CONSEIL AFRICAIN ET MALGACHE POUR L'ENSEIGNEMENT SUPÉRIEUR

01 BP 134 OUAGADOUGOU 01 (BURKINA FASO)
TEL (226) 25 36 81 46 - FAX (226) 25 36 85 73 - Email: cames@lecames.org

Article 10

Titre: Effects of Damp-heat on Shunt, Series Resistances and Fill Factor into Crystalline Silicon Photovoltaic Solar Modules in Tropical Zone

Auteurs: Minadohona Maxime Capo-Chichi, Vianou Irenée Madogni, **Clément Adéyèmi Kouchadé**, Géraud Florentin Hounkpatin, Macaire Agbomahéna and Basile Kounouhewa

Journal: Physical Science International Journal, ***Volume 26, numéro 6, pp. 1-16 (2022)***

Lien: 10.9734/psij/2022/v26i6747

Bases de données d'indexation : Chemical Abstracts (CAS Source Index - CASSI)

Nom **: KOUCHADE** Prénoms : **Adéyèmi Clément**

Institution : Université d'Abomey-Calavi **CTS: Sciences et Techniques de l'Ingénieur**

Tel: +229 94398889 **email : ckouchade@yahoo.fr**

Indexing

Abstracting, Indexing, other related databases, catalogue, reference citation etc.

A dedicated SDI indexing team is working to include all of our journals in reputed indexing services or journal evaluation services or catalogue or reference citations, etc. **Authors should cross-check the authenticity of claims of indexing before submitting to any publisher (including SDI). We strongly encourage authors to take 'informed decision' before submission of any manuscript. In order to help the authors to take 'informed decision', we are providing web-links/proofs beside most of our claims of indexing or journal evaluation services. In addition, authors should visit the official site of the indexing organization or journal evaluation services before submitting any manuscript. We hope scholarly communities will appreciate our efforts to maintain integrity and transparency.**

1. Index Copernicus ICV: 100.00
Proof: http://bit.ly/index-copernicus-PSIJ (http://bit.ly/index-copernicus-PSIJ)

2. Publons (https://publons.com/wos-op/publisher/5994/sciencedomain-international)

3. CNKI (China) (https://scholar.cnki.net/journal/index/SJDT234801300019)

4. Chemical Abstracts Service (CAS, American Chemical Society) (https://cassi.cas.org/publication.jsp?P=eCQtRPJo9AQyz133K_ll3zLPXfcr-WXfM1at5uejrMiMXPxcVRRYGBVqEvQYcnChXsuaZ3AJcvVvor98Mrg9AjLPXfcr-WXfMs9d9yv5Zd_72xFCYgjEkzLPXfcr-WXfMs9d9yv5Zd_XbRXU3aMOMGwOm4mJuHLo)

Make a Submission / Login
(https://www.peerreviewcentral.com/page/manuscript-submission-guide)

Information

For Readers
(https://journalpsij.com/index.php/PSIJ/information/readers)
For Authors
(https://journalpsij.com/index.php/PSIJ/information/authors)
For Librarians
(https://journalpsij.com/index.php/PSIJ/information/librarians)

Current Issue

ATOM 1.0
(https://journalpsij.com/index.php/PSIJ/gateway/plugin/WebFeedGatewayPl
RSS 2.0
(https://journalpsij.com/index.php/PSIJ/gateway/plugin/WebFeedGatewayPl
RSS 1.0
(https://journalpsij.com/index.php/PSIJ/gateway/plugin/WebFeedGatewayPl

5. Physical Science International Journal (ISSN: 2348-0130) (Past name: Physical Review & Research International; ISSN: 2231-1815)

6. NAAS score: 4.69 (2020) Proof: https://tinyurl.com/NAAS-2020 (https://tinyurl.com/NAAS-2020))

7. Google Scholar

8. Qualis (Brazilian index) (https://drive.google.com/file/d/1HFWKr4twkN3eugXHMEGn7DIkn3WcRLhs/view)

9. SHERPA/RoMEO (UK) (http://www.sherpa.ac.uk/romeo/index.php)

10. CrossRef (https://www.crossref.org/)

11. Scite Index (2021):
Link: https://scite.ai/journals/physical-science-international-journal-0G9RZ (https://scite.ai/journals/physical-science-international-journal-0G9RZ)

12. Scilit (https://www.scilit.net/journal/1649704)

13. Journalseek (http://journalseek.net/)

14. Baidu Scholar

15. Sparrho (https://www.sparrho.com/)

16. Citefactor (https://www.citefactor.org/)

17. WorldCAT (https://www.worldcat.org/)

18. ResearchGate (https://www.researchgate.net/)

19. ACADEMIA (https://www.academia.edu)

20. iSEEK (http://education.iseek.com/iseek/home.page)

21. Semanticscholar (https://www.semanticscholar.org/search?q=%22Physical%20Science%20International%20Journal%22&sort=relevance)

22. RefSEEK (https://www.refseek.com/)

23. WorldWideScience (https://worldwidescience.org/)

24. Bielefeld Academic Search (https://www.base-search.net/)

25. AGRIS

26. HINARI

27. Analytical sciences digital library

28. CiteSeerX (https://citeseerx.ist.psu.edu)

29. INSPIRE-HEP (http://inspirehep.net/?ln=en)

30. Mendeley
31. OAIster
32. OpenSIGLE
33. Paperity
34. RePEc
35. SSRN
36. CORE (https://core.ac.uk/)

© Copyright 2010-Till Date, Physical Science International Journal. All rights reserved.

CAS Source Index (CASSI) Search Result

Displaying Record for Publication: Physical Science International Journal

Entry Type	Active Serial
Title	Physical Science International Journal
Abbreviated Title	Phys. Sci. Int. J.
CODEN	PSIJAK
ISSN	2348-0130
Former Title Note(s)	Formerly
Former Title(s)	Physical Review & Research International
Language of Text	English
Summaries In	English
History	v4 n3 May 2014+
Publication Notes	Avail. from Internet at URL: http://www.journalpsij.com/index.php/PSIJ
Publisher Name	SCIENCEDOMAIN International

Disclaimer

Physical Science International Journal

26(6): 1-16, 2022; Article no.PSIJ.61357
ISSN: 2348-0130

Effects of Damp-heat on Shunt, Series Resistances and Fill Factor into Crystalline Silicon Photovoltaic Solar Modules in Tropical Zone

Minadohona Maxime Capo-Chichi [a,b*], Vianou Irenée Madogni [a,b], Clément Adéyèmi Kouchadé [a,b], Géraud Florentin Hounkpatin [a,b], Macaire Agbomahéna [c] and Basile Kounouhewa [a,b]

[a] Département de Physique (FAST), Formation Doctorale Sciences des Matériaux (FDSM), Université d'Abomey-Calavi, Bénin.
[b] Laboratoire de Physique du Rayonnement (LPR), FAST-UAC, 01 BP 526 Cotonou, Bénin.
[c] Laboratoire de Caractérisation Thermophysique des Matériaux et Appropriation Energétique (Labo CTMAE/EPAC/UAC), Abomey-Calavi, Bénin.

