GEOSPATIAL ANALYSIS OF SOLAR ENERGY POTENTIALS IN PARTS OF NORTHWESTERN NIGERIA

BY

Muhammad ISMA'IL
Ph.D/SCI/42094/2012-2013

A THESIS SUBMITTED TO THE SCHOOL OF POSTGRADUATE STUDIES, AHMADU BELLO UNIVERSITY ZARIA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF DOCTOR OF PHILOSOPHY DEGREE IN GEOGRAPHY

DEPARTMENT OF GEOGRAPHY
FACULTY OF PHYSICAL SCIENCES
AHMADU BELLO UNIVERSITY,
ZARIA

June, 2017

DECLARATION

I declare that this thesis entitled "**Geospatial Analysis of Solar Energy Potentials in Parts of Northwestern Nigeria**"has been carried out by me in the Department of Geography under the supervision of Professor I. J. Musa,Dr. A. L. Ahmed and Dr. A. I. Naibbi. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this thesis was previously presented for another degree or diploma at any other institution.

Muhammad ISMA'IL _____ _____

Signature Date

CERTIFICATION

This thesis entitled "**Geospatial Analysis of Solar Energy Potentials in Parts of Northwestern Nigeria**"by Muhammad ISMA'IL meets the regulations governing the award of the degree of Doctor of Philosophy (Ph.D) in Geography of the Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

Prof. I. J. Musa Chairman, Supervisory Committee	_____ Signature	_____ Date
Dr. A. L. Ahmed Member, Supervisory Committee	_____ Signature	_____ Date
Dr. A. I. Naibbi Member, Supervisory Committee	_____ Signature	_____ Date
Dr. A.K.Usman Head of Department	_____ Signature	_____ Date
Prof. S. Z. Abubakar Dean, School of Postgraduate Studies	_____ Signature	_____ Date

DEDICATION

This work is dedicated to the Almighty Allah, then to my parents.

ACKNOWLEDGEMENTS

All praise is to Allah, the Creator of everything, the Most Gracious and the Most Merciful, for giving me the ability, wisdom and the opportunity to undergo this study.

My gratitude goes to my mentor and supervisor, Professor I. J. Musa, who has been with me through proper guidance and focused supervision to ensure the successful completion of this work. No amount of words can be usedto express my deep appreciation for what he has done for mein my academic career. His commitment and constructive criticism in the course of supervising this work are highly acknowledged and sincerely appreciated. Then, my appreciation goes to Dr. A. L. Ahmed of the Department of Physics, Ahmadu Bello University, Zaria, for providing time in spite of his tight schedules to supervise this thesis. I remain ever grateful to him. I also appreciate Dr. A. I. Naibbi of the Department of Geography, Northwest University for sparing his time to scrutinize this work. Hisconstructive criticism and valuable suggestions cannot go unnoticed andit is highly appreciated. In addition, I would like to acknowledge the scholarly contributions of Alberto Pettazzi of MeteoGalicia - *Departamento de Climatología y ObservaciónConsellería de Medio Ambiente, Territorio e, Santiago de Compostela* in Spain, his valuable contributions have assisted in refocusing this work.

I sincerely appreciate the encouragement and the support given to me by my parents, my dear wife, the Queen, my children, Fadheel and Fadheela, my brothers and sisters, other relatives, good friends, and associates in order to ensure the successful completion of this work.

Special thanks go to my colleagues in the Department of Geography, Ahmadu Bello University, Zaria, for their support and advice in the course of this study. They include,

the Head of Departmentin person of Dr. A.U. Kibbon, Prof. E.O. Iguisi, Dr. A. A. Ibrahim, Dr. S. Abbas and Dr. A. Jibrin. My appreciation also goes to my other colleagues who have contributed in one way or the other namely, Mal. Abubakar Salisu, Mal. Muktar Ibrahim, Mal. Sule M. Zubairu, Mal. Hamza Mohammed and Mal. Jibrin Gani.

The concerns and contribution of good friends like Dr. Muhammad Akadalor, Inusa Musa and Reuben Jobien Jacob in ensuring the success of this work is highly appreciated. Several other members of staff have contributed in one way or the other but are too numerous to mention. I remain thankful to all of you.

I would like to extend my sincere appreciation to the staff of the Nigerian Meteorological Agency (NIMET)and the developers of National Aeronautics and Space Administration Surface meteorology and Solar Energy (NASA SSE) for providing the data used in this study. Also,the contributions of several scholarsdirectly and indirectly are highly appreciated.

ABSTRACT

Northwestern Nigeria falls within the solar belt and therefore has enormous solar energy potentials. But, information on solar radiation which is a fundamental requirement for harnessing the solar energy in the region is inadequate. Recently, geospatial techniques have been used to analyse solar energy potentials in different parts of the world.This study attempted to use geospatial techniques to integrate ground-measured solar radiation data with satellite-derived solar radiation data to assess solar energy potentials in Kano, Kaduna and Katsina states of Northwestern Nigeria. Inverse Distance Weighted (IDW) interpolation was used in order to map the ground-measured and the satellite solar radiation data. Scatter plots and visual analysis were employed to compare and contrast between ground-measured and satellite-derived solar radiation data in the study area. The ground-measured solar radiation data was merged with the satellite-derived solar radiation data to produce calibrated maps of solar radiation in the area. The calibration method was validated using the Mean Bias Error (MBE), Root Mean Squared Error (RMSE) and Mean Absolute Error (MAE). Then, weighted overlay and analytic hierarchy process were used to determine the solar energy potential sites in the area.It was found that the solar radiation received in the area range from 4.47kWh/m^2/day to 7.21kWh/m^2/day based on the ground and the satellite data. Maximum insolation of averagely 7kWh/m^2/day was observed in the months of March, April and May;while minimum insolationof averagely 4.5kWh/m^2/day was observed in July, August, December and January, over the study area. However, spatial variations exist among the three states in terms of the pattern of solar radiation. A positive correlation between the ground and the satellite data was found in terms of the minimum and the maximum solar radiation in the area. The validation process of the merging method obtained average MBE values of -0.45%, RMSE of 0.46%, and

MAEof 0.57%. These values indicate a good performance of the merging method used in this study. In addition, findings revealed that the amount of exploitable solar power in Kano, Kaduna and Katsina states were 118.773 X 10^6 MWh, 234.870 X 10^6 MWh and 162.086 X 10^6 MWh respectively. Geospatial techniques should be used to produce a more comprehensive solar radiation atlas of Kano, Kaduna and Katsina states covering all the local government areas in the three states. Satellite and calibrated solar radiation data are two alternatives, which should be used to complement or evaluate ground measurement of solar radiation that can be used to analyse the solar energy potentials in an area. The optimum periods for harnessing solar energy in the area (March – May) should be used to harness and conserve solar power. Areas with very high solar energy potentials should be used in siting of utility scale solar farms and Concentrating Solar Power plants while Photovoltaic solar panels can be used in areas with moderate solar energy potentials.The information provided in this study can be used to diversify the energy supply mix in Nigeria in a bid to address the power problem in the country.

TABLE OF CONTENTS

Title Page i

Declaration ii

Certification iii

Dedication iii

Acknowledgements iv

Abstract vii

Table of Contents ix

List of Figures xixi

List of Tables xxiii

List of Appendices xv

CHAPTER ONE : INTRODUCTION

1.1 Background to the Study 1

1.2 Statement of the Research Problem 5

1.3 Aim and Objectives 9

1.4 Scope of the Study 9

1.5 Significance of the Study 10

CHAPTER TWO : CONCEPTUAL FRAMEWORK AND LITERATURE REVIEW

2.1 Introduction 13

2.2 Conceptual Framework 13

2.2.1 Radiation and the Climate System 13

2.2.2 The Earth's Radiation Budget 14

2.2.3 Radiation and the Atmosphere 15

2.2.4 Radiation and Clouds 17

2.2.5 The Radiation Budget and the Earth's Surface 18

2.2.6 Models for the Estimation of Global Solar Radiation 18

2.2.7 Models for the Estimation of Global Solar Radiation from Satellite Data 22

2.3 LITERATURE REVIEW... 25

2.3.1 Renewable Energy Resource Information in Africa 25

2.3.2 Statistical Modelling of Solar Radiation in Nigeria 30

2.3.3 Geostatistical Approach to Solar Radiation Modelling 35

2.3.4 Satellite Remote Sensing and GIS Approach to Analysis of Solar Radiation 40

2.3.5 Improved Solar Information System for Nigeria 46

CHAPTER THREE : THE STUDY AREA AND METHODOLOGY

3.1 STUDY AREA 48

3.1.1 Location and Size 48

3.1.2 Geology and Landforms 49

3.1.3 Climate 49

3.1.4 Soils 52

3.1.5 Vegetation 53

3.1.6 People and Economic Activities 54

3.2 METHODOLOGY 55

3.2.1 Review of Methods of Data Analysis 55

3.2.2 Reconnaissance Survey 67

3.2.3 Types of Data Utilised 67

3.2.4 Sources of data 67

3.2.5 Data Analysis 69

CHAPTER FOUR : RESULTS AND DISCUSSION

4.1 Introduction 73

4.2 Insolation Maps Based on Ground Measurements 73

4.3 Insolation Maps Based on Satellite Data 80

4.4 Comparison between Ground-Measured and Satellite Solar Radiation Data 86

4.5 Pattern of Solar Radiation in the Three States 91
4.5.1 Solar Radiation in Katsina State 91
4.5.2 Solar Radiation in Kano State 93
4.5.3 Solar Radiation in Kaduna State 95
4.6 Insolation Maps Based on Calibration of Measured with Satellite Data 98
4.7 Validation of Satellite Solar Radiation with Ground-based Measurements 99
4.8 Comparison between Solar Radiations derived from Single&Multiple Sources 105
4.9 Solar Energy Potential Sites in Parts of Northwestern Nigeria 106
4.9.1 Solar Energy Potential Sites in Katsina State 109
4.9.2 Solar Energy Potential Sites in Kano State 111
4.9.3 Solar Energy Potential Sites in Kaduna State 113
4.10 Estimation of Potential Solar Electricity Generation 113
4.11 Economics of Solar Energy 116

CHAPTER FIVE : SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.1 Introduction 118
5.2 Summary 118
5.3 Conclusion 120
5.4 Contributions to Gap in Knowledge 122
5.5 Limitations of the Research 123
5.6 Recommendations 123
5.7 Recommendations for Further Studies 124

References 125

Appendices xv

LIST OF FIGURES

Figure Page

2.1: The Earth's Radiation Budget 14

3.1: The Study Area in Northwestern Nigeria 48

3.2 Analytic Hierarchy Process 63

3.3: Locations of NIMET stations in Northwestern Nigeria.....68

3.4: The Calibration and the Validation Stations in Northwestern Nigeria.....70

4.1a-d: Ground-measured Monthly Mean Daily Values of Global Solar Radiation ($kWh/m^2/day$).....77

4.1e-h: Ground-measured Monthly Mean Daily Values of Global Solar Radiation ($kWh/m^2/day$) 78

4.1i-l: Ground-measured Monthly Mean Daily Values of Global Solar Radiation ($kWh/m^2/day$) 79

4.2a-d: Satellite-derived Monthly Mean Daily Values of Global Solar Radiation ($kWh/m^2/day$).....83

4.2e-h: Satellite-derived Monthly Mean Daily Values of Global Solar Radiation ($kWh/m^2/day$).....84

4.2i-l: Satellite-derived Monthly Mean Daily Values of Global Solar Radiation ($kWh/m^2/day$).....85

4.3a: Comparison between the Two Sources of Solar Radiation Data in Kano State 88

4.3b: Comparison between the Two Sources of Solar Radiation Data in KadunaState… 88

4.3c: Comparison between the Two Sources of Solar Radiation Data in KatsinaState 89

4.4: Monthly Mean Daily Values of Global Solar Radiation in KatsinaState.....92

4.5: Monthly Mean Daily Values of Global Solar Radiation in KanoState.....94

4.6: Monthly Mean Daily Values of Global Solar Radiation in KadunaState.....97

4.7a-d: Calibrated Monthly Mean Daily Values of Global Solar Radiation.....100

4.7e-h: CalibratedMonthly Mean Daily Values of Global Solar Radiation.....101

4.7i-l: Calibrated Monthly Mean Daily Values of Global Solar Radiation 102

4.8: Solar Energy Potential Sites in Parts of Northwestern Nigeria 107

4.9: Solar Energy Potential Sites in Katsina State 110

4.10: Solar Energy Potential Sites in Kano State.....112

4.11: Solar Energy Potential Sites in Kaduna State 114

LIST OF TABLES

Table Page

2.1: Saaty's Pair-wise Comparison Table 64

4.1: Ground-measured Monthly Mean Daily Values of Global Solar Radiation 74

4.2: Satellite-derived Monthly Mean Daily Values of Global Solar Radiation.....80

4.3: Differences between Ground and Satellite Mean Daily Solar Radiation Data.....90

4.4: Monthly Mean Daily Values of Global Solar Radiation in Katsina State.....92

4.5: Monthly Mean Daily Values of Global Solar Radiation in KanoState.....94

4.6: Monthly Mean Daily Values of Global Solar Radiation in KadunaState.....96

4.7: Calibrated Monthly Mean Daily Values of Global Solar Radiation.....98

4.8: Temporal Validation of the Calibrated Solar Radiation Data.....103

4.9: Average Daily Electricity Production in the Study Area.....115

4.10: Average Monthly Electricity Production in the Study Area.....116

LIST OF APPENDICES

Appendix Page

I: Extract of mean daily solar radiation data for Katsina State xvi

II: Extract of mean daily solar radiation data for Kano State.....xix

III: Extract of mean daily solar radiation data for Kaduna State xxii

IV: Calibration of satellite with ground data.....xxv

V: Solar Radiation Map of the Study Area.....xvi

VI: Digital Elevation Model of the Study Area xvii

VII: Slope Map of the Study Area..... xviii

VIII: Aspect of the Study Area.....xix

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND TO THE STUDY

Radiation within the Earth's atmosphere consists of the solar radiation and the terrestrial radiation. While terrestrial radiation is infrared-based and belongs to the long-wave radiations, solar radiation (also called the shortwave radiation) is based on the visible and near-infrared with a small portion in the near-ultraviolet. The visible spectrum of radiation energy in solar radiation accounts for 44% of the total energy, ultraviolet accounts for 8% and infrared region accounts for 48% (Liao, Jiang and Zhao, 2012).

The global solar radiation reaching the Earth's surface can be classified into direct solar energy and diffuse solar energy. Direct solar energy is the energy reaching the Earth's surface from the Sun's direct beam, on a plane perpendicular to the beam, and is usually measured by a pyrheliometer mounted on a solar tracker (Australian Government Bureau of Meteorology, 2013). On the other hand, diffuse solar energy is the incoming solar radiation on a horizontal plane at the Earth's surface resulting from scattering of the Sun's beam due to atmospheric constituents. It is measured by a pyranometer, with its glass dome shaded from the Sun's beam. The total radiation is the sum of the direct and the diffuse radiation sometimes referred to as the global radiation or insolation. Solar radiation provides the information required for solar energy exploitation and development.

Solar energy is the use of sunlight to generate electricity. Generating energy from the Sun can be done through a direct method using the Photovoltaic (PV) technology which converts sunlight into electricity; or using indirect method referred to as Concentrating

Solar Power (CSP) where the sunlight is used to generate heat which is used to drive a turbine which powers a generator that provides electricity.

Solar energy can be considered as the most abundant renewable source of energy on the Earth's surface. The region of the Earth between latitudes of 40°N and 40°S is generally referred to as the solar belt where abundant supply of solar radiation is found (Aksakal and Rehman, 1999). Therefore, locations within this region are the most suitable for harnessing and exploiting solar energy. Although most locations within Africa are found in the solar belt, there is general scarcity of information on renewable energies such as solar radiation in the continent (REN-21, 2010; Monforti-Ferrario, 2011). Consequently, the level of solar energy development and utilization as an alternative source of power is very low resulting to millions of Africans lacking access to electricity.

Regionally, there is huge potential for the development of solar energy in African countries. For instance, in 2013, the world's biggest solar power plant was launched in Morocco and it is expected to supply electricity to over one million people in the country. Recently, forty solar power stations with the capacity of producing 2000MW of power were developed in Aswan town of Egypt. Other countries like Tanzania and Kenya have gone far ahead of Nigeria in terms of solar energy development and utilization.

The increasing demand for electricity in Nigeria coupled with the epileptic power supply in the country and the quest by government to diversify the energy supply mix in the country has necessitated the development of solar as an alternative source of power in the country. Although solar is now becoming a viable alternative source of power in Nigeria, studies on solar energy potentials such as Chiemeka (2008), Augustine and

Nnabuchi (2009), Sanusi and Abisoye(2011), Okundamiya and Nzeako (2011), Falayi, Rabiu and Teliat (2011), Ibeh, Agbo, Ekpe and Isikwue (2012), Musa, Zangina and Aminu (2012) have focused on southern Nigeria, in spite of the fact that northern Nigeria has more solar energy potentials, which can be harnessed to address the endemic problem of power supply in the country. Therefore, there is the need to study the abundant solar energy potentials in Northwestern Nigeria, which is the region where this study focuses with a view to facilitating solar energy development in the region. The region of Northwestern Nigeria has the highest population in northern Nigeria (National Population Commission, 2006). The region also has the highest concentration of economic and commercial activities in northern Nigeria, because Kano State which is regarded as the commercial nerve centre of northern Nigeria is found in the region. Therefore, there is high demand of energy for commercial, industrial and domestic, activities in the region. The available solar energy in the region can be harnessed in order to meet the high demand for energy in the region.

Information on the amount of both direct and diffuse solar radiation is essential for solar energy exploitation. Conventionally, such information is obtained from a dense network of solar radiation monitoring stations covering an area of interest. A dense network of such stations equipped with pyranometers, pyrheliometers and other data acquisition systems are required to collect solar radiation data at locations of interest. However, the stations that provide more reliable solar radiation data are very expensive to maintain; and limited in terms of coverage (Journée and Bertrand, 2010). The scarcity of solar radiation stations is more obvious among the African countries.

Rehman and Ghori (2000) observed that in developing countries where the number of radiation data collection stations is limited and direct measurements of solar radiation is

inadequate; the values of global solar radiation and sunshine duration for many geographic locations can be derived or estimated. This is because in the absence of actual measured data, radiation data can be calculated from other available meteorological parameters to provide necessary data coverage for a geographic location or region (Ramachandra, 2007). But to achieve this, empirical modelling is required. Therefore, several empirical models by Udo (2002), Augustine and Nnabuchi (2010),

Osueke, Uzendu and Ogbonna (2013) have been developed to estimate the global and diffuse solar radiation using available climatological parameters such as sunshine duration, cloud cover, relative humidity, maximum and minimum ambient temperatures. Previously, Angström (1924), Black, Bonython and Prescott (1954), Glover and McCulloch (1958) used the sunshine hours; while Gopinathan (1988) used the relative humidity and sunshine hours. Besides, Kalidindi *et al.* (2014) used a global climate model in testing the climate response to Solar Radiation Management by stratospheric aerosols and reduced solar constant. Their results showed that the climatic conditions produced by a reduction in solar constant and addition of aerosols into the stratosphere are approximately the same. Gaetani *et al.* (2015) used climate models in assessing the future energy potential from photovoltaic solar and wind energy for Europe. In addition, Oloo, Olang, and Strobl (2016) analysed atmospheric transmissivity and topography using spatial modelling to assess the potential of photovoltaic solar energy in Kenya. Okundamiya, Emagbetere and Ogujor (2016) evaluated various global solar radiation models for Nigeria. Their findings underscored the importance of the calibration and appraisal of solar radiation models before application for the design and development of solar systems.

An alternative approach to solar radiation modelling is the application of geospatial techniques to analyse satellite data. Geospatial analysis comprises of spatial analysis and associated modelling techniques that are provided within the Geographic Information Systems (GIS) and associated software that are used for the manipulation, transformation and display of geospatial data (De Smith, Goodchild and Longley, 2015). Geospatial analysis includes geographic visualisation also known as geovisualisation. Geographic visualisation is the creation and use of visual representations through the analysis of geospatial data to provide geographic information, facilitate understanding and knowledge construction about geospatial data (N¨ollenburg, 2007). Visualisation in this context is aimed at exploration, analysis, synthesis, and presentation of geographic data.

The use of satellite data as an alternative method to derive solar energy information was demonstrated by Journée, Müller and Bertrand (2011) and Janjai (2013). However, Journ´ee and Bertrand (2011) and Basir, Aziz, Ahmad and Wahid (2013) established that the integration of ground measurements with satellite data is currently used by researchers to estimate solar radiation in different parts of the world. In which case, the satellite data are processed, analysed and validated with data from ground-based stations. Therefore, this study adopts the current method of integrating ground-based measurements with satellite data to derive solar radiation information for some parts of Northwestern Nigeria, which can be used for solar energy development and utilization in the area. This is because providing alternative source of power will go a long way in providing the required energy for industrial, commercial and household activities for the large population in the area.

1.2 STATEMENT OF THE RESEARCH PROBLEM

Comprehensive knowledge of the behaviour of monthly mean daily values of global solar radiation reaching the Earth's surface, both spatially and temporally, is required in the design and development of solar conversion devices (Rehman and Ghori, 2000), which are used in solar energy systems. Traditionally, solar radiation data is acquired through ground-based measurements in meteorological stations. However, very few of such stations are available to provide comprehensive solar radiation data of the desired locations in Northwestern Nigeria.

The alternative methods which have been developed to model solar radiation on the basis of available meteorological data have been experimented by various scholars. For example, Bindi and Miglietta (1991) used air temperature and rainfall measurements to estimate solar radiation in eleven countries, Chegaar, Lamri and Chibani (1998) used sunshine hours to assess global solar radiation in Algerian and Spanish sites; Monedero, García, Dobon, Yanes and Hernandez (2007) modelled solar radiation in Canary Islands of Spain; Angela, Taddeo and James (2011) used Artificial Neural Network to predict global solar radiation in Kampala; Hussein (2012) used mathematical model to estimate global solar radiation in Egypt, while Lealea and Tchinda (2013) estimated diffuse solar radiation in Cameroun using ground measurements. Although modelling of solar radiation based on available meteorological parameters has been widely used by researchers, a survey of literature suggests that very few works like AbdulAzeez (2011), Gana and Akpootu (2013), Mohammed *et al.* (2015) have modelled solar radiation on the basis of the more readily available meteorological data in Northwestern Nigeria.

Another alternative approach is to estimate solar radiation by using satellite data and validate the results with ground-based measurements from available stations as

demonstrated in the works of Pinker, Frouin and Li (1995), Flores and Baldasano (2001), Bois *et al.* (2008), and Basir *et al.* (2013). However, the benefit of merging ground-based data with satellite data to derive solar radiation information has not been exploited in Northwestern Nigeria.

In Africa, some studies have been carried out to assess solar energy potentials in the continent. One of the attempts to map the solar radiation in Africa was done by Diabaté, Blanc and Wald (2004). Diabaté *et al.*(2004) adopted the climate zone classification approach which only gives information about similar values of the monthly mean of the daily clearness index over a geographical region. Although, this information is useful in preliminary assessment of solar energy modelling in Africa, it is insufficient for comprehensive assessment of solar energy potentials in the continent.

In Nigeria, researchers have assessed solar energy potentials in different parts of the country. One of the earliest attempts was done by Ojosu (1990) where he produced iso-radiation map for Nigeria using measured solar radiation data obtained from experimental stations and estimated solar radiation from empirical formulae. But, the iso-radiation maps do not clearly show spatial variation in solar radiation across the country. Subsequently, researchers like Udo (2002), Akpabio, Udo, and Etuk (2004), Chiemeka (2008), Augustine and Nnabuchi (2009), Sanusi and Abisoye(2011), Okundamiya and Nzeako (2011), Falayi, Rabiu and Teliat (2011), Ibeh, Agbo, Ekpe and Isikwue (2012), Musa, Zangina and Aminu (2012), Medugu, Adisa, Burari and Abdul'Azeez (2013), Ogbaka and Silikwa (2016) used various climatic parameters to estimate solar radiation in different parts of Nigeria.

Northwestern Nigeria falls within the solar belt and therefore has enormous solar energy potentials. But, solar radiation information which is a fundamental requirement for

exploiting the solar energy in the region is inadequate. Few studies have assessed the solar energy potentials for various locations in Northwestern Nigeria. Such studies include the works of Sambo (1988) in Kano; AbdulAzeez (2011) in Gusau; Gana and Akpootu (2013) in Kebbi; Mohammed *et al.* (2015) in Sokoto whom employed various statistical techniques to model solar radiation directly from insolation data, or, indirectly from other climatic variables.

However, attempt has not been made to use geospatial techniques to integrate ground-measured solar radiation with satellite data to assess solar energy potentials in Northwestern Nigeria, in spite of the capability of the methods in estimating solar radiation with high degree of reliability. Reliable assessment of the available solar radiation in the region will reveal the enormous solar energy potentials, which can be harnessed to facilitate socioeconomic development of the region and also revive industrialization in the region. Therefore, this study applied geospatial techniques to analyse solar energy potentials in three states (Kano, Kaduna and Katsina) of Northwestern Nigeria using ground-measured insolation and satellite-derived insolation data.

This study seeks to find answers to the following research questions:

1) How efficient is geospatial technique in visualising solar radiation in the area using both ground measurement and satellite data?
2) What are the similarities and differences between ground-measured and satellite-derived solar radiation data in the study area?
3) To what extent is merging ground measurement of solar radiation with satellite data going to improve the accuracy of solar radiation measurement in the area?
4) What is the spatiotemporal variation of solar energy potentials in the area?

5) Where are the optimum solar energy potential sites and what is the amount of exploitable solar power in the study area?

1.3 AIM AND OBJECTIVES

The aim of this study was to analyse solar radiation in Kano, Kaduna and Katsina states of Northwestern Nigeria with a view to reveal the solar energy potentials in the three states which can be used as an alternative renewable energy source to facilitate socioeconomic development in the region; and to contribute to the existing literature on the application of geospatial techniques in the analysis of renewable energy sources.

The specific objectives of the study are to:

i. visualise solar radiation in the area using both ground measurement and satellite data.
ii. compare and contrast between ground-measured and satellite-derived solar radiation data in the study area.
iii. merge the ground-measured solar radiation data with the corresponding satellite data in order to assess the solar energy potentials in the area.
iv. visualise the spatiotemporal variation of solar energy potentials in the area.
v. identify the optimum solar energy potential sites and values for solar energy development in the area.

1.4 SCOPE OF THE STUDY

This study is concerned with geospatial analysis of solar energy potentials in parts of Northwestern Nigeria. It covers three states namely: Katsina, Kano, and Kaduna. The study integrated ground-measured solar radiation data with satellite-derived solar radiation data to map solar energy potentials in the study area, compared the two

sources of solar radiation data, and analysed the spatiotemporal variability of solar energy in the area. The study also highlighted the maximum and minimum solar radiation values obtained in the study area, identified the distributions of solar energy potential sites over the area; determined the amount of exploitable solar power in each of the three states as well as the optimum periods for harnessing solar energy in the area. The data used for this study covered a period of thirty years (1986-2015).

1.5 SIGNIFICANCE OF THE STUDY

Appropriate information on solar energy resources is very essential in power generation, meteorology, hydrology, agriculture, forestry engineering, telecommunication engineering and water resources management. Knowledge of hourly solar radiation on horizontal surface as well as sunshine hours is essential in the design and development of solar energy systems. This is because hourly solar radiation data enable us to derive very precise information about the performance of solar energy systems (Gopinathan, 1992). Also, the values of hourly solar radiation in an area enable us to compute daily, monthly and annual solar radiation in that area. However, solar radiation measurement which provides the source of the data is costly and time-consuming. Hence, there is the need for exploring other alternative sources of the data.

Solar energy information is essential for developing renewable resource geodatabase. The geodatabase of renewable resource potentials is essential for regional renewable energy planning and assessment. The assessment provides valuable and much needed information to enhance the proper development and evaluation of solar energy systems in an area or region. Renewable energy such as solar has the capacity to curb climate change, improve the standard of living of the population in Africa and can serve as means of economic transformation and poverty alleviation. Research in renewable

energy potentials such as solar is required because of its applications in climatology, urbanization and industrialization.

With the extensive growth and deployment of solar energy technologies globally, forecasting irradiance becomes an important step in providing reliable information required for integration of solar electricity into electric power grids (Nobre *et al.*, 2016). The most important step however is to acquire sufficient knowledge of the spatiotemporal variability of solar radiation in an area which is critical for solar energy development and which is the focus of this kind of study.

Recent studies by Newsom (2012) estimated the concentrated solar thermal power potential in Nigeria at over 427,000MW, and the country's electricity generation was around 5000MW, which is insignificant compared to the country's demand for energy. This study would be significant in identifying the potential sites for deploying solar technology so that solar energy can be harnessed for power generation in Nigeria.

Importantly, the solar energy potentials in the area have the capability to revive industrialization in Northwestern Nigeria thereby creating jobs and other sources of revenue to the government. It can also provide the energy required by manufacturing and small scale industries which will result to employment generation, wealth creation and poverty alleviation in the states. Solar energy can also go a long way to boost irrigation farming and agriculture in Northwestern Nigeria where a large percentage of the population is engaged in agriculture. Other important application of solar energy include: monitoring plant growth and disease control; evaporation and irrigation; power generation; solar heating system design and use; weather and climate prediction models.

This study is capable of providing some of the required solar energy information for the implementation of the Power Purchase Agreements (PPAs) signed in 2016 between the

Nigerian Electricity Bulk Trading Plc (NBET) and 14 solar energy firms to the tune of $2.5 billion. It is described as the largest investment ever in the power sector (Ewepu and Ejoh, 2016). The firms will develop 14 solar power plants in different parts of northern Nigeria. When these projects are completed in the next 12 to 18 months, a combined 1000 megawatts of electricity will be generated and added to the national grid for public consumption (Ewepu and Ejoh, 2016).

In addition, this study will assist the Federal Government of Nigeria towards realizing the goal of developing 20% of the total energy consumed in the country from renewable sources by 2030 (Ewepu and Ejoh, 2016). It will also help the determination of the Federal Government of Nigeria in diversifying the energy supply mix in the country, and ensure that the country's power sector is no longer dependent on the vulnerability of one energy source.

This study provides relevant information to the companies licensed by the Nigerian Electricity Regulatory Commission (NERC) such as Pan Africa Solar, which is developing a 75MW solar plant in Katsina State; Nova Solar 5 Farm Limited which is developing 100MW in Katsina State; En Africa- developing 50MW in Kaduna State; Quaint Abiba Power Limited- developing 50MW in Kaduna State; and Anjeed Innova Group- developing 100MW also in Kaduna State (Ewepu and Ejoh, 2016).

CHAPTER TWO

CONCEPTUAL FRAMEWORK AND LITERATURE REVIEW

2.1 INTRODUCTION

This Chapter comprises of conceptual framework and literature review. The conceptual framework started with an overview of radiation and the climate system, then, described the Earth's radiation budget, discussed the interactions between the radiation and the Earth's atmosphere, and examined the concept of radiation budget and the Earth's surface. The conceptual framework concluded with a description of the relationship between radiation and clouds. This is followed by critical review of previous related literature. The literature review is divided into five sections. The first section reviews the available information on renewable energy resource in Africa. The second section reviews literature on statistical modelling of solar radiation in different parts of Nigeria. This is the most commonly used approach to solar energy analysis in Nigeria. The third and fourth sections review literature on geostatistical approach to solar radiation modelling and the application of satellite remote sensing and GIS in the analysis of solar energy potentials. Sections five and six discuss the application of geospatial techniques in developing solar information system for Nigeria in order to enhance the development of solar energy and electricity supply in the country.

2.2 CONCEPTUAL FRAMEWORK

2.2.1 Radiation and the Climate System

The Earth's climate system constantly adjusts in order to maintain a balance between the incoming and out-going radiation. This is referred to as Earth's "radiation budget". The components of the Earth system that are essential to the radiation budget are the Earth's surface, atmosphere, and clouds (Graham, 1999). The energy coming from the sun to

the Earth's surface is called solar energy. Most of this energy is in the form of radiation from the "visible" wavelengths. Visible radiation and radiation with shorter wavelengths, such as ultraviolet radiation are called "shortwave." Both the amount of energy and the wavelengths at which energy is emitted by any system are controlled by the average temperature of the system's radiating surfaces, plus the emission properties. The temperature of the sun's radiating surface, or photosphere, is more than 5500°C (9900°F). However, only a small fraction of the sun's energy comes in the direction of the Earth (Graham, 1999).

2.2.2 The Earth's Radiation Budget

The Earth's radiation budget comprises of the incident, reflected, absorbed, and emitted energies by the Earth system as shown in Figure 2.1. Based on the Physics principle of

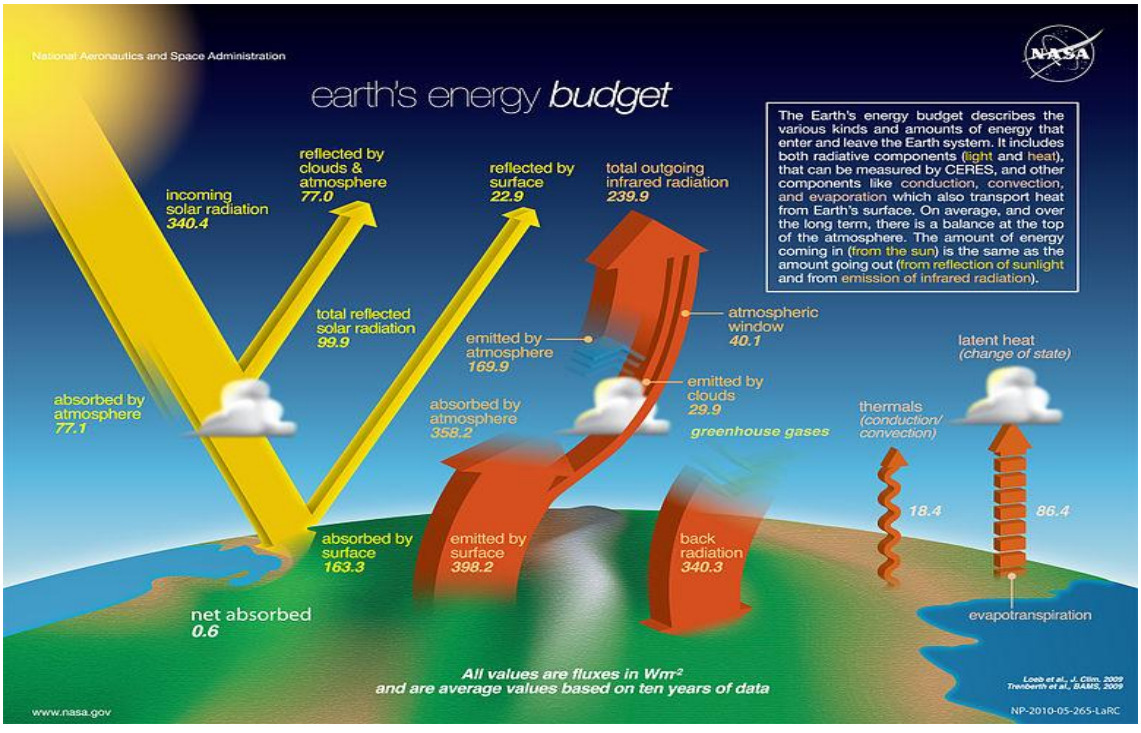


Figure 2.1: The Earth's Radiation Budget

Source: NASA, 2016

conservation of energy, this radiation budget represents the accounting of the balance between incoming radiation, which is almost completely solar radiation, and out-going radiation, which is partly reflected solar radiation and partly radiation emitted from the Earth system (terrestrial radiation), including the atmosphere (National Aeronautics and Space Administration, 2010).

2.2.3 Radiation and the Atmosphere

The radiation reaching the earth's surface passes through the atmosphere. The atmospheric components in form of particles and gasses can affect the incoming light and radiation. These effects are caused by the mechanisms of scattering and absorption (Natural Resources Canada, 2015).

2.2.3.1 Atmospheric Scattering

Scattering occurs when particles or large gas molecules present in the atmosphere cause the electromagnetic radiation to be redirected from its original path during radiation-atmosphere interaction. The extent of scattering depends on several factors including the wavelength of the radiation, the abundance of particles or gasses and the distance the radiation travels through the atmosphere. There are three types of scattering which take place in the atmosphere. These are:

a) Reyleigh scattering
b) Mie scattering
c) Nonselective scattering (Natural Resources Canada, 2015).

a) Rayleigh scattering occurs when particles are smaller compared to the wavelength of the radiation. These could be particles such as small specks of dust or nitrogen and oxygen molecules. Rayleigh scattering affects shorter wavelengths of energy much

more than longer wavelengths. It is the dominant scattering mechanism in the upper atmosphere (Natural Resources Canada, 2015).

a) Mie scattering occurs when the particles are almost the same size as the wavelength of the radiation. Dust, pollen, smoke and water vapour are causes of Mie scattering which usually affect longer wavelengths than those affected by Rayleigh scattering. Mie scattering mostly affect the lower portions of the atmosphere where larger particles are more abundant and dominates when cloud conditions are overcast.

b) Nonselective scattering: This occurs when the atmospheric particles are much larger than the wavelength of the radiation. Water droplets and large dust particles can cause this type of scattering. All wavelengths are scattered almost equally by nonselective scattering (Natural Resources Canada, 2015).

2.2.3.2 Absorption

Absorption is another process resulting from interaction of electromagnetic radiation with the atmosphere. In contrast to scattering, this phenomenon causes molecules in the atmosphere to absorb energy at various wavelengths. Ozone, carbon dioxide and water vapour are the thre main atmospheric which absorb radiation (Natural Resources Canada, 2015).

2.2.3.3 Effects of Earth's Atmosphere on Incoming Solar Radiation

Greenhouse gasses in the atmosphere absorb most of the Earth's emitted longwave infrared radiation, which heats the lower atmosphere. In turn, the warned atmosphere emits longwave radiation, some of which radiates toward the Earth's surface, keeping our planet warm and generally comfortable. Increasing concentrations of greenhouse gases such as carbon dioxide and methane increase the temperature of the lower

atmosphere by restricting the outward passage of emitted radiation, resulting in “global warming” or global climate change (NASA, 2010).

2.2.4 Radiation and Clouds

The nature of clouds and their characteristics, their occurrence and geographical location plays a significant role in the understanding of climate change (Graham, 1999). Low, thick clouds principally reflect solar radiation and col the surface of the Earth. High thin clouds primarily transmit incoming solar radiation; at the same time, they trap some of the outgoing infrared radiation emitted by the Earth and radiate it back downward, thereby warming the earth surface. The amount of heat transmitted by clouds to the Earth's surface depends on several factors such as the altitude of the cloud, it size and the composition of the particles that form the cloud (Graham, 1999).

When a cloud absorbs longwave radiation emitted by the Earth’s surface, the cloud remits a portion of the energy to outer space and a portion back toward the surface. The intensity of the emission from a cloud varies directly as its temperature and also depends upon several other factors, such as the cloud’s thickness and makeup of the particles that form the cloud (Graham, 1999).

The high, thin cirrus clouds are highly transparent to shortwave radiation, but they readily absorb the outgoing longwave, infrared radiation both out to space and back to the Earth’s surface. Also, in the presence of cumulonimbus cloud, the energy radiated to outer space is lower, because the cloud tops are high and clod (Graham, 1999).

2.2.5 The Radiation Budget and Earth's Surface

2.2.5.1 Reflection

Energy goes back to space from the Earth system in two ways: reflection and emission. Part of the of the solar energy that comes to Earth is reflected back to space in the same, short wavelengths in which it came to Earth (Graham, 1999). This is referred to as reflection.

2.2.5.2 The concept of Albedo

The fraction of solar energy that is reflected back to space is called the albedo. Different parts of the Earth have different albedos. For example, ocean surfaces and rain forests have low albedos, hence, they reflect only a small portion of the sun's energy (Graham, 1999).

2.2.6 Models for the Estimation of Global Solar Radiation

The models for the estimation of global solar radiation can be classified into models for the estimation of global solar radiation on horizontal and inclined/tilted surfaces.

2.2.6.1 Models for the Estimation of Global Solar on Horizontal Surface.

These models can be classified into Sunshine-based model, Temperature-based model, Cloud-based model, Meteorological-parameters-based model and hybrid-parameter-based models (Basharat, Dehgham and Faghih, 2013).

a) Sunshine-based models: These models use sunshine data that are usually obtained from weather stations to estimate solar radiation in an area or region. These types of models were used Gana and Akpootu (2013), Ogbaka and Silikwa (2016) to estimate

solar radiation in Kebbi and Yola states of Nigeria respectively. The models are usually employed due to availability of sunshine data in most weather stations.

b) Cloud-based models: Examples of the application of these models are found in Flores and Baldasano (2001), Basir *et al*. (2013). These models are usually applicable in temperate climate and regions experiencing high cloud cover.

c) Temperature-based models use temperature data to model solar radiation as demonstrated by Sanusi and Abisoye (2011), Okundamiya and Nzeako (2011).

c) The hybrid parameter-based models integrate meteorological and geographical parameters to predict the solar radiation on a horizontal surface as demonstrated by Bios *et al*. (2008). Although this model can predict solar radiation in an area, many of the required parameters are not readily available at most locations (Besharat *et al.,* 2013).

