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Titre : Damp-Heat Effects on Short Circuit Current, Open Circuit Voltage and Efficiency into Crystalline Silicon Photovoltaic Solar Modules in Tropical Zone

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Damp-Heat Effects on Short Circuit Current, Open Circuit Voltage and Efficiency into Crystalline Silicon Photovoltaic Solar Modules in Tropical Zone

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Authors' contributions

This work was carried out in collaboration among all authors. Author MMCC designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors BK and VIM managed the analyses of the study. Authors GFH, CAK and MA managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Photovoltaic solar modules, for their operation are necessarily exposed outdoors and subject to the inclinations of nature. These include: temperature, heat, moisture, wind, dust, sun ultraviolet rays etc. Each of these inclinations acts differently on the PV modules operation, contributing to affect its electrical parameters namely the short circuit current, the open circuit voltage, the form factor, the efficiency, the power etc. Several researchers have studied the behavior of these electrical parameters in different climatic zones around the world and have produced diverse results. The present study concerns the behavior of the module electrical parameters namely the short circuit current, the open circuit voltage and the efficiency of the PV module when exposed to outdoor conditions in the tropical zone under the effect of Damp Heat. For this, we simulated over a period of

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forty years, using the analytical degradation models of Peck, Braisaz and calculation methods from which we established new degradation models. These degradation models being a function of relative humidity and temperature, we used data from synoptic stations to see the impact of Damp Heat on the three electrical parameters involved. The results obtained vary from 2.86 - 7.14% for the short circuit current, 0.43-0.66% for the open circuit voltage and 7.75-19.44% for the efficiency over the study period. To validate the analytical models used, we used the experimental Damp Heat test results. The results obtained to compare with those obtained in the literature are conclusive and reveal the impact of the tropical zone (severe climatic conditions) on the electrical parameters of the module studied. So, future researches on crystalline silicon photovoltaic solar module can be effect of Damp-Heat on the photocurrent, saturation current and ideality factor in tropical zone.

Keywords: Electrical parameters; damp heat; short circuit current; open circuit voltage and efficiency.

1. INTRODUCTION

Nowadays, several energy sources are used to satisfy the world need energy. These energy sources are diversified and depended from one country to another. Thus, in the developed countries, nuclear in the recent past was privileged until the recent catastrophe of Fukushima (Japan) in 2011, where nuclear power stations were affected arousing the indignation of world economic powers. More and more, there has been a renewed interest in renewable energies which are designed to gradually replace the old generations' power stations. On the other hand in developing countries, hydroelectricity and thermal sources are preponderant because of great importance and security care that the nuclear need. But in recent years, because of the availability of solar energy and more particularly in Africa, there has been a growing effort by state to invest in photovoltaic energy sources. Fig. 1. shows the proportions of each form of energy produced on a global scale during the year 2017. From the quantities (electrical powers) installed in 2017, it appears that solar energy is by far the most important and the most produced today in the world.

However, its operation is not without drawbacks because, for example, for photovoltaic solar energy, the environmental and climatic conditions such as temperature, irradiation, heat, moisture, UV rays, wind speed, dust and mechanical shocks etc. etc., have a detrimental effect on the components of the solar modules contributing to affect the electrical performance of the latter. These environmental and climatic factors induce one or more types of degradation modes [3-5]. Fig. 2. illustrates the proportions of some degradation modes around the world in 2017.

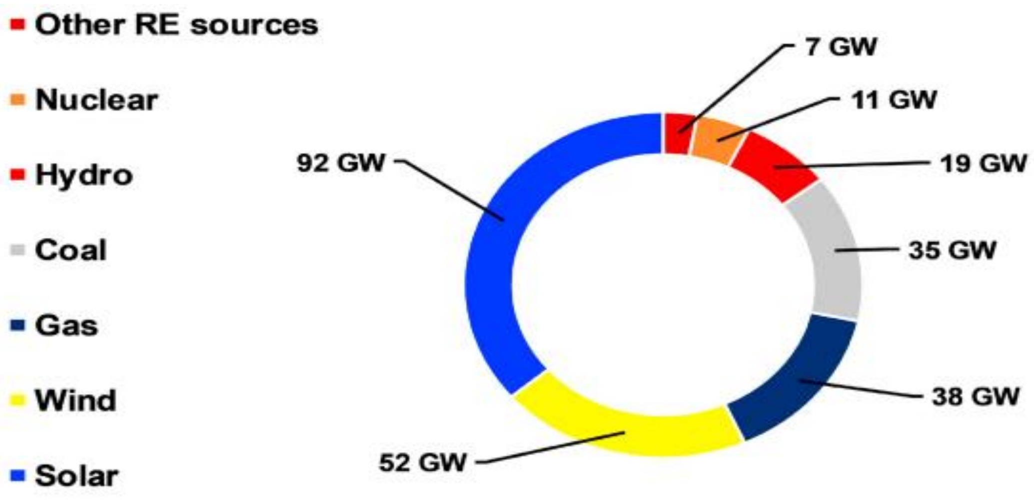

Fig. 1. Power generating capacity installed in 2017 [1,2]

