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Forecasted Changes in West Africa Photovoltaic Energy Output by 2045

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Abstract: The impacts of climate change on photovoltaic (PV) output in the fifteen countries of the Economic Community of West African States (ECOWAS) was analyzed in this paper. Using a set of eight climate models, the trends of solar radiation and temperature between 2006–2100 were examined. Assuming a lifetime of 40 years, the future changes of photovoltaic energy output for the tilted plane receptor compared to 2006–2015 were computed for the whole region. The results show that the trends of solar irradiation are negative except for the Irish Centre for High-End Computing model which predicts a positive trend with a maximum value of 0.17 W/m^2/year for Cape Verde and the minimum of -0.06 W/m^2/year for Liberia. The minimum of the negative trend is -0.18 W/m^2/year predicted by the Model for Interdisciplinary Research on Climate (MIROC), developed at the University of Tokyo Center for Climate System Research for Cape Verde. Furthermore, temperature trends are positive with a maximum of 0.08 K/year predicted by MIROC for Niger and minimum of 0.03 K/year predicted by Nature Conservancy of Canada (NCC), Max Planck Institute (MPI) for Climate Meteorology at Hamburg, French National Meteorological Research Center (CNRM) and Canadian Centre for Climate Modelling and Analysis (CCCMA) for Cape Verde. Photovolataic energy output changes show increasing trends in Sierra Leone with 0.013%/year as the maximum. Climate change will lead to a decreasing trend of PV output in the rest of the countries with a minimum of 0.032%/year in Niger.

Keywords: climate model; solar radiation; ambient air temperature changes; solar photovoltaic energy output; ECOWAS

1. Introduction

Renewable energies are considered the solutions for sustainable and clean energies. The importance of this key point led to the creation of the Centre for Renewable Energy and Energy Efficiency (ECREEE) by the Economic Community of West African States (ECOWAS) in 2010 [1]. Nevertheless, with climate changes mainly due to anthropic actions, variables that contribute to the production of these kinds of energies may change over the time. In this study, impacts of future climatic changes on the photovoltaic (PV) energy are investigated for West African countries. The most important variable in PV energy, compared with other local climatic and environmental factors such as extreme temperature, humidity, precipitation, and wind, is irradiation intensity [2]. In addition, Wild et al. [3] suggest that changes in ambient temperatures have to be taken into account, since increasing ambient temperatures negatively affect PV energy output. Concerning the irradiation intensity, as the cloud and the aerosol concentration change mainly due to the carbon dioxide concentration in the atmosphere, solar radiation that reaches the earth's surface may change over time. Many authors [4–6] have already shown the changes in surface air temperature.

The electricity generated by solar photovoltaic modules is showing quick growth, with an expected capacity of 135 GW to be installed by the end of 2013 worldwide [7] and more than 150 GW in 2014 [8], for example. Thus, the photovoltaic industry is one of the fastest growing industries at present [7]. Based on this trend, large-scale projects are planned for the region. Table 1 presents some of the planned PV projects in the ECOWAS region. Secondly, this region, like all of the inter-tropical belt, is considered a "hot-spot"and is more sensitive and vulnerable to impacts of climate change.

Table 1. Planned photovoltaic (PV) projects in Economic Community of West African States (ECOWAS).

N°	Name	Size	Location	Cost
1 *	Solar Power Plant 1	5.9 MW	Kandi, Northern region of Benin	€17.8 million
2 *	Solar Power Plant 2	5 MW	Djougou, Northern region of Benin	Not specified
3 **	Zagtouli Plant	22 MW	Ouagadougou, Burkina Faso	Not specified
4 **	Nzema Solar PV park	155 MW	Awoso, Ghana	Not specified
5 *	Togo Solar Power Plant	5 MW	Kara, Northern region of Togo	Not specified
6 *	Gambia Solar PV	20 MW	Birkama, West Coast region of Gambia	$42 million
7 *	Ghana Solar PV	12 MW	Not specified	€30 million
8 **	Tenergie Senegal PV project	50 MW	Tailf, Darou and Merina, Senegal	Not specified
9 **	Ivory Coast Scatec Solar PV park	45 MW	North Ivory Coast	Not specified
10 **	Akuo Energy Mali Solar Projects	41 MW	Kita, Kangaba, Mali	Not specified

* Economic Community of West African Renewable Energy Investment Week [9]; ** [10].

All of the planned or existing large-scale projects of PV energy production by ECOWAS may not respond like the other large-scale PVs all over the world due to climate differences.

According to Schaeffer et al. [11], climate impact assessment for energy systems constitutes a relatively new research field so an increasing number of studies in this field are needed. Indeed, from 2009 to 2015, some pioneering results are produced. Pryor and Barthelmie [12] examined climate change impacts on wind energy and provided a review of the available scientific literature on the subject. They found that up to the middle of the current century, natural variability will exceed the climate change signal in the wind energy resources and extreme wind speeds, but there will likely be a decline in icing frequency and sea ice, both of which will tend to benefit the wind energy industry. By the end of the twenty-first century, there is evidence for small magnitude changes in the wind resources (though the sign of the change remains uncertain), increases in extreme wind speeds, and continued declines in sea ice and icing frequencies. Kopytko and Perkins [13] investigated several ways in which climate change may affect water in ways that create issues for existing nuclear power plants by using two major criteria. Their study reveals that inland and coastal nuclear power plants present several weaknesses. Safety stands out as the primary concern at coastal locations, while inland locations encounter greater problems with interrupted operation. Adapting nuclear power to climate change entails either increased expenses for construction and operation or incurs significant costs to the environment and public health and welfare. The vulnerabilities of renewable energy production in Brazil for the cases of hydro-power generation and liquid biofuels production, given a set of long-term climate projections for the A2 and B2 IPCC emission scenarios, are analyzed by Lucena et al. [14]. Their main conclusion is that the most important result found in this study is the increasing energy vulnerability of the poorest regions of Brazil to global climate change. Both biofuel production and electricity generation may negatively suffer from changes in the climates of those regions. Other renewable energy sources such as wind power generation may also be vulnerable, raising the need for further research. The examination of the role of renewable energy in climate change mitigation through a review of 162 recent medium- to long-term scenarios from 15 large-scale, energy economic and integrated assessment models has been performed by Krey and Clarke [15]. The relationship between the climate change and the electricity market was also explored by Mideksa and Kallbekken [16]. They conclude that, in general, higher temperatures are expected to raise electricity demand for cooling, decrease demand for heating, and reduce electricity production from thermal power plants. The effect of climate change on the supply of electricity from non-thermal sources shows great geographical variability due to differences in expected changes to temperature and precipitation.

