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Effects of Damp-Heat into Crystalline Silicon Photovoltaic Solar Modules in Benin (Tropical Area)

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Abstract: During their outdoor service, photovoltaic (PV) modules are exposed to different set of environmental conditions that can affect their performance such as Damp-Heat. But theses external conditions varied from one area to another. This work aims to highlight the impact of environmental conditions on the performance of crystalline silicon photovoltaic solar modules exposed in the tropical environment which is a hot and humid area. We have firstly studied the degradation of the solar photovoltaic module under the effect of moisture and the heat by using the analytical models of Erying, Peck and Laplace transformed. Then we have compared these models to the experimental Damp Heat model of Hulkoff. We finally verified the impact of the environmental conditions of the tropical environment on the photovoltaic modules by simulating their behavior over time under real conditions using the relative humidity and average temperature data of the synoptic stations of Benin. The theoretical results obtained, compared to those obtained by Hulkoff in experiments showed firstly a reduction of about 3% in the electrical performance of photovoltaic solar modules over period and a loss of performance of PV modules ranging from 0.19% to 0.5% per year. The PV module performance degradation rates over the study period correlate with those found in the literature on different systems installed in various regions of the world. So, future researches on crystalline silicon photovoltaic solar module can be effect of Damp-Heat on its electrical parameters in tropical area.

Keywords: Environmental Conditions, Performance, Module, Damp-Heat, Electrical Power

1. Introduction

Photovoltaic solar technology has been considered for many years as a future solution to supplement conventional energy sources that were previously used in the world. Therefore many laboratories are engaged in the manufacture of the base material which is silicon while working for the improvement of its yield. Thus, several types of cells are used today in the manufacture of solar panels, namely mono-crystalline cells, poly-crystalline cells, amorphous cells, organic cells and very recently perovskite. The performance of these cells is strongly influenced by climatic conditions when exposed to long term [1]. Moisture could be one of the factors affecting the efficiency of these cells, which reduces their electrical performance. In fact, the absorption of the moisture leads to a darkening of the glass in its lower part in contact with the encapsulation material thus causing corrosion [2] and more particularly that of metallization [3]. Moreover, the penetration of moisture into the encapsulant can cause the reduction of light transmission [4]. Moisture also tends to increase the electrical conductivity of the coating material and therefore increases the leakage current thus impairing performance. Also, it may be the cause of the delamination of the module which, in turn, increases the temperature of the affected sites and accelerates the degradation process [3].

Several degradation tests have been used to monitor the degradation of the performance of exposed cells in outdoor conditions in various regions. This work was carried out

according to the following chronology: in Part 1, through a brief state of the art, we described the operating principle of the cell in question and gives an update on the effects of moisture and heat on the cells (the case of relative humidity), then in Part 2 the results obtained and the discussion were presented and finally in Part 3, the conclusion, perspectives and recommendations were made.

2. Material and Methods

2.1. Visual Degradation

In the literature, several authors had worked on the effect of the ingress of moisture into the solar panel in different climatic areas. They used various processes to study that phenomenon. Some of them used the laboratories tests as accelerated test and others observed the solar panel which was exposed for environmental stresses for several years. They noticed that moisture can enter into the solar panel in several ways. Thus:

1) Moisture can penetrate inside the solar panel through the Backsheet or the edges. It so tends to increase the electrical conductivity of the embedding material and therefore increases the leakage current thus implying degradation of performance [3]. Otherwise the intrusion of moisture can also be the cause of delamination of the module which in turn, increases the temperature of the affected sites and corrodes cell metallization in crystalline silicon panels [3].
2) It can also enter the panel through the rolled edges causes corrosion [8]. Moisture retention in the panel housing increases the electrical conductivity of the material. Indeed, corrosion attacks the metal connections of photovoltaic cells causing a loss of performance by increasing the leakage currents. Corrosion also degrades the adhesion between the cells and the metal frame (Figure 1b). In the same way, Skoczek and the co-workers [9] showed that moisture penetration into the panel resulted in various chemical and physical degradations such as metallic corrosion of the module structure (Figure 1c). The resulting delamination phenomenon is more common in hot and humid climates.
3) Mekhilef and the co-workers found that when photovoltaic cells are exposed to moisture for the long term, there is some degradation in their performance. The high content of water vapor in the air causes delamination of the encapsulant. The water droplets trapped inside the wall serve as an optical screen for the cells thus reducing their performance (Figure 2a, 2b) [10]. Moisture ingress into the module reduced adhesion strength that can cause delamination of PV modules [4] (figure 2b).
4) Moisture penetrates mainly from the open edges when the impervious back material is used while moisture can diffuse both from the backsheet and the edges, when the permeable back material is used. In addition to diffusion, moisture can also enter the modules through capillary cracks or delaminated areas, in which case permeability can be very important. In addition, penetration of moisture into the encapsulant can cause the reduction of light transmission (Figure 3).

