Heliyon 7 (2021) e07016

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Solar energy: A panacea for the electricity generation crisis in Nigeria

Emmanuel.P. Agbo [a,b,*], Collins.O. Edet [c], Thomas.O. Magu [d], Armstrong.O. Njok [a], Chris.M. Ekpo [a], Hitler Louis [d]

[a] Department of Physics, Cross River University of Technology, Calabar, Nigeria
[b] Faculty of Clinical Sciences, College of Health Sciences, Osun State University, Osogbo, Osun State, Nigeria
[c] Theoretical Physics Group, University of Port Harcourt, Port Harcourt, Nigeria
[d] Department of Pure and Applied Chemistry, University of Calabar, Calabar, Nigeria

HIGHLIGHTS

- General evaluation of the world's and Africa's solar energy situation.
- Discussion on the current energy situation, variables, and applications in Nigeria.
- An in-depth look at the solar photovoltaic mathematical model and its key components.
- Estimating the potential amount of energy generated in different regions of Nigeria; using solar radiation data.

ARTICLE INFO

Keywords:
Renewable energy
Solar energy
Nigeria's electricity generation
Photovoltaics
Solar radiation
Energy

ABSTRACT

In assessing the status of solar energy in Nigeria, efforts have been made to review researchers' works. This review article presents the status of solar energy in Nigeria. Also, it provides an all-inclusive contemporary analysis of the extensive research carried out in this field by Nigerians and renewable energy researchers in general. With her large population, Nigeria requires enormous energy for sustainability; this has caused somewhat an over-dependence on crude oil and natural gas for energy. This overdependence constantly puts the country in an energy consumption crisis when these resources are not readily available. It has its disadvantages as it affects climate change and her economy. Solar energy growth and application/adoption from the global, African, West African, and Nigerian perspectives were expounded with that of Nigeria buttressed on to bring into view the contrast between her adoption of this technology and the world. Albeit, the electricity generation from solar energy in Nigeria has also been estimated from solar radiation data, results of this analysis showed some areas in Northern Nigeria as the regions with the highest electricity generation capacity; the estimation using 1 kWp (Kilowatt-peak) PV (photovoltaic) modules were made from obtained data for possible electricity generation in kWh. The challenges to adopting these technologies were noted together with some recommendations/policies on how to curb these challenges and their implications. This review article will be of massive benefit to both the government and researchers in this research area and scientists who are currently working on renewable-related projects.

1. Introduction

Renewable energy (RE) is derived from essentially inexhaustible sources; these sources are naturally restored, unlimited, and rapidly replenished. The need to reduce the rate of greenhouse gas (GHG) emissions as a means of addressing climate change has made the adoption of RE more significant. Technological innovation is a crucial aspect of RE development as the world continuously seeks to be "carbon-free" [1]. Reducing these GHGs in the atmosphere will save the ozone layer from depletion, a depletion that will bring catastrophe to humanity.

Solar, wind, hydro, oceanic, geothermal, biomass, and other sources of energy that are derived directly or indirectly as an effect of the "sun's energy" are all classified as RE and are renewed indefinitely by nature [2]. This means that they are sustainable, they can be replenished, and they have no harmful side effects for the most part, except in the process

* Corresponding author.
E-mail address: emmanuelpaulagbo@gmail.com (Emmanuel.P. Agbo).

https://doi.org/10.1016/j.heliyon.2021.e07016
Received 1 January 2021; Received in revised form 20 February 2021; Accepted 4 May 2021

of harnessing them, which is a result of man's activities. They serve to curb the ongoing effects of man's anthropogenic activities. Developing RE projects is a huge opportunity from a technological and environmental perspective. From a strategic and financial standpoint, this development will be beneficial to a country or region as resources can be sold within or outside their territory; this can increase employment of labor and production [3].

The utilization of sunlight for electricity generation defines the adoption of Solar energy. This energy can be utilized directly using photovoltaics (PVs), where energy from the sun as photons strikes surfaces to bring about electrons' movement (photo-electric effect). An indirect method where the energy from the sun is focused on raising the temperature (heating) of water or enclosed space (solar collectors), which is used for the production of power, this method can be referred to as a concentrating solar power (CSP) [4].

The politics of power has affected the adoption of RE because countries with natural (raw) materials for the production of non-renewable energy fight over power to control the production and distribution of these resources to increase their Gross Domestic Produce (GDP) [5]. However, a country like Nigeria, that has these raw (non-renewable) materials, unlike most countries, is still fortunate to have sufficiently, these natural resources for utilization for clean energy production like solar energy, which will be our focus on this research. Adopting these alternative energy resources can go as far as creating jobs, improving energy access and security [5], and reducing the emission of fossil fuels, which depletes the ozone layer and contributes to the formation of GHGs; this ramps up the average global surface temperature. Studies by Agbo et al. [6, 7], Agbo and Ekpo [8], Agbo [9], and Alhaji et al. [10] have shown that the ambient temperature for their respective study locations in Nigeria is steadily increasing. This shows the importance of adopting clean, renewable energy.

Fossil fuels are the major sources of energy in Nigeria; unlike alternative energy sources, they can be quickly exhausted or made temporarily obsolete due to availability and/or price. This was observed in the recent outbreak of Covid-19 (Corona Virus Disease 2019), a pandemic that moved the Organization of Petroleum Exporting Countries (OPEC) to reach a consensus of cutting down oil production to an unprecedented figure of 10 million barrels per day in March 2020. This makes alternative (renewable) energy sources suitable and wonderful options because they are limitless.

Climate change, majorly caused by environmental pollution (e.g., carbon emission), has been the main trigger for actions taken by most world governing bodies towards the employment of these renewable (alternative) energy resources. These changes will help reduce environmental pollution to the barest minimum; because global warming has become one of the issues threatening humanity's longevity [4]. Variations of meteorological parameters affect the amount of energy gotten from the sun. According to studies from Agbo et al. [6, 7], Agbo and Ekpo [8], Agbo [9] Alhaji et al. [10], and Akinbami [11], climate change is one of the effects of these variations with its issue resulting from diverse anthropogenic activities. With the recent increase in cellular networks' deployment across the world and the most recent introduction of the 5th Generation (5G) technology, two main problems have been noticed; the cost of energy for running these mobile networks and its effects on the environment.

The problems of implementing these cellular networks can be observed from developing countries where the deployment of these networks has and is experiencing an increasing trend in growth. These countries usually have unreliable power grids derived from non-renewable resources; hence they are forced to rely on power generation from diesel or gas-powered generators; this increases the operating cost of electricity and contributes to pollution [12].

Cellular base stations (BSs) powered by RE, like solar power, has emerged as one of the most promising solutions to these issues, as solar energy implies no harmful emissions to the atmosphere and reduces cost for practical usage and maintenance in the long run.

The constant increase in the world's population, arising from the holistic rise in different nations' respective populations and the continuous growth in industrial activities, has brought about high energy demand in our industries and homes. Hence fossil fuels can no longer meet this exponential rise in demand for energy without taking a toll on the biosphere [12]. The energy from non-renewable sources is depletable. The increase in the energy demand of a country or region will only make it more challenging to switch to clean energy if governments don't act fast [13].

According to Abdulkarim (ND) [13], the sun has been shinning for about 4.5 billion years; they also went further to explain that all the energy from the earth arises as a direct or indirect result of solar energy. This shows that solar energy can be called 'primary renewable energy.' We discern this from the advantages of solar energy over conventional fuel sources. One of the disadvantages of other energy resources, including some RE resources to solar energy, is that the availability and access to these other energy sources are susceptible to natural disasters. The disadvantages of these conventional fuel sources are numerous compared with solar energy; the recent giant strides have improved this, consequently improving solar cell efficiency using PVs. These devices work by converting about 40.8% of the sunlight that hits them into electricity by the photo-electric effect [14].

The famous 'Solar energy' has always been discussed in many original research articles and review articles. Commitments have been made for its application in the power generation sector of Nigeria and other countries. Here we attempted to provide a review article that describes, in particular, the state-of-the-art researches which have been carried out on the status of solar energy in Nigeria. We thoroughly summarize the different usage strategies as well as their potential applications in Nigeria.

This review article is organized into ten main sections. The first section presents a brief introduction to renewable energy and solar energy in particular. The following section presents a literature review. In section 3, we discuss the world solar energy situation. The fourth section provides an all-embracing overview of the African solar energy situation, focusing on West Africa. The fifth section describes the energy situation in Nigeria organized with subsections; solar energy variables in Nigeria are discussed using figures. The sixth section presents some applications of solar energy organized in five subsections; in the first subsection, the solar-thermal conversion is being expounded, in the second subsection solar-electric (PV) conversion, in the third subsection critical components of the solar system model, in the fourth subsection photovoltaic mathematical model. In other subsections of section 6, different types of solar-powered systems are discussed. In section seven, we discuss solar radiation in Nigeria, reviewing methods applied to estimate solar radiation's potential energy. Results have been shown from the analysis of data after modeling equations. The results show the regions with the most significant potential to thrive in this development. In section eight, the renewable energy master plan is being discussed. In section nine, the challenges bedeviling Nigeria from harnessing this renewable energy potential are presented. We present some recommendations and conclusions relating to policy implications in section ten. Finally, we will offer our perspective on the future directions and challenges in the fascinating research area of solar energy.

2. Related literature

There are myriads of reviews and studies relating to solar energy and RE in general with a focus on Nigeria and the world. These studies have formed the basis for the ever-changing, enlightening, and improvement of solar energy discussions as a RE. These reviews point to better ways and policies in which our societies can adopt solar energy for its improvement.

2.1. Policies/statuses/future prospects

Policies are meant to fill the necessary gaps observed to enable the proper adoption of solar energy. A review by Aliyu et al. [15] took an in-depth look at the present standing and prospects of the future of RE and solar energy in Nigeria. Addressing the abundance of RE resources in Nigeria, they showed how solar energy utilization is one of the lowest of REs in Nigeria. They made references to the Renewable Energy Master Plan (REMP), which has been strengthened in this study. They also referred to the EASE (Energy Access to Sustainable Energy) program to improve the use of RE for Small and Medium Entreprises (SMEs). These policies, although advantageous, are not producing expected results of notable increases in RE adoption. Similarly, Oyedepo [16] examined the way forward for energy and sustainable development in Nigeria. He reviewed energy policies and concluded that Nigeria needs to intensify the further implementation of energy programs to improve RE adoption - saying that bringing up policies alone is just the beginning of the process.

Some factors hinder the adoption of RE policies in a country like Nigeria, Adeyanju et al. [17] discussed some potentials for RE adoption in Nigeria. They also discussed some barriers: high dependence on fossil fuels, high cost of infrastructure, high level of insecurities, and poor access to data on time, politics, etc. Learning from countries that have shown sustainable growth in solar energy will help reduce these hindrances. For example, the (Organization for Economic Co-operaton and Development) OECD buttressed the importance of improved policy commitments relating to the usage of green energy for growth. They talked about how essential these policies were to provide clear directions for infrastructural investments and to adopt strategies and changes for structural change and improvement such as the IEA's (International Energy Agency) energy efficiency policy recommendations. The study focused on the transformation for the sustainability of the energy sector's growth, promoting green growth to ensure positive transition to this sector, implementing this green energy through the proper reshaping of the political economy, and finally monitoring these progressions to provide sustainable green growth.

Solanji et al. [18] reviewed global solar energy policies adopted by different regions of the world. They outlined that most countries' policies include; exemption from tax, the introduction of subsidies, RE portfolio standards, and others. They also described that most formulated policies have been highly predicated on the effects on human health, the development of the economy, and the environment's quality, etc.

Fayaz et al. [19] explained how the Malaysian government is taking steps through policy implementation to catch up with the rest of the world's developed countries in the PV market. And from the results of the Renewable Energy Policy and Action Plan, they are making significant progress.

Jurasz et al. [20] reviewed the direction some applications and, most importantly, some future research directions for RE. These directions will include the practical applications of energy sources and not just statistical relationships.

2.2. PV modules and arrangement

Solar energy can be used for sustainable or supportive electricity generation, as analyzed in this study. However, Shaikh et al. [21] reviewed this and solar panel types and usage, focusing on applying this gift for electricity generation. Asides from their applications, which is explained in this study, they explained the types of solar PV models method of arrangement. These included a 4-cell PV cell, multiple cell PV modules, PV panels arranged in series, and finally, multiple PV modules arranged in an array.

Ravishankar et al. [22] discussed the application of solar energy for solar-powered green houses for harvesting and crop production. They explained that though the addition of ST-OSCs (semitransparent organic solar cells) to greenhouses (GHs) can improve electricity generation and plant cultivation, establishing the impact of these systems on indoor climate, plants' growth is important. They similarly outlined the processes for reaching net-zero energy GHs by integrating ST-OSCs in Ravishankar et al. [23]. They showed that implementing GHs will provide an opportunity to diversify solar energy by using OSCs.

The development of environmentally friendly PV and thermal panels, capable of shutting down the radiation of high temperature within a panel, has been studied by Terashima et al. [24]. With the addition of a decompression boiling heat collector (for absorbing heat from the PV module through water) and a cover glass which is emboss-processed (for reflection of high-temperature heat), the radiation temperature was proven to be at 45°C even in summer with an efficiency of about 71.3%.

Still relating to PV systems, Rahmatmand et al. [25] proposed innovative techniques for controlling a PV system's temperature on rooftops. The efficiency of PV panels due to the rise in temperature during the summer and the decrease in temperature during the winter demands this innovation; because as the temperature varies, so do the efficiencies of the panels. This calls for a design that can adapt to both seasons. They proposed a system that provides insulation during the summer by painting the back of the panel black while creating air vents through a 3 cm deep channel. The vents were closed during the winter to reduce snow.

Research has been carried out on solar cells by Sharma et al. [26]; they admitted that their efficiency and cost majorly hinder solar cell research development and applications. Technologies based on nano-crystal QD (quantum dot) of semiconductor-based solar cells can theoretically convert more than sixty percent of the whole solar spectrum into electric power. The polymer base solar cells are also a viable option. They showed that theoretically, nano-crystal QD cells convert more than 60% of solar energy into electric power. They went further to buttress on polymer-based solar cells being a reasonable option.

2.3. Solar radiation

The importance of the understanding of solar radiation data and trends cannot be trivialized. As elaborated in this review, we can, with almost complete accuracy, have an idea of the total energy we can utilize from the sun through PVs and CSP. Zell et al. [27] explained these applications, taking Saudi Arabia as a case study, taking into account her solar radiation resources. Their study was just limited to about 12 months, but this gave a great idea about possible applications in modeling power plants and, most importantly, preliminary technology forecasting. Albeit, understanding the inter-annual variability of this resource will require continuous measurements. Different solar radiation models (147 to be precise) were assessed by Sonmete et al. [28] to compare each model's accuracy for the prediction of the average monthly solar radiation for Turkey. Their result was vital in that it showed the model which was best suited for the region. This could be applied in different areas trying to understand their inter-annual variability for better prediction and policy adoption. Ozoegwu [29] discussed the solar energy assessment models in Nigeria, focusing on developing models for the Enugu metropolitan area of Nigeria. He addressed the Nigerian solar energy system's problem and referred to the lack of adoption of Artificial Intelligence (AI). He also said this about solar radiation data and analysis "it is better to use sunshine models and mixed-weather parameter models that include sunshine as one of the regressors" for the study.

