PAN-AFRICAN UNIVERSITY
INSTITUTE FOR WATER AND ENERGY SCIENCES
(including CLIMATE CHANGE)

# Master Dissertation

Submitted in partial fulfillment of the requirements for the Master degree in

Energy Policy

Presented by

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**Assessing Solar Energy Potential Over West Africa Under Climate Change: The Case of Niger**

***Defended on 04/09/2018 Before the Following Committee:***

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**DECLARATION**

I, **Mohamed Zodi Saddam**, hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

Signed:  Date: 31/07/2018

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## CERTIFICATION

This thesis has been submitted with my approval as the supervisor.

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# DEDICATION

I dedicate this humble work to my kind and lovely family and my country Niger.

# ACKNOWLEDGEMENTS

First and foremost, I am grateful to Almighty God for generously granting me good health and life and permitted these humble pursuits to be viable, worthy and meaningful to Him and society we all serve.

A special mention to my family: Mum, Dad and my brother Mohamed Zodi Alhassane, you are my rays of hope and have been a catalytic force in my academic life. Thank you so much for your multiple support.

I acknowledge with thanks the scholarships and research grants provided to me by the AUC, African Union Commission and BMBF, The Federal Ministry of Education and Research of Germany and the Pan African University Institute of Water and Energy Sciences (PAUWES).

I would like to express my sincere acknowledgements to Dr. Benjamin L. Lamptey, the acting director general of ACMAD and my supervisor. His Sympathy, enthusiasm, encouragement and patience were infinitely valuable in the course of my work. I thank him, particularly for the trust that he has given me throughout the preparation of this Mater thesis and for improving its content by the quality of his remarks.

I would like to thank the acting director of PAUWES, Professor Abdellatif Zerga as well as the deputy director, Professor Chewki Ziani-Cherif. I also extend my gratitude to the whole administration of PAUWES for their help and the University of Tlemcen.

My sincere gratitude to our lectures for the knowledge and values that they have transmitted to us during the years of studies.

Special thanks to my friend, Fatoumata Diallo for her precious help.
My acknowledgments to all those, whose names could not be quoted and that have in one way or another contributed to the achievement and the success of this work.

Last but not the least, I would like to thank all my classmates, friends for their sympathy and encouragement.

## ABSTRACT

In the context of climate mitigation and adaptation for sustainable development and given the rising energy consumption as a result of economic development and human population growth, renewable and clean energy alternatives have become of primary importance. Solar energy is considered one of the most popular sources of renewable energy. However, due to meteorological and environmental conditions, the solar energy potential varies depending on the geographical locations.

This study is aimed at assessing the solar energy potential of the cities of Niamey and Agadez in Niger for both present (1979-2005) and future (2019-2050) climates. The study required the collection and analysis of climatic data. As a modeling approach is being used, atmospheric model data from the West African Science Service Centre for Climate and Adapted Land Use (WASCAL) has been collected. The study was conducted using the output of the 12-km spatial resolution weather research and forecasting (WRF) model. The RCP 4.5 climate change scenario was used for the future climate. The results showed an increase of swddif of up to +2W/m$^2$ is observed in Agadez and around 1W/m$^2$ for Niamey. The increase in swddir is almost the same for Niamey and Agadez and is up to 6 W/m$^2$. The lowest radiation values are observed in December and January. The rainy season coincides with the high solar radiation summer months. For the temperature, in compared to the reference period (1979-2005), there is an increase of temperature over both localities for the near future (2019-2050) where the it is up 2.1°C in Niamey and 1.9°C in Agadez. As for the far future (2069-2100), the increase is up to 3° C for Niamey and 2.6° C for Agadez. Thus, based on the three parameters used in this study, both localities are suitable for solar energy applications but Agadez have slightly higher values of direct irradiation compared to Niamey. Additionally, investigations were conducted to determine the existing renewable energy policies and policy recommendations were made for the promotion of solar energy in the Niger.



Key Words: Solar energy, Climate change, WRF, swddir, swddif, ts, Energy policy

# RESUME

Dans le contexte actuel d’adaptation et d’atténuation du changement climatique pour un développement durable et compte tenu de la consommation d'énergie croissante résultant du développement économique et de la croissance démographique, les alternatives d'énergie renouvelable et propre sont devenues primordiales. L'énergie solaire est considérée comme l'une des sources d'énergie renouvelable les plus populaires. Cependant, en raison des conditions météorologiques et environnementales, le potentiel d'énergie solaire varie en fonction des emplacements géographiques.

Cette étude vise à évaluer le potentiel en énergie solaire des villes de Niamey et d'Agadez au Niger pour les climats actuels (1979-2005) et futurs (2019-2050). L'étude a nécessité la collecte et l'analyse de données climatiques. Comme une approche de modélisation est utilisée, les données de modèles atmosphériques ont été collectées au niveau de centre ouest africain de services scientifiques pour le climat et l'utilisation adaptée des terres (WASCAL). L'étude a été réalisée à l'aide des résultats du modèle de recherche et de prévisions météorologiques (WRF) à résolution spatiale de 12 km. Le scénario du changement climatique RCP 4.5 a été utilisé pour la projection de futur climat. Les résultats ont montré une augmentation de l’irradiance solaire diffuse (swddif) allant jusqu'à +2 $W/m^2$ à Agadez et autour de 1 $W/m^2$ pour Niamey. L'augmentation de l’irradiance solaire direct (swddir) est presque la même pour Niamey et Agadez et est de 6 $W/m^2$. Les valeurs de rayonnement les plus faibles sont observées en décembre et en janvier. La saison des pluies au Niger coïncide avec les mois d'été par conséquent avec des rayonnements solaires élevés. Pour la température, par rapport à la période de référence (1979-2005), il y a une augmentation de température dans les deux localités pour le futur proche (2019-2050) où des hausses de 2,1 ° C à Niamey et de 1,9 ° C à Agadez sont observés. Quant au futur lointain (2069-2100), l'augmentation de température est de 3 ° C pour Niamey et de 2,6 ° C pour Agadez. Ainsi, sur la base des trois paramètres utilisés dans cette étude, les deux localités sont adaptées aux applications de l'énergie solaire. Agadez a enregistré des valeurs d'irradiation directe légèrement supérieures à celles de Niamey. En plus de cela, des recherches ont été menées pour déterminer les politiques d'énergie renouvelable existantes et des recommandations ont été formulées pour la promotion de l'énergie solaire au Niger.