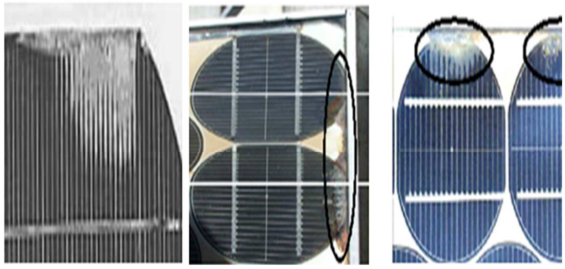

Figure 1. *Effect on Moisture ingress [3, 8, 9].*

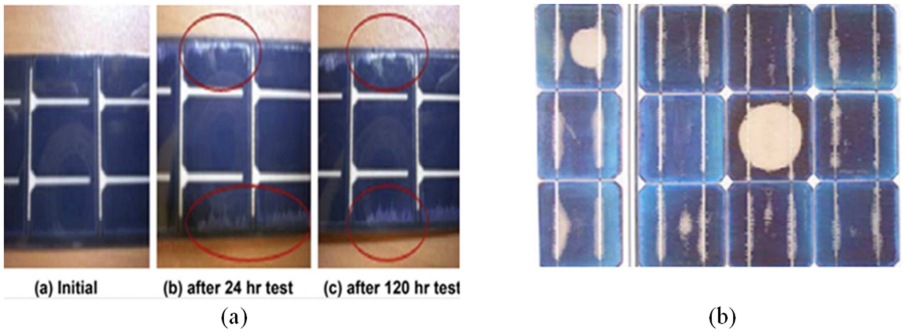

Figure 2. *Delamination of the encapsulant by the entry of moisture [10].*

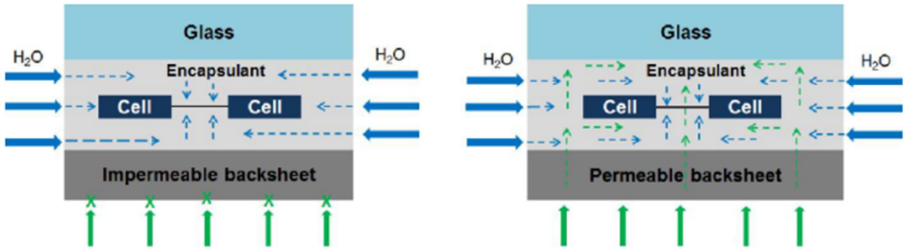

Figure 3. *Moisture ingress into PV modules [4].*

We can conclude that moisture ingress into PV module has some effects on it electrical performance. In the following part, we study those effects and their consequences on the lifetime of the module in our environment.

2.2. Humidity Induced-degradation

The lifetime of a PV module can be defined as a point in time when the module is no longer acceptable for any reason, or when the output power has fallen below a minimum acceptable value [11]. For the users, it difficult to know exactly when their module will lose its electrical performance though the manufacturer indicated his lifetime. We must also say that the module's lifetime depends on the environmental conditions in which it is used. Moisture, one of these conditions has many effects on the degradation of the various materials constituting the module. Figure 4 illustrate the different voices through which moisture ingresses the module.

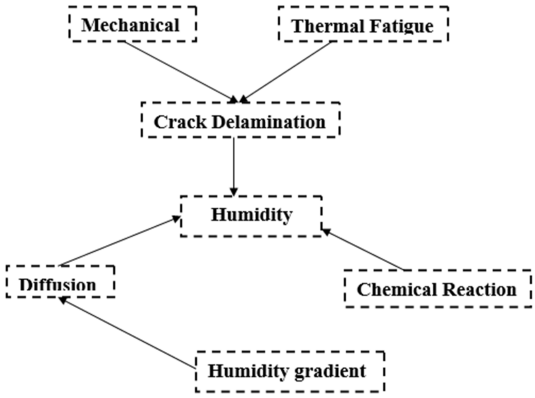

Figure 4. *Different voices of moisture ingress in the module [12].*

Figure 5 reveals the effects of humidity on the various module materials and the mechanisms those induced degradation.

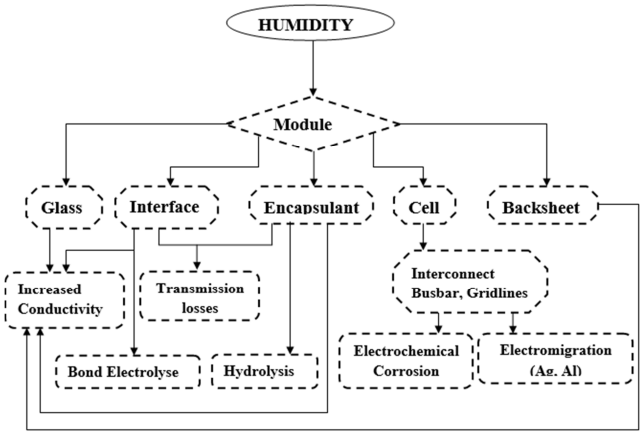

Figure 5. *Effects of moisture and degradation mechanism [12].*

The encapsulant material degradation induces by humidity ingress causes a loss of electrical performance of the module. Like show figure 6, the effect of humidity on the encapsulant material is very important.

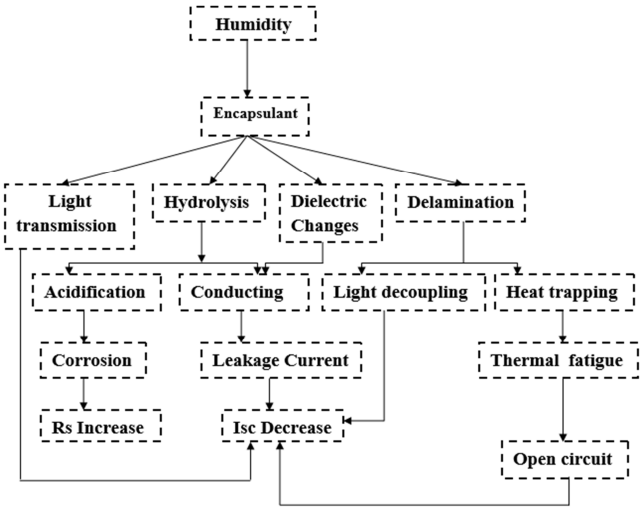

Figure 6. *Degradation mechanisms of PV module encapsulant-Impact on module performance [12].*

2.3. Thermally-induced Degradation

The temperature of cells/modules is usually higher than ambient temperature. Moreover, thermal effect acts as an accelerating factor for degradations caused by humidity or irradiance. Thermal cycles can reduce module reliability in a number of ways. For glass, residual strains may exist after lamination which can result breakage or delamination between glass/pottant under thermal strains. For encapsulant, different photo-thermal and thermal reactions can happen together with UV radiation from light. The principal reactions of EVA are what called Norrish I and Norrish II. In Norrish I, the vinyl acetate group can take off from the main chain to form acetaldehyde together with some gases which have potential to further lead to bubbles in the module. In Norrish II, C=C bonds (polyenes) are formed which have been widely considered as the chromophores group for EVA discoloration. Besides that, acetic acid is produced to catalyze discoloration and corrosion reaction.