2.2.6.2 Models for the Estimation of Diffuse Radiation on Horizontal Surface

The models that can be used to estimate diffuse radiation on horizontal surfaces can be classified into two types: Parametric Models and Decomposition Models.

2.2.6.2.1 Parametric Models

The parametric models require specific information on environmental conditions of an area such as atmospheric turbidity, fractional sunshine, cloud cover and perceptible water content as input parameters of the model. Examples are ASHRAE Model, Nijegorodov's Model and Parishwad's Model (Maleki, Hizam and Gomes, 2017).

2.2.6.2.2 Decomposition Models

Decomposition models determine diffuse radiation from solar radiation data. The models are based on a correlation between the diffuse and global radiation on a horizontal surface. This correlation is defined as a function of the hourly clearness index (Maleki *et al.,* 2017). Examples of decomposition models include Erbs' Model, Jacovides' Model, Muneer's Model, Spencer's Model, Lam and Li's Model, Liu and Jordan's Model. A review of these models is found in Maleki *et al.* (2017).

2.2.6.3 Models for the Estimation of Global Solar Radiation on Inclined Surface

These models can be classified into isotropic and anisotropic sky models. There are several isotropic and anisotropic models, some of which are discussed below

2.2.6.3.1 Isotropic Models

The isotropic models include Liu and Jordan, Koronakis, and Badescu models.

a) Liu and Jordan's Model

This model is based on the assumption that solar radiation on inclined surface is composed of the beam radiation, the reflected radiation from the ground and the diffuse fraction (Shukla, Rangnekar and Sudhakar, 2015). This model presumes that diffuse radiation intensity is distributed uniformly over the whole sky (Maleki *et al.*, 2017).

b) Koronakis' Model

Koronakis modified the assumption of isotropic sky diffuse radiation and proposed that the slope ß = 90^0 provides 66.7% of diffuse solar radiation of the total sky dome (Shukla, Rangnekar and Sudhakar, 2015).

2.2.6.3.2 Anisotropic Models

Examples of anisotropic models include Hey and Davies, Reindl *et al*., Perez' Model, Klucher's Model, Temps and Coulson's Model.

a) Hay and Davies Model

Hay and Davies assumed that the diffuse radiation from the sky is composed of an isotropic and circumsolar component only, whereas, the horizon brightening parts was not considered. It was assumed that the diffuse component coming directly from the sun's direction is circumsolar and diffuse component reaching through the rest of the sky dome isotropically (Shukla *et al.,* 2015).

b) Perez Model

This model is based on the in-depth applied mathematics analysis of the sky's diffuse components. The model divides diffuse radiation into three components: isotropic background, circumsolar, and horizon zones (Maleki *et al.,* 2015).

c) Temps and Coulson's Model

This model is based on the modification of the isotropic model of Liu and Jordan, in which two terms representing diffuse radiation by assuming a clear sky condition was introduced (Maleki *et al.*, 2015).

d) Klucher's Model

This model is based on the models by Temps and Coulson and Liu and Jordan. Klucher discovered that Liu and Jordan's isotropic model provides good result for overcast skies but ignores radiation for some sky conditions, such as partly overcast and clear

skies. To address such, the Temps and Coulson model was refined by introducing a function fk that determines the degree of cloud cover (Maleki *et al.,* 2017).

Although Maleki *et al.* (2017) found that the most accurate isotropic models are those of Liu-Jordan and Koronakis, while the Perez, Temps-Coulson, Klucher and Bugler models were the most accurate anisotropic model; the choices of model depend on the availability of data, geographical location and time.

2.2.7 Models for Estimation of Global Solar Radiation from Satellite Data

The models used to estimate global solar radiation from satellite data can be classified into empirical and theoretical. The empirical method establishes a relationship between the satellite data and the measurements made on the surface; while the theoretical method uses radiative transfer models in order to relate the satellite data with the surface measurement (Flores and Baldasano, 2001). The estimation of solar radiation from satellite data usually requires the use of Geographic Information System (GIS) techniques. The application of these models is found in the works of Ramachandra (2007), Pettazzi and Salson (2012), Janjai *et al.* (2013).

2.2.7.1 Factors that Influence Satellite Estimation of Global Solar Radiation

Several factors affect satellite retrieval of solar radiation data which include clouds and atmospheric constituents. Cloud detection is important when attempting to obtain precise estimates of global solar radiation (Flores and Baldasano, 2001). Therefore, estimating the total atmospheric transmission factor and the cloud-cover index for the satellite images are critical steps in estimating solar radiation from satellite images.

Solar radiation implies the electromagnetic radiation of the sun. As the solar radiation passes through the atmosphere, it undergoes absorption of scattering by various constituents (gases, water droplets and particulates) of the atmosphere(natural resources Canada, 2015). The amount of solar radiation finally reaching the earth surface depends quite significantly on the composition and concentration of various atmospheric constituent (Camfer University, 2017) at any point in time. Also, solar irradiance, which is the incident energy per unit area is influenced by geographical factors and therefore varies with season and time of the day due to the various sun's position. Therefore, knowledge of the effects of geographical factors on irradiance is vital for developing location-specific solar energy applications.

Likewise, information on global radiation is essential for research, engineering applications, for studying earth's climatic system dynamics, and for power supply. In spite of its various applications and importance as a prospective alternative energy source, global solar radiation measurement is still scarce in Nigeria. There are various ways to address the scarcity of information on solar radiation in an area or region. Rehman and Ghori (2000) proposed the application of spatial mapping in estimating the amount of solar radiation in an area. Spatial mapping in this case involves developing solar database which can be used for solar energy analysis. Other researchers such as Becker (2001), Monedero *et al*. (2007), Gadiwala, Usman, Akhtar and Jamil (2013) used empirical models to estimate global solar radiation in different parts of the world. Hence, spatial mapping and empirical modeling provide sources of solar information gathering and analysis.

Alternatively, maps of global solar radiation can be derived by spatial interpolation of ground-based measurements. But, the spatial density of solar radiation data required for

interpolation is often very limited and therefore the interpolation errors can be high (Perez, Seals, Stewart, Zelenka, Estrada-Cajigal, 1994). To complement the spares network of ground-based measurements, numerous algorithms have been developed to estimate the surface incoming global solar radiation from satellite images. Initially, empirical models were used to estimate solar radiation from available meteorological data. Empirical modeling approach has been adopted by several researchers.

Angstrom (1924) was the first scientist known to use empirical model to mathematically relate two solar properties (the average actual sunshine hours per day and the maximum possible sunshine hour per day) as a fraction of the global solar radiation of clear-sky day. Later on, the Angstrom formula was modified to estimate solar radiation at different locations. However, recent studies by Jounee *et al*. (2011) and Pettazi and Salson (2012a) have demonstrated the advantages of merging ground-measured and satellite-derived values of the global solar radiation to provide reliable high resolution maps of global solar radiation. For example, Journee and Bertrand (2010) carried out a study to improve the spatiotemporal estimation of the surface solar radiation over Belgium, by merging ground and satellite measurements. They found that the best estimation of the distribution of surface solar radiation is obtained when both satellite and ground data sources are combined to compensate errors inherent to the satellite data with accurate ground measurement. Likewise, Pettazzi and Salson (2012a) utilized twenty three years long series of satellite data together with in situ measurements distributed across Galicia (NW Spain) for detailed analysis of the solar radiation in the region. Both spatial and temporal analyses were performed.

Analysis of solar energy potentials in a region start from acquiring solar radiation data from available radiation stations, the data can be complemented through empirical

modeling or satellite remote sensing. Empirical modeling of solar radiation has the disadvantage of being time consuming and computationally complex while satellite derivation of solar radiation requires some technical knowledge of remote sensing and is prone to errors. In this study, merging ground-based measurements of solar radiation and satellite-derived data is considered because it gives better results based on the finding of Journee and Bertand (2010) and Pattazzi and Salson (2012a).

The conceptual framework highlighted that solar radiation as the electromagnetic radiation emanating from the sun which provides solar energy is influenced by the atmosphere, cloud and other geographical factors. Therefore, knowledge of the effects of these factors is essential for harnessing solar energy in an area or region.

2.3 LITERATURE REVIEW

2.3.1 Renewable Energy resource Information in Africa

There is general scarcity of information on potential of energy resources in Africa compared to the rest of the world, making it difficult to compare the potential for the different alternative sources of energy (Monforti-Ferrario, 2011) which is fundamental for investing in and harvesting alternative energy sources in the continent. This lack of information is even more obvious for renewable energies (REN-21, 2010) such as wind and solar which have been used in many countries to provide electricity in the rural areas. According to an elaboration of the International Energy Agency (IEA) data by the Alliance for rural electrification (ARE, 2011), about 589 million people in the African continent had no access to electricity in 2008. This shows the extent of energy poverty among the people in the continent. However, the pervasive energy poverty in the continent can be reduced by increasing access to electricity. Access to electricity in Africa and Nigeria in particular can be significantly improved by harnessing the

available renewable energy resources in the country. However, knowledge of the potentials of renewable resources in an area is required to be able to harness them properly.

Hermann, Miketa and Fichaux (2014) used a GIS-based approach to estimate the renewable energy potential in Africa. Their findings revealed that with the exception of Central African countries, solar energy resources have a significant potential in large parts of the continent but with remarkable differences when applied through different solar technologies – PV or CSP plants. They also reported that the bioenergy potential of the continent is enormous but characterised by extreme disparities between regions; while wind energy has the largest regional disparities in the continent.

Also, a scientific and technical report by the Joint Research Centre of the European Commission reported some information regarding renewable resources in Africa (Monforti-Ferrario, 2011). The report assembled geographical data on solar radiation, wind weather patterns, biomass resources of forests, agriculture and residues as well as water resource data in the continent. According to the report, the potential of smaller scale (<50kW) wind-energy systems within hybrid solar/biodiesel generator/wind electricity systems has not been studied.

Apart from the report by the Joint Research Centre, few studies have been carried out to assess solar energy potentials in Africa. An attempt to map solar radiation in Africais found in the work of Diabaté, Blanc and Wald (2004). Such a map is very useful for understanding solar radiation pattern as well as for preliminary assessment and modelling of solar energy systems in Africa. However, the climate zone classification proposed by Diabaté *et al.* (2004)only gives information about similar values of the monthly mean of the daily clearness index, making it unsuitable for direct solar energy

calculations. In addition, Diabaté *et al.* (2004)acknowledged the limitations of the zoning adopted in their work to estimate the solar radiation climate in Africa. This is because it was observed that the zoning they adopted was inconsistent all over the map. The reason for this being lack of stations in some places within the continent. One way to increase the quality of the zoning according to themwould be to use satellite-derived clearness index, which will be available at each pixel within the whole area. Such a dataset (satellite-derived data) which would have implied much larger computational resources is presently available (Diabaté *et al.*, 2004). The present study integrates available satellite data with ground measurements to map solar radiation in Northwestern Nigeria as proposed by Diabaté *et al.* and has been experimented in few African countries.

In developing countries like Uganda, solar radiation data is scarce due to the high costs involved in buying and maintaining solar measuring equipment. As a result of this, the long-term global solar radiation data is measured in very few locations in the country where the measuring instruments are installed and then estimated in other places where there is no equipment (Angela *et al.*, 2011). The same situation is found in Nigeria and specifically in the Northwestern region of the country where there are very few meteorological stations.There is therefore the need to devise methods of assembling solar radiation data as an important preliminary step for solar energy resource exploitation in Africa.

There are different methods that can be used to assemble and analyse solar radiation data for the development of solar energy in Africa. For instance, Hussein (2012) developed a mathematical model to estimate the hourly global solar radiation on horizontal surfaces in the Delta of Egypt, using the available meteorological data, which

are sunshine duration and cloud cover, as well as maximum, minimum and daily mean of ambient temperature covering the year 2009. Similarly, Angela *et al.* (2011) employed the artificial neural network to estimate the monthly average of daily global solar irradiation on a horizontal surface in Kampala, based on sunshine hours in the area. Likewise, Lealea and Tchinda (2013) estimated the diffuse radiation of four stations in North and Far North of Cameroon. The results obtained by these studies can be improved, in view of the fact that indirect methods were used in estimating solar radiation which are prone to errors. The results can be improved by using other climatic variables or through alternative methods. The need to improve the results is particularly important in order to have relatively accurate estimate of the amount of solar radiation in the areas which is required for design and exploitation solar energy in the African countries.

The successful design and effective utilization of solar energy systems and devices for application in power and water supply, for industrial, agricultural and domestic uses, largely depend on the availability of information and the characteristics of solar radiation in the locations where the systems and devices are to be situated (Falayi *et al.*, 2011). As such, there are solar information systems that are developed for specific locations. For instance, Photovoltaic Geographical Information System (PVGIS) has been developed to provide a map-based inventory of solar energy resource and assessment of the electricity generation from photovoltaic systemsin Europe, Africa, and South-West Asia (Huld *et al.*, 2005). PVGIS is famous, widely used and validated tool which is suitable for further analysis on solar energy deployment. The PVGIS also provides solar radiation data for the three continents.

It is noteworthy that there are areas in Africa that are endowed with higher solar energy potentials than other parts of the world. In these areas, the same type of photovoltaic panel can produce averagely twice as much electricity as in Central Europe (Monforti-Ferrario, 2011). But the actual quantities of these resources in many of these areas have not been determined due to lack of sufficient solar radiation data in the areas. Hence the resources remained unharnessed and therefore unutilized.

In addition to the need for adequate information on solar radiation in an area, Monforti-Ferrario (2011) affirmed that sufficient knowledge of the existing and viable energy infrastructures is an essential requirement for comprehensive assessment of the economically utilizable renewable energy in an area. He therefore recommended mapping the physical availability of renewable energy infrastructures as an important step in understanding their exploitability. Renewable energy maps serve as veritable tools for visualising renewable energy distribution, and geographic variations in renewable potentials, which will guide policy formulation and investment in renewable energy development.

Solar and Wind Energy Resource Assessment(SWERA) is an example of such a veritable information system for the analysis of renewable energy potentials. SWERA is a pilotproject designed to compile such data in thirteen developingcountries and to facilitate investments in solar and windenergy projects.SWERA is developing new informational tools for energyplanners and project developers. These tools includeregional and national maps of solar and wind energyresources and a GISthat will allow easy access to the detailed informationcontained in these maps. A similar application can be developed for Northwestern Nigeria and the preliminary steps have been taken by this study.

Solar energy information is required as input for solar energy mapping, assessment and exploitation. Such information is usually obtained from meteorological stations. However, the number of stations to provide sufficient data is very few in Africa. Therefore, solar radiation data is not available for many African countries like Nigeria which cannot afford the cost of managing and maintaining more stations. Hence, radiation data in Nigeria is usually derived or estimated from other related data. There are several models that relate global radiation to other climatological parameters which have been used to estimate solar radiation at various geographical locations in Nigeria. These models are reviewed in the following section.

2.3.2 Statistical Modelling of Solar Radiation in Nigeria

In Nigeria, a number of studies have modelled solar radiation on the basis of the more readily available meteorological data in the country. Some of the studies developed models and empirical correlations involving global solar radiation and sunshine hours for different locations in Nigeria. For example, Arinze and Obi (1983) developed a correlation with solar radiation using sunshine hours in Northern Nigeria with regression coefficients a = 0.2 and b = 0.74. Sambo (1985) developed a correlation with solar radiation using sunshine hours for Kano with the regression coefficients for all the months between 1980 and 1984. Another attempt was done by Ojosu (1990) in which he produced iso-radiation map for Nigeria using measured solar radiation data obtained from experimental stations, estimated solar radiation from empirical formulae using meteorological data, and the converted solar radiation data from the Meteorological Office in Nigeria. However, the iso-radiation maps do not clearly show the spatial variation in solar radiation in Nigeria.

Other studies developed theoretical and empirical correlations of broad applicability to provide solar data for systems design in Nigerian cities. For instance, Burari *et al.* (2001) developed a model for estimation of global solar radiation in Bauchi with regression coefficients a = 0.24 and b = 0.46. In addition, Udo (2002) used monthly average daily values of clearness index and relative sunshine covering a period of two years, to develop two equations (linear and quadratic) of the Angstrom-Prescott model for the estimation of global solar irradiation at Ilorin in northcentral Nigeria. Besides, multiple linear regression models were developed by Akpabio, Udo, and Etuk (2004) to estimate the monthly average daily global solar radiation using ten parameters during a period of sixteen years (1984 - 999) for Onne, in southwestern Nigeria. The parameters were extraterrestrial radiation, average daily temperature, ratio of minimum and maximum daily temperature, relative humidity, ratio of sunshine duration, solar declination, average soil temperature, average pan evaporimeter, average rainfall and average daily dew. Similarly, Chiemeka (2008) employed the Hargreaves equation using temperature data to estimate the solar radiation at Uturu in Abia State of southeastern Nigeria.

It is evidenced from the abovementioned studies that there are various approaches to solar radiation modelling as there are variant climatic parameters which can be used in the modelling, depending on the availability of the parameters. Therefore, Augustine and Nnabuchi (2009a) investigated set of models that can used to relate global solar radiation and sunshine hours in Calabar, Port Harcourt and Enugu respectively in southsouthern and southeastern Nigeria. They used seventeen-year (1999-2007) monthly mean daily data for global solar radiation and sunshine hours in Calabar, Enugu and Port Harcourt to develop a number of regression equations, Also, a correlation equation of the Angström type has been developed by Augustine and

Nnabuchi (2009b) to predict the monthly mean daily global solar radiation incident on a horizontal surface in Warri of southsouthern Nigeria. The researchers compared measurements of global solar radiation with those predicted using the equation, and a positive correlation between them was observed. The positive correlation observed by Nnabuchi (2009b) could be validated or compared with the results from a hybrid model which combines several climatological parameters as done in some other studies.

Augustine and Nnabuchi (2009c) developed a number of multilinear regression equations for Enugu town in southeastern Nigeria, to predict the relationship between global solar radiation with one or more combinations of the following meteorological parameters: fraction of sunshine, maximum temperature, cloudiness index and relative humidity for seventeen years (1991 – 2007). Likewise, Augustine and Nnabuchi (2010) used the monthly mean daily global solar radiation, sunshine hours, maximum temperature, cloudiness index and relative humidity data for some selected cities, Owerri and Enugu in southeastern Nigeria, Warri and Calabar in southsouthern Nigeria. The data covered a period of seventeen years (1991 - 2007), and was used to generate several linear and multilinear regression equations.

The methods used in the aforementioned studies are more of cloud-based integrating sunshine duration rather than the temperature-based methods which provide an alternative way of modelling and can be used to evaluate the performance of other solar radiation models. Sanusi and Abisoye (2011) evaluated the behaviour of three empirical models based on the difference between maximum and minimum temperatures at Ibadan in southwestern Nigeria. This was done by using monthly data on solar radiation and minimum and maximum temperature for a period of six years (2001–2006). The corresponding monthly value of extraterrestrial solar radiation (Ra) was calculated for

each data. The shortcoming of this method is the short period of six years that may not give reliable results in studies of this nature which requires a long time period.

Also, Okundamiya and Nzeako (2011) proposed a temperature-based model of monthly mean daily global solar radiation on horizontal surfaces for selected cities, representing the six geopolitical zones in Nigeria. The monthly mean daily global solar radiation on horizontal surfaces and monthly mean daily ambient temperatures (minimum and maximum) for a ten-year period (1996–2005) from six cities (Abuja, Benin, Katsina, Lagos, Nsukka, and Yola) were used as input parameters. The modelling was based on linear regression theory.

In addition, Falayi, Rabiu and Teliat (2011) estimated the diffuse solar radiation for eight stations (Sokoto, Maiduguri, Port Harcourt, Enugu, Owerri, Abeokuta, Yola, Jos) in Nigeria. The data used for the study were the monthly means of daily global solar radiation on horizontal surface, ambient temperature (minimum and maximum), relative humidity and sunshine duration of the eight locations for sixteen years (1995-2010). The validity of the individual correlations were measured using the two widely used statistical indicators, MBE and RMSE. Besides, Ibeh, Agbo, Ekpe and Isikwue (2012) estimated the global solar radiation with meteorological parameters at Calabar city in southsouthern Nigeria. The daily mean temperature and relative humidity for seventeen years (1991-2007) and the global solar radiation data were used. The artificial neural network and multiple regression models were used for the estimation. Based on their findings, they observed that better results were obtained from correlation with the measured, which indicates that artificial neural network model is a better model for estimation. Therefore, they recommended the use of this model for estimation of global solar radiation at locations with similar weather conditions.

Beisdes, Isikwue, Amah and Agada (2012) proposed the coefficients for Angstrom-Prescott type of model for the estimation of global solar radiation in Makurdi of northcentral Nigeria, using relative sunshine duration alongside the measured global solar radiation data for the period of 2001-2010. Also, Musa, Zangina and Aminu (2012) used the daily sunshine duration to estimate average global solar radiation for Maiduguri in northeastern Nigeria. The daily sunshine hour were measured for five years (2004-2007) from which the monthly mean values were determined. Angstrom model was then used to estimate the global solar radiation based on the monthly mean sunshine hour. The researchers observed that the monthly global solar radiation in the area is not uniform throughout the period of study.

In addition, a correlation between measured and predicted values of solar radiation in Mubi town of Adamawa State in Nigeria was presented by Medugu, Adisa, Burari and Abdul'Azeez (2013). In this case, a series of daily measurements of the global solar radiation on a horizontal surface was recorded in with the aid of a constructed pyranometer. The monthly average value was determined. The monthly average daily solar radiation on horizontal surface was also determined using sunshine duration. These parameters were input in some radiation models to compute the solar radiation. Finally, a prediction of the global solar radiation from climatological data was attempted. Then predicted values were compared with the corresponding measured values. Similarly, Osueke *et al.* (2013) examined the solar irradiance variation in four locations in Nigeria (Enugu, Lagos, Abuja and Maiduguri) using NASA meteorological data for twenty-two year period. This was achieved by developing models that were based on statistical regression analysis. Their findings revealed that the models developed from the statistical analysis showed good levels of linear conformity with correlation coefficients of 0.78 - 0.8 except for Abuja which had a fair value of 0.546.

The above mentioned studies indicate that in places where there is no direct measurement, solar radiation can be estimated using models and empirical correlations as highlighted. However, the accuracy of the models and empirical correlations can still be improved using alternative methods. An alternative method to derive solar radiation data is satellite remote sensing. Recently, satellite images have provided appropriate and up-to-date data on global solar radiation. The satellite data is usually analysed in a GIS to provide solar energy information in an area or region. This is discussed in the following section.

2.3.3 Geostatistical Approach to Solar Radiation Modelling

The use of geostatistics to study the spatial variation of global solar radiation on a horizontal surface has an advantage over other methods of solar radiation data analysis and modelling. This is due to the fact that solar radiation itself is location dependent, making it compliant to the geostatistical method (Rehman and Ghori, 2000). The section that follows review some geostatistical techniques applied to solar radiation modelling.

Geostatistics is a class of statistical techniques developed to analyze and predict values of a geographical phenomenon. Geostatistics is a subset of statistics specialized in analysis and interpretation of georeferenced data (Goovaerts, 1997) with a focus on inherently continuous fields (Hengl, 2009). The term geostatistics is generally applied to a set of data, which is characterized by spatial continuity using statistics. A data set may appear chaotic to the eye but may possess strong spatial correlation (Rehman and Ghori, 2000). It begins with a type of autocorrelation analysis called semivariance analysis, in which the degree of spatial self-similarity is displayed as a variogram. The

variogram is a useful tool for estimating the spatial behaviour of a property distribution such as ore grades and solar radiation (Rehman and Ghori, 2000).

Geostatistics has been used in the estimation of ore grades, rainfall, temperatures, weather forecasting, rock properties of oil bearing reservoirs (Rehman and Ghori, 2000) and solar radiation. The basic idea in geostatistics is that for many natural phenomena, such as solar irradiation, samples taken close to each other have higher probability of being similar in magnitude than samples taken further apart. This implies spatial correlation structure in the phenomena. In the literature, some studies have applied geostatistical methods for the estimation of solar radiation in various parts of the world. For example, Rehman and Ghori (2000) used experimental variogram calculations and ordinary kriging for the estimation of solar radiation in Saudi Arabia; Journée and Bertrand (2010) employed ordinary kriging (OK), kriging with external drift (KED) and regression kriging (RK) for geostatistical merging of ground-based and satellite-derived data of surface solar radiation over Belgium. One of the methods used is Kriging with External Drift (KED).

Besides, other methods are found in the literature. For instance, Rehman and Ghori (2000) used geostatistical techniques for the estimation of solar radiation in Saudi Arabia. The techniques include univariate analysis, experimental variogram calculations and model fitting, estimation using kriging and plotting contour maps. Variogram models were fitted to measured variograms for each month of the year. The error analysis showed that the mean percent errors were found to vary between a minimum of 0.5% and a maximum of 1.7% based on their findings and this is remarkable. They concluded that this technique could be used for the spatial estimation of solar radiation on regional and continental scales

Sen and Sahin (2001) found a regional procedure for estimating the solar irradiation value of any point from sites where measurements of solar global irradiation already exist. The spatial weights were deduced using geostatstical approach through the regionalized variables theory and the cumulative semivariogram (CSV) approach which helps to find the change of spatial variability with distance from a set of given solar irradiation data. It is then employed in the estimation of solar irradiation value at any desired point through a weighted average procedure. In this case, the number of adjacent sites considered in this weighting scheme is based on the least squares technique. The validity of the methodology was first checked with the cross validation technique. Hence, after the cross-validation each site will have different number of nearest adjacent sites for spatial interpolation. The application was achieved for monthly solar irradiation records over Turkey by considering 29 measurements stations. They demonstrated that the procedure presented in their work is better than the classical techniques such as the inverse distance or inverse distance square approaches.

Journée and Bertrand (2010) conducted a study to improve the spatio-temporal estimation of the surface solar radiation over Belgium, by merging ground and satellite measurements. Their study evaluated several merging methods with various degrees of complexity together with interpolated ground measurements and satellite-derived values only. The methods considered in their study to merge ground-based and satellite-derived data are: Mean Bias Correction, Interpolated Bias Correction, Ordinary Kriging with satellite-based correction and Kriging with an External Drift.

The global/surface solar radiation data over Belgium was acquired from 13 Belgian ground stations as well as the operationally derived surface incoming global short-wave radiation products from Meteosat Second Generation satellites imageries. Two years of

data (2008 and 2009) were used to evaluate the performance of the merging methods between in situ and satellite measurements. Prior to evaluating the merging methods, SAF products were first evaluated against ground data at each measurement site. The merging methods are then evaluated together with interpolations of ground measurements only. Finally, a spatial distribution of surface solar radiation is established. The performance of the different methods was assessed by leave-one-out cross-validation. They found that merging ground-based observations with the satellite-based data provides systematically an improvement over each of the data considered separately.

Journ´ee and Bertrand (2011) discovered that that merging both ground-based and satellite-derived data provides the most accurate mapping of surface solar radiation over Belgium. Therefore, they used Ground-based solar radiation measurements provided by The Royal Meteorological Institute of Belgium (RMIB) and MSG-derived surface solar irradiance Within the Satellite Application Facility (SAF) network, the down-welling short-wave irradiance at the Earth's surface is operationally retrieved from MSG imageries by three decentralized SAFs www.osi-saf.orgwww.cmsaf.eu. Their study considered three geostatistical mapping methods: Ordinary Kriging (OK), Kriging with External Drift (KED) and Regression Kriging (RK).

Journée *et al*. (2011)exploited the Meteosat solar radiation climate data records recently released by the Satellite Application Facility on Climate Monitoring (CMSAF, www.cmsaf.eu) to derive solar radiation climate maps over Belgium, the Netherlands and Luxembourg (i.e., the Benelux). The Meteosat climate data record is a long time-series of solar radiation derived from satellite information of the first generation of Meteosat satellites (CMSAF, 2010). This dataset provides hourly estimations as well as

daily and monthly means of both the global and the direct solar radiation from 1983 to 2005. Their study is based on daily global solar radiation values for the period 1995 to 2005. Firstly, the Meteosat climate dataset is validated against ground-based measurements from 45 stations located in Belgium and in the Netherlands. Then, the benefit of merging the Meteosat-retrieved data with the ground measurements is evaluated. Finally, based on the derived daily global solar radiation maps from 1995 to 2005, monthly, seasonal and annual solar radiation climate maps were computed.

Antonanzas-Torres, Cañizares and Perpiñán (2012) performed an analysis and comparison of daily and yearly solar irradiation from the satellite CM SAF database and a set of 301 stations from the Spanish SIAR network using data of 2010 and 2011. The analysis was completed with the comparison of the estimations of effective irradiation incident on three different tilted planes (fixed, two axis tracking, north-south horizontal axis) using irradiation from the satellite estimate and on-ground measurements. Ordinary kriging was initially tried within this study, generating inaccurate estimations due to the long distances among some stations.Hence, the improved model known as kriging with external drift (KED) or regression kriging was employed. They finally produced a new map of annual irradiation values both on the horizontal plane and on inclined planes combining both sources with geostatistical techniques (kriging with external drift, KED).

An alternative method to derive solar radiation data is satellite remote sensing. Recently, satellite images have provided appropriate and up to date information on global solar radiation. This is discusses in the following section.

2.3.4 Satellite Remote Sensing and GIS Approach to Analysis of Solar Radiation

Satellites are now considered as important sources of solar radiation data which is retrieved through the Remote Sensing and GIS techniques. GIS is a computer based information system for collection, storing, analysis and transformation of geographic data into geographic information. GIS has recently been used in the analysis of energy resources and energy systems as reported in the literature on Energy Geographies. Since solar radiation is measured at very few weather stations, it is often estimated from the duration of bright sunshine or from mean daily cloudiness. In the absence of these variables, irradiance can be estimated by means of standard meteorological observations, spatial interpolation techniques or satellite images (Bindi and Miglietta, 1991). Satellite remote sensing has provided an efficient alternative approach to derive solar radiation data. An extensive review of satellite methods to derive surface shortwave irradiance is found in Pinker *et al.* (1995). In addition, Dagestad (2005) discussed the Heliosat algorithm which estimates solar radiation at ground level from satellite images. The study analysed the performance of various versions of the algorithm and suggested modifications.

Appropriate information on solar resources is required for the development of solar energy systems and applications. Because ground-based measurements of solar radiation are usually scarce, several methods have been proposed to estimate the solar radiation incoming on a horizontal surface at ground level from images taken by satellites, and in particular by geostationary satellites (Journée *et al.*,2011).Geostationary meteorological satellites record backscattered solar radiation from the Earth-atmosphere system at high temporal frequencies, thereby providing means of estimating surface solar irradiance. Some models have been proposed to

derive solar radiation from satellite data. These models have been employed by different researchers and they are reviewed in the following paragraphs.

A model was presented by Flores and Baldasano (2001) for the determination of hourly global solar radiation from National Oceanic and Atmospheric Administration-Advanced Very High Resolution Radiometer NOAA-AVHRR satellite data, which provides wide coverage, together with adequate spatial resolution (around 1.1 km at the nadir). The process is divided into three steps: the first step consists of a cloud detection procedure; the second step determines the cloud index for each point on the satellite image, which is then used for the third step, which is the application of the global solar radiation statistical model. The coefficients for the model were determined by regression from the data obtained using pyranometers from eleven global surface solar radiation measurement stations. Then, a surface interpolation was performed in order to obtain the entire coefficient field for the area under study with the objective of applying the model. The estimates obtained from the model were compared to data from another ten ground radiation measurement stations in Catalonia, Spain. This model was tested for the eleven consecutive months beginning in February 1998, and a good correlation was obtained between the estimate provided by the model and the data from the measurement stations. This resulted in a coefficient of determination greater than 0.98 in all cases, together with RMSE of between 9.6% and 15.8% and a bias that varied from -9.5% to 1.3%.

Ramachandra (2007) employed GIS to map and analyse spatial variation in solar potential in Karnataka state of India, based on global solar radiation data. In stations where measurements of global solar radiation were available, data was used directly, and for locations where the data was not available, indirect methods were used. Both the

theoretically-based and empirical-based methods were used in the study. The study identified the area with the higher global solar radiation which is ideal for harvesting solar energy in Karnataka. The method employed by Ramachandra (2007) is applicable to Nigerian situation.

Bois *et al.* (2008) combined remotely sensed data and solar irradiation models based on orography to estimate the spatial and temporal variability of solar radiation interception of the Bordeaux winegrowing region in France over a twenty-year period (1985-2005). Their approach to solar radiation mapping of the area involved two steps: estimation of solar radiation on horizontal surfaces; and terrain integration for incoming solar radiation mapping. To achieve these, solar radiation data was retrieved from the HelioClim-1 database, elaborated from Meteosat satellite images, using the Heliosat-2 algorithm. Daily data was interpolated using ordinary kriging to produce horizontal solar radiation maps at a 500m resolution. Then using a digital elevation model, 50 m resolution daily solar radiation maps with terrain integration were produced for the period 2001-2005. Then the Bordeaux winegrowing region was classified into three zones of low, medium, and high solar radiation areas (Bois *et al.*, 2008).

Pettazzi and Salsón (2012) utilised twenty years long series of satellite data together with ground-based measurements distributed all across Galicia in Northwestern Spain for detailed analysis of the solar radiation in the region. The data from the weather stations were validated using a clear sky model, in order to eliminate those values unusually too high (greater than 110% of clear sky irradiance) or too low (less than 3% of extraterrestrial radiation). A visual analysis to detect systematic errors in the pyranometers and comparisons between nearby stations, were also performed. Finally, monthly averages were calculated. The calibration of satellite data with ground-based

measurements was achieved by means of residual techniques. First, differences between monthly values of insolation estimated by the Heliosat-2 algorithm and pyranometers data were calculated. Then, those differences were interpolated for Galicia, using Kriging geostatistical technique. Finally, climatic maps were produced by adding the residual calculated to the original data satellite (Pettazzi and Salsón, 2012). The resulting maps were validated using MBE, MAE and RMSE. The researchers compared the results obtained from their findings with previous works and concluded that their results showed some improvement over previous methods.

Basir *et al.* (2013) employed remote sensing in identifying the areas with maximum insolation in Pakistan by studying the cloud cover on Pakistan from June to August (Monsoon period having maximum clouds) in 2005-2009. The satellite data used for the study were obtained from NOAA-AVHRR images of June, July and August of year 2005-2009. Precipitation data and elevation maps were also included. The satellite images were processed by using ENVI image processing software through the following procedures: Georeferencing, Enhancement, Selection of Area of Interest for Classification (ROI), Supervised Classification (Maximum likelihood method), Subset (using Pakistan boundaries), Vector Conversion, Composite (Monthly Maps). In order to find out least cloudless area, GIS analysis was performed. The Union option was used to combine cloud vector layers of different years and resultant Union layer shows areas with and without clouds. Then, the Pakistan district vector layer was overlaid of on each Union layer, which provides location of least cloudless districts in Pakistan. The results indicated the locations with minimum cloud cover which have a great potential for solar energy.

Janjai *et al.* (2013) presented an improved model and demonstrated its application for mapping global solar radiation from satellite data in tropical environment of Thailand. Digital data from the visible channel of GMS4, GMS5, GOES9, and MTSAT-1R satellites collected during a 15-year period (1995–2009) was used as main input to the model. Satellite gray levels were converted into Earth-atmospheric reflectivity and used to estimate the cloud effect. The satellite data was further processed. In order to test its performance, the model was employed to calculate monthly average daily global solar radiation at thirty six solar monitoring stations across the country. Their finding showed that solar radiation calculated from the model and that obtained from the measurement are in good agreement, with a Root Mean Square Difference of 5.3% and a Mean Bias Difference of 0.3%. The model was used to calculate the monthly average daily global solar radiation over the entire country, and results were displayed as monthly and yearly maps. The maps showed that the geographical distribution of solar radiation in Thailand is strongly influenced by the tropical monsoons and local geographical features.

In Africa, GIS has also been used for the development of solar information system. For instance,Huld *et al.* (2005) presented a method for computing high resolution GIS database of global horizontal irradiation for Africa and the Mediterranean Basin. The primary solar radiation data used for the GIS database were previously computed from Meteosat satellite images by the Heliosat-2 method and stored in the HelioClim-1 database. From this database, the long term monthly and yearly averages of global irradiation on horizontal plane over a period of 1985-2004 were derived. Using the PVGIS method, based on a clear-sky model, as well as the interpolation of the clear-sky index and terrain shadowing, the original spatial resolution of HelioClim-1 database (15') was enhanced to 2Km. Then, using the daily global irradiation from the enhanced

PVGIS database, they estimated the electricity generation from a typical solar home system in Africa.

The interesting part of the method presented by Huld *et al.* (2005) is the use of satellite data to compute a high resolution GIS databaseof global solar radiation for a region of solar information scarcity, Africa. This can be regarded as a valuable contribution toward the development of solar information system for Africa. Similarly, Šúri *et al.* (2006) developed and presented an interactive web tools for map-based query of a solar radiation database and for assessment of the performance of solar photovoltaic systems. They adopted the PVGIS method in their design. The PVGIS provides an interface to a geographical database and tools designed for the assessment of photovoltaic systems in Africa, the Mediterranean Basin, and South-West Asia.

The model presented by Flores and Baldasano (2001) is well grounded in the principles of Remote Sensing, and it has highlighted the relevance of the use of very high resolution satellite data like the NOAA-AVHRR to obtain good results. In addition, the model can be considered to be empirically proven considering the results obtained using the model. But the model as presented by Flores and Baldasano (2001) is a typical cloud-based model which is more applicable in temperate climate where cloud cover is highly influential in determining the amount of solar radiation received per unit area. An alternative improved model for mapping global solar radiation from satellite data was presented by Janjai *et al.* (2013). Their results further underscored the use of satellites as reliable sources of solar radiation data.

Ramachandra (2007) demonstrated the application of GIS as an alternative method in analysing spatial variation in solar energy potentials over an area or region, and its ability in determining the most suitable locations for harnessing solar energy in an area

or region. Basir *et al.* (2013) employed Remote Sensing and GIS techniques in identifying the areas with maximum solar energy potentials. This is an alternative approach which combines Remote Sensing and GIS techniques. However, the application of this method is very rare in the analysis of solar energy in Nigeria.

Local geographical features (Janjai *et al.* (2013) and topography influence the solar radiation received in an area. Therefore, some GIS models like the *r.sun* have integrated the terrain effect in solar radiation mapping and modelling.Likewise, Bois *et al.* (2008) used a hybrid model which combined remotely sensed data and solar irradiation models based on topography to estimate the spatial and temporal variability of solar radiation.

Alternatively, Pettazzi and Salsón (2012) merged ground-based measurements and satellite data for detailed analysis of the solar radiation across Galicia in Northwestern Spain. Their methods involved several steps which include interpolation using kriging, merging using residual techniques, calibration and validation processes.

The foregoing review has shown how satellite remote sensing has provided a viable source of information on solar radiation. In most cases, satellite remote sensing and GIS techniques are combined together for the analysis of solar radiation data in order to develop a solar information system which is discussed in the following section.

2.3.5 Improved Solar Information System for Nigeria

The scarcity of ground-based measurements of solar radiation in Nigeria has denied the country the opportunity to build and improve the solar radiation dataset over the country. These dataset are necessary for the development of a solar database which is an integral part of Solar Information System. A solar information system enables the assessment and analysis of solar energy potentials in the country. However, information

derived from satellite images can be integrated with ground-based data to provide a comprehensive and reliable solar information system for Nigeria. In this study, attempt was made to exploit the benefit of merging ground measurements of the global solar radiation and estimations derived from satellites to provide reliable solar radiation data in parts of Northwestern Nigeria. This method of merging ground data with satellite data has the capability to assemble the solar data required for research to enhance the development of solar energy and electricity supply in the country. It can also be used to the increase access to electricity in Nigeria and reduce energy poverty among the people in the country.

The literature review examined the available information on renewable energy resource in Africa. It was found that in spite of the enormous renewable energy potentials in Africa, information on the potentials is scarce in the continent. The review also found that several methods are used to analyse solar energy potentials, but statistical modelling is the most commonly used method in analysing solar energy potentials in different parts of Nigeria. The review of literature on the application of satellite Remote Sensing and GIS in the analysis of solar energy potentials started from a global perspective to the African continent. It was found that various geostatistical and geospatial techniques were used by different researchers in different locations, however, this study employed geospatial techniques to merge ground-based measurements of solar radiation with satellite-derived solar radiation data as an alternative approach to analyse solar energy potentials in study area. The section concludes with a recommendation for the application of geospatial techniques in developing solar information system for Nigeria.

CHAPTER THREE

THE STUDY AREA AND METHODOLOGY

3.1 STUDY AREA

3.1.1 Location and Size

The study area comprises of the three states namely; Katsina, Kano, and Kaduna in Northwestern Nigeria, covering an area of 90,376Km^2. The area is located between Latitudes 9º00'N – 13º30' North of Equator, and Longitudes 6º00'E – 9º30' east of Greenwich Meridian as shown in Figure 3.1. The area is bordered by Niger Republic in the north, Bauchi Sate in east, Abuja in the south and Zamfara State in the west.

