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Longitudinal analysis of the performance of photovoltaic systems in northern Côte d'Ivoire : geospatial optimisation of solar power plants

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Abstract

This research work investigates the functioning of photovoltaic solar panel systems in six cities in northern Côte d'Ivoire (Odienné, Boundiali, Korhogo, Ferkessédougou, Téhini, and Bouna), all located above the 9th parallel. The methodological approach uses the PVSyst simulation technique with three photovoltaic technologies (monocrystalline, polycrystalline, and amorphous) compared. The results show that monocrystalline technology is the most efficient, followed by polycrystalline and amorphous technologies. Next, amorphous technology demonstrates a better performance ratio (PR) in humid conditions. A negative correlation exists between longitude and energy production, with a decrease of 5.2 % for amorphous technology and 5.3 % for crystalline technology between Odienné (West) and Bouna (East). The energy yields of monocrystalline technology range from 4.59 to 4.35 kWh/kWp/year, while amorphous technology exhibits better resilience to longitudinal variations due to a low temperature coefficient (-0.2 %/°C). Finally, the performance ratios are higher for amorphous (81.84 %) than for crystalline (80.63 %). Ultimately, this work determines the best location for a high-performance solar power plant in Côte d'Ivoire for clean and affordable energy.

Keywords : *PV system, performance, longitude, tropical climate, Côte d'Ivoire.*

Résumé

Analyse longitudinale des performances des systèmes photovoltaïques au Nord de la Côte d'Ivoire : optimisation géospatiale des centrales solaires

Ce travail de recherche investit le fonctionnement des systèmes de panneaux solaires photovoltaïques dans six villes du Nord de la Côte d'Ivoire (Odienné, Boundiali, Korhogo, Ferkessédougou, Téhini et Bouna), toutes situées au-dessus du 9e parallèle. L'approche méthodologique utilise la technique de simulation PVSyst à trois technologies photovoltaïques (monocristalline, polycristalline et amorphe) comparées. Les résultats montrent que la technologie monocristalline est la plus performante, suivie par les technologies polycristalline et amorphe. Ensuite, la technologie amorphe démontre un meilleur rapport de performance (PR) en conditions humides. Une corrélation négative existe entre la longitude et la production d'énergie, avec une baisse de 5,2 % pour la technologie amorphe et de 5,3 % pour la technologie cristalline entre Odienné (Ouest) et Bouna (Est). Les rendements énergétiques de la technologie monocristalline varient de 4,59 à 4,35 kWh/kWc/an, tandis que la technologie amorphe présente une meilleure résilience aux variations longitudinales grâce à un faible coefficient de température (-0,2 %/°C). Enfin, les ratios de performance sont plus élevés pour l'amorphe (81,84 %) que pour le cristallin (80,63 %). En définitive, ce travail détermine le meilleur emplacement pour une centrale solaire de bonne performance en Côte d'Ivoire pour une énergie propre et abordable.

Mots-clés : *système PV, performance, longitude, climat tropical, Côte d'Ivoire.*

1. Introduction

The transition to renewable energy sources is a key pillar for achieving the Sustainable Development Goals (SDGs), in particular SDG 7, which aims for universal access to clean and affordable energy. In tropical regions such as sub-Saharan Africa, where annual sunshine frequently exceeds 2,000 kWh/m², solar photovoltaic (PV) energy is a strategic solution [1]. However, the performance of photovoltaic systems varies considerably depending on the technology (monocrystalline, polycrystalline, amorphous) and local climatic conditions [2, 3], which means that context-specific studies are needed to optimise their deployment. This research follows on from two previous studies carried out by our team : the first phase evaluated the performance of three photovoltaic technologies experimentally and by simulation in three cities in Morocco (Rabat, Mohammedia, Errachidia) [4, 5], and three cities in Côte d'Ivoire (Abidjan, San Pédro, Korhogo). This research confirmed a robust simulation methodology, with a maximum deviation of 3 % for crystalline technology and 9% for amorphous technology between experimental data and numerical models. A second phase revealed a correlation between latitude and energy production, identifying the north of Côte d'Ivoire as an optimal area for solar power plants, due to accumulated sunshine and moderate temperatures. However, the northern zone of Côte d'Ivoire, stretching from north-east to north-west over almost 600 km, has significant microclimatic variations (rainfall, cloud cover, humidity) linked to longitude, which are likely to influence the performance of photovoltaic systems. The north-west (Odienné) receives annual rainfall records of 1,400 mm, while the north-east (Bondoukou) records 1,100 mm, which has a direct influence on effective solar irradiation. Numerous experimental studies on the performance of photovoltaic panels have been carried out worldwide [6, 7] including in Africa [9], notably in Morocco as part of the "propre.ma" project [10] in Algeria [2], and in various Asian countries [11]. Numerous comparative studies and performance simulations have been carried out, mainly in North Africa [12, 13] and Asia [8] , However, there is very little literature on the analysis of solar panel performance in West Africa [14 - 16] and virtually none in Côte d'Ivoire [17, 18] The north of Côte d'Ivoire has significant solar potential throughout the year, with average daily sunshine exceeding 5.5 kWh/m²/d. This article presents and analyses the results of PVSyst simulations of solar panels from three technologies, conducted in northern Côte d'Ivoire in six cities located above the ninth parallel : Odienné, Boundiali, Korhogo, Ferkessédougou, Téhini, and Bouna. The objectives of this study are as follows : to analyse the impact of longitude on the performance of three photovoltaic technologies in six cities in Côte d'Ivoire, and establish a correlation between the energy produced, the reference productivity, and the longitude in the northern part of the country. The objective is to pinpoint the optimal sub-region in Côte d'Ivoire for solar power plant installation, situated between the northeast and northwest.

2. Material and methods

2-1. Material

2-1-1. Technologies studied

As part of this study, three photovoltaic (PV) technologies were analysed in order to assess their performance under various climatic conditions [4].

- Monocrystalline silicon (m-Si): this technology is known for its high efficiency, with an average efficiency of 14.4 % according to data from PVsyst software. Polycrystalline silicon (p-Si): with an average efficiency of 13.6 %, this technology is widely used thanks to its cost-effectiveness [19].
- Amorphous silicon (a-Si) : Less efficient in terms of yield (8.1 %), amorphous silicon nevertheless offers advantages in low-light conditions.