However, as mentioned by Wild et al. [3] and Gaetani et al. [17], few previous works dealt with the future potential of PV systems. The impact of climate change on photovoltaic energy production has also been under evaluated as compared with hydro and wind power Schaeffer et al. [11]. Remund and Müller [18] presented solar radiation changes as projected with an earlier generation of climate models at the 10th European Conference on Applications of Meteorology (ECAM) using a total of 25 sites based on the Global Energy Balance Archive and the results of the fourth report of the IPCC. The results show that for the total period of 1950–2009 and all sites, a negative and statistically significant trend of -1.4 W/m^2 per decade could be found. For most grouped sites, no significant trend is visible. The forecasted changes of global radiation until 2100 for all scenarios are relatively small compared to temperature changes. They are in the range of one tenth of a percent to some percents. Crook et al. [19] used two versions of the Hadley Centre for Climate Prediction climate model to assess their projected changes in climate variables of relevance for solar power production. They have shown that PV output from 2010 to 2080 is likely to increase by a few percent in Europe and China, see little change in Algeria and Australia, and decrease by a few percent in western USA and Saudi Arabia. Concentrating Solar Plant (CSP) output is likely to increase by more than 10% in Europe, increase by several percent in China and a few percent in Algeria and Australia, and decrease by a few percent in western USA and Saudi Arabia. Using five regional climate models from the EU ENSEMBLES project, Panagea et al. [20] examined the projected changes in irradiance and temperature on the performance of photovoltaic systems in Greece.They found that the spatiotemporal analysis indicates a significant increase in mean annual temperature and mean total radiation by 2100. The performance of photovoltaic systems exhibits a negative linear dependence on the projected temperature increase, which is outweighed by the expected increase of total radiation resulting in an up to 4% increase in energy output. Using the UKCP09 probabilistic climate change projections, Burnett et al. [21] examined the impact of climate change across different regions of the UK. They found that the current average UK annual solar resource is 101.2 W/m^2, ranging from 128.4 W/m^2 in the south of England to 71.8 W/m^2 in the northwest of Scotland. It seems likely that climate change will increase the average resources in the south of the UK, while marginally decreasing it in the northwest. Using the ECHAM5 global climate to assess the near future changes of PV productivity in Europe and Africa, Gaetani et al. [17] found that reductions in aerosols emissions in the near future result in an increase of global warming, and a significant response in surface solar radiation and associated photovoltaic energy productivity. A statistically significant reduction in PVE productivity of up to 7% is observed in eastern Europe and northern Africa, while a significant increase of up to 10% is observed in western Europe and the eastern Mediterranean. Most recent studies are from Wild et al. [3] and Jerez et al. [22]. Wild et al. examine how the latest generation of climate models used for the fifth IPCC report projects potential changes in surface solar radiation over the coming decades, and how this may affect, in combination with the expected green-house warming, solar power output from photovoltaic systems. They conclude that statistically significant decreases in PV outputs will occur in large parts of the world under the RPC8.5 scenario, but notable exceptions with positive trends in large parts of Europe, southeastern North America and southeastern China. Projected changes between 2006 and 2049 under the RCP8.5 scenario overall are on the order of 1%/decade for horizontal planes, but may be larger for tilted or tracked planes as well as on shorter (decade) timescales. Jerez et al. evaluate climate change impacts on solar photovoltaic power in Europe using the recent EURO–COordinated Regional climate Downscaling EXperiment CORDEX ensemble of high–resolution climate projections together with a PV power production model and assuming a well–developed European PV power fleet. They found that the alteration of solar PV supply by the end of this century compared with the estimations made under current climate conditions should be in the range of −14% to +2%, with the largest decreases in northern countries.

First, the trends' magnitude and the degree of significance of these trends in solar radiation and ambient air temperature were assessed. Like the methodology used by Crook et al. [19] and taken back by Wild et al. [3], we have estimated the impacts of the changes in these climate variables on solar power generation. Different from the previous studies, however, the solar irradiation on a tilted plane was calculated by computing daily all-sky radiation data with free R package solaR [23].

2. Materials and Methods

2.1. Study Area

The interest region is the ECOWAS presented in Figure 1. This region's climate is strongly influenced by the West African Monsoon (WAM). The south–north oscillation of the Inter-tropical Convergence Zone (ITCZ) determines the seasonality of precipitations. In the southern parts (coastal region) where the monsoon regime predominates, the climate is sub-equatorial characterized by the succession of two rainy seasons and two dry seasons. The north (sahelian region) is mainly characterized by the succession in the year of only one rainy season and one dry season. The northern part of this study area is well known to be marked by the harmattan, a dry wind blowing from the Sahara in West Africa. Furthermore, the region is among the sunniest areas of the world, where around 335 million people live [1]. With unequal access to electricity between urban and rural areas, PV is set to become a major source of future electricity in the region.

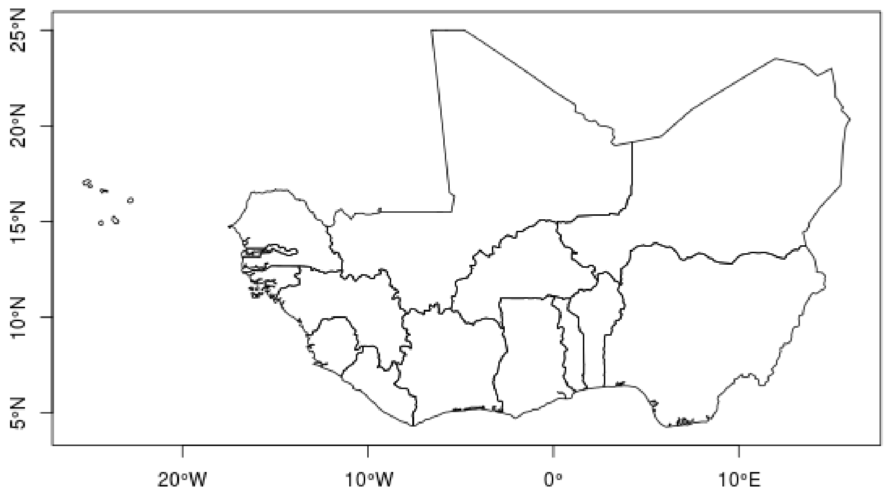

Figure 1. Map of Economic Community of West African States (ECOWAS) region.