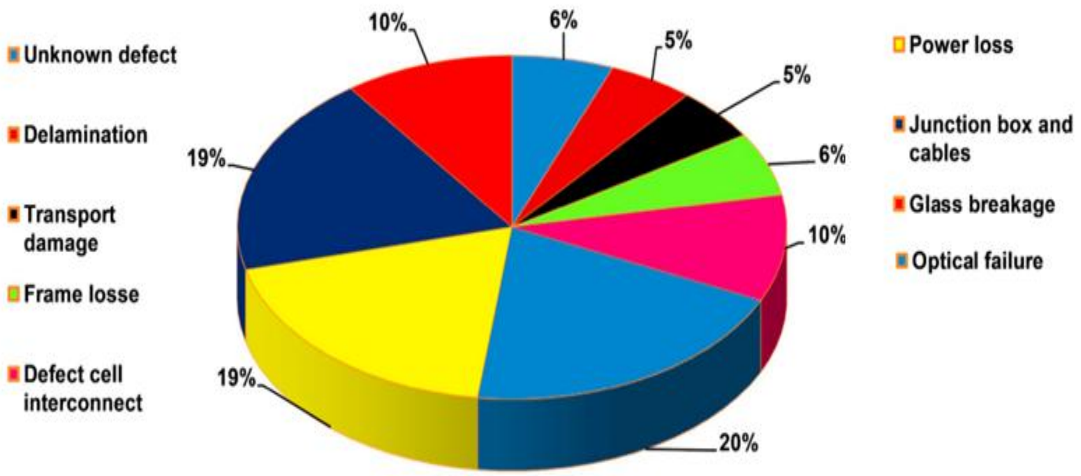

Fig. 2. PV panel failure rates according to customer complaints [6,7]

When these degradations modes occur in PV modules, its electrical parameters such as short circuit current density (J_{SC}), open circuit voltage (V_{OC}), fill factor (FF) and efficiency (η) [8] etc., are affected and contributed at its output power degradation. The Module performance is represented its efficiency (η), which depends on the short circuit current density, open circuit voltage and the fill factor [9]. The value of the short circuit current density increases with the output power, but does not significantly affect the module efficiency (η) because this increase is linear. Otherwise, by increasing the solar radiation, the open circuit voltage increases logarithmically whereas the short circuit current density elevates linearly. In consequence, the resulting output power increases [8-10].

It is important to study the effect of environmental and climatic factors on electrical parameters such as short circuit current, open circuit voltage and fill factor of PV modules exposed under real conditions in order to characterize the impact of these effects on their degradation.

In this study, the emphasis is on the tropical zone effect in the degradation of the electrical parameters of the PV (short circuit current, open circuit voltage and form factor) modules. Indeed, the tropical zone is an area characterized by a hot and humid climate where average daily ambient temperature can reach 26 °C. The solar cell temperature rises to an average high of about 80°C at mid-day and average low of about 15°C at mid-night. Tropical climates also experiences high rainfall with occasional high winds and thunderstorms. An average relative humidity of about 85% is usually recorded [11]. These extreme conditions of temperature and humidity are liable to induce accelerated degradation on the components of the module, thus affecting its electrical parameters and contributing to its loss of performance [12-14].

So, we are interested in studying the degradation over time of electrical parameters such as: short circuit current, open-circuit voltage and efficiency under the effect of Damp-Heat.

This work was carried out according to the following chronology: in Part 1, through a brief state of the art, we gave an update on the effects of moisture and heat on the electrical parameters of the PV module (the case of relative humidity), then in Part 2 the results obtained and the discussion were presented.

2. MATERIALS AND METHODS

2.1 Site Description

The tropical zone is the largest climatic group on the surface of the globe since it extends approximately symmetrically on both sides of the equator. It defined as the part of the earth's surface that twice a year, receives perpendicularly at midday the rays of the sun when its goes to the zenith. This zone is around the equator, from 23.5 degrees north latitude to 23.5 degrees south latitude and extends to 46°55 ' of latitude, symmetrically on both sides of the equator. Throughout the year and over the entire extension of the tropical zone, 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 crystalline silicon PV cells degradation [15]. It's characterized by high humidity (70 to 90% RH) [16] and a high temperature up to 45°C in real conditions.

Benin (in tropical area) is located between latitudes 6° and 12°30 N and longitudes 1° and 4°E (Fig. 3). It presents at south a subequatorial climate with two rainy seasons and two dry seasons. 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 Natitingou which receives on average 1300 mm [17].

2.2 Data Used

Temperature and relative humidity data of synoptic stations of Benin (Fig. 8) over 40 years (1967 to 2007) were used to evaluate the degradation of short circuit current density (J_{SC}), open circuit voltage (V_{OC}), and efficiency (η) into the photovoltaic solar modules. Fig. 7. showed average interannual temperature and relative humidity values of synoptic stations in Benin.

2.3 Module Characteristics

The Sharp NTS5E3E photovoltaic module is constituted of 72 monocrystalline silicon cells "125.5mm X 125.5mm" connected in series of maximum power 185 Watts. The module characteristics under standard test conditions (sunshine: 1000 W/m^2, atmosphere mass: 1.5, module temperature: 25°C) are giving in the Table 1.

The studied module structure is close to the module used in the Hukloff performance degradation experiments (Fig. 4).

