Current Journal of Applied Science and Technology

Volume 42, Issue 12, Page 15-23, 2023; Article no.CJAST.99752
ISSN: 2457-1024
(Past name: British Journal of Applied Science & Technology, Past ISSN: 2231-0843, NLM ID: 101664541)

Performance Analysis of PV/T Modules in West African Climate Zones

Kossoun Alain Tossa [a*], Cossi Télesphore Nounangnonhou [a,b], Maurel Richy Aza-Gnandji [b] and Guy Clarence Semassou [a]

[a] Laboratory of Energetics and Applied Mechanics (LEMA), Ecole Polytechnique d'Abomey-Calavi, Calavi, Benin.
[b] Laboratory of Electrical Engineering, Telecommunications and Applied Computer Science (LETIA), Ecole Polytechnique d'Abomey-Calavi, Cotonou, Benin.

Authors' contributions

This work was carried out in collaboration among all authors. Author CTN gave the idea for this article. Author KAT designed the study, carried out the statistical analysis, wrote the protocol and the first draft of the manuscript. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/CJAST/2023/v42i124107

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/99752

Original Research Article

Received: 08/03/2023
Accepted: 11/05/2023
Published: 22/05/2023

ABSTRACT

The use of solar photovoltaic (PV) panels has been seen as a viable solution to improve the rate of rural electricity supply in African states. Today, the use of solar PV systems has helped to overcome low electricity coverage rates. One of the bottlenecks of PV installations in sub-Saharan Africa is the low efficiency of solar PV modules caused largely by heat accumulation during system operation. This research work aims at studying the electrical performances of PV and PVT modules, in the different climatic zones of West Africa, in order to characterize and promote them in rural sanitary areas for the simultaneous production of hot water and electricity. The meteorological data used are of TMY type and come from the PVGIS site. The simulation of the operation of the different PV module technologies implemented in the Simulink/Simscape environment of MATLAB R2021a allowed to estimate the LCOE values, over a typical year, with the different meteorological

---

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

data of the studied climatic zones. The results obtained show that PVT modules offer LCOE gains ranging from 2% to 12% compared to conventional PV modules. The highest performances are obtained in the Sudanian and Sudan-Sahelian climatic zones, while the Guinean zone shows the lowest gain.

Keywords: PV and PVT modules; weather data; simulation; power generation; LCOE.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

a : Discount rates
C_R : Residual cost of main equipment
C_{st} : Binary parameter allowing to integrate or not the C_R or the d_m
d_m : Dismantling cost
Ej_{el} : Daily electrical energy requirement, kWh
Ej_{th} :Daily thermal energy requirement, kWh
Minimum value over the year of the monthly averages of the daily irradiation of the site considered, kWh/m /d
I_0 : Initial investment
LCC : Project life cycle cost, discounted to year 0
LCOE: Levelized cost of energy
Maintenance cost for cleaning the photovoltaic panels
Project life in years
P_c :Then PV or PVT field power, Wp
Performance ratio integrating module efficiency and various *losses (cables, dust, etc.)*
Qenergy: Generated over the period N, kW

1. INTRODUCTION

The production of energy to satisfy the needs, remains a universal challenge for the whole world. Most of the world's energy is produced from fossil deposits (oil, gas, coal . . .) [1]. The exploitation of these energy sources has led to extreme climatic upheavals in recent years. To avoid the worst, attention is increasingly focused on renewable energies such as: hydraulic, solar thermal, wind, biomass and solar photovoltaic. Of all these sources, solar energy has a huge potential and is well distributed in Sub-Saharan Africa. However, the share of photovoltaic solar energy in the production of electricity is still modest because of its intermittency and its low electrical efficiency due mainly to the accumulation of heat during its operation [2].

Nowadays, there are PVT modules with the ability to simultaneously produce heat energy by heat transfer fluids and electrical energy with higher efficiency [3,4]. Aware of the influences of weather data on solar collectors and the naturally more expensive cost of PVT technology, several studies have been devoted to the technical-economic interest of its deployment in different climatic zones.

