptable to different types of failure data. In this study, we assume that the PV module is being used for the first time, setting the position parameter to zero (γ = 0). Consequently, our research focuses on the two-parameter Weibull model to develop a mathematical framework that incorporates the effects of ambient and PV module temperatures on reliability in real-world scenarios, under the assumption that their lifespan follows a Weibull distribution. The mathematical model we propose is represented by equation (2) [12] by taking relative humidity (hr) equal 100%:

$$R(t) = \exp\left(-\frac{T_{\text{mod}}(t)}{T_{amb}}\left(\frac{t}{\eta}\right)^{\beta}\right) \tag{2}$$

It's the modified Arrhenius model, where T_{amb} is the ambient temperature; $T_{\text{mod}}(t)$ represents the temperature of the PV module at time t characterized by equation (3) [12]:

$$T_{\text{mod}}(t) = T_{\text{mod}} + 293\left(\frac{t}{\eta}\right) \tag{3}$$

The term T_{mod} in equation (3) represents the PV module temperature expressed by the relation (4) [3,5]:

$$T_{\text{mod}} = T_{amb} + \frac{G}{800}\left(T_{NOCT} - 20\right) \tag{4}$$

with, T_{NOCT} the nominal operating temperature of a photovoltaic cell. The term $293\left(\frac{t}{\eta}\right)$ in equation (3) represents a linear rise in the PV module's temperature as time progresses. We multiply the time t by $\frac{293}{\eta}$ to obtain an increase of 293 Kelvin over the nominal lifespan of the PV module [12].

Assuming $\alpha = \left(\frac{T_{\text{mod}}(t)}{T_{amb}}\right)$ equation (2) representing the survival function of a PV module becomes equation (5) [12]:

$$R(t) = \exp\left(-\alpha\left(\frac{t}{\eta}\right)^{\beta}\right) \tag{5}$$

where α is the correction factor related to PV module temperature and ambient temperature; β is the shape parameter of the Weibull distribution. The use of this parameter offers the possibility of guiding a diagnosis. It can be representative of certain failure modes. η is the scale parameter of the Weibull distribution in hours (h).

2.2. Reliability Under Constant Stress Conditions

Numerous studies in the literature have shown that temperature significantly affects PV module performance. The Arrhenius model is particularly relevant for describing the impact of ambient temperature on PV module lifespan, as it quantifies the relationship between temperature and degradation rate [5]. This makes it a suitable choice for predicting lifespan in our study. By applying this model, we can more accurately estimate how long a PV module will operate efficiently before experiencing significant heat-induced degradation, as represented by equation (6) [5]:

$$\tau = \exp\left(\gamma_0 + \frac{\gamma_1}{T_{\text{mod}}}\right) \tag{6}$$

with, T_{mod} the PV module temperature; γ_0 and γ_1, the parameters of the Arrhenius model.

We emphasize that in the Weibull distribution, the scaling parameter represents the lifetime of the PV module, so η = τ. When nominal conditions are held constant, temperature remains a stable parameter. By using equation (5) and (6), the reliability function is given by equation (7) [5,12]:

$$R(t) = \exp\left(-\alpha\left(\frac{t}{\exp\left(\gamma_0 + \frac{\gamma_1}{T_{\text{mod}}}\right)}\right)^{\beta}\right) \tag{7}$$

This reliability function provides insight into how power losses affect the lifespan of a PV module. It is directly linked to the PV module's power losses, and by inverting equation (7), we determine indirectly the time required for the PV module to reach a specific target power level. By calculating the time, it takes for the PV module's power to decline to a certain level, we can identify when the PV module's performance no longer meets expectations. The reliability of a PV module at time t is defined as the probability that the PV module will operate without failure during the period [0, t], meaning it functions correctly up to time. The key reliability functions associated with the Weibull distribution are as follows [4,15,16]:

- Failure probability density given by equation (8):

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1}.exp\left(-\left(\frac{t}{\eta}\right)^{\beta}\right) \tag{8}$$

- Instant failure rate expressed by relation (9):

$$\lambda(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \tag{9}$$

- Average lifespan or time to first failure given by equation (10):

$$MTTF = \eta.\Gamma\left(1 + \frac{1}{\beta}\right) \tag{10}$$

where β and η are the parameters of the Weibull distribution and Γ, the gamma function defined by equation (11):

$$\Gamma(\alpha) = \int_0^{+\infty} x^{\alpha-1} e^{-x} dx \tag{11}$$

It's important to mention that these functions enable the modeling and analysis of failure behavior in PV module, aiding in decision-making related to design, maintenance, and reliability management.