2.4 Degradation of Electrical Parameters Correlated with the Literature

A photovoltaic module is degraded when its electrical power reaches a level below 80% of its initial value [19]. But for the electrical power to drop, several components of the module have already been affected. The direct consequence is degrading the internal electrical parameters of the PV module. Since the degradation of the electrical parameters cannot be done by visual inspection, appropriate methods have been adopted in the laboratories and at the places of exposure of these modules. Failing to carry out experiments which generally require a relatively long time, degradation models of electrical parameters of PV modules are developed by several researchers with the aim of rapidly achieving results which cannot be achieved in record time when these modules are exposed in outdoor conditions. But the tiny number of these models and their reliability leave much to be desired. For this, we have, from existing degradation models, developed new models to assess the impact of Damp Heat on the short circuit current, the open circuit voltage and the efficiency of PV cells/modules in tropical areas. A brief literature review was carried out on the parameters aroused in order to understand their degradation mode when PV modules are exposed to outdoor conditions.

- **Short circuit current (J_{SC})**

For most climatic zones, the degradation of the short-circuit current (Isc) is the greatest degradation factor of the output power (Pmax). However, J_{SC} degradation is mainly caused by delamination, discoloration and cracked cells (Fig. 5. (b), (c) and (a)) due to environmental and climatic conditions such as Damp-Heat, light and soling [20-25] etc. Discoloration is one of the primary modes of degradation for modules having a glass / polymer construction. Encapsulant discoloration causes a drop in the short-circuit current [26].

In tropical areas, the photovoltaic modules degradation is much faster and more accentuated compared to other areas characterized by other environmental conditions [27-29]. It should be noted that delamination (Fig. 5. (b)) is more frequent and severe in tropical areas [29-31]. It therefore appears that in tropical area, short-circuit current degradation in PV modules is recurrent.

Moreover, [36] according to experimental Damp Heat tests on traditional modules (glass / encapsulant / cell / backsheet) comes to the conclusion that the short circuit current loss has a significant influence on PV module electrical power degradation.

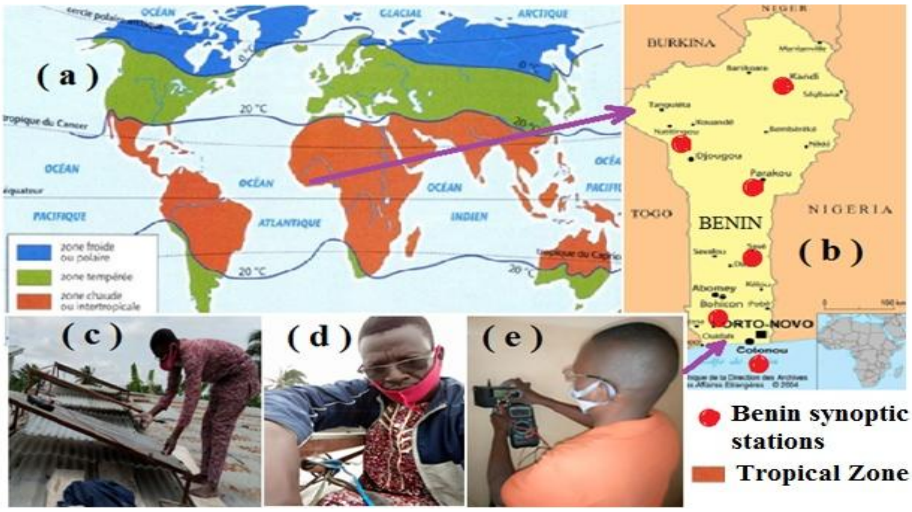

Fig. 3. (a) World map showing Benin in Tropical Zone, (b) BENIN map showing synoptic stations, (c) Picture showing solar field and Visual Inspection, (d) Picture showing connection cables degradation under Damp Heat effect, (e) Electrical parameters measurement phase [18]

Table 1. Module characteristic

Electrical data (STC)	**Sharp NTS5E3E**
Nominal Maximum Power	185W
Open circuit voltage	44.9V
Maximum peak power voltage	36.21V
Short circuit density	5.60A
Cell efficiency	17.1%
Module efficiency	14.2%
Series resistance	0.53Ω
Shunt resistance	185.2Ω
Coefficients relating to Short circuit density	+0.053A/°C
Coefficients relating to Open circuit voltage	-156mV/°C
Dimension	1575 x 826 x 46 mm

Fig. 4. Module used

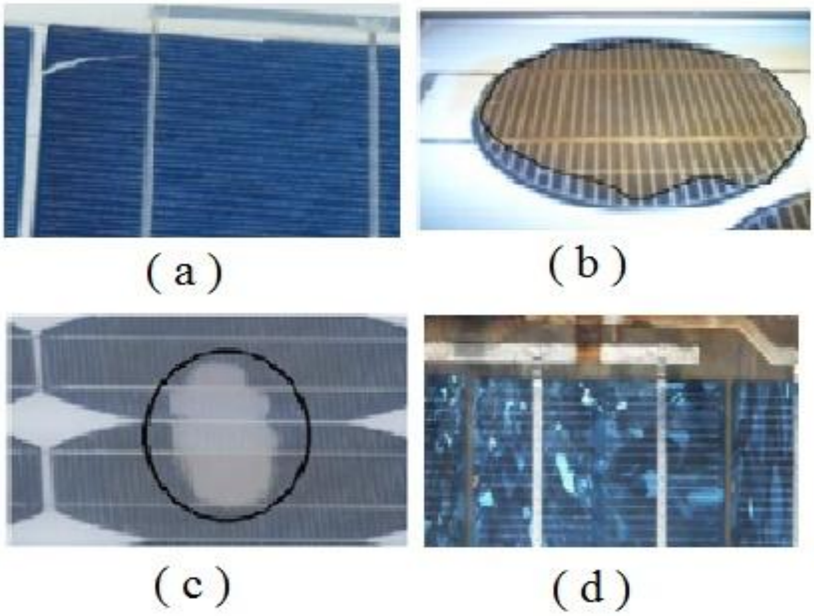

Fig. 5. (a) Cell crack (b) Delamination (c) Discoloration (d) interconnection corrosion [32-35]

- **Open circuit-voltage** (V_{oc})

Open circuit voltage and short circuit current are the two major electrical parameters generally used to characterize the solar cells [37].