2.2. Data

In this study, climate projections were taken from the COordinated Regional climate Downscaling EXperiment for Africa (CORDEX) [24–26] and available at [27]. Table 2 presents the home institution of used models and the model short-mane. The third column presents acronyms of eight used regional climate models RCMs to downscale eight global climate models (GCMs) that are presented in the second column. Primarily, two kinds of data are used: surface downwelling solar radiation (rsds), which has a wavelength range from 0.2 to 4.0 µm, and near surface air temperature (tas). The used data range from 2006 to 2100 at daily time steps with a spatial of 0.44° which corresponds to approximately 50 km. Climatic models are complex programs based on atmospheric circulation including its chemistry and radiation, oceanic circulation including its biochemistry, land-surface, river routing and sea ice modeling. The differences between them are mainly related to the physical parameterization of each component of the model structure. Considering the scenario which is run, the IPCC have established four Representative Concentration Pathway (RCP) scenarios which are linked to the concentration of greenhouse gas emissions during the 21st century. A major notion which guided these RCP scenarios is the radiative forcing reached at the end of the 21st century. Radiative forcing represents the difference between the received radiative energy and the emitted energy. According to the socio-economic, technological and policy development activities that disturb the concentration of carbon dioxide in the atmosphere, there are $RCP2.6$, $RCP4.5$, $RCP6.0$ and $RCP8.5$, where the associated number corresponds to the radiative forcing reached at the end of the 21st century. Within the Coupled Model Inter-comparison Project Phase 5 (CMIP5), predefined scenarios of radiative forcing obtained from socio-economic scenarios were used for the projections of climate change [25,28]. In this study, only experiments performed with $RCP8.5$, which is the highest radiative forcing, are considered. The $RCP8.5$ is based on the $A2r$ scenario [29] which combines assumptions about high population and relatively slow income growth with modest rates of technological change and energy intensity improvements, leading in the long-term to high energy demand and greenhouse gas emissions in the absence of climate change policies [30]. This set of data is the most up-to-date ensemble of high-resolution Regional Climate Model (RCM) projections [22]. On the temperature side, this scenario projects, on average, a global warming of 2.0 °C and 3.7 °C until the middle and end of the 21st century, respectively, relative to a reference period of 1985–2005 [4].

Table 2. Used climatic models.

Institute ID	Global Climate Model Name	Model Short Name	References for Each of the Models
NOAA–GFDL	GFDL–ESM2M	NOAA	[31]
NCC	NorESM1–M	NCC	[32]
MPI–M	MPI-ESM–LR	MPI	[33]
MIROC	MIROC5	MIROC	[34]
IPSL	IPSL–CM5A–MR	IPSL	[35]
ICHEC	EC–EARTH	ICHEC	[36]
CNRM–CERFACS	CNRM–CM5	CNRM	[37]
CCCma	CanESM2	CCCMA	[38]

2.3. Effects of Climate Changes on PV Energy Production Assessment

Solar radiation and the ambient air temperature are the main inputs of PV energy production. In this section, we investigate the impact, in these two variables above, of long-term changes on the output energy. To achieve this goal, the method used by Panagea et al. [20] and Wild et al. [3] was followed. This method defines the efficiency of PV, η_{cell}, which depends on the temperature by:

$$\frac{\eta_{cell}}{\eta_{ref}} = 1 - \beta(T_{cell} - T_{ref}) + \gamma \log_{10} G_{tot} \tag{1}$$

where η_{cell} is the reference efficiency of the PV modules, T_{ref} and G_{tot} are solar irradiation on the tilted plane computed with R package solaR [23] using the all-sky solar radiation (rsds) daily data as inputs. The coefficients β and γ depend on the cell material and structure. According to Parida et al. [39], mono-crystalline silicon cells are the most produced and for this type of cell $\beta = 0.0045$ and $\gamma = 0.1$. Still based on these two studies, T_{cell} is the temperature of modules and is given by:

$$T_{cell} = C_1 + C_2 T + C_3 G_{tot} \tag{2}$$

where T is the air ambient temperature in °C, C_1, C_2 and C_3 depend on the material properties, and, in this case (mono-crystalline silicon cells), their values are $C_1 = -3.75$, $C_2 = 1.14$ and $C_3 = 0.0175\ \mathrm{m^2 \cdot W^{-1}}$. The output power of PV system is assumed to be:

$$P_{pv} = G_{tot}\eta_{ref}(1 - \beta(T_{cell} - T_{ref}) + \gamma \log_{10} G_{tot}) \tag{3}$$

In the studies cited above, losses due to the other components such as rain, wind, humidity, are neglected. In addition, the fractional change in output presented in Equation (4) was examined. The first advantage is to eliminate η_{cell} in Equation (3) and the second one allowed comparing the future output energy to the reference period 2006–2015:

$$\begin{aligned}\frac{\Delta P_{pv}}{P_{pv}} &= -\Delta T G_{tot}\beta C_2 - \Delta G_{tot}^2 \beta C_3 \\ &+ \Delta G_{tot}(1 - \beta C_1 + \beta t_{ref} - 2\beta C_3 - T\beta C_2) + \Delta G_{tot}\Delta T\beta C_2 \\ &+ \Delta G_{tot}\gamma \log_{10}(G_{tot} + \Delta G_{tot}) + G_{tot}\gamma \log_{10}(\frac{G_{tot} + \Delta G_{tot}}{G_{tot}})\end{aligned} \tag{4}$$

The results presented in the next section of this study are based on annual means (temperature and rsds, which was computed with the Climate Data Operators [40] using daily data described in Section 2.2 as inputs. Then, the free software R [41] was used to compute all of these means. Each quantity was re-sampled to a common resolution. The detection of trends and their statistically significances were directly computed through the package Stats of R. Using *t*-test [42], only cells that match with *p*-values inferior or equal to 0.05 were kept.

3. Results

3.1. Changes in Projected Radiation and Temperature

The map presented in Figure 2 represents the linear trends of the annual mean of surface downward solar radiation under all-sky conditions (rsds) (W/m^2/year) between 2006 and 2100, while Table 3 shows the trend for all fifteen countries of ECOWAS. The white color on the map indicates the areas where the trend is not significant according to the *t*-test [42], with a significance level of 0.05. In Table 3, this situation was represented by the blank cells. Except for the ICHEC model, which predicts a negative trend only for Liberia, all of the seven models remaining predict a negative trend with small differences between countries.