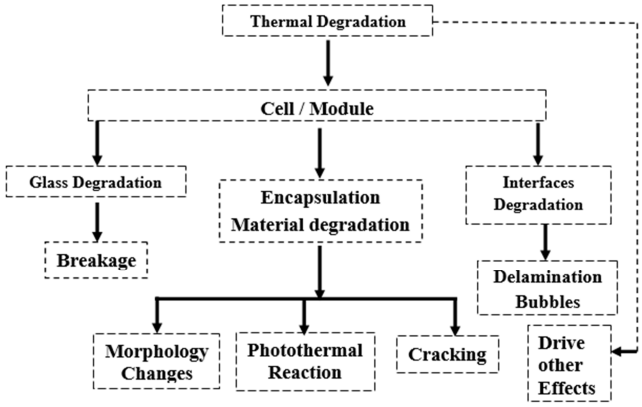

Figure 7. *Effects of temperature and degradation mechanism [12].*

The polyenes produced in Norrish II can further be oxidized to form α-β unsaturated carbonyl, another product leading to discoloration [13-15]. Besides chemical reactions, polymer may also undergo morphology changes under high

temperature. Cells can also suffer from thermal fatigue with reported cracking and solder joint degradation. With regards to interfaces, the thermal heterogeneity of different materials can induce cracks, bubbles and delamination under daily thermal cycles. Besides these direct defects, temperature can accelerate many degradation processes. The water diffusion through polymers has been reported to be accelerated by temperature in the Arrhenius form [16]. Other procedures like metallization corrosion, leakage current, diffusion of dopants, impurities, occur more rapidly at higher temperature.

2.4. Damp-Heat Exposure

During the aging, several types of visual defects have been observed. Some more severe are represented in (Figure 8). Delamination was observed, mainly in the corners and edges of the module. The absence of edge seal in the module has made the edge directly open to the environment where stronger influences were observed compared to the areas with a barrier effective against moisture. The penetration of moisture into the module was also observed and bubbles appeared at the glass/EVA interface. After 24 hours aging at 95°C/85% RH, a large bubble around the electrodes was observed. This is due to the bad protection around the external contacts where an access opening in the backsheet is not well sealed, allowing so the entry of water vapor.

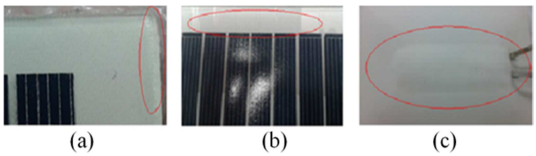

Figure 8. *Defaults observed after a Damp-heat test: (a): edge/corner separation; (b): moisture entry and (C): bubble near the electrode exit.*

The bubbles are usually due to chemical reactions that emit trapped gases in the cell/PV module. The bubbles located on the front side of the module produce a reduction in the radiation that arrives on the module. This causes decoupling of light and increases reflection [17]. This type of defect is similar to delamination. These defects appear in the center of the cell and may be due to poor cell adhesion due to high temperature [17, 18]. When the gas forms at the back of the PV module, a mass appears in the encapsulant or in the back sheet, forming a bubble. Bubbles make the heat dissipation of cells more difficult, overheating and reducing thereafter the lifetime of these cells.

2.5. Affected Parameters

Degradation factors affect many parameters in photovoltaic modules. Some of these affected parameters, the degradation modes, the affected materials as well as the degradation factors are recorded in the table below.

Table 1. *Affected parameters.*

Degradation categories	Degradation Behaviours	Influenced Materials	Contributing stress
Isc Losses	Light scatting by water	Interfaces and bulk encapsulant	Moisture, temperature, May drive, Moisture ingress
	Increased light absorption	Pottant	Moisture, thermal
	Encapsulant Discoloration	Pottant	Irradiance, thermal
	Light transmission decoupling due to cracks, delamination and bubbles	Glass, cell, interfaces	Thermal, Fatigue, moisture
	Light induced degradation	Cell	irradiance
	Diffusion of dopants/impurities causing recombination	cell	Voltage, thermal
R_s increase	Front/back Contact/Interconnect/lead corrosion	Metal components	Moisture, Voltage, Temperature May accelerate
	Solder joint crack	Solder joint	thermal
	Metal electro migration/diffusion	Metal component	Voltage, Temperature, May accelerate
	Diffusion of dopants lead to bulk Si resistance increasing	semiconductor	Voltage, thermal
R_{sh} reduction	Leakage current	Interface, Pottant, Glass surface	Voltage, Moisture
	Encapsulant dielectric damage	Encapsulant	Moisture
	Cell junction Conductivity increase	semiconductor	Voltage

The influence of degradation on the above-mentioned parameters induces degradation rates which vary from one environment to another as shown in Table 2.

Table 2. *Degradation rates obtained in the literature.*

Authors	R_D per year	Years
king and al.	0.5%	2000 [24]
Quintana MA and al.	0.5%	2000 Utah (USA) [25]
Realini A.	0.2% on 20 years	2001 and 2003 (Swiss) [26, 27]
Reis and al.	0.4% on 11 years	2002 Arcata (USA) [28]
Sakamoto and al.	$\prec 0.5\%$	2003 Osaka (Japan) [29]
Hedström J. and al.	0.17% on 30 years	2006 Sweden [30]
Saleh IM and al.	1% on 11 years	2009 Lybia [31]
Vignola F. and al.	Behind 0.6 and 1.5%	2009 Oregon (USA) [32]
Eikelboom JA. and al.	0.3% on 2 years	2000 [33]
Juan Lopez-Garcia	0.24% on 20 years	2017 (Luxembourg) [34]

2.6. Principle of Operation of the NTS5E3E Panels

The study was based on a mono crystalline silicon (inorganic cell) panels having as a band diagram the one represented in Figure 9. Its operation is based on the principle of converting the photon flux into electrical energy through the following mechanisms [5, 6]:

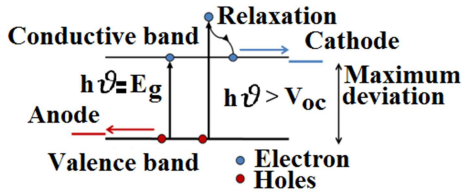

Figure 9. *Band diagram and operating principle of the cell [6].*

1) Absorption of incident photons by the active material constituting the cell;
2) Creation of electron-hole pairs in the semiconductor material;
3) Collection of the carriers generated in the device.

