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Analysis of the Effect of Temperature and Relative Humidity on the Reliability of a Photovoltaic Module

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Abstract

Photovoltaic energy occupies a significant place in the renewable energy market, with photovoltaic (PV) modules playing a vital role in converting solar energy into electricity. However, their effectiveness is likely to be affected by variations in environmental conditions, including temperature and relative humidity. The study examines the impact of these major climatic factors on the reliability of PV modules, aiming to provide crucial information for optimizing and managing these systems under varying conditions. Inspired by Weibull's law to model the lifespan of components, we proposed a mathematical model integrating a correction factor linked to temperature and relative humidity. Using this approach, simulations in Matlab Simulink reveal that increasing temperature and relative humidity have an adverse impact on the reliability and lifespan of PV modules, with a more pronounced impact on temperature. The results highlight the importance of considering these environmental parameters in the management and optimization of photovoltaic systems to ensure their long-term efficiency.

Keywords

Solar Energy, PV Module, Lifespan, Reliability, Efficiency

1. Introduction

Over the last few decades, the search for renewable energy sources has become a critical area of research for global clean and secure energy production [1]. Thus, in the current climate change context, renewable energies, particularly photovoltaic solar energy, are emerging as a viable solution in the transition to more sustainable and environmentally friendly energy sources, with photovoltaic (PV) modules serving as critical components [2]. These PV modules, which convert sunlight into electricity, are central to the energy revolution [3]. As a result, the electrical performance of a photovoltaic installation is heavily influenced by the PV module used.

In general, a standard PV module converts between 6% and 20% of received solar radiation into electricity, with the exact percentage varying depending on the nature of the solar cells and the surrounding climatic parameters [4]. The search for new materials for more efficient conversion of sunlight into electrical energy is central to the development of high-efficiency PV modules. At the same time, understanding the reliability and durability of existing technologies in operational photovoltaic systems is critical, as these systems deteriorate gradually, reducing their efficiency over time. Photovoltaic modules are typically designed to have a lifespan of 25 to 30 years, with the expectation that their performance will remain stable during this time [5]. Over a 25-year period, most manufacturers guarantee a power degradation of less than 80% of the nominal power of their PV modules [6]. Changes in environmental conditions, such as temperature and relative humidity, can, however, affect the efficiency of these photovoltaic modules. This is why Wohlgemuth and Kurtz investigated how humidity and temperature influence the deterioration of PV modules by conducting 85/85 tests (85˚C temperature and 85 percent relative humidity) in accordance with the IEC 61215 standard [7]. Their findings revealed that corrosion appeared 1000 hours after the PV module was exposed to these extreme temperature and humidity conditions. Furthermore, as Ndiaye *et al.* point out, the lack of precise information about the deterioration rate of PV modules increases financial risk [8]. As described in the studies of Laronde *et al.* and Charki *et al.*, the reliability and durability of a photovoltaic system are primarily determined by the energy performance of its components, particularly PV modules, and the various associated deterioration methods [5] [9]. Tsuda and Vázquez used accelerated testing methods to investigate the reliability of PV modules [10] [11]. In reality, their research was limited to crystalline silicon-based PV modules. It is important to emphasize that photovoltaic modules are manufactured for use in outdoor environments where various environmental parameters can influence their reliability and lifespan.

In order to take into account, the impact of variations in climatic parameters such as ambient temperature and relative humidity, we proposed a model in Matlab Simulink to evaluate the reliability of a PV module as a function of time, taking into account variations in these two environmental factors. This approach, which uses the Peck model's acceleration law and the Weibull distribution to estimate lifespan, aims to help PV system designers and operators make informed decisions about the design, operation, and maintenance of solar installations. In the following part of this study, we present the modeling of the reliability of a PV module while describing the Weibull distribution and propose a mathematical model taking into account the ambient temperature and the relative humidity rate in section 2. In section 3, we apply our mathematical model to PV modules. Finally, we give a conclusion.