In Ghana's hot and humid tropical climate in 2019, the study comparing the energy performance of a photovoltaic-thermal (PVT) module versus a conventional photovoltaic (PV) module over one year reveals average electrical/thermal efficiencies of 56.1% for PVT and 12.7% for PV [5]. The one conducted in 2021 by the analytical models on the techno-economic viability of PVT and monocrystalline silicon PV modules over 25 years in Ghana, shows that the PVT system generally performs better than the conventional PV system when both systems are installed with batteries, although the PVT system is more expensive. Without batteries, the study shows that the conventional PV system becomes more economically viable than PVT [6].

Slimani et al. [7] conducted in 2017, a comparative performance study of four solar module configurations: photovoltaic module (PV-I), conventional air hybrid solar collector (PV/T-II), glazed air hybrid solar collector (PV/T-III), and glazed collector, dual pass air hybrid solar collector (PV/T-IV). A numerical model has been developed and validated with experimental results. The model is used with a sample of meteorological data from the Algiers site. The numerical results show that the daily average of the overall energy efficiency reaches: 29.63%, 51.02%, 69.47% and 74% for the first (PV-I), second (PV/T-II), third (PV/T -III) and fourth (PV/T-IV) module respectively. These values are obtained with an air flow rate of 0.023 kg/s and by introducing a sample of experimental meteorological data collected at the Algiers site for a sunny day in summer.

Kulkarni et al., [8] installed in 2020, photovoltaic-thermal (PVT) modules to provide both electricity and heat extracted by a given water circuit. The study compared the performance of a normal PV module to the new PVT module. The PVT system is manufactured and experiments are conducted to evaluate the electrical and thermal efficiencies. An improvement of 2.17% was observed in the electrical efficiency of the PVT module compared to the normal PV module.

Manssouri et al., [9] presented in 2019, a theoretical study on a PV/T fluid bi-collector module. A numerical model was developed and simulated in MATLAB. A comparative analysis between a conventional water-based PV/T module and another bi-fluid (water/air-based) module, namely PV/Tb, is presented for winter and summer days. For the winter day studied, the numerical results show an overall performance improvement of the bi-fluid PV/T module, with an increase in thermal energy transferred to the liquid side of 20%, and 15.3% for the overall energy efficiency compared to the conventional PV/T collector. No performance improvement was observed during the summer day.

As shown in previous work, the performance of PVT modules varies from region to region. This study aims to investigate the potential value of PVT modules in West African climatic zones.

2. METHODOLOGICAL APPROACH

The methodology adopted is divided into three main steps, described below:

- **Step 1 - Definition of a daily energy requirement:** For simulation purposes, a single daily load profile (same energy requirement) is defined for all climate zones. On the one hand, it is a daily electrical energy requirement noted Ej_{el} and on the other hand, a daily thermal energy requirement Ej_{th}.
- **Step 2- Sizing the PV or PV/T solar array:** For each climate zone, the energy need Ej_{el} is used with the corresponding meteorological data to size the PV field to meet the said need. The power of the PV or PVT field is given by the following formula:

$$P_c\ (Wc) = \frac{Ej_{el}}{H \times PR} \qquad (1)$$

With H (kWh/m^2 /d), the minimum value over the year of the monthly averages of the daily irradiation of the considered site. PR, the performance ratio which integrates the efficiency of the modules and the various losses (cables, dust etc.)

In each of the climatic zones, the simulations will be done with PV and PVT fields of the same peak power equal to P_c.

- **Step 3- Simulation of the PV or PV/T solar array:** the previously dimensioned PV and PVT solar arrays are simulated in grid-connected solar systems (without storage). The mathematical models used for both types of modules (PV or PVT) have been experimentally validated in other works. The model used for conventional PV modules has been developed and experimentally validated by one of the authors of this paper [10,11]. The second model used for the PV/T modules results from the combination of part of the built-in library of the MATLAB R2021a Simscape environment and another recent study [12]. However, two modifications were made to the Simscape block model. First, the Simscape model has been modified so that it can also simulate variable loads. The second modification of the Simscape model made it possible to simulate PV fields of different powers. The two models thus obtained were embedded in Simulink diagrams and used to simulate PV and/or PVT modules in different climate zones.

Fig. 1 shows the Simulink model with the two blocks described below.

- **Calculation of the performance indicators of the simulated systems:** The outputs of the models are among others: the useful energy produced by the conventional and thermal PV systems. These data are used to calculate one of the best performance indicators of PV systems: LCOE (Levelized Cost Of Energy). It is given by the following formula and defined elsewhere [13,11]:

$$LCOE = \frac{LCC}{Q * \sum_{t=1}^{N} \frac{1}{(1+\mathrm{a})^{\mathrm{t}}}} \qquad (2)$$

With

- LCC: life cycle cost of the project, discounted to year 0.
- a: The discount rate
- N : the life of the project in years ;
- Q: Energy generated over period N in kWh.

