Scientific African 15 (2022) e01069

Contents lists available at ScienceDirect

Scientific African

journal homepage: www.elsevier.com/locate/sciaf

Effect of orientation and tilt angles of solar collectors on their performance: Analysis of the relevance of general recommendations in the West and Central African context

Kokouvi Edem N'Tsoukpoe

Laboratoire Énergies Renouvelables et Efficacité Énergétique (LabEREE), Département Génie Électrique, Énergétique et Industriel, Institut International d'Ingénierie de l'Eau et de l'Environnement (2iE), 01 BP 594 Ouagadougou 01, Burkina Faso

ARTICLE INFO

Article history:
Received 25 June 2021
Revised 26 October 2021
Accepted 8 December 2021

Editor: DR B Gyampoh

Keywords:
Optimum tilt angle
Solar panel orientation
Solar radiation
Solar energy
Solar tracking
Retscreen

ABSTRACT

Installing solar panels or collectors with optimum orientation and tilt angles to maximise energy generation over a specific period is important to improve the economics of solar systems, and hence, their large-scale utilisation. As a general rule, for installations aiming at maximum annual solar production in the intertropical region, it is recommended to point the panel towards the Equator at a tilt angle equal to the local latitude. However, there are several situations where it is difficult or even impossible to follow these general recommendations, for example in case of the presence of an obstacle creating shading, inadequate orientation or slope of the roofs, or when roofs are inaccessible. This raises the question of the impact of non-compliance with the general recommendations on solar systems' performance. We have used RETScreen software for the calculation of annual average irradiation on tilted panels in various locations in West and Central Africa, namely in the capital cities (latitudes between 0° N and 15° N). For each site, the maximum annual solar irradiation is simulated and taken as a reference value. The annual irradiations for various orientations and tilt angles were then recorded and compared to the reference. It appears that in West and Central Africa, a moderate deviation (up to 20°) from the optimal orientation and inclination does not significantly influence the incident solar radiation (reduction in irradiation $< 5\%$). Construction of structures dedicated to solar installations or architectural modification to comply with general recommendations is therefore generally not justified. A set of diagrams and tables, which allow us to quickly determine the percentage of incident solar radiation on a solar panel based on its orientation and tilt angle compared to the optimal tilt and orientation for any capital city in West and Central Africa, is provided.

Introduction

The starting point of this investigation is a real-world situation somewhere in West Africa. A company has installed solar streetlights along both sides of a road. For allegedly esthetical reasons, the panels were tilted downward the exterior of the

E-mail address: edem.ntsoukpoe@2ie-edu.org

https://doi.org/10.1016/j.sciaf.2021.e01069

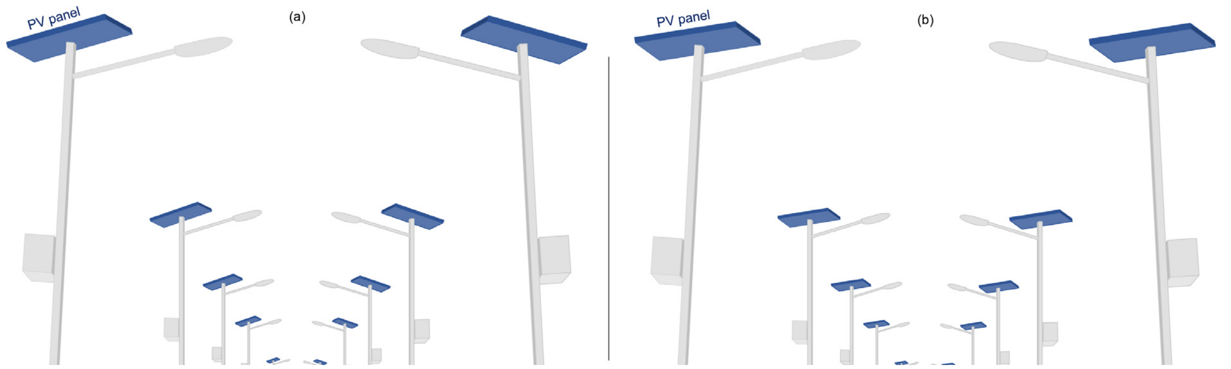


Fig. 1. (a) Panels orientated in opposite directions and (b) panels orientated toward the same direction along a road.

road i.e. panels on both sides are facing each other (Fig. 1a). The prime contractor refused the work. Then, the company has taken down the poles and orientated all the panels due south before the temporary reception of works. Of course, this has delayed the works and generated additional costs, especially with the mobilisation of cranes and workforce. We have initially initiated this short study to support decision-making for PV and solar thermal industry in the West and Central region [1].

Energy generation by solar systems, either from thermal collectors or photovoltaic modules, varies with the angle of incidence of the solar irradiation. Since the position of the sun varies in the sky throughout the day and year, a solar tracking system would be required to follow the daily and seasonal movement of the sun to collect the maximum amount of solar energy. However, the installation of a solar tracking system can prove to be expensive and not necessarily practical or justifiable economically, especially for small-scale installations [2]. Hence, for domestic solar harnessing applications, fixed slope panels are very often used or are the general rule. This requires defining an angle of inclination (tilt angle) and an angle of orientation of the panel. The selection of these angles is made judiciously to obtain the maximum benefit from the solar system when operating without solar tracking over a specific period.

To put it simply, for installations aiming at maximum annual solar energy recovery, the inclination given to a solar panel corresponds to the angular value of the latitude of the location of installation, with an orientation towards the Equator, that is to say, due south[1] for locations in the Northern Hemisphere, and an orientation towards the north for locations in the Southern Hemisphere. In addition to these general recommendations, a minimum tilt angle of 5° to rather 10° is required to facilitate the flow of rainwater and the evacuation of objects and dust that could be deposited on the panel [3]. Furthermore, for thermosiphon thermal solar collectors, a minimum tilt angle of 15° and 20° is required to assist the thermosiphon effect for flat plate collectors and evacuated tube heat pipes, respectively [4,5].

However, there are several situations where it is complicated, difficult, or simply impossible to follow these general recommendations. Here are just a few, most of which are roof related, since rooftop installations represent the majority of solar residential applications:

Case 1. Roof surfaces are not equator-facing (Fig. 2a). In this case, how much less efficient is the solar system installed while keeping the orientation of the roof that is different from due south? In this case, is the optimal tilt still close to the angular value of the latitude? The questions are the same for a configuration where it is impossible to orientate the panels towards the Equator, for example when the presence of an obstacle (trees, buildings, etc.) prevents this orientation (potential shading problems).

Case 2. The roof pitch or slope is different from the latitude or the optimal tilt angle (Fig. 2d). This is usually the case, especially in the coastal countries where the slope of roofs is usually steep. For instance, the national building code in Nigeria imposed a minimum pitch of 30° for common roof types [6]. Recovering the optimal inclination would require, for example, the construction of a metal structure to support the panels, which generates additional costs but also can affect the aesthetics and integration of the panels into the building (Figs. 2b, 2c and 2d). Is it relevant to build such a metal structure or integrate the panels into the existing roof slope? In the latter case, how much less efficient is the solar system? Is the optimal orientation always the equator-facing when the slope is imposed? These issues may be avoided in houses with flat roofs by orienting the structural mounting of the panel.

Case 3. The roof is inaccessible, inappropriate, or not sufficiently large and the architect decides to integrate the panels into the facades (vertical). The question may also arise in the case of Building Integrated Photovoltaic Systems (BIPV), which are under discussion in regional discussions [7–10]. Which facade(s) to favour? South? North? East? West?

[1] It is the geographic south, not the magnetic south indicated by a compass: a correction, that is equal to the magnetic declination, must therefore be taken into account. However, currently, the magnetic declination is not very important in Central or West Africa (around −2.4 ° in Ouagadougou, for example). If it is really necessary to know the geographic north (and therefore the geographic south), one can easily calculate the magnetic declination of the location using various online calculators and apply the relation True north = Magnetic North + Magnetic Declination. It is also possible to locate the south or the geographic north using a sundial.

Fig. 2. Solar thermal collectors installed on buildings at Osona village. Some collectors are installed in the plane of the roofs and in any direction (a and b) while others are installed using metal structures but still in any direction (c and d).

Case 4. The plant is to be used during a specific period of the year or when a large load is concentrated on a specific period of the year. For example, a solar thermal collector used for mango drying in Ouagadougou (latitude = 12.4° N), from the beginning of May to the end of July. Another similar situation is the use of solar thermal collectors for domestic hot water production, given that most use of hot water in a bathroom is during the cold season, from mid-November to the end of February in Ouagadougou.

To address these questions and other similar ones, this study is designed to elaborate a solar atlas for the West and Central Africa countries, especially in the capital cities that are located in the Northern Hemisphere. With this atlas, the recovery factor of solar radiation can be estimated to determine the annual sunshine received on the panel of an installation, as compared to the maximum incident radiation. Assuming that solar energy production is directly proportional to the sunshine received on the solar panel, then the "recovery factor" corresponds to the correction factor to be applied to determine the annual production of the installation given the maximum energy production. Strictly speaking, the efficiency and therefore the production of a solar photovoltaic or thermal panel also depends on the ambient temperature, so that the maximum production of useful energy would not necessarily correspond to the maximum collection of solar radiation. However, this difference would in practice not be very important for annual production, except for special cases.

Following this introduction, contributions on the effect of orientation and tilt angle on solar systems are reviewed, with an emphasis on West and Central African context-related works. Then, the methodology to establish the atlas is presented as well as the results. This is followed by a discussion focused on the main questions stated in this introduction and the level of relevance of orientation and tilt angle for solar panels.

Lessons learnt from the literature

West and Central Africa

This study is focused on two African sub-regions, namely West and Central Africa. The considered locations are presented in Fig. 3 and are located in the Northern Hemisphere, between latitudes 0 °N and 15° N.

The average yearly global irradiation in West and Central Africa varies from 1500 to 2500 kWh m^{-2} (Fig. 3). While the northern part of Niger benefits from high direct solar irradiation (beyond 2500 kWh m^{-2} year^{-1}), the rainy equatorial region receives more diffuse radiation than beam radiation. The region is located in the intertropical zone (Fig. 3), which implies that above each location, the sun can be seen at the zenith twice during the year. This happens when the local azimuth is equal to the declination. For Ouagadougou (latitude = 12.4° N) for instance, the zenith passages happen on April 23rd and

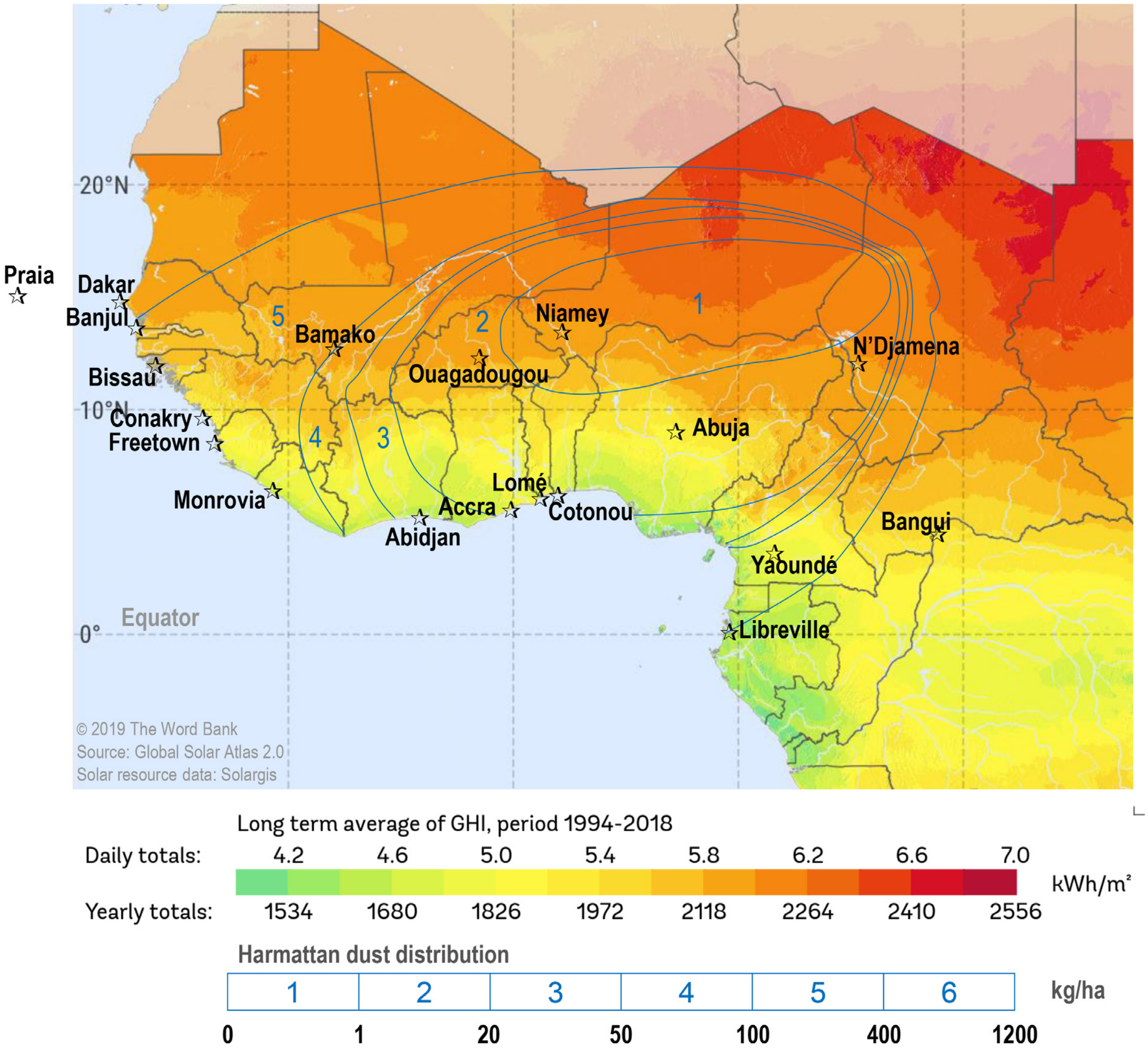


Fig. 3. Global horizontal irradiation in West and Central Africa and distribution of Harmattan dust. Irradiation data are from Solargis (https://solargis.com) while Harmattan dust distribution data are from Ref. [11].