2.3. Reliability Under Stochastic Conditions

As mentioned in Section 1, variables in accelerated life time models can be stochastic, particularly when a PV module is exposed to natural conditions. To assess his reliability under nominal conditions, three steps must be follows [5]:

- Determine the parameters of the lifetime distribution, especially the values of the scale factor and shape factor of the Weibull distribution for each severity level;
- Calculate the parameters of the Arrhenius model, including the values of γ_0 and γ_1 for this model;
- Adjust reliability functions, converting those measured at elevated temperatures to correspond to nominal conditions.

2.4. Meteorological Parameters

Ambient temperatures data for Ouagadougou, Gaoua, and Dori, collected by the National Meteorological Agency (ANAM) from 2007 to 2021, were processed into annual average using Python. Figure 1 shows the mean annual temperatures in these cities exceed 22°C, with Dori recording the highest temperature. The lowest temperature (T-MIN) occurred in 2008 and 2021in Gaoua, while the highest temperature (T-MAX) was observed in 2021 in Dori and Ouagadougou.

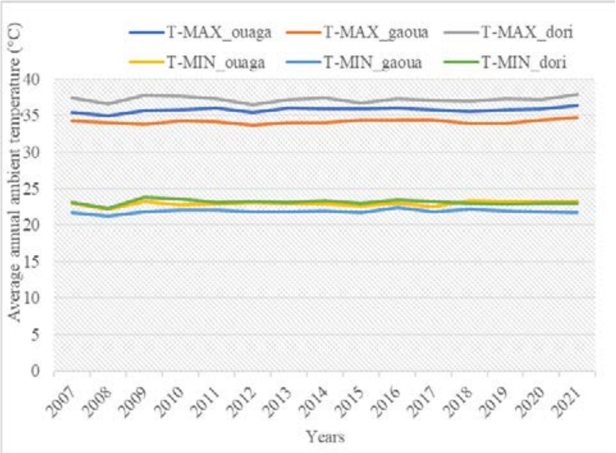

Figure 1. Average annual ambient temperature data for ANAM from 2007-2021

Figure 1 show that the average annual temperatures for these three (3) zones range between 22°C and 38°C. However, periods extreme heat can negatively affect the performance of PV installations. For instance, high temperatures, particularly in Dori, reduce the efficiency of PV modules by decreasing the voltage produced by solar cells, thereby diminishing energy output. By analyzing meteorological data such as ambient temperature and solar irradiance across different zones, we can predict the behavior and their lifespan of PV modules. Considering these environmental variables allows for better anticipation of long-term performance and optimization of PV installation management, ensuring both performance and durability are tailored to the specific climatic conditions of each region.

3. Application to Photovoltaic Modules

In this section, we detail the development and implementation of our model in Matlab/Simulink to analyze the reliability of PV modules and estimate their lifespan.

3.1. Modeling in Matlab/Simulink

Modeling and assessing the temporal reliability of a PV module using Matlab/Simulink is a well-established method in engineering and solar energy research. Figure 2 presents a typical schematic of the Simulink model developed in this study, which we developed and implemented in Matlab/Simulink to simulate the behavior of the PV module.