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.

Article Information

DOI: 10.9734/PSIJ/2022/v26i6747

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/61357

Original Research Article

Received 23 July 2020
Accepted 24 September 2020
Published 02 November 2022

ABSTRACT

Most solar module manufacturers guarantee the minimum performance of their modules for 20 to 25 years. But some time after their installation, one observes faults which appear on the various components of these modules. During long-term exposure to severe climatic conditions, these faults, which accumulate over time, lead to performance losses of the module. This performance degradation is due to several factors such as humidity, temperature, heat, irradiation etc. These factors cause various degradation processes which can be electrical, chemical, mechanical, thermal, etc. The tropical zone, the middle of our study being characterized by high heat and humidity, has definite impacts on the electrical parameters of photovoltaic modules. The electrical parameters degradation is among others cause of photovoltaic modules performance loss. This study purpose is to study the degradation of the shunt resistance, the series resistance and the form factor of photovoltaic modules installed in tropical areas in order to appreciate their impact on

**Corresponding author: E-mail: cachi1550@gmail.com;*

the performance loss of the latter. For that, we used Peck performance degradation analytical model and Braisaz degradation analytical models of shunt resistance and the series resistance to calculate over a period of forty years, in real conditions in the tropical environment, the degradation of these electrical parameters of the photovoltaic module. The results obtained are compared to those obtained during the Hulkoff experimental tests in the state of Miami in Florida in 2009. The degradation rates obtained in the six cities concerned by the study vary between 17.33-35.67% for resistance shunt, between 3.77-7.55% for the series resistance and between 8-19% for the fill factor. In addition, these electrical parameters degradation rates obtained experimentally by Hulkoff and taken up by [1], are respectively 35.14% for the shunt resistor, 9.43% for the series resistor and 3.03% for the fill factor over the study period.
So, future researches on crystalline silicon photovoltaic solar module can be effect of Damp-Heat on short circuit current and open circuit voltage in tropical area.

Keywords: Shunt resistance; series resistance; fill factor; damp heat; electrical parameters degradation.

1. INTRODUCTION

Electricity production on a global scale is increasingly based on renewable sources, namely: hydroelectric energy, geothermal energy, wind energy, biomass energy and photovoltaic energy. These renewable energy sources therefore constitute one of the major technological challenges over the past twenty years. For this, a lot of research work is carried out in the field of renewable energies in order to control the technologies linked to these new sources, specifically solar photovoltaic equipment. Attention is now focused on photovoltaic solar energy because of the availability of the sun, which is an inexhaustible source. Exposed outdoors in the long term, PV modules undergo many degradation processes [2] over time due to environmental and climatic factors that vary from one locality to another on the globe. But these degradation patterns can be observed only some time after exposure or occur later. Some of these modes can be observed after visual inspection while others require specific methods. The modes of degradation detectable by visual inspection are among others: corrosion, discoloration, delamination, bubbles etc (Fig. 1). But for the Hot Point, the short-circuit/open-circuit cracks and micro cracks, we use respectively: Infrared Imaging, Thermograph, Electroluminescence Imaging / Photoluminescence then Resonance of vibrations ultrasonic [3].

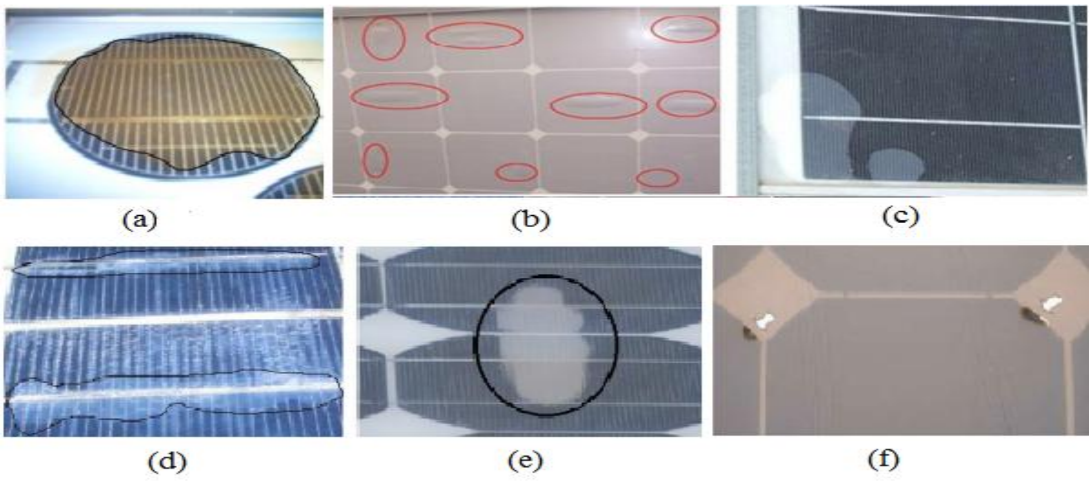

Fig. 1. (a) Discoloration of the encapsulant, (b) Bubbles rear face, (c) Bubbles front face, (d) and (e) Delamination of the encapsulant and (f) Hot spot [3,4,5,6]

When these degradations occur, they are the consequences of several factors including: temperature, humidity, heat, irradiation, wind speed, dust and mechanical shocks etc. These factors affect the performance and electrical parameters of the PV cells / modules inducing the degradation modes mentioned above [7,8,9].

In hot and humid areas such as the tropical area where temperature maxima can reach 40ºC and relative humidity can vary between 70 and 90%, moisture penetration into PV modules is by diffusion; which causes a drop in cell performance, also acting on their electrical parameters, sometimes resulting in degradation accelerated [7,10,11]. So, we are interested in studying the degradation over time of electrical parameters such as: photocurrent density, open-circuit voltage, series resistance and shunt resistance 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 described the operating principle of the cell in question and gives 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 Material

2.1.1 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 (Fig. 2). 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 [12]. It's characterized by high humidity (70 to 90% RH) [13] 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. 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 [14].

2.1.2 Data used

In this work, temperature and relative humidity data of synoptic stations of Benin over 40 years (1967 to 2007) were used to evaluate the degradation of shunt and series resistances and also the fill factor into the photovoltaic modules.