2. Reliability Modeling of a PV Module

For photovoltaic modules, reliability assessment is based on establishing a key measure, namely the mean lifespan [12]. Indeed, reliability, or the survival function $R(t)$, for PV modules represents the probability that they will perform their specific function without failure for a predetermined period of time when operated under specific conditions [13]. The technique of Accelerated Life Testing (ALT), depicted in **Figure 1**, is used in the literature to rapidly evaluate the reliability of a component prior to its use in real-world conditions [5].

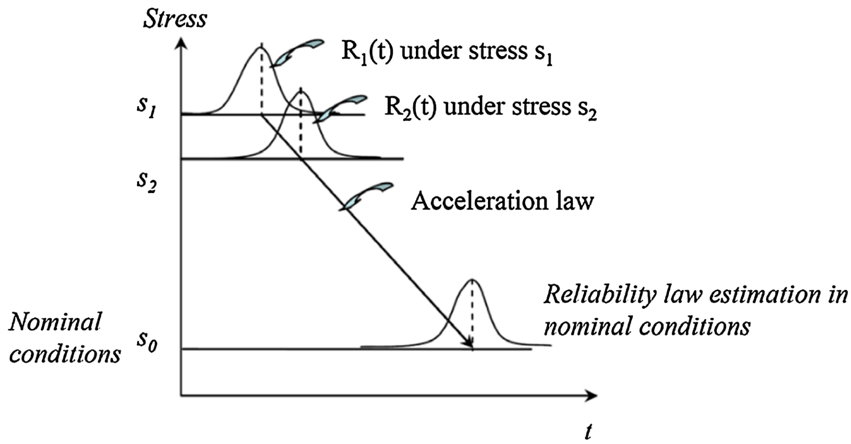

Figure 1. Reliability assessment using an accelerated test [5].

The three-parameter Peck model is another more comprehensive approach to modeling photovoltaic module accelerated aging. This is due to the fact that the tests are conducted in high humidity conditions, implying that the deterioration mechanism results from the interaction of temperature and humidity [14]. PV module reliability tests are performed to evaluate their performance in real-world environments and estimate their expected lifespan. Temperature and humidity tests, thermal stress tests, cell stability tests, and weather resistance tests are all common testing methods [5]. These tests are used to assess the strength and resistance of PV modules to environmental conditions. In this study, the robustness of a photovoltaic module will be examined. Modeling exposure to humid heat conditions in Matlab software will highlight how temperature and relative humidity influence the reliability of the aforementioned photovoltaic module. Equation (1) [5] establishes the relationship (1) between the lifespan, PV module temperature T_{mod} and the relative humidity hr in the Peck model:

$$\eta = \exp\left(\gamma_0 + \gamma_1 \times \log(hr) + \frac{\gamma_2}{T_{\text{mod}}}\right) \tag{1}$$

2.1. Weibull Distribution

Several reliability models, including the Weibull model, can be used in the context of these studies. According to the following relationship (2) [5], the reliability of equipment is expressed as the probability that it is still operational at a given time *t*:

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

where:

beta (β) is the shape parameter (dimensionless) and eta (η) is the scale parameter (time unit).

The analysis of a PV module's reliability focuses on the failures of this PV module. Its primary goal is to determine the expected operating lifespan of PV modules. However, the Weibull distribution is the best method for representing the distribution of lifetimes. Indeed, it is applicable in both electronics and mechanics, and it allows you to describe the behavior of a PV module in three phases: the initial phase, the productive operational period, and the deterioration or aging phase [12]. In the context of our study, we assume that the lifetime distribution of solar panels follows a Weibull distribution.