Table 3. Mean of surface downwelling solar radiation (rsds) trends by country (W/m^2/year) from 2006–2100. The blank cells correspond to non-significant values.

Countries	NOAA	NCC	MPI	MIROC	IPSL	ICHEC	CNRM	CCCMA
Benin	−0.08	0.08	−0.04	−0.11	−0.09	0.14	−0.09	−0.04
Cape Verde	−0.11	0.04	−0.05	−0.18	−0.07	0.17	−0.09	−0.08
Gambia	−0.03		0.06	−0.07	−0.07	0.16	−0.07	
Ghana	−0.08	0.06	−0.04	−0.10	−0.08	0.11	−0.08	
Guinea	−0.05	−0.05	−0.05	−0.08	−0.06	0.13	−0.07	
Cote d'Ivoire	−0.06		−0.05	−0.09	−0.06	0.07	−0.08	0.05
Liberia	−0.04	−0.07	−0.05	0.05	0.05	−0.06		
Mali	−0.08	0.08	−0.04	−0.08	−0.08	0.10	−0.06	−0.04
Niger	−0.09	0.10	−0.06	−0.07	−0.09	0.05	−0.07	−0.05
Nigeria	−0.07	0.09	−0.01	−0.10	−0.09	0.11	−0.10	−0.05
Guinea-Bissau	−0.03		−0.05	−0.05	−0.05	0.18	−0.07	
Senegal	−0.06		0.06	−0.09	−0.08	0.12	−0.07	
Sierra Leone	0.00		−0.06	0.02	−0.05	0.08	−0.06	
Togo	−0.07	0.06	−0.04	−0.09	−0.06	0.11	-0.08	
Burkina Faso	−0.09	0.09		−0.11	−0.09	0.14	−0.09	−0.05

Considering only the ICHEC model, the maximum of trend is 0.17 W/m^2/year for Cape Verde while the minimum is −0.06 for Liberia. No larger differences are observed either between coastal and inland countries or southern and northern countries. Most models, mainly NOAA, MIROC, IPSL and

CNRM, show a negative trend with slight differences. Considering the statistical significance of these trends, the NCC model and the CCCMA model present the largest area without trend significance.

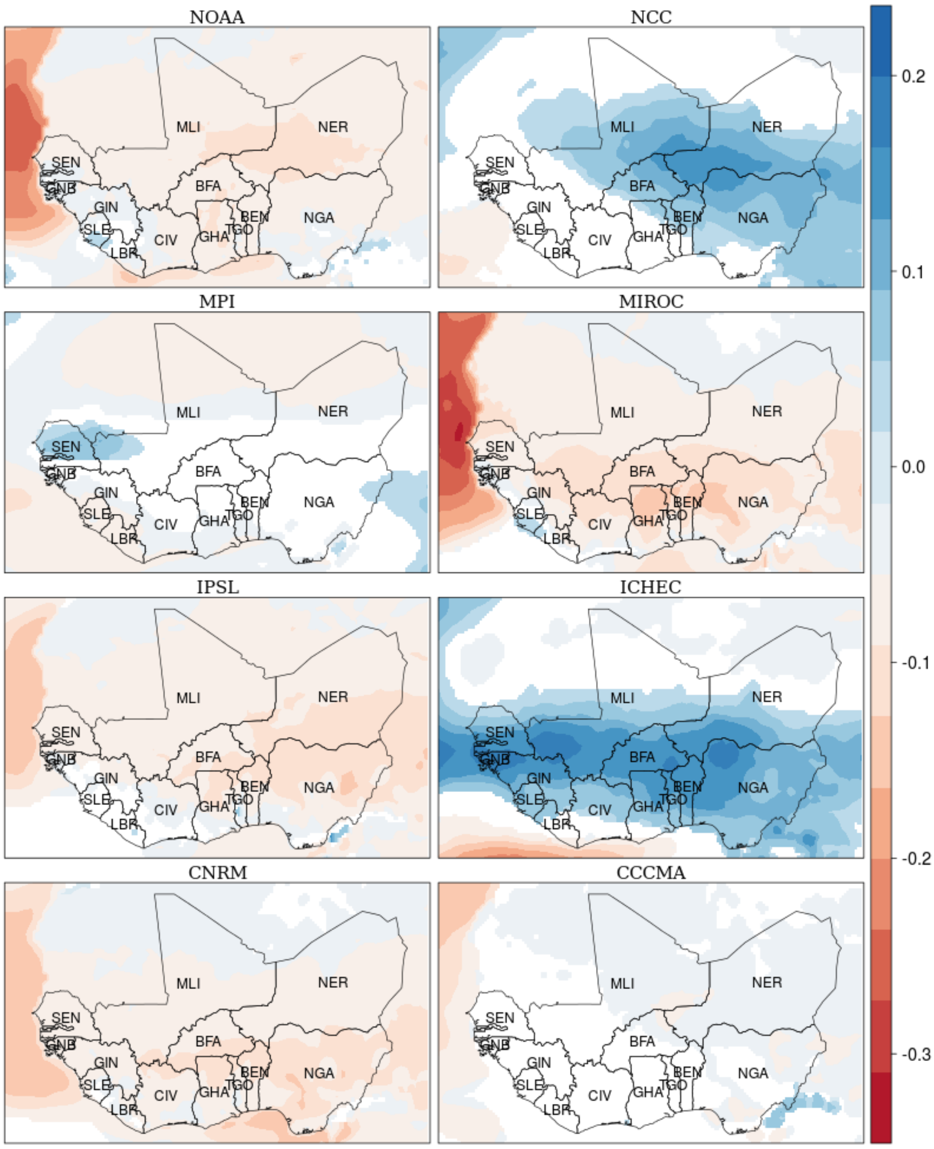

Figure 2. Linear trend of surface downwelling solar radiation (rsds) 2006–2100.

The same computation has been applied to the temperature. Figure 3 presents the results of the linear trend of the models and Table 4 summarizes the mean trend of each considered country. Contrary to the rsds trends, all used models predict positive trenda for temperature. The MIROC model is the one which predicts the largest trend with a maximum value of 0.08 K/year for Mali and Niger and a minimum value of 0.04 K/year for Cape Verde. In addition, all the models seem to predict the same trend with very slight differences in their values like the NOAA, MIROC, IPSL and CNRM models of rsds. Some differences can be observed between temperature trends and rsds trends. First, the trends in temperature are larger for western countries and secondly, the trend of northern countries are larger than those of southern countries.