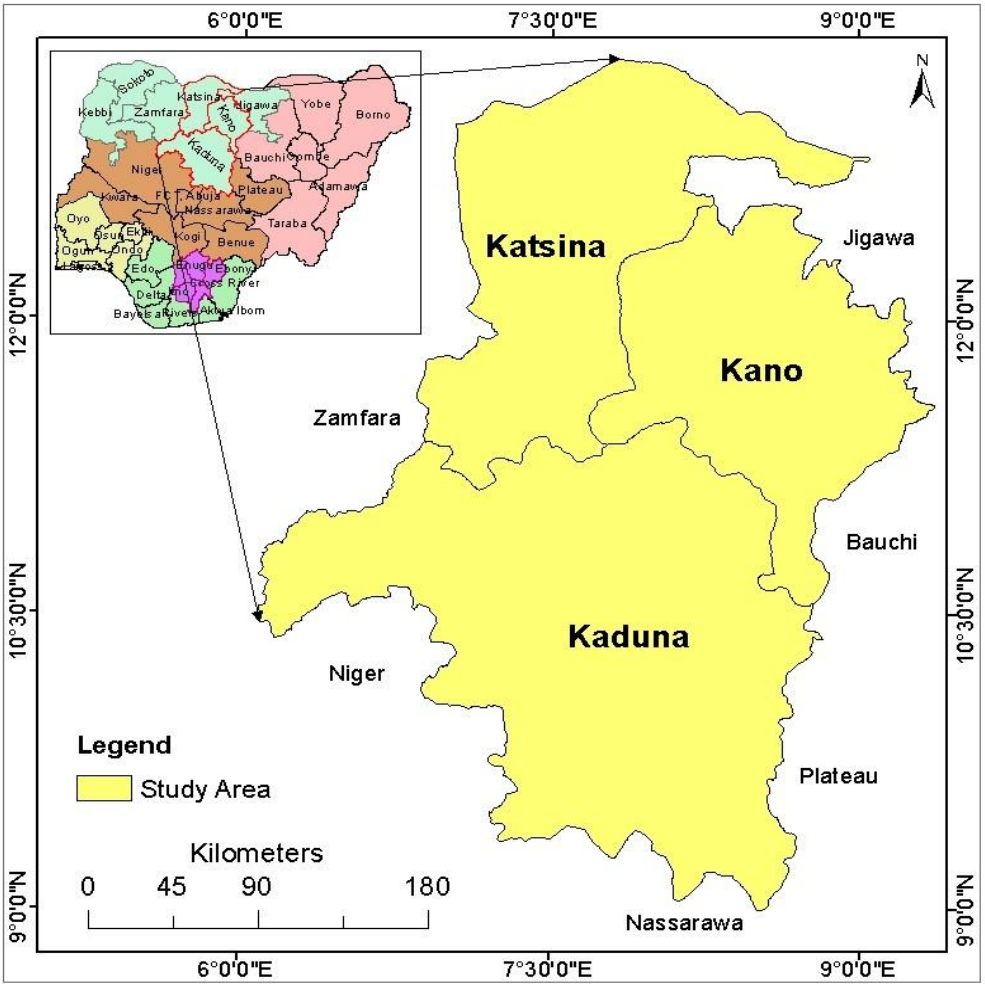


Figure 3.1: The Study Area in Northwestern Nigeria

Source: Adapted from the Administrative Map of Kaduna State

3.1.2 Geology and Landforms

The study area is located on the "High Plains of Northern Nigeria" which lies on altitude of between 450 to 745m above sea level (Udo, 1970). The area is underlain by the Precambrian Basement Complex Rocks. These rocks form part of the pan African mobile belt and are composed of igneous and metamorphic rocks such as granites, gneisses, migmatites and metasediments of the Precambrian ages. These rocks have been variably metamorphosed and granitised through tectonometamorphic cycles, to the extent that they have been altered into migmatite and granite-gneiss (Oyawoye, 1964). The landforms of the study area include granitic outcrops, inselbergs, hills in form of Ruwares, residual hills, and river valleys and plains which are found within the area. Apart from cloudiness and other atmospheric variability, topography determines the distribution of the incoming solar radiation at a smaller scale (Aguilar, Herrero and Polo, 2010).

3.1.3 Climate

The climate of the area is described as Aw based on Koppen's classification, characterized by alternating wet and dry seasons. The dry season is accompanied by a dust laden wind from the Sahara desert, known as Harmattan, which is brought by the Tropical Continental airmass, while the rainy season is heavily influenced by the Tropical Maritime from the Atlantic Ocean, occurring between April/May and September/October (Eludoyin, 2011).

The climate of the area is principally controlled by the two dominant airmasses affecting the sub-region. These are the Tropical Continental airmass which is dry and dusty originating from the Sahara desert; and the Tropical Maritime airmass which is moist and warm originating from the Atlantic Ocean. The influence of both airmasses

on the region is determined largely by the Inter-tropical Discontinuity (ITD). The ITD is the boundary at the ground between the two airmasses. The movement of the ITD northwards across the country between January and August, and its withdrawal after August from the southern fringe of the Sahara desert, is the reason why most locations in Nigeria experience seasonal rainfall (Olaniran and Summer, 1989). The interplay of the two airmasses gives rise to two distinct seasons (wet and dry) within the sub-region (Mortimore, 1970). Between June and September, the ITD is entrenched northward of the country and northern Nigeria is under influence of the Tropical Maritime (Tarhule and Woo, 1998). The main features of rainfall patterns in this region, as in other parts of the country are usually linked to the ITD (Hayward and Oguntoyinbo, 1987). Monthly rainfall over the area takes its conventional mono-modal pattern, and sufficient rainfall usually starts in April and peaks between July and September.

The annual average rainfall in Kano ranges from 884-1200 mm (from north to south of the state) which is characterized by one peak period, usually recorded in August (Tanko and Momale, 2013). The mean annual rainfall in Kaduna is 1187.5 mm (Obot, Chendo, Udo and Ewona, 2010). Katsina state has an average rainfall of 623 mm (Ati, Iguisi, and Mohammed, 2010). The rainfall pattern in an area significantly influences solar radiation in the area. This is due to the influence of cloud on the incoming solar radiation.

The overall average relative humidity in Nigeria is 61.98±24.8%. The study area is characterised by lower relative humidity than the overall mean (of the annual relative humidity). The least humid region in Nigeria is found in the extreme north; mainly the Sahel savanna, and the northern part of the Sudan savanna (Eludoyin, 2011).Humidity in the study area can be described as relatively low throughout the year, with average

relative humidity values varying between 40% and 70%(Oyewole, Thompson, Akinpelu and Jegede, 2014). From September through November, the northeast trade winds generally bring a season of clear skies, moderate temperatures, and lower humidity for most of the Nigeria. However, from December through February, the northeast trade winds blow strongly and often accompanied with a load of fine dust from the Sahara (The Library of Congress Country Studies, 2017). The Sudan savanna has a relative humidity of about 25% during the dry season.

The temperature in the area interchanges between hot and cold seasons with the occurrence of Harmattan (a very cold season) between November and February. The Harmattan greatly reduces the amount of solar radiation received in the area. However there is a little variation in air temperature in the month of April with subsequent increase northward in May and June only. Also, the Northern Nigeria is generally characterized by a northward increase in temperature extending from July to September before a reverse in trend in the month of October (Adefolalu, 2007). Air temperature values are generally lower in the Northern Nigeria during dry season when compared with the wet season. This can be ascribed to the Equator ward incursion of midlatitude systems (with alternating cool and warm air masses) which has greater influence on temperature variation over the northern part than over the southern part of Nigeria (Adefolalu, 2007).

The average minimum temperature in the area is 21.4 ± 3.43^{o}C. But there are locations within Katsina where average minimum temperatures fall below the overall average. The mean maximum temperature in the area is 32.8 ± 3.37^{o}C (Eludoyin, 2011). The maximum mean temperature in Kano is 33.284^{o}C (Amadi, Udo and Ewona, 2014). The mean temperature in Kaduna and Katsina states is 31.756^{o}C and 33.773^{o}C respectively

(Ibrahim and Mohammed, 2015). The regions of the Savanna are characterised by relatively higher temperature variability (4.0^{o}C) than other regions but the variability decreased towards the southern region. Annual mean temperature ranged between 21.8±1.68 and 28.6±2.98^{o}C. The mean temperature at all locations within the study area averaged 27.0±2.79^{o}C (Eludoyin, 2011). In most cases, temperature is a reflection of the amount of solar radiation received in an area.

3.1.4 Soils

The area is characterised by leached ferruginous tropical soil developed on deeply weathered Precambrian Basement Complex rock. Other soils found in the area are clayey loamy soils, the hydromorphic soils (*Fadama*). The majority of Nigerian Savanna soils are highly weathered and frail with low activity clays, hence their fertility decline under continuous cultivation (Federal Fertilizer Department, 2012).

Different soils have different albedos. Albedo refers to the proportion of solar radiation reflected by different surfaces. The most important factors affecting the soil albedo are the type and condition of the vegetation covering the soil surface, soil moisture content, organic matter content, particle size, iron-oxides, mineral composition, soluble salts, and parent material (Baumgardner *et al.*, 1985). The albedo value ranges from 0 to 1, where the value of 0 refers to a blackbody, a theoretical media that absorbs 100% of the incident radiation. Albedo ranging from 0.1–0.2 refers to dark-coloured, rough soil surfaces, while the values around 0.4–0.5 represent smooth, light-coloured soil surfaces. Dry sandy soils have albedo of 0.25–0.45, while the albedo of dry clay soils ranges from 0.15–0.35, and that of sand ranges 0.2–0.4 (Dobos, 2003).

3.1.5 Vegetation

The natural vegetation in the study area can be described as the Sudan Savanna type. It is characterised by scattered trees which barely exceed twenty meters high (Olofin, 1987), and abundant short grasses of averagely less than two meters high. The Sudan Savanna comprises oftree species that are mostly deciduous, with half of them having small leaves like the Acacia.

The common tree species found in the area include *Acacia senegalancies, Acacia Albidda, Anilotica, Adansonia digitata, Balanites aegyptiaca, Borrasus aethiopum, Isoberlinia doka, Khaya Senegalensis, Moringa Oleifera, Pekia bigloboza, Vitex Doniana* and *Tamarindus indica*.

One of the most significant factors that influence plants development is the solar radiation intercepted by the crop. The solar radiation brings energy to the metabolic process of the plants in form of photosynthesis(Campillo, Fortes and Prieto, 2012). Plants intercept both the direct and diffuse solar radiation. The upper leaves receive the two types of radiation, while the lower leaves intercept a small portion of direct solar radiation. Hence, diffuse radiation, becomes more significant in the lower leaves due to radiation transmitted and reflected from the leaves and the soil surface. Solar radiation transmitted by the leaves is mainly infrared. However, visible radiation, between the wavelengths of 400 and 700 nm, is the most important radiation to plants, as it relates to photosynthetically active radiation (PAR) (Campillo, Fortes and Prieto, 2012). The quantity of radiation intercepted by plant cover is influenced by several factors such as and the Sun's elevation, the distribution of direct and diffuse solar radiation, the leaf angle, the properties of the leaf surface affecting light reflection, as well as the thickness

and chlorophyll concentration, which affect the light transmission (Campillo, Fortes and Prieto, 2012).

3.1.6 People and Economic Activities in the Study Area

The estimated population of the area in 2006 was over twenty one million according to the National Population Commission (NPC), 2006). The population of the study area was projected using the following formula for population projection by Measure Evaluation (2017):

$$(P_t, {}_{t+n}) = P_{t+n} - P_t$$

Where,
$P_t, {}_{t+n}$ **= population change that took place between two time periods**
P_{t+n} **= population in the total population of the given area one time unit later**
P_t **= population in prior time period**

The projected population of the area in 2016 was about twenty seven million. Majority of the people in the area are Hausa-Fulani, other ethnic groups found in the area include Nupe, Katab, Gbagi, Igbo and Yoruba.

There are several economic activities in the area which include agriculture, business activities, professional, administrative, technical and production works, as well as craft industries in the area. Agriculture remains one of the major economic activities in the area because the area is blessed with fertile agricultural land for the production of different varieties of crops. There is vast arable land in the Savanna zone of Nigeria with high potentials for the production of mainly cereal crops like rice, maize, millet, guinea corn sorghum and wheat. In addition, there are several animal species found in the area.

Kano is the commercial nerve centre of Northern Nigeria characterised by a lot of trading, commercial and industrial activities. Kaduna was formally the administrative

headquarters of Northern Nigeria. There are several educational institutions and industries found in Kaduna state. Katsina state is characterised by a lot of agricultural activities. A significant number of the people in the state are engaged in administrative works and civil service.

3.2 METHODOLOGY

3.2.1 Review of Methods of Data Analysis

3.2.1.1 Solar Radiation Data Sources

There are different sources of solar radiation data such as ground measurement and satellite retrieval, but none of them is considered to be faultless (Photovoltaic Geographic Information System -PVGIS, 2016), so it is important to understand the strengths and weaknesses of each data source. Ground station measurements give a more accurate estimate of the solar radiation at a particular place or region. However, the main advantage of satellite-based methods is that they give a fairly uniform coverage of large areas while ground stations are often very far apart. It is also possible to measure solar radiation with a high resolution satellite at a specified time intervals, typically every minute or even more often using the satellite method. However, the quality of satellite-based estimates must be checked by comparing the data with that of high-quality ground station measurements (PVGIS, 2016).

3.2.1.2 Satellite Solar Radiation Data

a) NASA SSE Web Portal

The solar radiation and cloud parameters contained in SSE 6.0 are derived from parameters available from the NASA/Global Energy and Water Cycle Experiment Surface Radiation Budget (NASA/GEWEX SRB) Project Release 3.0 archive. The NASA/GEWEX SRB Project focuses on providing estimates of the Earth's Top of

atmosphere (TOA) and surface radiative energy flux component. The datasets contains global 3-hourly, daily, monthly/3-hourly, and monthly averages of surface and TOA longwave and shortwave radiative parameters on a 1°x1° grid. Primary inputs to the models include: visible and infrared radiances from International Satellite Cloud Climatology Project (ISCCP) pixel-level (DX) data, cloud and surface properties derived from those data, temperature and moisture profiles from GEOS-4 reanalysis product obtained from the NASA Global Modelling and Assimilation Office (GMAO) (NASA, 2016).

b) HelioClim-1 Database

HelioClim-1 is a unique and homogenized database created from Meteosat satellite images by the application of the Heliosat-2 method. The primary database contains only the cloud index and a set of parameters that are processed by a dedicated software to calculate daily global irradiation on horizontal plane from 1985 onwards. The database and software are accessible through the SoDa intelligent web system. The SoDa interface allows retrieving daily values or monthly averages for requested location and year (Huld *et al.*, 2015).

The spatial extent of the HelioClim-1 database corresponds to the field of view of the Meteosat Prime disc (the satellite being centred at latitude 0° and longitude 0°). Due to the lower reliability of results at low solar elevation angles (less than 12 degrees) the restriction of the software does not allow calculating irradiation data from extreme North and South latitudes in winter months (Huld *et al.*, 2015).

3.2.1.3 Merging of Satellite with Ground-Measured Solar Radiation Data

This section explains how the satellite data was merged with ground data to achieve objective three. Merging of satellite data with ground measurements requires two

different sets of stations referred to as the calibration and the validation stations as done by Pettazzi and Salsón (2012a). Also, there are several methods used to merge ground-based with satellite-derived insolation data. For example, Pettazzi and Salsón (2012a) combined satellite data with ground measurements using kriging to estimate global solar radiation in Galicia. Among the 28 locations that were selected for their study, 14 were used for calibration, while the remaining 14 were used as validation set. Similarly, Flores and Baldasano (2001) mapped solar radiation in Catalonia, out of the 21 stations used, 11 were used as calibration set and 10 as validation set.

For the calibration of satellite data with ground-based measurements, this present study adopted the method used by Vazquez *et al.* (2005). Vazquez *et al.* collected three years of satellite data and adjusted them, on a monthly basis, to the monthly averaged insolation from a ground station in Vigo city of Spain. The calibrated maps were validated against another pyranometer located in Coruña of Spain**.**In this case, the satellite insolation at every station was divided by the value of insolation measured by the pyranometer at that station. Then, this factor was applied to all the maps, and the maps were tested at the locations of the other pyranometers.

3.2.1.4 Validation of Satellite Solar Radiation with Ground-Based Measurements

Several statistical tests are used to validate satellite-derived solar radiation with ground-based measurements. These include Mean Bias Error (MBE), Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), Mean Percentage Error (MPE), etc. As part of the third objective (to merge the ground-measured solar radiation data with the corresponding satellite), this study used MBE, RMSE and MAE because they are the most commonly used statistical measures to investigate the goodness of the estimation of global solar radiation as shown in studies by Journée and Bertrand (2010), Journée *et*

al. (2011), Okundamiya and Nzeako (2011), Antonanzas-Torres *et al.* (2012), Pettazzi andSalsón (2012a). Also, Chai and Draxler (2014) affirmed that the RMSE and the MAE are regularly employed in model evaluation studies.

a) Mean Bias Error (MBE): This is an indication of the average deviation of the predicted values (satellite-derived) from the measured values (ground measurements) of solar radiation (Sanusi and Abisoye, 2011). This test provides information on the long-term performance. MBE is represented as:

$$MBE = \frac{1}{N} \sum_{i=1}^{N} (g(x_i) - G(x_i)) \quad \text{..... Equ. 3.2}$$

Where N is a set of pairs {G(xi),g(xi)}i=1,…, N; where x_i is a location,

G(xi) is the measured radiation at location xi, and

g(xi) is the corresponding satellite-derived value.

A low MBE is desired, and the ideal is that a zero value of MBE should be obtained (Khan and Ahmad, 2012). A negative value gives the average amount of underestimation in the calculated value (Muzathik *et al.*, 2011). A positive value gives the average amount of overestimation in the measured value and vice-versa. A disadvantage of this test is that overestimation of an individual observation will cancel underestimation in a separate observation (Muzathik *et al.*, 2011).

b) Root Mean Squared Error (RMSE): This is a measure of the variation of predicted values (satellite-derived) around the measured values (ground measurements) (Sanusi and Abisoye, 2011).

It is given by: $$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (g(x_i) - G(x_i))^2} \quad \text{..... Equ. 3.3}$$

Where N is a set of pairs {G(xi),g(xi)}i=1,…,N; where x_i is a location,

G(xi) is the measured radiation at location xi, and

g(xi) is the corresponding satellite-derived value.

This test provides information on the short-term performance of the correlations by allowing a term-by-term comparison of the actual deviation between the measured value and the predicted value (Muzathik *et al.*, 2011). A smaller value of RMSE is an indication of better performance of the model or pyranometer. However, a few large errors in the sum can produce a significant increase in RMSE (Medugu *et al.*, 2013). The RMSE is always positive, though a zero value is the ideal (Khan and Ahmad, 2012).

c) Mean Absolute Error (MAE): is a quantity used to measure how close predictions are to the eventual outcomes. The mean absolute error is given by:

$$\mathbf{MAE} = \frac{\mathbf{1}}{n}\sum_{i=1}^{n}|f_i - y_i| = \frac{\mathbf{1}}{n}\sum_{i=1}^{n}|e_i|\,.$$ ..... Equ. 3.4

As the name suggests, the mean absolute error is an average of the absolute errors

$$|e_i| = |f_i - y_i|$$ ..... Equ. 3.5

Where f_i is the satellite value, and y_i is the corresponding measured solar radiation value.

The Statistical analyses (MBE, MAE, and RMSE) were performed using Microsoft Excel.

3.2.1.5 Inverse Distance Weighted (IDW) Interpolation

IDW interpolation assumes that values that are closer are more related than those that are farther apart (Environmental Systems Research Institute - ESRI, 2016). It gives greater weights to points closest to the prediction location, and the weights diminish as a function of distance (De Smith *et al.*, 2015). IDW was used in the study because it is the simplest interpolation method (Fisher, Lewis and Embleton, 1987). In addition, the user has control over the mathematical form of the weighting function and the size of the neighbourhood in IDW (Fisher *et al.*, 1987). The general equation for the IDW interpolation is:

$$Z_o = \frac{\sum_{i=1}^{s} \frac{Z_i}{d_i^k}}{\sum_{i=1}^{s} \frac{1}{d_i^k}} \quad \text{..... Equ. 3.6}$$

Where,

Z_o is the estimated value at point o,

Z_i is measured sample value at point i,

d_i is the distance between points Z_o and Z_i,

s is the number of known points used in estimation and

k is the weighting power.

Also, IDW has the simplest technique for determining the weights of values. The simplest weighting function is represented by Shepard (1968) as inverse power:

$w(d)= 1/d^p$ .....,..... Equ. 3.7

with p>0. The value of p is specified by the user. The most common choice is p= 2.

3.2.1.6 Visualising the Spatial Variability in Solar Energy Potentials in the Study Area

The annual total solar radiation in an area is influenced by the slope, aspect, the surrounding topography, and it varies spatially and temporally (Hussein, 2012). The

spatial variability of solar radiation changes with time of day and time of year, and in turn affects the variability of microclimate in an area (Effat, 2016). Also, the variations in elevation, slope and aspect have combined affect on the amount of solar radiation received at different locations. However, topography is a major factor that influences the spatial variability of solar radiation in an area.

There are methods used in the literature to determine the effects of topography on the amount the solar radiation in an area. Firstly, the topography can be integrated with other factors in the analysis. Secondly, the effects of topography on solar irradiation can be determined by means of direct geometrical relations in *r.Sun*. The *r.Sun* isa solar radiation model implemented in GRASS GIS (a GIS software) (Hofierka and Suri, 2002). The *r.Sun* model estimates beam, diffuse and reflected components of solar incoming radiation on horizontal and inclined surfaces. Daily solar irradiation is calculated at a 15 minute time step and accumulated for each day. The *r.Sun* is not used in this study because it was originally developed for European climate.

3.2.1.7 The Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process is a valuable systematic procedure of estimating the relative importance of a set of criteria and sub-criteria in order to achieve a certain objective. In this case, the subjective importance of the criteria and sub-criteria is quantified and aggregated in order to reach a decision (Höfer *et al.*, 2014). AHP is a useful systematic decision-making tool which decomposes a complex multi-factor problem into a hierarchical structure, and each hierarchy is composed of specific elements (Asakereh *et al.*, 2014).

The analytic hierarchy process (AHP) has been an effective tool in structuring and modelling multi-criteria decision making problems. AHP assists decision makers to

evaluate a problem in the form of a hierarchy of references through a series of relative weighted criteria. The relative weights of the criteria are determined through pairwise comparisons (Bilal, Rustom and Mousa, 1999).

AHP consists of the following four steps (Sheth and Hughes, 2009):

a) Decomposition, that is, construction of hierarchical structure,

b) Comparative judgment,

c) Consistency analysis, and

d) Final ranking of the alternatives.

a) Decomposition

This stage defines the decision problem in order to understand the essence of the problem, then the problem is structured and a list of all related factors is used to construct a hierarchical structure (Trappey *et al.*, 2015). AHP decomposes a decision problem into a hierarchical structure consisting of three main levels. The highest represents the overall goal of the decision making process as shown in Figure 3.2. One or more intermediate levels contain the decision criteria and any optional sub-criteria. The lowest one consists of the decision alternatives (Sheth and Hughes, 2009).

b) Comparative judgment

Using the decision hierarchy formed in stage 1, the decision-maker can develop relative weights to rank each criterion and alternative. Then, the creation of the attributes of evaluation and the paired comparison matrix for each attribute under different programs (Trappey *et al.*, 2015).

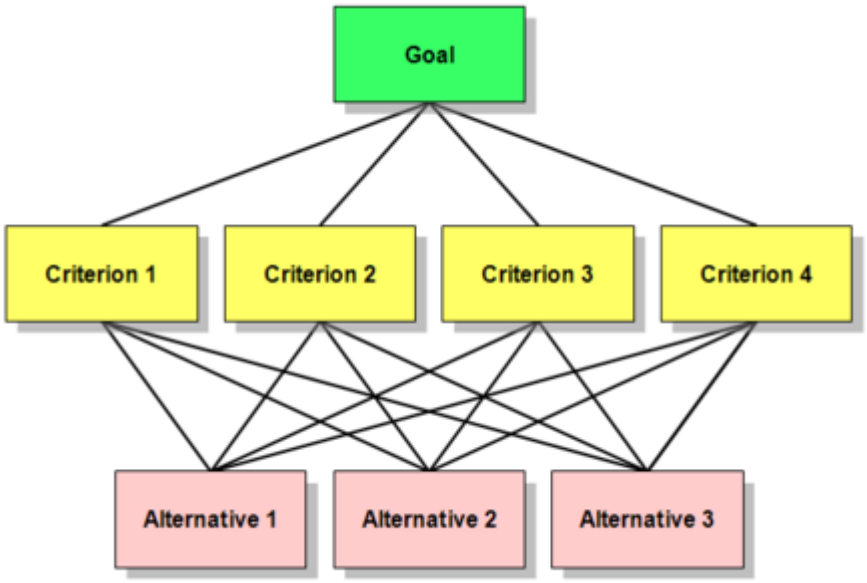


Figure 3.2: Analytic Hierarchy Process

Source: Citizendium, 2017

The first step is to perform pair-wise comparisons of the different criterion with respect to the overall goal of the decision-making process and the results of the comparisons are entered into a matrix. This matrix is the basic unit of the analysis and is called the "pair-wise comparison matrix" or simply, "judgment matrix" (Sheth and Hughes, 2009). Saaty developed a scale of 1 to 9 to perform pair-wise comparisons, as shown in Table 2.1 (Sheth and Hughes, 2009).

After the pair-wise comparison is completed, a vector of priorities is computed for the criteria. Saaty suggests a number of ways in which the vector can be obtained; one method is to multiply the n elements in each row and take the nth root (the geometric mean) of the result. The resulting n-element vector is then normalized, giving the priority vector. Next, the alternatives undergo comparisons.If the comparisons are qualitative, the alternatives are subject to pair-wise comparisons with respect to each criterion—as is done for the criteria—creating a judgment matrix for each criterion.

Table 2.1: Saaty's Pair-wise Comparison Table

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgement slightly favor one activity over another
5	Essential or strong importance	Experience and judgement strongly favor one activity over another
7	Very strong importance	An activity is favored very strongly and its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals	If activity *i* has one of the when compared with activity value when compared with *i*.	above numbers assigned to it *j*, then *j* has the reciprocal
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining *n* numerical values to span the matrix

Source: Saaty, 1990.

A vector of priorities is calculated from the judgment matrix, as described in the previous paragraph. On the other hand, if the comparisons are quantitative, the priority vector is obtained by summing the n values of the alternatives and creating a normalized vector of the alternatives (Sheth and Hughes, 2009).

c) Consistency analysis

In this stage, the consistency of the results is verified (Sheth and Hughes, 2009). One of the major advantages of AHP is that it allows inconsistency, while at the same time providing a measure of the inconsistency in each set of comparative judgments.

Inconsistencies in the judgment matrix can result from absence of information, clerical error, and lack of concentration (Forman and Gass 2001) (Sheth and Hughes, 2009).

d) Final ranking of the alternatives

If the criterion weights are denoted Cj, and weight (or priority) for alternative i with respect to criterion j is Ai,j, then the final priority of alternative i, Pi, can be calculated from following equation: $Pi= Ai,j\times Cjnj=1$ ..... Equ. 3.8 where n is the number of criteria. The alternative with the highest weight value is considered to be the most suitable solution for the decision problem, while the alternative with the lowest weight value is least appropriate for that decision problem (Sheth and Hughes, 2009).

AHP is widely used in the field of energy and environment, including such areas as energy policy analysis, energy utility operations and management, energy-related environmental policy analysis, energy-related environmental control and management, renewable energy analysis (Zhou, Ang and Poh 2006) (Sheth and Hughes, 2009).

In the literature, the application of AHP in handling multi-criteria decision analysis is common. For instance, Uyan (2013) used GIS and AHP to determine appropriate sites for solar farms in Karapinar region of Turkey. Asakereh *et al.* (2014) developed a GIS-based fuzzy AHP model to locate the most suitable sites for solar energy in Shodirwan Region of Iran. Effat (2016) integrated the AHP with GIS using remote sensing data to identify the potential zones for solar energy around Lake Nasser, in Aswan, Egypt. Therefore, the AHP was employed to achieve the fifth objective of this study.

In this study, in order to find out the solar energy potential sites over the study area, the insolation, DEM, slope and aspect were used in the AHP model. Uyan (2013) opined

that slope must be less than 3% for all aspects for suitable solar farms site. Li (2013) proposed a slope limit of < 4%. However, Omitaomu, Singh and Bhaduri (2015) believed that the optimum slope value is site dependent, but a 5% threshold for slope should be applicable for most solar energy applications. Asakereh *et al.* (2014) assigned weights to varying degrees of slope, where the value of 1 was given to any cell with slope of 0-3%, and cells with slope 3-10% were valued from 0 to 1. Generally, Aspect angles (orientation) and slope degrees are categorized, the milder slopes are considered to be highly suitable since the most suitable sites are those where the ground is flat and with aspect angle oriented towards the south (Effat, 2016). Specifically, southeast to southwest facing orientation are appropriate locations for harnessing solar energy (Li, 2013).

3.2.1.8 Scatter Plots

Scatter plots are used to investigate the possible relationship between two variables that both relate to the same "event" (SkyMark, 2016). They provide a visual representation of the correlation, or relationship between the two variables (Williams, 2016). A scatter plot can imply various kinds of correlations between variables with a certain confidence interval. Correlations may be positive (rising), negative (falling), or null (uncorrelated). If the data points slope from lower left to upper right, it indicates a positive correlation between the variables being examined. If the data points slope from upper left to lower right, it indicates a negative correlation (College of Education University of Illinois, 2016). A line of best fit can be drawn in order to examine the nature of the relationship between the variables. A scatter plot is also used to test how two comparable data sets agree with each other.

3.2.2 Reconnaissance Survey

This was carried out in order to familiarize with the study area and also observe the geographical features that influence solar radiation in the area. The researcher also visited the Sokoto Energy Research Centre at the Usman Danfodio University, Sokoto, in order to obtain relevant information on the research, but, he was referred to the Nigerian Meteorological Agency (NIMET).

3.2.3 Types of Data Utilised

The study used both ground measurements of solar radiation and solar radiation data derived from satellite as elaborated in the following sections.

3.2.4 Sources of Data

3.2.4.1 Ground-Based Solar Radiation Measurements

The ground-measured solar radiation data used for this study were obtained from the Nigerian Meteorological Agency (NIMET). This is because NIMET stations used the same calibrations for all the stations. NIMET has several weather stations located mostly at airports across Nigeria. Some of the stations in Northwestern Nigeria are shown in Figure 3.3. Previously, the NIMET stations used Gunn-Bellani pyranometers, but presently, the stations use Solarimeter to measure solar radiation in watt per meter square (Wm^2), and Campbell–Stokes sunshine recorder to measure sunshine duration in hours. Finally, daily average solar radiation data covering a period of thirty years were provided by NIMET in millijoule per meter square per day ($MJ/m^2/day$). Extracts of the ground data are shown in appendices I-III. The data were converted into kilowatt per hour per meter square per day ($kWh/m^2/day$) using the International Energy Agency (IEA) General Converter for Energy to achieve uniformity with the satellite data. This is

because solar radiation values are generally expressed in kWh/m^2/day, which is the amount of solar energy that strikes a square metre of the Earth's surface in a single day.

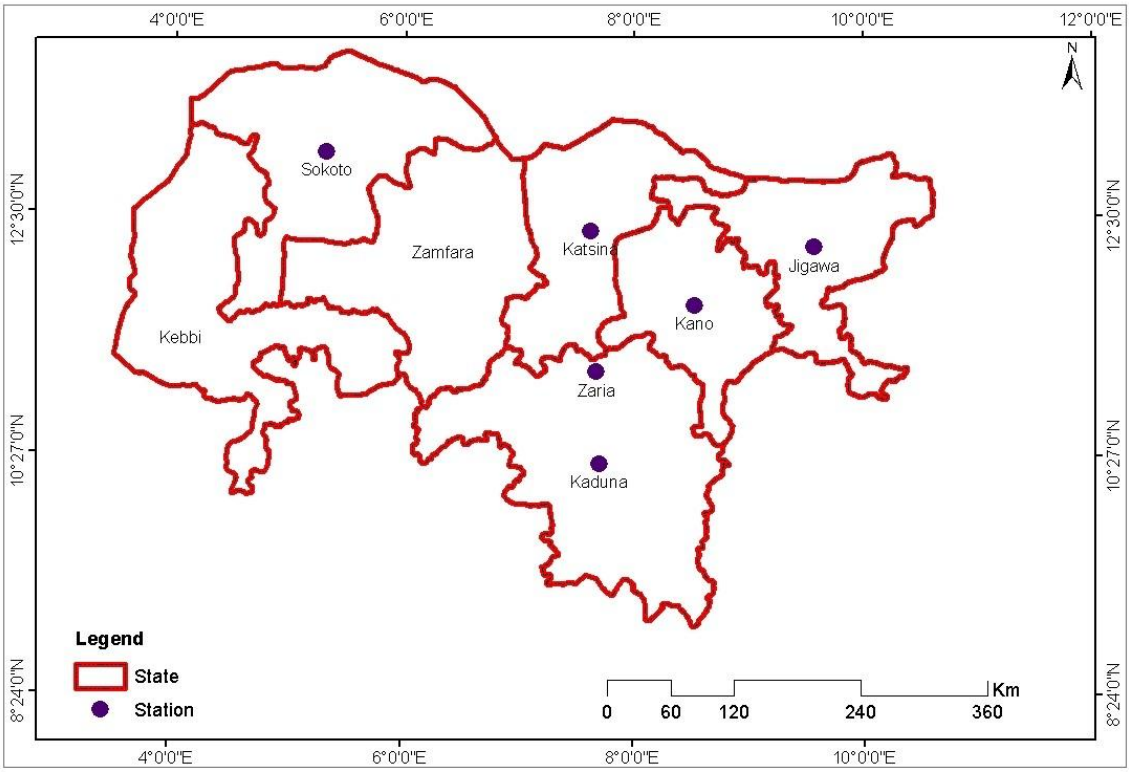


Figure 3.3: Locations of NIMET Stations in Northwestern Nigeria

Source: Fieldwork, 2016.

3.2.4.2 Satellite-Derived Solar Radiation Data

The satellite data used in this study were obtained from the following sources:

a) National Aeronautics and Space Administration Surface Meteorology and Solar Energy (NASA SSE);
b) SoDa HelioClim-1 database.

a) NASA SSE Web Portal

The NASA SSE web portal provides free solar radiation data with relatively good resolution. The solar radiation for SSE Release 6.0 (which is presently the latest

version) was obtained from the NASA Science Mission Directorate's satellite and re-analysis research programs (NASA, 2016). NASA SSE provided the daily averaged solar radiation data in kWh/m^2/day used in this study.

b) HelioClim-1 Database

HelioClim-1 is a unique and homogenized database created from Meteosat satellite images by the application of the Heliosat-2 method. The primary database contains only the cloud index and a set of parameters that are processed by a dedicated software to calculate daily global irradiation on horizontal plane from 1985 onwards. The database and software are accessible through the SoDa intelligent web system. The SoDa interface allows retrieving daily values or monthly averages for requested location and year (Huld *et al.*, 2015).

3.2.5 Data Analysis

Objective i: to visualise solar radiation in the area using both ground measurement and satellite data

In order to achieve objective 1, spatial mapping of solar energy potentials was employed, in which case, the ground-measured and the satellite data over the study area were used to generate the solar radiation maps using Inverse Distance Weighted (IDW) interpolation. This was achieved using the Spatial Analyst tool in ArcGIS software (version 10.3). The solar radiation data were arranged in Microsoft Excel, saved as coma separated values (csv) and imported into the ArcGIS environment as points, using these points, the interpolation was carried out to produce the solar radiation maps.

Objective ii: Tocompare and contrast between ground-measured and satellite-derived solar radiation data in the study area. In order to achieve this objective, visual analysis, tables and scatter plots were used.

Objective iii: To merge the ground-measured solar radiation data with the corresponding satellite data in order to assess the solar energy potentials in the area.

In order to achieve this objective, two different sets of stations referred to as the calibration and the validation stations were used as shown in Figure 3.4. The three stations (Kano, Kaduna, Katsina) were used as the calibration stations, and another three stations (Jigawa, Zaria, Sokoto) were used as the validation stations. The choice of the validation stations is based on the availability of more comprehensive radiation data at those stations over other stations in the region. Another reason is because the validation stations fall within the same geographical region (Northwestern Nigeria) with the calibration stations.

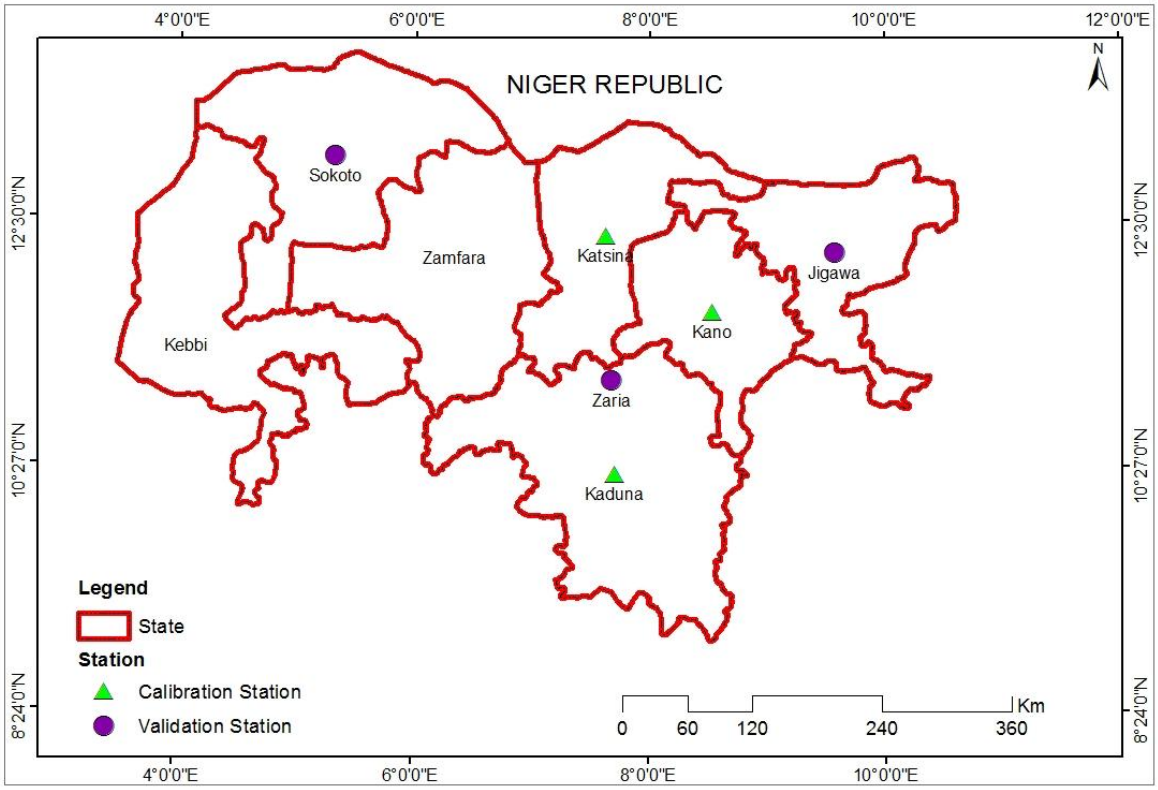


Figure 3.4: The Calibration and the Validation Stations

Source: Fieldwork, 2016.

For the calibration of satellite data with ground-based measurements, the following steps were adopted from Vazquez *et al.* (2005) as illustrated in appendix IV:

- Firstly, the satellite insolation at every station was divided by the corresponding ground insolation at that station to obtain a factor (X);
- then, the factor was multiplied by the satellite solar radiation values to obtain the calibrated solar radiation values (S*X),
- the calibrated solar radiation values were then used to produce the maps.

As part of objective iii, MBE, RMSE and MAE were used to test the reliability of the calibration method employed in this study.

Objective iv: To visualise the spatiotemporal variation of solar energy potentials in the area.

In order to achieve objective iv, spatial mapping of solar energy potentials was also employed as done in objective i.

Objective v: To identify the optimum solar energy potential sites and values for solar energy development in the area.

The optimum solar energy potential sites in the three states were identified using GIS weighted overlay and analytic hierarchy process. To achieve this, the solar radiation map, the digital elevation model (DEM), the slope and aspect maps of the study area were created in ArcGIS as shown in Appendices V-VIII; these maps were then used as input parameters to identify the solar energy potential sites in the study area.