August 21st. On the other days, the sun is radiating either from the "south" or from the "north" of the location. Then, using a fixed tilt non-tracking solar panel facing either direction means not collecting direct irradiation during a defined period of the year.

The entire region is under the influence of dust load from the Saharan desert, which happens to generates about 60% of the total global dust emission and the total dust in the troposphere [12,13]. The proximity of the region to the Saharan desert, with which it shares a large portion of land, is a source of a high atmospheric loading (Fig. 3) in West Africa, which is also the most affected area of the world by dust from this desert. It is a big challenge for the solar industry in the region [12], not in terms of irradiation but cleaning because of dust sedimentation on panels. This is mainly the case during the Harmattan season, from the end of November to mid of March.

Solar tracking from West and Central African perspective

Solar tracking is deemed to improve energy yields from solar PV modules or solar thermal collectors. Then, one would think that in West and Central Africa, which is an intertropical region i.e. for the same location radiations come from the northern or southern direction, depending on the period of the year, solar tracking could have significant yield improvement. Tracking systems may be classified as active or passive tracking, or as one axis or two axes tracking [2]. The efficacy of the tracking mechanism strongly depends on the sky clearance and latitude since tracking systems track the direct irradiation, which is correlated to the sky clearance and latitude [14].

Njoku [14] has compared theoretically the annual output of PV systems with 2-axis tracking as compared to fixed horizontal surfaces for 40 localities in Nigeria, using a constant system ratio performance of 0.75. It appears that the output of the systems with tracking is 20% to 37% higher than fixed horizontal PV systems. The performance increase increases from the location at the lowest latitude (Port Harcourt, latitude = 4.75° N, +21%) to the location with the highest latitude (Sokoto, latitude = 13.07° N, +37%). The author acknowledges a probable overestimate of the benefit of the tracking system, especially in the northern part where the effect of the ambient temperature should reduce the estimated gain. On the other hand, Okoye et al. [15] consider the comparison of the annual radiation received on an optimally tilted surface to the one obtained on surfaces with various tracking strategies. Based on estimations for 9 locations in Nigeria, the 2-axis tracking leads to gains in incident radiation between 14% and 32% as compared to the optimally fixed surface, depending on the latitude and the used model in the estimation of the diffuse component of the radiation on an inclined surface. For instance, for Onitsha (latitude = 6.17° N), depending on the model, the increase is 14% or 21%. Another theoretical comparison made in Sierra Leone (Mambolo, latitude = 8.92° N) showed that the PV system with 2-axis tracking system generated 29% more energy in the year as compared to the "no tracking system" (fixed slope and azimuth angles, which have not been indicated).

Despite these potential gains, solar tracking appears to be irrelevant in small systems and for regions with high diffuse radiation. Using data from more than 80 African weather stations to theoretically predict annual energy yields from PV panels, Kanyarusoke et al. [2] indicated that there is no relevant gain with solar tracking in rainy equatorial and sandy, windy Sahel regions due to the importance of diffuse radiation. In addition, solar tracking systems exhibit many drawbacks that prevent their large-scale utilisation: they are expensive, require power for their operation (especially active trackers), and proper maintenance. Indeed, the moving and mechanical parts require regular and careful attention including inspection, adjustments, or replacements [16]. The tracking systems usually installed in the Sahelian region operate under harsh climatic conditions, high atmospheric dust loadings with high-temperature gradients that can easily damage the mechanical and electronic controls [17]. Even passive solar trackers exhibit various issues [2,16].

Optimum fixed angles for solar energy generation systems

Both orientation and tilt angles affect the amount of solar radiation reaching a solar collector. The surface azimuth angle of a collector (α), also referred to as azimuth orientation angle or, commonly and simply, as orientation, is the angle measured clockwise, in the horizontal plane, between the true south direction (or sometimes the true north depending on the definition used) and the projection of collector's surface normal onto the horizontal plane Fig. 4) [18–20]. It is the deviation from the true south; hence, due south, towards the equator, is orientation of 0° by definition. The tilt angle (β), also referred to as inclination angle or slope, is the angle formed by the collector plane and the horizontal plane (Fig. 4) [18–20]. By definition, the tilt angle of a collector in the horizontal plane facing up toward the sky is 0°

Optimum angles of a solar panel, that is optimum orientation and tilt angles, are sought over a specific period: a day, a month, a season, or the whole year. Most of the time, it is the whole year so that in the paper, unless otherwise specified, the reference period is the year. In the latter case, equator-facing is the normal orientation that is why researchers mostly focus on the tilt angle instead of the pair "tilt and orientation" angles. The idea behind the determination of a daily, monthly or seasonal tilt angle is to have a daily, monthly or seasonal adjustment of the panel to maximise the energy output of the

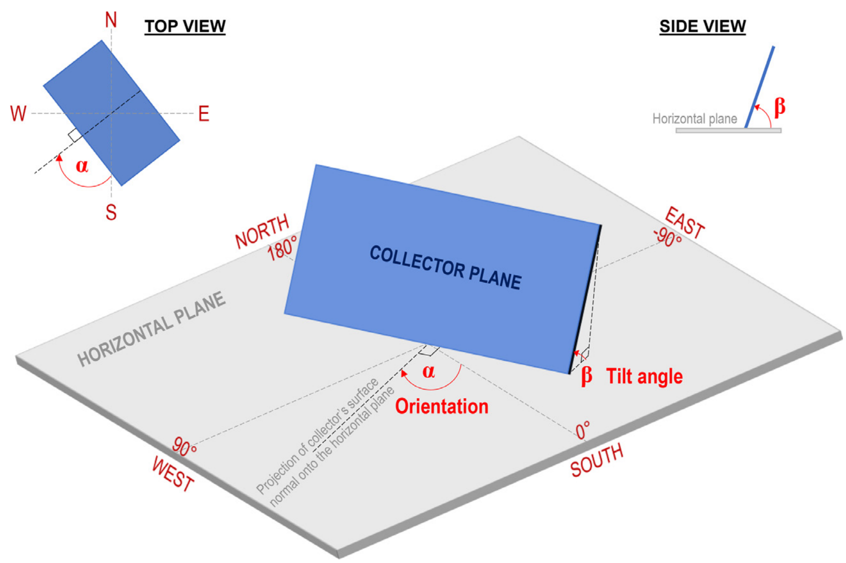


Fig. 4. Definition of orientation and tilt angles.

system. A daily adjustment is nearly impossible, at least, not practical. Furthermore, its rigorous determination, either theoretically or experimentally, would require information of exact climatic conditions – especially sky clearance and ambient temperature – on each day of the year, which cannot be predicted [21]. However, the tilt and orientation angles leading to the maximum collection of solar radiation for a defined day may be determined under the assumption of a completely transparent atmosphere. But once again, in practice, this would be of least interest. Monthly optimum angles, which are in themselves already simpler, and have been proposed by various authors, who suggested that it is easy to implement, are not yet very widespread. Seasonal adjustments, to be implemented for instance twice a year could be the most feasible fixed optimum angles. The rationale behind this is that energy gain would be more significant with monthly optimal tilt angles than seasonal and yearly tilt angles.

But what are optimum tilt and orientation angles? In any optimisation problem (maximisation or minimisation), the relevance of the model, as well as the proper selection of the objective function and the variables to optimise, determine the quality of the results and estimations. Hence, authors have targeted various objectives and used various techniques when it comes to the determination of the optimum tilt and orientation angles of a solar panel. Objectives include, but are not limited to, the maximisation of the following objective functions: (i) the incident solar radiation, (ii) the energy generation or the solar system output, and (iii) the economic gains (for instance value of energy in a context of real-time price (mornings vs afternoons, summer vs winter), reduction of cost of maintenance or cost of land, etc.). The first two functions mentioned above are the most commonly adopted. To maximise incident solar radiation, various techniques are used, from simple ones to much more complex: tilt angle–latitude relations, models to estimate solar radiation on a tilted surface, tilt angle optimisation using techniques such as genetic algorithm, artificial neural network, simulated annealing and particle swarm optimisation [22]. In practice, total solar radiation falling on a tilted surface is computed by varying tilt angle and the tilt angle at which the solar radiation on the surface is maximum is considered as the optimum tilt angle [22]. A similar approach is used when dealing with the other objective functions.

If we seek the maximisation of the incident solar radiation, the optimum tilt angle is equal to the local latitude under the assumption of a fully transparent atmosphere [23]. That is why it is generally advised to tilt the solar panel to an angle close to the local latitude for a year-round maximum radiation recovery. Other tilt angle–latitude relations are justified by the fact that the atmosphere is not completely transparent. But even studies [24,25] using models taking into account the sky clearness in the West or Central African region mostly end up with an optimum tilt angle equal or close to the latitude, as the case elsewhere, especially in the intertropical area [26]. The total annual radiation appears to be unaffected by tilting the surface for azimuth angles between 0° and 30° for locations representing the southern (latitude = 6.33° N), the middle (latitude = 8.48° N), and the northern (latitude = 11.85° N) zones in Nigeria [25].

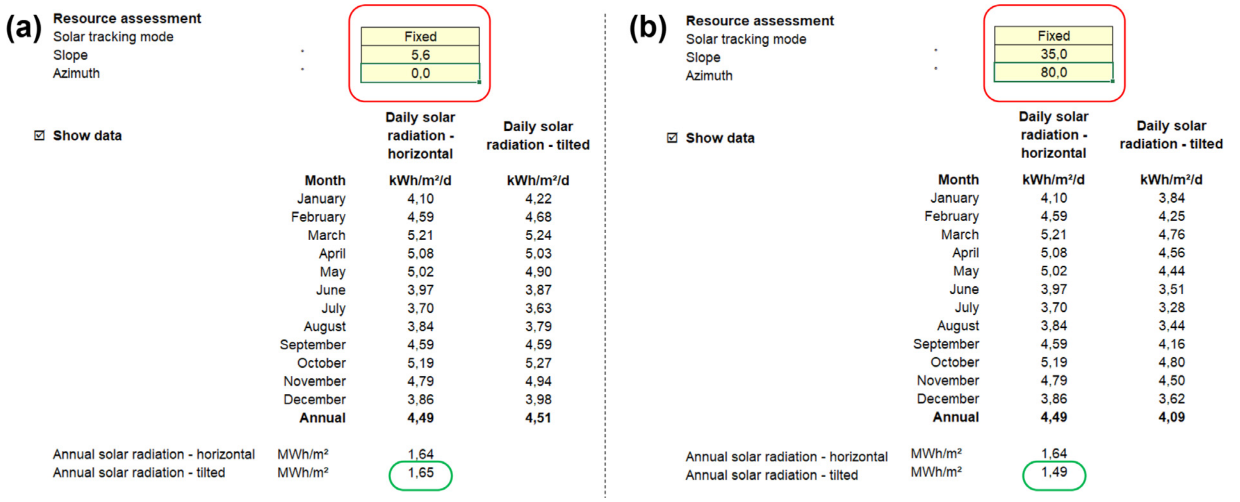
A study by Jacobson and Jadhav [27] used the National Renewable Energy Laboratory's PVWatts program to estimate for all countries in the world, the optimal tilt angles for fixed tilt solar PV panels, which corresponds to the tilt angle leading to the maximum annual average solar output. Though several West and Central African countries appear on the list, meteorological station data for the exercise were available only for two cities: Accra and Dakar. The obtained optimum tilt angles practically correspond to the latitude of these cities: Accra (latitude = 5.6° N, optimum tilt angle = 6°) and Dakar (latitude = 14.73° N, optimum tilt angle = 14°). The same study highlights the effect of atmospheric conditions such as cloudiness with remarkable differences at high latitudes, where two locations, practically at the same latitudes, namely Calgary (latitude = 51.12° N) and Beek (latitude = 50.92° N), have totally different optimum tilt angles (45° and 34°, respectively). Using data from NASA-SSE database, Njoku [28] also computed photovoltaic electricity generation potentials of 40 major cities in Nigeria and found that the optimum tilt angle for a year-round performance is β = latitude + 7.5°, facing south. He however concluded that positioning panels at that optimum fixed tilt angle does not lead to significant benefits as compared to horizontal installed panels.