E_g : Minimum energy for possible photon absorption when $h\vartheta > E_g$, the extra energy is lost to thermodynamic expansion [5, 7].

The absorption of a photon by the photoactive semiconductor is related to the energy of the band gap of the semiconductor. The photon of sufficient energy excites an electron from the valence band to pull it out of the material and pass it to the conduction band. The electron leaving the valence band leaves a positively charged hole in this band. The electron-hole doublet is then extracted by the external circuit generating a current whose power conversion efficiency is defined as [6]:

$$\eta = \frac{Jsc \times V_{oc}}{P_i} \times FF \times 100\% \quad (1)$$

With:

P_i : incident light power in W/m^2 ; J_{SC} : short-circuit current density in A/cm^2; V_{oc}: open circuit voltage, FF: fill factor.

2.7. Analytical Models

2.7.1. Erying's and Peck's Models

Moisture in a PV module is a degrading factor that affects the performance of the PV cell. But when this humidity penetrates the PV module, it affects differently the front and the backside of encapsulant. In a PV module, humidity is assumed to be constant when exposed to certain damp heat conditions. We used the Erying's and Peck's models to analytically simulate the entry of moisture into the module as a function of the humidity on the backside of the module at constant temperature and then as a function of temperature at constant humidity [19].

$$\mathrm{rh_{eff,Erying}} = (\mathrm{a} - \mathrm{b} \times \mathrm{T}) \times \frac{\mathrm{c} \times \mathrm{rh_{back}} + \mathrm{d}}{\mathrm{e}} \quad (2)$$

$$\mathrm{rh_{eff,Peck}} = (\mathrm{a'} - \mathrm{b'} \times \mathrm{T}) \times \frac{\mathrm{c'} \times \mathrm{rh_{back}} + \mathrm{d'}}{\mathrm{e'}} \quad (3)$$

Where a, b, c, d, e, a', c', d', e' are models parameters; T: ambient temperature; rh_{back} : humidity of the backside encapsulant.

Escobar and Meeker [20] in their work and Park [19], proposed two degradation models: Erying's and Peck's models, commonly used when the stress conditions are temperature and humidity (acceleration constraints during Damp Heat tests). Formulas 3 and 4 as follows give the expressions of the degradation rates of the PV cells:

$$R_{D,Erying} = A \times exp\left(\frac{-E_a}{k \times T} - \frac{\alpha}{\mathrm{rh_{eff,Erying}}}\right) \quad (4)$$

$$R_{D,Peck} = B \times exp\left(\frac{-E_a}{k \times T}\right) \times \left(\mathrm{rh_{eff,Peck}}\right)^n \quad (5)$$

Where Ea: thermal activation energy of the degradation process (eV), k: Boltzmann constant (8.62×10^{-5} eV/K), T: temperature (K), and rh: relative humidity (%). A and b: two constants dependent on the failure mode.

When the degradation rates are obtained, the expression of the average power given by [2] has been used to give the evolution of the mean power of the module as a function of time according to the two models. This expression is as follows:

$$\mathrm{P_{mean,t}} = \mathrm{P_{max,0}} \times (1 - \mathrm{R_D})^{\mathrm{t}} \quad (6)$$

We also determined from these two models the evolution in time of the form factor of the studied PV module by using the following expression:

$$FF = \frac{\mathrm{P_{mean,t}}}{V_{OC} \times j_{sc}} \quad (7)$$

Where:

V_{OC}: Open circuit voltage and j_{sc}: short circuit current.

2.7.2. Laplace Transformed

In this part we have used the results of the damp heat test (DH: damp heat) carried out in controlled atmosphere climatic chambers. The experimental results obtained by Hulkoff in 2009, we determined the law of evolution of the power output of the "Sharp NTS5E3E" module with mono crystalline silicon. From Laplace transform, we found the power transfer function using the evolution law obtained from experimental tests. The transfer function thus found was introduced into the model.

The equation of the linear trend curve of the power obtained experimentally by Hukloff is given by:

$$P_{max} = at + b \; with \; a = -21.56175 \; and \; b = 185 \quad (8)$$

The general expression of the transfer function in the Laplace domain is written:

$$S(p) = \int_0^{\infty} f(t) \exp(-pt)\, dt \quad (9)$$

The expression of the transfer function of the maximum output power is given by:

$$\mathrm{G_{P_{max}}(p)} = \frac{185\mathrm{p} - 21.56175}{\mathrm{p}} \quad (10)$$

The variation of the maximum output power of the module obtained with respect to the number of years of degradation is given as follows:

$$P_{max}(t) = -0.11655t + 185 \quad (11)$$

3. Results and Discussions

Figures 10 and 11 show the effect of the effective humidity in the module at constant temperature on the one hand and at constant humidity on the other. For that, we chose to use exclusively the model of Peck which is a model of humidity (eq. 3). First, the temperature is kept constant and the humidity varies and then the humidity is kept constant and the temperature varies. When the temperature is kept constant, the effective humidity increases, but when it is the humidity that is kept constant, the effective humidity decreases.