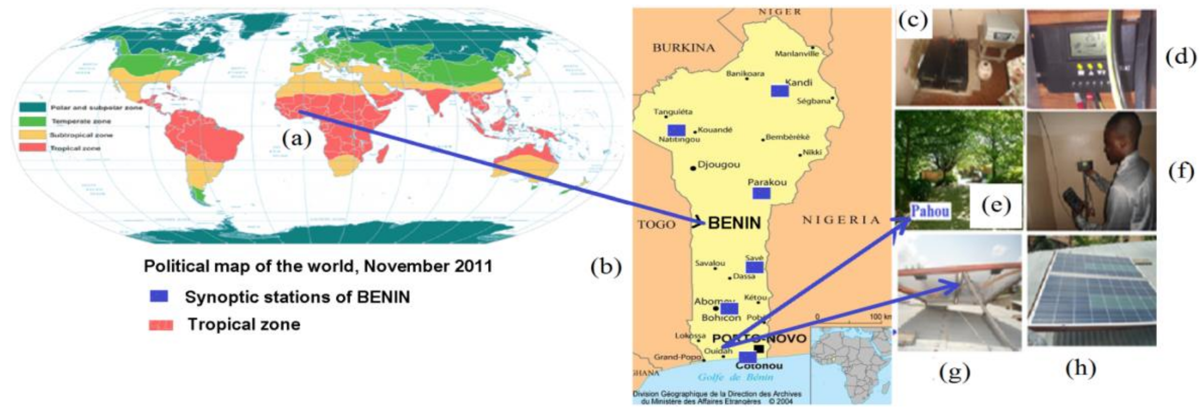

Fig. 2. (a) World map showing Benin in tropical zone, (b) Benin map showing synoptic stations,(c) Storage system and converter, (d) Charge controller, (e) Benin map showing one locality where solar panels were installed, (f) Phase of the electrical parameters measurement, (g) Under module (h) Visual Inspection [15]

2.1.3 Module characteristics

The Sharp NTS5E3E photovoltaic module is constituted of 72 monocrystalline silicon cells

"125.5mm X 125.5 mm" connected in series of maximum power 185 Watts. The module characteristics under standard test conditions are:

- Sunshine: 1000 W/m^2, atmosphere mass: 1.5, module temperature: 25°C,
- Open circuit voltage: 44.9V , maximum peak power voltage: 36.21V, short circuit density: 5.60A, maximum peak power:185.0 W, encapsulated cell efficiency: 17.1% , module efficiency: 14.2% ,
- Series resistance: 0.53Ω, shunt resistor: 185.2Ω.

The studied module structure is close to the module used in the Hulkoff performance degradation experiments (Fig. 3).

Fig. 3. Module used

2.1.4 Photovoltaic effect

We briefly mentioned the principle of photovoltaic conversion because this paper focuses on the degradation of the electrical parameters of PV cells outdoors.

Photovoltaic conversion is widely used nowadays in the search for new energy sources to supplement existing ones. It is defined as the transformation of the energy of photons into electrical energy by the process of absorption of light by matter.

When a photon is absorbed by material, it passes some of its energy by collision to an electron literally pulling it out of matter. The latter being previously at a lower energy level where it was in a stable state then moves to a higher energy level, creating an electrical imbalance within matter resulting in an electron-hole pair, of the same electrical energy (Fig. 4).

Usually, the electron-hole pair quickly returns to equilibrium by transforming its electrical energy into thermal energy. Likewise, all the energy of photons that fail to transform into electricity is absorbed by the material in thermal form. The material constituting the PV collectors then has its internal temperature which increases in proportion to the solar energy received. The photon-electron conversion rate is low because a number of conditions must be met for this phenomenon to occur. The thermal effect is therefore predominant on most sensors, which further deteriorates their performance [16].

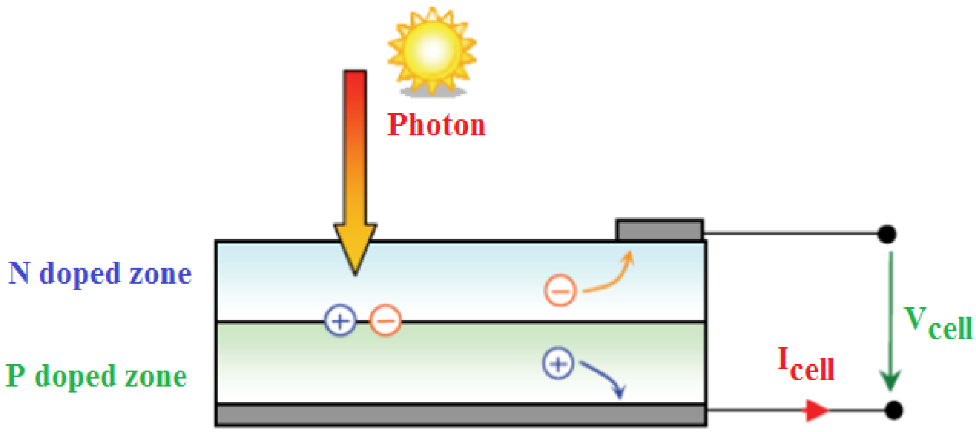

Fig. 4. Schematic diagram of photoelectric conversion [3]

The semiconductor material has two bands: a valence band and a conduction band. The valence band has an excess of electrons and the conduction band has an electron deficit. These bands are said to be n-type doped and p-type doped respectively and are separated by a band called the forbidden band.

An incident photon is absorbed by the photoactive semiconductor if the energy of the photons is greater than the band gap (gap energy Eg) of the semiconductor. This excites an electron from the valence band to the conduction band leaving a positively charged hole in the valence band. The electron and the hole are then extracted at the contacts by the external circuit.

Low gap energy is desirable in order to absorb as many photons as possible. However, for photons with hv> Eg, the extra energy is lost for thermodynamic relaxation [17,18,19] (Fig. 5). In general, assuming sunlight generation, the lower is the band gap, the higher is the J_{SC} and the lower is the V_{OC}, so there is an optimal band gap that maximizes the product of J_{SC} and V_{OC}.

2.1.5 Electrical parameters degradation correlated with the literature

A photovoltaic module is degraded when its electrical power reaches a level below 80% of its initial value [21]. 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. These methods have been listed above in the introduction.

- **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 due to environmental and climatic conditions such as Damp-Heat, light and soling [22-27] 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 [28].

In tropical areas, the photovoltaic modules degradation is much faster and more accentuated compared to other areas characterized by other environmental conditions [29-31]. It should be noted that delamination (Fig. 1: d, e) is more frequent and severe in tropical areas [31-33]. It therefore appears that in tropical area, short-circuit current degradation in PV modules is recurrent.

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

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 [28].

- **Series resistances (R_S), Shunt resistances (R_{sh}) and fill factor (FF)**

The resistance terms address the dissipative effects and construction defects causing parasite currents within the PV module [34]. These resistances are respectively series and shunt resistances. Degradation caused by series resistance comes under the reliability of module [35], which is one of the barriers needs to come across. It should be noted that one of the important parasitic parameters in a solar PV module is the series resistance. It affects the performance of the module in terms of power and efficiency. The increase in series resistance has been identified as the main reason for the degradation of module performance [36]. The series resistance increased, reduces the fill factor, and its too high value also reduces the short circuit current and also the output power [28].

Exposed to the outdoors for a long time, moisture migrates into solar PV module and EVA copolymer undergoes hydrolysis under the effect of Damp-Heat [37,38]. Acetic acid is so produced [37-42] and causes the grid corrosion or deterioration of the conductivity between the grid and the photovoltaic solar cell [43]. Metallic materials corrode considerably [41,42]. Photovoltaic modules therefore undergo degradation including the increase of cells series resistance caused by acetic acid.

As for the shunt resistor, it takes into account the current leaks which occur between the opposite bounds of a solar cell [44]. The greater is shunt resistance, the less is leakage currents and the better is the form factor [45].