Firstly, the study area map was used to delineate the Digital Elevation Model of the area in ArcGIS environment. Then the maps were georeferenced based on the WGS 1984 Geographic coordinate system. Then, the slope and aspect maps of the area were

generated from the DEM. Finally, the DEM, slope and aspect maps were integrated with the solar radiation data in Analytic Hierarchy Process (AHP) to produce maps of solar energy potential sites in the area.

However, in this study, four criteria namely: solar radiation, topography, slope and aspect were weighted based on the Analytical Hierarchy Process (AHP). Then, the final weights of the four criteria and sub-criteria were assigned. The output of this process is solar energy potential sites in the study area.

In order to determine the amount of exploitable power in each of the three states, the following formula was used: Cross sectional area X the average power intercepted at any time (Electropaedia, 2016).

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 INTRODUCTION

The results of this study and analytical discussion of the results in line with the objectives of this study are presented in this chapter. The chapter is structured into the following sections: sections one and two presented insolation maps separately based on ground measurements and satellite data; section three compared between ground-measured and satellite-derived solar radiation data to highlight the similarities and differences between them. The fourth section analysed the pattern of solar radiation in Katsina, Kano and Kaduna states; insolation maps based on calibration of measured and satellite data were presented in section five; validation of satellite-derived solar radiation with ground-based measurements was discussed in section six. The seventh section compared between solar radiations derived from single and multiple sources. Section eight viusalized the solar energy potential sites in the study area; section nine estimated the potential solar electricity generation in the area; and the chapter concluded with a discussion on the economics of solar energy.

4.2 INSOLATION MAPS BASED ON GROUND MEASUREMENTS

Ground measurement remains one of the major sources of solar radiation data. In this section, maps of global solar radiation were produced using spatial interpolation of ground measurements in order to test the effectiveness of geospatial approach in visualising the solar energy potentials in Kano, Kaduna and Katsina states. Mapping the solar energy potentials using ground measurement of solar radiation is a fundamental initial step in achieving comparison with the satellite data, and subsequent analysis of the spatial variations in the solar energy potentials over the study area.

The monthly mean daily values of solar radiation obtained from ground measurement in the whole study area over a period of thirty years are shown in Table 4.1. It can be observed from Table 4.1 that a maximum monthly mean solar radiation value of 7.00kWh/m^2/day was recorded in Kaduna state. It is also observed from Table 4.1 that the maximum solar radiation values were constantly recorded between March and April all over the study area. This can be attributed to the fact that the months of March, April and May fall within the period of longer days and shorter nights experienced in the northern hemisphere. A longer day implies longer sunshine hours per day. Under normal conditions, the longer the period of sunshine and shorter the night, the greater the amount of solar radiation received in an area (Rajan, 2017).

Results also showed that based on the ground measurements of solar radiation all over the study area as presented in Table 4.1, a minimum monthly mean solar radiation value of 4.92kWh/m^2/daywas recorded in Kaduna state in the month of August. The lowest solar radiation value of 4.92kWh/m^2/day recorded in Kaduna was found to be higher than the corresponding value of 4.64kWh/m^2/day recorded in Abuja (in northcentral Nigeria) as reported by Yakubu and Medugu (2012).

Table 4.1: Ground-measured Monthly Mean Daily Values of Global Solar Radiation (kWh/m^2/day) for 1986-2015

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Kaduna	6.08	6.53	7.00	6.73	6.25	5.94	5.33	4.92	5.81	6.37	6.48	6.17
Kano	5.63	6.70	6.99	6.81	6.68	6.48	5.65	5.48	5.78	6.27	6.06	5.64
Katsina	5.79	6.16	6.40	6.15	5.98	5.51	5.41	5.71	6.08	5.99	5.65	5.41

Source: NIMET, 2015.

It was also found that the lowest solar radiation values were recorded in the months of July and August in all the three states, as well as December and January in Kano and Katsina states as shown in Table 4.1.

The lowest radiation values recorded in the months of July and August is due to the rainy season which is characterized by cumulonimbus clouds in the area, which have high capacity to intercept the incident solar radiation received in the area. A similar conclusion was reached by Ojosu (1990) who observed that in Nigeria, the rainy season also records low levels of solar radiation especially in the months of July and August. The implication of this is that lower solar energy can be harnessed during these periods. In order to improve the efficiency of photovoltaic solar technology deployed to harness solar energy in the area during the periods of minimum insolation, batteries should be serviced or changed regularly, and solar panels should be cleaned to maximize solar energy potentials during these periods.

In addition, the difference of 2.08kWh/m^2/daybetween the maximum and the minimum values of solar radiation recorded in the area was found to be relatively large. But, it is observed that the average monthly mean solar radiation throughout the study area is approximately equal to 5kWh/m^2/day, which is conducive for solar energy development. Based on the fact that the average monthly mean solar radiation value all over the study area is approximately 5kWh/m^2/day, there are many potential sites in the area that are good for solar energy development. This is because the amount of solar energy favourable to the Photovoltaic and Concentrating Solar Power technologies is at least 5kWh/m^2/day(The U.S. Department of Agriculture and Forest Service- USFS, 2005).

Findings of this study revealed that the optimum times for harnessing solar energy all over the study area are the months of March, April and May. However, there are other months of the year that offer good times for harnessing solar energy which vary with locations within the study area.

In addition, temporal variations in the monthly means of solar radiation among the three states can be observed from Figures 4.1a – 4.1l. Also, spatial variation in solar radiation across the three states was observed from the ground data, whereby higher solar radiation values were recorded in Kaduna state during the months of October and November (Figures 4.1j and 4.1k); while higher values were observed in Kano state during the months of May (Figure 4.1e) and June (Figure 4.1f); whereas, higher solar radiation values were recorded in Katsina state in the month of March (Figure 4.1c).

The spatiotemporal variations in solar radiation over the study area can be seen in Figures 4.1a – 4.1l, where the mean monthly solar radiation maps from ground measurements are presented. Figures 4.1a – 4.1l also show that GIS visualisation of the pattern of solar radiation in the study area is better than the climatic zone classification adopted by Diabaté, Blanc and Wald (2004) to map solar radiation in Africa. This is because spatiotemporal variation in solar radiation is not clearly understood using the method adopted by Diabaté *et al.* (2004). Hence, the ability of GIS visualisation in revealing the solar energy potentials in the study area is established.

The information provided here are important parameters for the design, sizing, locating as well as pointing of solar panels and for concentrating solar thermal applications. Also, the monthly variation in solar radiation is required by designers and engineers of solar energy conversion systems in order to ascertain the amount of solar energy available to a collector and how it varies monthly and annually.

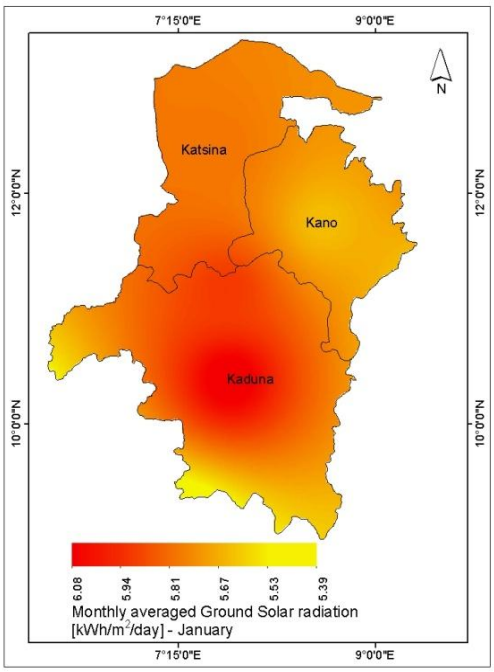


Fig. 4.1a: Month of January

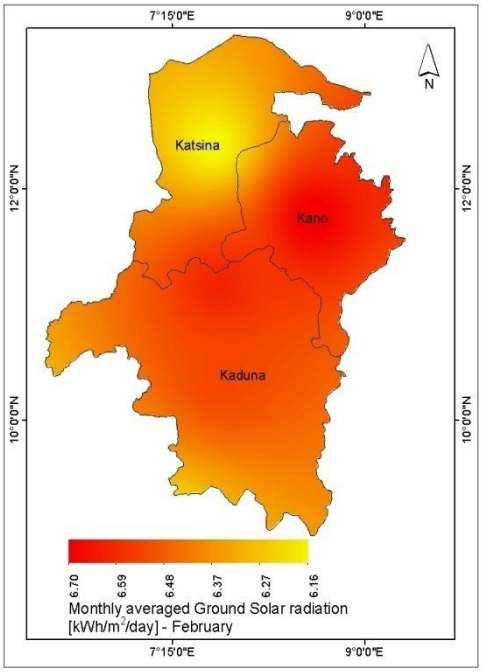


Fig. 4.1b: Month of February

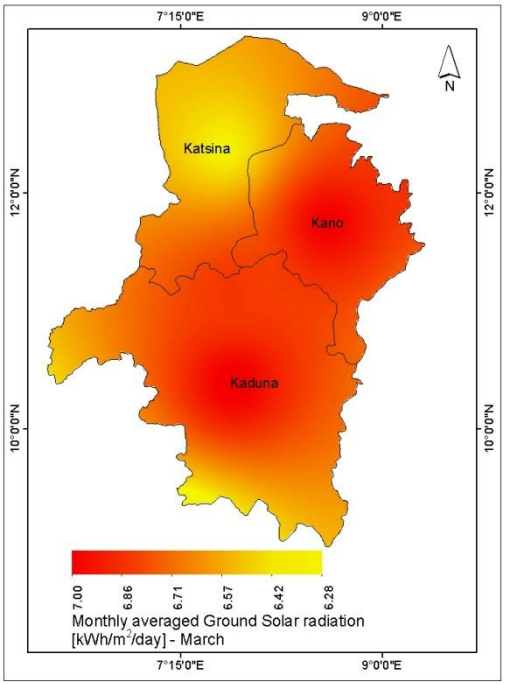


Fig. 4.1c: Month of March

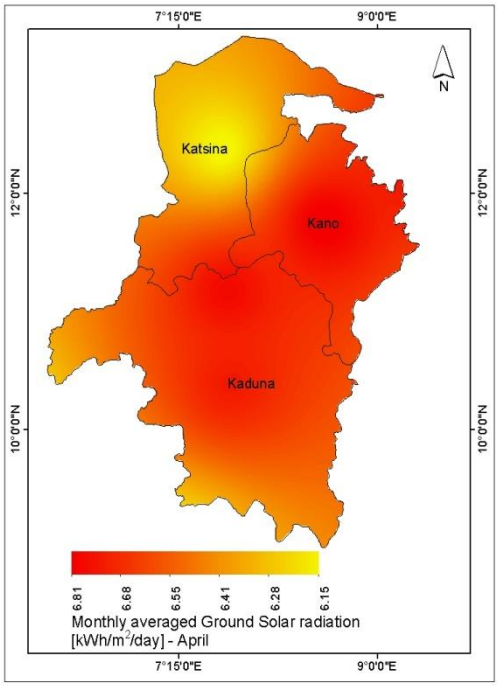


Fig. 4.1d: Month of April

Figure 4.1: Ground-measured Monthly Mean Daily Values of Global Solar Radiation (kWh/m^2/day) for 1986-2015

Source: Fieldwork, 2016.

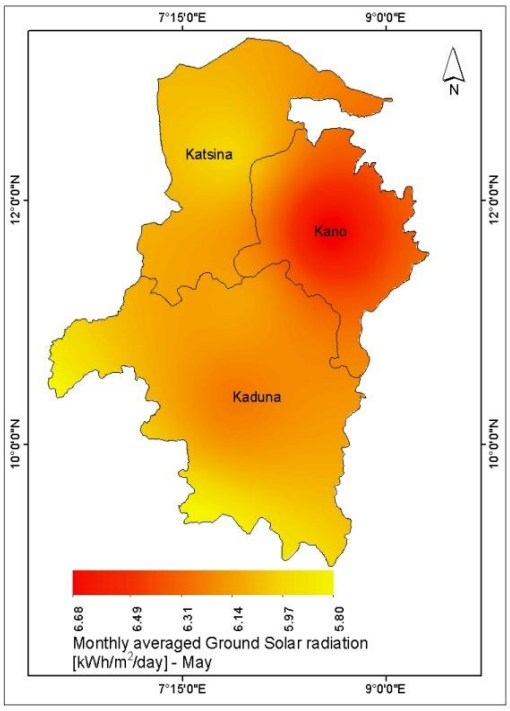


Fig. 4.1e: Month of May

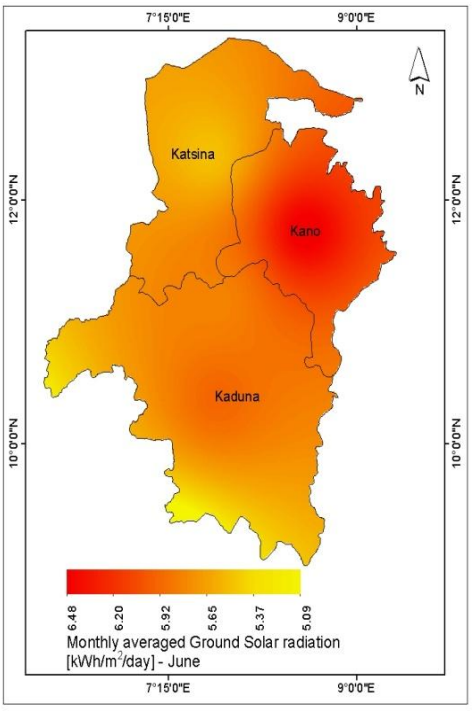


Fig. 4.1f: Month of June

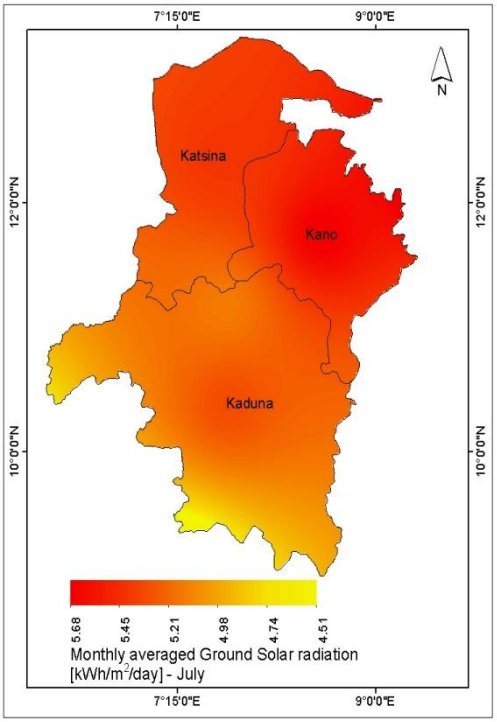


Fig. 4.1g: Month of July

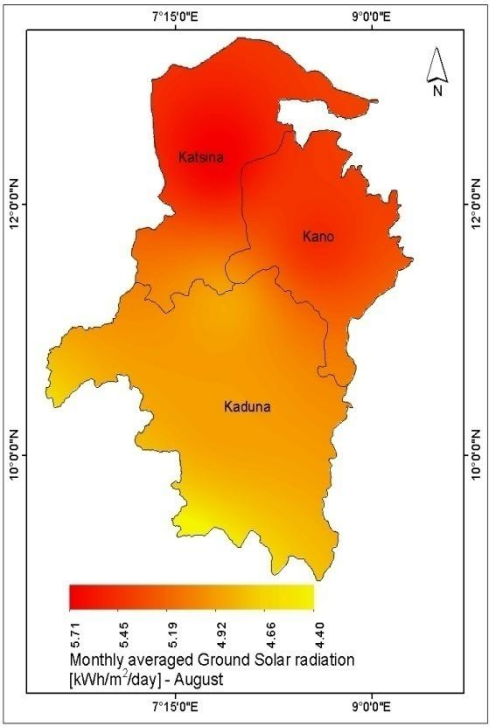


Fig. 4.1h: Month of August

Figure 4.1(Continued): Ground-measured Monthly Mean Daily Values of Global Solar Radiation (kWh/m^2/day)

Source: Fieldwork, 2016.

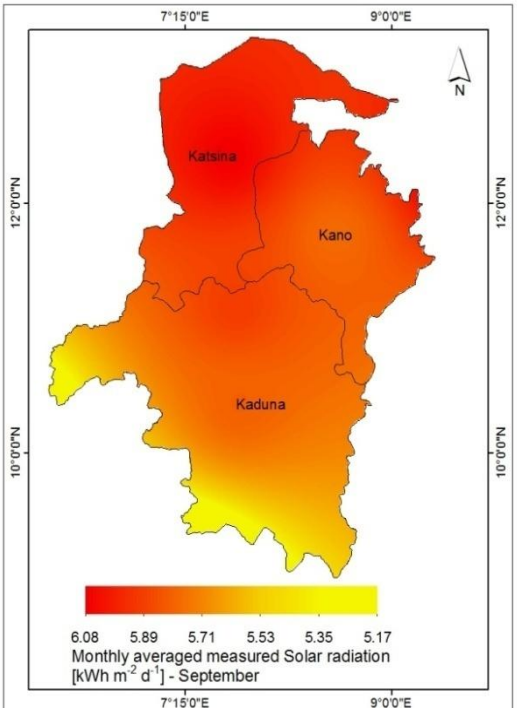


Fig. 4.1i: Month of September

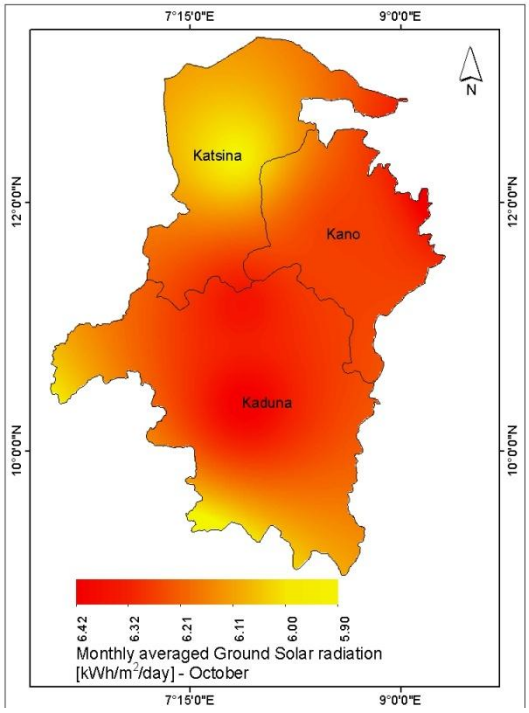


Fig. 4.1j: Month of October

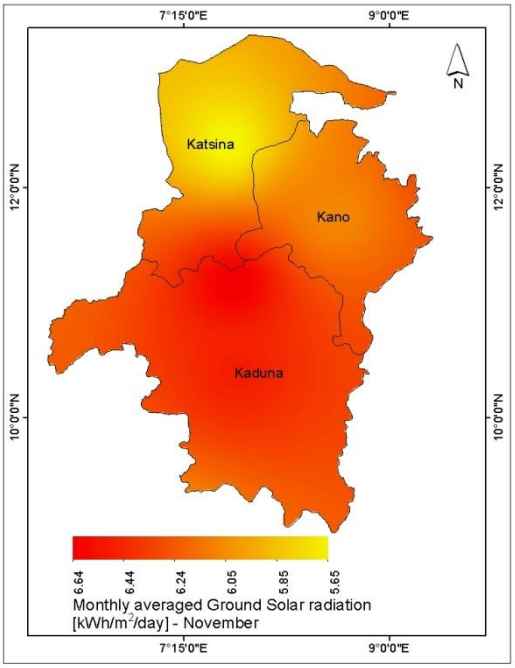


Fig. 4.1k: Month of November

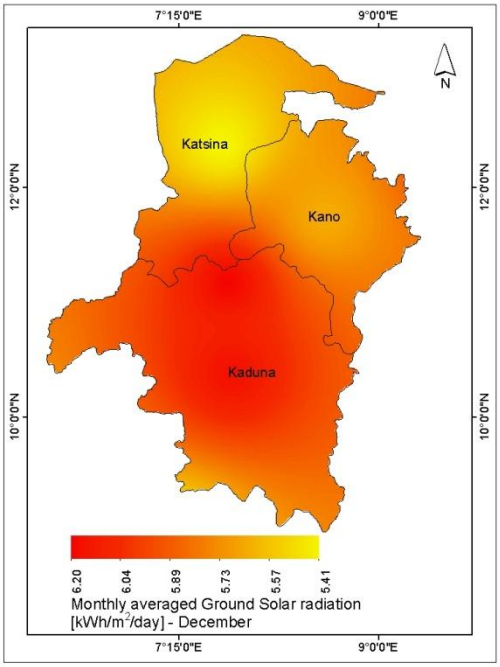


Fig. 4.1l: Month of December

Figure 4.1(Continued): Ground-measured Monthly Mean Daily Values of Global Solar Radiation (kWh/m^2/day)

Source: Fieldwork, 2016.

Ground measurement has been an important source of solar radiation data, but recently, satellite-derived values of solar radiation have proven to be more accurate than nearby surface observations (interpolated from ground measurements) for locations that are more than 25Km away from a properly maintained ground station (Zelenka, 1999). In addition, the ability of satellite to accurately delineate relative variations between adjoining locations has made it a reliable source of solar microclimate characterization (Perez *et al.*, 2002). With satellite pixel sizes of about 2.5Km, the spatial resolution of solar radiation estimates is much better than the data obtained from interpolating ground measurements (Dagestad, 2005; Ali *et al.*, 2008). Recently, there are satellites with a resolution of less than 2.5Km that provide a better and more reliable solar radiation data. The subsequent section (4.3) presents insolation maps based on satellite data.

4.3 INSOLATION MAPS BASED ON SATELLITE DATA

This section presents maps of solar radiation derived from satellite data. This is particularly important because of the limited number of solar radiation stations in the Northwestern Nigeria. Satellite is an important source of radiation data as highlighted by Perez *et al.* (2002), Dagestad (2005) and Ali *et al.* (2008). Therefore, satellite mapping of solar radiation complement the insolation maps from ground measurement as presented in section 4.2, and can be used to evaluate the maps from ground data.

Table 4.2: Satellite-derived Monthly Mean Daily Values of Global Solar Radiation (kWh/m^2/day)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Kaduna	5.76	6.1	6.32	6.3	5.94	5.4	4.8	4.47	5.11	5.63	6.11	5.79
Kano	5.49	6.3	6.79	6.96	6.76	6.42	5.8	5.41	5.67	5.9	5.72	5.27
Katsina	5.49	6.4	6.89	7.21	7.11	6.98	6.3	5.83	6.03	6.07	5.82	5.23

Source: NASA SSE, 2015

Analysis of the satellite-derived solar radiation in the study area as shown in Table 4.2, revealed that maximum insolation is recorded between the months of March and May throughout the study area, while the minimum insolation is usually recorded in the months of July, August, December and January, similar to the ground measurements. It can be seen from Table 4.2 that a maximum insolation of 7.21kWh/m^2/day was recorded in Katsina during the month of April, while the minimum insolation of 4.47kWh/m^2/day was recorded in Kaduna in the month of August, contrary to previous observations based on the ground measurement.

A further observation of Table 4.2 revealed that a peculiar pattern was observed in both Kano and Katsina states where insolation remains consistently high between February (Figure 4.2b) and June (Figure 4.2d), while in Kaduna state, the insolation remains high during the months of February, March and April. This can be accounted for the increasing sunshine hours observed from the winter solstice (December 22) till the summer solstice (June 21) in the northern hemisphere.

The maximum insolation received between March and May all over the study area is as a result of reduced cloud attenuation during these periods. The minimum insolation values received in the months of December and January is attributed to the Harmattan period in the area (Falodun, 2015), during which the solar radiation is significantly reduced as a result of the influence of the Tropical Continental airmass which is characteristically cool and dry.

However, the lower insolation experienced during the months of July and August is attributed to the influence of cloud which significantly reduces the intensity of solar radiation reaching the Earth's surface. In addition, the minimum insolation recorded in July can be attributed to the rainy season, or, due to the fact that the Sun is farther from

the Earth during this period. This is because the Earth is a little farther from the Sun on about July 4th annually, when the distance between the Sun and the Earth is about 152 million kilometres, a position known as aphelion (Rajan, 2017).

Comparison of the satellite solar radiation values with the corresponding values obtained from ground measurements confirms the ability of geostationary meteorological satellites with a coarse spatial resolution to provide solar radiation data that is reliable (Abdel Wahab *et al.*, 2009).

Figures 4.2a – 4.2l presents maps of solar radiation derived from satellite data. The Figures showed that it is possible to map the surface solar radiation at every point location from satellite data. The use of satellite data addresses the inconsistency observed in mapping solar radiation when climate zone classification is adopted as in the case of Diabaté *et al.* (2004). This also supports the hypothesis of Diabaté *et al.* (2004) that suggested the use of satellite-derived clearness index, which is available at every pixel to improve the quality of solar radiation mapping.

Both the ground measurements and satellite estimates of solar radiation data have advantages and disadvantages. Therefore, the two sources were compared in the following section (4.4).

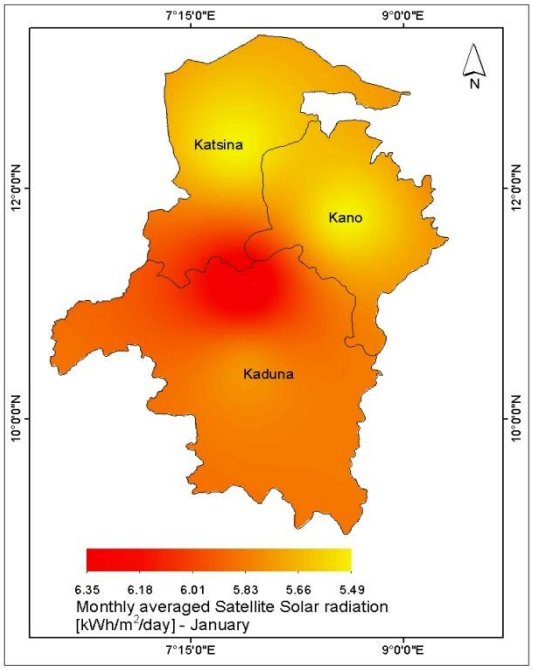


Fig. 4.2a:Month of January

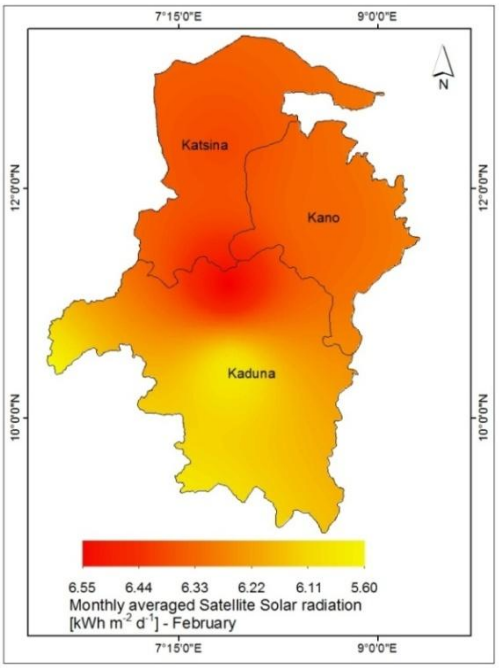


Fig. 4.2b:Month of February

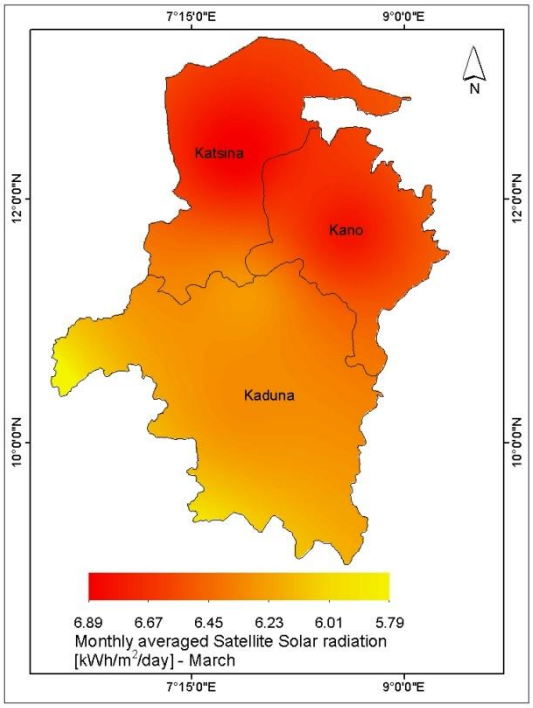


Fig. 4.2c: Month of March

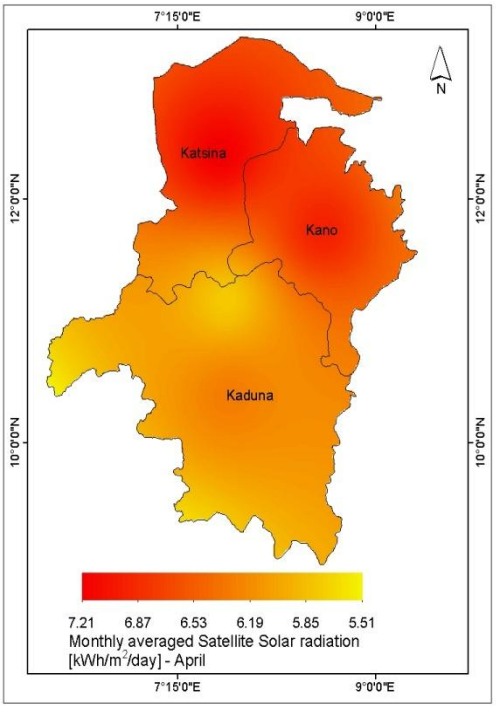


Fig. 4.2d: Month of April

Figure 4.2 a-l: Satellite-derived Monthly Mean Daily Values of Global Solar Radiation (kWh/m^2/day)

Source: Fieldwork, 2016.

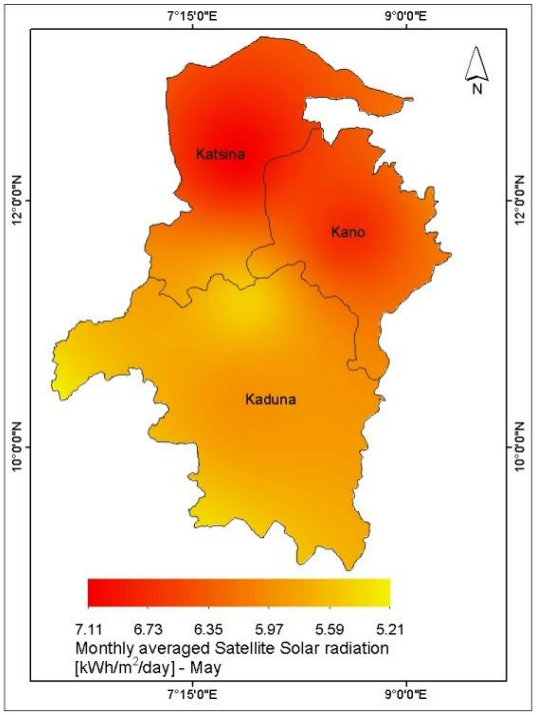


Fig. 4.2e: Month of May

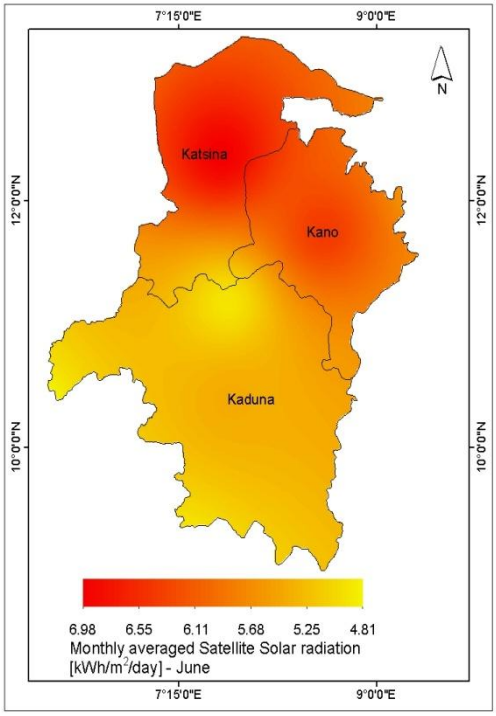


Fig. 4.2f: Month of June

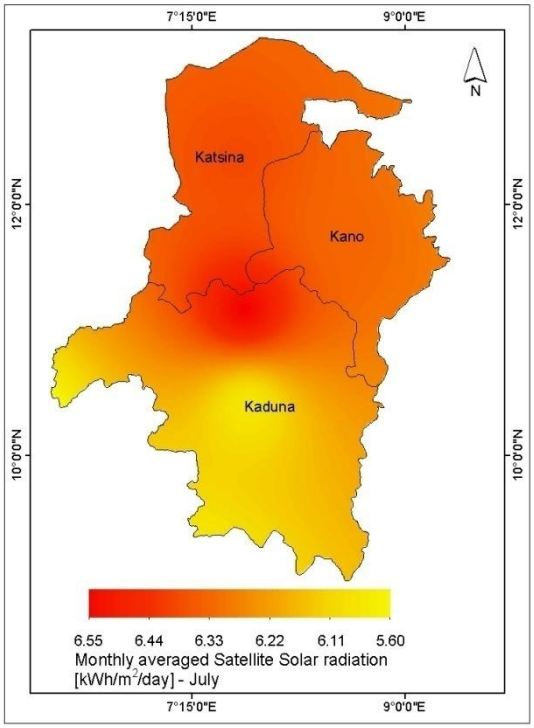


Fig. 4.2g: Month of July

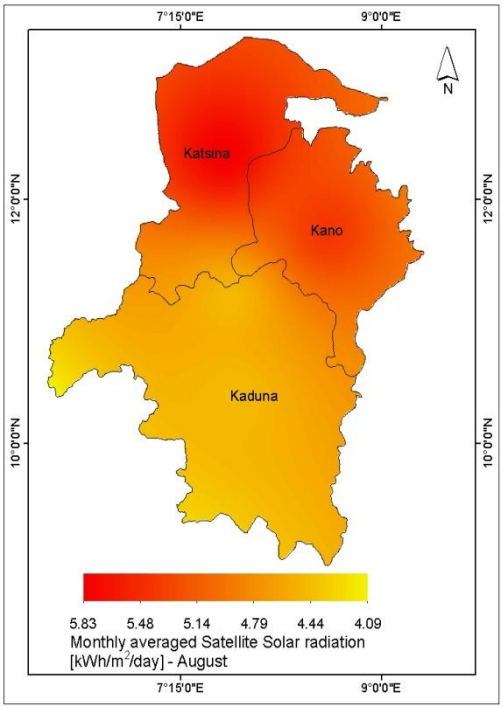


Fig. 4.2h: Month of August

Figure 4.2 (Continued): Satellite-derived Monthly Mean Daily Values of Global Solar Radiation (kWh/m^2/day)

Source: Fieldwork, 2016.

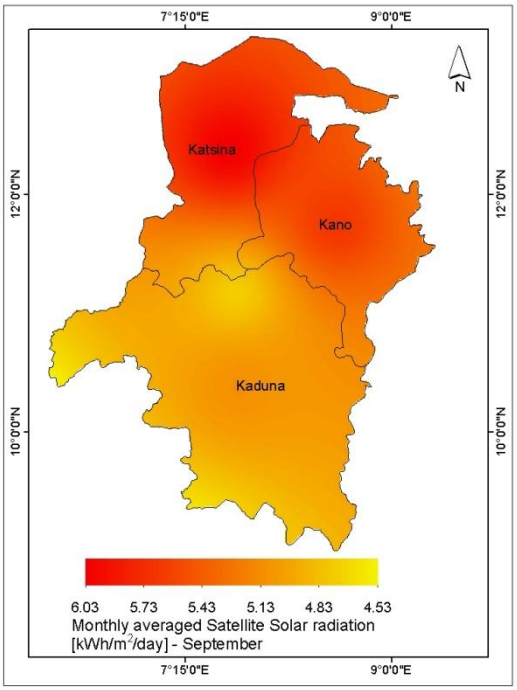


Fig. 4.2i: Month of September

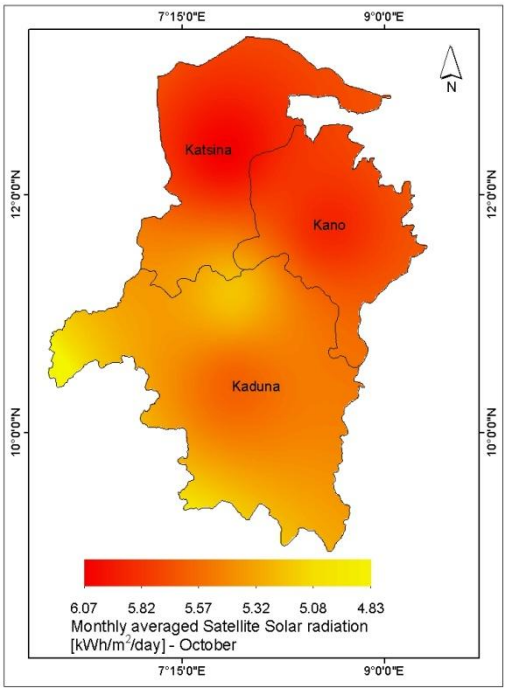


Fig. 4.2j: Month of October

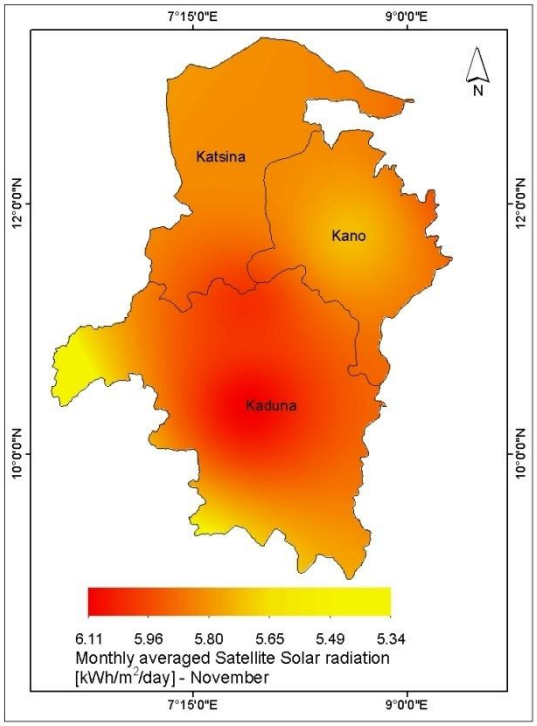


Fig. 4.2k: Month of November

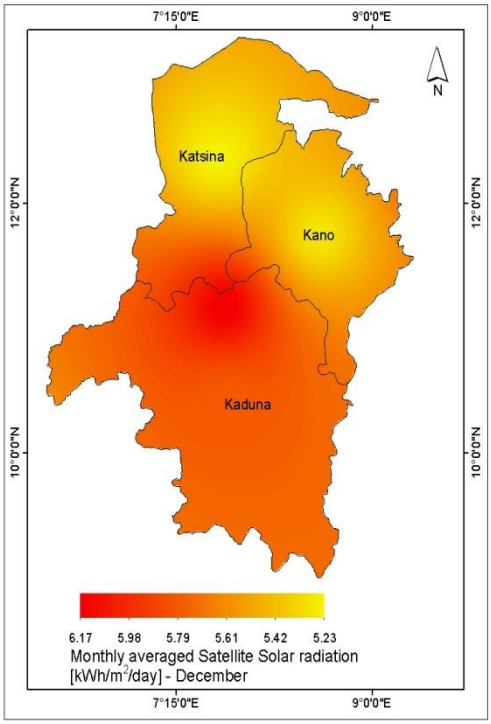


Fig. 4.2l: Month of December

Figure 4.2 (Continued): Satellite-derived Monthly Mean Daily Values of Global Solar Radiation (kWh/m^2/day)

Source: Fieldwork, 2016.

4.4 COMPARISON BETWEEN GROUND-MEASURED AND SATELLITE-DERIVED SOLAR RADIATION DATA

This section compares between the ground-measured and the satellite-derived solar radiation data with a view to highlight the relationship between them. The maximum and minimum solar radiation values obtained from the two sources and the magnitude of the differences between them were discussed. Also, the spatial and temporal variations of solar radiation observed in the study area were highlighted in this section.

Based on the two sources of data (ground-measured and satellite-derived), the minimum insolation value was recorded in Kaduna during the month of August as shown in Tables 4.1 and 4.2. The minimum ground-measured insolation value was found to be 4.92kWh/m^2/daywhile the corresponding satellite-derived value was 4.47kWh/m^2/day. It is observed that the difference between the ground-measured and the corresponding satellite-derived solar radiation value is 0.45kWh/m^2/day, which is relatively large.

The relatively lower insolation observed in August based on the satellite estimate can be attributed to the effect of cloud attenuation during the rainy season, which reduces the intensity of insolation received in the area. Other factors that might affect the satellite estimate of solar radiation are the resolution of the satellite and the correction method used in processing the satellite data.