Mots clés : Energie Solaire, Changement Climatique, swiddir, swiddif, ts, Politique Energétique

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## LIST OF ABREVIATIONS

AfDB. : African Development Bank

AR5. : Assessment Report Five

AU. : Astronomical Unit

CDO. : Climate Data Operator

CMIP-3. : Coupled Model Intercomparison Project phase 3

CMIP5. : Coupled Model Inter-comparison Project Phase 5

CNES. : National Center of Solar Energy

COP21. : 21st Conference Of the Parties

CORDEX. : Coordinated Downscaling Experiment

CSP. : Concentrating Solar thermal Power

DRC. *:* Democratic Republic of Congo

ECMWF. : European Centre for Medium-Range Weather Forecast

ECOWAS. : Economic Community of West African States

*ECREEE*. : ECOWAS Centre for Renewable Energy and Energy Efficiency

GCMs. : Global Climate Models

GHG. : Greenhouse Gas

GIS. : Geographical Information System

GW. : Giga Watt

HPC. : High-performance Computing Centers

IEA. : International Energy Agency

INS. : National Statistics Institute

IPCC. : Interngovernmental Panel on Climate Change

IRENA. : International Renewable Energy Agency

LPG. : Liquified Petroleum Gas

MoEP. : Ministry of Energy and Petroleum

MW. : Mega Watt

NCL. : NCAR Command Language

net-CDF-CF. : NetCDF network Common Data Form - Climate and Forecast

NIGELEC. : National Electricity Company of Niger

NOAA. : National Oceanic and Atmospheric Administration

ONERSOL. : Solar Energy Office

PAR. : Photosynthetic Active Radiation

PV. : Solar Photovoltaic

RCMs. : Regional Climate Models

RCP 4.5. : The Representative Concentration Pathway Scenario 4.5

RE. : Renewable Energy

REN21. : Renewable Energy Policy Network of 21st Century

RMSE. : RMSE: Root Mean Square Error

SDGs. : Sustainable Development Goals

SE4ALL. : Sustainable Energy For All

SONICHAR. : Coal Company of Anou-Araren

SONIDEP. : Hydrocarbon Company of Niger

SSA. : Sub-Saharan Africa

TWh. : Tera Watt-hour

UN-DESA. : United Nations Department of Economic and Social Affairs

UNFCCC. : United Nations Framework Convention on Climate Change

*UNIDO*. : United Nations Industrial Development Organization

USD. : United States Dollar

VAT. : Value-added tax

WAPP. : West African Power Pool

WASCAL. : West African Science Service Centre on Climate Change and Adapted Land Use

WMO. : World Meteorological Organization

WRF. : Weather Research and Forecasting

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# CHAPTER 1

# INTRODUCTION

## 1.1. Background

Presently, due to our continually increasing energy consumption and high life style many challenges exist. These include fossil resources limitation, environmental pollution, the need for energy-mix diversification and exploitation of more efficient energy technologies. These challenges have encouraged governments all over the world to opt for the promotion of the renewable energy share in their energy portfolios.

However, many factors could influence power generation from renewable energies. One such factor is without doubt climate change, which is a symptom of a bunch of challenges raised after the industrial revolution and considered to arise from the increased rate of emission of greenhouse gases and thus global warming.

During the United Nations Framework Convention on Climate Change (UNFCCC) Paris climate conference (COP21) in December 2015, the representatives of one hundred and ninety-five (195) countries committed to climate change, reached a legal and binding agreement on evaluating the environmental situation of the earth. The increase in the consumption of fossil fuels including oil and gas was deemed to be the main reason for the increased greenhouse gas emissions and global warming.

In the final COP21 statement, the different countries affirmed their commitment to maintain the increase in Earth's temperature to be below 2° C or even to keep it under 1.5° C above pre-industrial levels (UNFCCC, 2015).

According to the World Meteorological Organization (WMO), the build-up of greenhouse gases in the atmosphere during the past century is a result of the growing use of energy and development of the global economy. WMO considered the build-up of greenhouse gases in the atmosphere alters the radiative balance of the atmosphere. The net effect is the warming of the

Earth's surface and the lower atmosphere because greenhouse gases absorb some of the Earth's outgoing heat radiation and reradiate it back towards the surface. In 2007, IPCC undertook a most recent comprehensive scientific assessment on the impacts, causes and the possible responses to climate change (IPCC, 2015). The fundamental conclusion of the IPCC forth assessment report (AR4) is that climate change is a result of human activity, that the phenomenon will have devastating effects if left unchecked and that the cost of action on climate change are significantly lower than the costs of inaction. IPCC, 2007 describes climate change as any change in the state of the climate that is identified by changes in the mean and/or the variability of its properties that persist typically for decades or longer. Those changes are either due to natural variability or are a result of human activities (IPCC, 2007). On the other hand, the UNFCCC defines climate change as referring to changes in the climate that are attributable directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods (UNFCC, 2015).

The main objective of any climate change mitigation strategy is pushing toward lower greenhouse gas (GHGs) emissions. However, the most promising energy generation sources without emissions are renewable energy resources such as solar and wind and are typically climate depend (Fant and Schlosser, 2016). However, like all the regions, Africa must confront some key challenges associated with the use of renewable power sources such as dependency on the weather, intermittency in power and also the growing concentration of the GHGs in the atmosphere that will likely cause an uncertain and unstable state of the climate that may affect not only solar power but also hydro and wind power generation performance negatively or positively (Gebretsadik et al, 2014; Fant and Schlosser, 2016).

The sun is the primary source of energy for earth's climate system. So, any change in total amount of solar energy received at the surface of the earth may lead to climate change at the global, regional and local scales (Pan et al, 2004).

Without a doubt renewable energy resources are the most abundant resources of energy in the world and the potential is huge in many regions especially in Africa. According to REN21 (2011), solar energy is the cleanest source of energy. There are many ways of harnessing solar but generally in the power generation sector, the Concentrating Solar thermal Power (CSP) and photovoltaics (PV) are the two major technologies for exploiting solar energy. Many efforts have been made since the industrial revolution to make efficient use of solar energy and in anticipation of fossil resources termination in the future (Martin & Santigosa, 2016). The CSP and PV must be sited at a location for it to be used. It is therefore appropriate to explore locations with high solar energy potential under the present climate and how their current solar potential will change under future climate. This will particularly be useful for planning that will enable solar energy to be incorporated into the national electricity grid or instances where plans are being made for the use of solar panels for instance.

To appropriately carry out any study in solar energy sources, there is a need to have adequate information on solar radiation to predict the amount of energy that is received at the location of study. Along this line, Global Climate Models (GCMs) are available for the weather forecasting, understanding and projecting climate change as well as for simulating the response of the global climate system to the increase in GHGs concentrations in the atmosphere (Villegas & Jarvis, 2010; Daniels, et al., 2012; Hassan, Shamsudin, & Harun, 2013). But for the purpose of obtaining more accurate data and high spatial resolution, many impact studies used Regional Climate Models (RCMs) to downscale the GCMs (Denis et al., 2002; Min et al., 2013).
Along the same lines but with regards to climate change, Fant and Schlosser (2016) conducted a study to address the uncertainties created by climate change on the renewable energy namely solar and wind energy in southern Africa. The study presented a method of regionally detailed climate information from eight (8) GCMs available from the Coupled Model Intercomparison Project phase 3 (CMIP-3) in order to estimate the impacts of climate on the solar and wind potential. A median change close to zero was found by 2050 for both the solar radiation and the wind speed with only small changes in wind and solar electricity production potentials a consequence of climate change.

At the West African level, studies have been conducted by Ould-Bilal et al. (2007) to model the solar potential of the cities of Dakar and Nouakchott. The results obtained show that over each city the solar radiations measured and calculated are almost the same. A comparative study has led to a fairly good correspondence between the solar radiation of the two localities.