For Nigeria, her overdependence on oil and gas has made her lax in the RE sector's consistent growth. Ogunmodimu and Okoroigwe [30] talked about the novel adoption of CSP to utilize solar energy. They buttressed that this method was more economical after using data from the survey to determine which of the technologies were more suitable for solar thermal power plants. They concluded that the parabolic trough concentrator was the best as it would be cheap, reduce the wastage of water, etc. However, gaps were explained, for example, the increase in financial risk due to the very low installed capacities of these systems compared to solar PVs. Still relating to thermal energy storage, Koçak et al. [31] conducted a review on this storage type for industrial solar applications. Their points agree with that of Ogunmodimu and Okoroigwe [30], and they went further to highlight that to achieve cost-effective solutions for industrial applications in temperature (medium-high), STES (Seasonal Thermal Energy Systems) systems are the best for this.

Africa's energy situation is unfortunate as a study from Hafner et al. [32] showed that their refrigerator uses more than three times the energy in which an average Nigerian uses; this is a revelation of the level Nigeria is generally in terms of electricity generation – even with fossil fuels.

3. World solar energy situation

Solar energy has been seen as a viable solution towards energy, environmental, and global challenges. The burning of fossil fuels has consistently led to humans suffering from an energy crisis accompanied by our environment's pollution. Solar energy has received intense attention because RE is in tremendous focus [33]. Unlike other resources, solar is a readily available and renewable resource. Therefore, solar energy is considered an alternative RE source to grid power for BSs.

As explained in the preceding section, the sun provides, directly and indirectly, all the power we need for existence and life support of all forms. From driving weather and climate to a direct and indirect effect on other forms of RE - "without it, our world would be a frozen wasteland of ice-covered rock" [34].

Understanding the wonderful concept of solar energy is essential for developing any kind, from avoiding constant electricity bills to reliability; the sun is considered a vital energy source. Hence, solar energy for applications such as generation of electricity, running of automobiles, powering of BSs is becoming common.

The generation of electricity using solar energy can be done using PV technology. The solar PV cell works on the principle of conversion of sunlight into electricity (PV effect). For the generation of electricity in large quantities, an array of solar PV cells is either connected in series or parallel. Despite the relatively high cost of PV systems, solar power is considered an alternative energy source in many parts of the world.

The measure of solar power available on the earth's surface from the sun is termed 'solar irradiance'; 1000 W per square meter (W/sq.m) is the average power incident on earth [35]. If solar cells are exposed to the full radiation of the sun, we can be expected to generate electricity about 140–160 W per square meter, amounting to about 14–16% solar cell efficiency [35].

The measure of available energy from the sun is termed "insolation", and this can be expressed in terms of "full sun hours" (i.e., five full sun hours = 5 h of sunlight at an irradiance level of, say, 1000 W/sq.m). Clearly, some parts of the world will receive more energy and will have more or less "full sun hours" in a day than others as the production of electrical power from the sun depends on the region's geographical location.

To better understand the general idea of the "full sun hours per day" for different locations, the solar radiation map in Figure 1a and b will show which regions have higher solar irradiation. This map shows the amount of solar energy in hours (peak sun hours) received each day during the 'worst months of the year'. From the figure, it can be seen that Nigeria is a region blessed with higher amounts of solar energy. If this is utilized, the country's economy and Africa at large will be positively affected.

Even amid this high solar irradiance that Africa receives, Figure 2 shows that Africa only encompasses a tiny percentage of the world's solar energy generation. In 2018, for example, Africa had just 1.54% of the world's solar energy generation; the regions with the highest percentage were Asia Pacific, Europe, and North America with 53.74%, 23.78%, and 17.6%, respectively. Although still having an increase in solar energy generation year on year, the figure shows that North America has a reduced percentage contribution to the world's generation. In contrast, the Asia Pacific and Europe have both been working to increase their solar energy generation; Africa has to learn from this. The CIS (Commonwealth of Independent States), the Middle East, and South and Central America all have a percentage of 0.15%, 1.05%, and 2.13% respectively of the world's solar energy generation.

Figure 3 shows that China (world's second largest and fastest-growing economy), United States (world's largest economy), and Germany (Europe's largest economy) all have a high relationship between their installed solar energy capacity and solar energy generation; this is evident from their improving economy. Algeria is one of the largest in Africa, even without having the largest economy in Africa. This proves that Nigeria, as a large economy in Africa, can do better in solar energy installation and energy generation. Nigeria has to take note of China being the major producer of photovoltaics in the world. This is seen in Figure 3 in the solar energy generation versus installed solar capacity plot between 2016-2018 as China has generated electricity above 100,000 GWh (gigawatt-hour) from solar energy with an installed solar capacity of about 500 GW (gigawatts).

Figure 4 shows the trend of the world's installed PV capacity in GW, and this trend corresponds to that of solar generation. The trend shows an exponential increase in installed PV cumulative capacity from 0.3 MW (megawatts) in 1976 to 1500 MW in 2000 and finally to 303,000 MW in 2018. From the data obtained from [37] from 'our world in data', we plotted the exponential curve to show that the world's solar PV cumulative capacity will reach about 15,000,000 MW at this same growth rate of electricity in 2030. This is proof that "the cumulative and yearly global installed capacity have continued to grow markedly from year to year since the inception" [5].

Figure 5 shows the trend in the solar PV module prices from 1978 to 2016. These prices measured in cost (in dollars) per unit energy output (Watt peak: Wp) show that the prices of PV modules per energy output are reducing annually from about $66.10 in 1976 to $0.62 in 2016. This is evident from the increase in the cumulative solar PV capacity in Figure 4. This reduction shows that developing countries like Nigeria can adopt solar energy on a large scale at these prices.

4. Africa's solar energy situation; the West African region

Nigeria is blessed with an estimated 3,000 h of annual sunshine, having disappointing results to show, with about 97,000 rural communities characterized by the deprivation of electricity arising from poor infrastructure. Even with the availability of conventional energy, the energy supply is largely unreliable.

Mas'ud et al. [38] explained in their work that since Nigeria and Cameroon have similar climatic conditions, they can both work together to benefit from each other in the RE sector. The high solar irradiance and the excellent wind speeds can be effectively utilized for electricity generation by the two countries' cooperation. Good leadership and governance between both countries are needed for this to work. The coastal regions that form the border between the two countries are endowed with high wind speeds and large landmasses for windfarms and solar energy grids.

In a developing country like Nigeria, where there is an alarming dependence on fossil fuels, solar energy will remain the most efficient and attractive electricity generation method than other renewable energy sources because of its availability. Unlike wind energy and hydropower, which demands large open areas and large water bodies, respectively solar energy does not [39]. Solar energy can be applied in the following areas in Nigeria, including; agriculture, engineering, medical sciences, power generation, and recreation. The need to use solar energy in these areas becomes more critical with the fast depleting and finite availability of fossil fuels. To improve these areas, solar energy can be applied as mentioned above. Nigeria needs to be less dependent on nonrenewable energy; this is easy because, relating to solar energy, Nigeria is blessed with a sufficient amount of sunshine, favoring investments in solar energy [39].

Relating this to the world at large, the solar energy received by the earth in an hour can power the whole earth for approximately a year [40]. Most countries in Africa, West Africa as a whole, and particularly Nigeria, are located around the equator and receive a relatively high sunshine intensity. Still, research shows that Africa as a whole is lagging

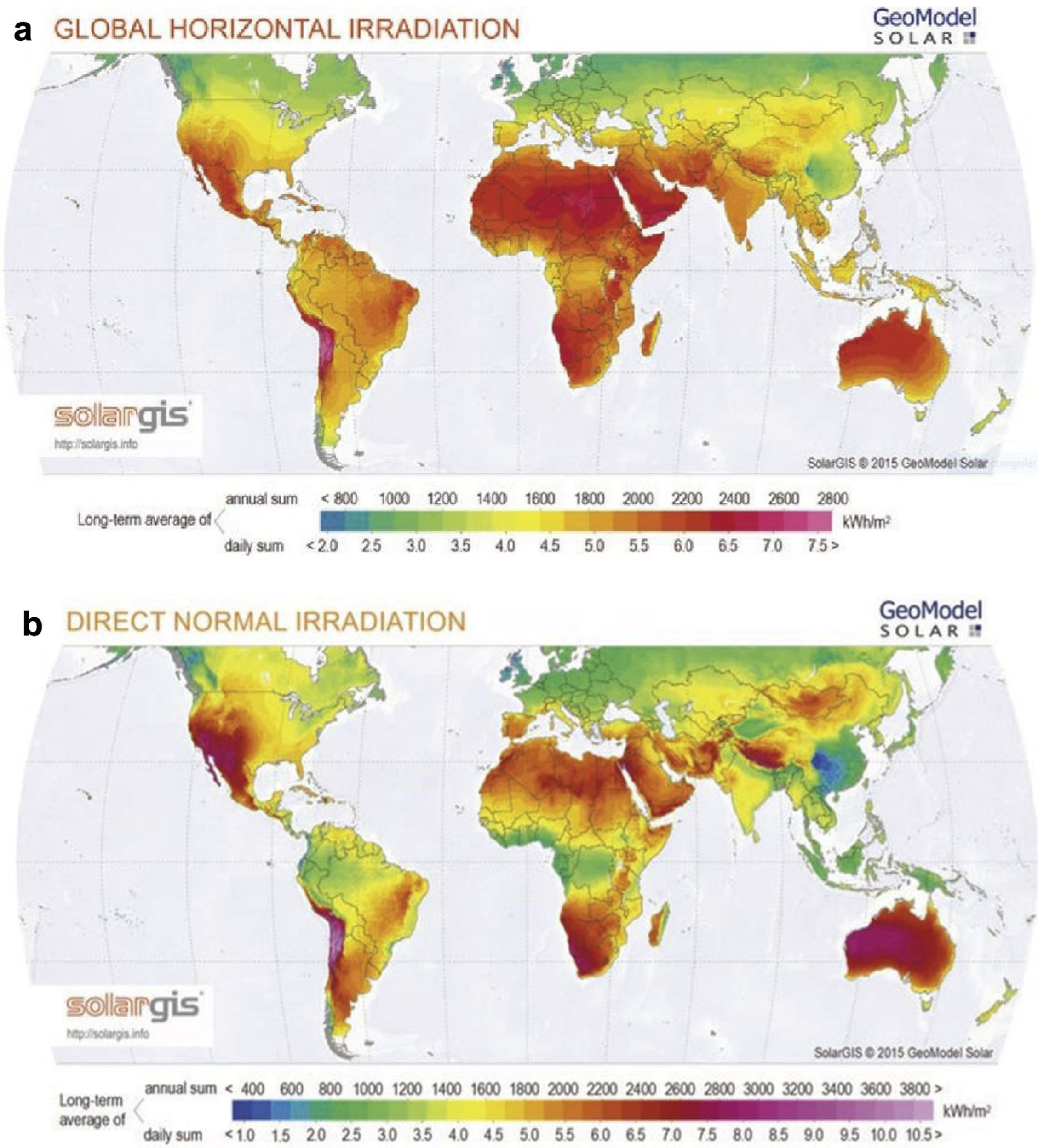

Figure 1. a: World Solar Global Horizontal Irradiation Map with indicted regions showing the long term average of their annual and daily sum in kWh (m^{-2}). Source: [36]. b: World Solar Direct Normal Irradiation Map with indicted regions showing the long term average of their annual and daily sum in kWh (m^{-2}). Source: [36].

behind other continents in adopting solar energy. In a country like Nigeria, where the electricity demand is ever-increasing, harnessing the power is paramount to the growth of the country's economy, as small businesses will be positively affected, diversifying the economy and increasing her GDP [4]. The use of conventional power generating systems which is very costly, has left the country's citizens with no choice but to invest more in privately owned power generating systems.

From Figure 1a and b, we can see from the world solar radiation map that Africa is arguably the continent with the most solar irradiance. Yet, from Figure 6, we see that not all countries in Africa have utilized this nature's blessing to generate electricity; most countries have not recorded data according to [37]. South Africa is the African country with the most solar energy generation.

Figure 7 paints a daunting picture of Africa's overall electricity generation, proving what we have in Figure 6, which emphasizes that Africa, most especially West Africa, needs to adopt alternative energy sources. Figures 8 and 9 shows a trend of the electrical energy generated from solar energy in West Africa and Africa as a whole respectively. The most recent year of study (2018) shows that West Africa generates power from solar energy of about 0.52 TWh (terawatt-hour), with Africa generating 9.03 TWh of electricity from solar energy. Figure 10 shows the trend of the percentage relationship of West Africa's electrical energy generation from solar energy to Africa's; this indicates that West Africa is lagging in Africa's overall solar energy power generation. The trend shows a relatively high percentage during the early parts of the millennium and then a decreasing trend going forward. This shows that Nigeria and other West African countries need to implement solar energy to keep and track their power generation for better analysis and growth.

5. Energy situation in Nigeria

Nigeria is located between longitude 8°E and latitude 10°N, having two major seasons, wet and dry. The seasons have affected the adoption of different RE resources; for example, the different seasons in the

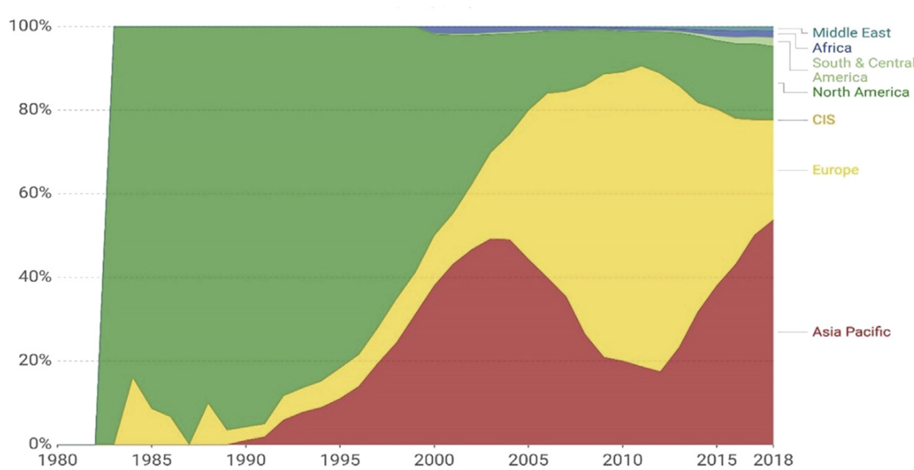

Figure 2. Percentage (relative) Solar energy generation by region from 1980 to 2018 (Solar energy generation is measured in terawatt-hours (TWh) per year. Source: [37].

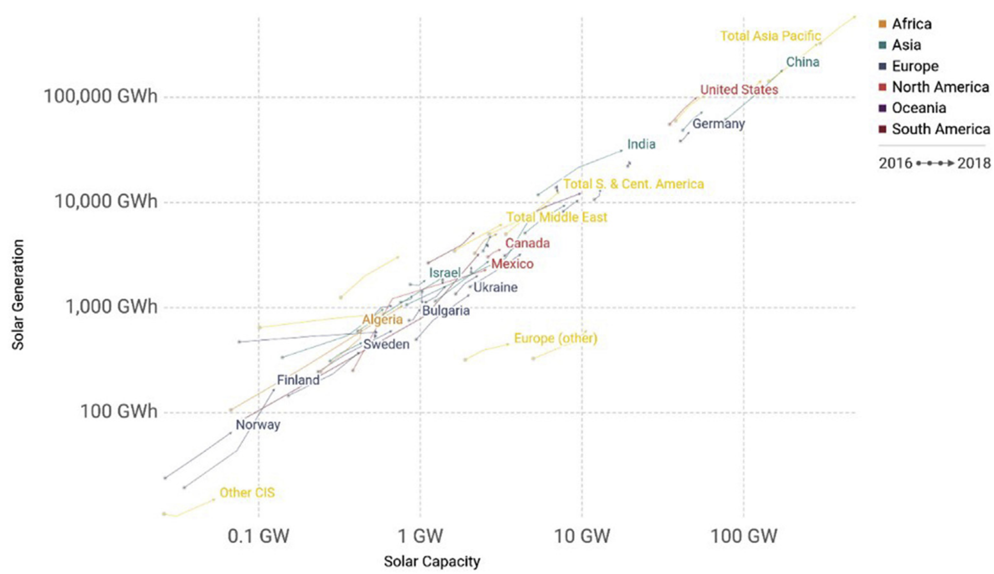

Figure 3. Solar energy generation, measured in gigawatt-hours (GWh) versus installed solar capacity in gigawatts (GW) from 2016 to 2018. Source: [37].