2-1-2. Simulation software

The performance of the various technologies was assessed using simulations carried out with PVsyst 7.3 software. Simulation parameters included :

- Meteorological data: integration of Meteonorm 8 data, including solar irradiation, ambient temperature and relative humidity.
- Geographical parameters: taking into account the altitude and inclination of the photovoltaic panels for each site.
- The alternative energies generated by the system were simulated and analysed. In addition to the energy generated, the performance indices calculated are:
- Final productivity (Y_f): ratio of net energy generated to installed peak power.
- Performance Ratio (PR): an indicator of the overall efficiency of the PV system, considering environmental and component losses.

2-1-3. Layout diagram

For comparison with our previous work, the PV panels used in this study are from the "propre.ma" project [10] in the Kingdom of Morocco. ***Figure 1*** depicts the layout of the PV modules on the site.

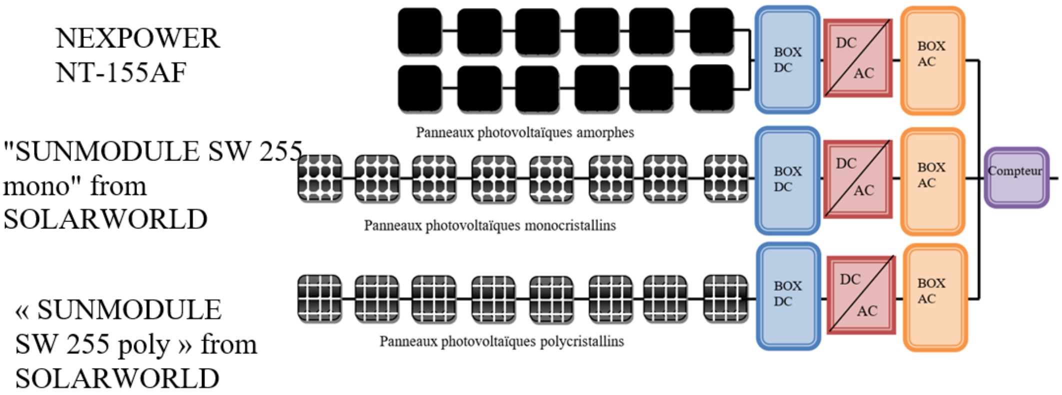
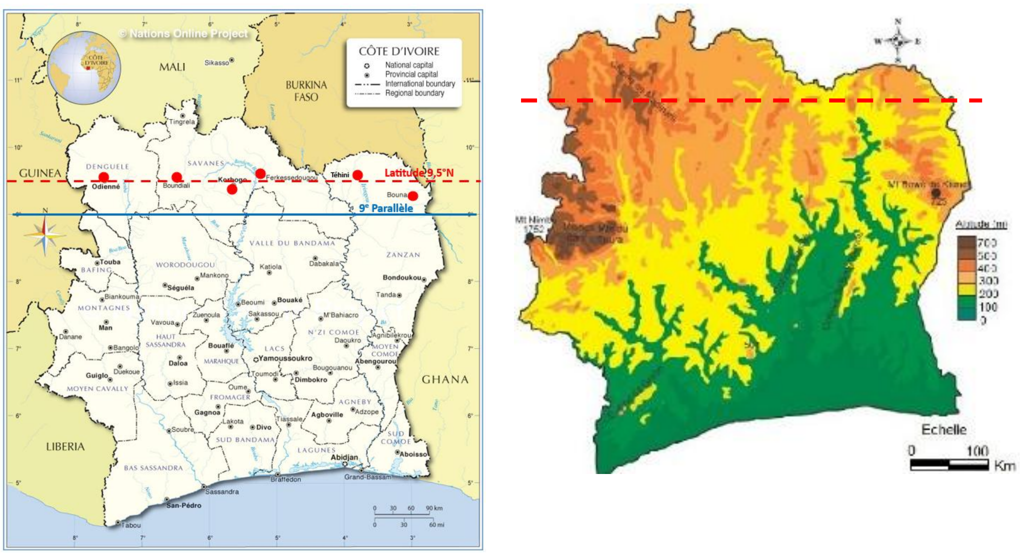


Figure 1 : *Photovoltaic module layout diagram*

Each field of the three photovoltaic fields is connected to a SMA Sunny Boy 2000HF inverter.

2-1-4. Geographical data for simulated sites

For a comprehensive analysis of the performance of photovoltaic (PV) systems, six towns in the northern region of Côte d'Ivoire have been selected. These locations span a longitudinal gradient centred around the average latitude of 9.5°N ***(Figure 2a)***, enabling an evaluation of the impact of geographical position on energy production. Additionally, as altitude can affect the amount of solar radiation received, Côte d'Ivoire topography is illustrated in ***Figure 2b***.



(a) **(b)**

Figure 2 : *Simulated sites : (a) geographical location of simulated sites and (b)Relief of Côte d'Ivoire*

The geographical coordinates that identify the precise locations of the sites for the installation of photovoltaic systems are presented in ***Table 1***. The six sites are located between 3.0° W and 7.6° W at an almost constant latitude of 9.5° N.

Table 1 : *Geographical data for simulated sites (Google Maps)*

City	φ	λ	h
Odienné	9,5	-7,55	428
Boundiali	9,52	-6,48	419
Korhogo	9,42	-5,63	376
Ferkessédougou	9,61	-5,19	328
Téhini	9,61	-3,67	290
Bouna	9,27	3	316

2-1-5. Meteorological data for simulated sites

Meteorological data [20] for the six towns are shown in ***Table 2***. This data highlights the variations of global irradiation on the inclined plane, ambient temperature [21], providing valuable insights for understanding local climate patterns.

Table 2 : *Meteorological data for simulated sites (source PVsyst ~& Meteonorm 8)*

	Odienné					Boundiali				
	GHI	DH	Ta	GI	Albl	GHI	DH	Ta	GI	Albl
	kWh/m²	kWh/m²	°C	kWh/m²	kWh/m²	kWh/m²	kWh/m²	°C	kWh/m²	kWh/m²
January	162,9	75,93	25,94	180,4	0,417	163,6	71,78	26,05	181,8	0,42
February	156,7	81,59	28,12	166,7	0,401	158,4	81,78	28,76	168,4	0,405
March	188	92,14	29,11	192,1	0,481	189,3	92,85	30,73	193,4	0,485
April	180,6	88,66	28,26	176,8	0,461	183,4	92,71	30,38	179,1	0,469
May	182,9	84,63	27,21	172,4	0,467	186,6	85,83	29,51	175,8	0,478
June	183,6	74,15	25,41	169,2	0,47	181,2	77,03	27,22	167,3	0,463
July	192,7	72,65	24,9	178,6	0,492	191,6	76,18	26,19	177,8	0,49
August	180,8	81,38	24,33	173,9	0,462	177,7	86,22	25,43	170,7	0,453
September	170,6	75,04	24,38	171,5	0,436	169,9	79,98	25,49	170,7	0,434
October	177	74,94	25,43	186,7	0,452	179,9	75,94	27,31	189,8	0,461
November	168,4	66,22	25,28	185,9	0,432	170,6	63,43	27,15	188,5	0,437
December	161,4	69,77	25,14	181,4	0,414	161,7	69,55	25,89	181,8	0,415
Total Year	2105,5	937,1	26,11	2135,6	5,386	2113,9	953,3	27,5	2145,2	5,409