It is to be noticed that we have not found investigations on optimum tilt angle determination based on an economic argument in the West and Central African region. One of the key points of these investigations elsewhere is related to the context of net metering schemes and feed-in-tariff, which are taking their first steps on the African continent [29]: grid operators may face difficulties if most PV producers choose the optimal tilt and orientation angles for a year-round power generation because most facilities would be peaking at the same time [30]. Readers who wish to learn more about the concepts may, for example, refer to Ref. [30–33].

Establishing an atlas for incident solar energy on a tilted surface in West and Central African capital cities

Methodology

We use RETScreen 4 clean energy project analysis software to map solar gains as a function of tilt and orientation of solar panels for major cities in Central and West Africa. The calculation of incident radiation of a tilted surface in RETScreen 4 is based on the Klein and Theilacker algorithm [34], described in the solar energy reference Solar Engineering of Thermal Processes [35]. For each site, the annual radiations for different orientations and tilt angles were recorded. The simulations were performed in 10° steps for orientation and 5° for tilt angle. First, the annual solar radiation I on tilted surface is determined using as input a slope corresponding to the local latitude, for azimuth angles ranging from −180° to 180° in steps of 10° The same approach is implemented for other values of the slope, from 0° to 90°, in 5° steps. The maximum



(a) Resource assessment

Solar tracking mode	Fixed
Slope	5,6
Azimuth	0,0

☑ Show data

Month	Daily solar radiation - horizontal kWh/m²/d	Daily solar radiation - tilted kWh/m²/d
January	4,10	4,22
February	4,59	4,68
March	5,21	5,24
April	5,08	5,03
May	5,02	4,90
June	3,97	3,87
July	3,70	3,63
August	3,84	3,79
September	4,59	4,59
October	5,19	5,27
November	4,79	4,94
December	3,86	3,98
Annual	**4,49**	**4,51**

Annual solar radiation - horizontal	MWh/m²	1,64
Annual solar radiation - tilted	MWh/m²	1,65

(b) Resource assessment

Solar tracking mode	Fixed
Slope	35,0
Azimuth	80,0

☑ Show data

Month	Daily solar radiation - horizontal kWh/m²/d	Daily solar radiation - tilted kWh/m²/d
January	4,10	3,84
February	4,59	4,25
March	5,21	4,76
April	5,08	4,56
May	5,02	4,44
June	3,97	3,51
July	3,70	3,28
August	3,84	3,44
September	4,59	4,16
October	5,19	4,80
November	4,79	4,50
December	3,86	3,62
Annual	**4,49**	**4,09**

Annual solar radiation - horizontal	MWh/m²	1,64
Annual solar radiation - tilted	MWh/m²	1,49

Fig. 5. Illustration of simulation steps in RETScreen 4 for Accra (latitude = 5.6° N): (a) The annual solar radiation on tilted surface using as input a slope of 5.6° is determined, for azimuth angles ranging from −180° to 180° in steps of 10°, i.e. of −180°, −170°, −160°, …170° and 180° (b) Then, 0° is used as input value for the slope and the annual solar radiation on tilted surface is determined again for azimuth angles ranging from −180° to 180° in steps of 10° And then, the value of slope is changed to 5°, and so on.

value[2] I_{max} obtained for each site is taken as a reference value. An illustration of the software interface with the city of Accra is provided in Fig. 5.

For each pair of orientation α and tilt angle β, the generated data allow the calculation of the recovery factor r for a given location: $r = I / I_{max}$, where:

I is the annual solar radiation on the surface with an orientation α and tilt angle β on a given site;
I_{max} is the maximum value of annual solar radiation obtained for the site.

The recovery factor r represents the percentage of the annual incident solar radiation for given orientation and tilt angles as compared to the maximum annual incident solar radiation. The maximum annual incident solar radiation obtained in Accra is I_{max} = 1646 kWh m^{-2} and the annual incident solar radiation for a surface with an orientation of 80° and a slope of 35° is I = 1494 kWh m^{-2} (Fig. 5). Therefore, r = 91%, which means that 9% of incident solar radiation is lost if a collector is orientated at 80° and tilted at 35° instead of an orientation of 0° with a tilt angle of 5.6° (which happens to be the local latitude in this case).

A discussion may arise regarding the preference of incident solar radiation objective function over another objective function, such as the energy generation or the solar system output. Yet, incident solar radiation objective function appears to be the most widely adopted by authors. It does not account for the effect of some parameters, such as the ambient temperature on the solar system performance, and hence, the optimal tilt angle. It has however been preferred because it appears neutral regarding solar thermal and solar PV since the efficiency of solar thermal collectors increases with temperature while that of PV decreases as the temperature increases. In addition, a comparison based on the performance of a PV module is limited by the fact that the extent of performance change with climatic conditions depends on the characteristics of the modules; hence a PV module that is suitable for the climatic conditions of Libreville (latitude = 0.5° N) is not necessary the relevant to consider for Niamey (latitude = 13.5° N). Anyway, lessons learnt from the literature (Section “Lessons learnt from the literature”) suggest that the conclusions achieved using either incident solar radiation objective function or energy generation or solar system output objective function are essentially the same.

Results

Fig. 6 presents the percentage of the annual reference solar irradiation arriving on a surface as a function of the orientation and inclination of the surface, for the capital cities in West and Central Africa. The cities are presented in ascending order of latitude. On the x-axis, the orientation changes from −180° (north) to 180° (north) passing through the east (−90°), the south (0°), and the west (90°). The name of the city, its latitude, the country, and the maximum annual incident solar irradiation are specified on the label. For example, for the city of Accra (Fig. 6e), the capital of Ghana, the maximum annual incident radiation is 1646 kWh m^{-2} year^{-1}. If the panel is orientated at 50° and tilted 25°, the reading on the map indi-

[2] The values of annual incident radiation do not change much, especially around the maximum so that the selected steps of 5° for tilt angle and 10° for orientation are fairly sufficient (consider the tables provided in Appendix).

cates that the annual incident radiation equals 96% of the maximum annual incident radiation, or 1580 kWh m^{-2} year^{-1}. The data shown on the diagrams are tabulated in Appendix.

Discussion

For locations close to the equator, the orientation is not very important, since the optimum slope is close to the horizontal. Thus, considering for example the city of Libreville (latitude = 0.5° N), for a given tilt angle (up to 20°), the solar irradiation is practically the same regardless of the orientation (Fig. 6a). When the slope is imposed and increases, east and west very quickly become the preferred orientations over the south. Thus, above a tilt angle of about 20°, orientation towards the east or the west is preferable to the orientation towards the south although the difference is small, the maximum of the collection difference being reached when the walls are vertical (Fig. 6a): a panel integrated into a vertical wall in Libreville will generate 25% more energy when it is east-facing than when it is south-facing, which corresponds however to only about 55% of expected irradiation in the classical optimal orientation and inclination conditions (Fig. 6a). Thus, for panels installed on house roofs in a locality close to the equator such as Libreville, east and west are to be considered when adopting the slope of the roofs for panels, especially for steep slopes. In such a context, the local climate, or a possible microclimate, can lead to prefer for photovoltaic:

- east-facing if the atmosphere is much dustier in the afternoon or if the temperature is much higher since the efficiency of a photovoltaic panel decreases when the temperature increases
- west-facing in the event of frequent morning mist

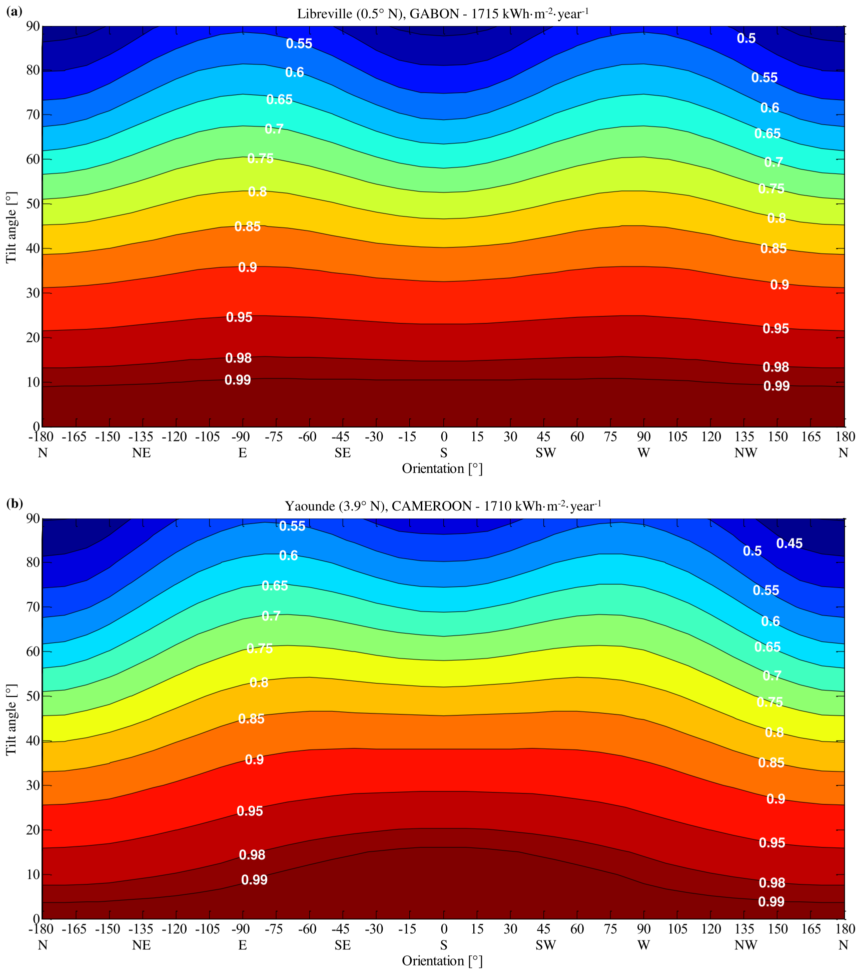


Fig. 6. Diagrams representing the ratio of incident solar radiation on a tilted surface to maximum incident solar radiation as a function of the adopted orientation and tilt angles. *N* = north, *S* = south, *W* = west and *E* = east.