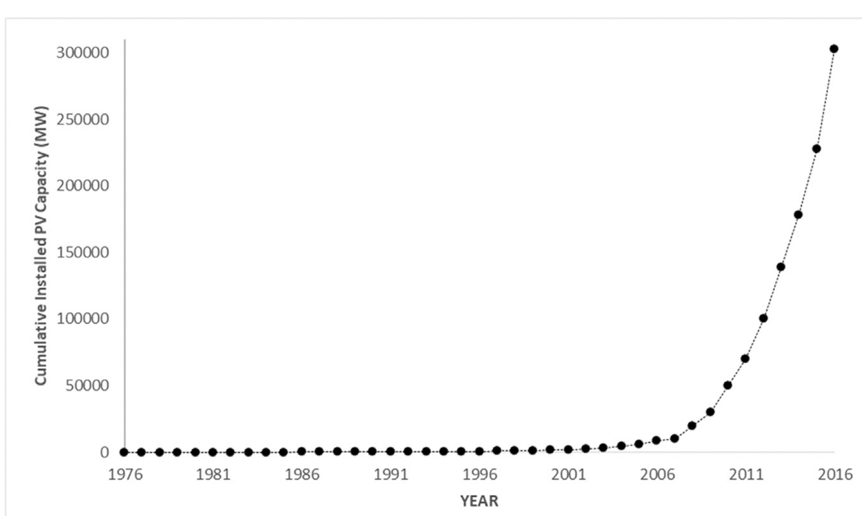

Figure 4. Global cumulative capacity of solar photovoltaic (PV) technology in megawatts (MW). Data source: [37].

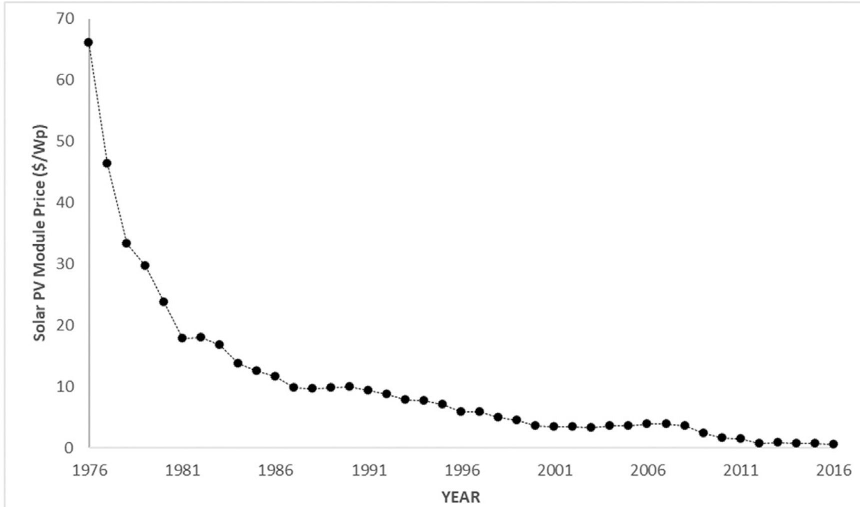

Figure 5. Global average price of photovoltaic (PV) modules, measured as the cost per unit of energy output ($/Wp). Data source: [37].

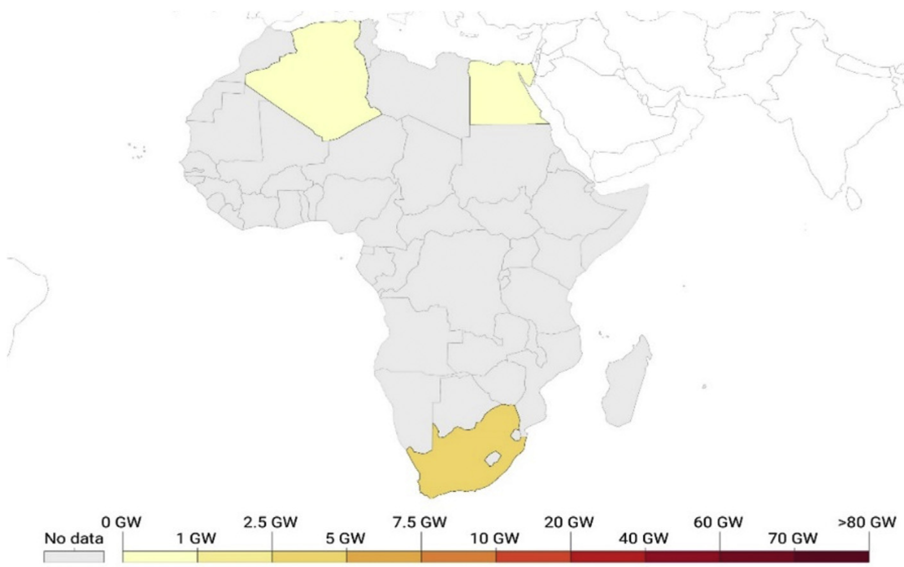

Figure 6. Installed solar energy capacity in Africa showing the countries with the highest notable installed solar energy capacity in gigawatts (GW). Source: [37].

country affect hydropower stations because of water availability variability. Even thermal-powered stations have been affected by the "lack of adequate supplies of natural gas from the various Niger Delta gas wells" [42]; this makes the use of petrol and diesel-powered generators the seemingly easy way out for Nigerians.

Since the early 2000s, Nigeria has identified RE as an additional source to improve electrical power generation.

This alternative energy has been somewhat introduced on a small scale to local economies, but it has not yet been implemented into the national grid on a larger scale [38]. The cost of oil, unnatural changes in climatic conditions (global warming), and the constant need for power supply have made the Nigerian government improve efforts towards adopting PV technology. As for now, solar PV systems are applied to specific areas in Nigeria "merely to provide additional power or to provide backup power in moments of fluctuating power supply or power outage" [43]; these areas include telecom masts, street lights, and parks, etc.

Although having resources for fossil fuels, Nigeria needs to encourage the growth of the energy mix from RE sources. This energy mix will lead to continuous foreign exchange earnings from exporting these raw materials, keeping in mind that the worldwide percentage growth in demand for these raw materials will keep reducing. This will reduce the country's total GDP if they keep being dependent on crude oil [44]. All this points to a dire need for the support of research, development, demonstration and diffusion activities in existing research centers, as well as identifying interested groups in other institutions. Local craftsmen's training on designing, constructing, operating, and maintaining solar energy production devices and introducing soft loans to drive production and adoption is a solution for this problem. Nigeria is a third-world country with an abundance of sunlight, and a large population without electricity represents one of the fastest-growing markets for solar energy. The solar radiation map in Figure 11 shows the distribution of solar irradiance in Nigeria, and this shows high values compared to other nations having high solar PV installed capacity [45]. "Due to the application of solar energy making it more extensive, there are now numerous kinds of PV cells available, with photovoltaic industries having a consolidated worldwide income of US$37 billion in 2008" [46]. The fastest-growing segment of the PV market arises from their application in grids [47]. Nigeria has a high percentage of electricity generation from fossil fuels (79% in 2012), with natural gas and oil encompassing about two-thirds of the generated thermal power. This contributed to her

Figure 7. A composite image, showing a global view of Earth at night, compiled from over 400 satellite images. NASA researchers have used these images of nighttime lights to study weather around urban areas. Source [41].

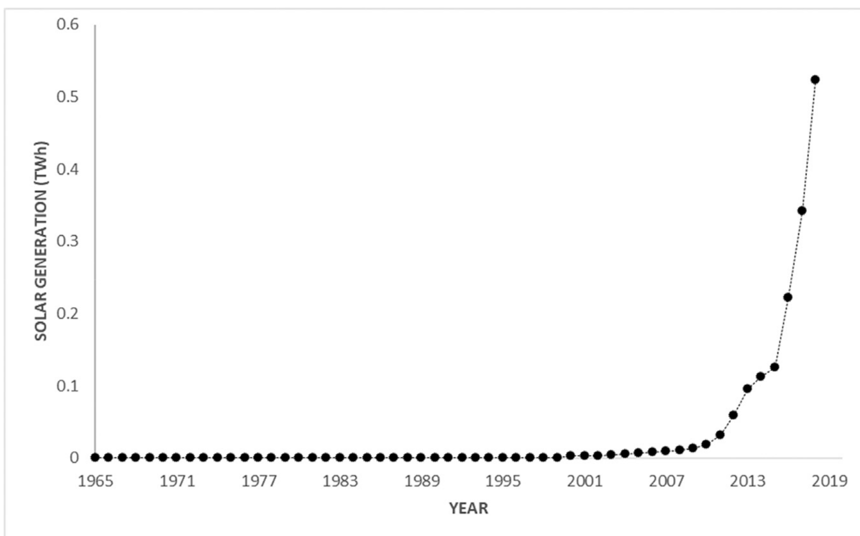

Figure 8. Solar energy generation in Western Africa. Data source: [37].

ranking as 46th globally for Carbon-di-oxide (CO_2) emissions, having a recorded release of about 73.69 metric tons of the gas to her atmosphere in 2011 [42].

5.1. Solar energy variables in figures in Nigeria

Any economy that seeks sustainable growth and results in higher dimensions, especially in the energy sector, naturally takes RE (solar energy) to be of utmost importance. The fact that in one daylight hour, the amount of energy from the sun that reaches the earth is far more than the total used on earth for a whole year underscores this importance. Within this period of one year, about 178,000 TW of solar energy is received; this amounts to about 15,000 times the energy the world consumes in a whole day. Nearly half of this energy is absorbed by the earth, while 30% is being reflected back into the earth's atmosphere [49].

The rate of radiation of the sun's energy is about 3.8×10^{23} kW/s, and Nigeria receives about 4.85×10^{12} kW/h of this energy per day [11, 49, 50]. This comes from about 4 - 8.5 (an average of 6) hours per day of sunlight, which is equivalent to the energy produced from about 1.082 million tons of oil per day [50, 51]. "This figure corresponds to about 4000 times the current daily crude oil production in Nigeria and about 13,000 times the natural gas daily production, based on standard energy units" [50]. The nation can achieve enough in different sectors of the economy with this large, free, and sustainable clean energy [49].

Based on the Nigerian land area of about 924 km^2 and an average irradiance per unit area of 5.535 KWh/m^2, the country has been estimated to have an average of 1831.06 kWh (Kilowatt-hour) incident solar energy annually. "The annual insolation of the solar energy is valued at about 27 times the national conventional energy resources in energy units and also over 117,000 times the amount of electric power that was generated in 1998" [4]. To produce energy equal in quantity to the conventional energy reserve, about 3.7% of the nation's land area has to be utilized.

Nigeria's ability to sustain energy production will be tested in the coming decades as her energy demand far outweighs her supply. The epileptic nature of energy supply has hindered her development and growth albeit, having vast natural resources and abundance of solar insolation. The fall of small businesses, some big companies is imminent as there is always an increase in the cost of energy from fossil fuels due to the expected inflation and trade imbalances, etc. [35].

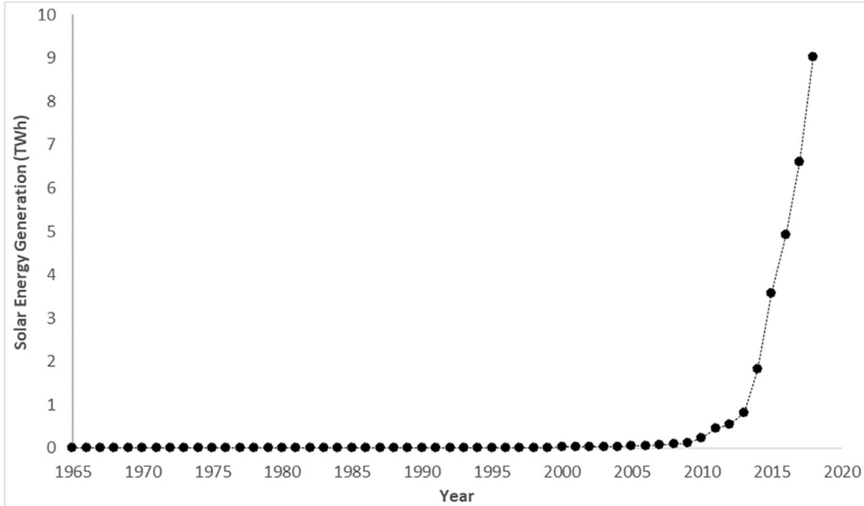

Figure 9. Solar energy generation in Africa. Data source: [37].

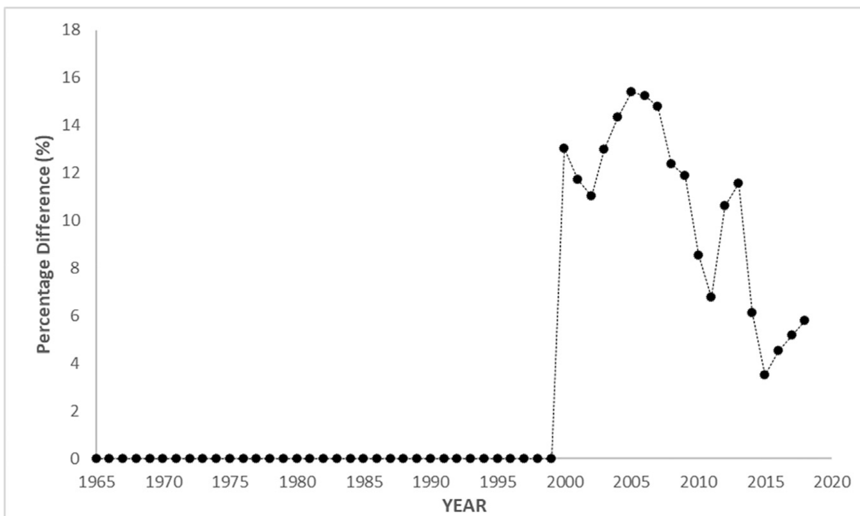

Figure 10. Percentage relationship between West Africa's solar energy generation and Africa's. Data source: [37].

This will affect primarily rural communities as reports show that about 18% of rural residents are exposed to electricity compared to almost 81% of their urban counterparts [30]. An article by Omisore in 2011 [53] shows that it costs the Nigerian government about 150 million, which is about $1.2 million to connect each village to the national grid; meanwhile, the solar energy project will cost around 10 million ($83,000) for each village. Despite the privatization of the Power Holding Company of Nigeria (PHCN), Nigeria's energy demand, which is always exponentially rising, still far outweighs the supply that is quite erratic. Adopting solar-thermal and solar PV technology (on a large scale) will reduce the national consumption of fossil fuel and its related products, boosting its availability and sustainability [54].