	Korhogo					Ferkessédougou				
	GHI	DH	Ta	GI	Albl	GHI	DH	Ta	GI	Albl
	kWh/m²	kWh/m²	°C	kWh/m²	kWh/m²	kWh/m²	kWh/m²	°C	kWh/m²	kWh/m²
January	162	75,78	26,46	180,1	0,481	161,2	75,89	25,53	180,2	0,55
February	155,5	83,39	28,64	165,4	0,462	155,4	83,8	28,69	166,4	0,532
March	185,6	94,78	29,91	189,2	0,551	184,8	96,06	31,06	185	0,62
April	184,2	89,79	29,19	179,4	0,546	184,9	89,53	30,9	179,8	0,63
May	183	85,06	28,6	171	0,545	183	91,75	29,71	170,3	0,624
June	174,3	78,55	26,63	159,8	0,518	173,6	82,67	27,54	153,2	0,573
July	185,2	75,23	25,99	170,7	0,547	184,5	82,07	26,76	161,6	0,601
August	172,5	78,45	25,25	165,3	0,511	171	88,66	25,75	154,3	0,551
September	164,8	83,72	25,39	164,9	0,489	164,2	73,92	25,81	161	0,547
October	177	78,9	26,91	186,4	0,525	176,1	83	27,56	180,1	0,583
November	168,5	67,27	27,05	186,3	0,5	168,4	68,09	27,04	185,4	0,569
December	158,9	71,22	26,41	178,8	0,472	157,4	72,27	25,57	177,5	0,536
Total Year	2064,8	2064,8	2064,8	2064,8	2064,8	2064,8	987,73	27,65	2054,9	6,917

	Téhini					Bouna				
	GHI	DH	Ta	GI	AlbI	GHI	DH	Ta	GI	AlbI
	kWh/m²	kWh/m²	°C	kWh/m²	kWh/m²	kWh/m²	kWh/m²	°C	kWh/m²	kWh/m²
January	161,3	75,89	25,53	180,2	0,55	161,9	76,82	25,44	179,9	0,48
February	156,2	83,8	28,69	166,4	0,532	156,2	83,61	28,59	165,8	0,464
March	181,9	96,06	31,06	185	0,62	180,9	98,18	30,96	184,1	0,537
April	184,9	89,53	30,9	179,8	0,63	184,9	89,33	30,79	180,1	0,55
May	183	91,75	29,71	170,3	0,624	180,8	88,69	29,61	168,9	0,536
June	168,4	82,67	27,54	153,2	0,573	166,4	81,13	27,44	152,5	0,494
July	176,1	82,07	26,76	161,6	0,601	172,5	78,5	26,74	159,4	0,512
August	161,9	88,66	25,75	154,3	0,551	159,3	81,54	25,76	152,6	0,473
September	160,6	73,92	25,81	161	0,547	156,9	70,7	25,69	156,7	0,467
October	171,1	83	27,56	180,1	0,583	169,5	86,41	27,45	177,8	0,504
November	166,9	68,09	27,04	185,4	0,569	165,5	71,51	26,94	182	0,49
December	157,4	72,27	25,57	177,5	0,536	158,1	73,07	25,5	177,3	0,469
Total Year	2029,6	987,73	27,65	2054,9	6,917	2012,8	979,5	27,57	2037,1	5,976

GH : Global horizontal irradiation, DH : Horizontal Diffuse Irradiation ; Ta : Ambient temperature, GI : Global irradiation on the inclined plane ; AlbI : Hard Albedo inclined plane of the sensor.

2-2. Methods

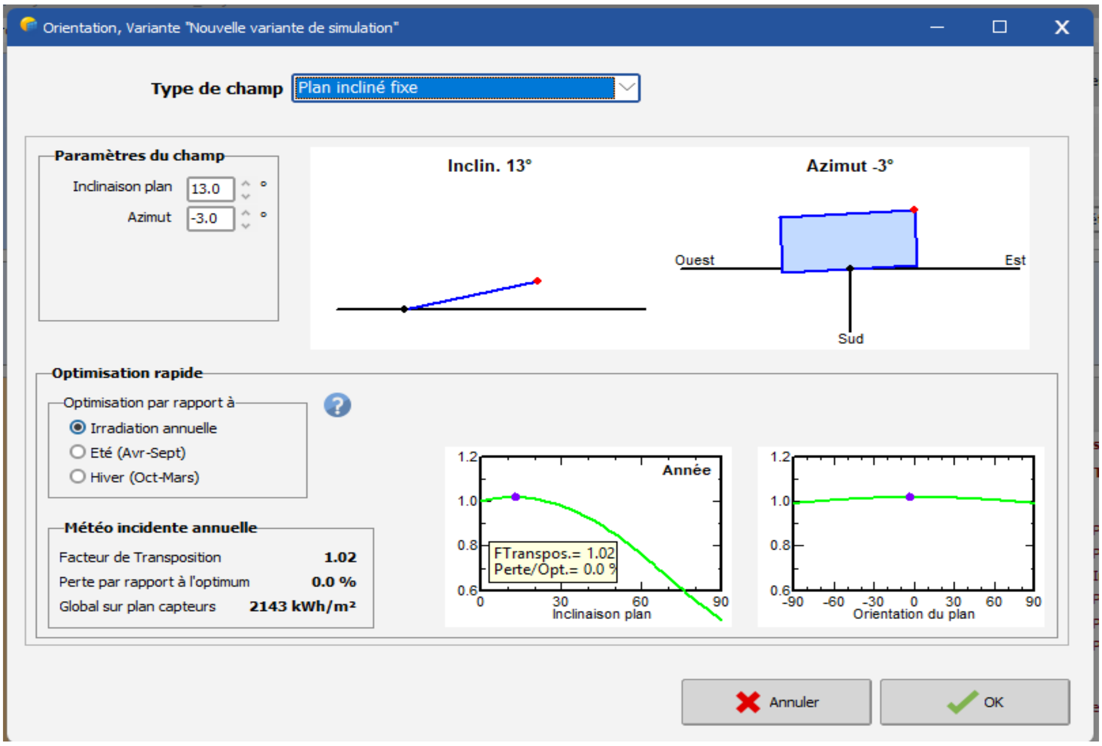
The simulated data [22] was used to highlight the energy generated and the performance indices in relation to the IEC 61724 [23] standard of the International Energy Agency. This standard is used throughout the world, [24 - 26]. Performance indicators are calculated according to equations (1)-(8) and summarized in ***Table 3***.