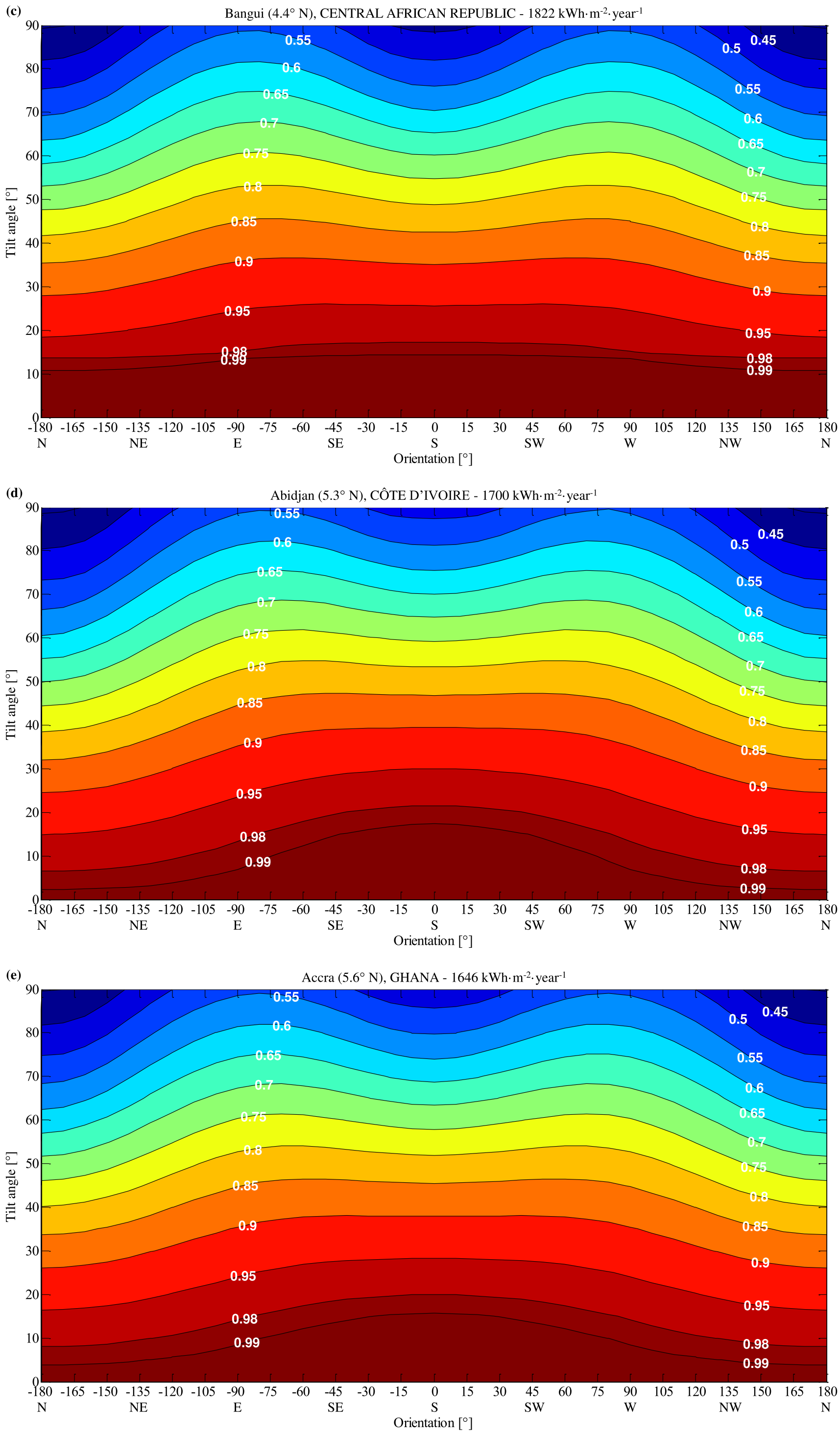


Fig. 6. Continued

For solar thermal, the efficiency of the collector increases with the ambient temperature; still, in the case where it is necessary to arbitrate between east-facing and west-facing, the decision would depend on the peak of hot water consumption and one would prefer:

- east-facing if hot water consumption is concentrated in the afternoon and evening
- west-facing if hot water need is to be met especially in the morning with storage.

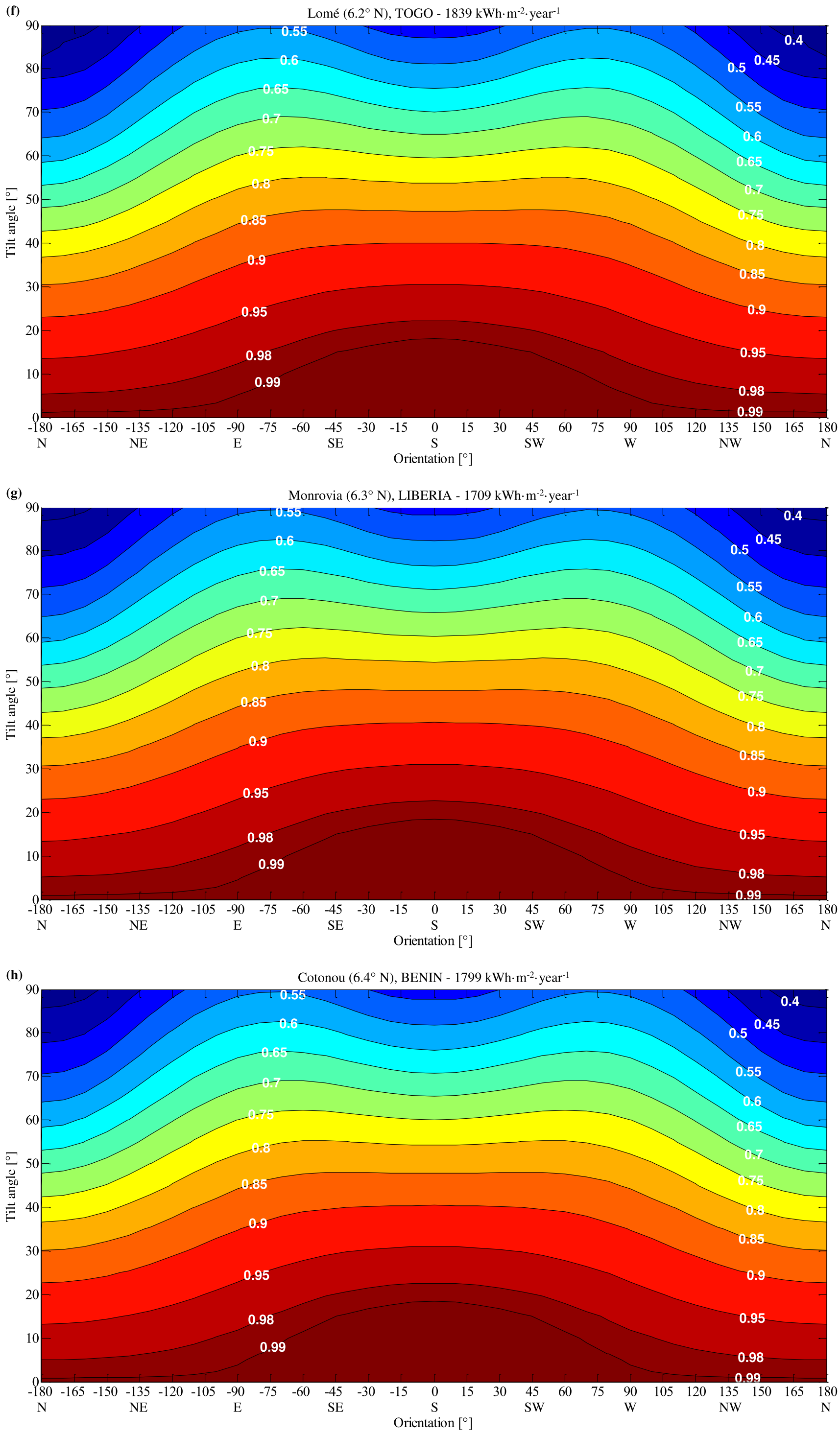


Fig. 6. Continued

When the tilt angle is imposed and greater than the latitude, the best orientation might not be south either. For example, in Lomé (latitude = 6.2° N, Fig. 6f), a panel tilted at 75° will receive 7% more energy when facing east instead of south. In particular, panels to be integrated into a vertical wall receive more irradiation when facing east or west. The panels thus face the sun in the morning or the afternoon. The gap narrows, however, as we move away from the equator, for example in Dakar (latitude = 14.7° N, Fig. 6p) where it drops to 1% under the same conditions, i.e. the annual incident radiation is basically the same when facing east, west or south under a tilt angle of 75°

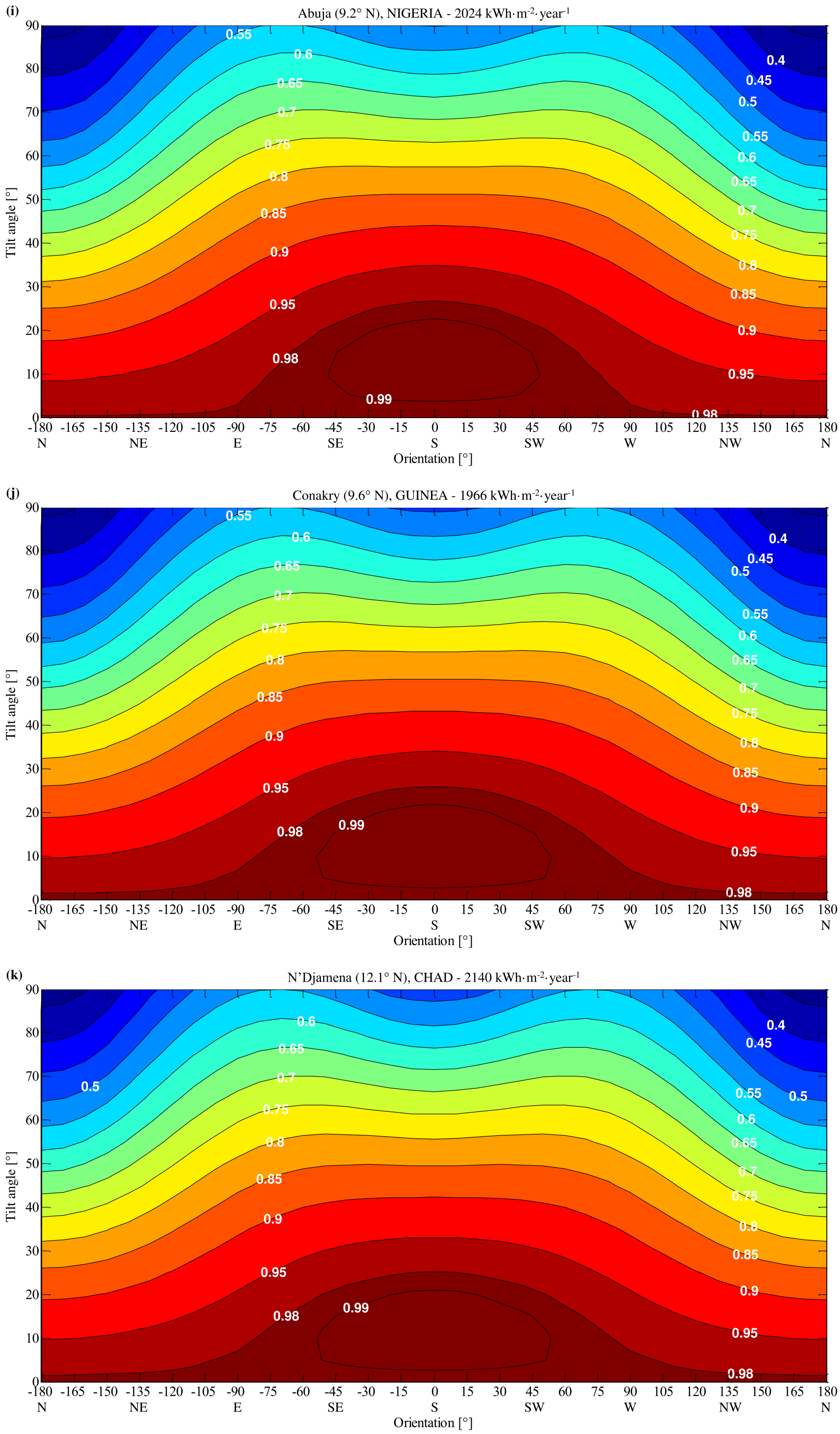


Fig. 6. Continued

More generally, it appears that a deviation of 20° from the classical optimal inclination and/or orientation (equator-facing orientation at a tilt angle equal to local latitude) leads to a maximum loss of 5% of the incident solar radiation on a panel. Furthermore, if one considers a minimum tilt angle of 10° to 15° as recommended for most installation in the investigated region to allow the flow of rainwater and the evacuation of objects and dust that could be deposited on the panel, the reduction of annual incident solar radiation is negligible (<5%) for any orientation starting from the east to the west via the south (orientation from −90° to +90°).