It is estimated by Bala EJ [52] that "when 1% of Nigeria's land area is covered with a solar technology of 5% efficiency, about 333,480 MW of electricity may be produced at about 26% capacity factor. This electricity generation capacity will be more than enough for the country up to 2050".

6. Applications

Power generation involves generating electrical energy from available sources into a suitable form for storage, consumption, and distribution. The lack of adequate infrastructure and equipment to measure and implement solar energy electricity generation has resulted in a lack of any exploitable solar resource-based amid the abundance of solar radiation in the country [55]. The Nigerian Meteorological Agency (NiMet) provides the necessary data to measure and estimate the country's total solar radiation from about 30 (primarily airport-based) stations.

There are two known ways of generating power from solar energy: solar PV conversion and CSP (solar thermal conversion) [35].

6.1. Solar-thermal conversion

This deals with heating gases of fluids for steam production and is applied in large-scale power generation for driving gas turbines (Figure 12). In the same way as coal plants, steam is being produced from CSP by focusing sunlight on receivers using mirror surfaced solar collectors (Figure 12), as well as glass, surfaced solar collectors (Figure 13) to produce super-heated fluids and gases. The steam is produced from this super-heated fluid. This steam or heat is stored in thermal tanks containing materials like paraffin wax which can absorb heat without changing its state [49]. Although research has been carried out to develop this area [56], most of Nigeria's solar energy power generation is from solar PV conversion.

6.2. Solar-electric (photovoltaic) conversion

This involves converting direct sunlight into electricity using PV cells. These PV cells are made up of unique materials known as semiconductors

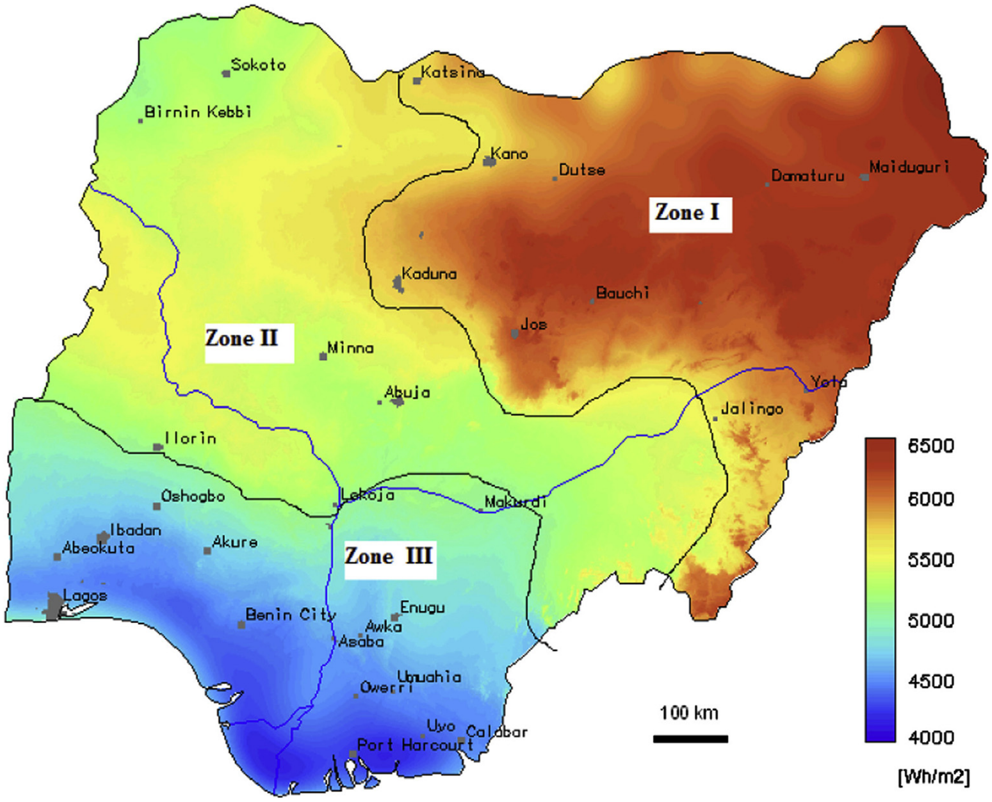

Figure 11. Solar radiation map in Nigeria [48].

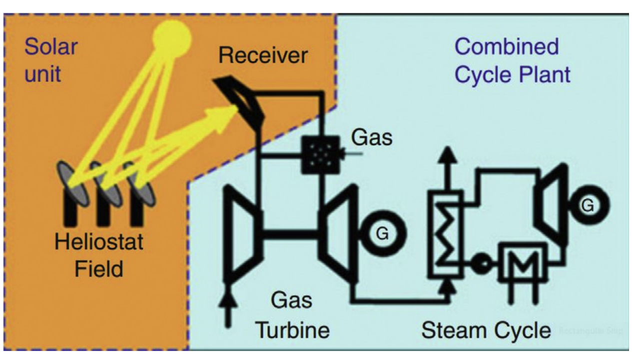

Figure 12. Concentrating Receiver Systems (Solar Power Tower). Scheme of solar-hybrid gas turbine system. Source [57].

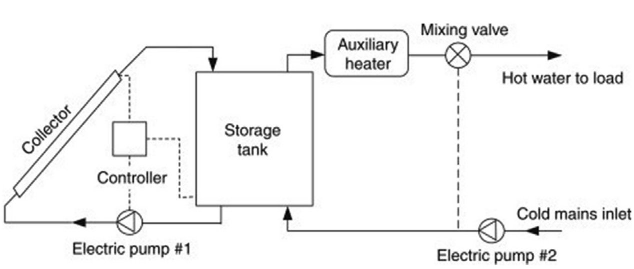

Figure 13. Generation of energy from solar thermal method by heating liquid [58].

and conduct electricity through the photoelectric effect. We combine PV solar panels, inverters, charge controllers, and solar batteries (Figure 14). This is ideal for the constant supply of undisrupted power [59]. A photosensitive switch can be used to switch ON and OFF the solar inverter system intelligently.

The first selenium PV cells were developed by William Grylls Adam and his student Richard Evans Day in the 1980s; these cells could convert energy from the sun into electricity with about 1–2 % efficiency. This has since been developed by improving efficiency, using automatic systems to adjust the orientation, etc. [13, 50]. The daily peak sun hours of a particular region are used to know the solar irradiance and, ultimately, the PV panel's input. This energy has its value in kWh incident of a square meter per day [59].

6.3. Key components of the solar system model

In 1839 Alexandre E. Becquerel (a French physicist) made the first discovery of the PV effect. His observations were clarified in Les Comptes Rendus de l'Academie des Sciences, "the creation of an electric current when two plates of gold or platinum are immersed in an acid, alkaline, or neutral solution is uncovered in an uneven way to solar radiation" [61]. The block diagram of a solar PV system explained below is shown in Figure 15.

6.3.1. Photovoltaic panel

Every solar electric system has the PV panel as its key and most crucial component. As explained, there are made up of semiconductors and work through the photo-electric effect as the energy produced is directly proportional to the sun's energy incident on it. Individual solar cells are connected in series to achieve more useful voltage as only about half a volt is produced from a typical solar cell. Solar panels rated 12-volts produce about 14–18 V when put under load; they can provide energy to charge a 12-volt battery [45].

PV panels absorb short wave solar irradiance, and these panels convert them to DC electricity which charges batteries and operates base stations. "A 1-kW PV panel typically has a 5 m^2 area, and the lifetime of a typical PV panel may exceed 25 years" [62].

The panel's DC rating, tilt angle, and geographic location or solar irradiation profile of the site can affect the power generated by the PV panel [63]. Panels rated 1 kW are valued at about $1000 [63].

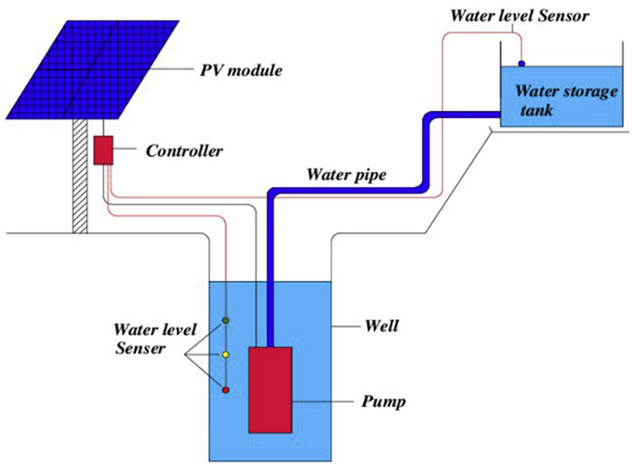

Figure 14. Essential components of a DC solar water-pumping system [60].

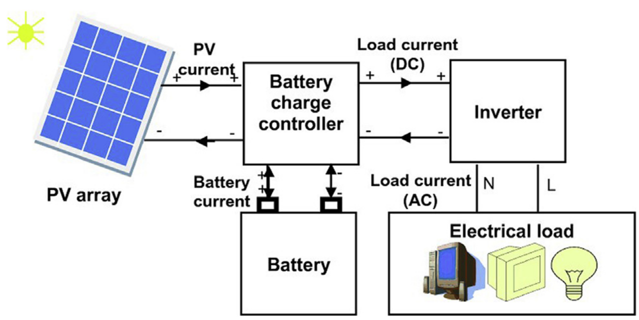

Figure 15. PV standalone system [69].

6.3.2. Battery

The amount of power a solar panel carries is directly in proportion to the incident sunlight. Solar panels are rarely used to power electrical equipment directly. The increase and decrease in the power of the sun's intensity on panels will vary the voltage produced by them. This variability is not suitable for most electrical equipment. A battery bank is always used to meet the base station load demand by storing voltage for consumption when the sun's energy fluctuates during the day or at night when the sun is down. Most solar batteries used for solar photovoltaic systems are 6-volt or 12-volt. And, like solar PVs, these can be connected from a battery bank.

There are different types of batteries based on their requirements. Examples include; Lithium-ion batteries, Lead-acid batteries, Nickel-metal hydride batteries, Zinc-air batteries, etc. Batteries are also chosen based on usage and sizes. 'The sizing of battery is also reliant on the variation in the operating temperature range, extremes in ambient temperature, rate of usage, voltage regulator design, and efficiency of the power electronics converter.' [64]. Multiple batteries used in series

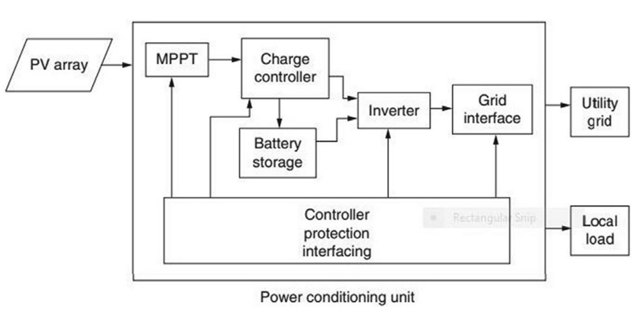

Figure 16. A grid-connected system with battery backup having an maximum power tracking tracking (MPPT) which yields higher returns as the panel voltage increases [68].

increase the capacity and the voltage of a battery bank while maintaining the same current. Multiple batteries can be connected in parallel to increase the current capacity while keeping the voltage constant. Batteries can also be connected both in series and parallel to increase both the output voltage and current.

6.3.3. Charge controller

As the solar intensity varies, the current produced from the solar PV is affected. Charge controllers are required to regulate the flow of current in and out of the battery, which is necessary for protecting the battery. This device protects the battery by limiting the rate at which the electric current produced from the panel is added to drawn from the battery; this can weaken the battery and can pose a safety issue when overcharged. In some cases, depending on the need, a direct current (DC) load can be connected directly to the charge controller for use as some electronic devices use DC voltage. Depending on the charge controller's configuration, it can prevent complete battery discharge by regulating the rate of discharge of current from the battery bank [65].

6.3.4. Inverter

An inverter is one of the most important elements of a solar system model. This device converts the DC voltage into an alternating current (AC) voltage which is useable. The value of this AC voltage will be dependent on the requirements, and for example, the required single-phase AC voltage in Nigeria is about 220 V. The AC voltages have a pure sine wave or a modified sine wave form [65]. From Figure 15, we can see that direct current is what goes into the inverter; the inverter is always connected to the solar array in the grid system or the battery bank in the standalone system (Figures 15 and 16). The latest innovations in inverter technology have been the micro inverters which are used in the grid system. They are connected directly to the individual solar panels making each panel produce AC voltage [34].

6.3.5. Electrical devices/Ac load

The devices that are to be powered by the solar PV system depend on the type of installed system as every device powered by electricity can be powered by the PV system depending on the mode of connection and capacity. For devices with a high demand for electric power, installing a grid system is better than using stand-alone systems. PV systems will demand high power to deal with the variation in the peak voltages. Standalone systems are usually for powering devices with low power.

6.4. Photovoltaic mathematical model

Understanding some parameters related to solar PVs is important in getting an idea of solar PV production capacity. The output energy Q of the solar array is calculated according to;

$$Q = Y_{PV} \times F_{PV} \times PSH \tag{1}$$

Where Y_{PV} is the capacity of the PV array, and PSH is the peak solar hour, is the PV derating factor. 'This derating factor reflects the impact of temperature, dust, wire losses, and other factors that can affect the solar array's output energy' [63, 65].

The performance ratio PR of the solar array indicates the percentage of the incident solar irradiance (power) that is being converted into electrical energy. This ratio can be calculated according to;

Performance ratio of Solar PVs:

$$PR = \frac{(P_{mea}/P_{\max})}{(E_{mea}/1000)} \tag{2}$$

Where E_{mea} is the measured incident solar irradiance (power) on the PV array, P_{mea} and $P_{\max}$ are the measured and maximum power respectively from the PV array [66].

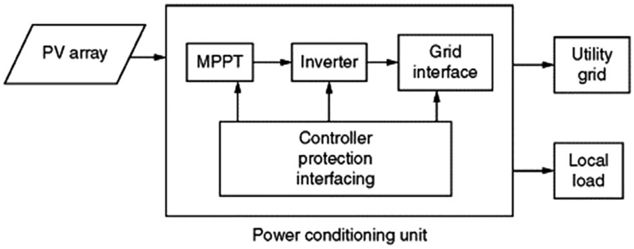

Figure 17. A grid-connected system without battery backup having an maximum power point tracking (MPPT) which yields higher returns as the panel voltage increases [68].

6.4.1. Energy storage using batteries

The maximum state of charge $SOC_{\max}$ of the battery bank is equal to the nominal capacity of the battery bank, i.e., if the minimum state of charge, $SOC_{\min}$ is 30%, it means the maximum energy that will be delivered from the battery bank is 70%. This value is called the depth of discharge, *DOD* and is expressed as [63, 65];

$$DOD = 1 - SOC_{\min} \tag{3}$$

The battery bank autonomy A_{batt}, is a relation (factor) that is used to represent the possible time (in days) in which a battery bank can feed a required load without any contribution from the PV panels. 'This factor can be expressed as the ratio of the battery bank size to the load' [62, 63].

$$A_{batt} = \left[\frac{N_{batt} \times V_{nom} \times Q_{nom} \times \left(1 - \frac{SOC_{\min}}{100}\right) \times \left(\frac{24h}{d}\right)}{L_{prim-avg}} \right] \tag{4}$$

Where N_{batt} is the number of batteries, is the voltage of a single battery, Q_{nom} is the capacity of a single battery, and $L_{prim-avg}$ is the average daily load. The battery lifecycle R_{batt} is another important issue that can reduce the total replacement cost during the project lifecycle. The throughput and the battery float life are the main factors that affect R_{batt}. The battery lifecycle can be calculated by [63, 65];

$$R_{batt} = \min\left(\frac{N_{batt} \times Q_{life}}{Q_{thr}} \times R_{batt.f}\right) \tag{5}$$

Where Q_{life} is the lifetime throughput of a single battery, Q_{thr} is the annual battery throughput, and $R_{batt.f}$ is the battery float life.