In addition, results showed that temporal variation exists in the amount of insolation received in the area. It was found that minimum insolation values were recorded in the months of July, August, December and January, based on the two sources of solar radiation data. This can be attributed to the fact that the months of July, August and December experience longer nights which implies shorter sunshine hours per day. This is because from June 21 to December 22, shorter days are experienced in the northern

hemisphere (Rajan, 2017). The minimum insolation recorded in January can be attributed to Harmattan season during this period in Northwestern Nigeria.

It was also observed from the results based on the two sources of data (see Tables 4.1 and 4.2) that maximum insolation is received between the months of March and May throughout the study area. This observation is in agreement with the results of simulation of global solar radiation over Nigeria by Ohunakin *et al*. (2015), which showed that the highest values of global solar radiation were observed during the late dry and early rainy season (March/ April) in the Northern Nigeria.

Based on the ground measurement, the maximum insolation value of 7.00kWh/m^2/day was recorded in Kaduna during the month of March, while the maximum insolation value of 7.21kWh/m^2/day was recorded in Katsina in the month of April based on the corresponding satellite data. In this case, the satellite insolation value is higher than the corresponding ground value by 0.21kWh/m^2/day. This could be due to reduced cloud and clear sky conditions during the months of March and April in the area, resulting to less interference of cloud with the sensors.

Furthermore, visual analysis of the solar radiation maps from the two sources of data as presented in Figures 4.1(a-l) and 4.2(a-l) suggests some level of correlation between the satellite-derived and the ground-measured solar radiation data. This correlation was tested using scatter plots in Figures 4.3(a-c), the correlation was found to be positive in all the three states suggesting that the relationship between the ground-measured and the satellite-derived solar radiation data is strong. But the correlation is stronger in the case of Kano and Kaduna states as depicted in Figures 4.3a and 4.3b and less strong as shown in Figure 4.3c. This suggests that in the absence of one source of solar radiation data, the other source can reliably serve as an alternative.

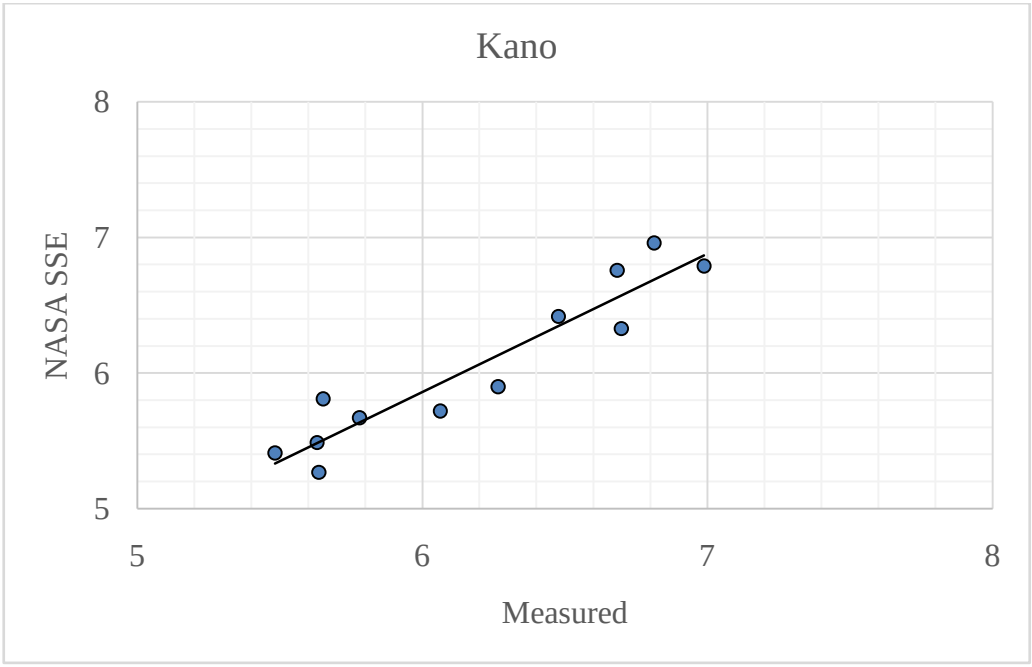


Figure 4.3a: Comparison between the Two Sources of Solar Radiation Data in Kano State

Source: Fieldwork, 2016

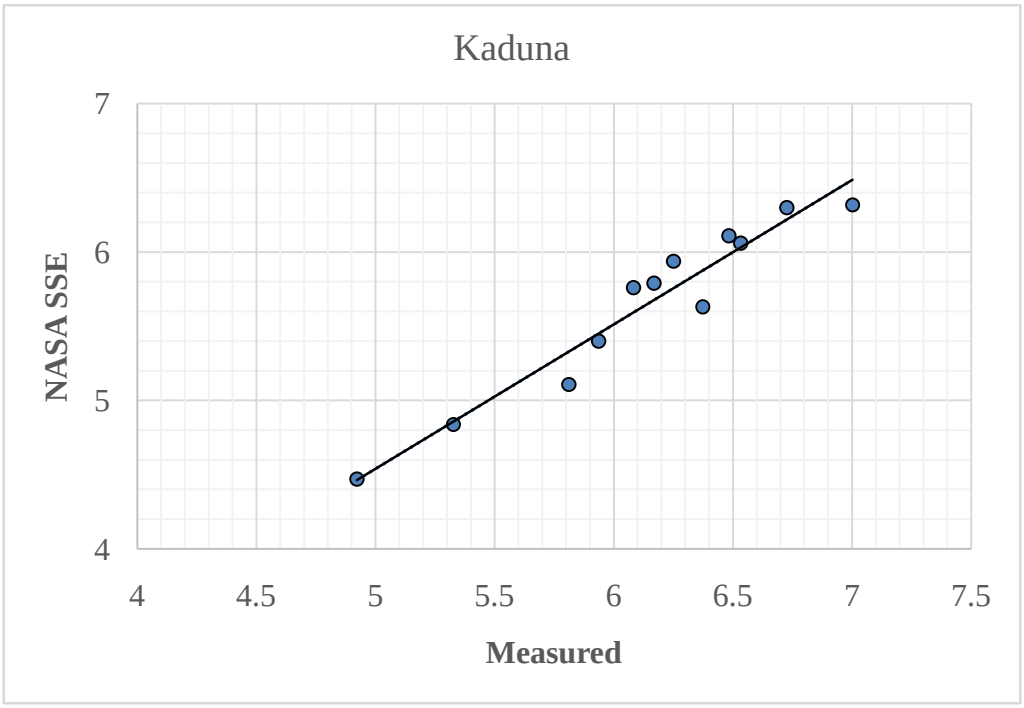


Figure 4.3b: Comparison between the Two Sources of Solar Radiation Data in Kaduna State

Source: Fieldwork, 2016

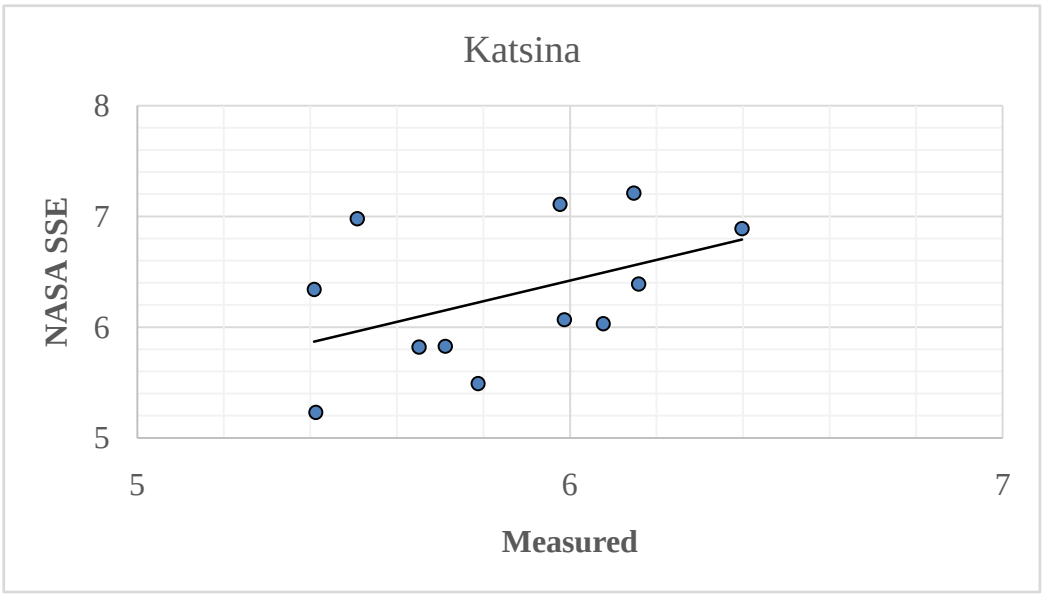


Figure 4.3c: Comparison between the Two Sources of Solar Radiation Data in Katsina State

The findings of this study can be supported by similar results obtained by Abdel Wahab *et al.* (2009) when they compared two databases of solar surface irradiance derived from satellites and ground measurements for Algeria, Egypt, Libya and Tunisia. Their results also showed good agreement between the measured and the satellite data.

Although a positive correlation between the two sources of data was observed, there are few cases where the measured solar radiation value is relatively lower than the corresponding satellite value and vice versa as shown in Figures 4.4-4.6. It was observed from the results that the satellite-derived solar radiation is lower in December and January. The situation in December and January is attributed to Harmattan season in Northwestern Nigeria which is characterized by dusty and hazy condition that has the potential to affect the satellite retrieval of solar radiation in the area.

Analysis of the differences between the mean monthly solar radiation data from the two sources (ground and satellite) is presented in Table 4.3. Results from the Table showed that in Kaduna, the minimum differences of 0.32 and 0.31kWh/m^2/day were recorded in May and January respectively, while the maximum differences of 0.70 and 0.74kWh/m^2/day were found in September and October respectively. In Kano, the minimum differences of -0.07 and -0.15kWh/m^2/day were observed in May and July respectively, while the maximum difference of 0.36kWh/m^2/day was recorded in December. In Katsina, the minimum difference of -1.47kWh/m^2/day was recorded in June, while the maximum difference of 0.29kWh/m^2/day was recorded in January. It can be observed that the maximum differences were recorded at lower latitudes while the minimum differences were recorded at higher latitudes.

Table 4.3: Differences between Ground and Satellite Mean Daily Values of Global Solar Radiation Data

Station	Jan	Jan	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Kaduna	0.32	0.47	0.68	0.42	0.31	0.53	0.48	0.45	0.70	0.74	0.37	0.37
Kano	0.13	0.36	0.19	-0.14	-0.07	0.05	-0.15	0.07	0.10	0.36	0.34	0.36
Katsina	0.29	-0.23	-0.49	-1.06	-1.13	-1.47	-0.93	-0.11	0.04	-0.08	-0.16	0.18

Source: Fieldwork, 2016

In addition, findings of this study revealed a spatial pattern of insolation between the satellite estimate and ground measurement as shown in Table 4.3. It was observed from the Table that the differences between measured insolation and satellite insolation decrease with increasing latitude. This is contrary to the findings of a Spanish case study reported by Antonanzas-Torres *et al.* (2012) where no significant latitudinal behaviour was observed in terms of the differences between the measured and the satellite insolation data in the area. However, no temporal trend was observed in terms

of the differences between the measured and the satellite insolation based on the findings of this study.

4.5 PATTERN OF SOLAR RADIATION IN THE THREE STATES

Although the three states (Katsina, Kano and Kaduna) covered by this study fall within the Northwestern Nigeria, spatial and temporal variations exist in terms of the availability and intensity of solar radiation in the three states as discussed in sections 4.5.1, 4.5.2 and 4.5.3. The spatiotemporal variations in solar radiation in the states have implication on solar energy potentials in the states. This section also discussed the similarities and differences between various sources of solar radiation data. In addition, the correlation between the ground-measured and the satellite data (NASA SSE) used in this study was presented.

4.5.1 Solar Radiation in Katsina State

The minimum solar radiation values recorded in Katsina in the months of December and January range from 5.05kWh/m^2/day to 5.23kWh/m^2/dayas shown in Table 4.4 and Figure 4.4. In addition, Table 4.4 indicates that high amount of solar radiation are usually received between the months of March and June with values ranging from 6.40kWh/m^2/daybased on the ground data to 7.21kWh/m^2/daybased on the satellite data. These findings support the observation of Okundamiya and Nzeako (2011) which discovered that during the beginning of dry season, only Katsina maintained a gradual decrease in global radiation when other cities with identical climatic variation experienced a rapid increase in their solar radiation. Besides, the value of 5.37kW/m^2/day as the least solar radiation recorded in Katsina in the month of December based on the results of Okundamiya and Nzeako (2011) is within the range of

the solar radiation values obtained in this study. This is because solar radiation is very low during the Harmattan in the northern fringes of the country including Katsina state.

Table 4.4: Monthly Mean Daily Values of Global Solar Radiation in Katsina (kWh/m^2/day)

Month	Measured	NASA SSE	PVGIS	Calibrated
Jan	5.79	5.49	5.65	5.21
Feb	6.16	6.39	6.26	6.63
Mar	6.40	6.89	7.17	7.42
Apr	6.15	7.21	6.64	8.46
May	5.98	7.11	6.44	8.46
Jun	5.51	6.98	6.24	8.84
Jul	5.41	6.34	5.75	7.43
Aug	5.71	5.83	5.33	5.95
Sep	6.08	6.03	5.95	5.98
Oct	5.99	6.07	6.09	6.15
Nov	5.65	5.82	5.80	5.99
Dec	5.41	5.23	5.49	5.05

Source: Fieldwork, 2016.

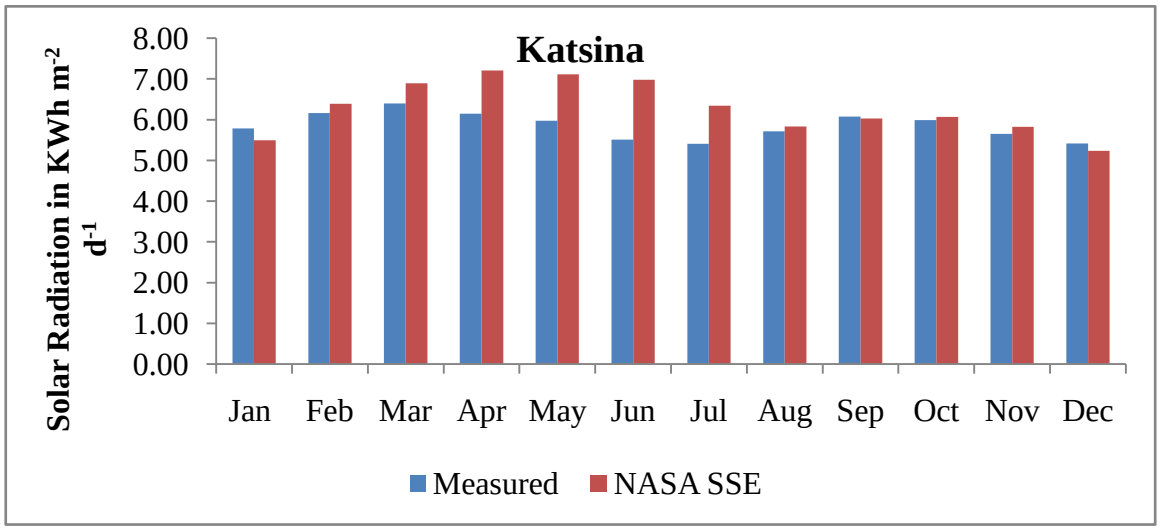


Figure 4.4: Monthly Mean Daily Values of Global Solar Radiation in Katsina (kWh/m^2/day)

Source: Fieldwork, 2016

This study is capable of providing the required solar energy information for the proposed 30MW and 175MW solar energy plants to be developed by two solar firms (The Pan African Solar and Nova Solar) in Kankia town of Katsina state. The solar plants are intended to serve the needs of industrial and commercial purposes in the state. The project would also encourage the development of new industries and creation of jobs for the citizen.

Solar radiation has significant impact on agroclimatology. It influences crop water balance, plant growth, development and ripening. This study has provided solar information which can be used for optimum production of tomatoes, cotton and cereals in Katsina state. In addition, the solar energy potential in the state can be harnessed to provide electricity and solar powered boreholes especially in the rural areas. It can also be used to provide light in schools, healthcare centres and other public facilities across the state.

4.5.2 Solar Radiation in Kano State

Based on the measured, satellite and calibrated insolation data as shown in Table 4.5, the maximum insolation values in Kano were observed between the months of March and June ranging from 6.60 – 7.18kW/m^2/day. On the other hand, the minimum solar radiation values were observed in the months of July, August, December and January as shown in Figure 4.5. The values range between 4.93 and 5.97kW/m^2/day. The minimum radiation values observed in Kano during the months of July and August correspond to the rainy season when radiation level is generally lower than for the dry season (Sambo, 1988). The minimum radiation values can also be attributed to the maximum albedo experienced in Kano during this period. This is because the period of maximum albedo,

which is characterized by the peak of cloud activity in Kano is found in the month of August (Audu, Isikwue and Eweh, 2014; Isikwue, Akiishi and Utah, 2014).

Table 4.5: Monthly Mean Daily Values of Global Solar Radiation in Kano (kWh/m^2/day)

Month	Measured	NASA SSE	PVGIS	Calibrated
Jan	5.63	5.49	5.77	5.35
Feb	6.70	6.33	6.28	5.98
Mar	6.99	6.79	7.18	6.60
Apr	6.81	6.96	6.68	7.11
May	6.68	6.76	6.41	6.84
Jun	6.48	6.42	6.14	6.36
Jul	5.65	5.81	5.66	5.97
Aug	5.48	5.41	5.35	5.34
Sep	5.78	5.67	5.91	5.56
Oct	6.27	5.90	6.13	5.56
Nov	6.06	5.72	5.91	5.40
Dec	5.64	5.27	5.60	4.93

Source: Fieldwork, 2016

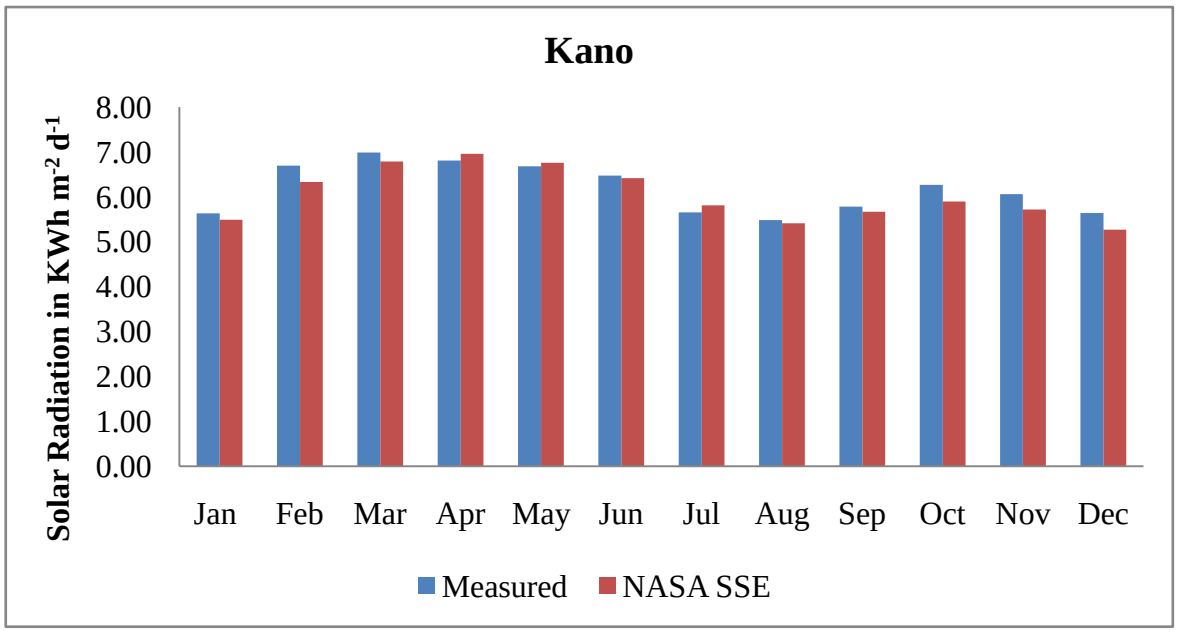


Figure 4.5: Monthly Mean Daily Values of Global Solar Radiation in Kano (kWh/m^2/day)

Source: Fieldwork, 2016

In addition, a similar trend of minimum solar radiation in Kano as observed by this study was confirmed by the findings of Ezenekwe, Ezemonye and Emeribe (2013), which revealed that radiation values in Kano start with lowest values in January and gradually increase to highest peak in April. Also, the findings of this study is in supported by the results of Isikwue *et al.* (2014) which showed that in Kano, high solar radiation values were obtained between February and June with the maximum attained in March and minimum attained in August.

The information provided in this study can be used for the design and deployment of the proposed 50MW solar-powered plant in Kumbotso Local Government Area of Kano state. Such solar-powered plant can provide power for crop drying, solar incubators and solar chick brooding, cooking and other household activities in the area. It can also be useful in street lightening, rural electrification, rural clinic and schools power supply, traffic lighting and lighting of road signs. Importantly, the solar energy potentials in Kano state have the capability to revive the grounded industries in the state thereby creating jobs and other sources of revenue to the government. It can also provide the energy required by small scale industries which will lead to job creation in the state. In addition, this solar radiation information can be used in the design and deployment of stand-alone solar photovoltaic which is the best option for a more affordable and reliable source of electricity, particularly in rural areas (Wansah *et al.*, 2015).

4.5.3 Solar Radiation in Kaduna State

The pattern of solar radiation in Kaduna State is presented in Table 4.6 and Figure 4.6. It can be observed from Table 4.6 that solar radiation received in Kaduna during the months of July and August is as low as 4kWh/m^2/day and barely reach 5 kWh/m^2/day. This is because the rainy season records low levels of solar radiation principally due to

the effect of cloud. The maximum solar radiation value in Kaduna ranges from 7 – 7.11 kWh/m^2/dayrecorded in March as shown in Table 4.6.

This study has the potential of providing solar radiation information for the proposed construction of the 50MW Photovoltaic Solar Farm along the Airport Road in Kaduna; a project being spearheaded by the Federal Ministry of Environment in partnership with Synergent Power Share Nigeria Ltd. The project which is under the auspices of the Renewable Energy Programme Unit of the Federal Ministry of Environment in Nigeria will provide an alternative source of power for administrative, industrial, and household energy needs in the state. It will also provide a viable source of power for small and medium scale enterprises and manufacturing industries which would create employment opportunities for the people in the state.

Table 4.6: Monthly Mean Daily Values of Global Solar Radiation in Kaduna (kWh/m^2/day)

Month	Measured	NASA SSE	PVGIS	Calibrated
Jan	6.08	5.76	5.98	5.45
Feb	6.53	6.06	6.38	5.62
Mar	7.00	6.32	7.11	5.70
Apr	6.73	6.3	6.34	5.90
May	6.25	5.94	6.04	5.64
Jun	5.94	5.40	5.49	4.91
Jul	5.33	4.84	4.81	4.40
Aug	4.92	4.47	4.38	4.06
Sep	5.81	5.11	5.25	4.49
Oct	6.37	5.63	5.74	4.97
Nov	6.48	6.11	5.99	5.76
Dec	6.17	5.79	5.79	5.43

Source: Fieldwork, 2016

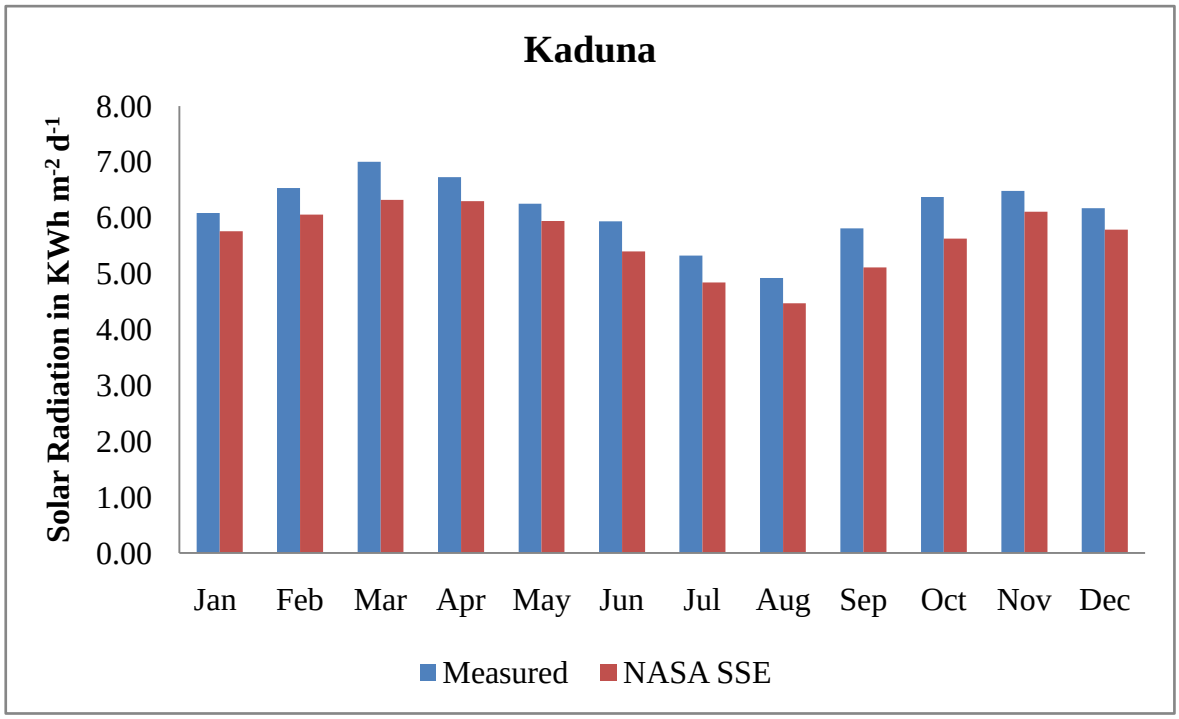


Figure 4.6: Monthly Mean Daily Values of Global Solar Radiation in Kaduna (kWh/m^2/day)

Source: Fieldwork, 2016

Although efforts are being made by Kaduna state government to install PV powered street lights, little effort has been done to harness the abundant solar energy to install solar boreholes, solar lanterns, PV pumps, PV domestic lighting units in the state.

The level of solar energy potential across the state as discovered by this study suggests that there is the need to harness solar to deliver Photovoltaic solar technology on a large scale. This can be used as an alternative source of power in the state and can be privatized to generate revenue to the government. In addition, findings of this study is essential in implementing the Kaduna State Government's plan of providing light to its various healthcare centres in the state using solar energy.

4.6 INSOLATION MAPS BASED ON CALIBRATION OF GROUND-MEASURED WITH SATELLITE DATA

Single sources of solar radiation have one problem or the other as mentioned in Section 3.2.2.1. Therefore, this study merged satellite-derived solar radiation data with ground-measured solar radiation data for the analysis of solar energy potentials in the study area as shown in Table 4.7. The calibrated solar radiation data in Table 4.7 is the monthly average over a period of thirty years.

Table 4.7: Calibrated Monthly Mean Daily Values of Global Solar Radiation (kWh/m^2/day) for 1986-2015

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Kaduna	5.45	5.62	5.70	5.90	5.64	4.91	4.40	4.06	4.49	4.97	5.76	5.43
Kano	5.35	5.98	6.60	7.11	6.84	6.36	5.97	5.34	5.56	5.56	5.40	4.93
Katsina	5.21	6.63	7.42	8.46	8.46	8.84	7.43	5.95	5.98	6.15	5.99	5.05

Source: Fieldwork, 2016

Based on the calibrated insolation values presented in Table 4.7, a maximum value of 8.84kWh/m^2/daywas observed in Katsina state in month of June, while maximum insolation values of 7.11 and 5.90kWh/m^2/day were observed respectively in Kano and Kaduna states in the month of April. In addition, it can be observed from the results in Table 4.7, that a regime of high insolation is maintained from February to March in Katsina state and from March to June in Kano state, while high insolation is observed in the months of March, April and November in Kaduna state. This is due to the fact that highest insolation values were observed during the early rainy season (in the month of April); while the months of March and November reflect the season of clear sky conditions when values of cloud cover are minimum (Ohunakin *et al*., 2015). Hence, high insolation values are received during these months.

Table 4.7 also showed that based on the calibrated data, minimum insolation values were found to be 4.40kWh/m^2/day observed in the month of July in Kaduna state; 4.93 kWh/m^2/day and 5.05 40 kWh/m^2/day observed in the month of December respectively in Kano and Katsina states. It is also observed from the Table 4.7 that Kaduna experiences a regime of low insolation from July to August. This corresponds to the period of peak values of cloud cover in northern Nigeria which is approximately 65% in the months of July, August and September (Ohunakin *et al*., 2015). The peak cloud cover over the area significantly reduced the amount of solar radiation received in the area. The calibrated solar radiation maps are presented in Figures 4.7a – 4.7l.

Calibration of satellite and ground data involves combination of data from different sources; consequently, discrepancies between the two types of data are inevitable. Therefore, statistical methods are used to measure the level of discrepancy when merging ground-measured with satellite-derived solar radiation data. This is done in section 4.7.

4.7 VALIDATION OF SATELLITE-DERIVED SOLAR RADIATION WITH GROUND-BASED MEASUREMENTS

Ground-measured and satellite-derived solar radiation data have some differences resulting from their different sources of acquisition. Ground stations record solar radiation at point locations while satellites record solar radiation over an area or theme. This section used statistics to measure the level of differences between the satellite and the ground data. The results were compared with those of previous studies found in the literature.

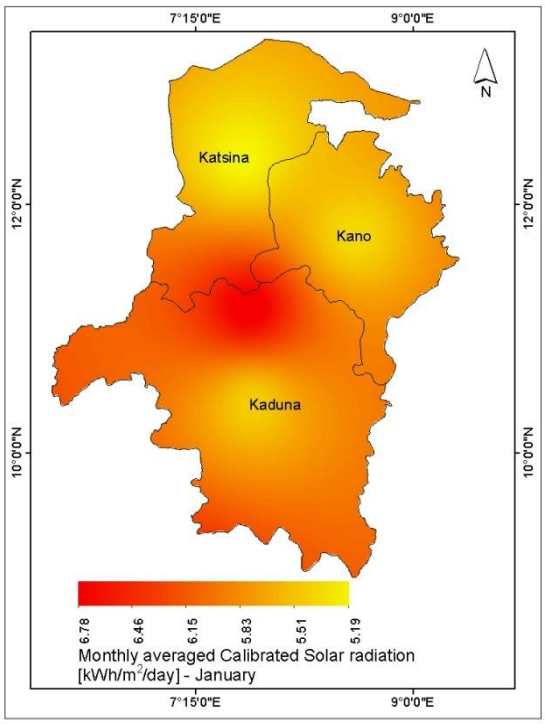


Fig. 4.7a: Month of January

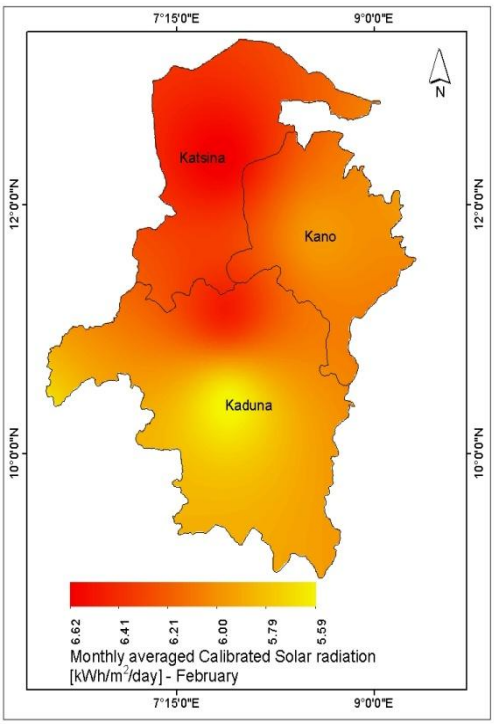


Fig. 4.7b: Month of February

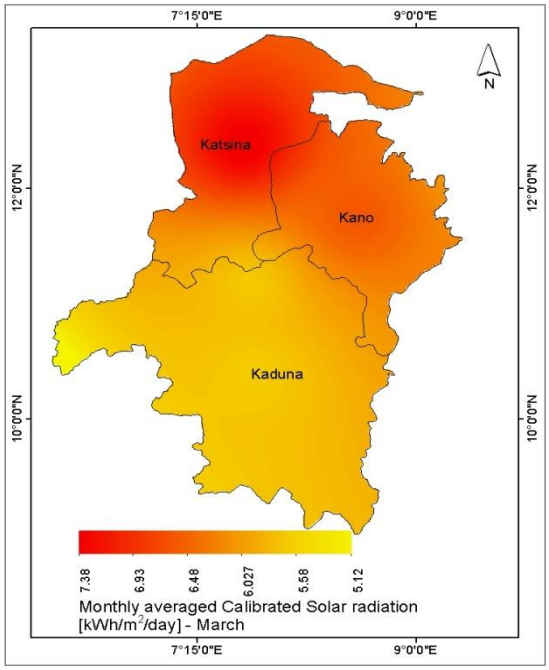


Fig. 4.7c: Month of March

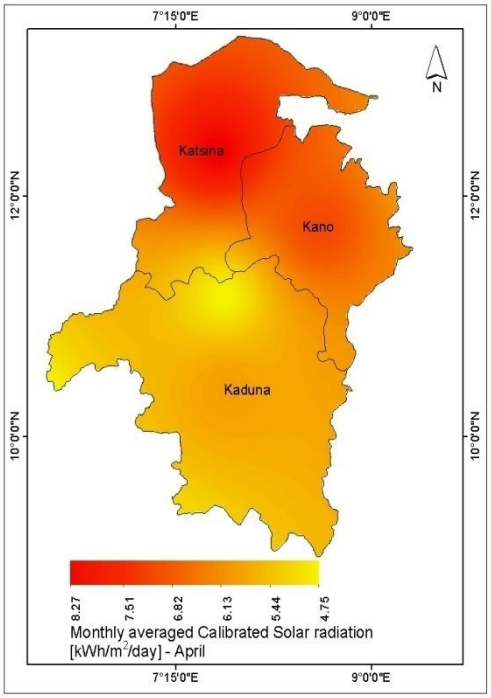


Fig. 4.7d: Month of April

Figure 4.7: Calibrated Monthly Mean Daily Values of Global Solar Radiation ($kWh/m^2/day$)

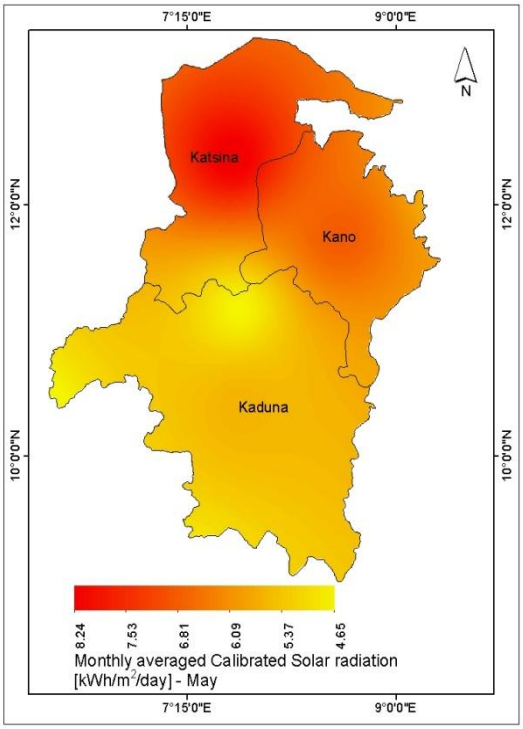


Fig. 4.7e: Month of May

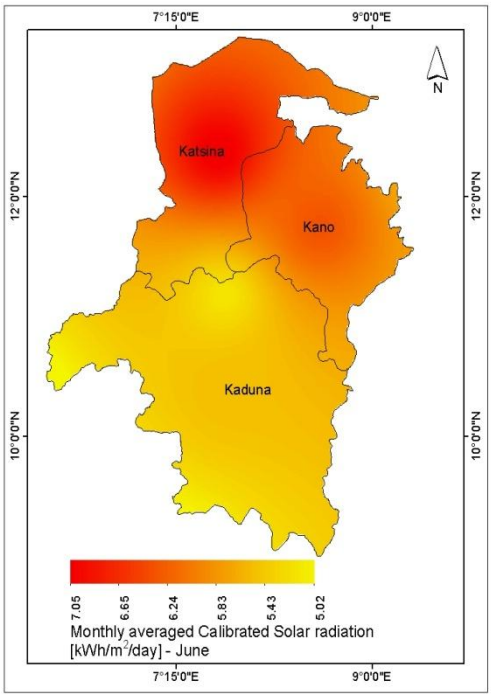


Fig. 4.7f: Month of June

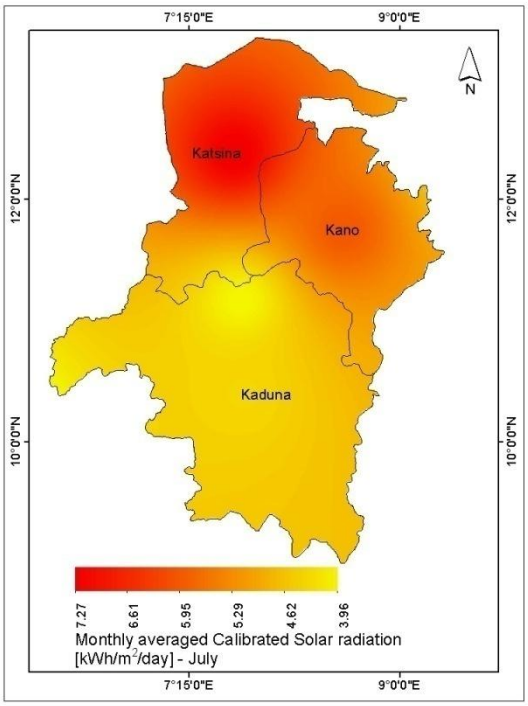


Fig. 4.7g: Month of July

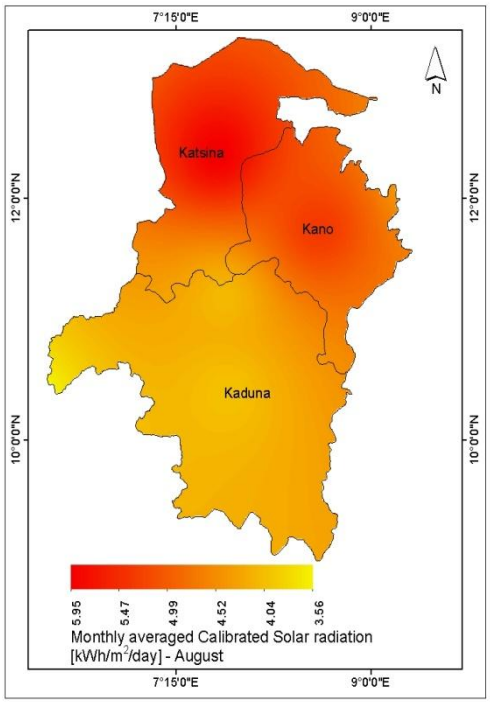
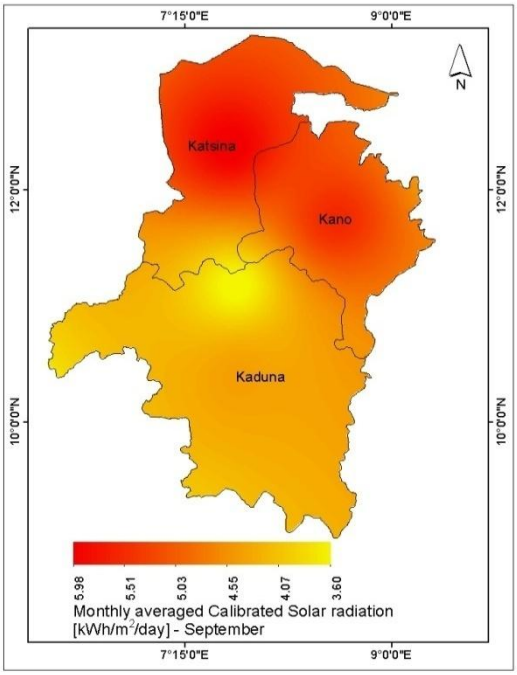


Fig. 4.7h: Month of August

Figure 4.7 (Continued): Calibrated Monthly Mean Daily Values of Global Solar Radiation (kWh/m^2/day)

Source: Fieldwork, 2016



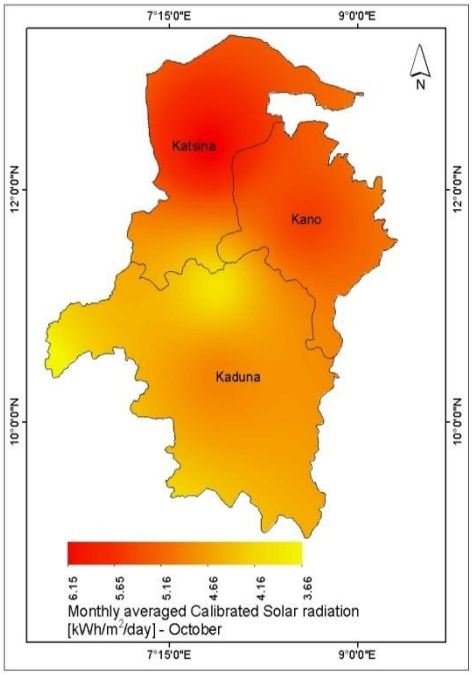
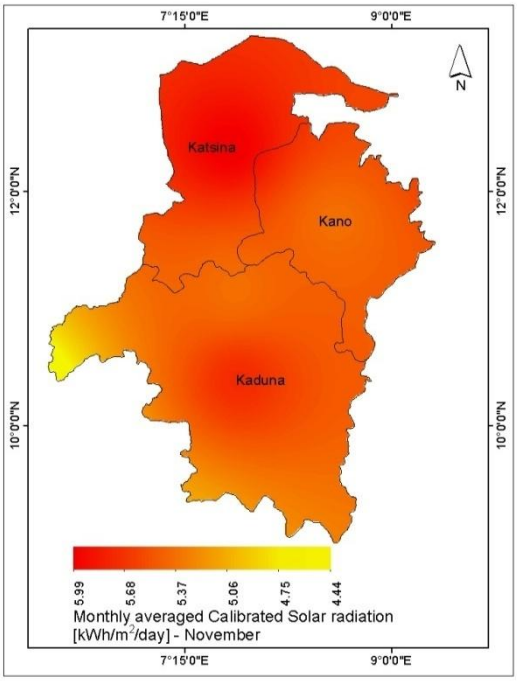


Fig. 4.7i: Month of September **Fig. 4.7j: Month of October**



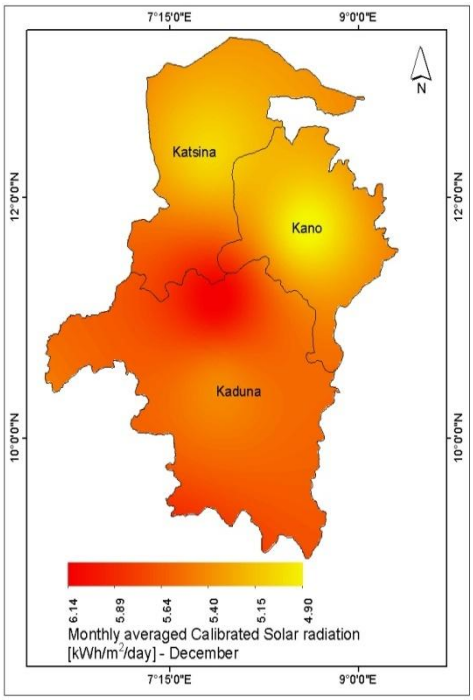


Fig. 4.7k: Month of November **Fig. 4.7l: Month of December**

Figure 4.7(Continued): Calibrated Monthly Mean Daily Values of Global Solar Radiation (kWh/m^2/day)

Source: Fieldwork, 2016.