Fatoumata (2018) carried out a study to investigate the impact of climate change on solar energy potential in Bamako and Mopti, both cities in Mali. The study was conducted using a 12-km spatial resolution Weather Research and Forecasting (WRF) model. The results of the study showed a variation in the Shortwave-Surface-Downward-Diffuse-Irradiance, Shortwave-

Surface-Downward-Direct-Irradiance and the surface temperature for the two cities for both present-day and future (near and far) climate. Based on these three parameters, the study concluded that the locality of Mopti is more suitable for solar energy panels.

Studies have also been conducted at the national level. For instance, Dankassoua et al. (2017), conducted a study using 2015 and 2016 insolation data of Niamey to evaluate the solar potential of the city. They carried out continuous measurement of the mean insolation using pyranometer at the National Center of Solar Energy in Niamey (CNES). The 2015 and 2016 data collected were daily values of the solar irradiance (or solar radiation fluxes density) on horizontal and inclined planes. The treatment and exploitation of those data allowed the authors to determine the impacts of cloud and dust on the solar radiation and the solar potential of that locality and to draw the conclusion that the solar potential of Niamey is very favorable for many applications.

In their study on the ambient temperature and relative humidity impacts on photovoltaic module under Niamey climatic conditions, Bonkaney at al. (2017) tested the impacts on those parameters on a rooftop mounted monocrystalline solar module and continually measured the output current and voltage every thirty minutes and the ambient temperature in addition to solar radiation form CNES. Results of the study showed a negative correlation between the conversion efficiency and the ambient temperature and between the PV electricity output and the relative humidity.

Another study was carried out by Tanimoune (2018) using multi criteria analysis and satellite images to generate different maps of the city of Niamey in order to determine the suitable sites for PV installation in Niamey. The results showed that three locations around the city were selected from the best suitable places with electric power generation per year of around $45.13*10^6$ kwh/day and this was based on the estimated annual average solar radiation per unit of surface area, the efficiency of the PV panel and the total suitable place.
Many of the previous studies are more focused on the assessment of the trends and variability of the global radiation but few studies have analyzed the variability of diffuse and direct component of solar radiation Fatoumata (2018). Most of the studies did not consider the impact of climate change.

## 1.2. Problem Statement

Socioeconomic development in sub-Saharan Africa will inevitably require massive expansion of access to electricity at all levels. In West Africa, institutions such as the West African Power Pool (WAPP) have been put in place to help solve the problem of the weak access to energy by sharing electricity among the member states. Niger, like many of the West African countries, experiences unscheduled and periodic power cuts. The National Statistics Institute (INS) released a report in 2016 which mentioned that the electricity access of Niger was 16.2% in 2015, for a population with annual growth rate of 3.9% (Dankassoua et al., 2017). The country has huge potential in renewable energy resources which if harnessed could contribute to satisfy the energy need of the country.

Additionally, given the current trend of changes in climate, it is important to understand the impact of climate variability and change on renewable energy resources. Concerning solar radiation only few studies have analyzed the variability in the diffuse and direct components of solar radiation globally. Understanding the variability of these parameters is critical for the integration of solar energy into the national energy sector. Thus, there is a need for high resolution climate simulations if meaningful studies on the impact of climate variability and change on renewable energy resources are to be carried out at the national level. So far, no study has been carried out on the assessment of solar energy potential under climate change in the country.

For the moment, only few studies have been conducted using Geographical Information System (GIS) or direct measurement of solar radiation focused on Niamey, which is capital intensive and requires a lot of time.

### 1.2.1. Objectives of the Thesis

The main objective of this study is to assess the impact of climate change on solar energy potential of two Sahelian cities of Niamey and Agadez, both in Niger.

The specific objectives are:

- to determine the trend in the climatic factors such as the surface temperature and the shortwave surface downward irradiance (direct and diffuse) that influence the solar energy potential;
- to explore which locations are currently suitable for solar energy applications and if theses locations will still be suitable under future climate;

- to determine the existing renewable energy policy of Niger;
- to investigate about appropriate policies that could enable the solar energy technologies deployment in Niger.

### 1.2.2. Research Questions

In order to appropriately assess the solar energy potential under changing climate in Niamey and Agadez, the following research questions will be addressed:

- What is the trend in surface temperature, direct (beam) and diffuse components of solar radiation over the two cities,
- What are the suitable locations for solar energy appilcations for present and future climates?
- What are the energy policies supporting the promotion of renewable energy in Niger?
- What could be the policy recommendations to scale up the deployment of solar energy in Niger?

### 1.2.3. Significance of the study

In order to assess the national solar energy potential under present and future climates, it is necessary to acquire the most accurate information of the locations as well as climatic data such as the variability of surface temperature, shortwave surface downward diffuse irradiance and shortwave surface downward direct irradiance. Currently, the most appropriate approach is by using high resolution climate models and scenarios which allows studies of both present and future climates. The results of this study together with the drop in solar PV capital cost and new regulations, will attract more attention of national policymakers and investors (given the electricity price which is still high), toward the important role that renewable energies can play in national energy sector. This will also encourage the diversification of energy mix of Niger and progressively increase the uptake of solar energy in the national energy portfolio which in turn will contribute to alleviate socio-economic constraints of the population.

### 1.2.4. Scope and Limitations of the Study

For the case of this study, a 12 km spatial resolution was used to assess the solar energy potential of the cities of Niamey and Agadez under changing climate. Physical parameters such as surface temperature, shortwave surface downward direct irradiance, shortwave surface downward diffuse irradiance were used. Additionally, an investigation was conducted about existing renewable energy policy in Niger and some solar energy policies were recommended too.

The limitation of the study is that, inferences could not be made about different locations within the two cities. The cities were treated as units.

## 12.5. Roadmap of the thesis

The first Chapter served as an introduction to the study. In the second chapter, a literature review is presented which comprise the renewable energy situation in Sub-Saharan Africa in general and West Africa in particular as well as the impact of climate on energy sector. The methodology of the study is explained in the third chapter. Results and discussions constitute the fourth chapter, while in the last chapter, a general conclusion and some policy recommendations are given as a way to scaling up the deployment and the integration of solar energy into the national energy mix.

# CHAPTER 2

# REVIEW OF THE LITERATURE

## 2.1. Introduction

This Chapter presents an overview of renewable energy situation in Sub-Saharan Africa in general and West Africa in particular with a focus on solar energy as well as the climate change impact on renewable energy potentials.

## 2.2. Renewable Energy in Saharan African

Africa accommodated 13% of the world's population in 2010 (Kebede, Kagochi, & Jolly, 2010) and will be home to at least 2 billion people in 2050 (IRENA, 2013). Despite many positive efforts made in sub-Saharan Africa, the access to modern energy services still remains limited with more than 620 million people still remaining without access to electricity and nearly 730 million relying on the traditional use of solid biomass for cooking (IEA, 2014). Energy access in the region depends on the different countries as shown in Fig. 2.1.