A study carried out in the hot and dry climate on the power degradation of glass / glass encapsulated modules revealed that this degradation is caused by the loss of voltage. The voltage loss is attributed to tripping of the bypass diode (s) due to current mismatch caused by poor transmittance on the delaminated cells [38].

The open circuit voltage (V_{OC}) is linearly reduced with increasing temperature [37]. According to [39], the conversion efficiency, Fill Factor (FF), open-circuit voltage (Voc), and short-circuit current (Isc) of as-prepared non-encapsulated modules and of modules degraded under high temperature, damp heat, or thermal shock decreased in function of the damp heat degradation time.

- **Efficiency (η)**

Photovoltaic solar energy is currently coveted by the whole world but it has its limits because the PV modules performance remains to be improved. Already the solar modules manufacturers foresee an efficiency of these PV modules lower than 20%. But when PV modules are exposed outdoors, their efficiency can be degraded.

The efficiency of the module has dependency on the environmental parameters of different zone of research [40,41]. Continuous humid environment for example causes degradation in solar cell/module efficiency and causes the transmittance decrease [42]. The PV module heat absorbed is responsible on raising the module temperature. When the module temperature increases the efficiency of the module decreases [43].

Among the degradation modes, discoloration primarily reduces the transmission of light to the solar cells, which directly reduces the short circuit current (Isc) and decreasing the module efficiency [44-47].

2.5 Moisture Effects on PV Cells Electrical Parameters

Moisture is one of the environmental factors that contribute to the PV cells/modules degradation. It can penetrate inside the PV module through the backsheet or its edges. When its enter into the PV module, several components are attacked. But, the encapsulant degradation affects more the electrical parameters. This moisture causes delamination due to salt accumulation [48] increasing the temperature of affected sites and accelerating the degradation process [49-51]. It should be noted that delamination is more frequent in hot and humid climates [52] such as the tropical zone. In such climates, the entry of humidity into the photovoltaic module is correlated with the rate of degradation and its condensation in the PV modules increases the corrosion of the latter [53]. When exposed over the long term, the water droplets are trapped inside the cell wall and thus serve as an optical screen for the cells, helping to reduce their performance [54].

2.6 Heat Effects on PV Cells Electrical Parameters

Heat is a factor that accelerates encapsulant delamination and discoloration when moisture has already penetrated the module. Once encapsulant degradation has occurred, one witnesses its morphology change, Photothermal reactions and cracking [55]. All this damage created on the encapsulant leads to PV module electrical parameters degradation.

2.7 Analytical Models: Models of Peck, Braisaz and Calculation Methods Used By [56]

Corrosion caused by humidity and heat is the most common of the main causes of performance and electrical parameters degradation into PV module [57]. The models of Peck, Braisaz and the calculation methods [56,57] were used to analytically evaluate the degradation of short circuit current, open circuit-voltage and efficiency of the photovoltaic modules [57,58].

2.7.1 Short circuit current calculation

The short-circuit current is expressed in terms, of G (solar irradiance) and T (temperature), using the following linear empirical relation [59-61]. Its calculating formula is given by [56]:

$$\mathrm{I_{sc}} = \frac{\mathrm{G}}{\mathrm{G_0}}\left[\mathrm{I_{sc,0}} + \alpha_{\mathrm{I_{sc}}}(\mathrm{T} - \mathrm{T_0})\right] \tag{1}$$

Where $\mathrm{G_0}$ is solar irradiance at standard test conditions (STC), $\mathrm{I_{sc,0}}$ is PV module short-circuit current value at standard test conditions (A), $\alpha_{\mathrm{I_{sc}}}$ is thermal coefficient of short-circuit current (A/°C) and $\mathrm{T_0}$ is PV module temperature at STC.

The irradiation data unavailability in our synoptic stations, led us to use the expression giving the series resistance as a function of the solar irradiation given by [56]:

$$R_s = \frac{G_0}{G} \times R_{s,0} \tag{2}$$

Where $R_{s,0}$ is the PV module series resistance at standard test conditions (Ω)

By replacing $\frac{\mathrm{G}}{\mathrm{G_0}}$ by $\frac{\mathrm{R_{s,0}}}{\mathrm{R_s}}$ from formula (2), equation (1) becomes:

$$\mathrm{I_{sc}} = \frac{\mathrm{R_{s,0}}}{\mathrm{R_s}}\left[\mathrm{I_{sc,0}} + \alpha_{\mathrm{I_{sc}}}(\mathrm{T} - \mathrm{T_0})\right] \tag{3}$$

This formula is the new model established to calculate over the study period, the PV module short-circuit current degradation.