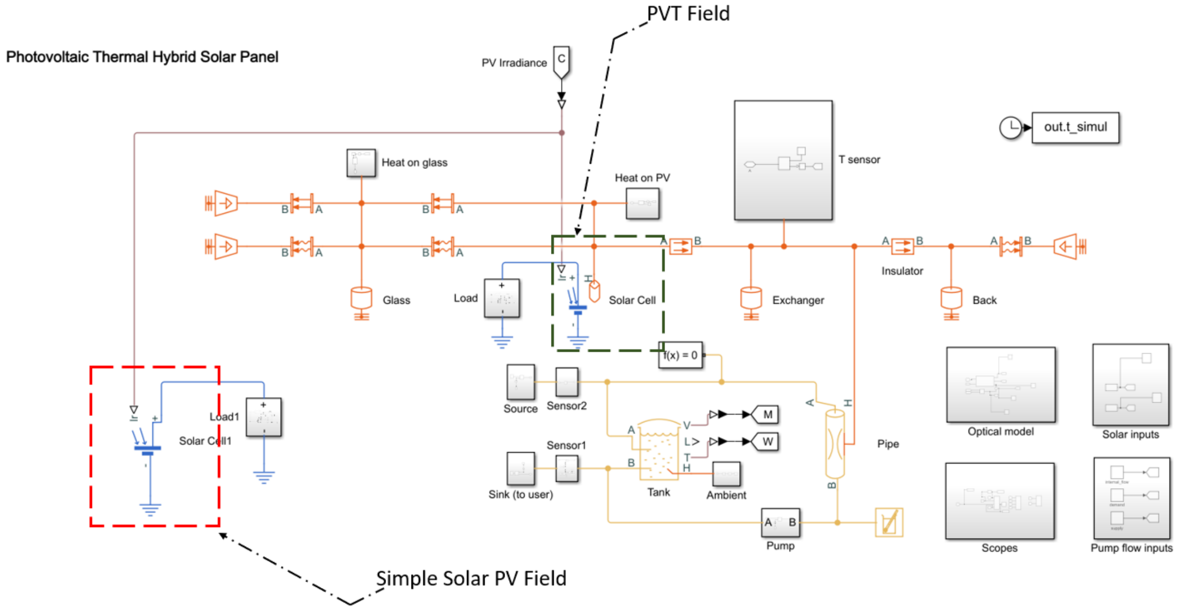


Fig. 1. Simulink/Simscape block for simulation of PVT and/or PV module behavior in the MATLAB 2021a environment

The total LCC cost is given by the following formula:

$$LCC = I_0 + M + R + Cst\ (C_R - d_m) \tag{3}$$

With :

- I_0 : Initial investment
- M: Maintenance costs for cleaning photovoltaic panels
- R : Replacement cost of the main equipment
- C_R: Residual cost of main equipment
- Cst : Binary parameter allowing to integrate or not the C_R and d_m
- d_m : dismantling cost

3. RESULTS AND DISCUSSION

3.1 Areas of Influence and Weather Conditions

Fig. 2 below shows the five climate zones of West Africa.

These are: (1) Bouake in Côte d'Ivoire, Guinean zone; (2) Kandi in Benin, Sudanian zone; (3) Ouagadougou, in Burkina Faso in the Sudano-Sahelian zone; (4) Bilma in Niger, Sahelian zone; and (5) Kidal in Mali in the Saharan zone. As shown in the figure, a representative locality was chosen in each of the climatic zones.

The TMY weather data for the five selected locations are obtained from the PVGIS website.

The Figs. 3 and 4 show respectively irradiance and ambient temperature in the five climate zones.