Table 3 : *Defining formulae*

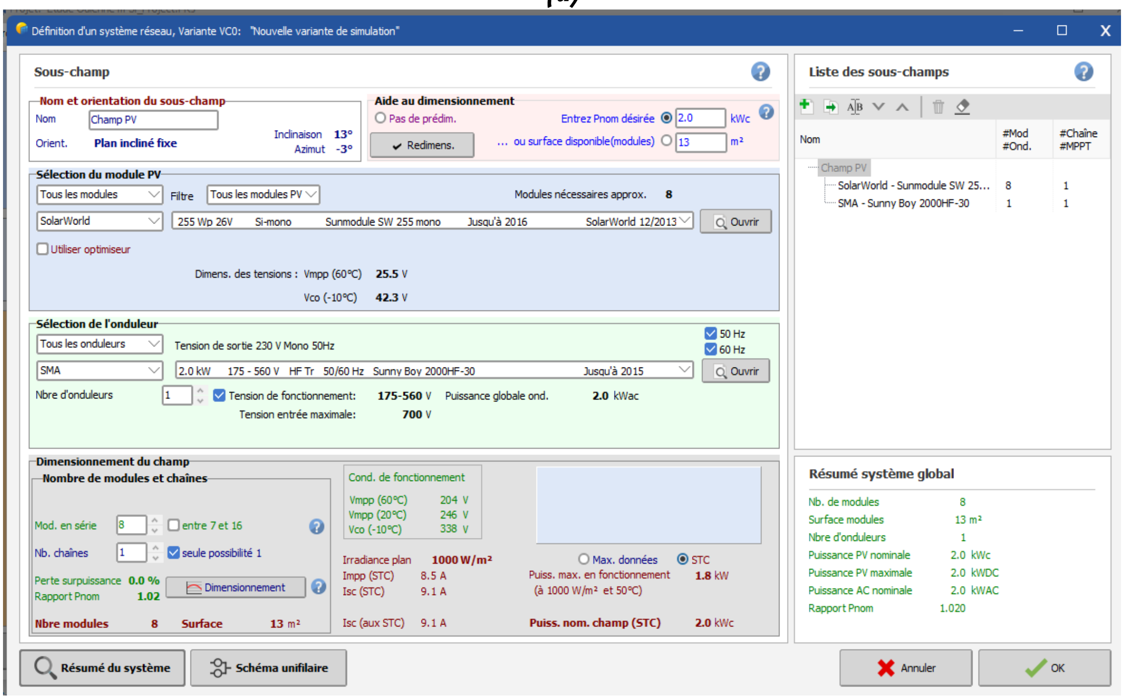
Symbols	Meanings	Formulas	Equations
E_{dc}	Annual energy production of the photovoltaic field	$E_{dc,y} = \sum_{d=1}^{n} E_{dc,d} (kWh)$	(1)
E_{ac}	Annual energy production	$E_{ac,y} = \sum_{d=1}^{n} E_{ac,d} (kWh)$	(2)
Y_a	Productivity of the photovoltaic array	$Y_a = \frac{E_{dc}}{P_0}$	(3)
Y_f	Final productivity	$Y_f = \frac{E_{ac}}{P_0}$	(4)
Y_r	Reference productivity	$Y_r = \frac{H}{G_0}$	(5)
L_C	Capture losses	$L_C = Y_r - Y_a$	(6)
L_S	System losses	$L_S = Y_r - Y_f$	(7)
P_r	Performance ratio	$P_R = \frac{Y_f}{Y_r}$	(8)

2-3. Assumptions and choice of parameters

In each city, we carried out a simulation [27] on PVSYST 7.3 using the same parameters as those used in the experiments carried out in our previous work : one simulation for each technology and one for the entire photovoltaic field. An example of the choice of parameters is detailed in ***Figure 3*** [28]. The hourly series come from Meteonorm 8. The inclination and azimuth have been optimised for the annual energy gain. Electrical losses follow IEA-PVPS T13-17:2023 recommendations [29].



(a)



(b)

Figure 3 : *Choice of (a) inclination and orientation, and (b) PV panel and inverter*

3. Results and discussion

3-1. Monthly energy production

The simulation presented monthly trends in the generation of alternative energy across various cities and technologies. In ***Figure 4***, the monthly energy production in the cities studied throughout the year is depicted.

Figure 4 : *Monthly energy production in the cities studied*

Overall, the energy produced follows a similar seasonal pattern in each city : a minimum between January-February and June-July, and a maximum around March-April or October-November.

- By technology: Monocrystalline (m-Si) and polycrystalline (p-Si) show very similar values (difference of less than 1 %) [19], clearly higher than amorphous (a-Si), whose average production is around 4 to 6 % lower, depending on the city.
- Amplitude of variations: The relative difference between monthly minima and maxima varies from ~13 % (Boundiali m-Si) to ~21 % (Tehini a-Si), showing that amorphous sometimes undergoes more marked fluctuations.
- By town : Odienné and Boundiali stand out with higher totals (3,250-3,400 kWh for a-Si/m-Si/p-Si). Korhogo and Ferkessédougou are in between (3,170-3,340 kWh). Tehini and Bouna have the lowest levels (~3,100-3,245 kWh).

- Monthly trend: In Odienné, Boundiali and Korhogo, the peak is clearly around March (e.g. 299-301 kWh for m-Si), while Téhini and Bouna peak slightly earlier or later depending on ambient humidity.
- Monthly differences: The difference between m-Si and a-Si is up to ~30 kWh in some months, reflecting better crystalline efficiency in the warmer months.

The m-Si/p-Si technologies dominate a-Si throughout the year, with narrower amplitudes of variation, and Odienné/Boundiali are the most favourable localities overall, with Téhini/Bouna the least productive.

3-2. Impact of longitude on energy generated (E_{ac})

3-2-1. Annual energy generated in each city

To analyses the influence of longitude [30] on the alternative energies generated, we summed the annual energies generated in each city by technology. The annual sums are reported in ***Table 4***.