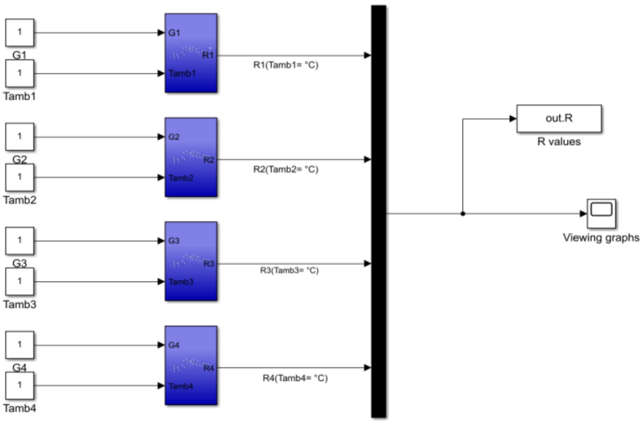

Figure 2. Simulink model developed

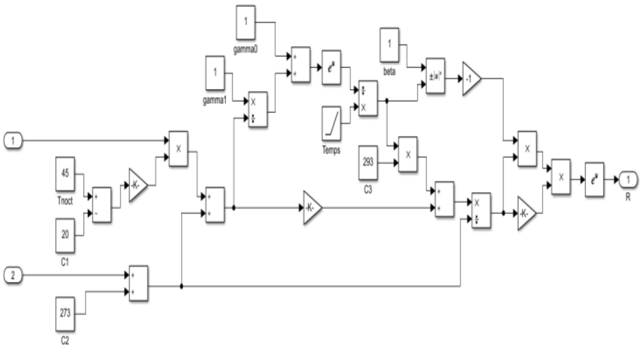

Figure 3. Calculation flow chart for the input and output of variables

Figure 2 shows four different blocks, with solar irradiance and ambient temperature as inputs, and R reliability values as outputs. Figure 3 shows the calculation flow diagram for the input and output variables in each of the four blocks. It shows the interconnection of the input variables (solar irradiance and ambient temperature) and their transformation into output (reliability R) through the various calculation stages.

3.2. Simulation

In this study, we did not implement an accelerated aging process. Instead, we conducted simulations using Matlab/Simulink software, based on the following criteria:

- the solar irradiance is taken to be G =1000 W/m²;
- the Weibull distribution shape parameter is $\beta = 2.6$ [5,16];
- the parameters of the Arrhenius acceleration law are $\gamma_0 = 5.23$ and $\gamma_1 = 2102$ [5];
- the lifespan is determined using equation (6).

As outlined in subsection 2.4, we conducted our simulations at ambient temperatures ranging from 25°C to 40°C with 5°C increments.

We emphasize that this work is based on a silicon PV module. In fact, silicon technology alone represents more than 90% of the technologies available on the photovoltaic market [3].

4. Results and Discussion

The performance of PV systems is heavily influenced by climatic factors, with temperature being the most critical. The temperature of PV modules is essential to the energy output of PV systems (PVS), and it varies in response to other factors such as solar irradiance, ambient temperature, and relative humidity [17]. In the following subsection, we examine the influence of ambient temperature on PV module temperature.

4.1. Effect of Ambient Temperature on PV Module Temperature

The PV module temperature (T_{mod}) has a linear relationship with the ambient temperature (T_{amb}). As the ambient temperature increases, so does the PV module temperature. The layered design of PV modules creates a greenhouse effect, which further amplifies the rise in the temperature of the solar cells. Over the 15-year period from 2007 to 2021, the average annual ambient temperature ranged from 22°C to 38°C, with the lowest recorded in 2008 and the highest in 2021. Using equation (4), we can graphically represent the variation in PV module temperature variation as a function of ambient temperature for an irradiation of G = 1000 W/m², as shown in Figure 4.

Figure 4 illustrates that as ambient temperature rises, PV module temperature increases linearly. Additionally, the impact of increasing ambient temperature on the electrical efficiency of a PV module can be determined using the temperature-adjusted PV efficiency equation developed by Evans and Florschuetz [17]:

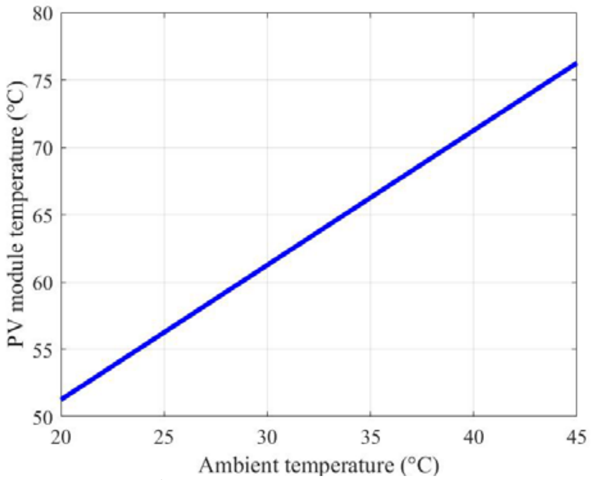

Figure 4. Variation of PV module temperature with ambient temperature

$$\eta_{\text{mod}}\eta_{T_{ref}}\left[1-\beta_{ref}\left(T_{\text{mod}}-T_{ref}\right)\right] \qquad (12)$$

with η_{mod} the PV module electrical efficiency, T_{mod} the PV module temperature, $\eta_{T_{\text{ref}}}$ the PV module electrical efficiency at reference temperature, T_{ref} the PV module reference temperature and β_{ref} the power temperature coefficient.