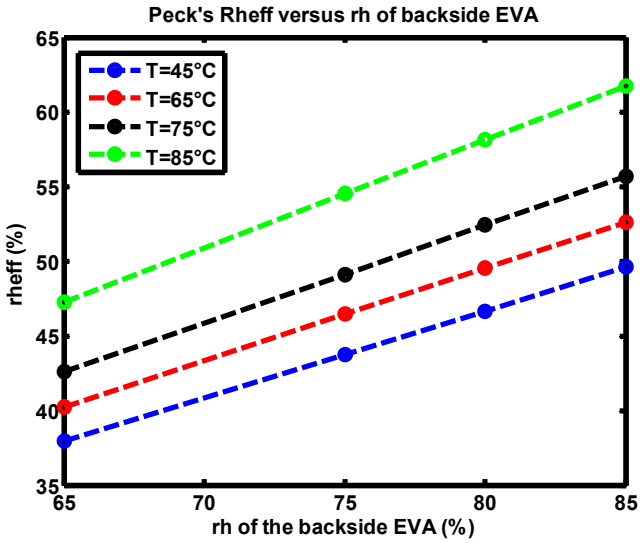

Figure 10. *Rheff versus rhback at constant temperature.*

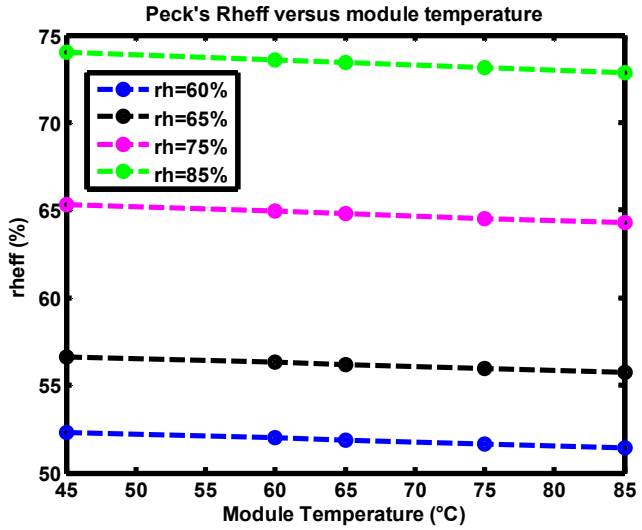

Figure 11. *Rheff versus module temperature at constant humidity.*

With the Erying model, when the humidity varies keeping the temperature constant, there is a higher loss of performance. When the temperature varies with constant humidity, there is less loss of performance at the cell level (Figure 12). The Erying's model is more sensitive to humidity variation when temperature is constant than when temperature varies by keeping the humidity constant.

With the Peck model, when the humidity varies keeping the temperature constant, there is less loss of performance. When the temperature varies with constant humidity, there is more loss of performance in the cells (Figure 14).

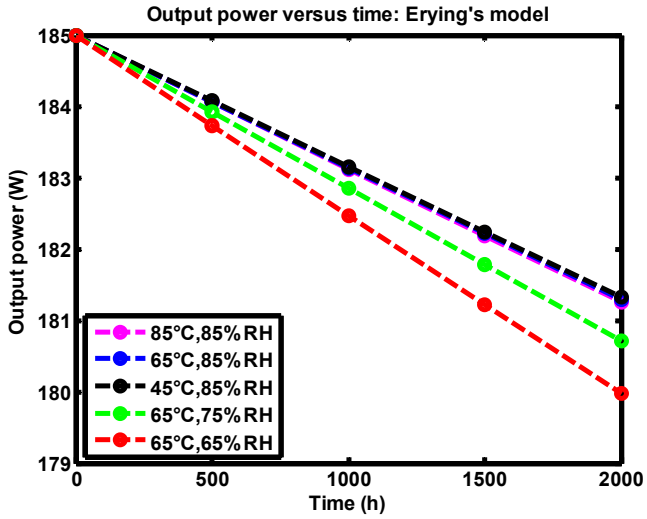

Figure 12. *Output power according to time.*

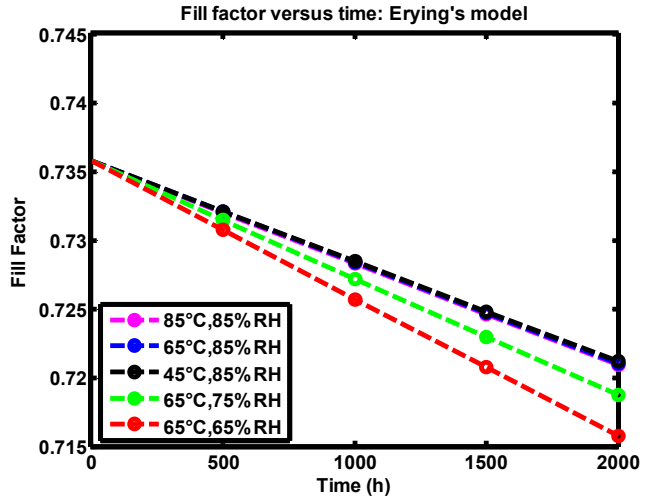

Figure 13. *Fill Factor according to time.*

The Erying's model is more sensitive to humidity variation when temperature is constant than when temperature varies by keeping the humidity constant. The Peck model is more sensitive to temperature variation when humidity is constant than when humidity varies by keeping the temperature constant.

The two models complement one another because Erying's is sensitive to humidity variation and Peck's is sensitive to temperature variation. The same results were obtained for the fill factor (Figures 13 and 15).