2.2. Average Lifetime of a PV Module

The average lifetime of a PV module represents the expected time before a PV module is likely to cease operating reliably. It is essential for determining reliability and estimating the expected lifetime of a PV module. This average lifetime noted μ, can be estimated using the parameters and of the Weibull distribution, as well as the gamma function using Equation (3) [13]:

$$\mu=\eta\cdot\Gamma\left(1+\frac{1}{\beta}\right) \tag{3}$$

where:

μ is the average lifetime (time unit), beta (β) is the shape parameter (dimensionless), eta (η) the scale parameter (time unit) and Γ is the gamma function defined by:

$$\Gamma(\alpha)=\int_{0}^{+\infty}x^{\alpha-1}\mathrm{e}^{-x}\mathrm{d}x \tag{4}$$

According to the study by Laronde, Charki and Bigaud [5], the majority of photovoltaic module manufacturers offer an electrical performance guarantee covering more than 80% (or even 90%) of the value specified on the label for a period of 25 years (or 20 years) [5]. By expressing the average lifetime in years, it becomes easier to compare differents PV modules and make informed decisions on the choice of technologies and manufacturers. In fact, a PV module with a higher average lifetime can be interpreted as more reliable and durable.

In this study, we estimate the average lifetime of the PV module when its reliability reaches a tolerable level of 80%, which corresponds to a 20% degradation of its rated power, as mentioned in the work of Laronde, Charki, Bigaud, Ndiaye *et al.* [5].

2.3. Proposed Mathematical Model

Our research is based on the two (2) parameters Weibull model, with the goal of developing a mathematical model that takes into account the effect of temperature and relative humidity on the reliability of solar panels in real-world usage scenarios. We begin with the assumption that photovoltaic module lifespan follows a Weibull distribution. The mathematical model that we propose for this purpose is represented by Equation (4):

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

with:

$$C = \frac{T_{\text{mod}} + 293\left(\frac{t}{\eta}\right)}{T_{\text{amb}}} \times (hr) \tag{6}$$

and

$$T_{\text{mod}} = T_{\text{amb}} + \frac{G}{800}\left(T_{\text{NOCT}} - 20\right) \tag{7}$$

where:

C is the correction factor related to the temperature of the PV module, ambient temperature and relative humidity, T_{mod} is the PV module temperature over time in Kelvin (K), T_{amb} is the ambient temperature in Kelvin (K), G is the solar irradiation (W/m²), T_{NOCT} is the nominal operating temperature of a photovoltaic cell, hr is the relative humidity in percentage (%), β is the shape parameter of the Weibull distribution, η is the scale parameter of the Weibull distribution in hours (h), τ is the lifetime of the PV module (time unit), which corresponds to the scale parameter η of the Weibull distribution in hours (h), γ_0, γ_1 and γ_2 are the parameters of the Peck model.

The expression $293\left(\frac{t}{\eta}\right)$ in Equation (5) corresponds to a linear increase in the temperature of the PV module over time. Here, we multiply the time t by $\frac{293}{\eta}$ achieve a 293 Kelvin increase over the nominal lifetime of the PV module.

3. Application to PV Modules

3.1. Modeling on Matlab Simulink

The use of Matlab Simulink in modeling and estimating the temporal reliability of a PV module is a well-established approach in the fields of solar energy engineering and research. **Figure 2**, which represents the model proposed for this study, is the usual diagram of the Simulink model developed to model the behavior of the PV module.