2.7.2 Open circuit voltage calculation

We used the method 5 formula to calculate the PV module open circuit voltage [56]. This formula is given by:

$$V_{oc} = \frac{V_0}{1+\beta ln\left(\frac{G_0}{G}\right)} \times \left(\frac{T_0}{T}\right)^{\gamma} \tag{4}$$

Where, V_0 is PV module open circuit-voltage value at standard test conditions (V), β and γ are the model parameters.

As previously indicated, the solar irradiation unavailability led us to use the expression giving the shunt resistance according to the solar irradiation given by [56]:

$$R_{sh} = \frac{G_0}{G} \times R_{sh,0} \tag{5}$$

Where $R_{sh,0}$ is PV module shunt resistance at standard test conditions (Ω).

By substituting $\frac{\mathrm{G}}{\mathrm{G_0}}$ by $\frac{\mathrm{R_{sh}}}{\mathrm{R_{sh,0}}}$ from formula (5), equation (4) becomes:

$$V_{oc} = \frac{V_0}{1+\beta ln\left(\frac{R_{sh}}{R_{sh,0}}\right)} \times \left(\frac{T_0}{T}\right)^{\gamma} \tag{6}$$

The formula (6) is the new model established to calculate over the study period, the PV module open circuit voltage degradation.

Formulas (3) and (6) involve other electrical parameters such as shunt and series resistances which degradation definitely impacts the short circuit current and open-circuit voltage of the PV module. For this, we used the analytical models established by Brasaiz, to calculate the shunt resistance (formula 10) and then developed a new model for calculating the PV module series resistance (formula 11).

2.7.3 Shunt and series resistances calculation: Braisaz model

The shunt and series resistances, are calculated from the voltage-current characteristics of the module under lighting and in the dark (Fig. 6).

The resistances are calculated under darkness and under illumination by linear approximation of the curves. Under solar illumination these resistances are deduced respectively from the slope of the curve around V_{OC} and $\boldsymbol{J_{sc}}$ as follows:

$$R_s = \frac{\Delta V}{\Delta J} \mid, V \sim V_{OC} \tag{7}$$

$$R_{sh} = \frac{\Delta V}{\Delta J} \mid, J \sim J_{SC} \tag{8}$$

When the PV module is exposed to external conditions, these resistances degrade. Two models are proposed by Braisaz to calculate these resistances over time.

$$R_s = R_S(0) + exp(R_D \times t - B) \tag{9}$$

$$R_{sh} = \frac{R_{sh}(0)}{1 + aR_D \times t} \tag{10}$$

Where R_{sh} et R_S are the shunt, series resistances at time (t), $R_{sh}(0)$, $R_S(0)$ are the initial shunt, series resistance, R_D is the degradation rate and a, b are the models parameters.

For the series resistance calculation the Braisaz model doesn't fit with humidity and temperature data from our study area. For that, one has proceeded to the limited development of order 1 and 2 of the model. According to the calculations made with these new models, only the first-order model gives a conclusive result. The model developed at order 1 was therefore used in this work for the calculation of series resistances.

$$R_s = \alpha + R_S(0) + (R_D \times t - \sigma) \tag{11}$$

Where, α and σ are the new parameters, whose choices depend of the model knowledge.

For these resistances calculation, a model to evaluate R_D was proposed by Braisaz.

$$R_D = A \times U \frac{B}{1+exp[-C(RH+D)]} \times exp\left(\frac{-E_a}{k_B T}\right) \tag{12}$$

Where A, B, C, and D are model coefficient, U is the applied voltage.

Since the model has many coefficients, prior knowledge of the impact of the parameters on which the coefficients are applied is necessary, which in our opinion makes its use complex.

Since R_s and R_{sh} are a function of the PV module degradation rate, we used the Peck degradation model, which is a function of humidity and temperature to calculate these two electrical quantities. It should be noted that we have already validated the Peck degradation model in a previous work by Hulkoff experimental Damp Heat model.

2.7.4 Degradation rate calculation: Peck's model

It's a Damp Heat model that is used to calculate the rate degradation of the PV module performance when exposed to outdoors.

$$\mathrm{R_{D,Peck}} = \mathrm{A} \times \exp\left(\frac{-\mathrm{E_a}}{\mathrm{k \times T}}\right) \times \mathrm{RH^n} \tag{13}$$

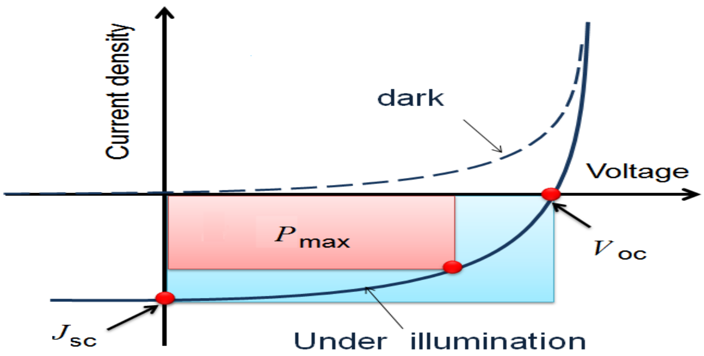

Fig. 6. Characteristics under darkness and under AM1.5 lighting [62]

Where, E_a is the activation energy of the degradation process [eV], T the temperature [K], k is the Boltzmann constant (8.62×10^{-5} eV/K) and RH is the relative humidity [%]. A is a constant dependent on the failure mode.