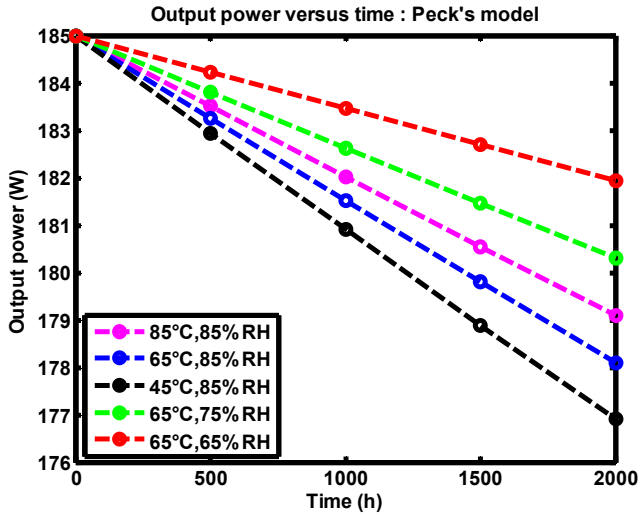

Figure 14. *Output power according to time.*

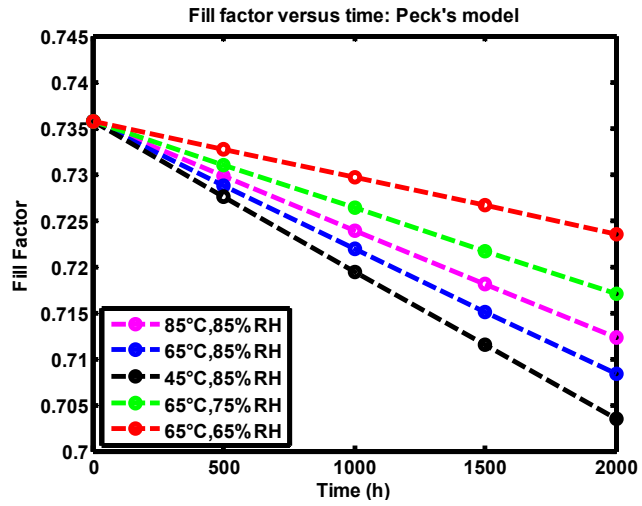

Figure 15. *Fill Factor according to time.*

3.1. Validation of the Analytically Models Used

The lifetime of PV cells is estimated at 20 years, according to several manufacturers. To find out the degradation mechanism, the cells are subjected to accelerated degradation tests in the laboratory. One of the tests of degradation carried out, the best known is that realized by Hukloff in 2009 in Miami in Florida State. The tests are carried out in a controlled atmosphere in climatic chambers under 85°C/85% RH for 1000 hours corresponding to 20 years in real conditions. These tests recommend not exceeding 5% degradation of the performance of the module. But in 1000 hours, this rate is not likely to be reached so it is recommended to extend up to 2000 hours corresponding to 40 years in real conditions. The analytical models were simulated over a period of 20 years and then 40 years. To validate the analytical models used by Hulkoff experimental model, we compared the times in laboratory and real conditions.

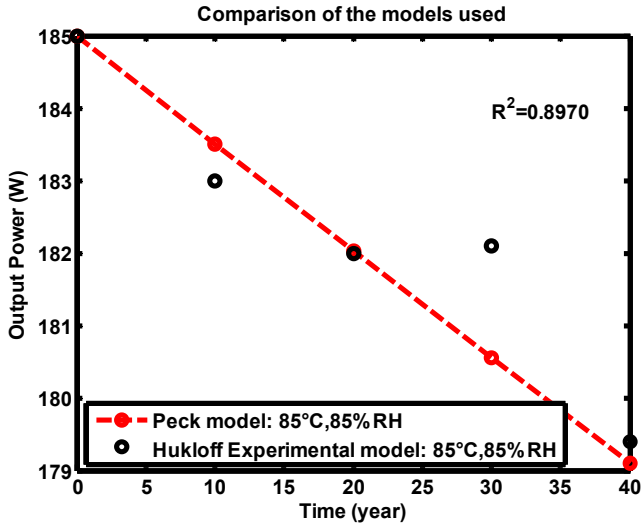

Figure 16. *Output power according to time (Peck and Hulkoff models).*

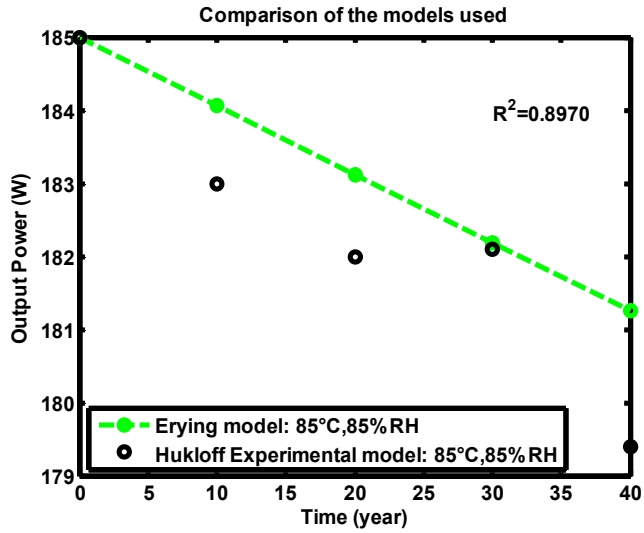

Figure 17. *Output power according to time (Erying and Hulkoff models).*

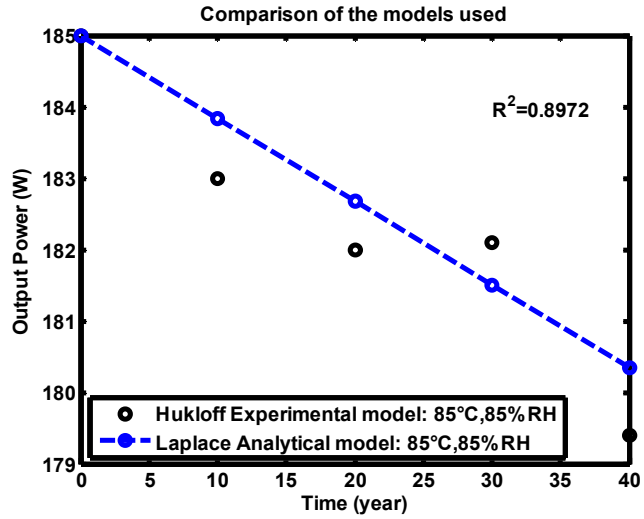

Figure 18. *Output power according to time (Laplace and Hulkoff models).*

Figure 19 shows the comparison between the two models, the Laplace transform and the Hulkoff experimental model.