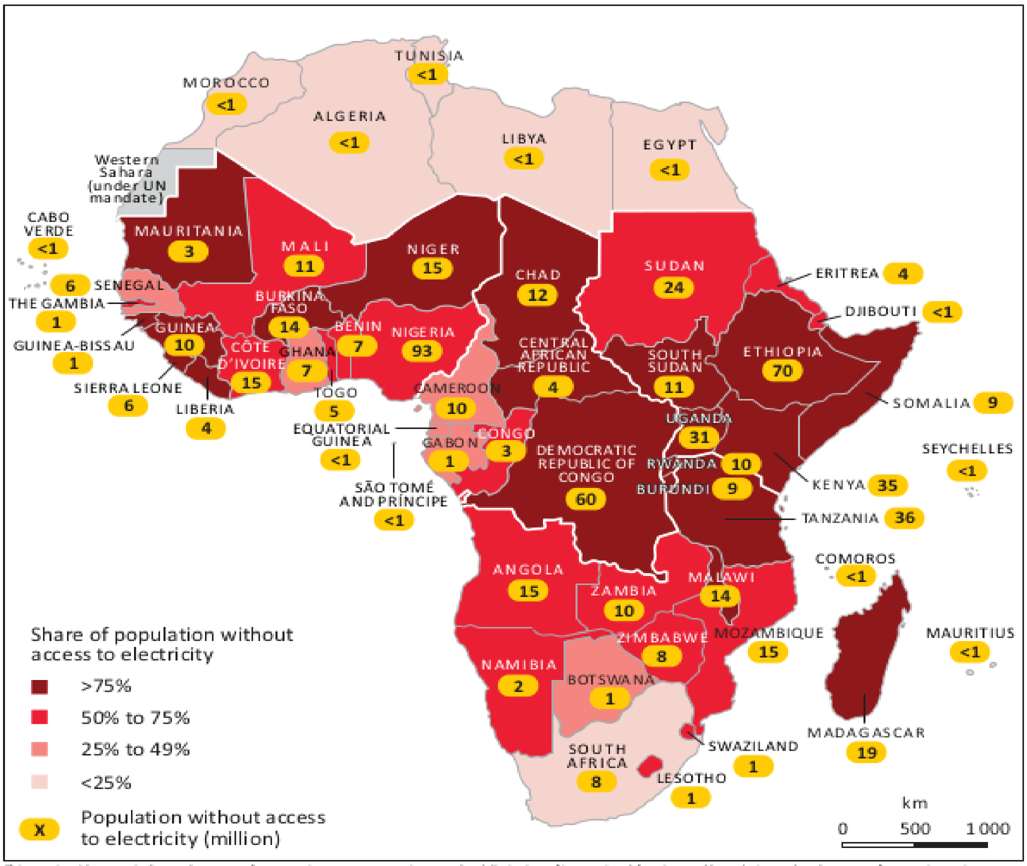


Fig. 2. 1: Number and share of people without access to electricity by country (IEA, 2014)

The energy consumption in sub-Saharan Africa is still dominated by the traditional use of biomass for domestic cooking and heating purposes which represent more than 80% of the energy consumed in many SSA countries. It is used in many cases with inefficient technologies such as three-stones cookstoves which cause harmful indoor pollution. The residential sector accounts for 37 % of the total energy used in SSA followed by the industry and transport sector accounting for 11 % and 9 % each (Mohammed et al., 2013).

In a time when the universal access to clean energy and sustainable development constitute the top priorities, as illustrated by the Sustainable Energy for all (SE4ALL) and United Nations Sustainable Development Goals (SDGs), it has become crucial for Africa to develop its renewable energy sector and encourage the productive use of that source of energy for its socio-economic development especially in non-urban areas where the access to clean energy will trigger the economic development through the increase of income generation and improvement of social wellbeing for the local population (IRENA, 2013).

Sub-Saharan Africa is endowed with a huge potential of renewable energy that can even satisfy the entire energy consumption of some countries (Table 2.1), but the sustainable political will and enthusiasm to create enabling environment for exploitation through modern techniques is low.

Table 2. 1. Annual production potential of RE to current domestic energy consumption (Mohammed et al., 2013).

| Country | Total | Country | Total | Country | Total |
|---|---|---|---|---|---|
| Namibia | 100.5 | Burkina Faso | 15.9 | Kenya | 6.5 |
| Central African Republic | 90.9 | Madagascar | 14.6 | Malawi | 6.4 |
| Mauritania | 86.2 | Guinea-Bissau | 14.2 | Ghana | 5.7 |
| Chad | 77.3 | Tanzania | 14.1 | Uganda | 3.1 |
| Mali | 58.4 | Cameroun | 12.7 | Gambia | 2.7 |
| Niger | 50.4 | Senegal | 12.5 | Burundi | 2.2 |
| Congo | 43.6 | Benin | 12.5 | Nigeria | 2.0 |
| Angola | 27.9 | Sierra Leone | 10.1 | Swaziland | 1.6 |
| Sudan | 27.6 | Cote d'Ivoire | 9.6 | Lesotho | 1.4 |
| Zambia | 25.2 | Eritrea | 9.5 | South Africa | 1.3 |
| Congo Dem. Republic | 24.7 | Guinea | 9.0 | Equatorial Guinea | 0.9 |
| Mozambique | 23.4 | Togo | 8.9 | Cape Verde | 0.9 |
| Botswana | 22.4 | Ethiopia | 8.5 | Rwanda | 0.7 |
| Gabon | 20.3 | Zimbabwe | 8.0 | Comoros | 0.2 |

Renewable energy technologies, hydropower in the first place, present a great share of the total power supply in Africa in general and it can expand to a wider range of technologies in the future. Many countries in the region are considering developing or making effort to actively develop their renewable energy potential to diversify their power mix and reduce the reliance on imported fossil fuels to enhance their energy security. Renewable energy technologies are crucial to provide access to electricity to the rural communities because they present the advantages that they can be deployed through decentralized systems which can help for a faster deployment more than the traditional centralized power plants. The region concentrated more attention on biomass fuel and charcoal while the other renewable sources such as solar, wind, hydropower and geothermal are less used in some regional countries according to (Mohammed et. al., 2013).

### 2.2.1. Bioenergy sources

The sub-Saharan energy mix is dominated mostly by bioenergy mainly the traditional biomass which constitute one of the largest renewable sources of energy of in SSA (Benoit, 2006; Karekezi & Kithyoma, 2003) and mainly used in the residential sector by low income population while the modern use of biomass and biogas only account for small share in the region. The total forest biomass stock is estimated at 130 billion in 2010 (IEA, 2014) as one third of SSA land is covered by forest, that is annually much smaller without deforestation. In addition to the solid biomass and gas there are also agricultural and forest products and residues. The region is potentially rich in biomass and forested areas which could provide fuel for an important share of electricity supply for some countries. (IEA, 2014) estimated that there exists an installed capacity of 325 MW of electricity from bioenergy in Southern and East Africa but the large-scale deployment is still challenging mainly because of the levelized cost of electricity from bioenergy which is higher than the one of electricity from hydropower and gas-fired generation.

### 2.2.2. Hydropower sources

Excluding bioenergy, Hydropower is the most used renewable energy source in Africa in general as showed by the distribution of large dams all over the continent in Fig. 2.2. The large-scale potential development and the low levelized cost of electricity generated compared to any other technology renewable or not, make hydropower very attractive renewable source of energy. The hydropower potential of Africa is estimated at 283 GW and the annual potential to generate up to 1200 TWh which is around 8% of the global technical potential (IEA, 2014). the bigger potential is in Democratic Republic of Congo (DRC) where a project is in place to construct the largest continental dam, the grand Inga project with a capacity of around 44 GW. If the project is completed it could transform Africa’s power supply.