Evans and Florschuetz equation provide a reliable approach to quantifying the impact of ambient temperature on PV module efficiency. It enables yield correction based on temperature variations, which is essential for accurately assessing the real-world performance of PV modules under diverse operating conditions. Figure 5 shows the variation in PV module electrical efficiency as a function of ambient temperature.

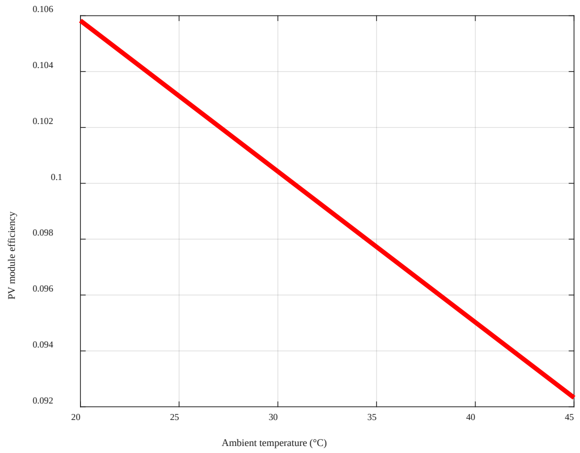

Figure 5. Influence of ambient temperature on PV module efficiency

Figure 5 shows a 0.5% drop in PV module efficiency for every degree increase in ambient temperature. As ambient temperature rises, the temperature of the PV cells increases, leading to high PV module temperature. This temperature rise reduces the PV module's efficiency, primarily due to a drop in open-circuit voltage. The lower voltage diminishes the PV module's ability to convert solar energy electricity, ultimately reducing its overall energy yield. This analysis is essential for predicting how PV module will perform in high-temperature environments, where the electrical efficiency tends to decline. In the following section, we examine the evolution of the PV module's reliability, failure probability density, and failure rate over time, within an ambient temperature range of 25°C to 40°C with 5°C increments.

4.2. PV Module Reliability as a Function of Time at Different Ambient Temperatures

In this subsection, we assess the reliability of a PV module, calculated using equation (5), as a function of time at different ambient temperatures, while maintaining a constant irradiation of 1000 W/m². Temperature is a key factor influencing the behavior of a PV modules. We also determined both lifespan and average lifespan (MTTF) using equations (6) and (10) respectively. The longer the average life of a PV module, the more reliable it will be. Figure 6 illustrates the evolution of a PV module's reliability over time for different ambient temperatures. The pattern aligns with established literature, showing a continuously decreasing over time. The reliability trend remains similar across different ambient temperatures, with the reliability PV module declining over time for a given temperature and constant irradiation of 1000 W/m².

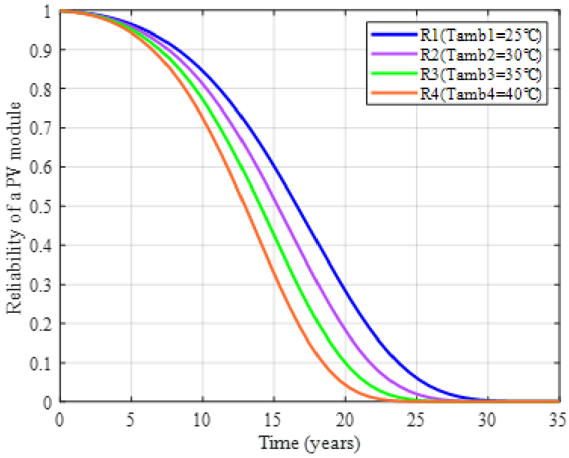

Figure 6. Evolution of PV module reliability for different ambient temperatures, under constant solar irradiation of 1000 W/m²

Figure 6 shows a slight decline in PV module reliability after 7 years, followed by accelerated degradation as ambient temperature increases, culminating in total failure after 25 years. This pattern is due to the accelerated aging of PV modules caused by the effects of ambient temperature on the solar cells and encapsulant material. After determining the reliability, we used equation (6) to calculate lifespan. Table 1 presents the reliability, lifespan, and MTTF values for a PV module under constant irradiance of 1000 W/m² at different ambient temperatures.