Table 4. Mean of ambient air temperature(tas) trends by country (K/year).

Countries	NOAA	NCC	MPI	MIROC	IPSL	ICHEC	CNRM	CCCMA
Benin	0.06	0.04	0.05	0.07	0.04	0.06	0.04	0.04
Cape Verde	0.04	0.03	0.03	0.04	0.04	0.04	0.03	0.03
Gambia	0.05	0.04	0.05	0.06	0.04	0.05	0.04	0.04
Ghana	0.05	0.04	0.05	0.07	0.04	0.05	0.04	0.04
Guinea	0.05	0.04	0.05	0.07	0.04	0.05	0.04	0.04
Cote d'Ivoire	0.05	0.04	0.05	0.07	0.04	0.05	0.04	0.04
Liberia	0.05	0.04	0.04	0.06	0.04	0.05	0.03	0.04
Mali	0.06	0.05	0.05	0.08	0.05	0.06	0.05	0.05
Niger	0.06	0.05	0.06	0.08	0.05	0.06	0.05	0.05
Nigeria	0.06	0.04	0.05	0.07	0.04	0.06	0.04	0.05
Guinea-Bissau	0.05	0.04	0.05	0.06	0.04	0.05	0.04	0.04
Senegal	0.06	0.04	0.05	0.06	0.05	0.05	0.04	0.05
Sierra Leone	0.05	0.04	0.04	0.06	0.04	0.05	0.03	0.04
Togo	0.06	0.04	0.05	0.07	0.04	0.05	0.04	0.04
Burkina Faso	0.06	0.05	0.05	0.07	0.05	0.06	0.04	0.05

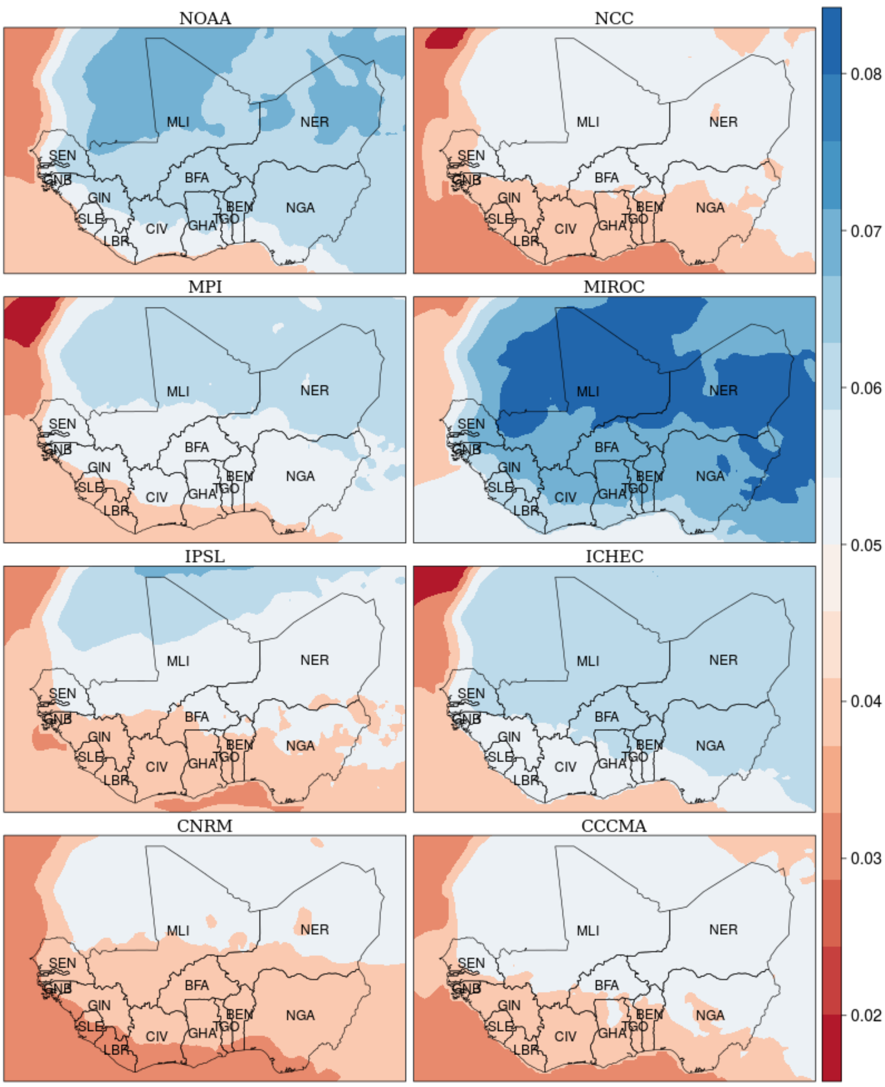

Figure 3. Linear trend of temperature 2006–2100.

To summarize this part, we can notice that most of the models of rsds predict negative trends for all of West Africa except the ICHEC model, which predicts a positive trend. The trends in temperature are in general more warming than those of rsds. Thus, the ECOWAS countries should know more warming temperatures.

3.2. Impact on PV Output Energy

Figure 4 shows the average annual mean of irradiation from 2006–2045 on a tilted surface. The free R package solaR [23] allows for computation of these values using daily irradiation value in network Common Data Form (NetCDF) format as inputs. More detailed information on the methodology incremented in this package are presented in Antonanzas-Torres et al. [43]. These eight maps that represent the average annual mean of irradiation from 2006–2045 for each model show that the MIROC model predicts the largest quantities while the NCC model predicts the lowest quantities. Compared with the current mean, the patterns do not change showing maxima over the desert areas and minima over the equatorial belt and mid–latitudes. These maps are the first step to compute the PV power output changes presented in Figure 5.