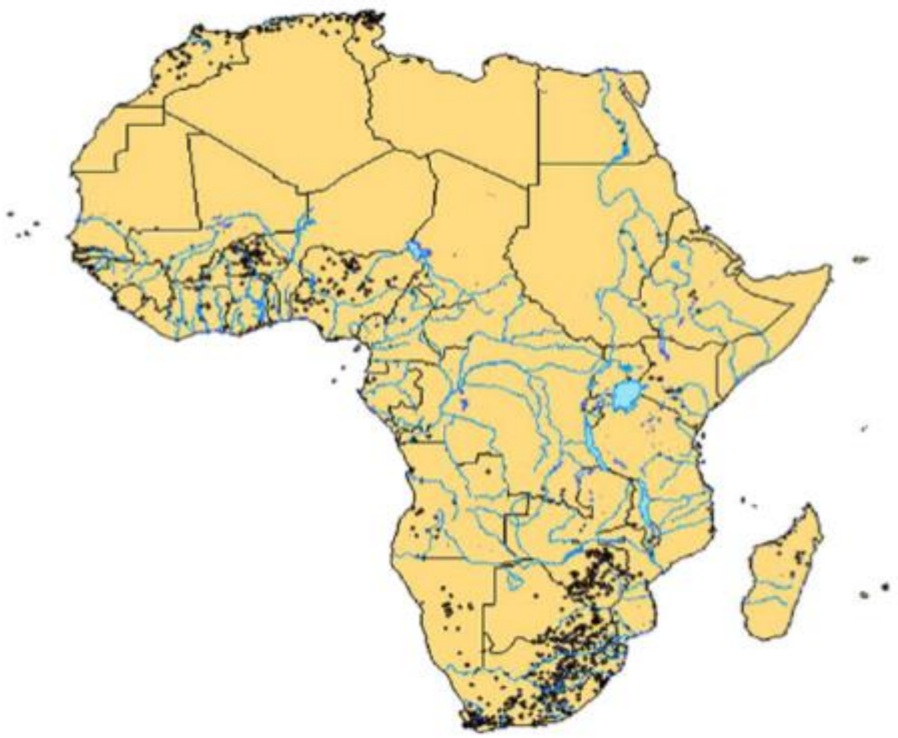

Fig. 2. 2: Large dams' distribution in Africa (Strobl, 2009).

### 2.2.3. Solar energy source

Each year, a large part of the African continent enjoys an average of more than 320 days of sunlight and the irradiance level in urban and rural areas is higher than the typical daily domestic load requirement of 2324 $Wh/m^2$ (Strobl, 2009). In spite of all that potential the solar energy technologies are contributing less to the power sector in Africa. Solar energy is mainly used for the purpose of domestic lighting, water pumping, water heaters in few places and solar community lighting as well as in limited urban street lights (Mohammed et al., 2013).

These current solar applications are still employed on a small-scale despite the large solar potential. IEA estimated that in 2010 the installed capacity of SSA is 40 MW which increased to 280 MW in 2013 (large PV and CSP plants included). The average cost of electricity was above $175/MWh according to the same report (IEA,2014), which is higher than the average cost of generation from other grid technologies (see Fig. 2.3 below). Despite the large-scale availability of the technology in the market nowadays and the decrease in the initial capital cost, the solar technology is still playing a limited role in the power sector mostly because of the unsuccessful policy mechanisms and the financial barriers.

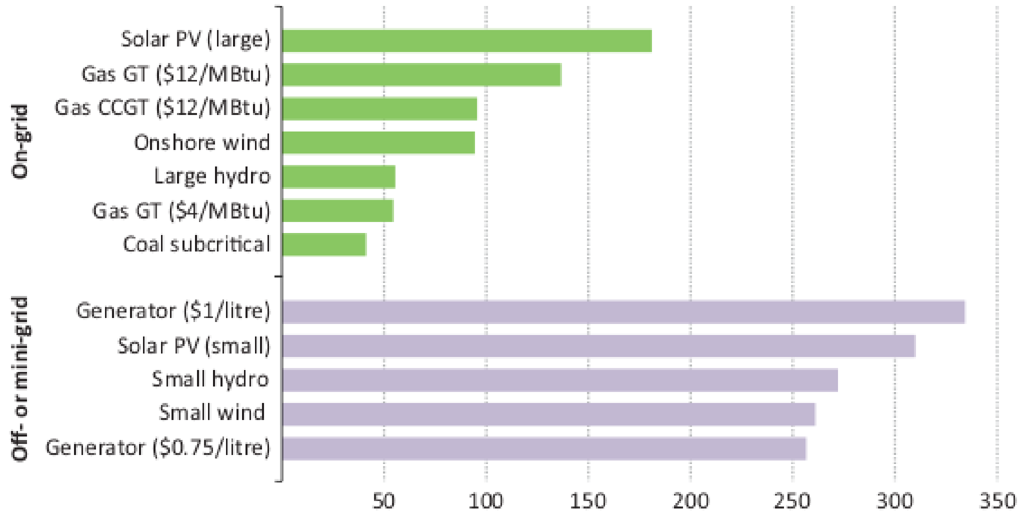


Fig. 2. 3: On-grid and off-grid levelized cost of electricity in sub-Saharan Africa in 2012 (IEA, 2014)

### 2.2.4. Wind energy source

Wind energy together with solar energy hold the advantage of being suitable for off-grid applications which could bring a huge contribution to meet the increasing energy demand to some extent and guarantee the energy supply security. But wind energy still plays a very limited role in the SSA power sector. In 2014 only 190 MW was generated from this source of energy in the region despite the fact that the levelized cost of electricity has significantly reduced for on-shore wind power. Stefano et al, 2014 estimated the sub-Saharan Africa wind potential at around 1300 GW. Few areas in the region have concentrated high quality wind resources. The areas include west and eastern Africa bordering the Sahara Desert, the horn of Africa, eastern Kenya and some part of southern Africa (AfDB, 2013). Wind power can be costly compared with the other technologies where the resources are high but are facing some limiting factors such as weak government policies and the slow pace of technological diffusion in the continent as a whole.

### 2.2.5. Geothermal energy

Only a very small share of Africa power supply is generated from geothermal energy resource in SSA but remain a very attractive option if resources are available. The region's geothermal source is mainly concentrated across different locations in the rift valley as shown in Fig. 2.4 with Kenya having around 250 MW of installed capacity (IEA, 2014). Studies estimated the country has still around 4000 MW to 7000 MW yet to be exploited (Simiyu & Keller, 2000).