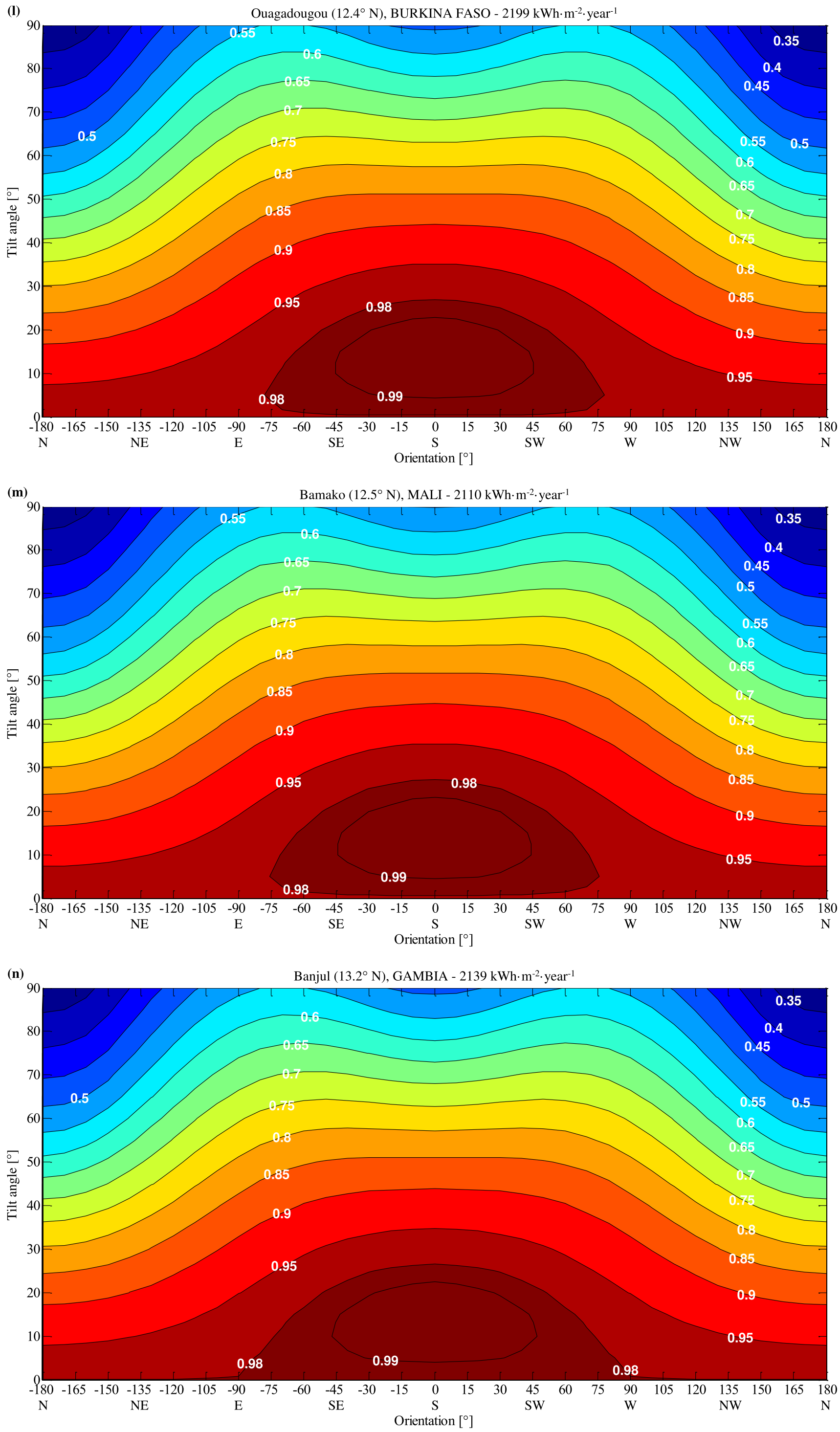


Fig. 6. Continued

In the particular situation where a system is to be used only or mostly in a defined timeframe, of course, the best orientation and tilt angle suited for that period is to be sought. Especially in the intertropical region, since the sun passes twice above any latitude, it is worth identifying the path of the sun in that period to determine the relevant orientation. Hence, for example, the collectors of the mango solar dryers as presented in the Introduction (Case 4) should be north-facing since, in Ouagadougou, solar radiations come from the northern direction between April 23rd and August 21st. Calculations

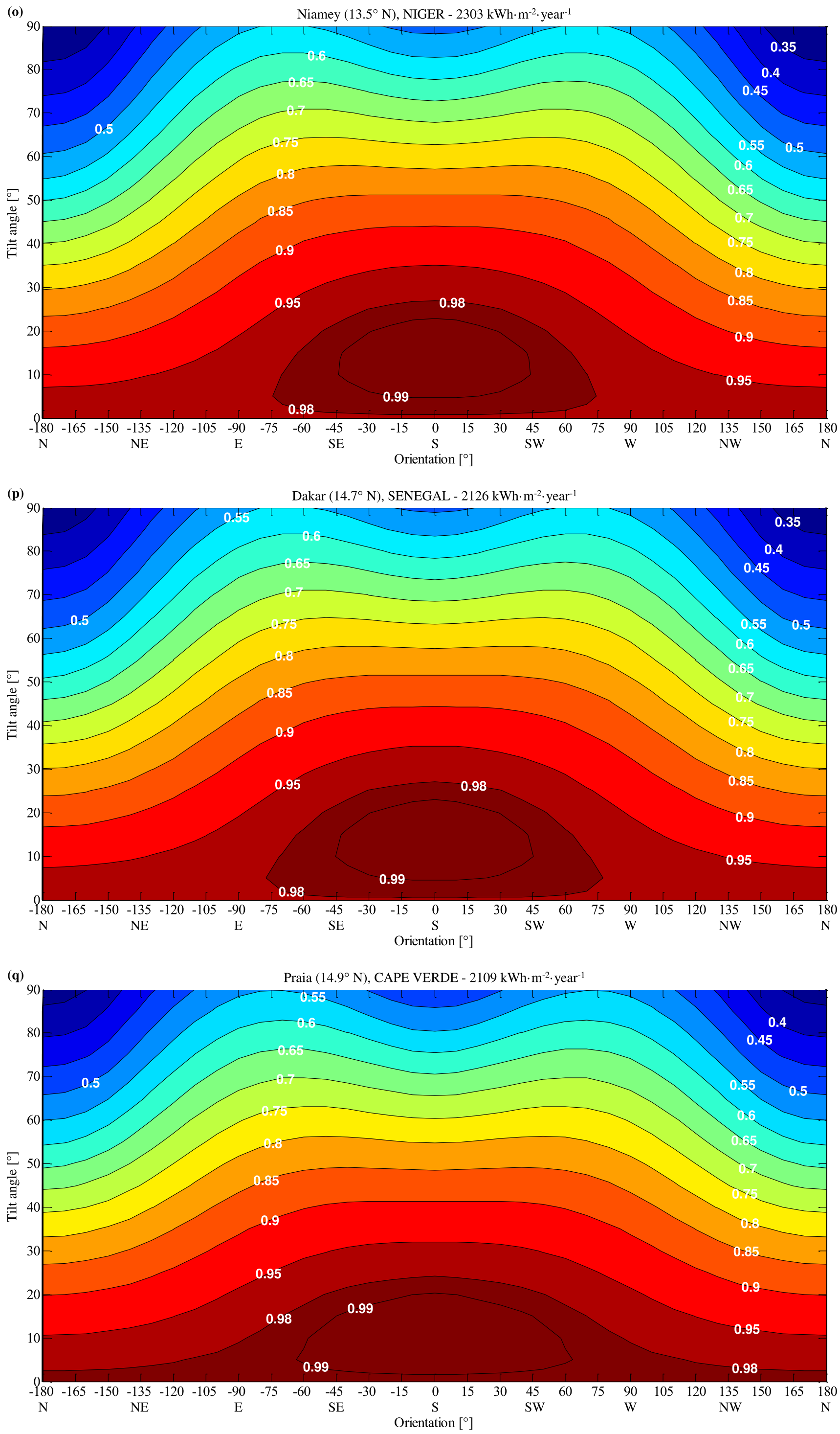


Fig. 6. Continued

indicate that the collector is receiving about 10% more solar irradiation in that position than if it were equator-facing with the tilt angle corresponding to the latitude.

Limitations of the study and remaining concerns

As already said, any optimisation problem (maximisation or minimisation), the relevance of the model, as well as the proper selection of the objective function and the variables to optimise, determine the quality of the results and estimations. This study has potential limitations, the most important of which is the use of RETScreen i.e. the model to estimate solar radiation on tilted surface. While RETScreen is widely used by researchers including in the region, there is a need to consider a model that better considers the specificity of the regional climatic conditions, especially the Harmattan haze implications, and, to a lesser extent, the cloudiness of the rainy equatorial region. This could be achieved through the use of statistical methods to compare and quantify the performance of the tilted surface transposition models, like the one performed by Nassar et al. [36] for the Middle East and North Africa region (MENA) through the analysis of 24 models.

Another aspect is the non-consideration of the tilt angle on the deposit of dust on the panels, a phenomenon that could be unfavourable for low tilt angles. Indeed, horizontal positions of the panels seem to be always promising in the region (Fig. 6) although performance losses could be expected from these positions due to dust deposit. So, the estimates assume panels installed with very regular cleaning.

Finally, as the presented curves in Fig. 6 are irradiation curves, they are symmetrical with respect to the south. The production curves would be slightly different if the ambient temperatures during the day (between sunrise and sunset) are not symmetrical with respect to solar noon since the performance of a solar panel is affected by the ambient temperature and afternoons may be warmer than mornings.

Conclusion

The usual recommendation for orientation to the equator and tilt to latitude should not be understood as a requirement that has a very significant impact on the installation, especially in the region studied. In West and Central Africa, a moderate deviation (up to 20°) from the optimal orientation and inclination does not significantly influence the incident solar radiation and therefore not the solar production. For some defined slopes, the optimal orientation is east or west. The construction of structures dedicated to solar installations or an architectural modification to comply with these recommendations is therefore generally not justified. We have compiled a set of diagrams and tables, which allow you to quickly determine the percentage of incident solar radiation on a solar collector based on its orientation and tilt relative to the classic optimal tilt and orientation. Of course, in the event of significant shading caused by obstacles, the atlas is no longer valid and simulations taking into account the obstacles as seen from the panel must be carried out.