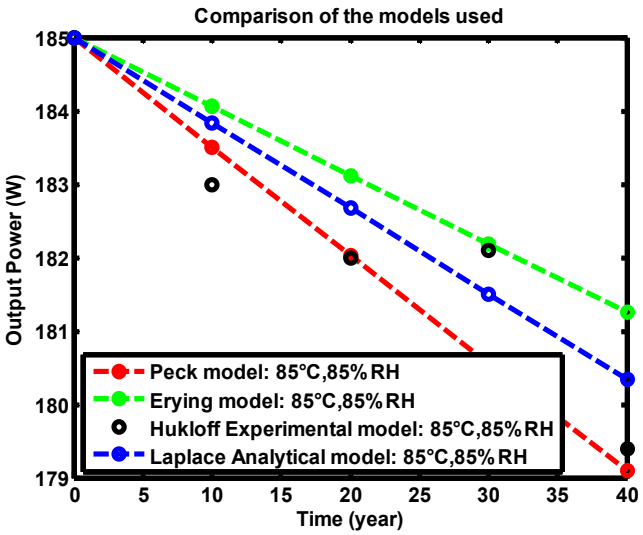

Figure 19. *Output power according to time (The four models).*

The variations of the degradation rate for the used models are given in the table 3 as follows:

Table 3. *Performance loss during 40 years.*

Models	Performance loss During 40 years	Study
Peck	2.76%	This study
Erying	2.02%	This study
Laplace	2.52%	This study
Laplace	2.70%	Radhia DOUMANE and al. 2013 [2]
Hulkoff	2.30%	Hulkoff, 2009 [36]

We have observed a better correlation between Hulkoff's experimental model and analytical modeling results.

3.2. Peck's Model Applied in the Tropical Area (Benin)

3.2.1. Site Description

The tropical humid area is the largest climatic group on the surface of the globe and the only one in a single unit, since it extends approximately symmetrically on both sides of the equator. This area is defined as the part of the earth's surface that twice a year, receives perpendicularly at midday the rays of the sun when it goes to the zenith. This zone is around the equator, from 23.5 degrees north latitude to 23.5 degrees south latitude and extends in total to 46°55 ' of latitude, symmetrically on both sides of the equator. Throughout the year, therefore, and over the entire extension of the tropical zone (Figure 20), the sun rises every day high in the sky: there is no real winter. The tropical zone is a hot and very rainy zone and the winds are laden with humidity. The persistent combination of heat and humidity can be the cause of the degradation of crystalline silicon PV cells [21].

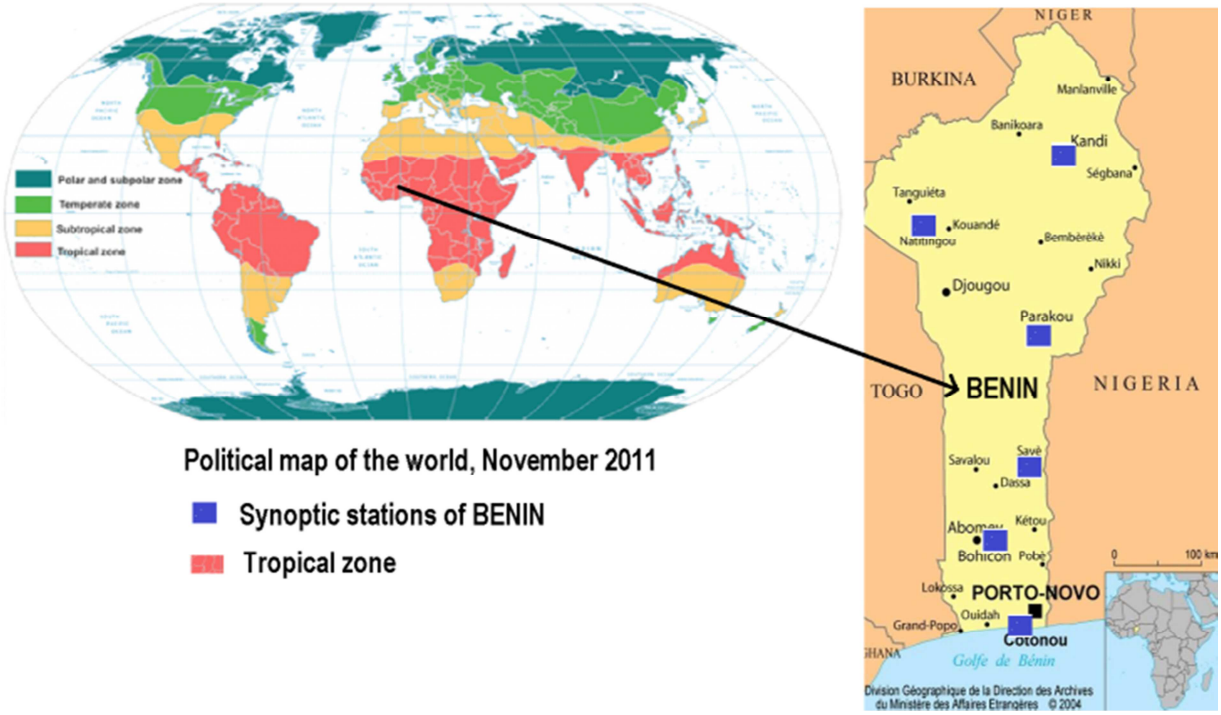

Figure 20. *Geographic location of Tropical Zone and the synoptic stations of BENIN (Source: political map of the world, November 2011).*

3.2.2. Modeling of PV Modules Degradation in the Tropical Area

The tropical area is characterized by high humidity (70 to 90% RH) [22] and a high temperature up to 45°C in real conditions. Erying's and Peck's models can therefore be used to simulate the degradation over time of crystalline silicon PV modules.