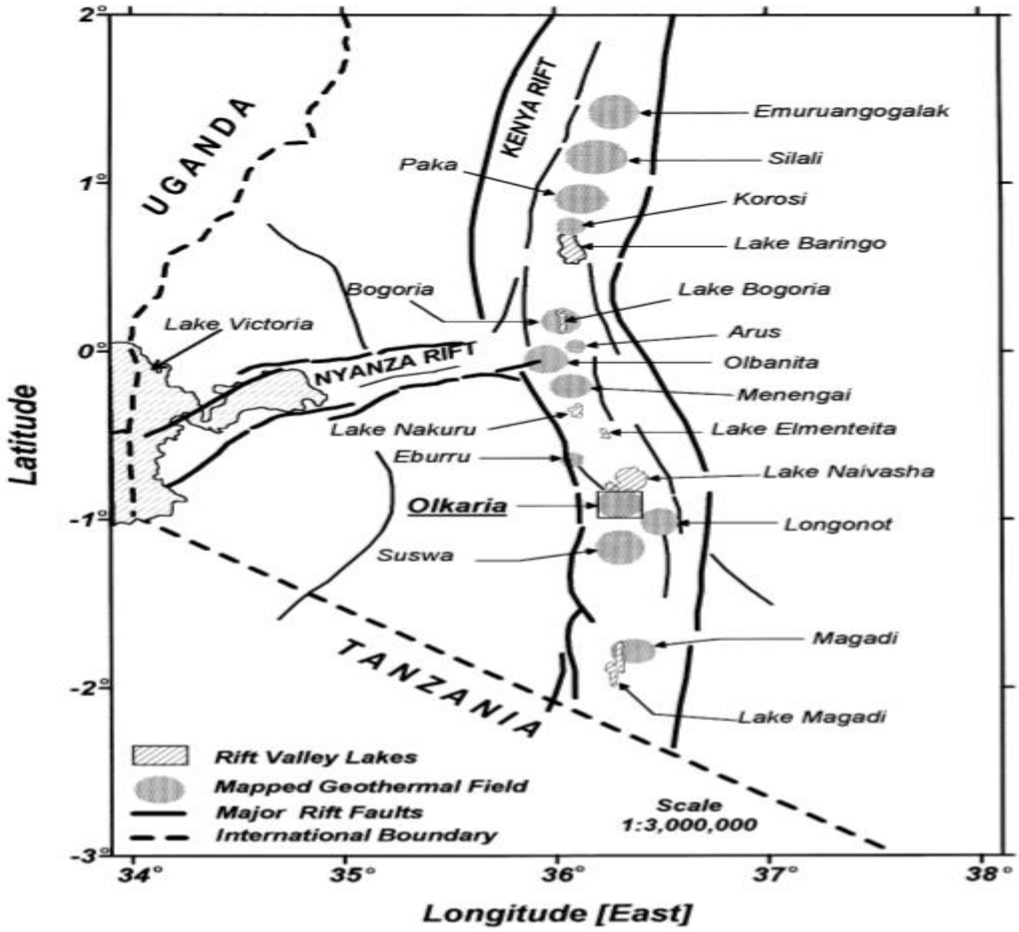


Fig. 2. 4: Rift valley of Kenya showing the geothermal field (Simiyu & Keller, 2000)

### 2.3. West African Context

The Economic Community of West African States (ECOWAS) region is endowed with huge potential for renewable energy, which could play a great role in overcoming the energy shortage issues, if harnessed. The energy demand in the region is expected to increase in the coming years due to the population growth of about 2.5 % per year according some studies, the rapid urbanization and economic development. This calls West African countries for urgent actions to exploit their renewable energy resources which are by the way more equitably distributed in the region in contrast with fossil fuels.

The recent development and trends of energy sector in ECOWAS states are covered in the ECOWAS Renewable Energy and Energy Efficiency Status Report (UNIDO, ECREEE, & REN21, 2014). The report provided used up-to-date data of renewable energy of West Africa and is targeted at industries, policy makers, investors and civil society in order to enable them to make informed decisions about the deployment of renewable energy. From the ECOWAS Renewable Energy and Energy Efficiency Status Report, we have the following findings in Renewable energy in West Africa:

- As of early 2014, The installed capacity of grid-connected renewable electricity (hydropower not included) is up to 39 megawatts (MW) in the ECOWAS region. The total installed renewable capacity, including hydro, was 4.8 gigawatts (GW).
- Renewable energy technologies contribute to an estimated of 28.8 % of the region's total installed capacity of grid-connected electricity.
- The new investment in renewable power and fuels in the region was USD 29.7 million in 2013, down significantly from the peak of USD 370 million in 2011 in the six leading ECOWAS Member States (Nigeria, Senegal, Ghana, Côte d'Ivoire, Liberia, and Sierra Leone).
- The regional leaders in the contribution of renewables to their final energy consumption are Guinea-Bissau, Ghana, and Sierra Leone at 30.3 %, 22.4 %, and 19 %, respectively, in early 2014, which was largely as a result of their use of modern biomass.
- Hydropower accounted for 57 percent of total installed electricity capacity in Ghana; it also played a significant role in Guinea (34.2 percent), Togo (28.8 percent), Côte d'Ivoire (28.2 percent), and Nigeria (16.2 percent). As of early 2014, only 19 percent of the ECOWAS region's estimated 25 GW of hydropower potential had been exploited.
- Wind energy accounted for 27 MW of installed electricity capacity, with 25.5 MW of this coming from Cabo Verde.
- The region's use of solar PV technology is limited largely to distributed and off-grid functions. Senegal leads with installed capacity of 21 MW, followed by Nigeria with 20 MW and Niger with 4 MW.
- 13 out of the 15 ECOWAS Member States had adopted renewable energy support policies with each member state having at least one policy or one target at the national level for the promotion of renewable energy technology by the end of 2014.
- Feed-in tariffs had been implemented in Ghana and Nigeria and were being developed in the Gambia and Senegal. Cabo Verde became the first and only country within the region to adopt net metering as of early 2014.
- A large part of the population using improved biomass cook stoves has grown with 20 % in the Gambia, 16 % in Senegal, 10% Sierra Leone, 6% in Nigeria, and 2.1 % Burkina Faso.

### 2.4. The Sun, Origin of Solar Energy

The Sun is one of the many billions of stars in the galaxy of our solar system in the universe (Milky Way Galaxy). It is the closest star to our planet earth which makes it very important for us.

The sun produces energy from a process similar to that of nuclear fusion in which hydrogen nuclei are believed to combine to form helium nucleus. The excess mass in the process is converted to energy in accordance with Einstein' s theory i.e., $\mathbf{E= mc^2}$, where E is energy in Joules, m is mass in kg and c is the speed of light in $m/s^2$.

The Sun radiates about $3.86 \times 10^{26}$ Joules of energy every second. Despite the fact that some of this energy is lost in the atmosphere, the amount reaching the earth's surface every second, if properly harnessed, could probably be enough to meet the world's energy demand (Babatunde, 2012). Today, it well known that the Sun is the primary source of energy for all the processes in the earth-atmosphere system. Its radiant energy is vital to all lives on the earth, because we all depend on it directly or indirectly.

The Sun is seen as the most popular emerging feasible source of renewable and reliable energy. It is free of any politics and is available free for all land and mankind. The only thing is, it needs to be converted into useful heat and work by appropriate devices able to capture its rays. The amount of solar energy received by any land depends on it locations relative to the sun.

The solar radiant energy falling on the earth's surface is in the shortwave spectrum and it is partly absorbed by the atmosphere and re-emitted back into space as longwave radiation.