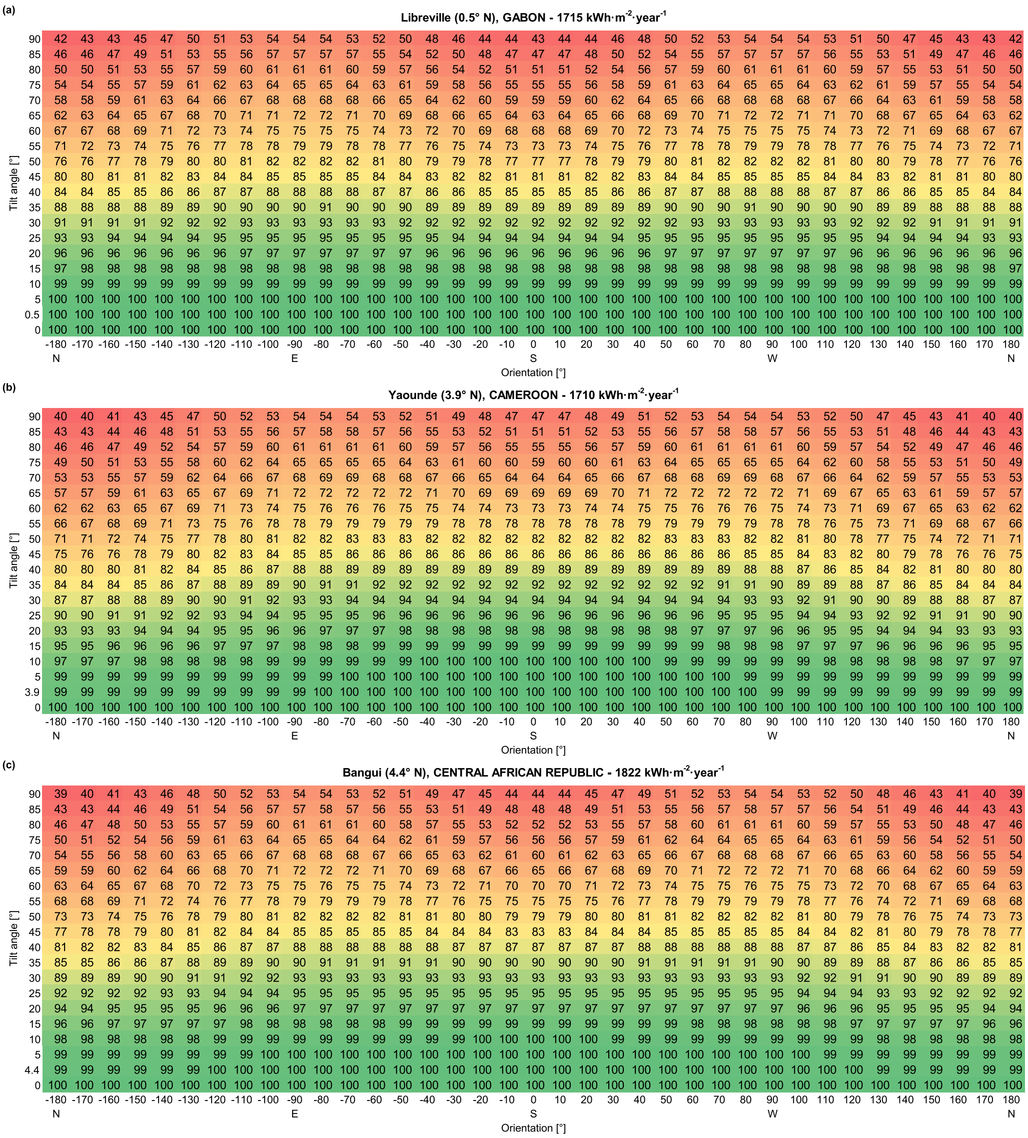
Funding statement

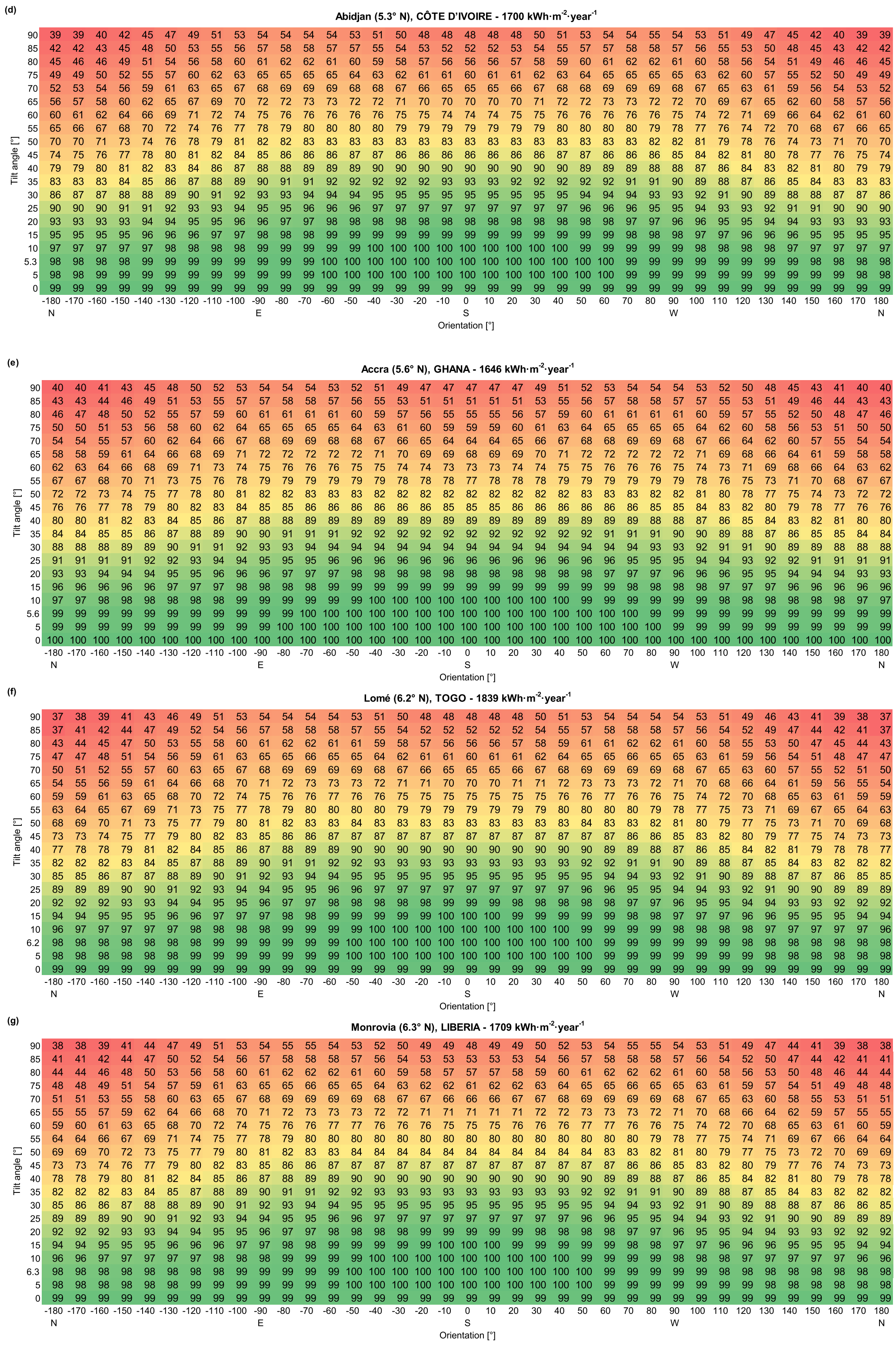
This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Declaration of Competing Interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix. Table representing the percentage (%) of the annual incident solar radiation according to the orientation and tilt angle as compared to the maximum annual incident solar radiation


(a)
Libreville (0.5° N), GABON - 1715 kWh·m-2·year-1
Tilt angle [°]
90 85 80 75 70 65 60 55 50 45 40 35 30 25 20 15 10 5 0.5 0
-180 -170 -160 -150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
N E S W N
Orientation [°]
(b)
Yaounde (3.9° N), CAMEROON - 1710 kWh·m-2·year-1
Tilt angle [°]
90 85 80 75 70 65 60 55 50 45 40 35 30 25 20 15 10 5 3.9 0
-180 -170 -160 -150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
N E S W N
Orientation [°]
(c)
Bangui (4.4° N), CENTRAL AFRICAN REPUBLIC - 1822 kWh·m-2·year-1
Tilt angle [°]
90 85 80 75 70 65 60 55 50 45 40 35 30 25 20 15 10 5 4.4 0
-180 -170 -160 -150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
N E S W N
Orientation [°]


(d)
Abidjan (5.3° N), CÔTE D'IVOIRE - 1700 kWh·m-2·year-1
Tilt angle [°]
Orientation [°]
N E S W N
(e)
Accra (5.6° N), GHANA - 1646 kWh·m-2·year-1
Tilt angle [°]
Orientation [°]
N E S W N
(f)
Lomé (6.2° N), TOGO - 1839 kWh·m-2·year-1
Tilt angle [°]
Orientation [°]
N E S W N
(g)
Monrovia (6.3° N), LIBERIA - 1709 kWh·m-2·year-1
Tilt angle [°]
Orientation [°]
N E S W N

(h)

Cotonou (6.4° N), BENIN - 1799 kWh·m^{-2}·year^{-1}

Tilt angle [°] \ Orientation [°]	-180 N	-170	-160	-150	-140	-130	-120	-110	-100	-90 E	-80	-70	-60	-50	-40	-30	-20	-10	0 S	10	20	30	40	50	60	70	80	90 W	100	110	120	130	140	150	160	170	180 N
90	37	38	39	41	43	46	49	51	53	54	55	55	54	53	52	50	49	48	48	48	49	50	52	53	54	55	55	54	53	51	49	46	43	41	39	38	37
85	40	41	42	44	47	49	52	54	56	57	58	58	58	57	56	54	53	52	52	52	53	54	56	57	58	58	58	57	56	54	52	49	47	44	42	41	40
80	43	44	45	47	50	53	55	58	60	61	62	62	62	61	60	58	57	57	57	57	57	58	60	61	62	62	62	61	60	58	55	53	50	47	45	44	43
75	47	47	48	51	53	56	59	61	63	65	65	66	65	65	64	63	62	61	61	61	62	63	64	65	65	66	65	65	63	61	59	56	53	51	48	47	47
70	50	51	52	54	57	60	63	65	67	68	69	69	69	69	68	67	66	66	66	66	66	67	68	69	69	69	69	68	67	65	63	60	57	54	52	51	50
65	54	55	56	58	61	64	66	68	70	71	72	73	73	73	72	72	71	71	70	71	71	72	72	73	73	73	72	71	70	68	66	64	61	58	56	55	54
60	58	59	61	63	65	67	70	72	74	75	76	76	77	77	76	76	75	75	75	75	75	76	76	77	77	76	76	75	74	72	70	67	65	63	61	59	58
55	63	64	65	67	69	71	73	75	77	78	79	80	80	80	80	80	80	79	79	79	80	80	80	80	80	80	79	78	77	75	73	71	69	67	65	64	63
50	68	68	70	71	73	75	77	79	80	81	82	83	83	84	84	84	83	83	83	83	83	84	84	84	83	83	82	81	80	79	77	75	73	71	70	68	68
45	73	73	74	75	77	79	80	82	83	85	86	86	87	87	87	87	87	87	87	87	87	87	87	87	87	86	86	85	83	82	80	79	77	75	74	73	73
40	77	77	78	79	81	82	84	85	86	87	88	89	89	90	90	90	90	90	90	90	90	90	90	90	89	89	88	87	86	85	84	82	81	79	78	77	77
35	81	82	82	83	84	85	87	88	89	90	91	91	92	92	93	93	93	93	93	93	93	93	93	92	92	91	91	90	89	88	87	85	84	83	82	82	81
30	85	85	86	86	87	88	89	90	91	92	93	94	94	95	95	95	95	95	95	95	95	95	95	95	94	94	93	92	91	90	89	88	87	86	86	85	85
25	89	89	89	90	90	91	92	93	94	94	95	95	96	96	97	97	97	97	97	97	97	97	97	96	96	95	95	94	94	93	92	91	90	90	89	89	89
20	92	92	92	92	93	93	94	95	95	96	97	97	98	98	98	98	99	99	99	99	99	98	98	98	98	97	97	96	95	95	94	93	93	92	92	92	92
15	94	94	94	95	95	95	96	96	97	97	98	98	99	99	99	99	99	100	100	100	99	99	99	99	99	98	98	97	97	96	96	95	95	95	94	94	94
10	96	96	96	97	97	97	97	98	98	98	99	99	99	99	100	100	100	100	100	100	100	100	100	99	99	99	99	98	98	98	97	97	97	97	96	96	96
6.4	98	98	98	98	98	98	98	98	99	99	99	99	99	100	100	100	100	100	100	100	100	100	100	100	99	99	99	99	99	98	98	98	98	98	98	98	98
5	98	98	98	98	98	98	98	99	99	99	99	99	99	100	100	100	100	100	100	100	100	100	100	100	99	99	99	99	99	99	98	98	98	98	98	98	98
0	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99

(i)