The differences between the ground-measured and the satellite-derived solar radiation data were measured using the Mean Bias Error (MBE), the Mean Absolute Error (MAE), and the Root Mean Square Error (RMSE) as highlighted in section 2.4.6.4. The results are presented in Table 4.8 as the annual average for the whole study area. It can be seen that from Table 4.8 that an annual average MBE value of -0.45, RMSE of 0.46, and MAE of 0.57 were obtained.

Table 4.8: Temporal Validation of the Calibrated Solar Radiation Data

Month	MBE (%)	MAE (%)	RMSE (%)
Jan	0.28	0.28	0.26
Feb	-0.08	0.22	0.23
March	-0.47	0.47	0.45
Apr	-0.71	0.71	0.67
May	-0.65	0.65	0.48
Jun	0.059	0.22	0.19
Jul	-0.71	0.71	0.58
Aug	-0.66	0.67	0.44
Sep	-1.15	1.15	0.88
Oct	-1.08	1.08	0.83
Nov	-0.23	0.42	0.41
Dec	0.07	0.20	0.10
Annual Average	**-0.45**	**0.57**	**0.45**

Source: Fieldwork, 2016

It can also be observed from Table 4.8 that the annual average MBE value of -0.45% obtained in the validation process is lower than the average MBE value of -0.78% obtained by Osinowo *et al.* (2015) for Sudan savannah. This suggests that the result of the validation process used in this study is better. Likewise, the results of the validation process confirm the findings of Journée *et al.* (2011) which observed that merging both ground and satellite solar radiation data into a single estimate further improves the results by reducing the MBE value very close to zero.

The low annual average MAE value of 0.57% obtained by this study is also an indication of good agreement between the measured and calibrated solar radiation data. Also, the low annual average RMSE value of 0.46% obtained in this study is desirable as recommended by Iqbal (1983). The RMSE value of 0.46% is another confirmation of the reliability of the calibration method used in this study, in view of the fact that it is greatly lower than the average RMSE value of 1.28% obtained by Osinowo *et al.* (2015) for selected locations (Kano, Sokoto, Bauchi and Yola) in Sudan savannah. Likewise, it is lower than the RMSE values of Kaduna (0.72) and Katsina (0.52), but higher than that of Kano (0.24) as obtained by Abdulsalam (2014) in modelling insolation levels in Northwestern Nigeria. In addition, the RMSE value obtained in this study is lower than that obtained by Zaharaddeen and Baba (2016) where they got RMSE values of 0.827 and 1.119 for Kaduna and Katsina states respectively.

However, the performance of the method used in this study is not as good as that of AbdulAzeez (2011) which obtained an RMSE value of 0.003 while estimating global solar irradiation for Gusau town in Northwestern Nigeria. A better and more significant improvement with respect to RMSE test could be obtained if the number of the calibration and validation stations is increased.

In the temporal analysis, this study found slight overestimation with respect to the satellite data. It was also observed that the measured and the satellite solar radiation data agree better than the calibrated as illustrated in Tables 4.4-4.6. While the ground-measured is lower in most cases (especially in July, December and January), the calibrated is higher especially between April and June as shown in Tables 4.4-4.6. This can be attributed to clear sky conditions which do not hamper the satellite retrieval of solar radiation.

4.8 COMPARISON BETWEEN SOLAR RADIATIONS DERIVED FROM SINGLE AND MULTIPLE SOURCES

In this section, solar radiation data from four different sources were compared. The sources are: measured (obtained from ground measurement); NASA SSE (the satellite data used in this study); PVGIS (another satellite data); and calibrated (merged ground and satellite data) as shown in Table 4.4-4.6. This aimed at determining the level of correlation and variance between the various types of solar radiation data obtained from different sources.

Comparison of the various sources of solar radiation data shows good relationship between the calibrated solar radiation values and solar radiation values obtained from the other sources (measured, NASA SSE, PVGIS) as shown in Tables 4.4-4.6. But there are cases where some solar radiation values are comparatively higher or lower than the corresponding values from other sources of data.

The temporal analysis as illustrated in Figure 4.4 showed that in Katsina, the satellite insolation is consistently higher than the ground insolation throughout the year with the exception of December and January, where the ground insolation is higher than the satellite insolation. This could be attributed to the hazy condition of the atmosphere in the area during these months which affected the satellite retrievals of solar radiation in the area. Conversely, in Kano state, the satellite insolation is slightly lower than the ground insolation throughout the year with the exception of April, May and July where the reverse is the case as shown in Figure 4.5.

Comparing Katsina and Kano states, a greater oscillation is observed, where for instance in Kano state, the satellite insolation is lower than the ground insolation from January to March, then from August to December, and slightly higher in April, May and

July as shown in Figure 4.5. However, in Katsina state, the satellite insolation is higher than the ground insolation from February to August, and slightly lower in December and January as shown in Figure 4.4. However, in Kaduna state, a uniform pattern is observed where the satellite insolation is significantly lower than the ground insolation over the period of study as shown in Figure 4.6.

It is observed that there is positive correlation between the ground measurements and the satellite data, but the level of correlation is higher between the various types of satellite data. However, while the ground-measured insolation is lower in most cases, the calibrated insolation is higher especially between April and June.

Findings of this study support the assertion by Olomiyesan *et al.* (2015), that hybrid parameter based models predict global solar radiation on horizontal surface with a high degree of reliability in many locations across the world. This is applicable to many locations in Northwestern Nigeria, although, the results of this study indicate that there are exceptions in some parts of the study area.

4.9 SOLAR ENERGY POTENTIAL SITES IN PARTS OF NORTHWESTERN NIGERIA

There are some factors that determine the solar energy potentials in an area as mentioned in section 3.2.3.5. These include the intensity of insolation in an area, the topography, the slope and aspect of the area. Therefore, this section highlights the solar energy potential sites in the study area based on the above mentioned factors.

The solar energy potential sites in the study area are presented together in Figure 4.8 and separately in Figures 4.9 – 4.11. It is observed that many locations within the area

are potential sites for solar energy development though the magnitude of the potentials sites varies from one place to another.

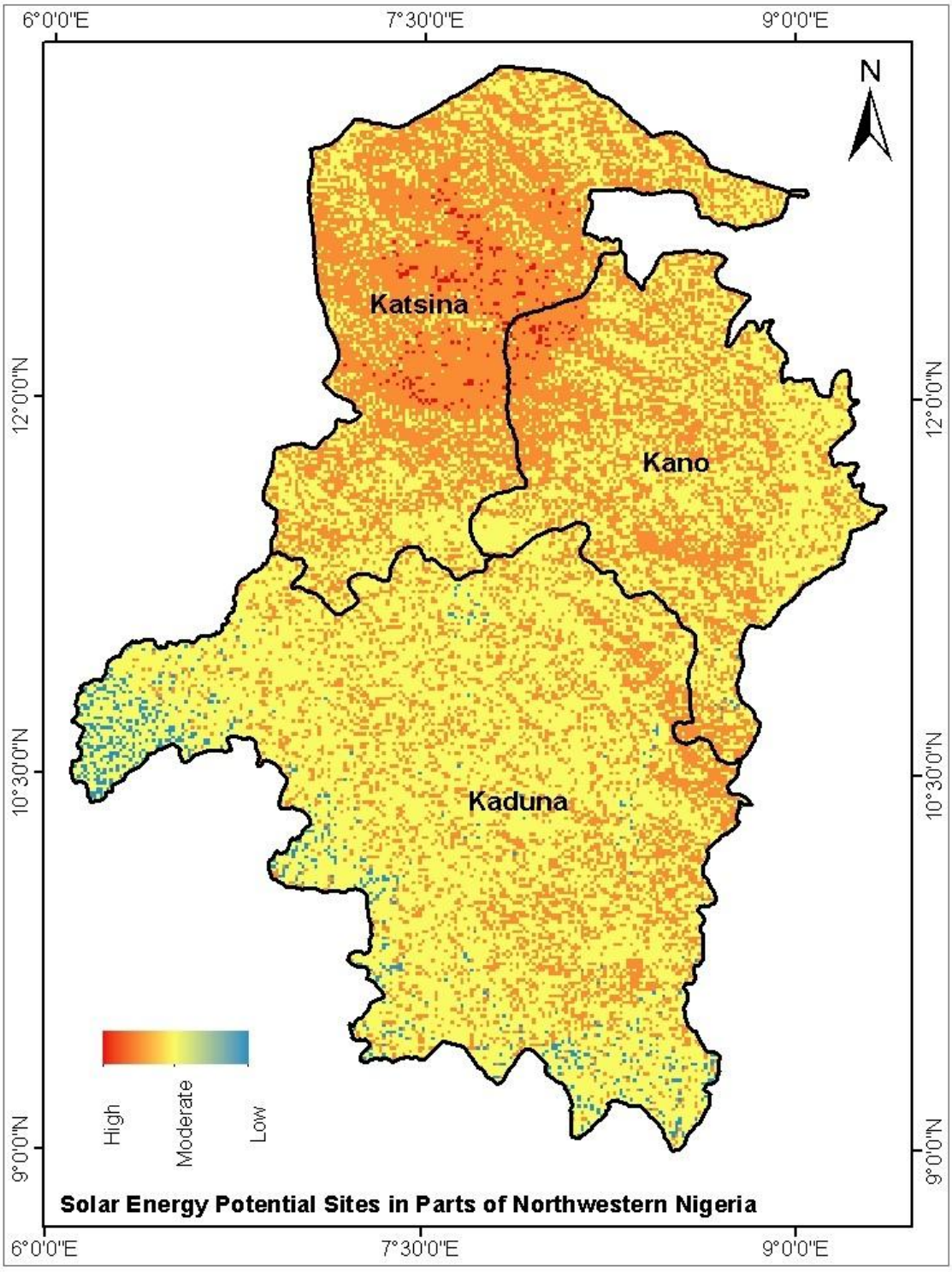


Figure 4.8: Solar Energy Potential Sites in Parts of Northwestern Nigeria

Source: Fieldwork, 2016

Figure 4.8 showed that there is high level of spatial variability in solar energy potentials within the study area. It can be seen from the Figure that a concentric zone of very high solar energy potential sites exist in the centre of Katsina state surrounded by a zone of high potentials; followed by a zone of moderate solar energy potentials in the northeastern and southeastern part of Katsina state. It can also be observed from Figure 4.8 that the level of solar energy potentials decreased with increasing distance from the city centre outwards.

Also, it can be observed from Figure 4.8 that the pattern of solar energy potentials in Kano is different from that of Katsina, where a region of high potential sites exists in the heart of the city interspaced by a narrow region of lower potentials. This is followed by a region of relatively very high potentials in the northwestern part of Kano bordering Katsina state, and a region of lower potentials towards the eastern part of Kano state. A further observation of Figure 4.8 indicates that solar energy potential sites in Kano are dispersed.

Furthermore, Figure 4.8 shows that there exist regions of high solar energy potentials in northeastern part of Kaduna state and another region of moderate potentials in northwestern and southwestern fringes of the state. In addition, areas of relatively high solar energy potentials are dispersed all over the state. Also, areas of lower solar energy potentials are found in various parts of Kaduna state. However, areas of vey low potentials are concentrated in the northeastern and sounthern fringes of the state. It can also be seen from Figure 4.8 that the northeastern part of Kaduna and the neighbouring region of Kano have similar solar energy potentials. Generally, it can be observed from the Figure that the boundaries of the three states share similar and in some cases the same pattern of energy potentials.

4.9.1 Solar Energy Potential Sites in Katsina State

The spatial variation in solar energy potentials in Katsina state is highlighted below. Figure 4.9 shows that areas with very high solar energy potentials in Katsina state are: Kankia, Charanchi, Dutsinma, Kankara, Musawa and Rimi Local Government Areas (LGAs). These are the most ideal areas for exploiting solar energy in the state. Areas with high potentials are: Katsina, Batagarawa, Batsari, Kurfi, Sandamu, Kusada, Ingawa, Bindawa, Matazu and Mani LGAs.

Areas with moderate solar energy potentials are: Daura, Safana and Kaita, Malumfashi and Danmusa Local Government Areas. Areas with low potentials are: Jibia, Mashi, Mai'adua, Dusti, Baure, Zango, Faskari, Bakori, Kafur, Sabuwa, Dandume, Funtua and Danja LGAs.

One of the key factors required in establishing the actual potential sites for the installation of Photovoltaic and Concentrating Solar Power technology is that the direct and horizontal solar radiation at the site should be ≥5 kWh/m^2/day(USFS, 2005). Based on this, many places within Katsina state are potential sites for harnessing solar energy.

4.9.1.1 Available solar power in Katsina State

Knowledge of the average solar radiation received in an area and the cross sectional area extent is required in order to estimate the available solar power in the area (the average power intercepted at any time). This is illustrated below:

Since Katsina state's cross sectional area =24,192 km^2;

and the average solar radiation in Katsina= 6.7 kWh/m^2/day;

thus, the average power intercepted at any time in the state =

Cross sectional area X the average power intercepted at any time (Electropaedia, 2016)

=24,192 X 6.7 = 162086.4 X 10^6= 162.086 X 10^9 kWh = 162.086 X 10^6 MWh

= 13,936,887.36 tonne of oil equivalent.

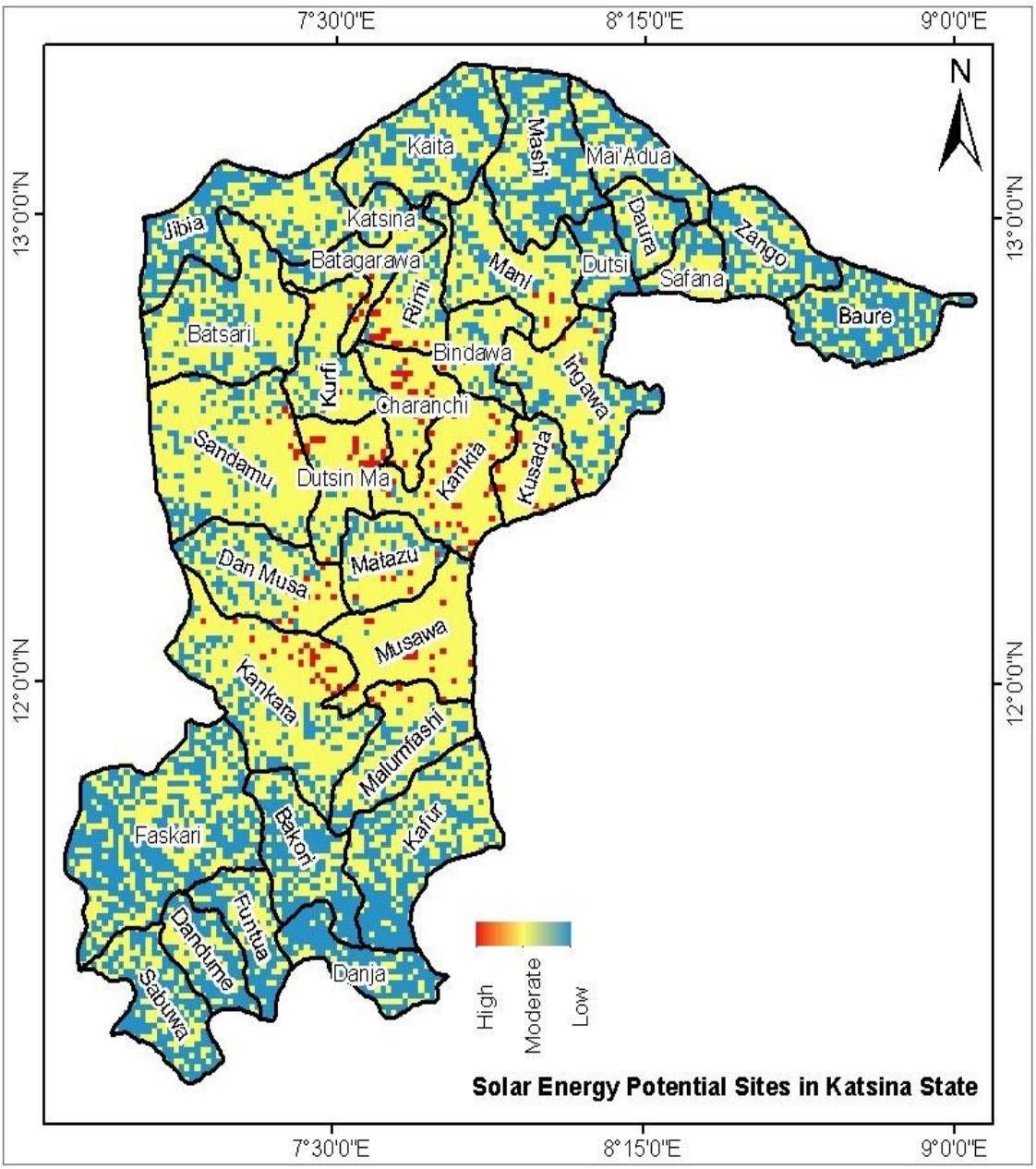


Figure 4.9: Solar Energy Potential Sites in Katsina State

Source: Fieldwork, 2016

4.9.2 Solar Energy Potential Sites in Kano State

The spatial variation in solar energy potentials in Kano state is highlighted below. Figure 4.10 shows that areas with very high solar energy potentials in Kano state are: Tsanyawa, Shanono and Gwarzo Local Government Areas (LGAs). These are the best areas for harvesting solar energy in the state.

Areas with high potentials are: Dala, Kumbotso, Rimin Gado, Kabo, Dawakin Kudu, Karaye, Bebeji, Bichi, Rano, Bagwai, Tudun Wada, Kura, Kiru, Wudil, Garko, Sumaila and Doguwa LGAs. Areas with moderate potentials are: Kunchi, Makoda, Danbatta, Minjibir, Gabasawa, Gezawa, Warawa, Ajingi, Gaya, Albasu, Madobi, Kibiya, Garun Mallam, Bunkure, Takai, and Rogo LGAs.

4.9.2.1 Available solar power in Kano State

Since Kano state's cross sectional area =20,131 km^2;

and the average solar radiation in Kano = 5.9 $kWh/m^2/day$;

thus, the average power intercepted at any time in the state =20,131 X5.9

= 118772.910^6 = 118.773 X 10^9 kWh = 118.773 X 10^6 MWh

= 10,212,639.725 tonne of oil equivalent

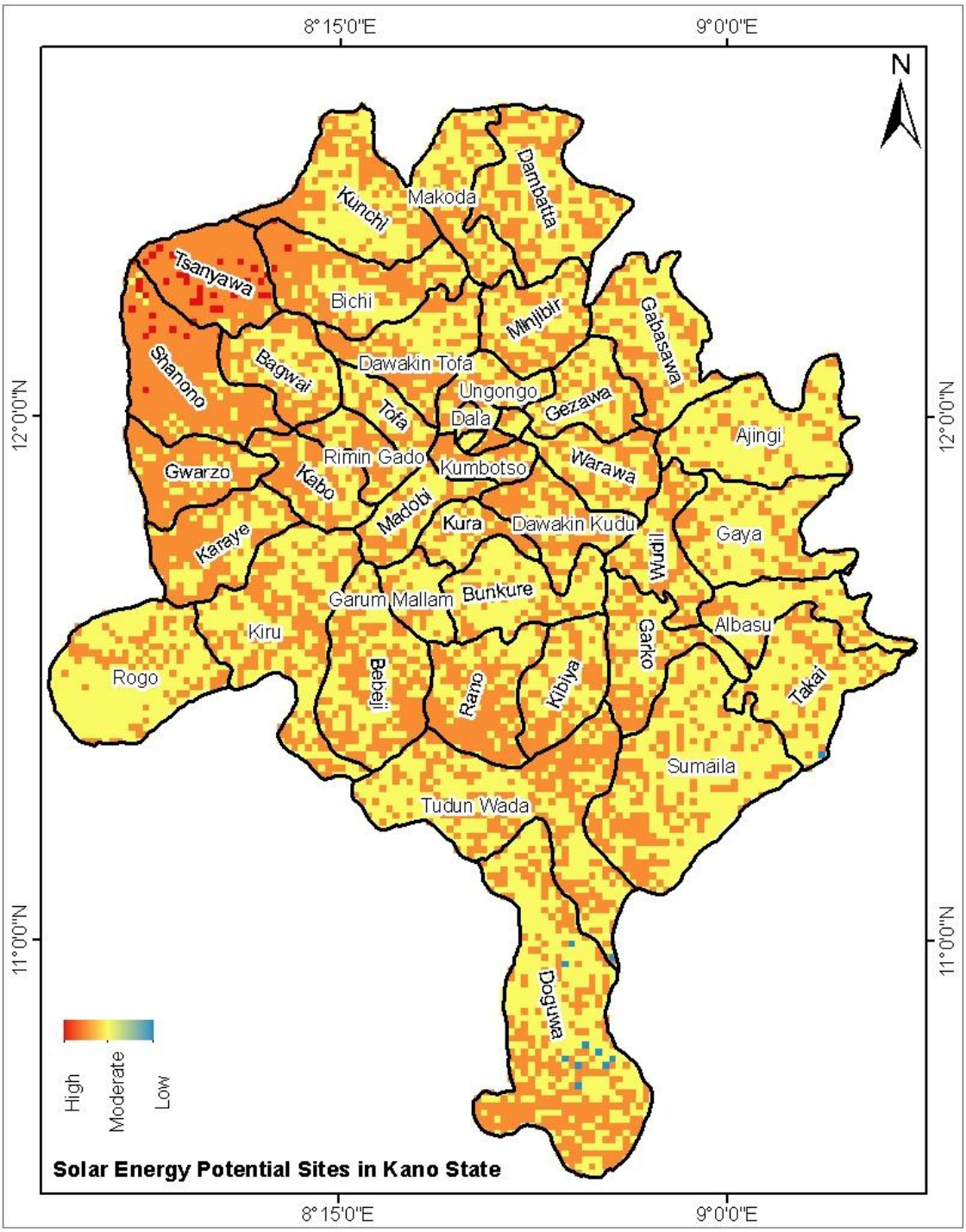


Figure 4.10: Solar Energy Potential Sites in Kano State

Source: Fieldwork, 2016

4.9.3 Solar Energy Potential Sites in Kaduna State

Figure 4.11 shows that areas with very high solar energy potentials in Kaduna state are: Kubau, Lere, Zangon Kataf, Kauru and Ikara Local Government Areas. These are the most suitable areas for harvesting solar energy in the state.

Areas with high solar energy potentials are: Giwa, Igabi, Kaduna South, Kaduna North, Zaria, Soba, Kajuru, Kachia, Kudan, Kaura, Makarfi and Jaba LGAs. Areas with moderate solar energy potentials are: Birnin Gwari, Chikun, Kagarko, Jama'a and Sanga LGAs.

4.9.3.1 Available solar power in Kaduna State

Since Katsina state's cross sectional area =46,053km^2;

and the average solar radiation in Kaduna = 5.1kWh/m^2/day;

thus, the average power intercepted at any time in the state =46,053X5.1

= 234870.3X 10^6= 234.870 X 10^9 kWh = 234.870 X 10^6 MWh

= 20,195,184.867 tonne of oil equivalent

4.10 ESTIMATION OF POTENTIAL SOLAR ELECTRICITY GENERATION

The PVGIS (2016) is one of the major sources of solar radiation data. It has developed Photovoltaic GIS (PVGIS) databases for Europe and Africa. These data are based on calculations from Meteosat satellite images performed by Satellite Application Facility on Climate Monitoring (CM-SAF). The PVGIS has also provided an online PV performance calculator to help give users an idea of the potential of PV as an energy source. It is used in order to measure the performance of Grid-connected PV in an area.

The PVGIS assumes a constant Peak power of 1000W of solar irradiation per square meter in the plane of the array at an array temperature of 25°C. The Estimated system losses were given a default value of 14%. For fixed (non-tracking) systems, the way the modules are mounted will have an influence on the temperature of the module, which in turn affects the efficiency (PVGIS, 2016) of the system.

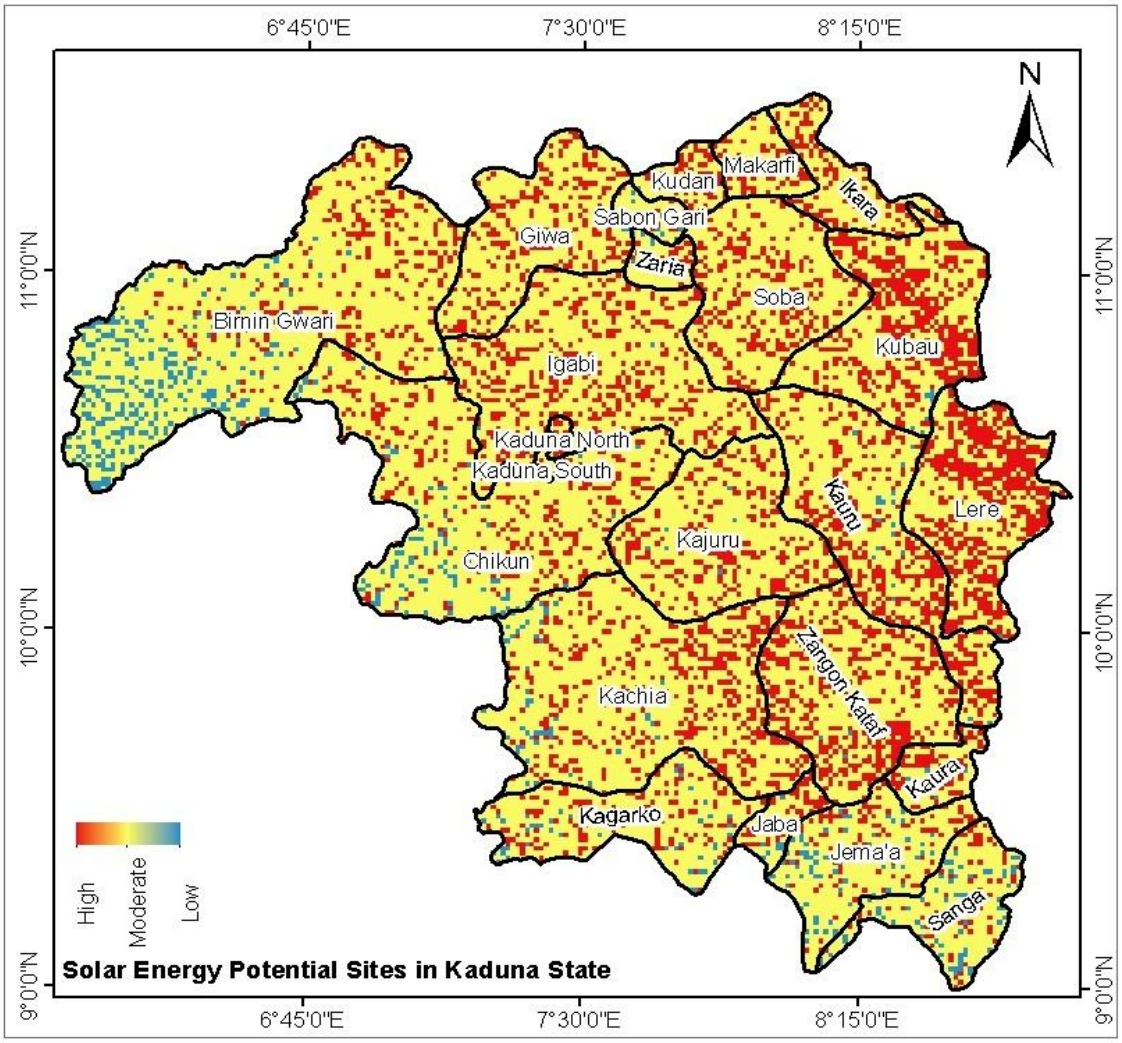


Figure 4.11: Solar Energy Potential Sites in Kaduna State

Source: Fieldwork, 2016

In this section (4.8), PVGIS was used in order to measure the potential of PV in the electricity generation in the study area. Tables 4.9 and 4.10 present the average daily and monthly solar electricity production respectively in the study area, which indicates

that there is variation in the average daily electricity production across the three states. But there exists a good relationship between Kano and Katsina states as can be seen from the daily average in Table 4.9 and monthly average in Table 4.10. In addition, the highest average daily electricity production of 5.04kWh is expected in Kano and Katsina states during the month of March, while the lowest average daily electricity production of 3.16kWh is expected in Kaduna state during the month of August as shown in Table 4.9.

Overall, lower average daily electricity production is observed in August in all the three states as can be seen in Table 4.9. Therefore, lower average monthly electricity production is expected in August in all the three states as can be observed from Table 4.10. Generally, Tables 4.9 and 4.10 showed that the potential of PV system (whether it is free-standing or building-integrated) in electricity generation is high in the study area. The free-standing can be used to provide electricity in a relatively large scale while the building-integrated can be used to supply electricity to individual houses.

Table 4.9: Average Daily Solar Electricity Production in the Study Area

Month	Ed(kWh)		
	Kaduna	Kano	Katsina
Jan	4.34	4.23	4.15
Feb	4.55	4.49	4.47
March	4.99	5.04	5.04
April	4.40	4.61	4.56
May	4.29	4.46	4.48
June	3.97	4.34	4.39
July	3.48	4.06	4.11
August	3.16	3.86	3.85
Sept	3.80	4.23	4.26
Oct	4.13	4.33	4.28
Nov	4.31	4.22	4.16
Dec	4.20	4.07	4.01
Annual average	**4.13**	**4.33**	**4.31**

Ed: Average daily electricity production from the given system (kWh)
Source: Adapted from PVGIS (2016).

Table 4.10: Average Monthly Solar Electricity Production in the Study Area

Month	Em(kWh)		
	Kaduna	Kano	Katsina
Jan	134	131	129
Feb	127	126	125
March	155	156	156
April	132	138	137
May	133	138	139
June	119	130	132
July	108	126	127
August	97.9	120	119
Sept	114	127	128
Oct	128	134	133
Nov	129	127	125
Dec	130	126	124
Annual average	**126**	**132**	**131**

Em: Average monthly electricity production from the given system (kWh)
Source: Adapted from PVGIS (2016).

4.11 ECONOMICS OF SOLAR ENERGY

The development of solar energy as an alternative source of electricity has a lot of social and economic benefits. These include providing renewable energy that is environmentally friendly to mitigate climate change, increasing the energy supply mix of Nigeria to attain energy security, reviving industrialisation and other economic activities leading to employment generation. However, the development of solar energy technology is only feasible if there are suitable locations for harnessing solar radiation. Findings of this study as highlighted in Section 4.9 revealed that there are many suitable locations in all the three states that receive an annual average global solar radiation of $\geq$5kWh/m^2/day. Therefore, these locations are considered ideal for flat plate photovoltaic plants or concentrated solar power.

The advantage of harnessing solar energy in this area is minimizing the environmental costs in terms of cutting down greenhouse gas emission and reduction of hydrocarbon

pollution. This is particularly significant considering the large population size and the increasing economic activities in the study area.

Besides, in distant rural areas of Katsina, Kano, and Kaduna states that are not connected to the national grid, rooftop or building-integrated solar PV can be provided and the cost can be subsidized since the demand is high and the source of supply is renewable. Alternatively, Concentrating Solar Powered technology can be provided for a whole local government area in each of the three states to provide affordable and more sustainable source of electricity than the use of petrol/diesel generators which release greenhouse gases that are harmful to the environment.

The use of solar power as an alternative energy source for household activities would significantly increase household savings by cutting down expenditure on household energy. Also, it will assist in saving time spent on energy sourcing as well reducing health risks from hydrocarbon-based energy sources. It will also create job opportunities, boost small scale industries and increase non-agricultural activities in the area.

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.1 INTRODUCTION

This concluding chapter presented the summary of findings,conclusion, contributions to gap in knowledge, limitations of the research, recommendations and recommendations for further studies.

5.2 SUMMARY

This study applied geospatial techniques to analyse solar energy potentials in Kaduna, Kano and Katsina states of Northwestern Nigeria. Spatial interpolation, weighted overlay and analytic hierarchy process were employed to produce maps of solar radiation in the study area using ground measurements. Based on these measurements, the minimum insolation values recorded in Kaduna, Katsina and Kano states respectively were 4.92kWh/m^2/day in August, 5.41kWh/m^2/day in July and December, and 5.63kWh/m^2/day in January. In addition, the maximum insolation values recorded in Kaduna, Kano and Katsina states were 7.00kWh/m^2/day, 6.99kWh/m^2/day and 6.40kWh/m^2/day respectively. These maxima are found between March and May all over the study area. Therefore, the optimum times for harnessing solar energy in the area are the months of March, April and May.

Insolation maps were also produced in a GIS environment using satellite data. Based on these data, the maximum insolation values recorded in Katsina, Kano and Kaduna states respectively, were found to be 7.21kWh/m^2/dayin April, 6.96kWh/m^2/dayin April, and 6.32kWh/m^2/dayin March. A peculiar pattern was observed in both Kano and Katsina states where insolation remains consistently high between February and June, while the

insolation remains high during the months of February, March, April and November in Kaduna state. Based on the satellite data, the minimum insolation received in Kaduna, Katsina, and Kano states respectively, were found to be 4.47kWh/m^2/day in August, 5.23kWh/m^2/day and 5.27kWh/m^2/dayin July.

Then, the two sources of solar radiation data were compared. Based on the ground measurement, the maximum insolation value of 7.00kWh/m^2/day was recorded in Kaduna during the month of March, while the maximum value of 7.21kWh/m^2/day was recorded in Katsina in the month of April based on the corresponding satellite data. Based on the two sources, the minimum insolation value of 4.92kWh/m^2/daywas obtained from the ground measurement and the corresponding value of 4.47kWh/m^2/daywas obtained from the satellite data; these minima were both recorded in Kaduna during the month of August. It was also found that the maximum differences between ground and satellite insolation were recorded at lower latitudes while the minimum differences were recorded at higher latitudes. These differences decreased with increasing latitude.

A careful comparison between the two sources of solar radiation data showed a positive correlation, which implies a high level of agreement between them, except that there are few cases where the measured solar radiation value is relatively lower than the corresponding satellite value and vice versa.

This study merged satellite-derived solar radiation data with ground-measured solar radiation data for the analysis of solar energy potentials in the study area. The calibration method was validated using statistics. An average MBE value of -0.45%, RMSE of 0.46%, and MAE of 0.57% were obtained. These values indicate a good performance of the merging method used in this study.

Although most locations in Northwestern Nigeria receive high amount of solar radiation, there is high level of spatial variability in solar energy potentials within the study area. Areas of very high, high and moderate solar energy potentials were identified in all the three states. Also, the amounts of exploitable solar power in each of the three states were determined in this study.

Areas with very high solar energy potentials in Kano state are: Tsanyawa, Shanono and Gwarzo Local Government Areas. Areas with very high solar energy potentials in Kaduna state are: Kubau, Lere, ZangonKataf, Kauru and Ikara Local Government Areas. Areas with very high solar energy potentials in Katsina state are: Kankia, Charanchi, Dutsinma, Kankara, Musawa and Rimi Local Government Areas. Besides, areas of high and moderate solar energy potentials in all the three states were identified. Therefore, many places within the study area as shown in the maps are potential sites for harnessing solar energy.

The available solar power in Katsina State is 162.086 X 10^6 MWh; in Kano State it is 118.773 X 10^6 MWh; while in Kaduna State, it is 234.870 X 10^6 MWh. Kaduna has higher exploitable solar power than the other two states owing to its cross sectional area.

5.3 CONCLUSION

Geospatial technique is an efficient method of solar radiation mapping which was used in analysing the solar energy potentials in the study area. The solar radiation maps produced in this study were found to be better than the climatic zone classification and iso-radiation mapping used previously to analyse solar energy potentials in Nigeria.

A positive correlation was found between the two types of solar radiation data used in this study. Therefore, in the absence of ground-based measurement, satellite data can be used reliably to map and understand the pattern of solar radiation in an area.

Merging of ground-measured with satellite-derived solar radiation data has improved the solar radiation information in the study area. Hence, this provides another alternative method which can be used to analyse the solar energy potentials of an area. In addition, a good relationship between the calibrated solar radiation data and the radiation data from the other sources (ground, NASA SSE, PVGIS) was observed.

Ground-measured and satellite-derived solar radiation data in the study area have both similarities and differences. Based on the two sources of data, minimum insolation values were recorded in the months of July, August, December and January; while maximum insolation values were recorded between the months of March and May throughout the study area. Therefore, the months of March, April and May provide the best periods for harnessing solar energy potentials in the area.

Analysis of the differences between the mean monthly solar radiation data from the ground measurement and satellite data showed that the highest differences were recorded at lower latitude while the lowest differences were recorded at higher latitude. Spatially, differences between the monthly mean measured solar radiation data and the corresponding satellite data decrease with increasing latitude.

There is high level of spatial variability in solar energy potentials across the whole area of study. There are areas of very high, high and moderate solar energy potentials in Katsina, Kano and Kaduna states of Northwestern Nigeria. It can therefore be established that there is enormous exploitable solar power in these states, which can be used to address the problem of power supply in the region.

Although the methods applied in this study have been used in other parts of the world, it is pertinent to mention that these methods have not been commonly used in Nigeria and as such there could be room for modifications and improvement.

This study emphasized that the Northwestern Nigeria is a potential area for the generation of solar energy, which can be used to provide electricity for domestic and industrial use. This will have multiplier effect on job creation leading to human capital development and economic sustainability in the region.

5.4 CONTRIBUTIONS TO GAP IN KNOWLEDGE

This study has contributed to the literature on Energy Geographies, and specifically on the application of geospatial techniques in the analysis of renewable energy sources by producing the atlas of solar radiation in Kano, Kaduna and Katsina states using geographical visualisation.

The application of geospatial techniques to identify solar energy potential sites in the study area has provided important knowledge that is required to maximally harness solar energy in the area. Therefore, geospatial approach has proven to be an alternative efficient method for the analysis of solar energy potentials.