We used the data of temperature and relative humidity of synoptic stations of Benin (Figure 20) over a period of 40 years (1967 to 2007) to evaluate the degradation rates of the PV modules.

Benin is located between latitudes 6° and 12°30 N and longitudes 1° and 4°E, presents at south a subequatorial climate with two rainy seasons and two dry season. At north the climate is Sudanese with a moist season and a dry season. At south the average annual pluviometric decreases from Porto-Novo (1200 mm) to Grand-Popo (820 mm). The average monthly temperature varies from 20°C to 34°C. At north the temperatures are high, and the rainfalls are weaker between 890 and 700 mm except on the which receives on average 1300 mm in Natitingou [23].

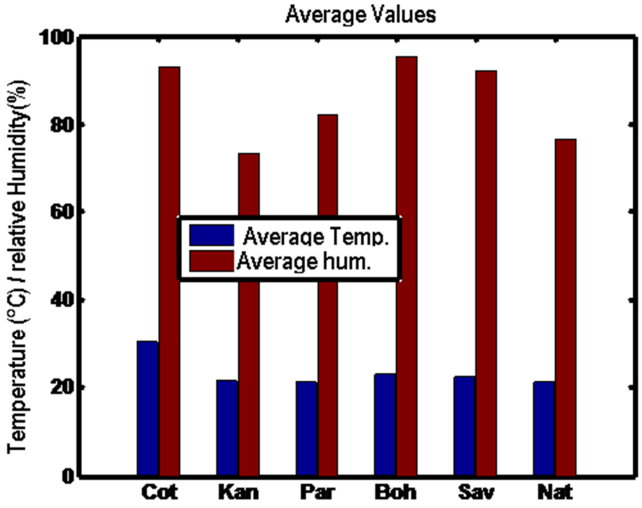

Figure 21. *Average interannual temperature and relative humidity.*

Figure 21, showed average interannual temperature and relative humidity values of synoptic stations in Benin.

With peck model, numerical simulation performed with the average values of temperature and relative humidity over 40 years, has achieved the degradation of electrical power modules (Figure 22).

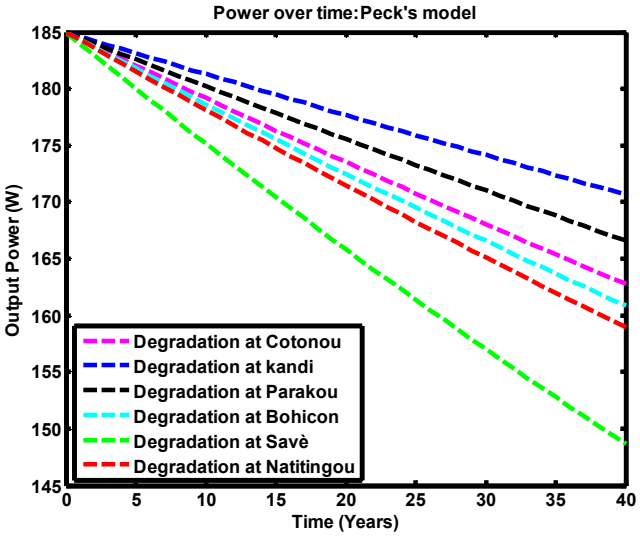

Figure 22. *Interannual degradation of power Electric: 1967 to 2007.*

The annual electrical power degradation rates of the NTS5E3E module in the six cities of Benin are calculated and summarized in the following table.

Table 4. *Degradation rates in the six synoptic stations of Benin (Figure 20).*

Cities	Cotonou	Kandi	Parakou	Bohicon	Savè	Natitingou
R_D (40 years)	12.02%	7.76%	9.95%	13.03%	19.64%	14.07%
R_D (per year)	0.3%	0.19%	0.25%	0.33%	0.5%	0.35%

These degradation rates obtained in the six cities of Benin were compared with those found in the literature (Table 2).

The results found to compare with those obtained in this work show that the results are similar and that the model used is appropriate.

4. Conclusion

We have from the experimental Damp-Heat data of Hulkoff (2009), validated the Erying and Peck analytical models. The results obtained compared with those obtained in the literature are consistent. The power degradation rates obtained are less than 5% as recommended by the International Electro technical Commission [2]. The Peck model was used to calculate, over a period of 40 years, in different cities of Benin, the degradation rate of the PV module NTS5E3E with peak power 185 Wc. The results obtained showed degradation rates of between 0.19% and 0.5%/year. This rate varies from one city to another. But the results obtained are consistent with those found in the literature (Table 4) where for crystalline silicon the rate is around 0.5%/year. Degradation rates of less than 0.5%/year are required to meet long-term guarantees. The peck model that is used when the damage mechanism is sensitive to humidity and temperature allows determining in real time and in real conditions, the degradation rate of the electrical power.

The highest rate (0.5%/year) was obtained at Savè in the center of the country which is a hilly region and therefore an area of excessive heat from the reflexivity of the hills and the fact that the atmospheric humidity coastline (monsoon flow) is trapped by the latter. This reveals that the high atmospheric humidity and temperature have an important effect on the degradation of the modules. A similar result was recently found by Park, who after doing an accelerated Damp-Heat test on three types of modules with different encapsulant (PVB, olefin and EVA) realized that after 1000h of test corresponding to 20 years in real conditions, PV modules encapsulated with EVA and olefin exhibiting a degradation rate of approximately 0.5%, a rate lower than that necessary to meet reliability or stability requirements. So modules encapsulated with EVA and olefin are more suitable for environments where environmental conditions (Humidity and temperature) are more severe such as in the tropics [37]. The utility of the Damp-Heat test is confirmed by Hyun-A Kim who believes that Damp Heat test is the degradation test of PV

modules in harsh environments like tropical area [38]. Further research is thus needed on PV to perform the profile effect of Damp-Heat on the electrical parameters into crystalline silicon photovoltaic solar modules in tropical area.

Competing Interests

Authors have declared that no competing interests exist.

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