2.7.5 Efficiency calculation

The module efficiency is a function of the electrical power in operating and the incident power of solar radiation. The incident power depends on PV module area and the irradiation. Under the standard conditions, the photovoltaic module electrical power is function of the open circuit voltage and the short-circuit current. When the degradation rates are obtained, the expression of the average power given by [63] has been used to give the evolution of the mean power of the module as a function of time according to the model.

The expression of the average power is as follows:

$$\mathrm{P_{mean,t}} = \mathrm{P_{max,0}} \times \left(1 - \mathrm{R_{D,Peck}}\right)^{\mathrm{t}} \quad (14)$$

Then the evolution in time of the efficiency is giving by the following expression:

$$\eta = \frac{\mathrm{P_{mean,t}}}{G \times S} \quad (15)$$

Where, G is solar irradiation, S the module area (m^2).

The models validation was made by the experimental results obtained during Damp Heat test [39,64].

Ultimately, the knowledge of the degradation rate ($\mathrm{R_{D,Peck}}$), the series resistance (R_s), the shunt resistance (R_{sh}) and the average electric power ($\mathrm{P_{mean,t}}$) makes it possible to calculate the short circuit current, the open circuit voltage and the efficiency of the PV module over the study period.

3. RESULTS AND DISCUSSION

3.1 Average Temperature and Relative Humidity

Fig. 7. showed average interannual temperature and relative humidity values of synoptic stations in Benin. These data were used to make the different simulations of the electrical parameters degradation of the studied photovoltaic module. The annual average temperature and humidity varies from one site to other. The lowest temperature value is obtained at Kandi with a value of 21.46°C and the highest value (30.3°C) is observed at Cotonou. The site of Cotonou presents higher humidity (93.1%) than other sites due to its proximity to the Atlantic Ocean.

3.2 Short Circuit Current, Open Circuit Voltage and Efficiency Modeling

Using Equations 3, 6, and 15, we simulated analytical models of short circuit current, open circuit voltage, and module efficiency over the study period. The simulations results are shown on Figs. 8,9 and 10.

Overall, we find that these electrical quantities decrease as a function of time over the study period considered. These models are in agreement with the results of many authors who, through experiments and simulations, have confirmed for the most part that under the effect of damp heat, these electrical quantities are decreasing.

To assess the effect of damp heat on these electrical parameters, we calculated their degradation rate in the six cities where the synoptic stations are located.

The highest degradation rates in this study are obtained respectively at Savè (7.14%) and Natitingou (5.36%) for short-circuit current, at Kandi (0.66%) and Parakou (0.61%) for open-circuit voltage and at Savè (19.44%) and Natitingou (13.94%) for efficiency of the PV module over the study period. Savè is located in the center of Benin a few kilometers from the coast (Atlantic Ocean) therefore humidified by the monsoon flow that leaves the coast in a northerly direction. In addition, Savè is a region where one observes the presence of many hills. It's a zone of strong heat due to the sun rays reflexivity by the hills and also to the restitution in the atmosphere of the heat which they store. Natitingou is a city located in the north-east of the country where the humidity is not as high (annual maxima can reach 80%) but a hot region due to the reflexivity of the mountains and also to the flow of the Harmattan (humidifying the region) which crosses the country in the direction of the South of the Country. Furthermore, Parakou and Kandi cities where the open circuit voltage degradation rates are maximum and those of the short-circuit current are minimum respectively 2.86% for Kandi and 3.57% for

Parakou, are high heat regions located in the north of the country. It is also in these cities that we observe the lowest degradation rates of the efficiency of PV modules evaluated respectively at 7.75% in Kandi and 9.86% in Parakou.

It emerges from these analyzes that the atmosphere's Damp Heat has a detrimental effect on the short-circuit current and the efficiency of PV modules (case of the cities of Savè and Natitingou) and on the efficiency of these modules. In addition, the study showed that when the heat is dry, it has more impact on the open circuit voltage and less impact on the short-circuit current and the efficiency of PV modules (case of towns of Kandi and Parakou).

What is interesting is that this study revealed that the most humidified towns (Cotonou, Bohicon, Savè and Natitingou) in the country have a negative impact on the short-circuit current and on the efficiency and the least humidified towns (Kandi and Parakou) have a more impact on the short circuit voltage then a less accentuated impact on the short circuit current and the efficiency of the PV modules.

One conclude that Damp Heat has a detrimental effect on the efficiency of PV modules, and the electrical parameter most affected is the short-circuit current since it's the most degraded. This result is confirmed by [32] who asserts that the short circuit current loss has a significant influence on PV module electrical power degradation. Table 2 summarizes the different degradation rates obtained in this study.

3.3 Validating the Analytically Models Used

The lifetime of PV cells is estimated at 20 years, according to several manufacturers. Several tests are used to assess the degradation rates of PV cell performance. The most performed test is that of Damp Heat carried out by Hulkoff in 2009 in the state of Florida. The conditions of this test are 85°C/ 85% RH. It takes place for 1000 hours in the laboratory corresponding to 20 years in real conditions. During this test, the degradation rate of 5% of the performance of the module must not be exceeded. But to reach the 5% degradation rate of electrical performance, several electrical parameters in turn undergo degradation rates that are no less important. Since the 1000 hours do not allow this rate to be reached, so the test is extended over 2000 hours corresponding to 40 years in real conditions. For this, in this work, we simulated the analytical models of electrical parameters degradation over 40 years. To validate the analytical models used, we used the experimental Damp Heat test realized by [39] over 1000hours at 85°C/85%HR corresponding to 20 years in real conditions. We have therefore studied the behavior of short circuit current, open circuit voltage, and module efficiency due to Damp Heat in the tropical zone.