The data in Table 1 clearly demonstrate that an increase in ambient temperature results in a shorter PV module lifespan and a corresponding decline in reliability. Specially, in Table 1 reveals an approximate 1.8% reduction in average lifespan for each degree increase in temperature of one degree Celsius, when PV modules are exposed to high ambient temperatures. Indeed, a lower MTTF indicates more frequent failure occurrences, further diminishing reliability. Moreover, PV modules exposed to higher temperature endure greater thermal stress, accelerating their degradation and reducing long-term reliability. Overall, the MTTF values in Table 1 highlight a significant relationship between ambient temperature rises. The findings emphasize the importance of considering thermal conditions to optimize the durability of PV systems.

Table 1. Variation of lifespan and MTTF of a PV module for a reliability threshold at different ambient temperatures, under constant solar irradiation of 1000 W/m²

Environmental Parameters		Reliability	Lifespan (Years)	MTTF (Years)
G(W/m²)	$T_{amb}\left({}^{\circ}C\right)$			
700	32	0.8003	13.2320	11.7528
800	32	0.7998	12.4503	11.0585
900	32	0.8017	11.7282	10.4171
1000	32	0.8061	11.0602	9.8238

4.3. Impact of Solar Irradiation on PV Module Reliability as a Function of Time at Constant Ambient Temperature

To assess the impact of solar irradiation on the reliability of PV modules, simulations were performed at irradiation levels of 700 W/m², 800 W/m², 900 W/m², and 1000 W/m² while maintaining a constant temperature of 32°C. The results, illustrated in Figure 7, indicate that PV module reliability changes in response to varying levels of solar irradiation.

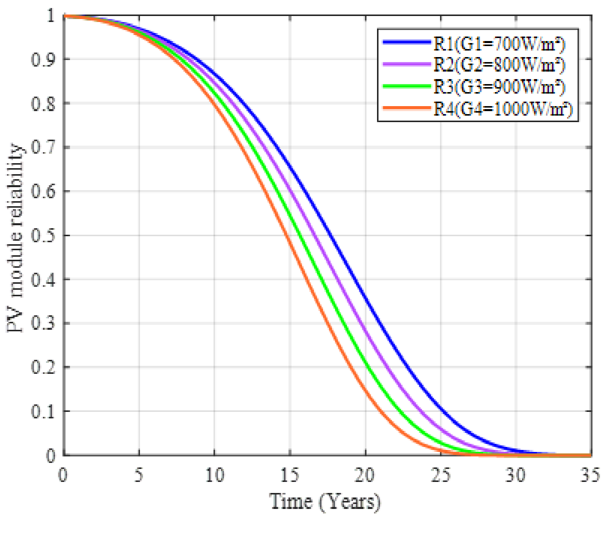

Figure 7. Evolution of PV module reliability for different solar irradiation levels at constant temperature of 32°C

As shown in Figure 7, PV module reliability experiences a slight decrease slightly over the first 10 years, followed by a more significant decline as solar irradiation levels rise, eventually stabilizing after 30 years. This trend is attributed to the fact t that increased solar irradiation leads to higher PV module temperature, which accelerate aging and degradation processes. Temperature is a critical factor that can degrade the internal components of a PV module, ultimately reducing their reliability and lifespan. Table 2 presents the values for PV module reliability, lifespan, and MTTF, under constant temperature conditions (32°C), at different levels of solar irradiation.

Table 2. Variation in lifespan and average lifespan of a PV module for different levels of solar irradiation at a constant temperature

Environmental Parameters		Reliability	Lifespan (Years)	MTTF (Years)
G(W/m²)	$T_{amb}\left({}^{\circ}C\right)$			
1000	25	0.7984	12.6323	11.2201
1000	30	0.8205	11.4817	10.1982
1000	35	0.8174	10.4653	9.2954
1000	40	0.8178	9.5647	8.4954

Analysis of the data in Table 2 underscores the impact of solar irradiation on the reliability of a PV modules. As solar irradiation increases, both the lifespan, and the reliability of the PV modules decrease. Specifically, the data indicate a 0.06% reduction in the lifespan and average lifespan for every 1 W/m² increase in solar irradiation. The decrease in MTTF with increasing solar irradiation suggests that failure occurs more frequently, leading to reduce reliability of the PV modules under these conditions.