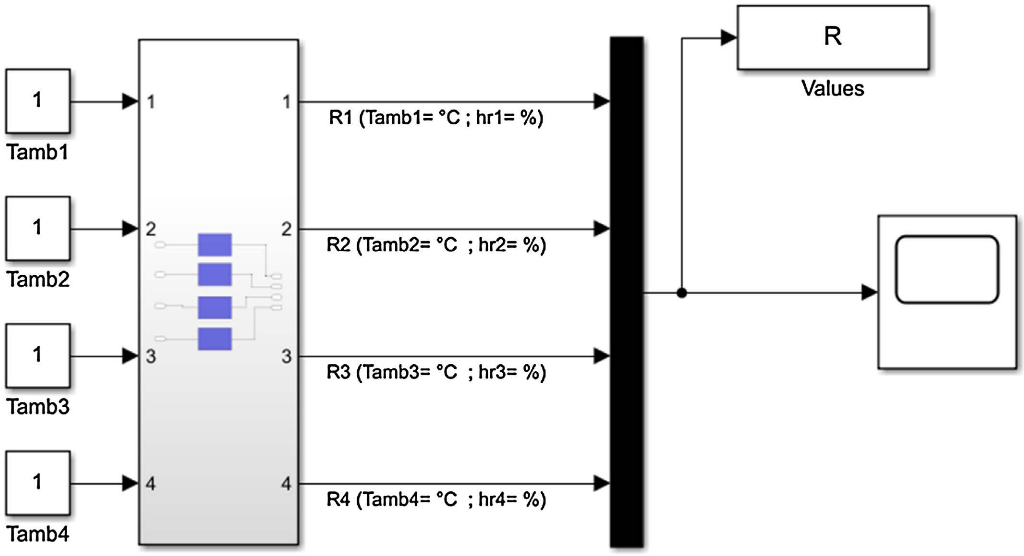

Figure 2. Simulation with Matlab Simulink.

3.2. Simulation

We experimented with accelerated aging during this study. The simulations are running using Matlab software, based on the following criteria:

- The Peck acceleration law parameters used in our simulations are as follows: $\gamma_0 = 3.287$, $\gamma_1 = -1.894$ and $\gamma_2 = 2615.98\ \text{K}$ [5].
- the shape parameter of the Weibull distribution is $\beta = 2.6$ and the scale parameter η is determined using Equation (1) [5].

By examining the influence of temperature and relative humidity on the survival function of photovoltaic modules, it is observed that the scale parameter η of the Weibull distribution ideally adjusts to the lifespan τ of these PV modules.

Our research will look into how temperature and relative humidity affect the reliability of a photovoltaic module. As a result, during our simulations, we will only change the temperature of the PV module while maintaining the relative humidity constant, and vice versa. In the simulation, the meteorological data (temperature and relative humidity) used come from the national meteorological agency (ANAM). These annual average weather data for fifteen years from 2007 to 2021 for Ouagadougou station are recorded in **Table 1**.

During our investigation of the effect of temperature on the PV module in this publication, we kept relative humidity at 55 percent. Furthermore, we investigated how relative humidity affects the reliability and lifespan of the PV module while maintaining the module's temperature at 32˚C. Indeed, Burkina Faso enjoys high temperatures all year round. Dry air blows in from the northeast in winter, with maximum temperatures of around 30/32˚C in the north and 32/33˚C in the south [15].

We note that we deliberately selected the pair of values ($T_{\text{amb}} = 32^\circ\text{C}$; $hr = 55\%$)

Table 1. ANAM annual average weather data from 2007 to 2021.

Years	Maximum temperature (˚C)	Minimum temperature (˚C)	Maximum relative humidity (%)	Minimum relative humidity (%)
2007	35.37205	22.93699	67.07671	31.53151
2008	34.9418	22.09754	66.43989	30.70219
2009	35.62219	23.21288	68.2411	32.18082
2010	35.7726	22.76219	70.57808	34.37808
2011	36.04438	22.85425	67.09341	30.63836
2012	35.42978	23.03525	66.12568	31.64481
2013	35.98027	22.90986	67.14795	30.56164
2014	35.89315	22.88301	68.85753	31.40274
2015	35.88712	22.63671	65.06027	29.94247
2016	35.96339	22.94754	68.43443	31.95082
2017	35.71288	22.46767	66.20822	31.3863
2018	35.55753	23.27808	66.01918	30.76164
2019	35.70548	23.21041	64.7589	30.95616
2020	35.9265	23.21503	65.01093	30.19126
2021	36.34603	23.17425	64.60822	29.69315

with the aim of analyzing the behavior of the reliability function over time for different values of temperature or relative humidity.

3.3. Results and Discussion

This section describes the simulation results for the analysis of the effect of ambient temperature and relative humidity on reliability.

3.3.1. Influence of Module Temperature on Reliability

In this section, we investigate the effect of photovoltaic module temperature on module reliability, as determined by Equation (3). To demonstrate this, Figure 3 depicts the module's reliability as a function of time for various temperature values while keeping the relative humidity constant at 55 percent. The reliability curves in Figure 3 reflect the results of our simulations regarding the analysis of the influence of ambient temperature on reliability.