6.5. Types of solar powered systems

Depending on the grid or other power sources' availability, a BS may be powered solely or partially by solar energy. There are four (4) major types of electrical designs for PV powers used for base stations. These include;

- Grid-connected (No battery backup)
- Grid-connected (Battery backup)
- Solar stand-alone
- Hybrid stand-alone

6.5.1. Grid-connected system (No battery back-up)

This is the cheapest and most reliable configuration of solar PVs. They are the simplest systems because they require no battery backup because they are designed to contribute power and not for backup [67]. These systems are used to support loads connected to other energy sources where there might be fluctuations in power. This system has the grid power available. It is a solar-powered system with no battery backup (Figure 17); this is usually used for bad grid sites. Although cheap, this system has its disadvantages because if grid power failure, there might be insufficient power produced from the solar PV due to the low solar irradiance or the night hours. This is unreliable because power in BSs will continuously fluctuate, and this is not advisable, which is why this system is used for support and not as an alternative power supply.

6.5.2. Grid-connected system (battery back-up)

Battery backup maintains power to electrical equipment when there's a power outage from the electrical grid. In the case of a grid power failure and insufficient renewable energy generation, the batteries can be used to power the BSs. The advantage here is that unlike grid-connected systems with no battery backup, systems with battery backup can maintain a constant power level when used, as the battery stores energy when not in use (Figure 16). However, this system has its disadvantages as batteries are expensive (installation, maintenance, and replacement). They also consume energy in discharging and charging, which reduces the output and efficiency of the solar PV system, especially for lead-acid batteries.

6.5.3. Solar stand alone

These systems are used a utility power substitutes; they use only solar energy to provide electricity to the load. Due to the variation of the solar irradiance at different times of the day, and its negligibility at night, it is crucial to include battery backups in solar standalone systems (Figure 15). BSs in off-grid sites, etc., use solar standalone systems, and the battery backup has to be designed carefully to produce the required voltage and/or current for the BSs. Solar standalone systems can be used in conjunction with a diesel generator in BSs.

6.5.4. Hybrid standalone

These systems are similar to stand-alone systems, but as the name implies (*hybrid*), they have more than one renewable energy source instead of one renewable energy source for power generation. These systems are usually configured to meet the power needs of a broader range in remote areas; they are rarely used for BSs. They need fewer storage devices compared to solar standalone systems, and they can also combine nonrenewable energy sources like natural gas and diesel, etc. Figure 18 shows a hybrid system with solar energy, wind power as renewable energy sources, and diesel generator as the secondary power.

7. Solar radiation in Nigeria

We can quickly understand and almost accurately calculate the amount of electrical energy that can be gotten from the sun if appropriately utilized. Using solar irradiance data, we can understand their variation by taking a deep look at Figure 11; this will give us a slight idea of what to expect. However, a more accurate method can be employed [71].

There have been studies on global solar radiation at different locations in Nigeria [72, 73, 74, 75, 76, 77]. Most of these locations use sunshine hours to evaluate the electrical energy that can be generated from the sun by taking note of the Global Solar Radiation G_{hi} and the extra-terrestrial irradiance $H_{o.}$

The geographical location is one of the major factors affecting global solar radiation [78]. Another effect is the climatic condition of the region; this is related to the region's location.

One of the main reasons why most countries do not utilize this primary source of energy is that they do not directly study and understand global solar radiation variation. This laxity in the study will lead to projected energy production that cannot realistically be reached [79] and models that cannot become a reality [80].

Solar irradiance over Nigeria has been studied and shows that her northern region possesses more significant potential for solar energy electricity generation [81].

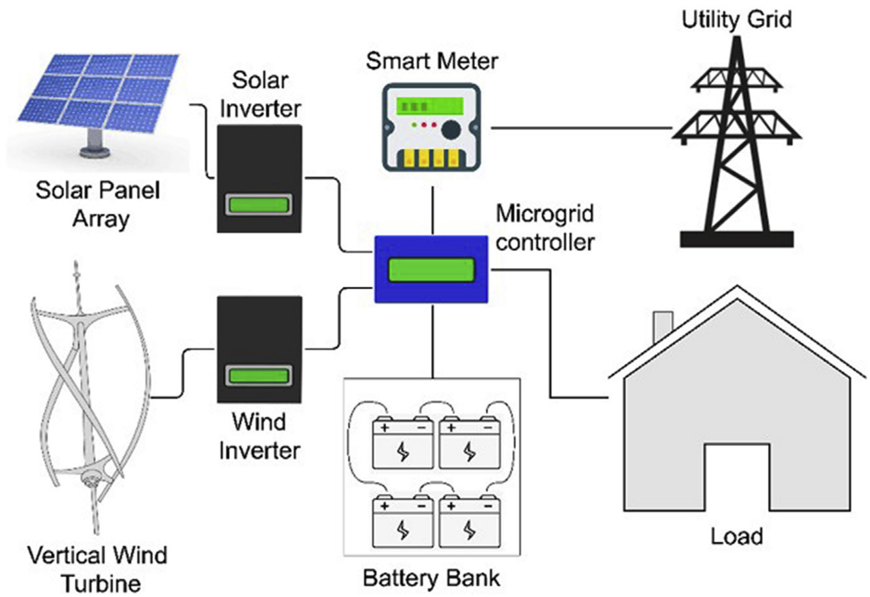

Figure 18. Solar and diesel generator hybrid standalone system [70].

7.1. *Methodology; estimating solar radiation potential*

Models have been made for different locations; estimating the solar energy potential can be accurately done by taking note of the solar irradiance data. The area of the PV module 'A' can directly determine the solar energy potential too;

$$E = ArG_{hi}P_R(kWh) \tag{6}$$

Eq. (6) shows the energy in kWh. A is the area (in m^2) of the PV module, r is the yield (%) of the PV module, G_{hi} is the average irradiation (kWh/m^2/day) on the solar PV module at any specific angle. The performance ratio (P_R) can be explained from Eq. (2) and is usually 0.75 for typical systems.

To estimate the solar energy generation potential from the daily values of solar irradiance, we use the equation below;

$$E = 365P_K G_{hi} P_R(kWh) \tag{7}$$

The equation above gives the total estimated annual energy output (E) by considering the average daily solar radiation data G_{hi}, the performance ratio $P_{R,}$ and the unit Peak power (P_K). The constant 365 signifies the 365 days of the year, taking the average daily solar radiation (G_{hi}) into account. We assume that a unit peak power (P_K) of 1 kWp for the PV module; will give the value of P_K to be 1 [81].

To correctly estimate the annual energy output (E), we consider the average monthly radiation data obtained from a PVGIS (Photovoltaic Geographic Information System) Satellite. As used by Akorede et al [71], the daily radiation data to estimate (using equation 7) may not be entirely accurate as it did not take into account the leap years.

Eq. (8) below gives a more accurate estimation.

$$E = 12P_K G_{hi(mo)} P_R(kWh) \tag{8}$$

The factor "365" has been replaced with "12," signifying the 12 months of the year, which never changes, unlike 365 days which varies in leap years. $G_{hi(mo)}$ represents the monthly solar radiation data for optimally inclined planes (kWh/m^2/mo), P_R and P_K is the performance ratio (0.75) and the peak power (1 kWp), respectively.

The global radiation data for the optimally inclined planes (H_{opt}) of the PV module used in Eq. (8) is the value of the summation of the monthly radiation energy incident on 1 Sq-m (one square meter) (which is facing the direction of the equator. The angle of inclination (optimally

Table 1. Monthly averaged global irradiation (kWh/m^2/mo) for North-Central Nigeria (2005–2016).

Month	Abuja		Illorin		Jos		Lafia		Lokoja		Makurdi		Minna	
	H_{opt}	H_h	H_{opt}	H_h	H_{opt}	H_h	H_{opt}	H_h	H_{opt}	H_h	H_{opt}	H_h	H_{opt}	H_h
Jan	221.02	194.81	213.97	192.29	229.01	199.02	220.66	196.60	211.44	192.49	215.38	194.79	219.54	193.28
Feb	196.85	182.74	192.97	181.04	209.50	191.86	196.70	183.74	189.48	179.26	190.46	179.68	198.98	184.18
Mar	202.86	199.93	197.45	194.87	217.78	213.54	202.07	199.43	195.19	193.04	196.22	194.07	208.01	204.44
Apr	179.39	186.25	181.78	187.52	177.70	184.95	179.76	185.95	179.24	184.30	177.64	183.14	187.03	193.99
May	161.13	173.73	167.29	179.18	159.86	173.70	164.34	176.33	167.00	177.48	163.43	174.32	170.35	184.02
Jun	138.04	150.53	146.55	158.75	145.39	160.62	142.42	154.95	150.92	162.67	143.57	154.86	146.53	160.22
Jul	131.07	141.17	135.38	144.43	135.82	147.89	140.13	151.02	147.28	156.95	139.70	149.22	136.14	147.03
Aug	123.29	128.85	128.00	132.84	132.16	138.68	131.54	137.26	143.51	148.67	135.47	140.55	129.11	134.80
Sep	146.00	147.06	145.41	146.20	157.19	158.10	147.76	148.77	155.76	156.43	147.51	148.41	155.79	156.51
Oct	179.21	171.29	176.62	169.64	196.75	185.75	184.84	176.95	181.72	174.89	176.03	169.65	190.22	180.80
Nov	208.76	186.57	196.29	179.16	222.05	195.06	207.14	186.99	199.55	183.43	196.89	180.66	210.66	187.76
Dec	220.35	190.50	211.32	187.01	229.08	194.32	218.28	191.33	209.77	188.38	212.07	189.29	219.97	189.85
Average	175.66	171.12	174.42	171.08	184.36	178.62	177.97	174.11	177.57	174.83	174.53	171.55	181.03	176.40

Table 2. Monthly averaged global irradiation (kWh/m^2/mo) for North-Eastern Nigeria (2005–2016).

Month	Bauchi		Damaturu		Gombe		Jalingo		Maiduguri		Yola	
	H_{opt}	H_h	H_{opt}	H_h	H_{opt}	H_h	H_{opt}	H_h	H_{opt}	H_h	H_{opt}	H_h
Jan	226.37	197.74	227.79	195.69	226.45	198.25	225.70	199.47	229.00	196.12	225.68	199.81
Feb	210.19	192.82	211.43	191.71	208.97	192.06	205.25	190.23	211.52	191.59	206.66	191.63
Mar	222.04	217.19	227.94	221.39	221.34	216.53	213.84	210.36	227.75	221.22	218.01	214.13
Apr	195.23	202.01	205.24	212.30	196.58	203.37	189.22	196.34	205.73	213.09	193.33	200.04
May	180.63	195.01	191.61	207.76	182.18	196.68	168.91	182.43	190.11	206.52	174.61	188.02
Jun	164.19	180.63	172.40	190.28	165.30	181.79	149.32	163.42	167.67	185.28	159.67	174.73
Jul	157.16	170.84	168.15	183.41	158.22	171.80	137.68	148.90	164.14	179.24	153.07	165.73
Aug	153.47	160.72	161.37	169.02	149.12	155.88	133.90	139.99	158.27	165.94	148.95	155.70
Sep	174.89	175.08	182.11	181.49	173.42	173.49	153.43	154.23	181.82	181.27	167.24	167.70
Oct	208.48	196.52	213.15	199.06	207.28	195.62	192.92	183.79	213.43	199.10	202.07	191.94
Nov	219.98	194.49	220.00	191.60	218.38	193.47	215.18	192.39	220.08	191.26	217.66	194.73
Dec	224.23	192.20	223.77	188.46	223.28	191.85	223.94	194.18	225.13	188.92	224.18	194.81
Average	194.74	189.60	200.41	194.35	194.21	189.23	184.11	179.64	199.55	193.29	190.93	186.58

Table 3. Monthly averaged global irradiation (kWh/m^2/mo) for North-Western Nigeria (2005–2016).

Month	Birnin Kebbi		Dutse		Gasau		Kaduna		Kano		Katsina		Sokoto	
	H_{opt}	H_h	H_{opt}	H_h	H_{opt}	H_h	H_{opt}	H_h	H_{opt}	H_h	H_{opt}	H_h	H_{opt}	H_h
Jan	222.43	190.35	223.29	193.06	222.75	191.06	225.92	195.73	222.50	191.73	222.53	189.44	220.04	187.48
Feb	207.15	187.41	208.50	189.64	209.92	189.89	208.16	190.33	208.91	189.60	210.84	189.52	207.93	187.16
Mar	223.70	216.84	225.14	218.89	225.43	218.73	219.08	214.30	225.86	219.35	230.47	222.62	225.11	217.59
Apr	204.35	211.11	205.47	212.29	203.10	210.15	193.90	201.57	206.26	213.16	208.91	215.84	207.39	214.06
May	188.85	204.79	189.93	205.37	187.58	203.49	175.79	190.88	190.56	206.06	194.77	211.55	193.25	209.64
Jun	170.74	188.65	171.75	188.91	169.42	187.13	151.86	167.00	172.33	189.78	176.60	195.23	175.81	194.39
Jul	165.70	180.95	166.64	181.39	162.48	177.16	143.31	155.31	168.08	183.18	172.64	188.59	171.14	186.91
Aug	159.53	167.11	164.99	172.78	158.22	165.85	138.15	144.68	164.70	172.55	168.07	176.17	164.58	172.36
Sep	181.01	180.06	183.70	183.06	182.57	181.91	163.00	163.57	185.63	184.89	192.26	190.93	187.62	186.25
Oct	215.07	199.93	214.06	200.09	212.97	198.39	199.52	187.98	215.80	201.29	219.12	202.89	215.53	199.65
Nov	214.63	186.57	218.13	190.89	218.39	189.73	219.15	192.30	218.01	190.22	219.23	189.01	215.57	186.23
Dec	220.03	184.58	219.90	186.48	221.77	186.23	225.78	191.40	220.07	185.95	220.90	184.03	218.33	182.31
Average	197.76	191.53	199.29	193.57	197.88	191.64	188.63	182.92	199.89	193.98	203.03	196.32	200.19	193.67

inclined angle) is the one that gives the highest annual irradiation in KWh/m^2.

The value of the total monthly horizontal irradiation H_h (in kWh/m^2/mo) (hitting a horizontal plane) was collected and presented in tables alongside H_{opt} for all state capitals in Nigeria separated by their respective geopolitical zones in Tables 1, 2, 3, 4, 5, and 6.

7.2. Results and Discussion

.

Data of the optimally inclined angles of the global radiation H_{opt} and the horizontal plane H_h were collected and presented in Tables 1, 2, 3, 4, 5, and 6. Each table represents the six geopolitical zones in Nigeria; North

Table 4. Monthly averaged Monthly global irradiation (kWh/m^2/mo) for South-Eastern Nigeria (2005–2016).