Table 4 : *Alternative energy generated at simulated sites*

Cities	Latitudes (°)	Longitudes (°)	Altitudes (m)	E_{ac} a-Si (kWh)	E_{ac} m-Si (kWh)	E_{ac} p-Si (kWh)
Odienné	9,50	-7,55	428	3250,70	3417,90	3399,90
Boundiali	9,52	-6,48	419	3252,80	3405,60	3387,70
Korhogo	9,42	-5,63	376	3183,80	3343,60	3325,60
Ferkessédougou	9,61	-5,19	328	3170,80	3325,40	3307,50
Téhini	9,61	-3,67	290	3108,70	3263,80	3245,70
Bouna	9,27	-3,00	316	3082,00	3237,10	3219,30
Total				19048,80	19993,40	19885,70

3-2-2. Comparison of the performance of PV technologies

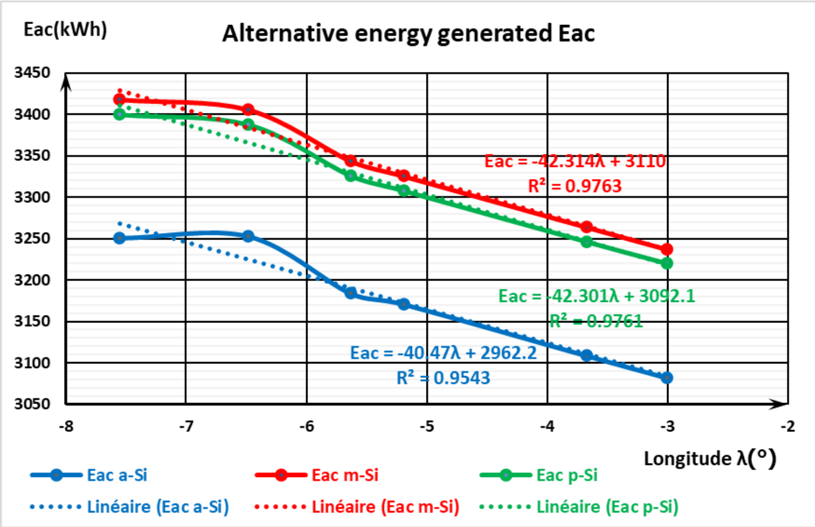
Monocrystalline (m-Si) technology consistently produced the highest energy output (Eac) in all cities, confirming its superiority in terms of energy efficiency. Polycrystalline (p-Si) technology follows closely on the heels of m-Si technology, with relatively small differences (less than 1 % on average). Finally, Amorphous technology (a-Si) has the lowest performance, which is consistent with its lower average efficiency compared with crystalline technologies. The performance gaps between technologies are relatively constant from one city to the next, indicating that environmental conditions affect the different PV technologies in a similar way. However, the gap is slightly wider in the eastern towns (Bouna, Tehini), which could be due to climatic conditions that are more unfavourable to amorphous technology.

3-2-3. Variation in production as a function of longitude

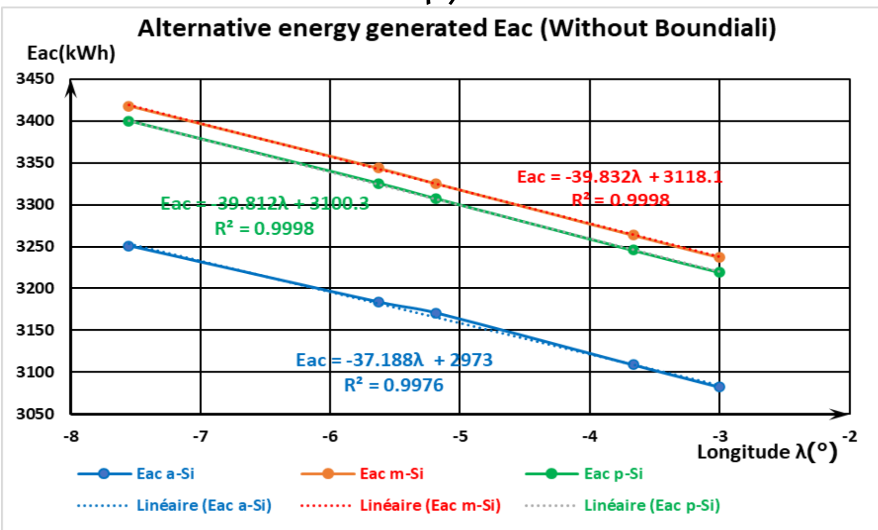
Looking at energy production as a function of longitude, there is a general downward trend in energy production as you move from west (Odienné, longitude 7.55°W) to east (Bouna, longitude 3.00°W): production is highest for all three technologies in Odienné (7.55°W) and lowest for all three technologies in Bouna (3.00°W). This can be explained by variations in sunshine, altitude and local weather conditions. The altitudes of towns in the west are generally higher than those in the east (Odienné, 428m and Bouna, 316m). This observation suggests a possible negative correlation between longitude and energy production.

3-2-4. Correlation between longitude and energy production

The curves showing the energy output from the inverter have been plotted against longitude in ***Figure 5***. It demonstrates the variations in energy output across various geographical locations, emphasising notable trends and singularities.



(a)



(b)

Figure 5 : *Energy generated E_{ac} as a function of longitude (a) inluding Boundiali, and (b) excluding Boundiali*

There is a correlation between the energy generated and longitude. The curves obtained are affine functions with a singularity at Boundiali. If we allow this singularity to be ignored, the R^2 coefficient goes from excellent values of over 0.95 to almost perfect values of over 0.99. This gives us the following ***Equations*** :

$$\text{m-Si} \qquad E_{ac} = -39.832\lambda + 3118.1 \qquad R^2 = 0.9998 \tag{9}$$

$$\text{p-Si} \qquad E_{ac} = -39.812\lambda + 3100.3 \qquad R^2 = 0.9998 \tag{10}$$

$$\text{a-Si} \qquad E_{ac} = -37.188\lambda + 2973 \qquad R^2 = 0.9976 \tag{11}$$

It should be remembered that these energies relate to the peak powers given at the outset: 1.86 kWp for a-Si, and 2.04 kWp for crystalline.

3-2-5. Advantages of amorphous technology (a-Si)

Despite a lower yield (8.1 %), a-Si shows better resilience to longitudinal variations (steering coefficient -37.2 compared with -39.8 for m-Si/p-Si), thanks to its low temperature coefficient (-0.2 %/°C).

3-2-6. Differences in performance between cities

The difference between the best-performing town (Odienné) and the worst-performing town (Bouna) is around 168 kWh for m-Si technology, 180 kWh for p-Si technology and 169 kWh for a-Si technology. This represents a difference of around 5 % for m-Si technology, which is significant on a large scale, particularly for solar power plant projects.