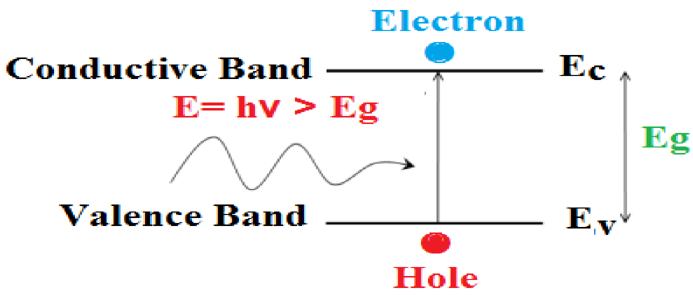

Fig. 5. Operating principle of the cell [20]

Under the effect of Damp-Heat, the degradation of the electrical parameters of the modules encapsulated with glass / polymer is more accentuated [46].

2.1.6 Moisture effects on PV cells electrical parameters

When the moisture enters into the PV module, several components of this module are attacked. But, the degradation of the encapsulant affects more the electrical parameters more since even degraded; the PV cells once illuminated continue to produce electricity. The Fig. 6 shows the different module components attacked by moisture as well as its apparent effect.

The encapsulant material degradation induces by moisture ingress causes a loss of electrical performance of the module. Like show Fig. 7, the effect of moisture on the encapsulant material is very important.

2.1.7 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 [47]. All this damage created on the encapsulant leads to PV module electrical parameters degradation.

2.1.8 Affected electrical parameters

In addition to damp heat, other factors also contribute to PV module electrical parameters degradation. One can cite among others, electric voltage, irradiation etc. These factors act negatively on various components of the PV module and contribute to the destruction of its electrical parameters (Table 1).

2.2 Analytical Models: Models of Peck and Braisaz

Corrosion caused by humidity and heat is the most common of the main causes of performance and electrical parameters degradation into PV module [48]. The models of Peck and Braisaz were used to analytically evaluate the degradation of shunt and series resistances and also the fill factor into the photovoltaic modules [48,49].

2.2.1 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.

$$\mathrm{R_{D,Peck}} = \mathrm{A} \times \exp\left(\frac{-\mathrm{E_a}}{\mathrm{k} \times \mathrm{T}}\right) \times \mathrm{RH^n} \qquad (1)$$

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.

2.2.2 Fill factor calculation

The module fill factor is a function of the electrical power in operating and the electrical power under standard conditions. 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 [1] has been used to give the evolution of the mean power of the module as a function of time according to the model.

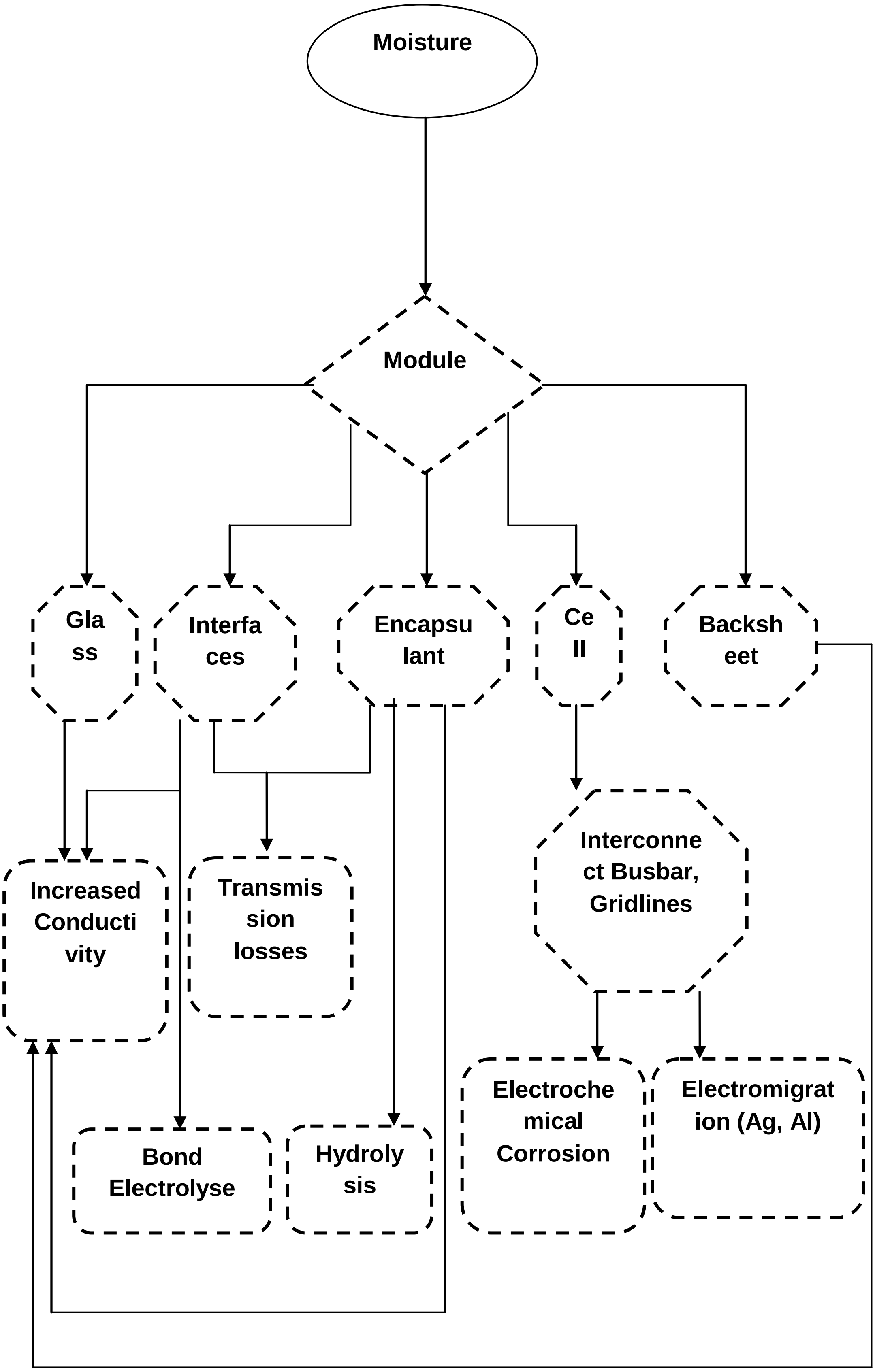

Fig. 6. Effects of moisture and degradation mechanism [47]