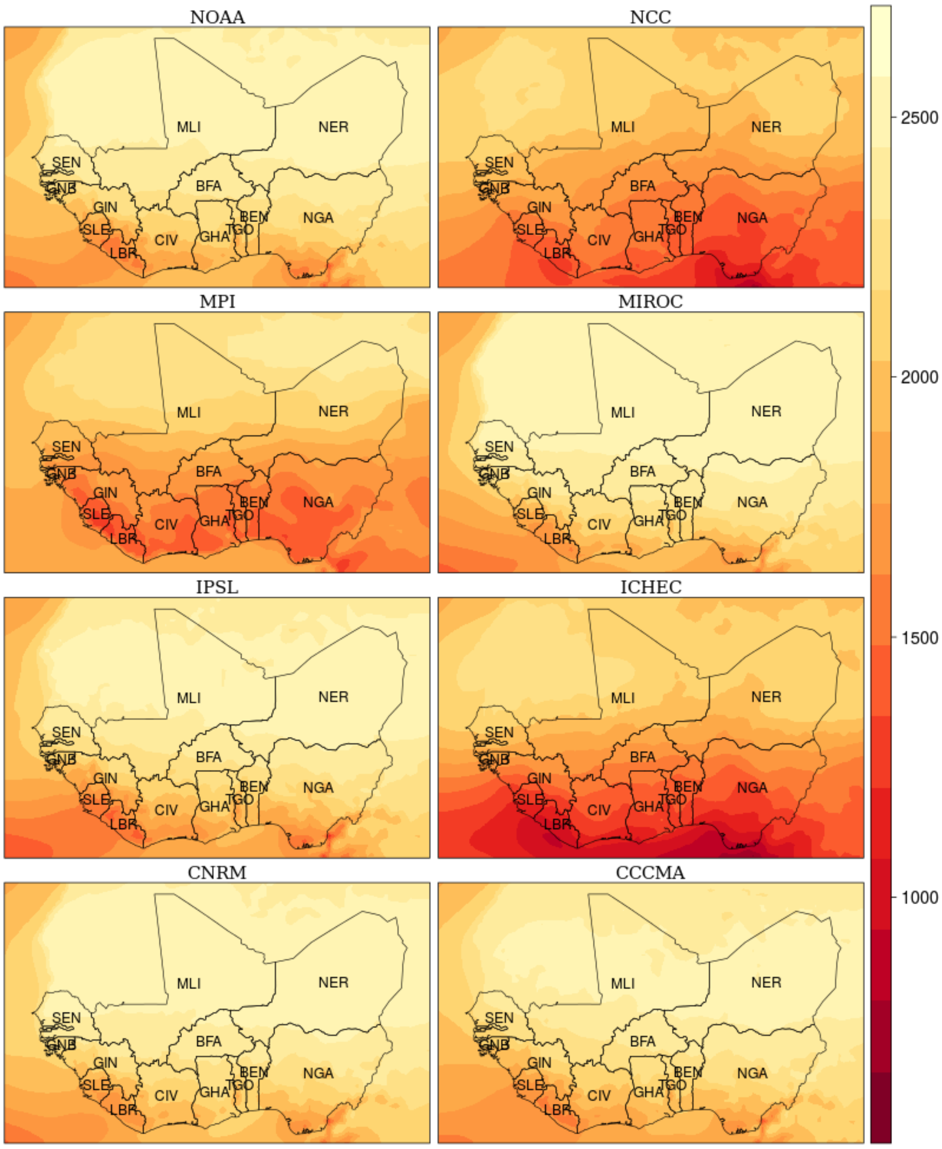

Figure 4. Average of the annual mean of irradiation from 2006–2045.

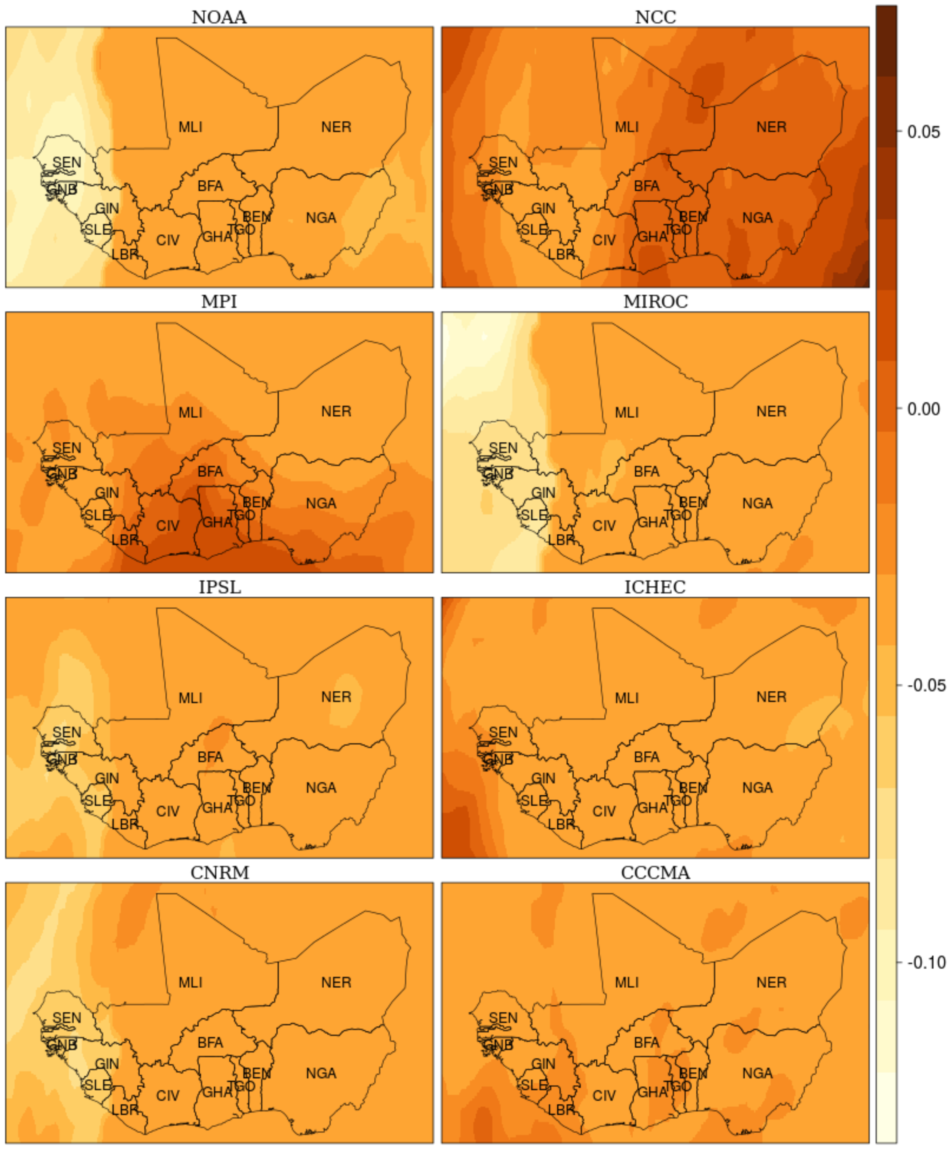

Figure 5. Photovoltaic (PV) output trends change repartitions.