3-2-7. Identifying optimal areas for the installation of solar power plants

Odienné and Boundiali appear to be the most favourable sites for the installation of solar power plants, given their higher energy output. Bouna and Tehini, although less efficient, could still be viable, but further studies would be needed to assess the economic benefits. Based on our findings, single-crystal silicon solar panels consistently generate the most energy across all locations studied. Energy output tends to decline marginally as we move from west to east, indicating an inverse relationship between energy production and longitude. We successfully represented this trend using linear functions with considerable precision. Consequently, we conclude that the northwestern region of Côte d'Ivoire (specifically Odienné and Boundiali) is particularly well-suited for solar energy development. For less densely populated areas, thin-film technology is recommended, despite its larger space requirements.

3-3. Performance ratio and final productivity

3-3-1. Annual value of the performance and energy ratio

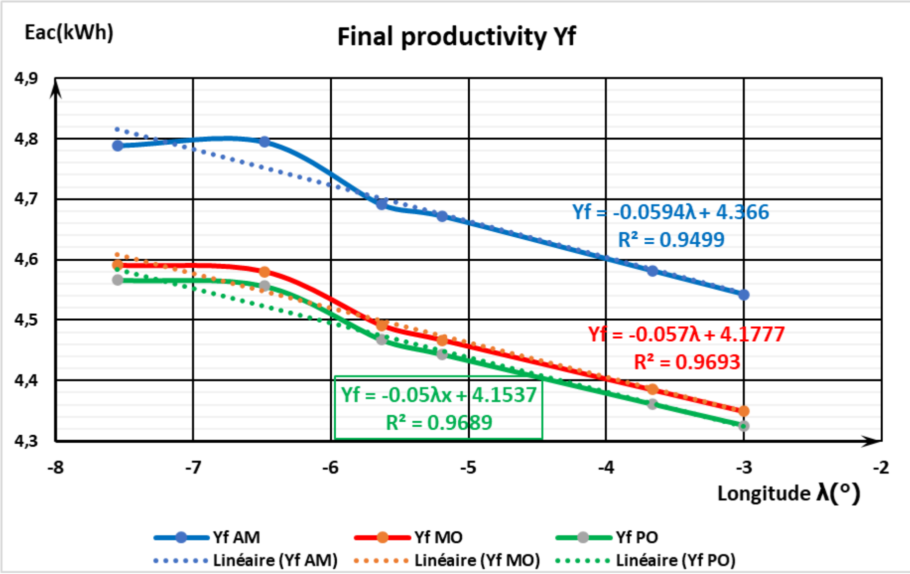
Based on the energy generated, we have calculated the final productivity Y_f and the performance ratio (PR) of all the technologies in each city. The values obtained are shown in ***Table 5***.

Table 5 : *Performance ratio and final productivity of simulated sites*

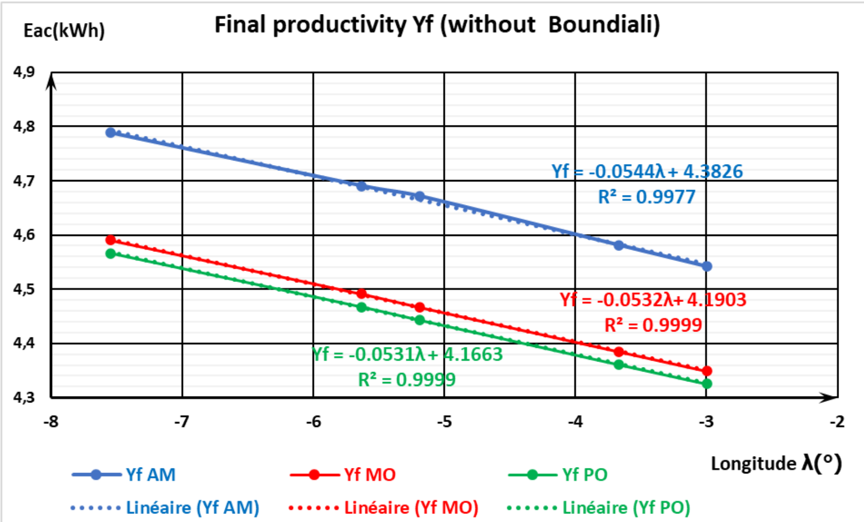
Cities	Y_f a-Si	Y_f m-Si	Y_f p-Si	PR a-Si	PR m-Si	PR p-Si
Odienné	4,79	4,59	4,57	81,84 %	78,46 %	78,05 %
Boundiali	4,79	4,57	4,55	81,54 %	77,86 %	77,45 %
Korhogo	4,69	4,49	4,47	81,62 %	78,18 %	77,76 %
Ferkessédougou	4,67	4,47	4,44	81,46 %	77,93 %	77,51 %
Téhini	4,58	4,38	4,36	81,34 %	77,91 %	77,48 %
Bouna	4,54	4,35	4,33	80,63 %	77,26 %	76,83 %

3-3-2. Graphical representation of Y_f

A graphical representation of final productivity Y_f as a function of longitude λ is provided for each technology in ***Figure 6*** to illustrate the variations in productivity across different regions, highlighting the impact of geographical factors on technological efficiency. Additionally, they provide insights into how specific technological approaches may perform better in certain longitudinal contexts.



(a)



(b)

Figure 6 : *Final productivity Y_f as a function of longitude (a) (inluding Boundiali), and (b) (excluding Boundiali)*

There is a gradual decrease in the values of Y_f and P_R as one moves eastwards. For example, for a-Si technology, Y_f productivity falls from 4.79 kWh/kWp/year at Odienné (longitude ≈ -7.5°) to 4.54 kWh/kWp/year at Bouna (longitude ≈ -3.0°), a drop of 5.2 %. The m-Si and p-Si technologies followed the same trend, with decreases of 5.3 % and 5.4% respectively. P_R performance ratios are also down, confirming that the reduction in productivity is linked to environmental or technical factors (temperature, diffuse irradiation, thermal losses) rather than to variations in theoretical insolation.