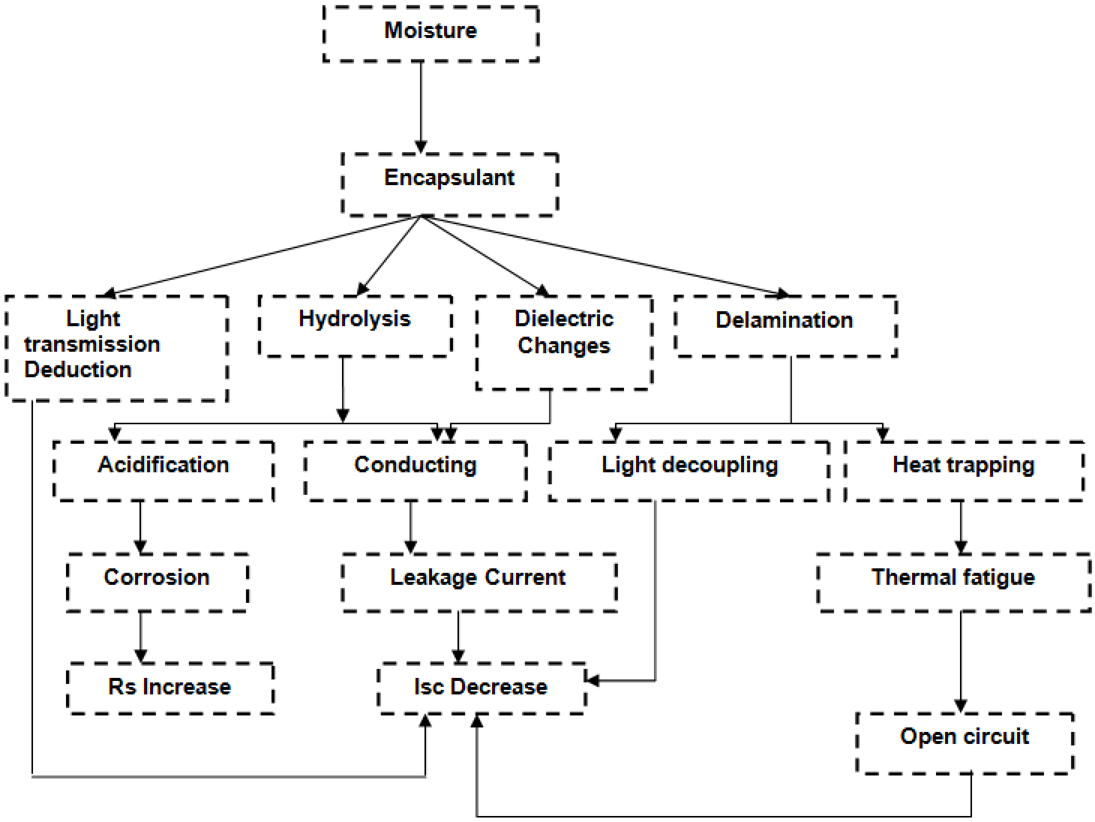

Fig. 7. Degradation mechanisms of PV module encapsulant-Impact on module electrical parameters [47]

Table 1. Affected electrical parameters [47]

Degradation categories	Degradation Behaviors	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 dopant / 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 dopant 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 expression of the average power is as follows:

$$P_{mean,t} = P_{max,0} \times \left(1 - R_{D,Peck}\right)^{t} \quad (2)$$

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

$$FF = \frac{P_{mean,t}}{V_{OC} \times J_{sc}} \quad (3)$$

Where: V_{OC} is the open circuit voltage and $\boldsymbol{J_{sc}}$ is the short circuit current.

2.2.3 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. 8).

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 J_{sc} as follows:

$$R_s = \frac{\Delta V}{\Delta J} \Big|, V \sim V_{OC} \quad (4)$$

$$R_{sh} = \frac{\Delta V}{\Delta J} \Big|, J \sim J_{SC} \quad (5)$$

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

$$R_s = R_S(0) + \exp(R_D \times t - B) \quad (6)$$

$$R_{sh} = \frac{R_{sh}(0)}{1 + aR_D \times t} \quad (7)$$

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

$$R_D = A \times U \frac{B}{1 + \exp[-C(RH + D)]} \times \exp\left(\frac{-E_a}{k_B T}\right) \quad (8)$$

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. For this, we used the Peck degradation model (Eq.1) that we have in a previous work validated by Hulkoff experimental Damp Heat model.

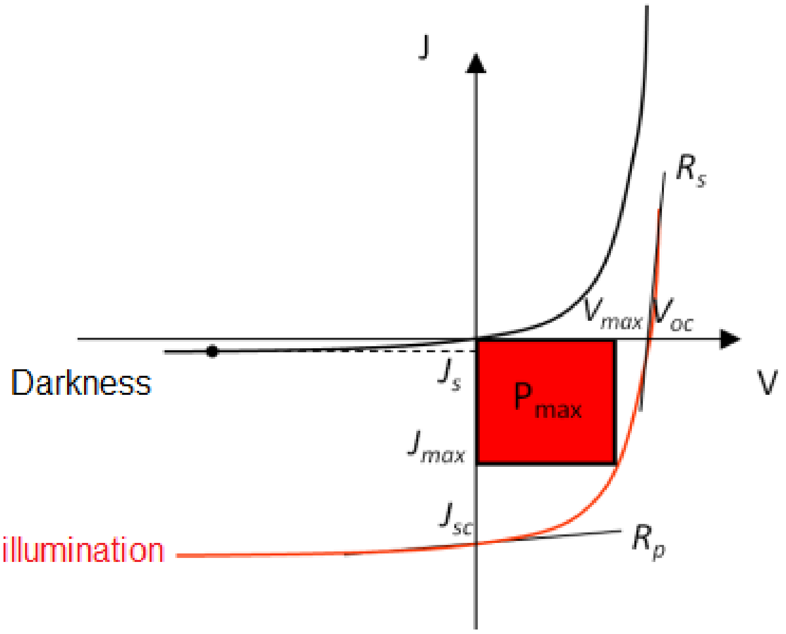

Fig. 8. I-V characteristics under darkness and under AM1.5 lighting [50]

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.

$$R_s = \alpha + R_S(0) + (R_D \times t - \beta) \qquad (9)$$

Where, α and β are the new parameters, whose choices depend of the model knowledge. The two models validation was made by the experimental results obtained during Hulkoff damp heat test.

3. RESULTS AND DISCUSSION

3.1 Average Temperature and Relative Humidity

Fig. 9, 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 Shunt, Series Resistances and Fill Factor Modeling

From analytical models (Eqs. 3, 7 and 9), we simulated the evolution of these electrical parameters of the module over the study period. The evolution of these parameters is shown in the Figs. 10, 11 and 12.

In Fig. 10 the shunt resistance decreases, in Fig. 11 the series resistance increases and in Fig. 12, the fill factor decreases. The models used are therefore in agreement with the results of various studies on PV modules [47].