In the Table 3, we have firstly, shown the degradation rates of the short circuit current, open circuit voltage and efficiency deduced from the experimental Damp Heat test realized by [39] and secondly, these rates are compared to those found in the present study.

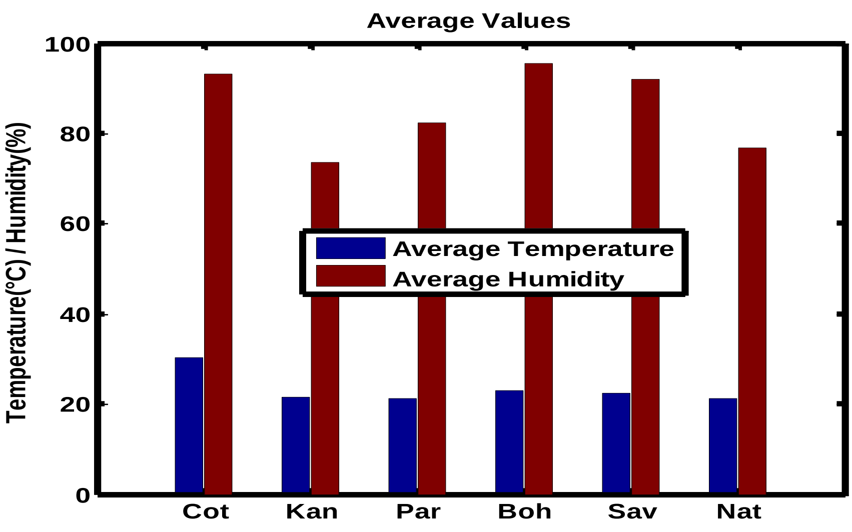

Fig. 7. Operating principle of the cell [12]