### 2.5. Electromagnetic spectrum of the sun

The energy from the Sun is emitted in the form of electromagnetic waves (radiation) which are propagated in space without any need of a material medium and at a speed of $C = 3 \times 10^8$ ms-1. Electromagnetic radiation from the Sun reaching out in waves extends from fractions of an Angstrom ($1A = 10^{-8}$ cm $= 10^{-4}$ $\mu$m) to hundreds of meters, from X-ray to radio waves. These electromagnetic radiations are divided in groups of different wavelengths. The wavelength regions that are principally important to the earth and its atmosphere are:

- Ultraviolet (UV) – (0.3 - 0.4 $\mu$m) representing 1.2%
- Visible (VIS) - (0.4 - 0.74 $\mu$m) representing 49%
- Infrared (IR) - (0.74 – 4. 0 $\mu$m) representing 49%

Studies discovered that 99% of the Sun's radiant energy reaching the earth is contained in these wavelength ranging between 0.3 and 4 $\mu$ m.

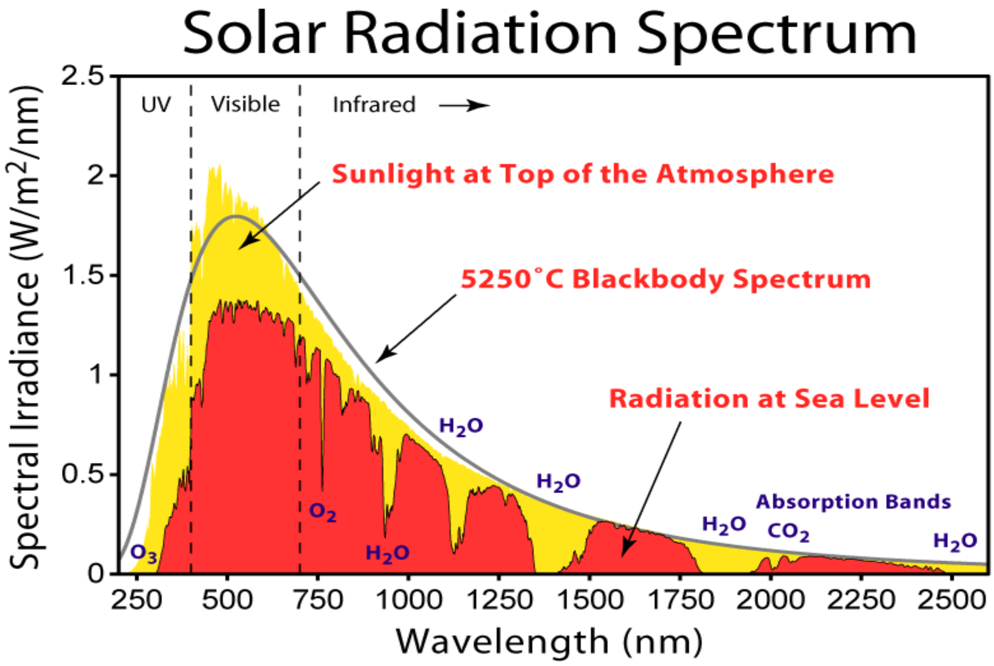


Fig. 2. 5: Spectrum of solar radiation

Source: https://upload.wikimedia.org/wikipedia/commons/4/4c/Solar_Spectrum.png

**2.6. Factors affecting the amount of solar radiation received on the earth surface**

**2.6.1. Astronomical factor**

It is known that only a tiny portion of the energy of the sun reaches the earth's surface. The distance between the Sun and Earth is one of the factors affecting the amount of solar energy received on the Earth. The Earth orbit around the sun once a year and also rotates about its own axis once in a day. Those two rotations determine the amount of solar energy received at the surface of the Earth at any place at any time.

The trajectory of earth during its rotations around the Sun is an elliptical orbit wherein the Sun is located at one of the foci of the ellipse. This implies that the distance between the Earth and the Sun is variant, therefore the amount of the Sun radiation on the surface of the Earth varies too. For example, the shortest distance of the Sun from the earth takes place on December 21$^{st}$ and is called Perihelion (0.993 AU) and the longest distance (1.017 AU) is on the 4$^{th}$ July and is called Aphelion. AU is the astronomical unit of distance (AU=1.496 $\times$ $10^8$km).

The Earth rotations also result on variations of the path of Sun's rays with of the day, season of the year, and the location of the site on surface of the Earth. The path of the Sun's ray becomes decreases toward the noon time and the Perihelion position buy increases toward Aphelion. Thus, the of the distance between the Sun and the Earth result in the variation in the amount of solar radiation received the earth surface. Also, perhaps one of the most important factors in solar radiation depletion is due to the path of the sun's ray through the atmosphere, which determines the amount of radiation loss through scattering and absorption in the atmosphere.

### 2.6.2. The atmospheric factor

The atmospheric factors together with the astronomical factors are the main factors affecting the amount of solar radiation available at the ground surface. During its passage through the atmosphere, solar radiation is subjected to various interactions leading to absorption, scattering and reflection of the radiation. As a result of these mechanisms, the solar radiation decreases considerably and reach the ground surface in reduced amount.

## 2.7. Other radiation and atmospheric related parameters

To utilize solar energy, there is a need to know the different radiation parameters through which passes the Sun's rays. Those parameters are such as Clearness index, Cloudiness index, albedo, turbidity, transmittance, absorbance and reflectivity of the atmosphere. Additionally, the knowledge of the meteorological parameters such as number of sun shine hours per day, temperature, pressure, relative humidity, wind speed, rainfall etc. is important for accurate calculation of parameters of some solar energy devices. For example, for the case of study, it is important to know the number of sunshine hours per day for an accurate calculation of solar PV power needed for the sizing of the PV module for the electrification of a given locality. For example, the number of sunshine hours is more than eight hours on average in Niger. This value varies with geographical locations. That is the reason why the measurement of solar radiation amount and its spectral distribution under all atmospheric conditions is undertaken at many radiation networks around the world (Babatunde & Aro, 1990).

Also, the knowledge of the spectral distribution of solar radiation available is important for development of semiconductor devices such as light emitting diodes, power diodes, photo detectors, photo cells, etc.

### 2.8. Solar radiation measurement and analysis

The knowledge of the daily and monthly solar energy potential at the site of solar energy application is important, not only its amount but also its quality and its spectral composition. Therefore, measurement of the solar radiation is undertaken in many radiation stations throughout the world.

As said above, the Solar radiation energy arriving at the edge of the earth's atmosphere is conveyed in electromagnetic spectrum, of wavelengths ranging from about 0.2µm to 4µm. These groups of wavelengths are of principal importance especially for the calculation of absorption by clouds, gases and aerosols in the atmosphere as well as for the calculation of the spectral variation of the earth to atmospheric albedo. They are also essential for photosynthesis, photobiology and photochemistry taking place in the atmosphere.

The basic solar radiation fluxes such as the shortwave total (global) solar irradiance, shortwave direct solar irradiance, shortwave diffuse or sky irradiance are being measured and studied throughout different radiation network station around the world. Other radiation fluxes measured include global and diffuse photosynthetic active radiation (PAR), the sun photometric measurement and ultraviolet total optical depth, and the sun shine hours which is a commonly measured radiation parameter.