Month	Abakiliki		Awka		Enugu		Owerri		Umuahia	
	H_{opt}	H_h	H_{opt}	H_h	H_{opt}	H_h	H_{opt}	H_h	H_{opt}	H_h
Jan	204.95	189.94	201.14	186.51	203.94	188.26	197.09	184.38	199.14	186.09
Feb	179.44	171.89	174.53	167.39	174.22	166.79	170.75	164.55	172.09	165.72
Mar	182.77	181.49	178.75	177.61	177.23	176.14	173.24	172.36	171.85	170.97
Apr	170.35	174.66	165.64	169.88	166.77	171.26	163.04	167.02	162.04	166.00
May	158.06	166.64	150.58	158.54	154.15	162.79	147.81	155.01	148.59	155.98
Jun	140.61	149.62	134.32	142.79	137.83	146.99	126.31	133.29	128.17	135.45
Jul	131.29	138.04	124.72	131.12	127.21	134.02	119.47	124.82	120.29	125.81
Aug	130.57	134.42	127.63	131.55	128.24	132.30	126.27	129.82	126.14	129.70
Sep	142.13	142.86	134.82	135.61	137.44	138.25	132.02	132.77	132.01	132.80
Oct	166.93	162.42	158.98	154.87	165.92	161.22	154.55	151.15	157.09	153.52
Nov	181.25	170.17	179.69	168.78	183.73	171.73	169.81	160.87	171.21	161.93
Dec	198.26	182.20	196.80	180.83	200.61	183.13	189.67	176.22	192.54	178.55
Average	165.55	163.70	160.63	158.79	163.11	161.07	155.84	154.35	156.76	155.21

Table 5. Monthly averaged Monthly global irradiation (kWh/m^2/mo) for South-South Nigeria (2005–2016).

Month	Asaba		Calabar		Benin City		Port Harcourt		Uyo		Yenagoa	
	H_{opt}	H_h	H_{opt}	H_h	H_{opt}	H_h	H_{opt}	H_h	H_{opt}	H_h	H_{opt}	H_h
Jan	199.70	186.40	196.36	184.14	195.16	181.88	190.67	179.21	193.07	181.53	193.04	180.84
Feb	171.80	165.34	168.21	162.39	169.55	162.94	162.03	156.67	164.37	158.93	163.32	157.61
Mar	176.88	175.80	162.70	162.07	173.07	171.93	157.61	157.01	161.22	160.60	162.76	162.11
Apr	168.75	172.73	150.18	153.84	163.91	167.82	150.16	153.90	153.88	157.50	149.59	153.44
May	155.98	163.88	143.38	150.53	153.16	160.99	136.63	143.24	141.63	148.27	134.41	141.15
Jun	138.25	146.36	115.93	122.09	132.08	139.83	106.83	112.28	116.40	122.48	111.32	117.40
Jul	127.39	133.40	102.07	106.37	119.87	125.47	104.52	108.85	107.34	111.85	107.86	112.65
Aug	130.47	134.11	106.51	109.26	123.43	126.97	113.64	116.66	114.90	117.91	117.76	121.18
Sep	138.15	138.81	118.46	119.19	130.73	131.36	116.23	116.97	120.44	121.13	116.63	117.42
Oct	162.04	157.95	143.14	140.38	158.32	154.29	137.64	135.01	143.42	140.59	139.76	136.88
Nov	179.44	169.26	153.45	146.35	172.05	162.42	149.89	142.90	157.87	150.44	158.91	150.72
Dec	194.24	179.88	184.80	172.32	187.41	173.37	182.31	170.32	184.54	172.36	186.29	173.19
Average	161.92	160.33	145.43	144.08	156.56	154.94	142.35	141.08	146.59	145.30	145.14	143.72

Table 6. Monthly averaged Monthly global irradiation (kWh/m^2/mo) for South-Western Nigeria (2005–2016).

Month	Abeokuta		Ado-Ekiti		Akure		Ibadan		Ikeja		Osogbo	
	H_{opt}	H_h	H_{opt}	H_h	H_{opt}	H_h	H_{opt}	H_h	H_{opt}	H_h	H_{opt}	H_h
Jan	200.922	184.68	205.96	187.61	202.10	185.31	200.95	184.01	192.51	178.39	204.87	186.14
Feb	176.98	168.72	182.20	172.70	176.98	168.50	177.54	168.83	167.27	160.35	182.83	172.95
Mar	177.62	176.13	186.29	184.53	180.22	178.77	181.23	179.68	171.77	170.60	186.89	185.03
Apr	165.54	170.06	172.61	177.76	168.46	173.16	168.67	173.50	162.59	166.91	171.01	176.15
May	158.16	167.59	160.50	170.81	158.11	167.73	160.07	170.21	145.90	153.94	158.70	169.03
Jun	132.51	141.30	141.55	152.25	138.13	147.93	135.20	144.73	114.00	120.90	138.12	148.68
Jul	122.45	129.02	131.54	139.57	126.93	133.97	121.29	128.02	115.58	121.43	122.65	130.09
Aug	120.75	124.41	127.31	131.67	122.01	125.90	117.75	121.46	125.74	129.72	115.45	119.37
Sep	132.68	133.36	139.92	140.69	137.70	138.45	132.51	133.26	125.28	126.00	131.99	132.81
Oct	163.05	158.28	171.02	165.22	167.01	161.76	166.93	161.55	149.18	145.12	162.98	157.67
Nov	177.58	165.99	192.84	177.60	186.53	173.08	183.46	170.21	165.12	155.35	187.04	172.33
Dec	195.48	178.06	207.48	186.01	201.31	182.11	197.29	178.59	184.95	170.03	203.06	181.93
Average	160.31	158.13	168.27	165.53	163.79	161.39	161.91	159.50	151.66	149.89	163.80	161.01

Central (Table 1), North East (Table 2), North West (Table 3), South East (Table 4), South-South (Table 5), and South West (Table 6). The global total monthly radiation was collected from 2005-2016, and the average was found for each month and presented for all state capitals of the different regions. From mere observations, it can be concluded that the Northern states evidently have higher values of global solar radiation, which is in agreement with facts as the Northern States are hotter, and the Southern States generally have lower temperature values, mainly because of their closeness to the Atlantic Ocean [6, 7, 8, 9].

After using the total monthly global solar radiation with Eq. (8), the estimated solar energy generation for all the six geopolitical zones has been calculated and presented in Tables 7, 8, 9, 10, 11, and 12. Table 7

Table 7. Estimated electricity generation from 1 kWp PV module in North Central Nigerian cities.

City	Coordinates (Decimal)	Optimal inclination angle (°)	Yearly Averaged Monthly radiation for H_h (kWh/m^2/mo)	Yearly Averaged Monthly radiation for H_{opt} (kWh/m^2/mo)	Annual Electricity generation from H_h (kWh)	Annual Electricity generation from H_{opt} (kWh)
Abuja	9.063N 7.489E	16	171.12	175.66	1,540.07	1,580.97
Illorin	8.491N 4.549E	14	171.08	174.42	1,539.69	1,569.77
Jos	9.922N 8.859E	17	178.62	184.36	1,607.62	1,659.21
Lafia	8.490N 8.513E	15	174.11	177.97	1,566.99	1,601.73
Lokoja	7.800N 6.744E	12	174.83	177.57	1,573.49	1,598.15
Makurdi	7.729N 8.540E	13	171.55	174.53	1,543.98	1,570.77
Minna	9.617N 6.547E	16	176.40	181.03	1,587.64	1,629.25
Average		14.71	173.96	177.93	1,565.64	1,601.41
Total			1217.72	1245.54	10,959.48	11,209.85

Table 8. Estimated electricity generation from 1 kWp PV module in North-Eastern Nigerian cities.

City	Coordinates (Decimal)	Optimal inclination angle (°)	Yearly Averaged Monthly radiation for H_h (kWh/m^2/mo)	Yearly Averaged Monthly radiation for H_{opt} (kWh/m^2/mo)	Annual Electricity generation from H_h (kWh)	Annual Electricity generation from H_{opt} (kWh)
Bauchi	10.308N 9.843E	16	189.60	194.74	1,706.43	1,752.64
Damaturu	11.838N 11.901E	17	194.35	200.41	1,749.11	1,803.73
Gombe	10.279N 11.171E	15	189.23	194.21	1,703.09	1,747.89
Jalingo	8.967N 11.309E	15	179.64	184.11	1,616.80	1,656.97
Maiduguri	11.837N 13.156E	17	193.29	199.55	1,739.65	1,795.97
Yola	9.254N 12.45E	14	186.58	190.93	1,679.22	1,718.33
Average		15.67	188.78	193.99	1,699.05	1,745.92
Total			1,132.70	1,163.95	10,194.31	10,475.52

Table 9. Estimated electricity generation from 1 kWp PV module in North-Western Nigerian cities.

City	Coordinates (Decimal)	Optimal inclination angle (°)	Yearly Averaged Monthly radiation for H_h (kWh/m^2/mo)	Yearly Averaged Monthly radiation for H_{opt} (kWh/m^2/mo)	Annual Electricity generation from H_h (kWh)	Annual Electricity generation from H_{opt} (kWh)
Birnin Kebbi	12.454N 4.198E	17	191.53	197.76	1,723.75	1,779.88
Dutse	11.751N 9.341E	16	193.57	199.29	1,742.13	1,793.63
Gusau	12.164N 6.663E	17	191.64	197.88	1,724.79	1,780.95
Kaduna	10.518N 7.435E	17	182.92	188.63	1,646.27	1,697.70
Kano	12.000N 8.532E	16	193.98	199.89	1,745.82	1,799.03
Katsina	12.988N 7.600E	17	196.32	203.03	1,766.85	1,827.25
Sokoto	13.057N 5.2360E	17	193.67	200.19	1,743.02	1,801.72
Average		16.71	191.95	198.10	1,727.52	1,782.88
Total			1343.63	1386.69	12,092.64	12,480.17

shows the estimated electricity generation from 1 kWp (kilowatt-peak) PV module for North Central Nigerian cities. Each city's coordinates are clearly shown, and the angle for the optimal reception of the sun's energy. The annual electricity generation in kWh (kilowatt-hour) is presented for all cities in the North-Central geopolitical zone.

In the same way, the estimated electricity generation from 1 kWp PV module for North Eastern (Table 8), North Western (9), South Eastern (Table 10), South Southern (Table 11), and South Western (Table 12) Nigerian cities. The tables show that the region with the higher potential for annual electricity generation from 1 kWp PV modules is the Northern states. The Northern states are closer to the Sahara Desert, and these regions have higher elevations above the sea level than the cities located towards the South.

Figure 19 clearly shows the average estimated electricity generation for each geopolitical zone. We can see from this representation that this gives an accurate description of the electrical energy that can be generated from each major city in each geopolitical zones. The North Western cities have the highest average estimated electricity generation with

Table 10. Estimated electricity generation from 1 kWp PV module in South-Eastern Nigerian cities.

City	Coordinates (Decimal)	Optimal inclination angle	Yearly Averaged Monthly radiation for H_h (kWh/m$_2$/mo)	Yearly Averaged Monthly radiation for H_{opt} (kWh/m$_2$/mo)	Annual Electricity generation from H_h (kWh)	Annual Electricity generation from H_{opt} (kWh)
Abakiliki	6.312N 8.107E	11	163.70	165.55	1,473.27	1,489.96
Awka	6.218N 7.083E	11	158.79	160.63	1,429.11	1,445.69
Enugu	6.463N 7.542E	11	161.07	163.11	1,449.67	1,467.97
Owerri	5.490N 7.034E	10	154.35	155.84	1,389.19	1,402.53
Umuahia	5.525N 7.517E	10	155.21	156.76	1,396.89	1,410.86
Average		10.60	158.62	160.38	1,427.62	1,443.40
Total			793.12	1163.95	10,194.31	10,475.52

Table 11. Estimated electricity generation from 1 kWp PV module in South-South Nigerian cities.

City	Coordinates (Decimal)	Optimal inclination angle	Yearly Averaged Monthly radiation for H_h (kWh/m$_2$/mo)	Yearly Averaged Monthly radiation for H_{opt} (kWh/m$_2$/mo)	Annual Electricity generation from H_h (kWh)	Annual Electricity generation from H_{opt} (kWh)
Asaba	6.025N 6.693E	10	160.33	161.92	1,442.95	1,457.31
Calabar	4.977N 8.313E	10	144.08	145.43	1,296.69	1,308.88
Benin	6.325N 5.607E	10	154.94	156.56	1,394.45	1,409.05
Port Harcourt	4.814N 7.080E	10	141.08	142.35	1,269.76	1,281.14
Uyo	5.048N 7.907E	10	145.30	146.59	1,307.70	1,319.31
Yenagoa	4.904N 6.234E	10	143.72	145.14	1,293.45	1,306.22
Average		10.00	148.24	149.67	1,334.17	1,346.99
Total			889.45	1163.95	10,194.31	10,475.52

Table 12. Estimated electricity generation from 1 kWp PV module in South Western Nigerian cities.

City	Coordinates (Decimal)	Optimal inclination angle	Yearly Averaged Monthly radiation for H_h (kWh/m$_2$/mo)	Yearly Averaged Monthly radiation for H_{opt} (kWh/m$_2$/mo)	Annual Electricity generation from H_h (kWh)	Annual Electricity generation from H_{opt} (kWh)
Abeokuta	7.155N 3.339E	12	158.13	160.31	1,423.20	1,442.79
Ado-Ekiti	7.601N 5.273E	13	165.53	168.27	1,489.81	1,514.41
Akure	7.258N 5.218E	12	161.39	163.79	1,452.51	1,474.11
Ibadan	7.371N 3.964E	12	159.50	161.91	1,435.54	1,457.17
Ikeja	6.626N 3.361E	11	149.89	151.66	1,349.05	1,364.91
Osogbo	7.754N 4.581E	13	161.01	163.80	1,449.13	1,474.19
Average		12.17	159.25	161.62	1,433.21	1,454.60
Total			955.47	1163.95	10,194.31	10,475.52

about 1,783 kWh, followed by other northern cities (North East and North Central respectively). The Southern states have low estimated electricity generation, with the South-South cities having the lowest (about 1347 kWh). Their proximity to the Atlantic Ocean can explain this. These facts agree with results presented by Adejumo et al. [77] when they explored measured solar radiation from three geopolitical zones in Nigeria (Ibadan, Port-Harcourt, and Sokoto, respectively).

Figure 20 shows the total estimated electricity generation for each geopolitical zone. The cities in the North-Western region produce the highest estimated electrical energy (about 12,480 kWh), the cities in the Southern region all have the same estimated electricity generation (about 10,475 kWh).

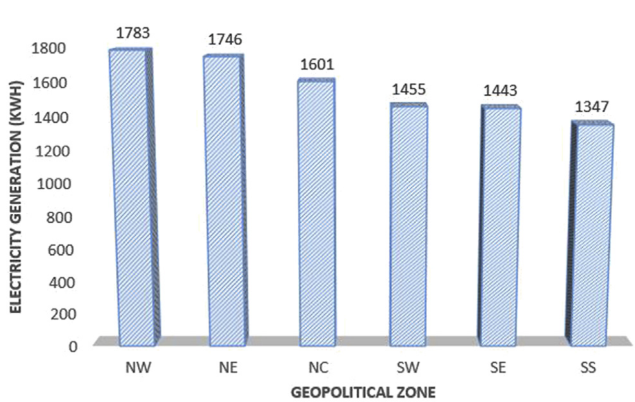

Figure 19. Average estimated electricity generation from each geopolitical zone in kWh.