It is worth noting that the patterns of the curves shown in Figure 3 and those from Ndiaye's study are strikingly similar. The reliability of a photovoltaic module remains constant at $R = 1$ for the first two years, then begins to decline. The rate of decrease in reliability accelerates with increasing temperature, eventually leading to failure at 28, 30, and 34 years. Elevated temperatures have a negative impact on the performance of PV modules in general. As ambient temperature rises, so does the temperature of the PV module, and so does its output voltage, leading to a reduction in the efficiency of the conversion of solar energy into electricity. Furthermore, high temperatures can accelerate the aging and degradation of PV module materials, such as solar cells and encapsulation materials. This deterioration can shorten the life of the photovoltaic module and compromise its long-term reliability.

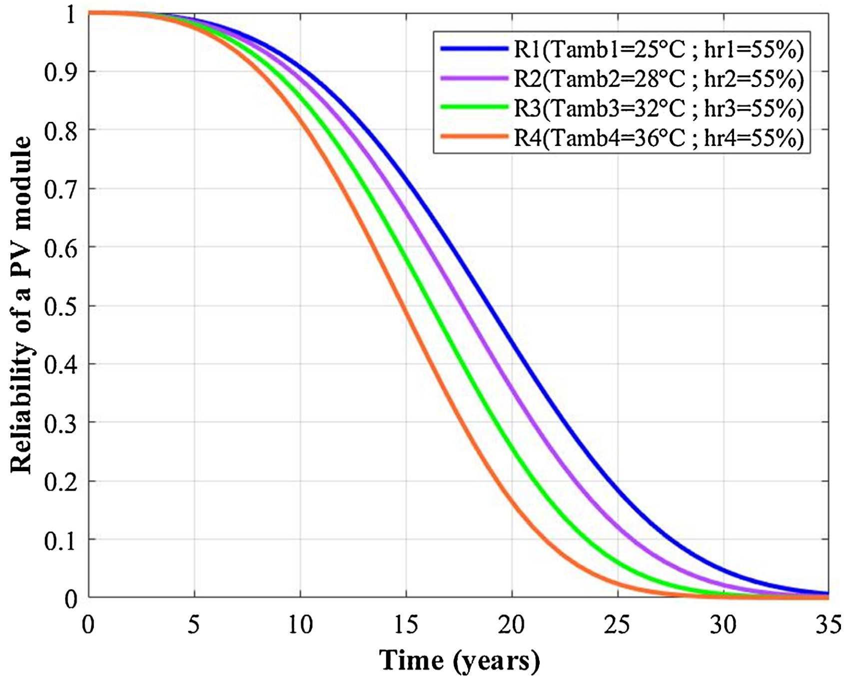

Figure 3. Influence of ambient temperature on reliability.

After determining the PV module's dependability, we use equation (3) to calculate the average lifetime. Table 2 shows the reliability and average lifetime values for the PV module.

Table 2. Variation in the lifespan of modules based on the temperature of the PV module.

Environmental parameters		Reliability (R)	Lifetime (Years)	Average lifetime (Years)
T_{amb} (˚C)	hr (%)			
25	55	0.7937	14.1063	12.5294
28	55	0.8166	13.1298	11.6620
32	55	0.8036	11.9559	10.6193
36	55	0.7909	10.9109	9.6912

The examination of the various average lifetime data in Table 2 reveals that an increase in ambient temperature has a significant impact on its lifespan and, as a result, its reliability. Indeed, a lower average lifetime value indicates a shorter time between failure incidents, which leads to lower reliability. In summary, the analysis of the various average lifetime values in Table 2 reveals a significant relationship between ambient temperature and lifespan, resulting in a decrease in average lifetime value as ambient temperature rises.

3.3.2. Influence of Relative Humidity on the Reliability of a PV Module

Figure 4 depicts the time-dependent reliability curves of a PV module for various relative humidity values while keeping the ambient temperature constant at 32˚C.