This study has shown the possibility of merging ground-measured solar radiation data with satellite-derived solar radiation data in order to derive solar energy information for the study area. This is considered as a valid contribution to the existing literature on the current method of integrating ground-measured solar radiation data with satellite-derived solar radiation data, which has not been applied in the analysis of solar energy potentials in Northwestern Nigeria.

In addition, the amount of exploitable solar power in each of Kano, Kaduna and Katsina states has been determined in this study.

5.5 LIMITATIONS OF THE RESEARCH

Although the objectives of this study have been achieved, there are limitations which are outlined below:

a) This study is constrained by lack of ground measurements in most locations, which is the reason why only the few available stations were used for the calibration and validation processes.
b) The satellite data used in this study is of lower resolution compared to other satellite data with higher resolution.
c) Lack of ground-measured solar radiation data in many locations is responsible for the generalization in many cases found in this study.

5.6 RECOMMENDATIONS

The findings of this study have demonstrated the capability of geospatial techniques in the analysis of solar energy potentials. Based on this, the followings are recommended:

1) Geospatial techniques should be used to produce a more comprehensive solar radiation atlas of Kano, Kaduna and Katsina states covering all the local government areas in the three states, with a view to reveal the solar energy potentials at a finer scale.
2) Satellite and calibrated solar radiation data are two alternatives, which should be used to complement or evaluate ground measurement of solar radiation that can be used to analyse the solar energy potentials in an area. The satellite and the

calibrated solar radiation data could also be used in other climatological studies to help our understanding of the atmospheric systems.

3) The optimum periods for harnessing solar energy in the area (between March and May) should be used to harness and conserve solar power, and during the periods of lower potentials such as July, August, December and January, other sources of energy can be relied upon. Therefore, there is the need to diversify the energy mix of the area.
4) Areas with very high solar energy potentials should be used in siting of solar farms and Concentrating Solar Power plants in order to maximize the available solar energy potentials in the region. Nevertheless, building-integrated or rooftop solar panels can be used in areas with moderate solar energy potentials.

5.7 RECOMMENDATIONS FOR FURTHER STUDIES

a) A study covering the local government areas in Kano, Kaduna and Katsina states is recommended in order to test the merging of ground-based measurement with satellite insolation data using larger number of the calibration and the validation stations.
b) This study is based on NASA SSE satellite database which is of lower resolution than other emerging satellite solar radiation databases. There is the need to explore the use of satellite data with higher resolution in further studies.
c) The GIS solar radiation model (*r.Sun*) should also be explored as an alternative method of solar energy modelling in the study area.

REFERENCES

Abdel Wahab, M., El-Metwally, M., Hassan, R., Lefevre, M., Oumbe, A. and Wald, L. (2009). Assessing surface solar irradiance in Northern Africa desert climate and its long-term variations from Meteosat images. *International Journal of Remote Sensing*, 31(01): 261-280.

AbdulAzeez, M. A. (2011). Artificial Neural Network Estimation of Global Solar Radiation Using Meteorological Parameters in Gusau, Nigeria. *Archives of Applied Science Research*, 3(2): 586-595.

Abdulsalam, D., Mbamali, I., Usman, M. and Bala, K. (2014). Insolation Levels Using Temperature Model for Sustainable Application of Photovoltaic Technology in Some Selected Locations of Nigeria. *Journal of Energy Technologies and Policy*, 4(1): 19-28.

Adefolalu, D. O. (2007). "Climate change and economic sustainability in Nigeria", Paper presented at the *International Conference on Climate Change and Economic Sustainability* held at Nnamdi Azikiwe University, Enugu, Nigeria. June, 2007, 1-12.

Akpabio, L.E. and Etuk, S.E. (2003). Relationship between Global Solar Radiation and Sunshine Duration for Onne, Nigeria. *Turk J Phys*, 27, 16-167.

Akpabio, L.E., Udo, S.O. and Etuk, S.E. (2004). Empirical Correlations of Global Solar Radiation with Meteorological data for Onne, Nigeria. *Turk J Phys*, 28, 205-212.

Aksakal, A. and Rehman, S. (1999). Global solar radiation in Northeastern Saudi Arabia. *Renewable Energy*, 17, 461-472.

Ali, M.S., Rahman, H. and Mazumder, R. K. (2008). Estimation of solar radiation in Bangladesh from NOAA AVHRR time series digital images, *In Proceeding of Asian Conference on Remote Sensing*, Colombo, Srilanka.

Amadi, S. O., Udo, S. O. and Ewona, I. O. (2014). Trends and variations of monthly mean minimum and maximum temperature data over Nigeria for the period 1950-2012. *International Journal of Pure and Applied Physics*, 2(4): 1-27.

Amillo, A. G., Huld, T. and Müller, R. (2014). A New Database of Global and Direct Solar Radiation Using the Eastern Meteosat Satellite, Models and Validation. *Remote Sens.*, 6, 8165-8189.

Angström, A.S. (1924): Solar and Terrestrial Radiation, *Meteorological Society*, 50, 121-126.

Angela, K. Taddeo, S. and James, M. (2011). Predicting Global Solar Radiation Using an Artificial Neural Network Single-Parameter, *Model Advances in Artificial Neural Systems*, 2011, 1-7.

Antonanzas-Torres, F., Cañizares, F. and Perpiñán, O. (2012). Comparative assessment of global irradiation from a satellite estimate model (CM SAF) and on-ground measurements (SIAR): a Spanish case study *Submitted to Renewable and Sustainable Energy Reviews*.

Audu, M. O., Isikwue, B. C. and Eweh, J. E. (2014). Estimation of Seasonal and Annual Albedo of the Earth's Atmosphere over Kano, Nigeria. *IOSR Journal of Applied Physics*, 6(5), I: 56-62.

Asakereh, A., Omid, M., Alimardani, R. and Sarmadian, F. (2014). Developing a GIS-based Fuzzy AHP Model for Selecting Solar Energy Sites in Shodirwan Region in Iran. *International Journal of Advanced Science and Technology*, 68, 37-48.

Ati, O. F., Iguisi, E. O. and Mohammed, S. O. (2010). Effects of El Nino/Southern Oscillation (ENSO) on rainfall characteristics in Katsina, Nigeria. *The African Journal of Agricultural Research*, 5(23): 3273-3278.

Augustine, C. and Nnabuchi, M. N. (2009). Relationship between global solar radiation and Sunshine hours for Calabar, Port Harcourt and Enugu, Nigeria, *International Journal of Physical Sciences*, 4(4): 182-188.

Aust, A. (2014). Energy: Nonrenewable and Renewable Energy Resources. Retrieved on 19/01/2017 from KQED https://ww2.kqed.org/quest/2014/02/13/nonrenewable-and-renewable-energy-resources-2/

Australian Government Bureau of Meteorology (2013). *Solar Radiation Definitions.* Retrieved on 27/08/2013 from http://www.bom.gov.au/climate/austmaps/solar-radiation-glossary.shtml#globalirradiance

Baumgardner, M. F., Sylva, L. F., Biehl, L. L., Stoner, E. R. (1985). Reflectance Properties of Soils. *Adv. Agron.*, 38, 1–44.

Basir, R., Aziz, N., Ahmad, S.S. and Wahid, A. (2013). Satellite remote sensing for identification of solar potential sites in Pakistan. *International Journal of Basic and Applied Sciences*, 2(2): 200-209.

Becker, S. (2001). Calculation of direct solar and diffuse radiation in Israel. *Int. J. Climatol*., 21, 1561-1576.

Besharat, F., Dehghan, A. A. and Faghih, A. R. (2013). Emperical Models for estimating global solar radiation: a review and case study. *Renewable and Sutainable Energy Reviews*, 21: 798-21.

Bilal, A. A., Rustom, M. and Mousa, S. M. ((1999). Multi-criteria selection of electric power plants using analytical hierarchy process. *Electric Power Systems Research*, 52, 29–35.

Bindi, M. and Miglietta, F. (1991). Estimating daily global radiation from air temperature and rainfall measurements. *Clim. Res.*, 1, 117-124.

Black, J. N., Bonython, C. W. and Prescett, J. A. (1954). Solar radiation and duration of Sunshine, *Q.J.R Metero. Soc.*, 80, 231-235.

Bois, B., Wald, L., Pieri, Ph., Van leeuwen, C., Commagnac, L., Chery, Ph., Christen, M., Gaudillère, J.-P.and Saur, É (2008). Estimating Spatial and Temporal Variations in Solar Radiation within Bordeaux Winegrowing Region Using Remotely Sensed Data. *J. Int. Sci. VigneVin*, 42(1): 15-25.

Burrough, P. A. and McDonnell, R. (1998). *Principles of Geographical InformationSystems*. Oxford University Press, Oxford.

Camfer University (2017). *Remote Sensing & Image Analysis*. Camfer University of Carlifornia at Berkeley. Retrieved on 26/01/2017 from http://nature.berkeley.edu/~penggong/textbook/chapter2/html/sect24.htm

Campillo, C., Fortes, R. and Prieto, M. d. H. (2012). *Solar Radiation Effect on Crop Production, Solar Radiation*, Prof. Elisha B. Babatunde (Ed.), ISBN: 978-953-51-0384-4, InTech, Retrieved on 25/5/2017 from: http://www.intechopen.com/books/solar-radiation/solar-radiation-effect-on-crop-production

Chai, T. and Draxler, R. R. (2014). Root mean square error (RMSE) or mean absolute error (MAE)? – Arguments against avoiding RMSE in the literature. *Geosci. Model Dev.*, 7, 1247-1250.

Chegaar, M., Lamri, A. and Chibani, A. (1998). Estimating Global Solar Radiation Using Sunshine Hours. *Rev. Energ. Ren. : Physique Energétique*, 7-11.

Chiemeka, I. U. (2008). Estimation of solar radiation at Uturu, Nigeria. *International Journal of Physical Sciences*, 3(5): 126-130.

Citizendium (2017). Analytic Hierarchy Process. Retrieved on 06/04/2017 from http://en.citizendium.org/wiki/Analytic_Hierarchy_Process

College of Education-University of Illinois (2016). *Scatter plots*. MSTE Office for Mathematics, Science, and Technology Education, College of Education University of Illinois. Retrieved on 25/01/2017 from http://mste.illinois.edu/courses/ci330ms/youtsey/scatterinfo.html

Dagestad, K-F. (2005). *Estimating global radiation at ground level from satellite images*. University of Bergen.

De Smith, M. J., Goodchild, M. F. and Longley, P. A. (2015). *Geospatial Analysis: A Comprehensive Guide to Principles, Techniques and Software Tools*. Fifth Edition.TheWinchelsea Press, Winchelsea, UK.

Diabaté, L., Blanc Ph., and Wald, L. (2004). Solar Radiation Climate in Africa *Solar Energy*, 76, 733-744.

Dobos, E. (2003). Albedo. In *Encyclopedia of Soil Science* by Marcel Dekker, Inc.

Effat, H. A. (2016). Mapping Solar Energy Potential Zones, using SRTM and Spatial Analysis, Application in Lake Nasser Region, Egypt. *International Journal of Sustainable Land Use and Urban Planning*, 3(1): 1-14.

Electropaedia (2016). *Solar Power (Technology and Economics).* Retrieved on 16/01/2016 from http://www.mpoweruk.com/solar_power.htm

Eludoyin, O. M. (2011). Air Temperature and Relative Humidity Areal Distribution over Nigeria. *Ife Research Publications in Geography*, 10(1):134-145.

Environmental Systems Research Institute - ESRI (2016). *ArcGIS Desktop Help: "How Inverse Distance Weighted Interpolation Works"*. ESRI, Inc., USA.

Ewepu, G. And Ejoh, E. (2016).*Solar power development: Investors commit $2.5bn into 14 projects*. Vanguard News of Thursday July 22, 2016.

Ezenekwe, L. N., Ezemonye M. N. and Emeribe, C. N. (2013). Modelling the temporal patterns of short wave and long wave radiations over Sudan and Sahel Savannah. *Sacha Journal of Environmental Studies*, 3(1): 34-44.

Falayi, E.O., Rabiu, A.B. and Teliat, R.O. (2011). Correlations to estimate monthly mean of daily diffuse solar radiation in some selected cities in Nigeria. *Advances in Applied Science Research*, 2(4): 480-490.

Falayi, E. O. and Rabiu, A. B. (2012). Solar Radiation Models and Information for Renewable Energy Applications, *Solar Radiation*, Prof. Elisha B. Babatunde (Ed.): InTech, Retrieved from: http://www.intechopen.com/books/solar-radiation/solar-radiation-models-and information-for-renewableenergy applications

Falodun, S. E. (2015). Analysis of Global Solar Radiation in Some Selected Cities across Nigeria. *Nigerian Journal of Solar Energy*, 26, 51-57.

Federal Fertilizer Department. (2012). *Fertilizer Use and Management Practices for Nigeria*. Federal Fertilizer Department, Federal Ministry of Agriculture and Rural Development, Abuja, Nigeria, pp: 1-215.

Fisher, N. I., Lewis, T. and Embleton, B. J. J. (1987). Statistical Analysis of Spherical Data. Cambridge University Press, UK.

Flores H. and Baldasano J.M. (2001). Solar Radiation Mapping from NOAA AVHRR Data in Catalonia (Spain). *Journal of Applied Meteorology*, 40(11): 1821-1834.

Freedman, D. A. (2005). *Statistical Models: Theory and Practice*. University Press, Cambridge.

Friedl, S. (2017). *Renewable & Non-Renewable Resources: Definition and Differences*. Retrieved on 19/01/2017 from Study.com http://webcache.googleusercontent.com/search?q=cache:http://study.com/academy/lesson/renewable-non-renewable-resources-definition-differences.html

Gadiwala, M.S., Usman, A., Akhtar, M. and Jamil, K. (2013). Empirical Models for the Estimation of Global Solar Radiation with Sunshine Hours on Horizontal Surface in Various Cities of Pakistan. *Pakistan Journal of Meteorology*, 9(18): 43-49.

Gaetani, M., Vignati, E., Monforti, F., Huld, T., Dosio, A. and Raes, F. (2015). *Climate modelling and renewable energy resource assessment*. European Commission Joint Research Centre. European Union, Italy.

Gana, N. N. and Akpootu D. O. (2013). Estimation of global solar radiation using four Sunshine based models in Kebbi, North-Western, Nigeria. *Advances in Applied Science Research*, 4(5): 409-421.

Gelman, A. (2005). "Analysis of variance? Why it is more important than ever". *The Annals of Statistics*, 33, 1-53.

Glover, J. and McCulloch, F. (1958). The empirical relationship between solar radiation and hours of Sunshine. *Q.J.R. Met. Soc.*, 84(359): 56-60.

Gopinathan, K. K. (1988). A new model for estimating total solar radiation. *Solar and Wind technology*, 5(1): 107-109.

Goovaerts, P. (1997). Geostatistics *for Natural Resources Evaluation (Applied Geostatistics).* Oxford University Press, New York.

Graham, S. (1999). *Clouds & Radiation*. NASA Retrieved on 21/03/2017 from https://earthobservatory.nasa.gov/Features/Clouds/.

Hayward, O. F. and Oguntoyinbo, J. S. (1987). *The Climatology of West Africa*. B and N Books, New Jersey. pp: 263.

Hengl, T. (2009). *A Practical Guide to Geostatistical Mapping.* European Communities, Luxembourg.

Hermann, S., Miketa, A. and Fichaux, N. (2014). *Estimating the Renewable Energy Potential in Africa, IRENA-KTH working paper*. International Renewable Energy Agency, Abu Dhabi.

Höfer, Sunak, Y., Siddique, H. and Madlener, R. (2014). *Wind Farm Siting Using a Spatial Analytic Hierarchy Process Approach: A Case Study of the Städteregion Aachen*. FCN Working Paper No. 16/2014: 1-52. Director, Institute for Future Energy Consumer Needs and Behavior (FCN): Aachen University, Germany.

Hofierka, J. and Sùri, M. (2002). The solar radiation model for open source GIS: implementation and applications. *GRASS Users Conference*. Trento, Italy.

Huld, T., Súri, M., Dunlop, E., Albuisson, M. and Wald, L. (2005). Integration of HelioClim-1 database into PV-GIS to estimate solar electricity potential in Africa. *20th European Photovoltaic Solar Energy Conference and Exhibition*, Bacelona, Spain.

Hussein, T.A.T. (2012). Estimation of Hourly Global Solar Radiation in Egypt Using Mathematical Model. *Int. J Latest Trends Agr. Food Sci.,* 2, 74-82.

Ibeh, G. F., Agbo, G. A., Ekpe, J. E. and Isikwue, B. C. (2012). Estimation of global solar radiation at Calabar using two models. *Journal of Natural Sciences Research,* 2(5): 17-25.

Ibrahim, K. and Mohammed, B. M. (2015). Rising Temperature: Evidence of Global Warming in Northern Nigeria. *Journal of Environment and Earth Science*, 5(22): 50-55.

Isikwue, B.C., Amah, A.N. and Agada, P.O. (2012). Empirical Model for the Estimation of Global Solar Radiation in Makurdi, Nigeria. *Global Journal of Science Frontier Research Physics and Space Science*, 12(1): 58-61.

Iqbal, M. (1983). *An Introduction to Solar Radiation*. Academy Press, New York.

Janjai, S. (2013). A method for estimating direct normal solar irradiation from satellite data for a tropical environment. *Solar Energy*, 84, 1685-1695.

Janjai, S., Masiri, I., Pattarapanitchai, S. and Laksanaboonsong, J. (2013). Mapping Global Solar Radiation from Long-Term Satellite Data in the Tropics Using an Improved Model. *International Journal of Photoenergy*, 2013, 1-11.

Journée, M. and Bertrand, C. (2010). Improving the spatio-temporal distribution of surface solar radiation data by merging ground and satellite measurements *Remote Sensing of Environment,* 114, 2692-2704.

Journ´ee, M. and Bertrand, C. (2011). Geostatistical merging of ground-based and satellite-derived data of surface solar radiation. *Adv. Sci. Res*., 6, 1-5.

Journée, M., Müller, R. and Bertrand, C. (2011). *Towards a climatology of surface incoming solar radiation over the Benelux by merging long time- series of Meteosat-derived estimations and ground- based measurements*. Royal Meteorological Institute Belgium (RMIB): Brussels, Belgium.

Kalidindi, S., Bala, G., Modak, A., Modak, A. and Caldeira, K. (2015). Modelling of solar radiation management: a comparison of simulations using reduced solar constant and stratospheric sulphate aerosols. *Climate Dynamics,* 44(9): 2909-2925.

Kensler, J. (2017). *T-Tests and Analysis of Variance.* LISA-Laboratory for Interdisciplinary Statistical Analysis, VirginiaTech. Retrieved on 17/01/2017 from www.lisa.stat.vt.edu

Khan, M. M. and Ahmad, M. J. (2012). Estimation of global solar radiation using clear sky radiation in Yemen. *Journal of Engineering Science and Technology Review*, 5(2): 12-19.

Lealea, T. and Tchinda, R. (2013). Estimation of diffuse solar radiation in the north and far north of Cameroon *European Scientific Journal*, 9(18): 370-381.

Liao, S., Jiang, L. and Zhao, H. (2012). Estimation of Spatial Distribution of Solar Energy Resource in China *Communications in Information Science and Management Engineering (CISME),* 2(1): 25-28.

Li, D. (2013). *Using GIS and Remote Sensing Techniques for Solar Panel Installation Site Selection.* University of Waterloo, Waterloo, Ontario, Canada.

Maleki, S. A. M., Hizam, H. and Gomes, C. (2017). Estimation of Hourly, Daily and Monthly Global Solar Radiation on Inclined Surfaces: Models Re-visited. *Energies*, 10(134): 1-28.

Measure Evaluation. (2017). *Creating a Demographic Profile.* Carolina Population Center University of North Carolina. www.measureevaluation.org

Medugu, D. W., Adisa, A.B., Burari, F. W. and Abdul'Azeez, M. A. (2013). Solar radiation: Correlation between measured and predicted values in Mubi, Nigeria *International Journal of Science and Technology Education Research*, 4(1): 11-17.

Mohammed, G., Abubakar, A. G., Umar, B. A., Mustapha, A. and Manga, P. J. (2015). Modelling of Cloudiness Index with Maximum Temperature and Relative Humidity of Sokoto Northwestern, Nigeria. *International Journal of Marine, Atmospheric & Earth Sciences*, 3(1): 28-46.

Mohandes, M. and Rehman, S. (2010). *Global Solar Radiation Maps of Saudi Arabia.* King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia.

Monedero, J., García, J., Dobon, F., Yanes, M.A. and Hernandez, F. (2007). *Calculation of PV potential maps in the Canary Islands.* A Project funded by Spanish Ministry of Industry, Tourism and Commerce and the European Regional Development Fund.

Mortimore, M. J. (1970). *Zaria and its Region: A Nigerian Savanna City and its Environs.* Department of Geography, Ahmadu Bello University, Zaria.

Muhammad, A. and Darma, T. H. (2014). Estimation of Global Solar Radiation for Kano State Nigeria Based on Meteorological Data. *IOSR Journal of Applied Physics*, 6(6), I: 19-23.

Musa, B., Zangina, U. and Aminu, M. (2012). Estimation of global solar radiation in Maiduguri, Nigeria using angstrom model. *ARPN Journal of Engineering and Applied Science*, 7(12): 1623-1627.

Muzathik, A. M., Nik, W. B. W., Ibrahim, M. Z., Samo, K. B., Sopian, K. and Alghoul, M. A. (2011). Daily global solar radiation estimate based on Sunshine hours. *International Journal of Mechanical and Materials Engineering (IJMME)*, 6(1): 75-80.

National Aeronautics and Space Administration, Science Mission Directorate. (2010). *The Earth's Radiation Budget*. Retrieved [insert date - e.g. August 10, 2016], from NASA Science website: http://science.nasa.gov/ems/13_radiationbudget

National Population Commission (2006). *Federal Government of Nigeria 2006 Population Census*. NPC., Abuja, Nigeria.

NASA SSE (2016). *A renewable energy resource web site (release 6.0)* sponsored by NASA's Applied Science Program in the Science Mission Directorate developed by POWER: Prediction of Worldwide Energy Resource Project. http://eosweb.larc.nasa.gov/sse

Natural Resources Canada (2015). *Fundamentals of Remote Sensing: A Canada Centre for Remote Sensing Remote Sensing Tutorial*. Government of Canada. Retrieved from http://www.nrcan.gc.ca/Earth-sciences/geomatics/satellite-imagery-air-photos/satellite-imagery-products/educational-resources/9309

N¨ollenburg, M. (2007). "Geographic Visualisation". In A. Kerren, A. Ebert, J. Meyer (Editors), *Human-Centreed Visualisation Environments.* Lecture Notes in Computer Science, 4417, 257-294. Springer, Berlin Heidelberg.

Nobre, A. M., Severiano Jr., C. A., Karthik, S., Kubis, M., Zhao, L., Martins, F. R., Pereira, E. B., Rüther, R., and Reind, T. (2016). PV power conversion and short-term forecasting in a tropical, densely-built environment in Singapore. *Renewable Energy*, 94, 496-509.

Obot, N. I., Chendo, M. A. C., Udo, S. O. and Ewona, I. O. (2010). Evaluation of rainfall trends in Nigeria for 30 years (1978-2007). *International Journal of the Physical Sciences*, 5(14): 2217-2222.

Ogbaka, D. T. and Silikwa, N. W. (2016). The Use of Sunshine Based Models to Estimate Global Solar Radiation in Yola, Nigeria. *Journal of Scientific and Engineering Research*, 3(4): 334-338.

Ohunakin, O. S., Adaramola, M. S., Oyewola, O. M., Matthew, O. J. and Fagbenle, R. O. (2015). The effect of climate change on solar radiation in Nigeria. *Solar Energy*, 116: 272–286.

Olaniran, O.J. and Sumner, G.N. (1989). A study of climate variability in Nigeria based on the onset, retreat and length of the rainy season. *Int. J. Climatol*., 9: 253-269.

Omitaomu, O. A., Singh, N. and Bhaduri, B. L. (2015). Mapping suitability areas for concentrated solar power plants using remote sensing data.*Journal of Applied Remote Sensing*, 9(097697): 1-14.

Ojosu, J. O. (1990). Theiso-radiation map for Nigeria. *Solar and Wind Technology,* 7(5): 563-575.

Okundamiya, M.S. and Nzeako, A.N. (2011). Empirical Model for Estimating Global Solar Radiation on Horizontal Surfaces for Selected Cities in the Six Geopolitical Zones in Nigeria. *Journal of Control Science and Engineering,* 2011, 1-7.

Okundamiya, M. S., Emagbetere, J. O. and Ogujor, E. A. (2016). Evaluation of various global solar radiation models for Nigeria. *International Journal of Green Energy*, 13(5): 505–512.

Olofin, E. A. (1987). *Some Aspect of Physical Geography of Kano Region and Related Responses.* Debis Press, Kano.

Oloo, F., Olang, L. and Strobl, J. (2016). Spatial Modelling of Solar Energy Potential in Kenya. *International Journal of Sustainable Energy Planning and Management*, 06, 17-30.

Olomiyesan, B. M., Oyedum, O. D., Ugwuoke, P. E., Ezenwora, J. A. and Ibrahim, A. G. (2015). Solar Energy for Power Generation: A Review of Solar Radiation Measurement Processes and Global Solar Radiation Modelling Techniques. *Nigerian Journal of Solar Energy*, 26, 58-65.

Osinowo, A. A., Okogbue, E. C., Ogungbenro, S. B. and Fashanu, O. (2015). Analysis of Global Solar Irradiance over Climatic Zones in Nigeria for Solar Energy Applications. *Journal of Solar Energy*, 2015, 1-9.

Osinowo, A. A., Okogbue, E. C., Ogungbenro, S. B. and Fashanu, O. (2015). Analysis of Global Solar Irradiance over Climatic Zones in Nigeria for Solar Energy Applications. *Journal of Solar Energy*, 2015, 1-9.

Osueke, C. O., Uzendu, P. and Ogbonna I. D. (2013). Study and Evaluation of Solar Energy Variation in Nigeria. *International Journal of Emerging Technology and Advanced Engineering*, 3(6).

Oyawoye, M. O. (1964). The Geology of the Nigerian Basement Complex. *Journal of Nigeria Mining, Geology and Metallurgical Society,* 1(2): 87-103.

Oyewole, J. A., Thompson, A. M., Akinpelu, J. A. and Jegede, O. O. (2014). Variation of Rainfall and Humidity in Nigeria. *Journal of Environment and Earth Science*, 4(2): 29-37.

Perez, R., Seals, R., Stewart, R., Zelenka, A., Estrada-Cajigal V. (1994). Supplementing radiation network data by cokriging with satellite images s. *Solar Energy*, 53(6): 491.

Perez, R., Ineichen, P., Moore, K., Kmiecik, M., Chain, C., George, R. and Vignola, F. (2002). *A new operational satellite-to-irradiance model – description and validation*. ASRC: The University at Albany, Albany, NY, USA.

Pettazzi, A. and Salsón, S. (2012a). Merging remote sensing data with in-situ measurements of global solar radiation: the right path to estimate the solar resource in Galicia. *International Conference on Renewable Energies and Power Quality (ICREPQ'12).* Santiago de Compostela (Spain).

Pettazzi, A. And Salsòn, S. (2012b). Coupling digital terrain to radiative transfer model to assess surface solar radiation athigh resolution scale: validation of GIS module r.SuninGalicia. *International Conference on Renewable Energies and Power Quality (ICREPQ'12).* Santiago de Compostela (Spain).

Pettazzi, A. and Salsòn, S. (2012c). Introducing the Solar Radiation Atlas of Galicia, the ultimate resource to assess and exploit solar radiation in Galicia (NW Spain). *International Conference on Renewable Energies and Power Quality (ICREPQ'12).* Santiago de Compostela (Spain).

Pion (2017). *Electromagnetic Spectrum.* Retrieved on 24/01/2017 from http://www.pion.cz/en/article/electromagnetic-spectrum

PhysicalGeography.net (2016). *Energy and Matter Earth-Sun Relationships and Insolation*. Retrieved on 29/12/2016 from http://www.physicalgeography.net/fundamentals/6i.html

Pinker, R. T., Frouin, R. and Li, Z. (1995). A Review of Satellite Methods to Derive Surface Shortwave Irradiance. *Remote Sens. Environ.,* 51, 108-124.

PVGIS (2016). *Photovoltaic Geographical Information System*. European Commission, Joint Research Centre, Institute for Energy, Renewable Energy Unit. Available at http://re.jrc.ec.europa.eu/pvgis/index.htm

Rajan, D. (2017). *What are the factors affecting the distribution of insolation?* Retrieved on 14/04/2017 from http://www.preservearticles.com/2011111217104/what-are-the-factors-affecting-the-distribution-of-insolation.html

Ramachandra, T.V. (2007). Solar energy potential assessment using GIS. *Energy Education Science and Technology,* 18(2): 101-114.

Ramachandra, T.V. andShruthi B.V. (2007). Spatial mapping of renewable energy potential. *Renewable and Sustainable Energy Reviews*, 11, 1460-1480.

Rehman, S. and Ghori, S.G. (2000). Spatial estimation of global solar radiation using geostatistics. *Renewable Energy,* 21, 583-605.

Saaty, T. L. (1990). How to make a decision: The Analytic Hierarch Process. *European Journal of Operational Research,* 48: 9-26.

Sayigh, A. A. M. (1987). The Iso-radiation Map for the Arab Region. *Solar and Wind Technology,* 4(2): 163-177.

Sambo, A. S. (1988). The measurement and prediction of global and diffuse components of solar radiation for Kano in Northern Nigeria. *Solar and Wind Technology,* 5(1): 1-5.

Sanusi, Y. K. and Abisoye S. G. (2011). Estimation of Solar Radiation at Ibadan, Nigeria. *Journal of Emerging Trends in Engineering and Applied Sciences (JETEAS),* 2(4): 701-705.

Shepard, D. (1968). A two-dimensional interpolation function for irregularly-spaced data, *Proc. 23rd National Conference ACM,* ACM, 517-524.

Shukla, K.N., Rangnekar, S. and Sudhakar, K. (2015). Comparative study of isotropiuc and anisotropic sky models to estimate solar radiation incident on tilted surface: A case study of Bhopal, India. *Energy Reports,* 1(2015): 11-21.

SkyMark (2017). *Scatter Plots*. Retrieved on 03/01/2017 from http://www.skymark.com/resources/tools/scatter_plots.asp.

Sen, Z. and Sahin, A. D. (2001). Spatial Interpolation and Estimation of Solar Irradiation by Cumulative Semivariograms. *Solar Energy,* 71(1): 11-21.

Sharma, B. D. (2011). *Performance of Solar Power Plants in India.* Submitted to Central Electricity Regulatory Commission New Delhi.

Sheth, N. and Hughes, L. (2009). Quantifying energy security: An Analytic Hierarchy Process approach. *TheFifth Dubrovnik Conference on Sustainable Development of Energy, Water, and Environment Systems.* Dubrovnik, Croatia, September 2009.

Solar Insolation (2016). Retrieved on 29/12/2016 from http://solarinsolation.org/

Šúri, M., Huld, T. A., Dunlop, E. D., Albuisson, M. and Wald, L. (2006). Online data and tools for estimation of solar electricity in Africa: the PVGIS approach. *Proceedings from 21st European Photovoltaic Solar Energy Conference and Exhibition,* 4-8 October, 2006. Dresden, Germany.

Tanko, A. I. and Momale, S. B. (2013). *Geography of Kano Region*. Adonis and Abbey Publishers Ltd., New York, USA. pp: 33.

Tarhule, A. and Woo, M-K. (1998). Changes in Rainfall Characteristics in Northern Nigeria. *Int. J. Climatol*. 18, 1261-1271.

The Library of Congress Country Studies (2017). *The Climate of Nigeria.* Retrieved on 25/01/2017 from The Geography Site http://www.geography-site.co.uk/pages/countries/climate/nigeria_climate.html

The United States Department of Agriculture, Forest Service (USFS) (2005). *Assessing the Potential for Renewable Energy on National Forest System Lands,*USDA Forest Service and NREL, United States.

Trabeaa, A. A. and Shaltout, M. A. M. (2000). Correlation of global solar radiation with meteorological parameters over Egypt. *Renewable Energy*, 21, 297-308.

Trappey, A. J. C., Trappey, C. V., Wang, D. Y. C., Ou, J. J. R. and Li, S. J. (2015) An integrated self-organizing map and analytic hierarchy process modeling approach for evaluating renewable energy policies. *International Journal of Electronic Business Management*, 13, 3-14.

Udoakah, Y. N. and Umoren, M. A. (2015). Analysis of Solar Potential and Energy Production of Photovoltaic Modules at Optimum Tilt Angles in Nigeria. *Nigerian Journal of Solar Energy*, 26, 92-99.

Udo, R. K. (1970). *Geographical Regions of Nigeria.* University of California Press, pp. 157.

Udo, S.O. (2002). Contribution to the Relationship between Solar Radiation and Sunshine Duration in the Tropics: A Case Study of Experimental Data at Ilorin, Nigeria. *Turk J Phys*, 26, 229-236.

Uyan, M. (2013). GIS-based solar farms site selection using analytic hierarchy process (AHP) in Karapinar region, Konya/Turkey. *Renewable and Sustainable Energy Reviews*, 28, 11-17.

Vàzquez, M., Santos, J. M., Prado, M. and Rodrigues, F. M. (2005). *Atlas de radiaciòn solar de Galicia*. Universidad de Vigo.

Wansah, J. F., Udounwa, A. E., Ezike, S. C., and Akpan, M. S. (2015). Stand-Alone Solar Photovoltaic System for Remote Residential House in Ikot Obio Nsu. *Nigeria. Nigerian Journal of Solar Energy*, 26, 100-108.

Williams, Y. (2016). *Scatterplot and Correlation: Definition, Example & Analysis.*Retrieved on 03/01/2017 from http://study.com/academy/lesson/scatter-plot-and-correlation-definition-example-analysis.html

Yakubu, D. and Medugu, D. W. (2012). Relationship between the global solar radiation and the Sunshine duration in Abuja, Nigeria. *Ozean Journal of Applied Sciences*, 5(3): 221-228.

Yang, K., and Koike, T. (2005). A general model to estimate hourly and daily solar radiation for hydrological studies. *Water Resour. Res*., 41, 1-13.

Zaharaddeen, I. and Baba, I. I. (2016). New data set for Applied Climatological Research in Former Kaduna State. *Proceedings of the Academic Conference of Sub-Sahara African Academic Research Publications on Multi-Disciplinary Approaches:* 5(2). 9th June, 2016. Bayero University Kano, Old Campus, Kano State, Nigeria, West Africa.

Zelenka, A., Perez, R., Seals, R., Renné, D. (1999). Effective Accuracy of Satellite-Derived Hourly Irradiances. *Theoretical and Applied Climatology*, 62: 199-207.

APPENDIX I

EXTRACT OF MEAN DAILY SOLAR RADIATION DATA (MJ/m^2/day) FOR KATSINA STATE

KATSINA

Month	Day	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Jan	**1**	23.2	24.0	28.1	25.4	24.0	27.4	25.3	26.1	23.2	24.7	26.1	24.7
Jan	**2**	23.2	24.7	27.5	27.5	24.7	27.5	25.8	26.1	25.4	27.5	27.5	24.0
Jan	**3**	24.7	26.1	27.5	26.8	24.7	26.1	25.5	25.4	25.4	24.7	26.8	23.2
Jan	**4**	23.2	26.2	28.8	27.5	19.9	24.0	25.3	25.5	23.2	22.5	26.8	24.0
Jan	**5**	23.3	26.9	27.5	27.5	20.8	23.3	24.8	25.5	26.2	24.8	28.2	19.9
Jan	**6**	23.3	26.9	28.8	26.2	18.0	24.0	24.5	24.0	24.0	27.5	26.2	19.9
Jan	**7**	24.8	26.2	26.9	25.5	21.7	24.1	24.9	22.5	19.0	28.2	21.7	14.7
Jan	**8**	25.5	25.5	28.2	25.5	22.5	22.5	24.8	23.3	18.1	27.6	21.7	18.1
Jan	**9**	26.3	25.6	29.5	24.8	22.5	23.3	24.5	25.6	20.0	28.9	21.7	20.9
Jan	**10**	25.6	24.9	28.9	24.9	20.9	24.9	25.3	24.9	21.7	26.3	24.1	19.1
Jan	**11**	26.3	24.2	27.7	24.9	19.1	25.6	24.5	26.3	19.1	27.0	24.9	18.1
Jan	**12**	27.0	22.6	28.3	24.9	19.1	24.9	24.0	26.3	17.1	25.6	23.4	18.1
Jan	**13**	26.4	25.7	27.1	25.7	20.1	25.7	23.0	27.1	21.0	27.1	23.4	23.4
Jan	**14**	25.7	24.2	26.4	24.2	21.0	25.7	24.3	30.3	21.8	27.1	21.8	24.2
Jan	**15**	25.0	25.7	25.0	27.8	22.7	25.7	24.1	29.7	24.3	25.7	24.3	25.7
Jan	**16**	23.5	23.5	24.3	27.8	25.8	26.5	24.7	29.1	22.7	23.5	25.0	25.0
Jan	**17**	21.9	25.1	25.8	23.5	24.3	27.8	24.7	27.8	22.7	21.0	27.2	23.5
Jan	**18**	21.9	25.1	24.3	24.3	24.3	27.9	24.3	27.9	25.1	24.3	22.8	25.1
Jan	**19**	25.8	23.6	27.2	25.1	25.8	27.2	24.4	25.8	25.1	26.5	22.8	24.4
Jan	**20**	27.3	24.4	27.3	24.4	25.1	26.6	24.8	24.4	25.9	26.6	24.4	27.3
Jan	**21**	26.6	25.2	27.3	21.1	25.2	26.6	25.2	25.9	25.2	25.9	23.6	25.9
Jan	**22**	26.6	22.9	26.6	22.9	26.6	28.0	24.7	25.9	24.4	28.0	25.9	22.0
Jan	**23**	25.2	22.1	26.7	22.9	26.7	28.0	26.0	26.0	23.7	27.4	23.7	22.1

Jan	**24**	26.7	24.5	25.3	23.7	26.7	28.1	26.2	24.5	24.5	25.3	26.0	25.3
Jan	**25**	26.7	21.3	27.4	25.3	27.4	27.4	26.2	24.5	23.8	26.0	26.0	25.3
Jan	**26**	26.1	22.1	28.2	25.3	26.1	28.2	25.6	26.1	25.3	24.6	25.3	25.3
Jan	**27**	26.8	23.0	28.2	26.8	27.5	23.8	24.7	26.1	24.6	26.1	23.8	25.4
Jan	**28**	26.1	23.9	28.2	27.5	26.8	23.9	24.5	26.1	24.6	25.4	25.4	26.1
Jan	**29**	24.7	23.9	27.6	24.7	26.9	23.1	25.0	27.6	25.4	23.9	26.9	26.2
Jan	**30**	23.1	24.7	28.3	23.9	27.6	26.2	25.2	26.9	21.4	26.9	28.3	26.9
Jan	**31**	23.9	26.9	28.3	21.4	27.6	26.2	25.4	27.6	22.3	26.2	26.9	27.6
Feb	**1**	22.3	25.5	27.0	18.6	27.7	26.3	24.0	29.0	23.2	27.7	25.5	23.2
Feb	**2**	20.6	26.3	29.7	20.6	26.3	27.0	24.8	29.1	24.0	25.6	22.3	25.6
Feb	**3**	24.8	25.6	27.1	23.2	27.8	27.1	24.8	24.8	24.0	26.3	20.6	27.1
Feb	**4**	24.9	24.9	27.1	23.3	27.8	25.6	24.1	25.6	26.4	24.1	19.7	25.6
Feb	**5**	24.9	22.4	27.8	20.6	28.5	26.4	27.1	23.3	27.8	26.4	20.6	25.7
Feb	**6**	25.7	24.1	28.5	23.3	26.4	22.5	27.9	23.3	26.4	27.2	19.7	26.4
Feb	**7**	26.5	25.7	27.9	24.9	26.5	23.3	25.7	23.3	26.5	27.2	18.7	27.2
Feb	**8**	27.2	26.5	28.6	25.0	25.7	25.7	25.7	26.5	27.9	29.3	21.6	27.9
Feb	**9**	28.0	26.5	29.3	24.2	25.0	25.8	25.8	26.5	26.5	27.3	25.8	25.8
Feb	**10**	28.7	27.3	28.0	26.6	25.0	26.6	25.8	27.3	21.7	28.0	26.6	26.6
Feb	**11**	26.6	27.3	28.0	21.7	22.6	27.3	27.3	25.8	24.3	29.4	27.3	23.4
Feb	**12**	28.1	26.6	26.6	23.5	22.6	28.8	26.6	26.6	25.1	28.1	26.6	21.7
Feb	**13**	28.1	25.9	27.4	25.9	18.8	28.1	25.9	25.1	25.9	26.6	28.1	22.6
Feb	**14**	27.4	25.9	28.8	25.2	22.7	29.5	26.7	25.2	23.5	28.8	25.2	25.2
Feb	**15**	27.4	26.0	27.4	24.4	24.4	28.8	26.7	26.7	27.4	25.2	26.0	26.0
Feb	**16**	28.9	28.2	29.6	24.4	25.2	28.2	26.7	25.2	28.9	27.5	21.8	28.2
Feb	**17**	28.9	27.5	28.2	27.5	26.0	24.4	26.8	25.2	26.8	22.7	26.0	28.2
Feb	**18**	28.2	27.5	25.3	28.2	26.0	25.3	26.8	25.3	26.8	26.0	25.3	27.5
Feb	**19**	29.0	26.8	26.8	26.1	26.8	25.3	26.8	26.8	27.5	24.5	26.1	27.5
Feb	**20**	25.3	26.1	27.6	25.3	25.3	26.1	27.6	28.3	30.3	26.1	24.5	26.8