To assess Damp Heat effect on the shunt resistance, series resistance and fill factor, we evaluated their degradation rates in different cities over the study period. The highest degradation rates of the shunt resistance in this study are obtained at Savè and Natitingou. These two cities are mountainous regions where we observe the presence of many hills and mountains, consequently areas of strong heat due to the reflexivity of the rays of the sun and also to the restitution in the atmosphere of the heat stored by them. The heat density released by hills and mountains has a detrimental effect on PV cells and contributes to their degradation. In addition, Savè is a town close to the coast characterized by high humidity. This could explain the high degradation rate of the shunt resistance (a decrease of 35.67%) observed. In fact, during the monsoon, humid air currents cross this region towards the north of the country

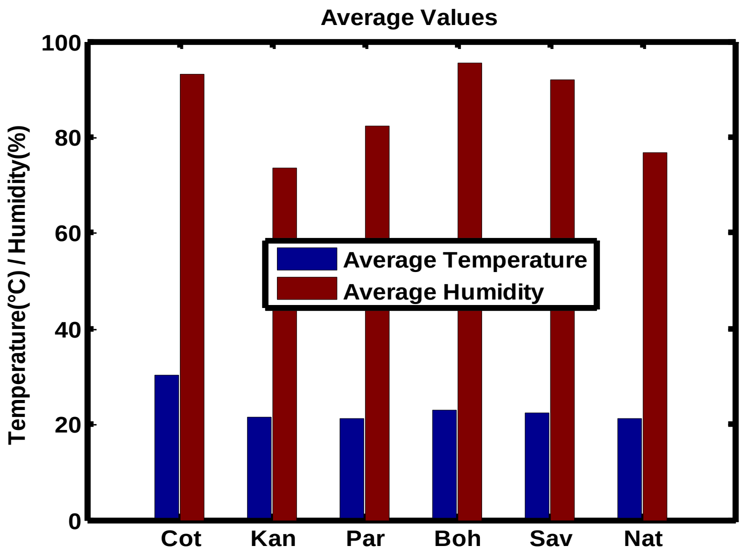

Fig. 9. Average interannual temperature and relative humidity

where they are trapped by the hills, moistening the already warm atmosphere. It appears that Savè is a hot and humid region not favorable to the PV module.

Furthermore, we can also see that it's at Savè that the series resistance (a growth of 7.55%) and the fill factor (a decrease of 19%) are also better degraded over the study period. This result is confirmed by [28,36,51] who according to the studies concludes that when the series resistance increases, the output power therefore the fill factor decreases significantly.

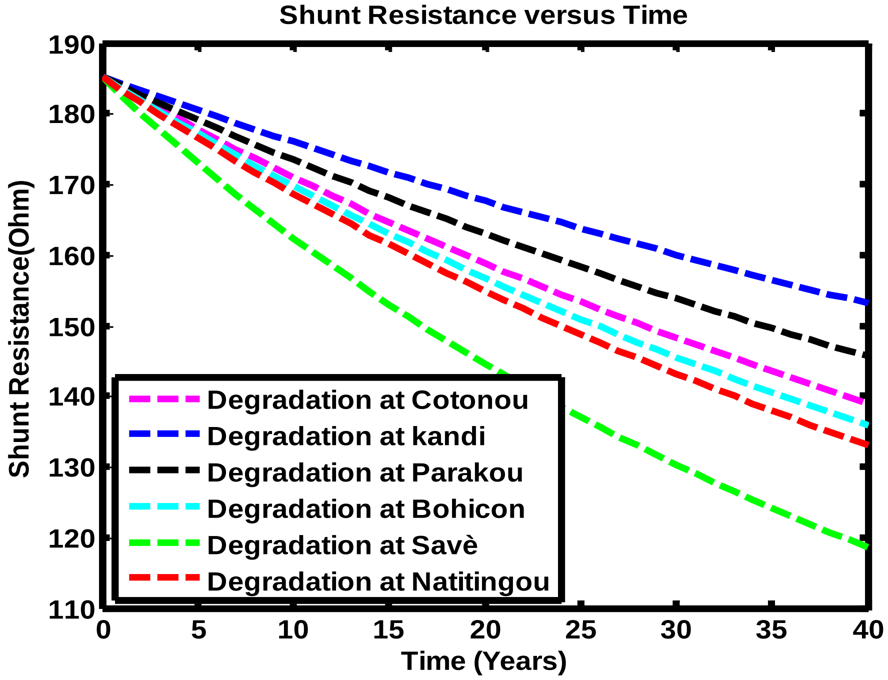

Fig. 10. Shunt resistance degradation

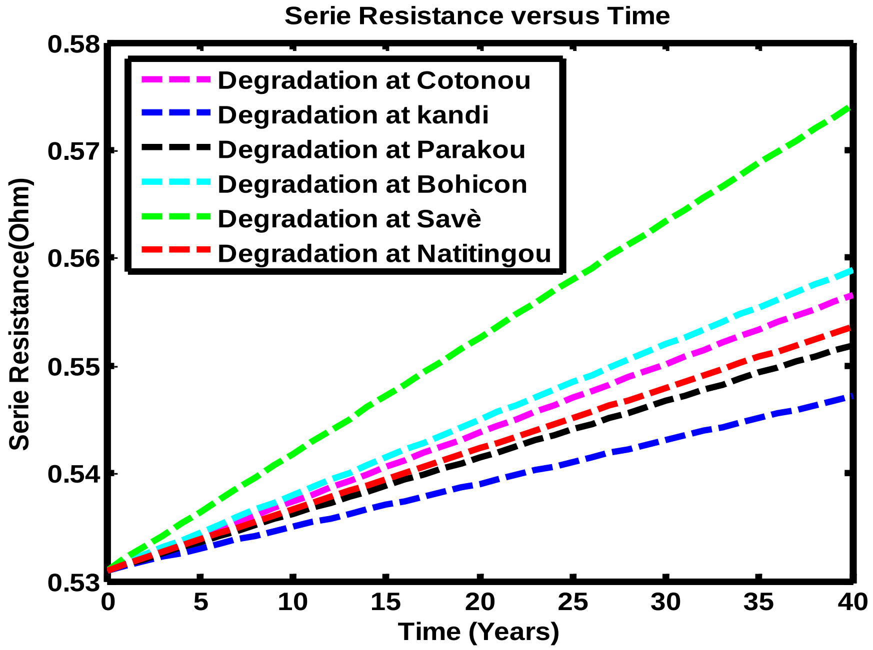

Fig. 11. Series resistance degradation

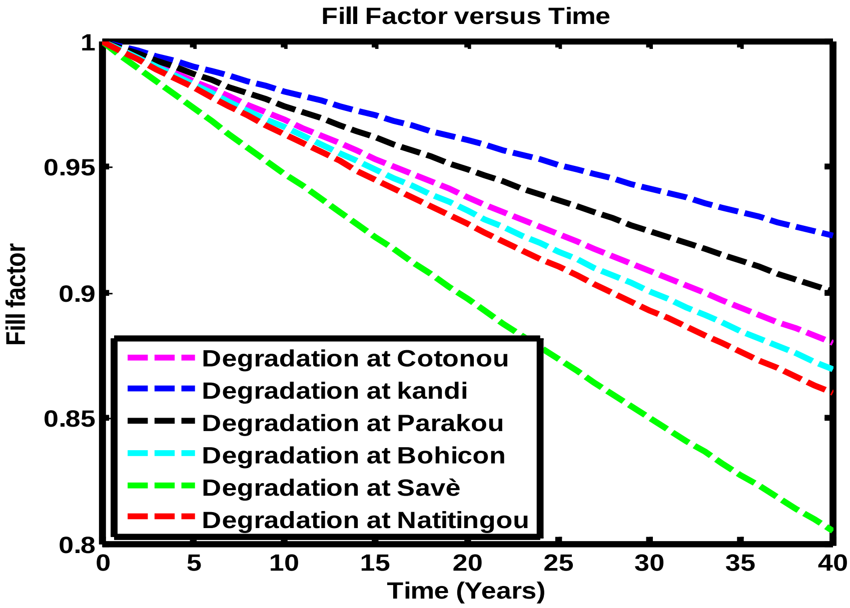

Fig. 12. Fill Factor degradation

In addition, this study shows that the more the shunt resistance is degraded, the more the fill factor is also degraded. So the less it degraded, the best is the fill factor (case of Kandi city) [45].