7.3. PV module inclination and its effects on electricity generation

The inclination angle of PV modules has enormous effects on the electrical energy that can be gotten from the sun. Extracting maximum power from solar panels and these inclination angles can be altered monthly with respect to the region [82]. These angles are somewhat the same across all months of the year, with slight variations. Tables 7, 8, 9,

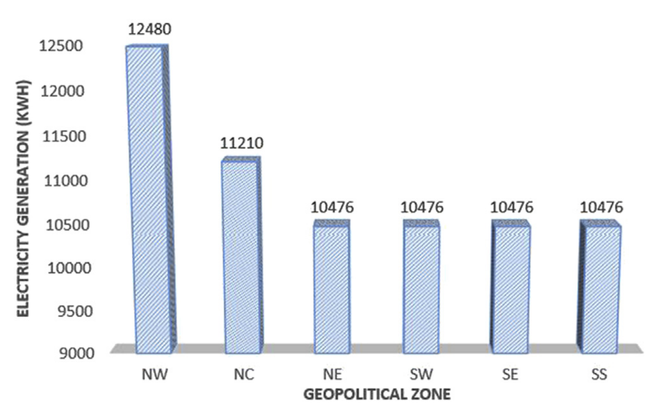

Figure 20. Total estimated electricity generation from each geopolitical zone in kWh.

10, 11, and 12 show the annual electricity generation from solar radiation for both the optimally inclined angles and the PV modules on a horizontal plane. It can be clearly seen from the tables that the estimated electricity generation from the optimally inclined angles (H_{opt}) is higher for all cities in all zones than the estimated electricity generation from PV modules on the horizontal plane (H_h). The inclination angles are presented for all cities and the average found for each zone. We can see from Tables 7, 8, 9, 10, 11, and 12 that the optimal inclination angle for the northwestern cities is about 17° on average, 16° for the northeastern cities, 15° for the north-central cities, 12° for the southwestern cities, 11° for the southeastern cities, and 10° for the South-South cities. This trend is highly dependent on the elevation of the region [74, 77]. The Southern cities have lower elevation on average, compared to the Northern cities. This is because the Southern cities are close towards the shore of the Atlantic Ocean in the Southern region, making their elevation close to the sea level.

7.4. Effects of unsustainable energy in Nigeria

The negative consequences of unsustainable renewable energy cannot be over-emphasized. They have substantial negative impacts on the environment, health sector, economy, domestic sector, and others [54]. One major cause of these negative impacts is the lack of sound resource management arising from lack of commitment from the governing bodies to developing the RE sector. These have significant effects on a region reaching her energy generation goals. Going against these negative processes will increase renewable energy utilization (e.g., solar energy) for a region's growth amid an exponential increase in the population [83].

Solar-thermal energy has been the most utilized form of solar energy in Nigeria for years, especially in rural areas. It is used for agro-processing purposes like drying of produce for preservation, etc. It can also be used to heat animal pens [48], food and vaccine storage, etc. Energy from solar PVs has not been utilized globally; it has majorly been adopted in street lighting and small-scale rural electrification.

8. The renewable energy master plan

Nigeria developed the Renewable Energy Master Plan (REMP) by inputs from experts from the Energy Commission of Nigeria (ECN) and the United Nations Development Programme (UNDP) in 2005. They developed objectives and targets to improve the development challenges facing the adoption of RE in the nation. [2, 84];

The objectives were summarized as follows [85];

- ✓ To raise the standard of living in rural areas by expanding their access to renewable energy services, stimulating the growth of the economy, empowering citizens, and increasing employment.
- ✓ Reducing the environment's degradation and health risks (especially to women and children); improving the quality and scope of rural areas (schools, health care, water availability, information, and entertainment).
- ✓ Enhancing learning, research, development, capacity building on every available RE sector in the nation.
- ✓ Encouraging and providing a path to achieving an energy mix (both renewable and non-renewable).

Until these targets are achieved perfectly, crude oil will continue to be the primary energy source in the country, even with the steady reduction of solar PV modules per unit watt-peak (Figure 5).

The REMP seeks to achieve a gradual increase in the percentage generation of electricity in Nigeria from RE sources from 13% (2015) to 23% (2025) to 36% (2030).

By these targets, the country's electricity consumption from renewable energy will be said to about 10% of the total energy consumption in 2025, including about 500 MW from solar PVs. It is important to note that until these plans are implemented, they will be mere targets.

9. Challenges

Finance: Even with the reduction of the average price of PV modules per unit energy output (Figure 5), the availability of these modules for Nigerian citizens is low, and if available, the cost is high. This may be attributed to the exchange rates and the government's inability to adopt this technology on a large scale and subsidizing importation or production prices. Nigeria adopting this technology might opt to go into debt and long payback times [35].

Low level of awareness: The low level of awareness about the country's utilization is quite disappointing. The public is generally unaware of the processes of implementing solar PVs. For instance, a typical Nigerian home without proper electricity access can install solar PVs for personal use. Comparing this price to the relative price from their total fuel consumption, the cost from the former overwhelms the latter. Solar PVs can be used side by side with electric generators to reduce cost-effectively. The information available on the implementation, application, and development, etc., of solar energy resources and renewable energy as a whole, is low and inadequate. For the country to step up in this, the media and the educational sector have to work together with the government [54].

Technological incapability: Some technological components for developing and harvesting solar energy are not developed in Nigeria significantly [35]. This importation has hiked up the price for large-scale investment in solar energy. Nigeria is overly dependent on her crude oil utilization; this has reduced investments in solar PV modules and renewable energy as a whole. The lack of equipped laboratories for research has affected this too [54]. This has made the citizens fall back to the cheap, easily assessable fuel and firewoods for industrial and domestic use without considering the health implications, environmental sustainability, and climate change.

9.1. Economics of photovoltaics

As explained in Figure 5, the global cost of PV modules per generated electricity is reducing annually, but the economics of PVs in Nigeria affects these PV modules' costs. They include; the price per unit area, the Nigerian market's size, the status of technology development, the quality of manufacturing automation, lifetimes module efficiency, the economics of scale, etc. With an estimated 54% of the Nigerian population living below the poverty line (90% in northern Nigeria) (Nigeria Country Programme document, 2014–2017, UNICEF) [54], the adoption of solar PV technology will be challenging given the above drawbacks.

9.2. Maintenance and operation costs

The lack of enough technically skilled persons, information on the proper use and management of PV modules, and the availability of these modules, etc., has appreciated the operation and maintenance costs for adopting solar energy in Nigeria [48]. The above-mentioned effects of operation and maintenance have prevented the adoption of solar PVs, especially for rural and personal use.

9.3. Effects of sunshine intensity variation

If sunshine could be made stable, it would, but storage devices and controllers are needed since it isn't. These devices increase the cost of operation of solar energy with their cumulative prices even higher than PVs. Because of the sunshine duration and intensity variation, the availability will vary, and demand will follow suit [46]. Nigeria has about 6–9 h (south and north, respectively) of sunshine intensity, and the availability will be limited to those hours, emphasizing the need for an energy mix.

9.4. Low efficiencies of PV panels

The southern region of Nigeria is primarily humid, and the northern part of the country is dusty; both of these reduces the efficiencies of solar PV cells [86]. The low efficiency of solar PV cells is a considerable disadvantage [14]. Oghogho et al. [14] suggested that exploiting the multifunction PV technology will provide PV panels with higher efficiencies.

The rise in temperature above the maximum operating cell temperature in PVs will reduce the efficiency, too [66]. This shows that dust, high ambient temperature, and relative humidity can affect solar PVs' efficiencies.

10. Solar energy recommendations

To encourage the effective utilization of solar energy in Nigeria, the federal government and citizens should follow the recommendations below;

1. National laboratories meant for the research and development of solar energy with a given target for its utilization should be funded and supported. Studies on the proper utilization of solar PVs, their efficiencies and orientation, etc., should commence on a nationally approved level.
2. Subsidizing the press for importing solar photovoltaics will go a long way in encouraging private individuals to invest in solar energy.
3. Authorities have to bring up benefits to entice private individuals to adopt solar technology. These may include state governments discounting the prices as a method of encouraging purchase.
4. The unions of research institutes (colleges and manufacturing industries) should agree and reach a consensus with the government's support for the processes required for the adoption of solar technology. These are the most experienced institutes with a better understanding of solar technology.
5. Subsidizing the price of solar PV modules and discounting them will go a long way, alongside limiting diesel and petrol generators' importation. This will curb its adverse effect on the environment and improve the adoption of solar technology.
6. The creation of awareness of these technologies' utilization and adoption should be encouraged by the government in partnership with the media. This should go a long way by gathering, empowering, and training experienced personnel.
7. The high humidity, dust, and high-temperature variations in the country have emphasized the dire need for funding in research to develop solar PVs with better efficiency to adapt to the country's weather conditions. Therefore, PVs should be developed that are appropriate for the Nigerian weather. This has been observed in other nations.

Following these recommendations will help any region reach 100% renewable energy.

11. Conclusion

Nigeria is a country abundantly blessed with solar energy potential [87]. She is located at a globally competitive position with relatively high sunshine intensity and longer average sunshine hours than other countries with better utilization records. Studies [6, 7, 8, 9] have shown that even in her coastal regions, there still exist a great potential for harnessing and utilizing solar energy.

Based on this, the current status of solar energy research in Nigeria has been thoroughly reviewed. The study was focused on the potential benefits of solar energy in Nigeria, her systems, and her applications. Solar energy is the most important renewable energy because all other renewable energies are directly or indirectly connected to it (Wind energy, hydropower, biomass, biogas, etc.). This study further focused on the challenges to the effective use of solar energy in Nigeria and some recommendations on how to curb these challenges and improve solar energy usage to reduce the emission of GHGs significantly. Costa Rica just recently banned the use of fossil fuels, and Nigeria has to learn from them.

The global status of solar energy was explained to show that other countries with lower sunshine intensities are producing more power from solar energy than Nigeria and Africa as a whole. The global prices of solar PV modules per unit energy output are decreasing annually, showing no excuse whatsoever for countries like Nigeria to utilize these technologies.

The electricity generation from solar energy in Nigeria was estimated from solar radiation data, and this showed that some areas in the North had the highest capacity for electricity generation. Estimations were done assuming 1 kWp PV modules and electricity generation results estimated in kWh.

Challenges to the adoption of these technologies were enlisted, and recommendations on how to curb these challenges.

In conclusion, the following few policies can be adopted for solar energy improvement by Nigeria and the world at large;

- The continuous sending of incremental and policy signals to inspire gradual developments in the deployment of solar technologies
- Development of renewable electricity standards (RECs) that are solar-specific to meet solar set-aside requirements
- Renewable energy certificates, setting appropriate capacity limits that will not be overly optimistic at a certain period in time. This will increase targets over time as the region's capacity increases to support long-term solar development vision. China has adopted this.
- Loan guarantees, Tax measures, Asset-backed securities, commercialization and market deployment of RE technologies, etc.
- Setting appropriate and declining alternative compliance payment (ACP) rates, and finally;
- Not over-projecting results from implementing these technologies will be beneficial; this is achieved by genuinely considering project size, location, and land use.

Below are the Implications to adoption of the policies above;

- Commitment to expenses by the government of the region in question. The positive effect of this will not be observed in the short term, but this is a massive advantage in the long term.
- Stability and increase in the magnitude of application due to the federal research and development expenditures on patent applications Liang and Fiorino [88]. Encouragements from the leading bodies, which will, in turn, bring about an improvement in technology innovation. This arises from the policies involving technology commercialization and marketization, leading to cheaper (Figure 5) and readily available solar products.
- Provision of investors will provide a greater degree of confidence while making long term decisions

The folly here is that although the adoption of these policies will demonstrate that incremental, predictable, and credible expenditures facilitate renewable energy technology development, a '*boom-bust cycle*' of resource support will eventually fail to translate policy goals into intended results. This has been expounded in research by Liang and Fiorino [88] and should be a lesson to other countries.

Overdependence of industries on government support will always bring about complacency; this has been shown in studies that it can affect the stability and the magnitude of government financial commitments over time.

Other countries, especially developing countries like Nigeria, should note this possibility of complacency in solar energy development (RE in general) due to overdependence on the federal government. Although the development of RE demands a government push, it also requires all sectors to be involved.

Nigeria has shown short and long-term plans to utilize solar energy, but to make this target a reality, the recommendations listed will go a long way in curbing laxity.

Declarations

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

Data will be made available on request

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

This paper is written in honour of Professor Alexander Animalu, the father of Solar Energy in Nigeria.