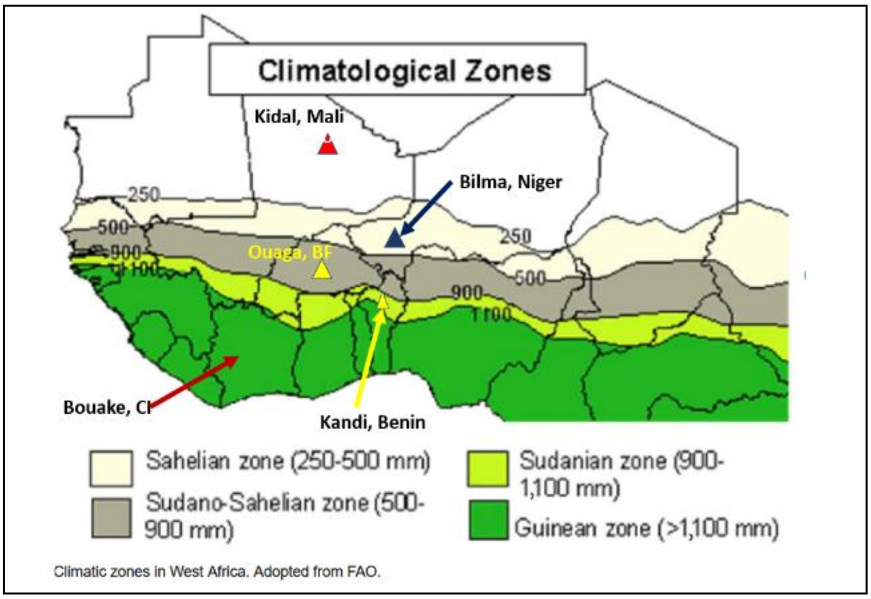
3.2 Daily Balance of Electrical and Thermal Energy

For the purposes of this study, research was conducted in some health centers and in feasibility study reports for electrification in rural areas in some countries such as Benin. A typical daily load profile for both the electrical and thermal energy needs of a typical health center emerged. Figs. 5 and 6 below show the different load profiles.

The total daily requirement is 25316 Wh/d. The profiles are selected to have the same thermal and electrical requirements of12,658 kWh/d.

3.3 Sizing of PV or PVT Systems

For the comparison purposes required by this study, the modules chosen are all monocrystalline technologies and have the same 300 Wp peak power. Table 1 presents the main characteristics of the two modules.



Climatic zones in West Africa. Adopted from FAO.

Fig. 2. The five climate zones of West Africa [14]

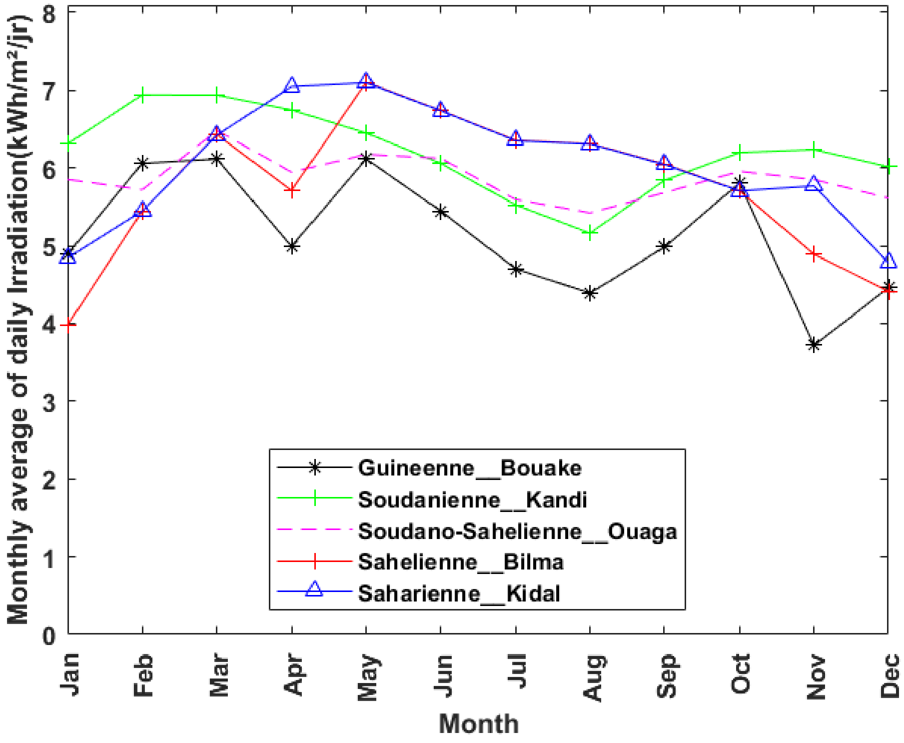


Fig. 3. Monthly average daily irradiance (kWh/m^2 /d) in the five different climatic zones of West Africa