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 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 degradation over 40 years. To validate the analytical models used, we used Hulkoff's experimental results taken up by [1] over the study period. We have therefore studied the behavior of shunt resistance, series resistance and fill factor due to Damp Heat in the tropical zone.

In the Table 2, we have shown the degradation rates of the shunt resistance, series resistance and fill factor deduced from the output power during Hulkoff experimental Damp Heat test [1]. These rates are compared to those found in the present study.

From this study, it appears after comparison of the rates calculated with those obtained during Hulkoff experimental test in the state of Miami in Florida that the degradation rates of the shunt resistance and series resistances agree to a large extent with those of the experimental results. However, the tropical zone characterized by a hot and humid climate has a more accentuated effect on the fill factor and therefore on the performance loss of PV modules. It is therefore opportune and recommended for the manufacturers of PV modules to adapt the PV modules electrical parameters to the tropical zone climate conditions (high heat and humidity) in order to reduce the loss of performance of the PV modules intended for these zones.

Table 2. Degradation rates

Electrical parameters	Shunt resistance decrease	Series resistance increase	Fill Factor decrease
Experimental Rate (%) [1]	35.14	9.43	3.03
Rates variation in this study (%)	17.33-35.67	3.77-7.55	8-19

4. CONCLUSION

We have, from the Peck analytical models for the degradation of the performance (fill factor) and the Braisaz analytical model for the degradation of shunt resistance, calculated the degradation rates of fill factor and shunt resistance of PV modules on a period of forty years in six localities of Benin (Tropical Zone). The degradation rate of the series resistance was calculated from a new model obtained from that of Braisaz. The results obtained compared to those obtained in the literature are consistent (Table 2) in comparison with those obtained experimentally by Hulkoff in 2009.

The degradation rates obtained in the six cities concerned by the study vary between 17.33-35.67% for resistance shunt, between 3.77-7.55% for the series resistance and between 8-19% for the fill factor. In addition, the electrical parameters degradation rates obtained experimentally by Hulkoff and taken up by [1], are respectively 35.14% for the shunt resistor, 9.43% for the series resistor and 3.03% for the fill factor over the study period. These results are in agreement with those found in the present study. [52] confirm that, series resistance increase upon exposure to the damp heat test and [53] has reveal that PV modules power loss is associated to the increasing series resistance (Rs).

It appears that, the tropical zone characterized by a hot and humid climate has a more accentuated effect on the fill factor and therefore on the performance loss of PV modules. Also in some cities, the climatic conditions have remarkable effects on series resistance. It is therefore opportune and recommended for the manufacturers of PV modules to adapt the PV modules electrical parameters such as series resistance and fill factor to the tropical zone climate conditions (high heat and humidity) in order to reduce the loss of performance of the PV modules intended for these zones.

ACKNOWLEDGEMENTS

Authors wish to acknowledge Odjounchi Raoufou YESSOUFOU, Guy Hervé HOUNGUE and H. E. Venance DONNOU for useful advice and suggestions.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Radhia D. Modélisation du vieillissement du module photovoltaïque. Mémoire de Magister, Université M'hamed Bougar, Boumerdes; 2011.
2. Rémi L. Fiabilité et durabilité d'un système complexe dédié aux énergies renouvelables - Application à un système photovoltaïque. Thèse de Doctorat, Université d'Angers; 2001.
3. Ndiaye A. Etude de la dégradation et de la fiabilité des modules photovoltaïques Impact de la poussière sur les caractéristiques électriques de performance. Thèse de Doctorat, Université Cheikh Anta Diop de Dakar ; 2013.
4. Chris B. Why glass sometimes breaks. Presented at Photovoltaic Module Reliability, Workshop Golden, Colorado, USA; 2010.
5. Yang S. Characterization and aging study of encapsulant (EVA) and backsheet for PV modules. NREL PV Module Reliability Workshop, Denver West Marriott, Golden, Colorado; 2011.
6. Kaplanis S, Kaplani E. Energyperformance and degradation over 20 years performance of BP c-Si PV modules. Simulation Modeling Practice and Theory. 2011;19:1201-1211.
7. Wu D, Zhu T, Betts R, Gottschalg. Degradation of interfacial adhesion strength within photovoltaic mini-modules during damp-heat exposure. Progress in Photovoltaics Research and Application. 2014;22:22796-809.
8. Polverini D, Field M, Dunlop E, Zaaiman W. Polycristalline silicon PV modules performance and degradation over 20 years. Pogress in Photovoltaics Research and Applications. 2013;21:1004-1015.
9. Miyashita M, Kawai S, Masuda A. Measuring method of moisture ingress into photovoltaic modules. Japanese Journal of Applied Physics. 2012;1:51.
10. Han X, Wang Y, Zhu L, Xiang H, Zhang H. Mechanism study of the electrical performance change of silicon concentrator solar cells immersed in the