Figure 5 shows trends of the fractional change of the power output between 2006 and 2045 relative to the mean of the decade period (2006–2015) of rsds and temperature. Contrary to the study of Wild et al. [3], the pattern of PV output changes with trend significance presented in Figure 6 do not strongly look like the trends of all-sky radiation (see Figure 2). We have to expect this fact since the surface temperature, the second meteorological variable contributing to power output changes, increases with a larger value for West Africa according to Figure 3. The common situation between our study and Wild et al. [3] is the fact that the PV output decreases with increasing temperatures.

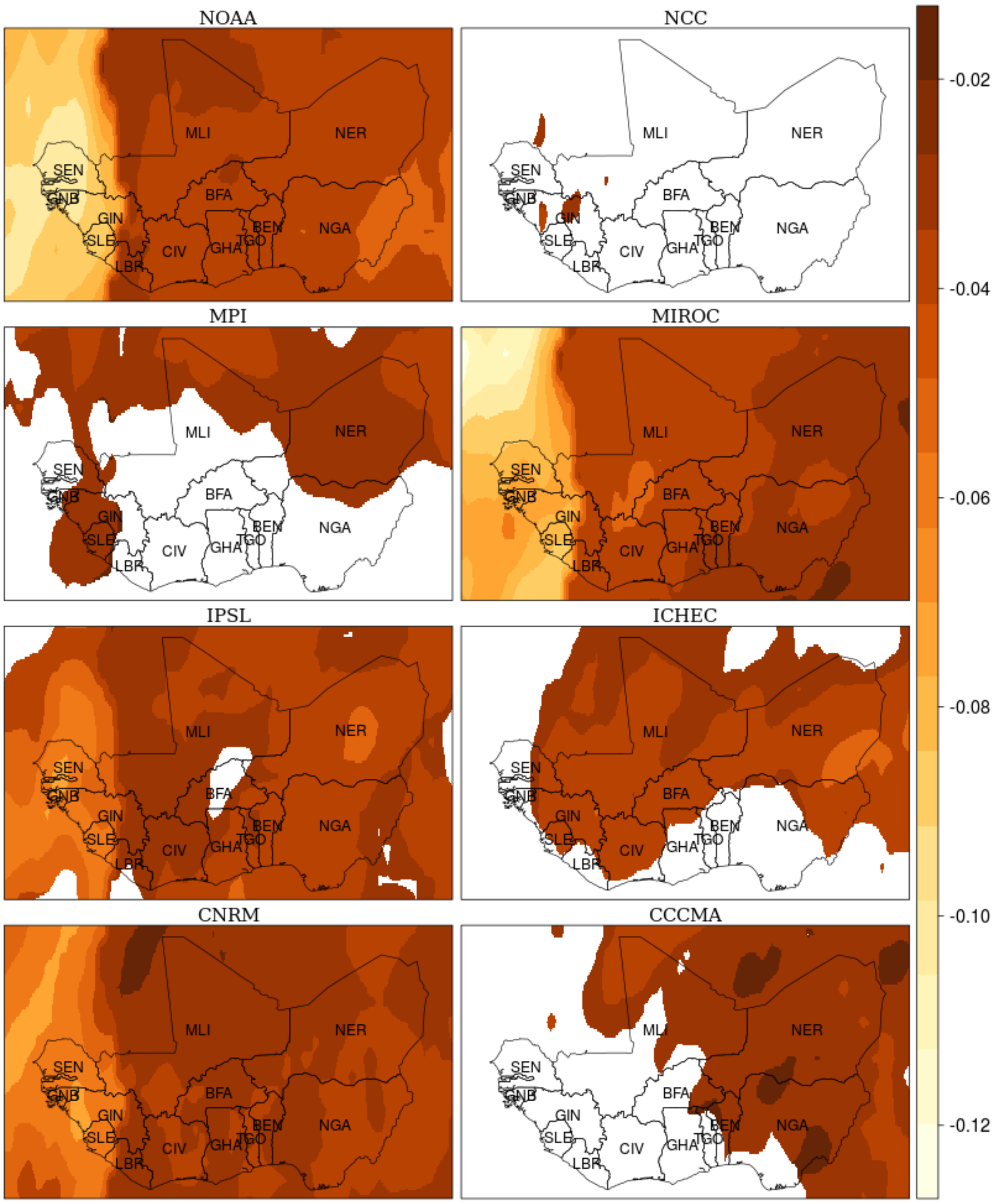

Figure 6. PV output changes with trend significances.

All models predict a negative trend for West Africa. Taking into account the significance of the trend, all models present areas with no significant trends. Another fact is that models presented in Figure 2 with a positive trend are those that have maximum areas of statistical non-significance. Time series of the response of PV output changes are presented in Figure 7. The red line for each plot represents the mean trend of the eight models. This figure shows that mean trends for PV output changes in all countries are negative except for Liberia and Sierra Leone. The minimum is reached in Niger with a value of −0.032%/year while the maximum of 0.013%/year was observed for Liberia. Finally only Liberia and Sierra Leone may profit from climate change in terms of PV energy production, whereas the other countries of the ECOWAS are likely to face declining energy outputs. We are aware that the trend are very low, but it could increase because this study neglects other factors that influence the PV energy production.