References

[1] E. Uyigue, M. Agbo, A. Edeubara, Promoting renewable energy and efficiency in Nigeria, in: The Report of a One-Day Conference Which Held at the University of Calabar, 2007.
[2] U.B. Akuru, O.I. Okoro, Renewable energy investment in Nigeria: a review of the renewable energy master plan, J. Energy South Afr. 25 (30) (2005).
[3] N.V. Emodi, N.E. Ebele, Policies enhancing renewable energy development and implementations in Nigeria, Sci. Educat. Publ. 4 (1) (2016), 7-6.
[4] S.L. Nadabo, Renewable Energy as a Solution to Nigerian Crisis, University of Applied Sciences, 2010.
[5] C.G. Ozoegwu, C.A. Mgbemene, P.A. Ozor, The status of solar energy integration and policy in Nigeria, Renew. Sustain. Energy Rev. 70 (2017) 457–471.
[6] E.P. Agbo, E.B. Ettah, E.E. Eno, The impacts of meteorological parameters on the seasonal, monthly and annual variation of radio refractivity, Indian J. Phys. (2020).
[7] E.P. Agbo, C.M. Ekpo, C.O. Edet, Analysis of the effects of meteorological parameters on radio refractivity, equivalent potential temperature and field strength via Mann-Kendall test, Theor. Appl. Climatol. 143 (3) (2021) 1437–1456.
[8] E.P. Agbo, C.M. Ekpo, Trend analysis of the variations of ambient temperature using Mann-Kendall test and Sen's estimate in Calabar, southern Nigeria, J. Phys.: Conf. Ser. 1734 (1) (2021 Jan), 012016. IOP Publishing.
[9] E.P. Agbo, The role of statistical methods and tools for weather forecasting and modeling, in: Weather Forecasting, IntechOpen, 2021 Mar 22.
[10] U.U. Alhaji, A.S. Yusuf, C.O. Edet, C.O. Oche, E.P. Agbo, Trend analysis of temperature in Gombe state using Mann Kendall trend test, J. Sci. Res. Rep. 20 (2018) 1.
[11] J.K. Akinbami, Renewable Energy Resources and Technologies in Nigeria, Present Situation, Future Prospects and Policy Framework, Kluwer Academic Publishers, 2001, pp. 155–181.
[12] K.O. Chilakpu, Renewable energy services, its benefits, potentials and challenges in Nigeria, J. Energy Technol. Pol. 5 (9) (2015).
[13] Abdulkarim HT. Techno-economic Analysis of Solar Energy for Electric Power Generation in Nigeria. (n.d.).
[14] I. Oghogho, O. Sulaimon, B. Adedayo, D. Egbune, A. Kenechi, Solar energy potential and its development for sustainable energy generation in Nigeria: a road map to achieving this feat, Int. J. Eng. Manag. Sci. 5 (2) (2014) 61–67.
[15] A.S. Aliyu, J.O. Dada, I.K. Adam, Current status and future prospects of renewable energy in Nigeria, Renew. Sustain. Energy Rev. 48 (2015 Aug 1) 336–346.
[16] S.O. Oyedepo, Energy and sustainable development in Nigeria: the way forward, Energy Sustain. Soc. 2 (1) (2012 Dec) 1–7. http://www.energsustainsoc.com/content/2/1/15.
[17] G.C. Adeyanju, O.A. Osobajo, A. Otitoju, O. Ajide, Exploring the potentials, barriers and option for support in the Nigeria renewable energy industry, Discov. Sustain. 1 (1) (2020 Dec) 1–4.
[18] K.H. Solangi, M.R. Islam, R. Saidur, N.A. Rahim, H. Fayaz, A review on global solar energy policy, Renew. Sustain. Energy Rev. 15 (4) (2011 May 1) 2149–2163.
[19] H. Fayaz, N.A. Rahim, R. Saidur, K.H. Solangi, H. Niaz, M.S. Hossain, Solar energy policy: Malaysia vs developed countries, in: 2011 IEEE Conference on Clean Energy and Technology (CET), IEEE, 2011 Jun 27, pp. 374–378.
[20] J. Jurasz, F.A. Canales, A. Kies, M. Guezgouz, A. Beluco, A review on the complementarity of renewable energy sources: concept, metrics, application and future research directions, Sol. Energy 195 (2020 Jan 1) 703–724.
[21] M.R. Shaikh, S.B. Waghmare, S.S. Labade, P.V. Fuke, A. Tekale, A review paper on electricity generation from solar energy, IJRASET 5 (IX) (2017) 1884–1889.
[22] E. Ravishankar, M. Charles, Y. Xiong, R. Henry, J. Swift, J. Rech, J. Calero, S. Cho, R.E. Booth, T. Kim, A.H. Balzer, Balancing crop production and energy harvesting in organic solar-powered greenhouses, Cell Rep. Phys. Sci. (2021 Mar 17) 100381.
[23] E. Ravishankar, R.E. Booth, C. Saravitz, H. Sederoff, H.W. Ade, B.T. O'Connor, Achieving net zero energy greenhouses by integrating semitransparent organic solar cells, Joule 4 (2) (2020 Feb 19) 490–506.
[24] K. Terashima, H. Sato, T. Ikaga, Development of an environmentally friendly PV/T solar panel, Sol. Energy 199 (2020 Mar 15) 510–520.
[25] A. Rahmatmand, S.J. Harrison, P.H. Oosthuizen, An innovative method to control surface temperature of a rooftop photovoltaic system, Sol. Energy 195 (2020 Jan 1) 581–591.
[26] S. Sharma, K.K. Jain, A. Sharma, Solar cells: in research and applications—a review, Mater. Sci. Appl. 6 (12) (2015) 1145.
[27] E. Zell, S. Gasim, S. Wilcox, S. Katamoura, T. Stoffel, H. Shibli, J. Engel-Cox, M. Al Subie, Assessment of solar radiation resources in Saudi Arabia, Sol. Energy 119 (2015 Sep 1) 422–438.
[28] M.H. Sonmete, C. Ertekin, H.O. Menges, H. Hacıseferoğullari, F. Evrendilek, Assessing monthly average solar radiation models: a comparative case study in Turkey, Environ. Monit. Assess. 175 (1) (2011 Apr) 251–277.
[29] C.G. Ozoegwu, The solar energy assessment methods for Nigeria: the current status, the future directions and a neural time series method, Renew. Sustain. Energy Rev. 92 (2018 Sep 1) 146–159.
[30] O. Ogunmodimu, E.C. Okoroigwe, Concentrating solar power technologies for solar thermal grid electricity in Nigeria: a review, Renew. Sustain. Energy Rev. 90 (2018 Jul 1) 104–119.
[31] B. Kocak, A.I. Fernandez, H. Paksoy, Review on sensible thermal energy storage for industrial solar applications and sustainability aspects, Sol. Energy 209 (2020 Oct 1) 135–169.
[32] M. Hafner, S. Tagliapietra, L. de Strasser, The challenge of energy access in Africa, in: Energy in Africa, Springer, Cham, 2018, pp. 1–21.
[33] F.A. Kamgba, C.O. Edet, A.O. Njok, Effects of some meteorological parameters on wind energy potential in Calabar, Nigeria, Asian J. Phys. Chem. Sci. 4 (1) (2017) 1–7.
[34] M. Boxwell, Solar Electricity Handbook: A Simple, Practical Guide to Solar Energy – Designing and Installing Photovoltaic Solar Electric Systems, sixth ed., Greenstream Publishing, United Kingdom, 2012, p. 409.
[35] J.O. Oji, N. Idusuyi, T.O. Aliu, M.O. Peterin, O.A. Odejobi, A.R. Adetunji, Utilization of solar energy for power generation in Nigeria, Int. J. Energy Eng. 2 (2) (2012) 54–59.
[36] L. Matejicek, Solar energy: estimates of energy potential and environmental issues, in: Assessment of Energy Sources Using GIS, Springer, Cham, 2017, pp. 221–244.
[37] H. Ritchie, M. Roster, Renewable Energy, in: ., Published online at ourworldindata.org, 2020. Retrieved from: https://ourworldindata.org/renewable-energy. (Accessed 18 June 2020).
[38] A.A. Mas'ud, A.V. Wirba, F. Muhammed-Sukki, I.A. Mas'ud, A.B. Munir, N.M. Yunus, An assessment of renewable energy readiness in Africa; case study of Nigeria and Cameroon, Renew. Sustain. Energy Rev. 51 (2015) 775–785.
[39] O.I. Okoro, T.C. Madueme, Solar energy; a necessary investment in the developing economy, Niger. J. Technol. 23 (1) (2004).
[40] T. Olaoye, T. Ajilore, K. Akinluwale, F. Omole, A. Adetunji, Energy crisis in Nigeria: need for renewable energy mix, Am. J. Electr. Electron. Eng. 4 (1) (2016) 1–8.
[41] NASA, Image of the Day Gallery, in: Jim Wilson (Ed.), Published online at nasa.gov, March 23, 2008. https://www.nasa.gov/multimedia/imagegallery/image_feature_35.html. (Accessed 25 April 2021).
[42] A. Charles, in: P. Meisen (Ed.), How is 100% Renewable Energy Possible in Nigeria?, Global Energy Network Institute, 2014.
[43] A.O. Njok, J.I. Iloke, M.K. Panjwani, S.K. Panjwani, The impact of coloured filters on the performance of polycrystalline photovoltaic panel in an uncontrolled environment, Int. J. Electr. Comput. Eng. 10 (4) (2020) 3927–3935.
[44] A.S. Sambo, Renewable energy for rural development: the Nigerian perspective, ISESCO Sci. Technol. Vision (2005) 12–22.
[45] A.O. Njok, J.C. Ogbulezie, M.K. Panjwani, R.M. Larik, Investigation of monthly variations in the efficiencies of photovoltaics due to sunrise and sunset times, Indones. J. Electr. Eng. Comput. Sci. 18 (1) (2020) 310–317.
[46] A.S. Shaharin, H.H. Haizatul, H.H. Nik Siti, S.I.R. Mohd, Effects of dust on the performance of PV panels, Int. J. Mech. Aerosp. Industr. Mechatron. Manufact. Eng. 5 (10) (2011) 2028–2033.
[47] O.E. Onuk, U.B. Akuru, A.O.E. Animalu, G.O. Unachukwu, O.U. Oparaku, Utility interactive solar PV energy demonstration project at the University of Nigeria, Nsukka, Afr. J. Phys. 4 (2011).
[48] O.S. Ohunakin, M.S. Adaramola, O.M. Oyewola, R.O. Fagbenle, Solar energy applications and development in Nigeria: drivers and barriers, Renew. Sustain. Energy Rev. 32 (2014) 294–301.
[49] B.A. Adelekan, Recent advances in renewable energy: research, applications and policy initiations, Phys. Rev. Res. Int. 2 (1) (2012) 1–21.

[50] M. Shaaban, J. Petinrin, Renewable energy potentials in Nigeria: mentoring rural energy needs, Renew. Sustain. Energy Rev. 29 (2014) 72–84.
[51] E.J. Bala, Nigeria's Power Sector Reform: what Next after privatization, in: A Paper Presented at the Power and Electricity World Africa Conference, Johannesburg, 2014.
[52] E.J. Bala, G.Y. Pam, Energy Sources and Sustainable Development of the north, in: A Paper Presented at the Conference on "The North and Strategies for Sustainable Development", Organized by Arewa House, Kaduna, 2012.
[53] B. Omisore, Nigeria's solar projects yield both failure and success, Published online at api.nationalgeographic.com, https://www.google.com/amp/s/api.nationalgeographic.com/distribution/public/amp/news/energy/2011/11/111102-solar-power-in-nigeria, 2011. (Accessed 15 July 2020).
[54] P.A. Nwofe, Utilization of solar and biomass energy: a panacea to energy sustainability in a dwelling economy, Int. J. Electron. Eng. Res. 2 (3) (2014) 10–19.
[55] T. Sesan, Status of Renewable Energy Policy and Implementation in Nigeria, Institute of Science and Society, Faculty of Sciences, Law and Education, University of Nottingham, United Kingdom, 2008.
[56] C. Newsom, Renewable Energy Potential in Nigeria, International Institute for Environmental Development, 2012.
[57] S. Alexopoulos, B. Hoffschmidt, Concentrating receiver systems (solar power tower), in: Solar Energy 10, Springer, New York, 2013, pp. 978–981.
[58] C.A. Cruickshank, C. Baldwin, Sensible thermal energy storage: diurnal and seasonal, in: Storing Energy, Elsevier, 2016 Jan 1, pp. 291–311.
[59] C.O. Osueke, C.A.K. Ezugwu, Study of Nigeria's energy resources and its composition, Int. J. Sci. Res. Eng. 2 (12) (2011).
[60] M. Girma, A. Assefa, M. Molinas, Feasibility study of a photovoltaic water pumping system for rural Ethiopia, Environ. Sci. 2 (3) (2015) 697–717.
[61] P. Wolfgang, Power for the World - the Emergence of Electricity from the Sun, Pan Stanford Publishing, Belgium, 2010, p. 575.
[62] M.A. Marsan, G. Bucalo, A. di Caro, M. Meo, Y. Zhang, Towards zero grid electricity networking: powering BSs with renewable energy sources, in: Proceedings of the 2013 IEEE International Conference on Communications, ICC), Budapest, Hungary, 2013, pp. 596–601.
[63] M.H. Alsharif, J. Kim, Optimal solar power system for remote telecommunication base stations: a case study based on the characteristics of South Korea's solar radiation exposure, Sustainability 8 (2016) 942.
[64] H.A. Sher, K.E. Addoweesh, Power storage options for hybrid electric vehicles-A survey, J. Renew. Sustain. Energy 4 (2012), 052701.
[65] G. Schmitt, The green base station, in: Proceedings of the 4th International Conference on Telecommunication-Energy Special Conference, TELESCON, Vienna, Austria, 2009, pp. 1–6.
[66] J.C. Ogbulezie, A.O. Njok, M.K. Panjwani, S.K. Panjwani, The impact of high temperature and irradiance source on the efficiency of polycrystalline photovoltaic (PV) panels in a controlled environment, Int. J. Electr. Comput. Eng. 10 (4) (2020) 3942–3947.
[67] T. Lambert, P. Gilman, Micro Power System Modeling with HOMER, 2017.
[68] L. El Chaar, Photovoltaic system conversion, in: Alternative Energy in Power Electronics, Butterworth-Heinemann, 2011 Jan 1, pp. 155–175.
[69] T. Touahri, N. Aoun, R. Maouedj, S. Laribi, T. Ghaitaoui, Design of Stand-Alone PV system to provide electricity for a house in Adrar, Algeria, in: M. Hatti (Ed.), Renewable Energy for Smart and Sustainable Cities. ICAIRRES 2018, Lecture Notes in Networks and Systems, 62, Springer, Cham, 2018.
[70] K. Shivam, J.-C. Tzou, S.-C. Wu, Multi-Objective sizing optimization of a grid-connected solar-wind hybrid system using climate classification: a case study of four locations in southern Taiwan, Energies 13 (10) (2020) 2505.
[71] M.F. Akorede, O. Ibrahim, S.A. Amuda, A.O. Otuoze, B.J. Olufeagba, Current status and outlook of renewable energy development in Nigeria, Niger. J. Technol. 36 (2017) 196–212.
[72] C. Augustine, M.N. Nnabuchi, Relationship between global solar radiation and sunshine hours for Calabar, Port Harcourt and Enugu, Nigeria, Int. J. Phys. Sci. 4 (4) (2009) 182–188.
[73] N.O. Adeniji, J.A. Akinpelu, S.O. Adeola, J.O. Adeniji, Estimation of global solar radiation, sunshine hour distribution and clearness index in Enugu, Nigeria, J. Appl. Sci. Environ. Manag. 23 (2) (2019) 345–349.
[74] A.A. Osinowo, E.C. Okogbue, S.B. Ogungbenro, O. Fashanu, Analysis of global solar irradiance over climatic zones in Nigeria for solar energy applications, J. Solar Energy (2015). Article ID 819307.
[75] A.E. Lawin, C. Niyongendako, C. Manirakiza, Solar irradiance and temperature variability and projected trends analysis in Burundi, Climate 7 (2019) 83.
[76] B.M. Dada, E.C. Okogbu, Estimating daily solar radiation from monthly values over selected Nigeria stations for solar energy utilization, J. Fund. Renew. Energy Appl. 7 (6) (2017) 1–3.
[77] A.O. Adejumo, E.A. Suleiman, A.I. Okagbue, Exploration of solar radiation data from three geo-political zones in Nigeria, Data in Brief 13 (2017) 60–68.
[78] O.O. Ajayi, O.D. Ohijeagban, C.E. Nwadialo, O. Olasope, New model to estimate daily global radiation over Nigeria, Sustain. Energy Technol. Assessments 5 (2014) 28–36.
[79] U.B. Akuru, I.B. Onukwubeb, O.I. Okoroc, E.S. Obea, Towards 100% renewable energy in Nigeria, Renew. Sustain. Energy Rev. 71 (2017) 943–953.
[80] M.S. Okundamiya, J.O. Emagbetere, E.A. Ogujor, Evaluation of various global solar radiation models for Nigeria, Int. J. Green Energy 13 (5) (2016) 505–512.
[81] C.I. Ezekwe, The solar radiation climate of Nigeria, Sol. Wind Technol. 5 (5) (1998) 563–571.
[82] K. Nfaoui M El-Hami, Extracting the maximum energy from solar panels, Energy Rep. 4 (2018) 536–545.
[83] N. Kannan, D. Vakeesan, Solar energy for the future world; - a review, Renew. Sustain. Energy Rev. 62 (2016) 1095–1105.
[84] A.S. Sambo, A place for renewable energy in the Nigerian economy sector, in: Presented at the World Future Council Workshop on Renewable Energy Policies. Addis Ababa, Ethiopia, 2009.
[85] IEA/IRENA Renewables Polices Database, Nigeria Renewable Energy Master Plan, 2013. https://www.iea.org/policies/4974-nigeria-renewable-energy-master-plan. (Accessed 25 July 2020).
[86] A.O. Njok, J.C. Ogbulezie, The effect of relative humidity and temperature on polycrystalline solar panels installed close to a river, Phys. Sci. Int. J. 20 (4) (2018) 1–11.
[87] K. Uduma, T. Arciszewski, Sustainable energy development: the key to a stable Nigeria, Open Access Sustain. (2010).
[88] J. Liang, D.J. Fiorino, The implications of policy stability for renewable energy innovation in the United States, 1974–2009, Pol. Stud. J. 41 (1) (2013) 97–118.