ionized water. Energy Convention and Management. 2012;53:1-10.
11. Ndiaye A, Abdéraficharki A, kobi Cheikh MF, Pape A, Ndiaye VS. Degradations of silicon photovoltaic modules. Literature Review Solar Energy. 2013;96:140-151.
12. Emmanuel N. Recherche et développement pour l'environnement en Afrique Sub-Saharienne. Hydrologue, Unesco-PHI; 2019.
13. Koukpemedji AA, et al. Influence de la température, de la pression et de l'humidité relative de l'air sur le potentiel éolien dans la zone côtière du Bénin dans le Golfe de Guinée. Revue des Energies Renouvelables. 2015;18(2):217–226.
14. Duffie JA, Beckman WA. Solar engineering of thermal processes. Second ed. John Wiley & Sons Inc., New York; 1991.
15. Capo-Chichi MM, et al. Effect of dust deposition on the quantum efficiency of bps150-36 polycrystalline silicon photovoltaic modules during winter months in Pahou, Benin. Advances in Research; 2018.
16. Emery K, Burdick J, Caiyem Y, Dunlavy D, Field H, Kroposki,B, Moriarty T, Ottoson L, Rummel S, Strand T, Wanlass M W. Temperature dependence of photovoltaic cells, modules and systems Photovoltaic Specialists Conference. Conference Record of the Twenty Fifth IEEE. 1996;13-17:1275–1278
17. Nyman M. Interfacial effects in organic solar cells. Thèse de Doctorat, Abo Akademi University Finland; 2015.
18. Shockley W, Queisser HJ. Detailed balance limit of efficiency of p-n junction solar cells. British Journal of Applied Physics. 1961;32:510-519.
19. Deibel C. Dyakonov V, Polymer - fullerene bulk heterojunction solar cells. Reports on Progress in Physics. 2010;73.
20. Théodulf R. Elaboration et caractérisation de cellules solaires organiques à base de nouvelles classes de matériaux actifs. Thèse de Doctorat, Université d'Angers; 2011.
21. Wohlgemuth J, Cunningham D, Nguyen AM, Miller J. Long term reliability of PV modules. Proc. 20 th European Photovoltaic Solar Energy Conference. 2005;1942-1946.
22. Report IEA-PVPS T13-01. Performance and reliability of photovoltaic systems: Subtask 3.2. Review on failures of PV modules. IEA PVPS Task 13, External final draft report IEA-PVPS; 2013.
23. Quintana MA, King DL. Commonly observed degradation in field-aged photovoltaic modules. Proceedings of the 29th IEEE Photovoltaic Specialists Conference New Orleans; 2002.
24. Jordan DC, Wohlgemuth JH, Kurtz SR. Technology and climate trends in PV module degradation. Proceedings of the 27th European Photovoltaic Solar Energy Conference and Exhibition, Frankfurt; 2012.
25. Smith RM, Jordan DC, Kurtz SR. NREL, outdoor PV module degradation of current-voltage parameters: Preprint. Proceedings of the World Renewable Energy Forum, Denver, Colorado. 2012; 13–17.
26. Sakamoto TO. Field test results on the stability of crystalline silicon photovoltaic modules manufactured in the 1990s. Proceedings of the 3rd World Conference on Photovoltaic Energy Conversion, Osaka, Japan. 2003;11–18.
27. Lindroos J, Savin H. Review of light-induced degradation in crystalline silicon solar cells, Sol, Energy Mater. Sol. Cells. 2016;147:115–126.
28. Janakeerama SV, et al. A statistical analysis on the cell parameters responsible for power degradation of fielded PV modules in a Hot-Dry climate, IEEE. 2014;978:4799-4398.
29. Hülsmann P, Peike C, Blüml M, Schmid P, Weiß KA, Köhl M. Impact of permeation properties and back sheet/encapsulation interactions on the reliability of PV modules. Proceedings of the ASME, International Mechanical Engineering Congress and Exposition, IMECE. (PARTS A AND B). 2011;4.
30. Ottersböck G, Oreski G, Pinter. Correlation study of damp heat and pressure cooker testing on backsheets, J. Appl. Polym. Sci; 2016.
31. Knausz M, Oreski G, Eder GC, Voronko Y. Duscher B, Koch T, Pinter G, Berger KA. Degradation of photovoltaic backsheets: Comparison of the aging induced changes on module and component level. J. Appl. Polym. Sci. 2015;132(42093):1–8.

32. Czanderna AW, Pern FJ. Encapsulation of PV modules using ethylene vinyl acetate copolymer as a pottant: A critical review. Sol. Energy Mater. Sol. Cells. 2013; 43(1996):101–181.
33. Chattopadhyay S, Dubey R, Kuthanazhi V, John JJ, Solanki CS, Kottantharayil A, Arora BM, Narasimhan KL, Vasi J, Bora B, Singh YK, Sastry OS. All India survey of photovoltaic module degradation. Survey Methodology and Statistics. 2014;1–6.
34. Orioli A, Gangi AD. A procedure to calculate the five-parameter model of crystalline silicon photovoltaic modules on the basis of the tabular performance data. Applied Energy. 2013;102:1160–1177.
35. Shrestha SM, Mallineni JK, Yedidi KRB, Tatapudi KS, Kuitche J, Tamizhmani G. Determination of dominant failure modes using FMECA on the field deployed C-Si modules under hot-dry desert climate. IEEE Journal of Photovoltaics, IEEE PVSC; 2014.
36. McMahon TJ, Basso TS, Rummel SR. Cell shunt resistance and photovoltaic module performance. Proceedings of the 25 Photovoltaic Specialists Conference. 1996; 1291–1294.
37. Oreski G, Wallner GM. Aging mechanisms of polymeric films for PV encapsulation. Sol. Energy. 2005;79:612–617.
38. Kempe MD, Jorgensen GJ, Terwilliger KM. Acetic acid production and glass transition concerns with ethylene-vinyl acetate used in photovoltaic devices. Sol. Energy Mater. Sol. Cells. 2007;91:315–329.
39. Pern FJ. Luminescence and absorption characterization of ethylene-vinyl acetate encapsulant for PV modules before and after weathering degradation, Polym. Degrad. Stab. 1993; 41:125–139.
40. Jiang S, Wang K, Zhang H. Encapsulation of PV modules using ethylene vinyl acetate copolymer as the encapsulant. Macromol. React. Eng. 2015; 9:522–529.
41. Shi XM, Zhang J, Li DR. Effect of damp-heat aging on the structures and properties of ethylene-vinyl acetate copolymers with different vinyl acetate contents. J. Appl. Polym. Sci. 2009;112: 2358–2365.
42. Chen S, Zhang J, Su J. Effect of damp-heat aging on the properties of ethylene-vinyl acetate copolymer and ethylene-acrylic acid copolymer blends. J. Appl. Polym. Sci. 2009;114:3110–3117.
43. Peike C, Hoffmann S, Hülsmann P. Origin of damp-heat induced cell degradation. Sol. Energy Mater. Sol. Cells. 2013;116: 49–54.
44. Ricaud A. Photopiles solaire de la physique de conversion photovoltaïque aux filières, matériaux et procédées. Presses Polytechniques et Universitaires Romandes; 1997.
45. Jean GZ. Étude de la fiabilité des structures silicium employées dans le domaine des énergies renouvelables suite à leur fonctionnement sous conditions extrêmes. Optique [physics.optics]. Université de Lorraine; Université libanaise; 2017.
46. Xiong H, et al. Corrosion behavior of crystalline silicon solar cells. Microelectronics Reliability. 2017;70:49–58.
47. Dan W, et al. PV module degradation mechanisms under different environ-mental stress factors, Hutchins M, Pearsall N, Cole A. (eds.). Proceedings of the 8th Photovoltaic Science Application and Technology Conference (PVSAT-8), Northumbria, University. 2012; 177-180.
48. Lindig S, et al. Review of statistical and analytical degradation models for photovoltaic modules and systems, IEEE, 2018;2156-3381.
49. Park NC, et al. Effect of temperature and humidity on the degradation rate of multicrystalline silicon photovoltaic module. International Journal of Photoenergy; 2013.
50. Théodulf R. Elaboration et caractérisation de cellules solaires organiques à base de nouvelles classes de matériaux actifs, Thèse de doctorat. Université d'Angers; 2011.
51. Elif A. Analysis of degradation and evolution of model parameters of a-si/µ-si PV modules. Màster universitari en Enginyeria de l'Energia. UPC; 2016.
52. Takatoshi H. Influence of degradation in units of PV modules on electric power output of PV system. Journal of International Council on Electrical Engineering. 2018;8(1):118-126.

DOI: 10.1080/22348972.2018.1477095
53. Frank KA, et al. Robust crystalline silicon photovoltaic module (c-Si PVM) for the tropical climate: Future facing the technology. Scientific African. 2020;8: 00359.

© 2022 Capo-Chichi et al.; This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/61357