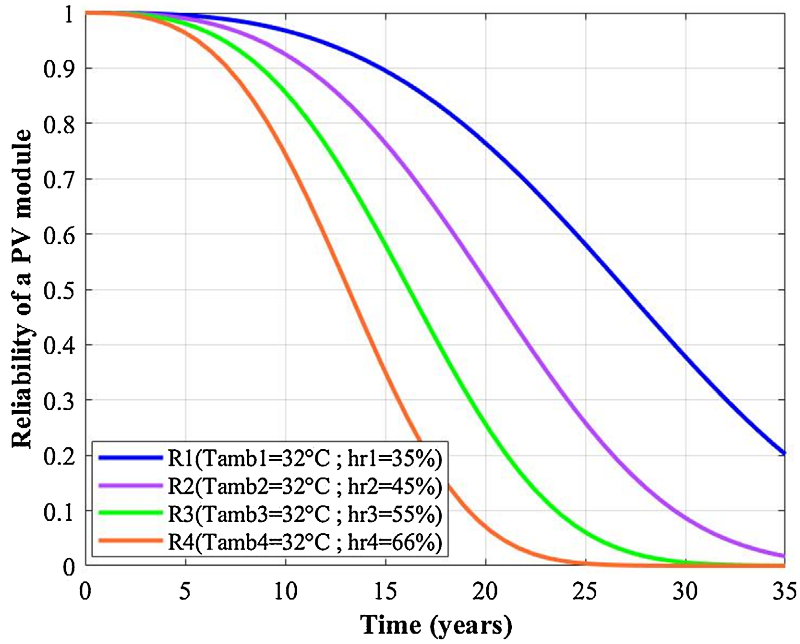

Figure 4. Influence of relative humidity on the reliability of the PV module.

The graphs presented in **Figure 3** show the evolution of the reliability of a PV module for different relative humidity values. These graphs are typical for reliability functions, with a change in shape after five (5) years. In this representation, the curves exhibit linear behavior for the first two years before showing a slight decrease until the fifth year. After this, they begin a gradual decline as a result of the increase in relative humidity, and tend to fail between 25 and 30 years. These curve models reflect the effects of relative humidity on PV module reliability. In reality, relative humidity can have an impact on the reliability of PV modules, particularly the integrated electronic components in the system. High humidity levels can corrode metal contacts, resulting in electrical connection losses and lowering PV module performance. Furthermore, humidity can enter the PV module through microcracks or encapsulation flaws, damaging the solar cells and other constituent elements. Prolonged exposure to high humidity levels can hasten the deterioration of the PV module, resulting in decreased reliability. **Table 3** shows the reliability values derived from the reliability curves over time, as well as the average lifetime values calculated using Equation (3).

The analysis of the various average lifetime values listed in the **Table 3** reveals a significant relationship between relative humidity increase and PV module lifespan. Indeed, we see a decrease in average lifetime as relative humidity rises. From the above, we conclude that the reliability of solar panels depends on both ambient temperature and relative humidity.

Table 3. Variation in the lifespan of modules as a function of relative humidity.

Environmental parameters		Reliability (R)	Lifetime (Years)	Average lifetime (Years)
T_{amb} (˚C)	hr(%)			
32	35	0.7986	17.3470	15.4078
32	45	0.8053	14.1041	12.5274
32	55	0.8036	11.9559	10.6193
32	66	0.8027	10.2891	9.1389

3.3.3. Influence of the Combined Effect of Temperature and Humidity on the Reliability of a PV Module

The combination of temperature and humidity can have a significant impact on photovoltaic module reliability. High temperatures combined with high humidity levels, on the other hand, have the potential to accelerate degradation processes within PV modules. This can include material degradation, corrosion of metal contacts, layer delamination, and other issues. Humidity can also promote the growth of mold or microorganisms, which can harm the PV module's components. Ambient temperature and humidity can also have an impact on the electrical performance of PV modules. High temperatures can cause internal resistance to increase, open-circuit voltage to decrease, power output to decrease, and overall efficiency to decrease. Humidity can affect material electrical conductivity, amplify ohmic losses, and cause short circuits. Furthermore, the combined effect of temperature and humidity can shorten the useful lifespan of PV modules. Harsh environmental conditions can hasten the aging and deterioration processes, resulting in an early decline in PV module performance and reliability, as illustrated in Figure 5.