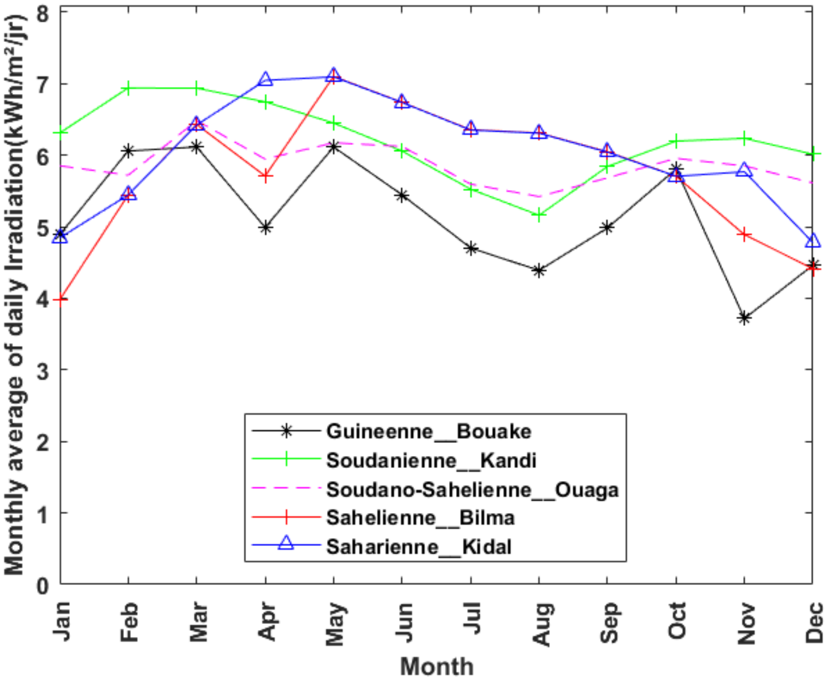


Fig. 4. Monthly average ambient temperature in the five different climatic zones of West Africa