3-3-3. Mathematical modelling between Y_f and longitude (λ)

To quantify the relationship between Y_f and longitude (λ), we can use linear regression. The data suggest a negative correlation: as longitude increases (eastwards), Y_f decreases. The approximate equations for each technology, obtained by fitting the data in ***Table 6***. As in the case of energy, the case of Boundiali is a singularity that could be explained by the existence of a microclimate.

$$\text{m-Si} \quad Y_f = -0.0532\lambda + 4.1903 \quad R^2 = 0.9999 \tag{12}$$
$$\text{p-Si} \quad Y_f = -0.0531\lambda + 4.1663 \quad R^2 = 0.9999 \tag{13}$$
$$\text{a-Si} \quad Y_f = -0.0544\lambda + 4.3826 \quad R^2 = 0.9977 \tag{14}$$

These relationships allow us to obtain the equations for any peak power by applying the relationship below, which follows from the definition of Y_f:

$$E_{ac} = 365 \times P_0 \times Y_f \tag{15}$$

The result is:

$$\text{m-Si} \quad E_{ac} = (-19.418\lambda + 1529.4595) \times P_0 \quad R^2 = 0.9999 \tag{16}$$
$$\text{p-Si} \quad E_{ac} = (-19.3815\lambda + 1520.6995) \times P_0 \quad R^2 = 0.9999 \tag{17}$$
$$\text{a-Si} \quad E_{ac} = (-21.024\lambda + 1599.649) \times P_0 \quad R^2 = 0.9977 \tag{18}$$

3-3-4. Analysis of equations

The negative directional coefficients indicate that a 1° increase in longitude (eastward shift) results in a decrease in Y_f of about 0.053 kWh/kWp/year and a decrease in energy of about 20 kWh/year, all technologies combined. The very high coefficient of determination (R^2) expresses the high consistency of the differences, confirming a strong linear correlation. Finally, the slight differences between the predicted and actual values could be explained by variables not considered (humidity, local albedo).

3-3-5. Factors explaining correlation

Solar irradiation : in Côte d'Ivoire, the west region (Odienné) benefits from more direct sunshine that is less disrupted by cloud cover, unlike the east (Bouna), where humidity and rainfall are more frequent. Temperature: The eastern regions, which are more continental, are subject to higher temperatures, reducing the efficiency of the panels (crystalline m-Si/p-Si technologies lose 0.3-0.5 % yield per °C above 25°C). Albedo and diffuse reflection: Light soil or reflective vegetation in the west amplifies diffuse light, giving an advantage to amorphous panels (a-Si), which are more efficient in low light conditions.

3-3-6. Practical implications

Geographical optimisation: Installing panels in the north-west of the country maximises productivity, especially for a-Si technologies. Technological choice: Amorphous panels (a-Si) are less sensitive to thermal losses, hence their higher P_R (+3 % vs m-Si/p-Si). Predictive modelling: Incorporating longitude into yield prediction algorithms improves accuracy, especially if combined with local weather data.

4. Conclusion

The study examines the impact of longitude on the performance of photovoltaic (PV) technology in six cities in northern Côte d'Ivoire. The results show a negative correlation between longitude and PV energy yield, with amorphous technology achieving the highest energy yield. Polycrystalline technology exhibits similar performance, while amorphous technology shows a higher performance ratio due to its lower temperature coefficient. The study proposes a geospatial optimization strategy, focusing on the northwest region for large-scale solar plants based on crystalline silicon technology and on the northeast region for amorphous or thin-film technologies. Longitude can be integrated as a key predictive variable in PV performance models, thereby improving yield accuracy. Furthermore, these findings provide actionable guidelines for policymakers to prioritize investments in Odienné and Boundiali for utility-scale solar farms, maximizing return on investment through higher irradiation (up to 2,144 kWh/m²/year).

References

[1] - MPE CÔTE D'IVOIRE, "Plan d'Action National des Énergies Renouvelables de la Côte d'Ivoire (PANER) 2016-2020/2030", Abidjan, (2016). Available at: https://leap.unep.org/en/countries/ci/national-legislation/plan-daction-national-des-energies-renouvelables-de-la-c-te (accessed 8 Aug 2024)

[2] - A. FEZZANI, HACHI R., BOUFANA S. and SAHRAOUI R., "Energy Efficiency of Multi-Technology PV Modules under Real Outdoor Conditions—An Experimental Assessment in Ghardaïa, Algeria", *Sustainability*, 14 (3) (2022) 1771, doi: 10.3390/su14031771

[3] - A. K. MAURYA, A. K. RAI and H. AHUJA, "Performance Analysis of a 40 kWp Grid-Connected Solar PV System in Northern India", *Journal of Research and Advancement in Electrical Engineering*, 4 (3) (2022) s.p. Available at: https://www.researchgate.net/... (accessed 25 Oct 2024)

[4] - N. EL HAJJAM, B. HARTITI, A. BATAN *et al.*, "Comparative Study of the Electrical Performance of Three Types of Photovoltaic Technologies in Rabat and Errachidia Station", *Materials Today: Proceedings*, 66 (2022) 412 - 415. Available at: https://www.sciencedirect.com/... (accessed 25 Oct 2024)

[5] - L. MOGMENGA, A. BATAN, N. EL HAJJAM et *al.*, "Comparative Study of the Performances of Different Silicon-Based Photovoltaic Technologies", Communication, Paris, (2018)

[6] - I. ROMERO-FIANCES, E. MUÑOZ-CERÓN, R. ESPINOZA-PAREDES, G. NOFUENTES and J. DE LA CASA, "Analysis of the Performance of Various PV Module Technologies in Peru", *Energies*, 12 (1) (2019) 186, doi: 10.3390/en12010186

[7] - S. KHANAM, V. CHAUDHARY, D. SHRIVASTAVA et *al.*, "Comparative Performance Analysis of Photovoltaic Modules of Different Materials for Four Climatic Zones of India", *Urban Climate*, 39 (2021) 100957. Available at: https://www.sciencedirect.com/... (accessed 25 Oct 2024)

[8] - M. M. KHAN, S. AHMAD, A. RAZA, H. SIKANDAR, R. G. HASSAN and M. A. SHAFI, "Performance Analysis of PVSyst-Based Grid-Connected Photovoltaic Systems in Pakistan Compared to SAARC Countries", *Mehran University Research Journal of Engineering and Technology*, 43 (2) (2024) 112, doi: 10.22581/muet1982.3027

[9] - M. ALMAKTAR, A. M. ALBREKI, F. A. MOHAMED, K. YAHYA and T. HUSSEIN, "Performance Evaluation of Different Solar Photovoltaic Technologies in Libya", in "*2020 11th International Renewable Energy Congress (IREC)*", Ed. IEEE, Hammamet, (2020) 1-5, doi: 10.1109/IREC48820.2020.9310421

[10] - A. BENNOUNA, H. RABHI, R. EL HOUSSAINI and B. HARTITI, "Energy Performance of Three Silicon-Based PV Module Technologies in Twenty Sites of Morocco", *Energy for Sustainable Development*, 53 (2019) 30 - 56, doi: 10.1016/j.esd.2019.09.002