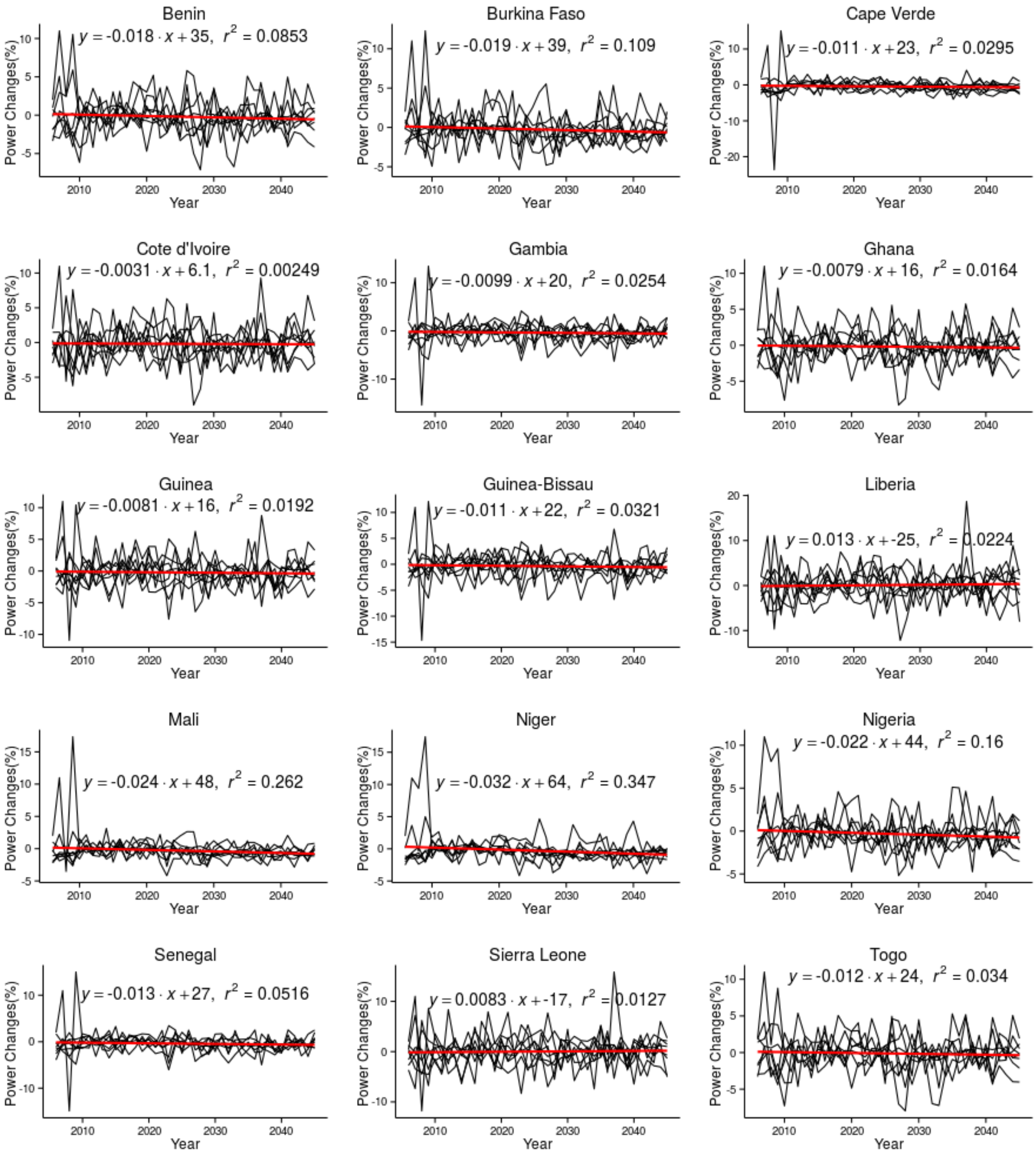

Figure 7. Time series of PV output changes. The **red** line for each plot represents the mean trend of the eight models.

4. Discussion

The purpose of this study is to examine the future response of present or planned PV projects in West Africa to climate change. The results of future changes presented in Figure 7 show that, for the entire considered region, PV output changes are decreasing except Liberia and Sierra Leone, which have very slightly increasing changes. It appears that all-sky radiation (rsds) and surface temperature changes play an important role in PV output changes. Trends for all-sky radiation (rsds) are negative for all considered models. Compared to the results of the ECHAM5–HAM aerosol-climate model Gaetani et al. [17], the results show negative changes for all-sky radiation (rsds) but more negative in the case of ECHAM5–HAM aerosol-climate model. Our results are closer to those of Wild et al. [3]. The slight differences can be from the data since the common key is the representative concentration pathway equal to 8.5 W/m^2. However, the lowest gradient of latitude avoids highlighting the implications of latitude on the changes of solar radiation. Contrary to rsds data, surface air data changes are close to the results of Gaetani et al. [17]. The examined region (comprised between 0° and 30°N). The negative changes of rsds added to positive changes of temperature make our results consistent, which Finally show negative changes of PV output. The negative dependency of PV output on temperature have been proved by Huld [44]. The changes of PV output are similar to those of Gaetani et al. [17] and Wild et al. [3] for the same region. This situation is expected since the negative dependency of PV output on temperature has been proved by Huld [44]. Nevertheless, the values of PV output changes are not consistent with those predicted by Huld et al. [45], who found, on horizontal planes at sites in Germany, that changes on the tilted plane should be larger than those of the horizontal plane. Compared with the other regions, PV output changes are relatively small.

5. Conclusions

An analysis of climate change impacts on PV energy output has been performed. To achieve this target, eight data sets of solar radiation and ambient air temperature from climate models have been used. Trend of solar radiation and ambient air temperature have been computed on one hand, and, on the other hand, response of PV output changes compared to the decade 2006–2015 has been calculated. For each model, maps of trends, mean of yearly sum of solar radiation and future changes were plotted. The results show that the trends of solar irradiation are negative except for the IPSL model, which predicted a positive trend with a maximum value of 0.17 W/m^2/year for Cape Verde. In addition, a minimum value with a negative trend is -0.18 W/m^2/year predicted by the MIROC model for Cape Verde. Concerning the temperature trend, temperature trends are positive with a maximum of 0.08 K/year predicted by MIROC for Niger and minimum of 0.03 K/year predicted by NCC, MPI, CNRM and CCCMA for Cape Verde. The response of PV output is that, except for Liberia and Sierra Leone, which will profit from climate changes, the rest of the countries should face a decrease in PV output with a minimum of -0.032%/year in Niger. To summarize, this study provides enough information that can help energy planners and policy makers to avoid unexpected surprises in the coming years. All of these results can be reconsidered when we take into account the fast growing science in the PV field.

We can improve this paper in further studies by finding areas with lesser variation of solar radiation and temperature variation. Furthermore, after this first step, we could compare from among the fixed plane south orientation with an optimum tilted plane, north–south horizontal axis tracker, and two axis tracker systems, which one is most suitable for each region. Finally, the results could be more precise by taking into account the effect of future humidity and precipitation on PV energy estimation.

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