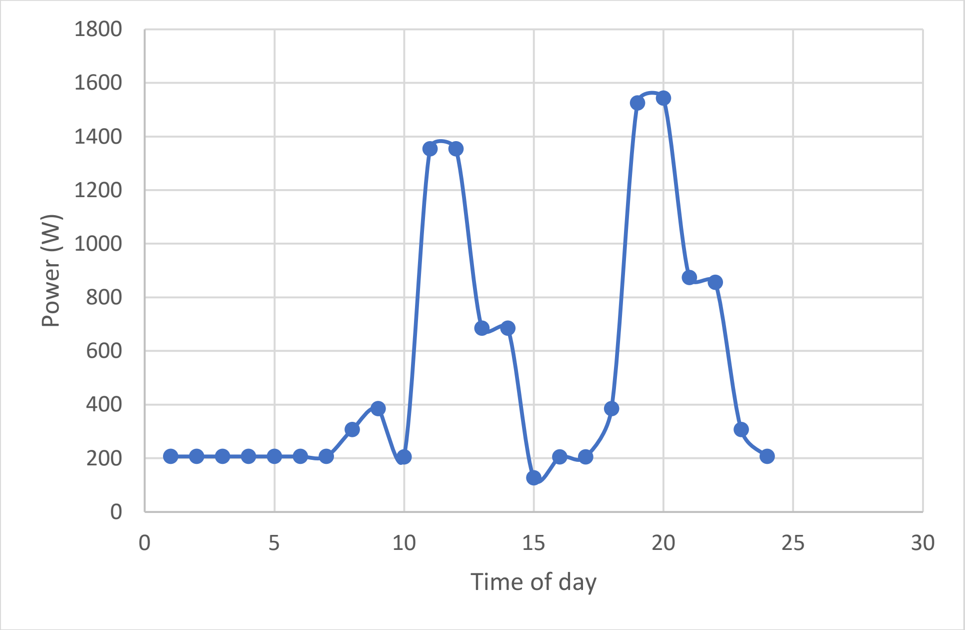


Fig. 5. Daily electricity load profile

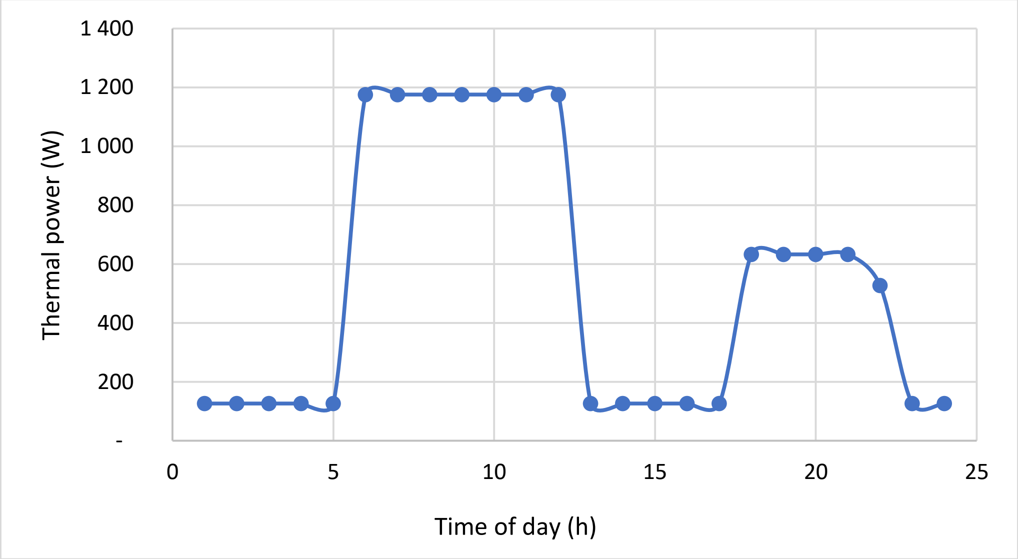


Fig. 6. Daily thermal load profile

Table 1. Main characteristics of the selected modules (PV and PVT)

References	**Dualsun 300 Black**	**SPM 033002400**
PV technology	Monocrystalline	Monocrystalline
Number of cells	60	60
Cell area (m $)^2$	0,02725	0,0269
Short circuit current Icc [A]	9,77	8,56
Open circuit voltage [V].	39,9	45,5
Nominal power (Wp)	300	300
Voltage (V) at rated power (Vmpp)	32,6	36
Current (A) at rated power (Impp)	9,19	8,33
Temperature coefficient Voltage (%/°K)	-0,29	+0,037
Temperature coefficient Current (%/°K)	0,05	0,037
Temperature coefficient Power (%/°K)	-0,39	-0,48

Table 2. PV field sizing results for the five West African climate zones

	Zone Guinean woman	**Sudanian zone**	**Sudano-Sahelian zone**	**Sahelian zone**	**Saharan zone**
Daily energy Ej_{el} (kWh/d)	12,658				
Daily irradiation (kWh/d/m $)^2$	3,72	5,16	5,42	3,98	4,77
Minimum peak power (kWp)	4,86	3,50	3,34	4,54	3,78
Number of PV or PVT modules	17	12	12	16	13

Table 3. Performance of PVT modules in different climatic zones of West Africa

Climate zone	**City**	**LCOE_PV (FCFA/kWh)**	**LCOE_PVT (FCFA/kWh)**	**LCOE gain (%)**
Guinean woman	Bouake	625	610	2%
Sudanese	Kandi	294	258	12%
Sudanese-Sahelian	Ouaga	300	271	10%
Sahelian	Bilma	400	350	12%
Sahara Desert	Kidal	502	462	8%

Table 2 above shows the main data used as inputs and the design results obtained in each of the climate zones.

In view of the irradiations and the dimensioning results, it would seem that the most favourable zones for photovoltaic are the Sudanian and Sudano-Sahelian zones.

Table 3, shows the cross-performance of PV and PVT systems in the five climate zones. In general, we note that solar modules (PVT or not) do not have the same performance from one zone to another.

However, PVT modules always provide better performance. The gains obtained in terms of LCOE vary from 2% to 12%.

The smallest gains are obtained in the Guinean zone. Knowing for example that the city of Cotonou belongs to the Guinean zone, we can estimate that the two types of modules are equivalent there. On the other hand, the results show a substantial interest in deploying PVT modules in the other climatic zones of Benin (Sudan and Sudan-Sahel),

4. CONCLUSION

This study made a comparative analysis of the performance of PVT modules versus PV modules in the five West African climatic zones. The overall objective is to assess the potential value of promoting these types of modules in rural health areas for the simultaneous production of hot water and electrical energy in West African countries.