Abuja (9.2° N), NIGERIA - 2024 kWh·m^{-2}·year^{-1}

Tilt angle [°] \ Orientation [°]	-180 N	-170	-160	-150	-140	-130	-120	-110	-100	-90 E	-80	-70	-60	-50	-40	-30	-20	-10	0 S	10	20	30	40	50	60	70	80	90 W	100	110	120	130	140	150	160	170	180 N
90	33	34	35	37	40	44	47	50	52	54	55	55	55	54	53	52	50	50	50	50	50	52	53	54	55	55	55	54	52	50	47	44	40	37	35	34	33
85	36	36	37	40	43	47	50	53	55	57	58	59	59	58	57	56	55	54	54	54	55	56	57	58	59	59	58	57	55	53	50	47	43	40	37	36	36
80	39	39	40	43	46	50	53	56	59	61	62	63	63	62	61	60	59	59	59	59	59	60	61	62	63	63	62	61	59	56	53	50	46	43	40	39	39
75	42	42	44	46	50	53	57	60	62	64	66	66	67	66	66	65	64	64	64	64	64	65	66	66	67	66	66	64	62	60	57	53	50	46	44	42	42
70	45	46	47	50	53	57	60	63	66	68	69	70	70	70	70	70	69	69	68	69	69	70	70	70	70	70	69	68	66	63	60	57	53	50	47	46	45
65	49	49	51	54	57	60	64	67	69	71	73	74	74	74	74	74	74	73	73	73	74	74	74	74	74	74	73	71	69	67	64	60	57	54	51	49	49
60	53	53	55	58	61	64	67	70	72	75	76	77	78	78	78	78	78	78	78	78	78	78	78	78	78	77	76	75	72	70	67	64	61	58	55	53	53
55	57	58	60	62	65	68	71	73	76	78	79	80	81	82	82	82	82	82	82	82	82	82	82	82	81	80	79	78	76	73	71	68	65	62	60	58	57
50	62	63	64	66	69	72	74	77	79	81	82	84	84	85	85	86	86	86	86	86	86	86	85	85	84	84	82	81	79	77	74	72	69	66	64	63	62
45	67	68	69	71	73	75	78	80	82	84	85	87	87	88	89	89	89	89	89	89	89	89	89	88	87	87	85	84	82	80	78	75	73	71	69	68	67
40	72	72	74	75	77	79	81	83	85	87	88	89	90	91	91	92	92	92	92	92	92	92	91	91	90	89	88	87	85	83	81	79	77	75	74	72	72
35	77	77	78	79	81	82	84	86	88	89	90	92	93	93	94	94	95	95	95	95	95	94	94	93	93	92	90	89	88	86	84	82	81	79	78	77	77
30	81	81	82	83	84	86	87	89	90	91	93	94	95	95	96	96	97	97	97	97	97	96	96	95	95	94	93	91	90	89	87	86	84	83	82	81	81
25	85	85	86	86	87	89	90	91	92	93	94	95	96	97	97	98	98	98	99	98	98	98	97	97	96	95	94	93	92	91	90	89	87	86	86	85	85
20	89	89	89	90	90	91	92	93	94	95	96	97	97	98	99	99	99	99	100	99	99	99	99	98	97	97	96	95	94	93	92	91	90	90	89	89	89
15	92	92	92	92	93	94	94	95	96	96	97	98	98	99	99	99	100	100	100	100	100	99	99	99	98	98	97	96	96	95	94	94	93	92	92	92	92
10	94	94	94	95	95	95	96	96	97	97	98	98	99	99	99	100	100	100	100	100	100	100	99	99	99	98	98	97	97	96	96	95	95	95	94	94	94
9.2	95	95	95	95	95	96	96	97	97	97	98	98	99	99	99	100	100	100	100	100	100	100	99	99	99	98	98	97	97	97	96	96	95	95	95	95	95
5	96	96	97	97	97	97	97	97	98	98	98	98	99	99	99	99	99	99	99	99	99	99	99	99	99	98	98	98	98	97	97	97	97	97	97	96	96
0	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98

(j)

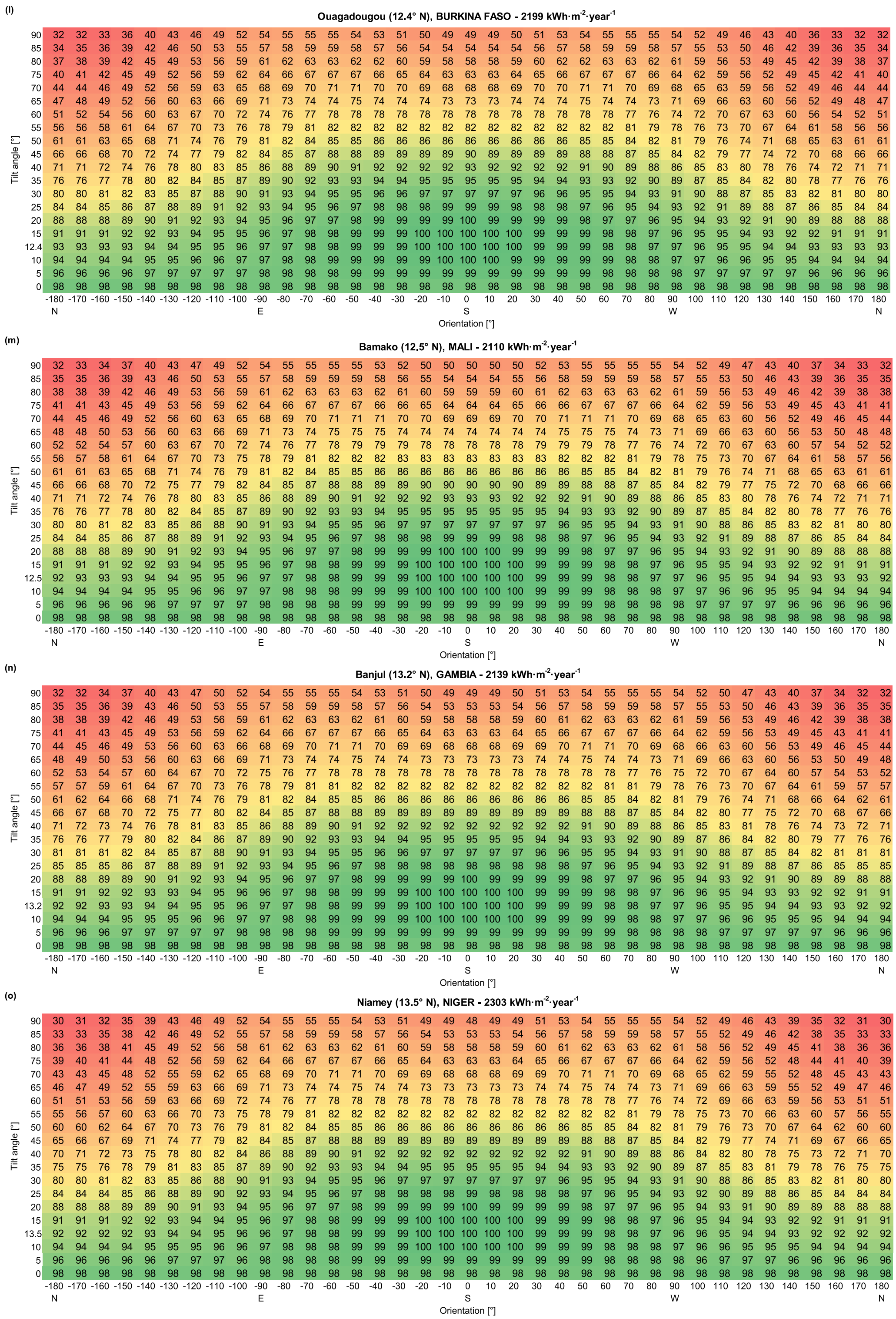
Conakry (9.6° N), GUINEA - 1966 kWh·m^{-2}·year^{-1}

Tilt angle [°] \ Orientation [°]	-180 N	-170	-160	-150	-140	-130	-120	-110	-100	-90 E	-80	-70	-60	-50	-40	-30	-20	-10	0 S	10	20	30	40	50	60	70	80	90 W	100	110	120	130	140	150	160	170	180 N
90	34	34	36	38	41	44	47	50	52	54	55	55	55	54	53	51	50	49	49	49	50	51	53	54	55	55	55	54	52	50	47	44	41	38	36	34	34
85	37	37	38	41	44	47	50	53	56	57	58	59	59	58	57	55	54	54	53	54	54	55	57	58	59	59	58	57	56	53	50	47	44	41	38	37	37
80	39	40	41	44	47	51	54	57	59	61	62	63	63	62	61	60	59	58	58	58	59	60	61	62	63	63	62	61	59	57	54	51	47	44	41	40	39
75	43	43	44	47	51	54	57	60	62	64	66	66	66	66	65	65	64	63	63	63	64	65	65	66	66	66	66	64	62	60	57	54	51	47	44	43	43
70	46	47	48	51	54	57	61	63	66	68	69	70	70	70	70	69	68	68	68	68	68	69	70	70	70	70	69	68	66	63	61	57	54	51	48	47	46
65	50	50	52	55	58	61	64	67	69	71	73	74	74	74	74	73	73	73	73	73	73	73	74	74	74	74	73	71	69	67	64	61	58	55	52	50	50
60	54	54	56	59	62	65	68	70	73	75	76	77	78	78	78	78	77	77	77	77	77	78	78	78	78	77	76	75	73	70	68	65	62	59	56	54	54
55	58	59	61	63	66	69	71	74	76	78	79	80	81	81	82	82	82	82	81	82	82	82	82	81	81	80	79	78	76	74	71	69	66	63	61	59	58
50	63	64	65	67	70	72	75	77	79	81	83	84	84	85	85	85	85	85	85	85	85	85	85	85	84	84	83	81	79	77	75	72	70	67	65	64	63
45	68	69	70	72	74	76	78	80	82	84	86	87	87	88	88	89	89	89	89	89	89	89	88	88	87	87	86	84	82	80	78	76	74	72	70	69	68
40	73	74	75	76	78	80	82	83	85	87	88	89	90	91	91	92	92	92	92	92	92	92	91	91	90	89	88	87	85	83	82	80	78	76	75	74	73
35	78	78	79	80	81	83	85	86	88	89	91	92	93	93	94	94	94	95	95	95	94	94	94	93	93	92	91	89	88	86	85	83	81	80	79	78	78
30	82	82	83	84	85	86	88	89	90	92	93	94	95	95	96	96	96	97	97	97	96	96	96	95	95	94	93	92	90	89	88	86	85	84	83	82	82
25	86	86	86	87	88	89	90	91	93	94	95	95	96	97	97	98	98	98	98	98	98	98	97	97	96	95	95	94	93	91	90	89	88	87	86	86	86
20	89	89	90	90	91	92	93	94	94	95	96	97	98	98	99	99	99	99	99	99	99	99	99	98	98	97	96	95	94	94	93	92	91	90	90	89	89
15	92	92	93	93	93	94	95	95	96	97	97	98	98	99	99	99	100	100	100	100	100	99	99	99	98	98	97	97	96	95	95	94	93	93	93	92	92
10	95	95	95	95	96	96	96	97	97	98	98	98	99	99	99	100	100	100	100	100	100	100	99	99	99	98	98	98	97	97	96	96	96	95	95	95	95
9.6	95	95	95	95	96	96	96	97	97	98	98	98	99	99	99	100	100	100	100	100	100	100	99	99	99	98	98	98	97	97	96	96	96	95	95	95	95
5	97	97	97	97	97	97	98	98	98	98	98	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	98	98	98	98	98	97	97	97	97	97	97
0	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98

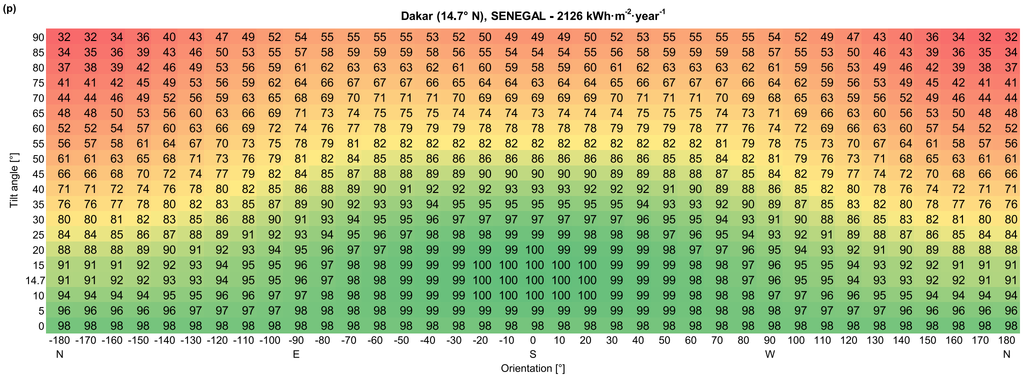
(k)