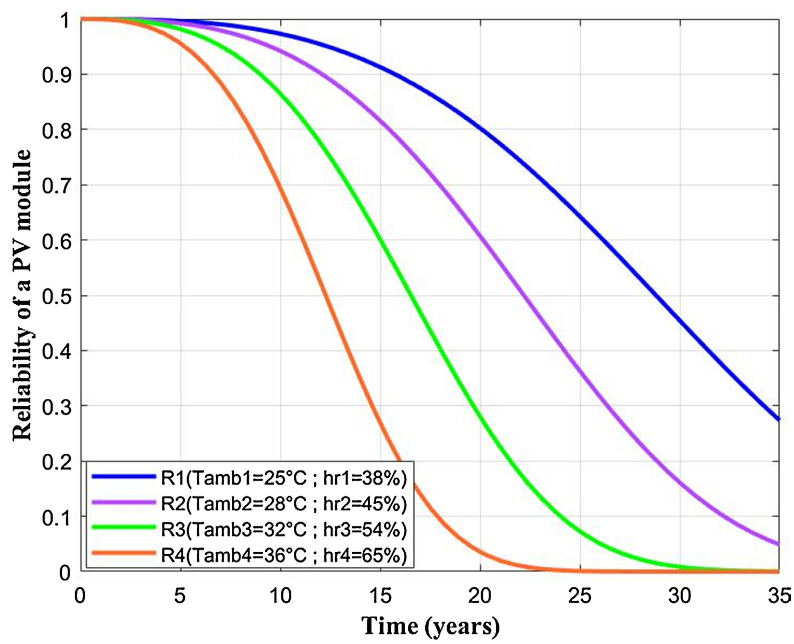

Figure 5. Influence of the combined effect of temperature and humidity on the reliability of a PV module.

Figure 5 depicts the gradual decline in the reliability of a photovoltaic module over time. These graphs clearly show that the combination of high temperatures and high humidity has a negative effect on the reliability of photovoltaic technology. This decrease in reliability can be explained by the fact that this combination of environmental conditions hastens the deterioration of the PV module's performance, resulting in a shorter useful lifespan. It should be noted that when the module's reliability deteriorates, the photovoltaic system's electricity production suffers immediately. Table 4 contains information such as reliability results extracted from reliability curves over time, lifespan estimation obtained from Equation (1), and average lifetime calculation performed using Equation (3).

Table 4. Variation in the lifespan and average lifetime of a PV module as a function of high temperature and humidity.

Environmental parameters		Reliability (R)	Lifetime (Years)	Average lifetime (Years)
T_{amb} (˚C)	hr (%)			
25	38	0.8134	19.1270	16.9888
28	45	0.8021	15.4890	13.7575
32	54	0.8147	12.1379	10.7810
36	65	0.8082	9.5086	8.4456

Table 4 shows that for high levels of temperature and relative humidity, with a specific reliability threshold, the estimated lifespan and average lifetime are reduced. It is worth noting that the estimated lifespan values and various average lifetime values listed in the table clearly show the significant impact of increasing temperature and relative humidity on the PV module's lifespan.

4. Conclusion

To conclude, we will note that the proposed modeling approach made it possible to simulate the reliability and lifespan of PV modules. Simulation results in Matlab Simulink highlight the detrimental consequences that adverse environmental factors can have on the performance and lifespan of PV systems. The effects of environmental factors, notably temperature and relative humidity, were observed with the annual average data from ANAM from the Ouagadougou station. These results reveal that increasing temperature and relative humidity or a combination of these two climatic factors has a negative impact on the reliability and lifespan of PV modules, with a more pronounced impact on increasing temperature. Thus, understanding these influences allows us to identify critical thresholds and optimize operating conditions to guarantee efficient use and long-term reliability of PV modules. By deepening our understanding of these factors, we help promote a more stable and sustainable use of solar energy, thereby strengthening our transition to a clean and renewable energy source.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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