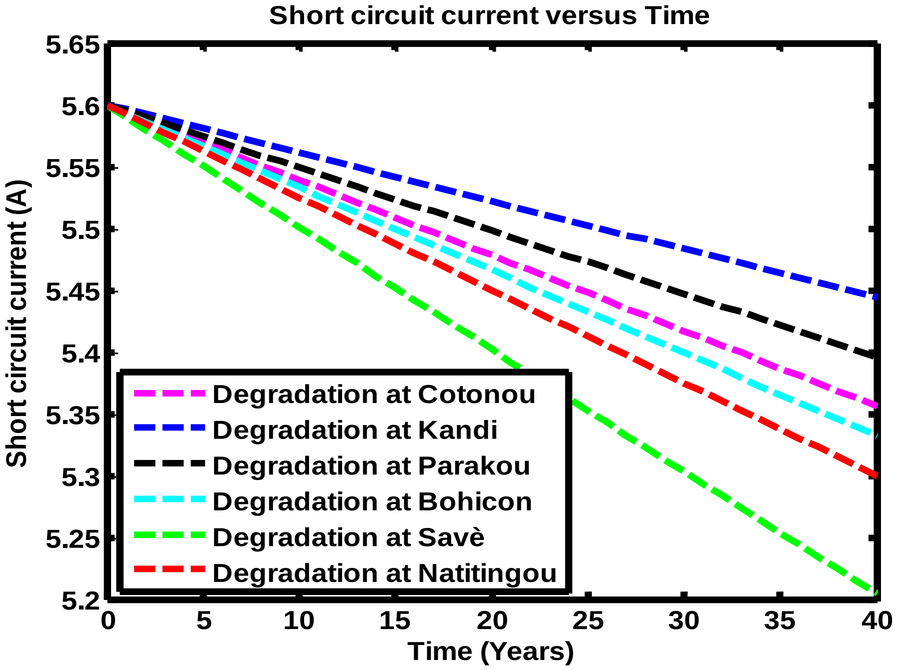

Fig. 8. Short circuit current degradation

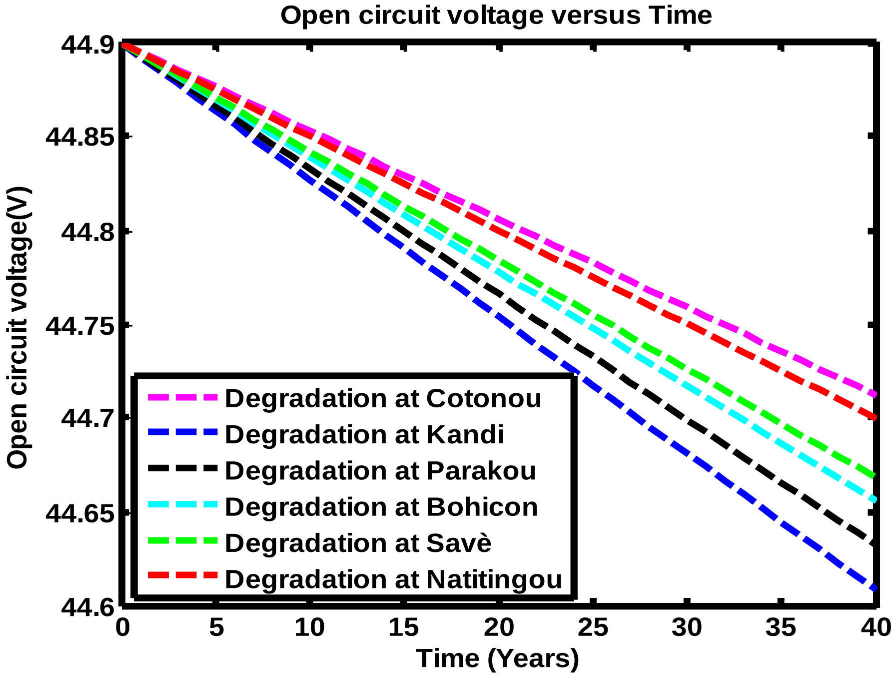

Fig. 9. Open circuit voltage degradation

Table 2. Electrical parameters rates variation over the study period

Electrical parameters	Short circuit current	Open voltage current	Efficiency
Rates variation in this study over 40 years (%)	2.86 – 7.14	0.43-0.66	7.75-19.44

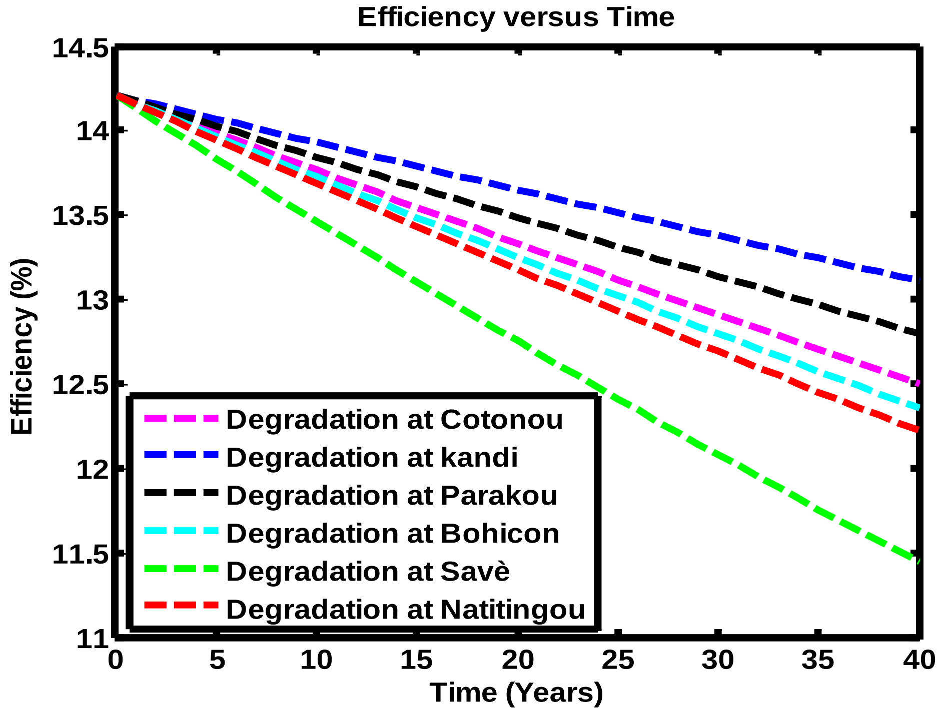

Fig. 10. Module efficiency degradation

Table 3. Degradation rates over 20 years

Electrical parameters	Short circuit current decrease	Open circuit voltage decrease	Efficiency decrease
Experimental Rate (%) over 2000 hours at 85°C/85%HR [39]	3.17	8.25	16.26
Rates variation in this study over 20 years (%)	1.39 - 3.57	0.20 – 0.33	3.87 - 9.51

4. CONCLUSION

We have, from the Peck analytical models for the degradation of the performance, the Braisaz analytical model for the degradation of shunt resistance, series resistance and the calculate methods [56,57] calculated the degradation rates of short circuit current, open circuit voltage and the efficiency of PV modules on a period of forty years in six localities of Benin (Tropical Zone). The degradation rate of the short circuit current and open circuit voltage were calculated from a new model obtained from that of [56]. The results obtained compared to those obtained in the literature are consistent (Table 3) in comparison with those obtained experimentally by [39].

The degradation rates obtained in the six cities concerned by the study vary between 2.86 – 7.14% for short circuit current, between 0.43-0.66% for open circuit voltage and between 7.75-19.44% for the PV module efficiency over the study period. In addition, the electrical parameters degradation rates obtained experimentally during damp heat exposure test by [39], are respectively 3.17% for short circuit current, 8.25% for open circuit voltage and 16.26% for PV module efficiency over 1000 hours corresponding to twenty years in real conditions. For twenty years (real conditions) corresponding to 1000 hours (experimental test), we find respectively between 1.39 - 3.57% for short circuit current, 0.20 – 0.33% for open circuit voltage and 3.87- 9.51% for PV module efficiency. The results obtained show that only the open circuit voltage is not too degraded compared to the results obtained by [39]. These results are confirmed by [65,66] during their various studies.

It appears that, the tropical zone characterized by a hot and humid climate has a more accentuated effect on short circuit current therefore on the PV module efficiency. It's therefore opportune and recommended for the manufacturers of PV modules to adapt the PV modules electrical parameters such as short circuit current and obviously other parameters, which could avoid the degradation of the efficiency of PV module in the tropical zone.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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