N'Djamena (12.1° N), CHAD - 2140 kWh·m^{-2}·year^{-1}

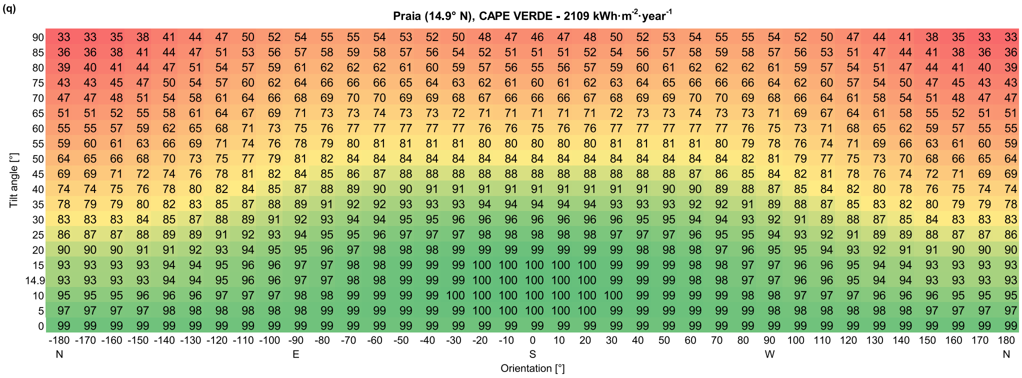
Tilt angle [°] \ Orientation [°]	-180 N	-170	-160	-150	-140	-130	-120	-110	-100	-90 E	-80	-70	-60	-50	-40	-30	-20	-10	0 S	10	20	30	40	50	60	70	80	90 W	100	110	120	130	140	150	160	170	180 N
90	33	33	35	37	41	44	47	50	52	54	55	55	55	54	52	50	49	48	48	48	49	50	52	54	55	55	55	54	52	50	47	44	41	37	35	33	33
85	36	36	37	40	44	47	50	53	56	57	58	59	58	58	56	55	53	52	52	52	53	55	56	58	58	59	58	57	56	53	50	47	44	40	37	36	36
80	39	39	40	43	47	50	54	57	59	61	62	62	62	62	61	59	58	57	56	57	58	59	61	62	62	62	62	61	59	57	54	50	47	43	40	39	39
75	42	42	44	47	50	54	57	60	62	64	66	66	66	66	65	64	63	62	61	62	63	64	65	66	66	66	66	64	62	60	57	54	50	47	44	42	42
70	46	46	47	50	54	57	60	63	66	68	69	70	70	70	69	68	68	67	67	67	68	68	69	70	70	70	69	68	66	63	60	57	54	50	47	46	46
65	49	50	51	54	57	61	64	67	69	71	73	74	74	74	73	73	72	72	72	72	72	73	73	74	74	74	73	71	69	67	64	61	57	54	51	50	49
60	54	54	56	58	61	65	68	70	73	75	76	77	78	78	77	77	77	76	76	76	77	77	77	78	78	77	76	75	73	70	68	65	61	58	56	54	54
55	58	59	60	63	65	68	71	74	76	78	79	80	81	81	81	81	81	81	81	81	81	81	81	81	81	80	79	78	76	74	71	68	65	63	60	59	58
50	63	64	65	67	70	72	75	77	79	81	83	84	84	85	85	85	85	85	85	85	85	85	85	85	84	84	83	81	79	77	75	72	70	67	65	64	63
45	68	69	70	71	74	76	78	80	82	84	86	87	87	88	88	88	88	88	88	88	88	88	88	88	87	87	86	84	82	80	78	76	74	71	70	69	68
40	73	73	74	76	77	79	81	83	85	87	88	89	90	91	91	91	91	91	91	91	91	91	91	91	90	89	88	87	85	83	81	79	77	76	74	73	73
35	78	78	79	80	81	83	85	86	88	89	91	92	92	93	94	94	94	94	94	94	94	94	94	93	92	92	91	89	88	86	85	83	81	80	79	78	78
30	82	82	83	84	85	86	88	89	90	92	93	94	94	95	96	96	96	96	96	96	96	96	96	95	94	94	93	92	90	89	88	86	85	84	83	82	82
25	86	86	86	87	88	89	90	91	93	94	95	95	96	97	97	98	98	98	98	98	98	98	97	97	96	95	95	94	93	91	90	89	88	87	86	86	86
20	89	89	90	90	91	92	93	94	94	95	96	97	98	98	99	99	99	99	99	99	99	99	99	98	98	97	96	95	94	94	93	92	91	90	90	89	89
15	92	92	93	93	93	94	95	95	96	97	97	98	98	99	99	99	100	100	100	100	100	99	99	99	98	98	97	97	96	95	95	94	93	93	93	92	92
12.1	94	94	94	94	95	95	96	96	97	97	98	98	99	99	99	100	100	100	100	100	100	100	99	99	99	98	98	97	97	96	96	95	95	94	94	94	94
10	95	95	95	95	96	96	96	97	97	98	98	98	99	99	99	100	100	100	100	100	100	100	99	99	99	98	98	98	97	97	96	96	96	95	95	95	95
5	97	97	97	97	97	97	98	98	98	98	98	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	98	98	98	98	98	97	97	97	97	97	97
0	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98


(l)
Ouagadougou (12.4° N), BURKINA FASO - 2199 kWh·m-2·year-1
Tilt angle [°]
Orientation [°]
N E S W N
(m)
Bamako (12.5° N), MALI - 2110 kWh·m-2·year-1
Tilt angle [°]
Orientation [°]
N E S W N
(n)
Banjul (13.2° N), GAMBIA - 2139 kWh·m-2·year-1
Tilt angle [°]
Orientation [°]
N E S W N
(o)
Niamey (13.5° N), NIGER - 2303 kWh·m-2·year-1
Tilt angle [°]
Orientation [°]
N E S W N

(p)



(q)



References

[1] N'Tsoukpoe K.E. Effet des angles d'inclinaison et d'orientation des capteurs solaires sur leur production: cas des capitales des pays d'Afrique de l'Ouest et du Centre 2016]. Available from: www.ecowrex.org/system/files/ntsoukpoe_-_orientation_des_capteurs_solaires.pdf.

[2] K.E. Kanyarusoke, J. Gryzagoridis, G. Oliver, Are solar tracking technologies feasible for domestic applications in rural tropical Africa? J. Energy South Afr. 26 (2015) 86–95.

[3] T. Berrill, A. Blair, Solar Water Heater Training course, Installer and User Manual, Australian Business Council for Sustainable Energy, 2007]Available from: http://waterheatertimer.org/pdf/Solar-water-heater-Installation-manual.pdf .

[4] Pacific Power Association (PPA), Sustainable Energy Industry Association of the Pacific Islands (SEIAPI). Solar water heaters selection and installation guidelines 2019 [cited 23 octobre 2021]. Available from: www.ppa.org.fj/wp-content/uploads/2020/10/Solar-Water-Heaters-Guidelines-V1-Aug-2019.pdf.

[5] AEE – Institute for Sustainable Technologies. Dimensioning and design of solar thermal systems s. d. [cited 23 octobre 2021]. Available from: www.crses.sun.ac.za/files/services/events/workshops/Dimensioning%20of%20ST%20Systems.pdf.

[6] Federal Republic of NigeriaFederal Republic of Nigeria National Building Code, LexisNexis, Durban, South Africa, 2006]Available from: https://epp.lagosstate.gov.ng/regulations/National_Building_Code_of_Nigeria_2006.pdf .

[7] K.A. Gyimah, Solar Photovoltaic installation cost reduction through building integrated photovoltaics in Ghana, J. Energy Nat. Resour. Manag. JENRM 1 (2014).

[8] Ikedi C. Barriers and Strategies for Building Integrated Photovoltaics (BIPV), 2010.

[9] A. Batagarawa, Y.A. Abdulkarim, M.L. Sagada, Optimizing building form for integration of solar photovoltaic in the design of a textile industry in Katsina, Nigeria, in: A Sayigh (Ed.), Renew. Energy Sustain. Build. Sel. Pap. World Renew. Energy Congr. WREC 2018, Springer International Publishing, Cham, 2020, p. 257–79, doi:10.1007/978-3-030-18488-9_20. [cited 19 juin 2021]. Available from:.

[10] 3E. Technical due diligence for Sterling Bank's BIPV project s. d. [cited 19 juin 2021]. Available from: https://3e.eu/projects/technical-due-diligence-sterling-banks-bipv-project.

[11] O.A. Ogunseitan, Harmattan haze and environmental health, Afr. J. Environ. Sci. Technol. 1 (2007) F5F958211359.

[12] Y.N. Chanchangi, A. Ghosh, S. Sundaram, T.K. Mallick, Dust and PV performance in Nigeria: a review, Renew. Sustain. Energy Rev. 121 (2020) 109704.

[13] T.Y. Tanaka, M. Chiba, A numerical study of the contributions of dust source regions to the global dust budget, Glob. Planet Change 52 (2006) 88–104.

[14] H.O. Njoku, Upper-limit solar photovoltaic power generation: estimates for 2-axis tracking collectors in Nigeria, Energy 95 (2016) 504–16.

[15] C.O. Okoye, A. Bahrami, U. Atikol, Evaluating the solar resource potential on different tracking surfaces in Nigeria, Renew. Sustain. Energy Rev. 81 (2018) 1569–81.

[16] E.O. Ogundimu, E.T. Akinlabi, C.A. Mgbemene, Maximizing The Output Power Harvest Of A Pv Panel: a Critical Review, J. Phys. Conf. Ser. 1378 (2019) 032054.

[17] Diallo A.S. Investigation of the effect of the inclination and dust deposit on the performance of PV modules at Kamboinsé (campus of 2iE) [Etude de l'influence de l'inclinaison et des dépôts de poussière sur les performances des modules PV à Kamboinsé (site du 2iE)]. Master thesis. International Institute for Water and Environmental Engineering, 2010]. Available from: http://documentation.2ie-edu.org/cdi2ie/opac_css/doc_num.php?explnum_id=260.

[18] Rey-Stolle I. Fundamentals of photovoltaic cells and systems. Sol. Energy, vol. Volume 2, WORLD SCIENTIFIC; 2015, p. 31–67 [cited 24 octobre 2021]. Available from: https://www.worldscientific.com/doi/abs/10.1142/9789814689502_0002.

[19] J. Page, Chapter II-1-A - the role of solar-radiation climatology in the design of photovoltaic systems, in: SA Kalogirou (Ed.), McEvoys Handb. Photovolt, 3rd Ed., Academic Press, 2018, p. 601–70. https://www.sciencedirect.com/science/article/pii/B9780128099216000161. [cited 24 octobre 2021]. Available from:.

[20] N. Phadnis, R.J. Yang, P.U. Wijeratne, H. Zhao, C. Liu, The impact of solar PV design tilt and orientation on project values, in: P Kaparaju, RJ Howlett, J Littlewood, C Ekanyake, L Vlacic (Eds.), Sustain. Energy Build, Springer International Publishing, Cham, 2019, p. 301–10. 2018.
[21] F. Jafarkazemi, S. Ali Saadabadi, H Pasdarshahri, The optimum tilt angle for flat-plate solar collectors in Iran, J. Renew. Sustain. Energy 4 (2012) 013118.
[22] A.K. Yadav, S.S. Chandel, Tilt angle optimization to maximize incident solar radiation: a review, Renew. Sustain. Energy Rev. 23 (2013) 503–13.
[23] G. Lewis, Optimum tilt of a solar collector, Sol Wind Technol 4 (1987) 407–10.
[24] M.T. Oladiran, Total solar radiation received at various collector inclinations, Appl. Energy 48 (1994) 149–61.
[25] M.T. Oladiran, Mean global radiation captured by inclined collectors at various surface azimuth angles in Nigeria, Appl. Energy 52 (1995) 317–30.
[26] H. Zang, M. Guo, Z. Wei, G. Sun, Determination of the optimal tilt angle of solar collectors for different climates of China, Sustainability 8 (2016) 654.
[27] M.Z. Jacobson, V. Jadhav, World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels, Sol. Energy 169 (2018) 55–66.
[28] H.O. Njoku, Solar Photovoltaic Potential in Nigeria, J. Energy Eng. 140 (2014) 04013020.
[29] M. Meyer-Renschhausen, Evaluation of feed-in tariff-schemes in African countries, J Energy South Afr 24 (2012).
[30] E. Sánchez, J. Izard, Performance of photovoltaics in non-optimal orientations: an experimental study, Energy Build. 87 (2015) 211–9.
[31] I.H. Rowlands, B.P. Kemery, Beausoleil-Morrison I. Optimal solar-PV tilt angle and azimuth: an Ontario (Canada) case-study, Energy Policy 39 (2011) 1397–409.
[32] R. Tybout, G. Lof, Solar house heating, Nat. Resour. J. 10 (1970) 268.
[33] G.O.G. Löf, R.A. Tybout, Cost of house heating with solar energy, Sol. Energy 14 (1973) 253–78.
[34] RETScreen® International Clean Energy Decision Support CentreClean Energy Project Analysis: RETScreen Engineering & Cases. Photovoltaic project Model, 3e éd., Natural Resources Canada, Québec: Quebec, 2005 [cited 1 juin 2021]. Available from: http://msessd.ioe.edu.np/wp-content/uploads/2017/04/Textbook-clean-energy-project-analysis.pdf .
[35] J.A. Duffie, W.A. Beckman, Solar Engineering of Thermal Processes, 2e éd., John Wiley & Sons, New York, USA, 1991.
[36] Y.F. Nassar, A.A. Hafez, Alsadi SY, Multi-factorial comparison for 24 distinct transposition models for inclined surface solar irradiance computation in the state of palestine: a case study, Front. Energy Res. 7 (2020).