4.4. Evolution of a PV Module's Failure Probability Density and Failure Rate Over Time Under Different Ambient Temperatures

In the following, we examine the evolution of the failure probability density and failure rate of a PV module over time at different ambient temperatures. Figure 8 and 9 illustrate how both metrics change as time progresses under different ambient temperature conditions. These graphs provide a clear visualization of the impact ambient temperature has on the reliability of the PV module over time. The temporal trends in failure probability density and failure rate exhibit consistent patterns across different temperature values, aligning with established findings in the literature. In the context of this reliability analysis study, the failure probability density of a PV module corresponds to a function that describes the probability that the PV module will fail during a given time interval.

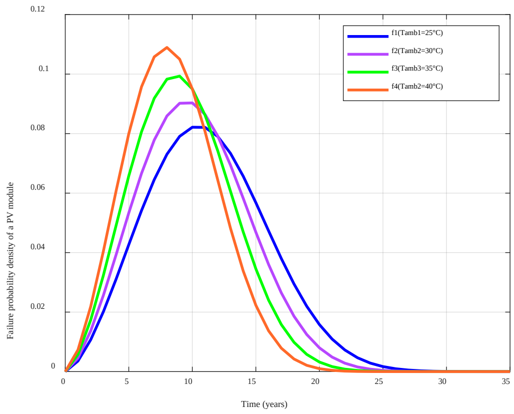

Figure 8. Evolution of a PV module's failure probability density over time under different ambient temperatures

As shows in Figure 8, the probability density of failure steadily increases over time, peaking at approximatively 8, 9, 10 and, 11 for ambient temperature of 25°C, 30°C, 35°C, and 40°C respectively. These peaks signify critical period in the PV module’s life cycle, when thermal degradation has caused significant damage to internal components, heightening the likelihood of failure. After these peaks, the probability density declines gradually, reaching zero as the PV module nears the end of its operational life, with all components having reached their reliability limits.

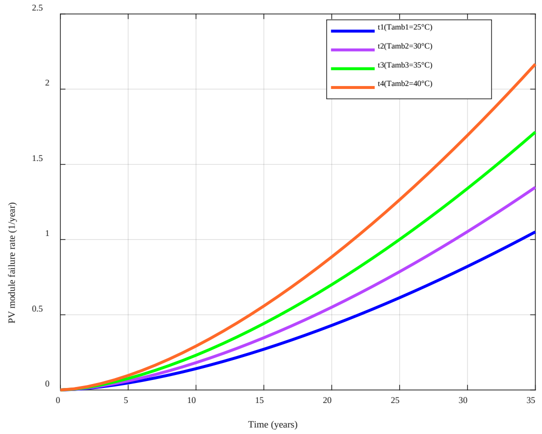

Figure 9. Evolution of a PV module's failure rate over time under different ambient temperatures

Figure 9, illustrates that the failure rate a continuously increase over time at all studied ambient temperatures a hallmark of the PV module’s aging phase. This phase is characterized the accelerated degradation of components, leading to a higher frequency of failures. The failure rate represents the number of failures per unit of time, and in harsh environments, it rises sharply, indicating a high likehood of frequent failure over short period. The shape parameter ($\beta = 2.6$) in the Weibull distribution confirms that the PV module is in the aging phase at high time values, and the failure rate surpasses 1, indicating numerous failures per unit of time. This trend is attributed the cumulative thermal and mechanical stresses caused by high ambient temperatures, which accelerates the degradation of materials such as the encapsulant, solder joints, and the solar cells. The steady increase in the failure rate across different temperatures underscores the critical importance of accounting for thermal conditions when evaluating the longevity and reliability of PV modules.

5. Conclusion

In conclusion, this study highlights the importance of assessing the reliability of photovoltaic (PV) modules under different ambient temperature conditions to guarantee their long-term performance. It has been observed that a 1°C increase in ambient temperature results in a 0.5% drop in PV module efficiency. Analysis of the reliability function over time, at constant illuminance, revealed that reliability decreases as ambient temperature rise, with a total loss of reliability after 30 years. The lifespan and average lifespan of a PV module decreases by 1.8% per additional degree, and by 0.06% for every 1 W/m² increase in solar irradiance. Peak failure probabilities appear after 7 years at 40°C and after 11 years at 25°C, with a progressively increasing failure rate, indicating accelerated degradation at high ambient temperatures. This highlights the importance of limiting the exposure of PV modules to heat, or adopting technologies that reduce its effects.

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