Simulation blocks with previously validated models of PVT and conventional modules were deployed in the Simulink environment of Matlab R2021a. The TMY meteorological data used were taken from the PVGIS website. The simulation of the different models developed, over a typical period of one year, allowed the estimation of the LCOE values of the technologies in the different climate zones.

The results obtained show that PVT modules offer LCOE gains ranging from 2% to 12% compared to conventional PV modules. The best performances of PVT modules are obtained in the Sudanese and Sudan-Sahelian climatic zones, while the Guinean zone shows the lowest gain.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Abdessamad R. Dimensionnement d’une installation PV hybride ”application a un Systeme raccorde au RESEAU”. Université Aboubekr Belkaid de Tlemcen. Consulté le: 10 Juin 2022 ligne]. Sur D; 2017.
   Available:http://dspace.univ-tlemcen.dz/bitstream/112/11470/1/Ms.ELN.Rahmoun%2B Habibes.pdf.
2. Engager l’Afrique sur la voie de l’accès universel à l’électricité.
   Available:https://blogs.worldbank.org/fr/africacan/engager-lafrique-sur-la-voie-de-lacces-universel-lelectricite (consulté le 10 juillet 2022).
3. Tselepis S, Tripanagnostopoulos Y. Ecomomic analysis of hybrid photovoltaic/thermal solar systems and comparison with standard PV modules; 5.
4. Ul Abdin Z, Rachid A. A Survey on Applications of Hybrid PV/T Panels. Energies. févr 2021;14(4):1205.
5. Abdul-Ganiyu S, Quansah DA, Ramde EW, Seidu R, Adaramola MS. Investigation of solar photovoltaic-thermal (PVT) and solar photovoltaic (PV) performance: A case study in Ghana. Energies. janv 2020;13(11):Art n^o 11.
6. Abdul-Ganiyu S, Quansah DA, Ramde EW, Seidu R, Adaramola MS. Techno-economic analysis of solar photovoltaic (PV) and solar photovoltaic thermal (PVT) systems using exergy analysis. Sustain Energy Technol Assess. oct 2021;47: 101520.
7. Slimani MEA, Amirat M, Kurucz I, Bahria S, Hamidat A, Chaouch WB. A detailed thermal-electrical model of three photovoltaic/thermal (PV/T) hybrid air collectors and photovoltaic (PV) module: comparative study under Algiers climatic conditions. Energy Convers Manag. févr 2017;133:458-76.
8. Kulkarni RS, Talange DB, Dharme AA, Mate NV. Development and performance analysis of solar photovoltaic–thermal (PVT) systems. Sādhanā. 2020;45(1):208.
9. Manssouri OE, Fouas CE, Hajji B, Bouselham L, Rabhi A, Tina GM. et al. Performance analysis of bi-fluid

photovoltaic/ thermal (PV/T) solar collector. In: 7th International Renewable and Sustainable Energy Conference (IRSEC). Agadir, Morocco: IEEE Publications. 2019;1-6.

10. Tossa AK, Soro YM, Azoumah Y, Yamegueu D. A new approach to estimate the performance and energy productivity of photovoltaic modules in real operating conditions. Sol Energy. déc 2014;110:543-60.
11. Tossa AK, Soro YM, Coulibaly Y, Azoumah Y, Migan-Dubois A, Thiaw L. et al. Artificial intelligence technique for estimating PV modules performance ratio under outdoor operating conditions. J Renew Sustain Energy. Sep 2018;10(5): 053505.
12. Ventura C, Tina GM, Gagliano A, Aneli S. Enhanced models for the evaluation of electrical efficiency of PV/T modules. Sol Energy. 2021;224:531-44.
13. Ouedraogo BI, Kouame S, Azoumah Y, Yamegueu D. Incentives for rural off grid electrification in Burkina Faso using LCOE. Renew Energy. 2015;78:573-82.
14. Koalaga MZ, Migan-Dubois MA, Youm MI, Merten MJ, Coulibaly MY, Soro MM. Etude comparative des performances de technologies photovoltaïques dans différentes zones climatiques de l'Afrique de l'ouest; 171.

Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/99752