Feb	**21**	25.3	26.9	27.6	23.7	23.7	26.9	27.6	28.3	31.0	26.1	26.1	24.5
Feb	**22**	27.6	26.9	30.4	20.0	22.8	25.3	29.0	26.1	30.4	25.3	23.7	20.0
Feb	**23**	27.6	27.6	31.1	20.1	20.1	26.1	27.6	26.1	29.7	27.6	26.1	26.1
Feb	**24**	24.6	28.4	28.4	21.0	22.9	26.9	29.1	27.7	29.8	27.7	27.7	27.7
Feb	**25**	26.2	27.7	32.4	23.8	25.4	28.4	29.1	26.9	26.2	28.4	27.7	24.6
Feb	**26**	27.0	28.4	29.1	27.0	27.0	28.4	21.1	29.1	27.0	26.2	27.0	24.6
Feb	**27**	28.4	25.4	29.8	23.8	27.0	27.7	23.8	30.5	25.4	25.4	28.4	22.9
Feb	**28**	29.8	28.5	28.5	24.6	24.6	28.5	27.0	27.0	24.6	27.7	27.7	27.0
Feb	**29**	*	*	26.3	*	*	*	23.0	*	*	*	29.2	*
Mar	**1**	28.5	29.9	26.3	24.7	24.7	26.3	23.8	27.8	27.0	27.0	29.9	27.8
Mar	**2**	29.2	28.5	28.5	20.1	26.3	27.0	27.8	28.5	27.0	22.1	26.3	27.8
Mar	**3**	27.8	29.9	29.9	18.0	26.3	28.5	27.1	28.5	26.3	24.7	22.1	24.7
Mar	**4**	27.8	29.9	28.5	20.2	25.5	25.5	28.5	27.8	28.5	23.0	21.2	25.5
Mar	**5**	27.1	30.6	28.5	22.1	24.7	27.8	24.7	29.2	28.5	27.1	21.2	28.5
Mar	**6**	27.8	29.9	28.5	23.9	23.9	29.9	27.8	29.2	29.2	29.9	22.1	25.5
Mar	**7**	28.5	28.5	28.5	23.9	20.2	29.9	27.8	29.9	29.2	25.5	23.0	24.7
Mar	**8**	28.5	29.3	28.6	23.9	23.0	27.1	26.3	30.6	27.8	27.1	21.2	25.5
Mar	**9**	27.8	28.6	29.3	26.3	25.5	26.3	25.5	31.3	21.2	25.5	23.0	27.1
Mar	**10**	27.8	28.6	29.3	26.3	28.6	28.6	27.8	30.6	23.0	25.5	22.1	23.0
Mar	**11**	27.1	28.6	27.8	27.1	27.1	27.8	27.8	30.0	26.3	23.9	24.7	23.0
Mar	**12**	27.1	27.1	23.9	25.5	27.1	26.3	25.5	28.6	26.3	25.5	27.8	23.0
Mar	**13**	26.3	28.6	23.9	25.5	24.7	26.3	28.6	27.1	27.8	26.3	27.8	21.2
Mar	**14**	27.8	27.8	24.7	24.7	25.5	26.3	26.3	28.6	26.3	26.3	27.8	23.9
Mar	**15**	27.1	27.1	25.5	25.5	23.0	29.3	27.1	27.1	28.6	27.1	26.3	27.1
Mar	**16**	26.3	27.1	27.1	24.7	22.1	27.1	28.5	27.1	28.5	28.5	25.5	26.3
Mar	**17**	25.5	27.8	27.8	24.7	22.1	27.1	29.9	28.5	27.8	28.5	23.9	23.9
Mar	**18**	27.1	23.0	27.1	24.7	23.0	29.2	29.2	28.5	27.1	27.8	23.0	24.7
Mar	**19**	27.8	23.9	27.0	22.1	22.1	28.5	28.5	28.5	23.9	23.0	24.7	25.5

Mar	**20**	27.8	23.9	29.2	24.7	24.7	27.8	25.5	29.2	23.9	27.8	22.1	25.5
Mar	**21**	27.0	26.3	29.2	25.5	24.7	28.5	27.0	29.9	21.1	27.8	22.1	27.0
Mar	**22**	26.3	27.0	27.0	23.8	25.5	27.8	28.5	29.2	21.1	28.5	26.2	26.3
Mar	**23**	27.0	25.5	28.4	22.9	27.0	27.0	27.7	29.2	24.6	24.6	25.4	26.2
Mar	**24**	26.2	23.8	27.7	23.8	24.6	24.6	27.0	25.4	28.4	22.9	27.7	27.0
Mar	**25**	27.0	27.7	27.7	22.0	26.2	25.4	23.8	28.4	27.7	24.6	27.7	24.6
Mar	**26**	26.9	28.4	25.4	21.1	26.9	25.4	26.2	28.4	27.7	24.6	27.7	25.4
Mar	**27**	27.7	27.7	24.6	21.0	26.9	28.4	26.9	28.4	26.2	22.0	27.6	28.4
Mar	**28**	29.7	28.4	28.3	24.6	22.9	29.1	27.6	31.1	26.9	23.7	26.9	27.6
Mar	**29**	29.7	27.6	28.3	23.7	24.5	28.3	29.0	29.0	22.8	25.3	27.6	29.0
Mar	**30**	27.6	29.7	29.0	20.0	25.3	29.0	29.0	29.0	27.6	28.3	26.1	26.9
Mar	**31**	27.6	29.7	29.6	21.0	25.3	29.0	29.6	27.6	29.0	29.7	26.8	28.3

Source: NIMET, 2015

APPENDIX II

EXTRACT OF DAILY AVERAGE SOLAR RADIATION DATA (MJ/m^2/day) FOR KANO STATE

	Days											
		1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Apr	1	24.96	22.86	26.90	25.36	28.35	23.72	26.14	28.35	25.36	26.90	25.36
Apr	2	24.85	21.94	26.11	22.83	27.61	25.33	25.33	29.02	24.53	27.61	24.53
Apr	3	24.74	21.91	26.84	26.08	28.99	21.91	24.50	25.30	25.30	25.30	25.30
Apr	4	24.71	23.64	26.81	25.27	27.54	21.89	24.47	24.47	26.05	24.47	26.05
Apr	5	24.60	24.44	26.77	23.61	27.51	24.44	24.44	24.44	24.44	25.24	26.02
Apr	6	24.57	24.41	21.83	18.91	26.74	25.99	24.41	22.72	23.58	25.21	25.99
Apr	7	24.46	27.43	24.38	21.80	26.70	25.18	23.55	24.38	24.38	26.70	25.95
Apr	8	24.34	26.67	25.14	21.77	28.11	25.14	23.52	24.34	21.77	27.40	26.67
Apr	9	24.31	25.88	24.31	24.31	28.07	27.36	23.48	25.88	22.63	25.88	26.63

Apr	10	24.19	25.84	25.84	24.27	25.84	26.59	25.07	24.27	25.07	27.32	28.72
Apr	11	24.07	25.80	25.80	25.80	25.80	25.80	24.24	25.03	26.55	27.28	26.55
Apr	12	24.04	22.53	26.51	27.23	24.99	24.99	21.64	20.72	26.51	24.20	26.51
Apr	13	23.92	22.49	27.90	27.90	21.61	24.95	24.95	24.16	25.72	27.19	24.95
Apr	14	23.80	23.30	26.42	23.30	24.91	23.30	24.12	23.30	25.68	26.42	25.68
Apr	15	23.76	24.08	27.10	24.08	24.87	25.64	22.42	20.62	25.64	24.87	28.49
Apr	16	23.64	23.23	27.06	23.23	26.34	23.23	23.23	20.59	27.06	25.59	24.83
Apr	17	23.51	22.34	26.29	24.79	25.55	23.19	20.55	21.47	25.55	27.01	24.79
Apr	18	23.47	25.50	25.50	22.30	24.74	20.52	23.14	21.43	24.74	22.30	23.14
Apr	19	23.35	21.39	22.26	24.70	25.46	23.91	22.26	23.10	25.46	18.52	24.70
Apr	20	23.23	23.87	22.22	26.15	22.22	24.65	25.41	23.06	23.06	23.87	24.65
Apr	21	23.18	21.31	23.02	25.37	19.45	22.18	22.18	23.83	22.18	23.02	25.37
Apr	22	23.06	15.04	22.14	22.98	19.42	21.27	21.27	22.14	22.14	21.27	25.32
Apr	23	22.93	22.93	23.74	21.23	22.93	21.23	21.23	22.93	22.10	22.10	22.93
Apr	24	22.81	22.89	20.29	22.06	24.47	22.89	21.19	25.22	22.89	20.29	24.47
Apr	25	22.76	22.84	23.65	21.15	25.17	22.01	23.65	25.17	22.84	23.65	22.01
Apr	26	22.64	21.11	19.27	23.60	26.56	20.21	20.21	23.60	24.37	21.11	20.21
Apr	27	22.51	17.20	21.93	22.76	26.51	23.55	21.07	22.76	25.08	18.25	21.93
Apr	28	22.47	20.13	20.13	21.03	25.03	21.88	21.88	21.88	23.51	21.88	21.88
Apr	29	22.34	20.09	22.67	23.46	22.67	20.98	24.23	23.46	20.98	19.16	21.84
Apr	30	22.21	21.80	20.05	24.93	24.18	21.80	23.41	24.18	22.62	21.80	21.80
May	1	22.17	15.96	14.78	23.37	22.57	23.37	22.57	25.60	20.90	20.01	20.90
May	2	22.04	15.93	20.86	24.08	21.71	26.25	22.53	26.25	22.53	14.75	21.71
May	3	21.91	19.00	22.48	24.04	23.27	22.48	20.82	25.49	23.27	19.93	22.48
May	4	21.87	22.44	20.77	23.99	23.22	19.89	20.77	26.82	22.44	16.96	22.44
May	5	21.74	15.83	21.58	23.94	23.94	20.73	23.18	26.09	23.18	18.92	21.58
May	6	21.62	18.89	23.13	23.89	23.89	24.62	23.13	24.62	22.35	18.89	20.69
May	7	21.57	17.88	23.08	23.08	19.77	20.65	21.49	25.29	21.49	20.65	15.77

May	8	21.45	20.60	21.45	21.45	23.04	20.60	23.04	24.52	23.04	20.60	23.04
May	9	21.32	21.40	23.74	22.99	21.40	20.56	21.40	23.74	21.40	20.56	21.40
May	10	21.28	22.17	19.65	22.94	22.17	19.65	22.94	22.17	22.17	21.36	17.77
May	11	21.15	21.32	22.12	21.32	21.32	20.48	22.90	25.77	20.48	22.90	21.32
May	12	21.03	21.28	23.60	21.28	24.33	17.70	22.08	22.85	22.85	22.08	21.28
May	13	20.99	22.03	21.23	11.78	23.56	20.40	19.53	22.03	21.23	21.23	20.40
May	14	20.86	21.99	21.19	21.99	23.51	17.63	22.76	21.19	19.49	21.99	20.36
May	15	20.74	21.15	21.15	21.15	22.72	17.60	22.72	21.15	20.32	21.95	19.46
May	16	20.70	22.68	21.11	21.11	22.68	18.51	21.91	21.91	21.11	21.91	19.42
May	17	20.58	21.07	21.07	21.07	21.87	20.24	22.63	20.24	20.24	23.38	20.24
May	18	20.46	21.03	21.03	22.59	21.82	21.03	21.82	23.33	20.21	24.75	17.50
May	19	20.42	22.55	21.78	22.55	20.99	21.78	21.78	22.55	20.17	20.17	19.31
May	20	20.30	20.95	20.13	20.95	20.95	21.74	22.51	20.95	21.74	19.27	18.38
May	21	20.18	22.47	21.71	20.92	23.20	21.71	20.10	22.47	20.92	20.92	19.24
May	22	20.14	23.16	21.67	21.67	23.88	22.43	20.06	23.16	18.31	19.21	19.21
May	23	20.03	21.63	20.03	20.03	23.12	22.39	23.12	18.28	20.03	21.63	20.03
May	24	19.99	23.08	19.99	19.99	19.14	21.59	22.35	20.81	19.14	23.08	19.99
May	25	19.88	19.96	19.11	19.96	21.56	20.77	23.76	19.96	19.96	21.56	14.11
May	26	19.76	21.52	22.28	17.26	21.52	19.08	23.01	21.52	20.74	21.52	19.08
May	27	19.73	22.97	19.90	18.16	22.24	20.71	21.49	22.97	22.97	20.71	19.90
May	28	19.62	22.94	19.87	19.87	19.87	22.21	21.46	19.87	17.20	21.46	20.68
May	29	19.59	14.03	22.18	18.99	18.99	17.18	22.18	20.65	18.11	21.43	18.99
May	30	19.47	18.96	18.96	17.15	20.62	18.96	22.87	17.15	17.15	19.81	18.08
May	31	19.45	19.78	15.11	18.94	19.78	19.78	22.11	20.59	18.06	18.94	18.94
Jun	1	19.34	19.75	19.75	19.75	20.56	12.75	21.34	18.03	20.56	21.34	16.13
Jun	2	19.23	18.89	12.73	18.89	19.73	18.89	16.11	18.01	17.08	18.89	20.53
Jun	3	19.20	19.70	13.93	17.99	19.70	20.51	19.70	17.99	18.86	17.06	19.70
Jun	4	19.10	17.97	17.97	17.04	19.68	18.84	20.48	18.84	17.04	18.84	17.97

Jun	5	19.08	22.70	17.94	21.98	20.46	19.66	21.98	21.23	17.02	18.82	19.66
Jun	6	18.97	13.89	17.93	19.64	17.01	11.34	12.68	18.80	17.93	21.21	17.93
Jun	7	18.95	16.99	21.19	21.19	18.78	16.99	19.62		17.91	16.99	20.42
Jun	8	18.85	21.17	16.00	20.40	18.76	18.76	19.60	22.63	17.89	14.97	19.60
Jun	9	18.83	19.58	18.75	21.15	20.38	19.58	17.87	19.58	18.75	16.96	17.87
Jun	10	18.73	18.73	17.86	21.13	19.56	17.86	18.73	13.83	18.73	18.73	14.94
Jun	11	18.72	21.11	18.72	16.93	19.55	16.93	18.72	20.35	19.55	18.72	18.72
Jun	12	18.62	14.92	19.53	20.33	19.53	18.70	19.53	17.83	18.70	21.10	17.83
Jun	13	18.60	15.94	22.54	21.08	18.69	18.69	18.69	20.32	19.52	17.82	19.52
Jun	14	18.51	11.26	17.81	20.31	18.68	19.51	23.22	18.68	20.31	16.89	18.68
Jun	15	18.50	19.50	17.80	17.80	20.29	18.67	18.67	19.50	18.67	20.29	16.89
Jun	16	18.49	13.78	15.91	21.05	16.88	13.78	21.05	19.49	21.05	23.20	18.66
Jun	17	18.40	17.78	19.48	21.78	19.48	19.48	18.65	17.78	18.65	19.48	18.65
Jun	18	18.39	16.86	18.64	19.47	17.78	19.47	20.27	20.27	15.90	18.64	16.86
Jun	19	18.30	18.64	17.77	21.03	14.87	17.77	20.26	14.87	19.47	20.26	14.87
Jun	20	18.29	17.77	20.26	20.26	16.86	19.46	19.46	19.46	20.26	11.24	17.77
Jun	21	18.29	20.26	16.85	21.76	16.85	19.46	19.46	14.86	19.46	15.89	17.77
Jun	22	18.20	15.89	14.86	19.46	18.63	11.24	19.46	16.85	20.25	15.89	16.85
Jun	23	18.20	18.63	18.63	20.25	18.63	16.85	20.25	16.85	17.76	15.89	19.46
Jun	24	18.20	18.63	22.47	20.25	17.76	16.85	16.85	15.89	16.85	21.76	22.47
Jun	25	18.12	15.89	19.46	18.63	15.89	18.63	19.46	17.77	16.85	19.46	18.63
Jun	26	18.12	16.86	22.48	17.77	17.77	18.64	17.77	17.77	18.64	16.86	16.86
Jun	27	18.13	20.27	17.77	17.77	20.27	16.86	19.47	17.77	21.03	19.47	17.77
Jun	28	18.04	18.65	18.65	20.27	17.78	15.90	19.48	19.48	18.65	19.48	19.48
Jun	29	18.05	17.79	17.79	18.65	19.48	14.88	20.28	20.28	17.79	17.79	18.65
Jun	30	18.06	13.78	16.88	18.66	19.49	19.49	18.66	18.66	16.88	18.66	17.79

Source: NIMET, 2015

APPENDIX III

EXTRACT OF MEAN DAILY SOLAR RADIATION DATA (MJ/m^2/day) FOR KADUNA STATE

Month	Day	2004	2005	2006		2007	2008	2009	2010	2011	2012	2013
Oct	**1**	19.1	18.0	16.9	22.1	20.5	20.8	20.7	20.0	21.3	21.3	**2014**
Oct	**2**	21.1	15.6	21.1	18.0	22.1	20.3	22.0	21.5	19.4	19.9	18.0
Oct	**3**	20.1	12.7	21.1	16.9	19.5	19.6	21.9	21.7	21.0	21.6	20.5
Oct	**4**	19.1	22.1	20.1	19.1	20.0	22.3	21.6	21.9	20.2	20.6	19.6
Oct	**5**	22.1	20.1	20.1	20.1	22.2	21.7	19.3	19.8	20.8	21.7	19.5
Oct	**6**	22.1	20.1	20.1	20.1	22.1	20.9	21.5	11.9	18.2	21.0	20.5
Oct	**7**	23.8	21.1	20.1	20.1	22.3	16.4	22.4	21.1	21.1	19.3	21.0
Oct	**8**	20.1	20.1	21.1	22.9	17.2	18.4	20.9	20.8	19.1	18.1	21.1
Oct	**9**	21.1	22.0	22.0	18.0	18.1	22.0	20.8	20.7	21.3	18.1	22.3
Oct	**10**	21.1	20.1	22.0	21.1	19.6	21.0	21.4	20.2	21.5	21.7	22.9
Oct	**11**	21.1	19.1	19.1	20.1	18.7	21.0	20.4	21.6	21.9	20.0	19.2
Oct	**12**	22.0	22.9	22.0	12.7	21.1	20.3	21.2	21.2	21.0	22.8	20.3
Oct	**13**	20.1	22.9	20.1	21.1	21.2	21.3	20.1	21.1	20.9	22.4	18.7
Oct	**14**	22.9	22.9	19.0	22.0	16.1	18.8	21.2	20.8	21.1	17.6	19.6
Oct	**15**	23.7	22.0	20.1	20.1	21.4	17.7	21.0	20.2	21.2	19.7	20.3
Oct	**16**	21.0	20.1	21.0	22.0	19.0	22.3	23.4	21.5	21.2	20.5	20.6
Oct	**17**	24.5	20.0	20.0	16.8	21.3	20.6	22.0	20.0	17.5	23.2	22.0
Oct	**18**	26.8	21.0	21.0	17.9	22.4	19.2	21.0	20.7	21.5	23.7	24.0
Oct	**19**	26.1	19.0	21.0	20.0	21.8	20.0	21.6	19.4	21.6	24.4	17.0
Oct	**20**	24.5	20.0	21.9	17.9	25.5	19.1	22.4	21.4	21.1	26.4	20.8
Oct	**21**	22.8	21.0	21.9	20.0	27.2	20.5	18.1	20.4	21.7	23.5	20.6
Oct	**22**	21.9	17.9	21.9	15.5	24.9	19.3	19.7	19.3	20.7	24.0	24.6
Oct	**23**	22.7	25.2	20.9	23.6	22.4	20.7	20.8	20.5	19.9	25.2	24.7

Oct	**24**	19.9	23.6	22.7	25.2	24.4	20.4	17.0	23.4	19.5	25.4	24.4
Oct	**25**	22.7	22.7	21.8	20.9	25.0	17.2	21.2	23.6	21.4	25.2	23.0
Oct	**26**	23.5	25.2	20.9	24.4	25.7	21.6	20.5	22.8	21.4	26.4	22.6
Oct	**27**	25.1	25.1	21.8	25.9	27.4	17.8	22.2	25.6	21.2	26.5	23.1
Oct	**28**	22.6	25.1	23.5	25.1	24.7	18.7	21.7	24.8	22.3	25.6	24.0
Oct	**29**	24.3	25.9	20.8	25.9	24.1	17.0	19.1	24.1	22.5	23.8	23.8
Oct	**30**	19.8	25.1	24.3	24.3	25.4	19.5	18.9	25.0	20.9	22.8	22.7
Oct	**31**	22.6	25.0	25.0	25.8	25.0	21.0	22.0	24.7	21.7	24.3	24.2
Nov	**1**	22.5	22.6	23.4	27.3	24.4	21.8	19.4	25.0	23.1	23.7	25.7
Nov	**2**	23.4	24.2	22.5	25.8	24.8	22.4	21.5	25.9	25.4	24.3	28.0
Nov	**3**	23.3	23.4	23.4	23.8	26.1	24.2	23.8	27.5	22.9	25.8	27.0
Nov	**4**	24.9	24.9	24.1	24.9	26.1	24.2	24.9	27.7	22.6	25.5	28.9
Nov	**5**	24.1	26.4	25.7	23.1	26.4	21.8	23.1	26.6	23.6	25.7	26.2
Nov	**6**	24.1	25.7	26.4	24.0	27.4	23.9	22.6	26.5	24.4	25.0	26.1
Nov	**7**	25.6	27.1	24.1	24.6	27.4	23.0	22.1	28.1	25.0	26.0	26.2
Nov	**8**	26.3	25.6	22.4	24.8	26.4	23.9	21.6	27.6	23.1	25.3	26.7
Nov	**9**	25.5	23.2	20.6	25.9	26.6	20.8	24.3	25.9	24.5	25.4	28.4
Nov	**10**	24.0	24.0	20.5	22.2	26.6	19.8	23.9	25.8	23.6	22.7	15.9
Nov	**11**	24.7	24.7	19.6	20.5	23.1	22.3	24.7	27.7	25.3	25.3	25.5
Nov	**12**	23.9	25.5	23.1	21.4	23.2	21.6	24.3	27.4	23.6	25.5	27.9
Nov	**13**	23.1	26.2	24.7	22.9	23.6	22.5	25.5	27.4	23.6	25.8	28.1
Nov	**14**	23.1	27.6	23.1	25.1	21.1	23.8	22.5	26.1	25.5	25.7	29.3
Nov	**15**	26.1	24.6	23.1	25.5	24.6	23.5	24.6	25.4	25.2	24.2	30.7
Nov	**16**	24.6	26.8	21.3	23.4	24.3	22.8	22.8	26.5	26.6	26.0	30.9
Nov	**17**	26.1	27.5	22.2	22.7	24.2	23.0	24.4	24.2	27.7	25.9	30.1
Nov	**18**	25.3	26.8	22.1	23.5	26.5	21.9	25.8	26.3	26.9	27.3	29.1
Nov	**19**	24.5	27.4	23.8	25.9	24.4	22.1	24.5	26.7	26.8	26.0	28.2
Nov	**20**	24.5	27.4	23.7	25.3	24.8	25.3	24.5	27.2	26.3	25.0	28.3

Nov	**21**	22.1	28.1	25.2	26.8	25.1	23.9	24.8	24.3	24.7	26.2	29.4
Nov	**22**	22.9	28.0	25.2	23.0	25.9	24.7	24.7	26.5	26.0	27.0	30.6
Nov	**23**	21.1	25.9	26.6	25.0	26.6	24.0	25.3	26.0	25.3	25.3	29.5
Nov	**24**	24.4	27.3	25.2	25.8	25.7	20.9	25.0	25.2	25.6	24.2	27.5
Nov	**25**	24.4	27.3	26.6	26.6	26.5	22.8	25.1	26.7	25.1	24.9	27.3
Nov	**26**	25.1	25.9	26.6	24.9	26.2	22.6	25.0	27.9	24.7	24.8	28.0
Nov	**27**	23.6	27.2	25.8	26.1	25.1	23.2	25.7	26.7	25.1	25.5	27.0
Nov	**28**	21.9	27.2	26.5	24.7	27.7	22.7	25.2	24.9	25.8	26.0	27.2
Nov	**29**	21.0	27.2	25.1	26.8	27.0	21.7	25.8	21.8	26.1	25.4	29.9
Nov	**30**	22.7	27.2	25.8	25.8	27.7	22.9	25.7	27.6	28.1	27.0	30.6
Dec	**1**	25.7	28.5	25.8	27.6	28.4	25.9	26.0	24.5	27.3	25.7	30.1
Dec	**2**	25.0	25.7	24.3	25.9	26.1	24.0	27.1	25.1	24.9	24.6	25.7
Dec	**3**	24.2	26.4	21.0	27.6	26.7	24.6	25.6	24.2	23.5	25.4	24.6
Dec	**4**	25.7	27.1	22.7	26.2	21.8	23.0	26.7	25.6	26.2	25.8	25.4
Dec	**5**	26.4	25.0	22.7	24.8	18.5	26.0	24.1	26.6	25.2	25.3	25.8
Dec	**6**	25.7	26.4	24.2	24.6	19.9	25.5	24.3	27.2	27.0	24.3	25.3
Dec	**7**	27.0	25.7	24.9	25.2	23.5	23.4	25.8	25.2	26.2	25.2	24.3
Dec	**8**	28.3	27.0	24.2	24.3	24.5	23.7	23.9	23.3	25.6	25.1	25.2
Dec	**9**	27.0	26.3	21.8	24.3	24.9	24.3	22.8	22.7	26.8	25.1	25.1
Dec	**10**	27.0	24.9	21.8	23.4	25.6	23.6	25.7	21.0	23.8	24.5	25.1
Dec	**11**	27.0	26.3	23.4	19.7	25.3	24.7	26.0	20.6	24.7	23.8	24.5
Dec	**12**	27.0	24.9	23.4	23.8	25.8	25.4	27.5	23.8	24.7	23.8	23.8
Dec	**13**	27.6	26.3	24.9	24.0	26.0	26.9	27.5	24.1	24.4	21.0	23.8
Dec	**14**	27.0	23.4	26.3	24.5	27.0	25.2	25.3	24.4	25.0	20.0	21.0
Dec	**15**	27.0	24.1	25.6	22.3	27.0	26.6	25.2	24.7	24.6	20.3	20.0
Dec	**16**	26.3	23.4	24.1	25.9	26.4	26.7	25.9	23.8	23.1	21.5	20.3
Dec	**17**	24.1	27.6	23.4	25.3	25.1	26.3	24.7	26.0	23.4	21.7	21.5
Dec	**18**	24.9	27.6	26.3	26.1	23.4	24.8	24.9	27.0	23.7	22.5	21.7

Dec	**19**	27.6	25.6	27.0	24.3	24.3	26.5	23.2	26.8	22.0	23.7	22.5
Dec	**20**	27.0	24.9	26.3	24.3	25.6	27.8	25.3	25.9	24.8	26.1	23.7
Dec	**21**	26.3	23.4	24.9	24.0	23.8	26.6	26.4	24.9	24.5	24.8	26.1
Dec	**22**	26.3	23.4	22.6	23.5	23.5	24.7	27.4	25.0	23.7	26.0	24.8
Dec	**23**	24.9	23.4	28.3	22.7	23.2	24.9	26.5	24.1	25.3	26.4	26.0
Dec	**24**	24.9	22.6	26.3	23.4	21.0	26.2	26.8	24.0	22.6	25.7	26.4
Dec	**25**	24.9	24.1	27.7	25.3	21.1	24.9	27.1	23.0	21.8	24.4	25.7
Dec	**26**	25.6	23.4	27.0	27.0	22.5	27.3	25.7	22.7	21.7	24.4	24.4
Dec	**27**	27.0	23.4	24.9	26.2	23.6	28.5	26.1	24.8	24.4	26.3	24.4
Dec	**28**	24.9	22.6	24.2	25.3	24.3	28.0	26.0	25.4	24.8	26.8	26.3
Dec	**29**	24.9	24.9	23.4	25.5	25.3	25.2	20.3	25.9	26.8	25.8	26.8
Dec	**30**	27.1	27.0	22.6	26.8	26.2	23.1	21.8	25.9	25.9	25.5	25.8
Dec	**31**	24.2	26.4	22.6	27.1	25.2	22.2	23.9	24.4	25.7	26.2	25.5

Source: NIMET, 2015

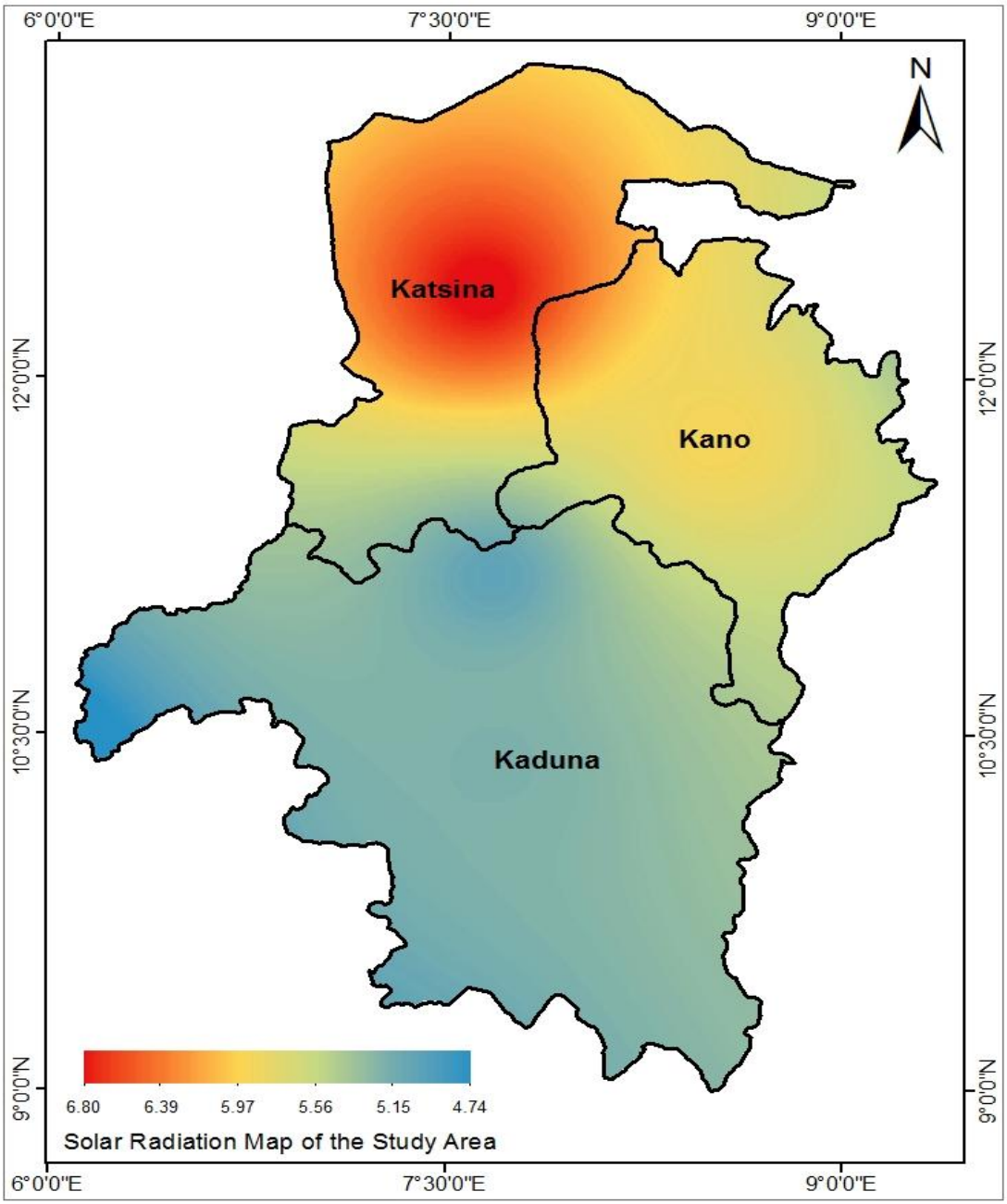
APPENDIX IV

CALIBRATION OF SATELLITE WITH GROUND DATA(kWh/m^2/day)

STN	Jan Ground (G)	Jan Sat (S)	S/G=X	S*X	Feb (G)	Feb (S)	S/G=X	S*X
Kaduna	6.0834993	5.76	0.946823	5.45	6.5336	6.06	0.927513	5.62
Kano	5.6298267	5.49	0.975163	5.35	6.697922	6.33	0.945069	5.98
Katsina	5.7870046	5.49	0.948677	5.21	6.158516	6.39	1.037588	6.63

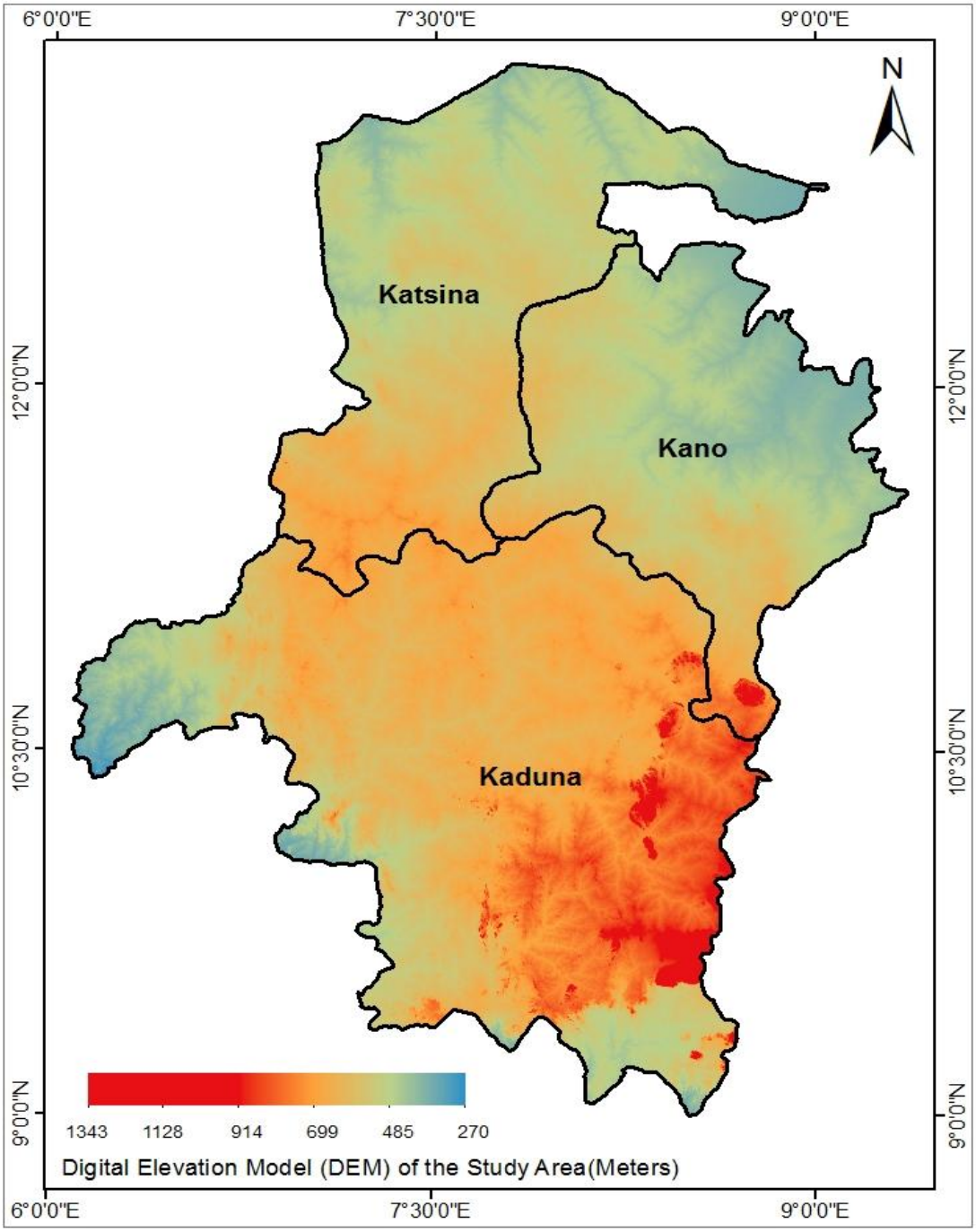
APPENDIX V

SOLAR RADIATION MAP OF THE STUDY AREA



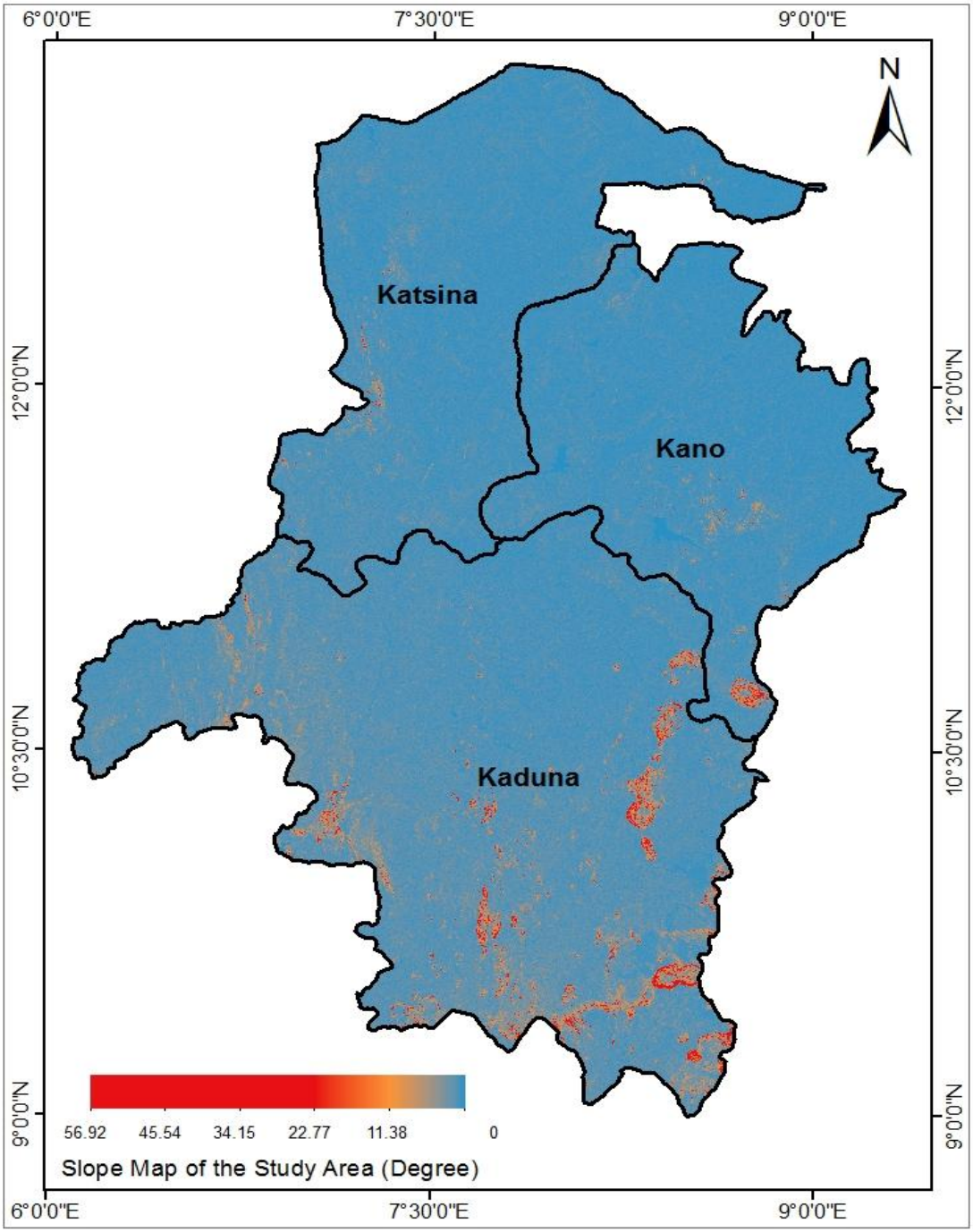
APPENDIX VI

DIGITAL ELEVATION MAP OF THE STUDY AREA



APPENDIX VII

SLOPE MAP OF THE STUDY AREA



APPENDIX VIII

ASPECT OF THE STUDY AREA