[11] - B. KHIKMATOV, M. MIRZAEV, K. SAMIEV and O. KHAMIDOV, "Performance Analysis of 1210 kW Grid-Connected Solar Photovoltaic Systems at Bukhara State University", *Results in Engineering*, 26 (2025) 105465, doi: 10.1016/j.rineng.2025.105465

[12] - M. A. DERICHE, A. HAFAIFA, A. TAHRI, K. MOHAMMEDI and F. TAHRI, "Energy and Environmental Performance Analysis of Grid-Connected Photovoltaic Systems under Similar Outdoor Conditions in the Saharan Environment", *Diagnostyka*, 21 (2) (2020) 13 - 23, doi: 10.29354/diag/122035

[13] - M. MEHDI, N. AMMARI, A. A. MERROUNI, H. EL GALLASSI, M. DAHMANI and A. GHENNIOUI, "An Experimental Comparative Analysis of Different PV Technologies Performance Including the Influence of Hot-Arid Climatic Parameters", *Renewable Energy*, 205 (2023) 695 - 716. Available at: https://www.sciencedirect.com/... (accessed 25 Oct 2024)

[14] - G. TAKYI and O. G. LARYEA, "Comparative Study of the Performance of Solar Photovoltaic Module Technologies Installed in Kumasi, Ghana, in Sub-Saharan Africa", *Scientific African*, 13 (2021) e00877, doi: 10.1016/j.sciaf.2021.e00877

[15] - G. TAKYI, A. S. ADUNYAH and A. AGYEI-AGYEMANG, "Performance Evaluation of Monocrystalline and Polycrystalline Silicon Solar Photovoltaic Modules under Low and High Irradiance Conditions in Kumasi, Ghana", *Nigerian Journal of Technology*, 40 (3) (2021) 414 - 426, doi: 10.4314/njt.v40i3.8

[16] - D. O. AKINYELE, R. K. RAYUDU and R. H. G. TAN, "Comparative Study of Photovoltaic Technologies Based on Performance, Cost and Space Requirement: Strategy for Selection and Application", *International Journal of Green Energy*, 13 (13) (2016) 1352 - 1368, doi: 10.1080/15435075.2015.1112287

[17] - A. DAJUMA, I. YAO, B. AKPA et *al.*, "Sensitivity of Solar Photovoltaic Panel Efficiency to Weather and Dust over West Africa : Comparative Experimental Study between Niamey (Niger) and Abidjan (Côte d'Ivoire)", *Computational Water, Energy and Environmental Engineering*, 5 (4) (2016) 1 - 12, doi: 10.4236/cweee.2016.54012

[18] - I. GUAITA-PRADAS and B. M. SOUCASE, "Energy Production and Financial Analysis of Photovoltaic Energy Plants in Ivory Coast", *Research report*, Valencia, (2015)

[19] - S. SUGIANTO, "Comparative Analysis of Solar Cell Efficiency between Monocrystalline and Polycrystalline", *Intek*, 7 (2) (2020) 92 - 100, doi: 10.31963/intek.v7i2.2625

[20] - S. DUBEY, J. N. SARVAIYA and B. SESHADRI, "Temperature-Dependent Photovoltaic Efficiency and Its Effect on PV Production Worldwide—A Review", *Energy Procedia*, 33 (2013) 311 - 321, doi: 10.1016/j.egypro.2013.05.072

[21] - Z. R. TAHIR, F. AHMAD, R. ADHIKARI et *al.*, "Effect of Temperature and Wind Speed on Efficiency of Five Photovoltaic Module Technologies for Different Climatic Zones", *Sustainability*, 14 (23) (2022) 15810, doi: 10.3390/su142315810

[22] - L. J. WEI, M. M. ISLAM, M. HASANUZZAMAN and E. CUCE, "Energy Consumption, Power Generation and Performance Analysis of Solar Photovoltaic Module-Based Building Roof", *Journal of Building Engineering*, 90 (2024) 109361, doi: 10.1016/j.jobe.2024.109361

[23] - IEC, "IEC 61724-1:2021—Photovoltaic System Performance Monitoring", Geneva, (2021). Available at: https://cdn.standards.iteh.ai/... (accessed 23 Jun 2025)

[24] - I. OMAR NOUR-EDDINE, B. LAHCEN, O. H. FAHD, B. AMIN and O. AZIZ, "Outdoor Performance Analysis of Different PV Technologies under Hot Semi-Arid Climate", *Energy Reports*, 6 (2020) 36 - 48. Available at: https://www.sciencedirect.com/... (accessed 25 Oct 2024)

[25] - H. LOTFI, M. ADAR, A. BENNOUNA, D. IZBAIM, F. OUM'BARK and E. H. OUACHA, "Silicon Photovoltaic Systems Performance Assessment Using the Principal Component Analysis Technique", *Materials Today: Proceedings*, 51 (2022) 1966 - 1974, doi: 10.1016/j.matpr.2021.04.374

[26] - M. ADAR, H. BAZINE, A. ABOUNADA and M. MABROUKI, "Simulation and Comparative Study of Different PV Module Technologies of Silicon (Monocrystalline, Polycrystalline and Amorphous) in Beni Mellal", Internal communication, in Beni Mellal, (2016), doi:10.9790/1676-110304112121

[27] - G. SABAH and S. YASMINE, "Simulation of a Grid-Connected PV Plant with 'PVSYST' and 'HOMER Pro' Software", Communication, Algiers, (2019)

[28] - J. L. SÁNCHEZ-JIMÉNEZ, F. J. MUÑOZ-RODRÍGUEZ, G. JIMÉNEZ-CASTILLO, A. J. MARTÍNEZ-CALAHORRO and C. RUS-CASAS, "Analysis of Different Scenarios to Include PV Rooftop Systems with Battery Energy Storage Systems in Olive Mills", *Energies*, 17 (1) (2023) 144, doi: 10.3390/en17010144

[29] - IEA PVPS, "Trends in PV Applications 2023", Paris, (Oct 2023). Available at: https://iea-pvps.org/trends_reports/trends-2023/ (accessed 3 Aug 2025)

[30] - I. NEHER, S. CREWELL, S. MEILINGER, U. PFEIFROTH and J. TRENTMANN, "Photovoltaic Power Potential in West Africa Using Long-Term Satellite Data", *Atmospheric Chemistry and Physics*, 20 (21) (2020) 12871 - 12888, doi: 10.5194/acp-20-12871-2020