#### 2.8.1. Global (total) Solar irradiance (H)

Global solar irradiance is the total shortwave radiation flux, measured on a horizontal surface on the ground surface of the earth. It comprises the direct shortwave solar irradiance and diffuse shortwave irradiance. In simple mathematics, the three fluxes are connected as in the following:

**Global solar irradiance = Direct shortwave solar irradiance + Diffuse shortwave irradiance**

$$(H = H_b + H_d)$$

The figure below shows the global solar energy potential of Niger.

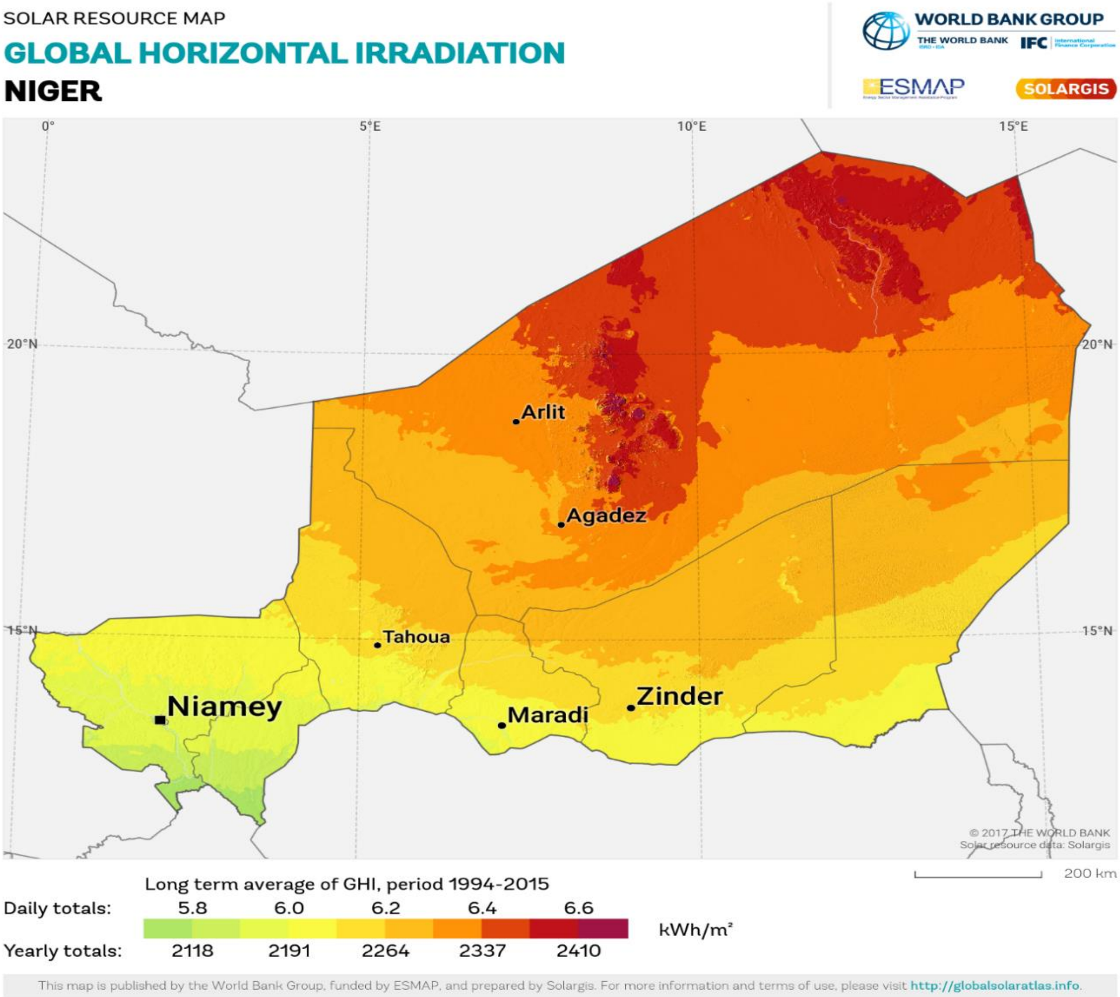


Fig. 2. 6: The global solar irradiation in Niger (SOLARGIS)

### 2.8.2. Direct Solar irradiance ($H_b$)

The direct solar irradiance also known as solar beam ($H_b$), is the component of the global solar irradiance (H) coming directly from the top of the atmosphere, through the atmosphere, to the surface of the earth and is not deviated, nor scattered nor absorbed. The ratios of it to the global solar irradiance ($H_b/H$) can be used to indicate the clearness of the atmosphere and the ratio of it to the extraterrestrial radiation (Ho), i.e. $H_b/H_o$ may be used to indicate the cleanness of the atmosphere and to determine the transmittance property of the atmosphere.

The measuring instrument of the direct solar irradiance is called pyrheliometer. It is used with a solar tracking system to keep the instrument positioned perpendicular to the sun.

### 2.8.3. Diffuse irradiance ($H_d$)

Also known as sky radiation, it is shortwave radiation, which comes from the sky covering angular directions of 180° to the sensor. As a result of scattering and reflection by particles in the atmosphere, the diffuse irradiance is incident on the ground surface. The ratio ($H_d/H$) measures the cloudiness and turbidity of the sky and its ratio to extraterrestrial radiation ($H_d/Ho$) is used to measure the scattering co-efficient of the atmosphere.

Pyranometer on a planar surface, is used as measuring instrument of the diffuse solar irradiance.

## 2.9. Solar Energy Applications

Solar energy has many applications of which the most common are the direct conversion to electricity through Photovoltaic cells and indirect conversion to electricity through turbines as well as for the low and high-grade heat.

Thus, it makes solar energy possible to be exploited through the principle of energy conversion from one form of energy to another. The thermal and electrical conversion of the solar, gave it various applications mentioned below.

### 2.9.1. Solar Energy Thermal Conversion Application

- Production of hot water for domestic use.
- Cooling and Refrigeration.
- Solar passive drier in agriculture drying, wood seasoning, mushroom culturing or growing and the production of pure water-distillation.

### 2.9.2. Solar Electrical Conversion Application

- Thermal to electricity conversion (CSP)
- Solar electric power systems (PV) Photovoltaic (Solar water pumping, Hydrogen Fuel etc.)

## 2.10. Solar Energy in Niger

Niger has a long history of solar energy use. It began in the mid-1960s when the National Solar Energy Centre (CNES) was created, known previously as the Solar Energy Office (ONERSOL). The institution had been established to undertake applied research on renewable energy (mostly solar and wind) and provide data on the use of renewable energy technologies for various sectors of the economy (Fig.2.7 and Fig. 2.8). Additionally, one of the objectives of the center is to run training programs in renewable energy systems. A factory was put in place to assemble and produce various types of solar equipment that were distributed locally with strong government support. However, in the long run, it became difficult for CNES to maintain its promise due to high production costs, poor management and product quality control as well as its inability to compete against cheaper and better-quality equipment imported.

Solar energy is one of the largest renewable energy sources throughout the territory where the average insolation level is 5 to 7 kW/m2/day with an average of 8.5 hours per day according to the CNES. Its applications are various in the country.

Recently, there is a growing investment interest in PV off grid especially for the rural electrification as well as grid connection as a result of the falling cost of PV which brings the technology closer to grid parity in many parts of the world. In 2014, the total installed PV capacity was around 5 MW and distributed among various national sectors in the different regions as shown on the figures below.

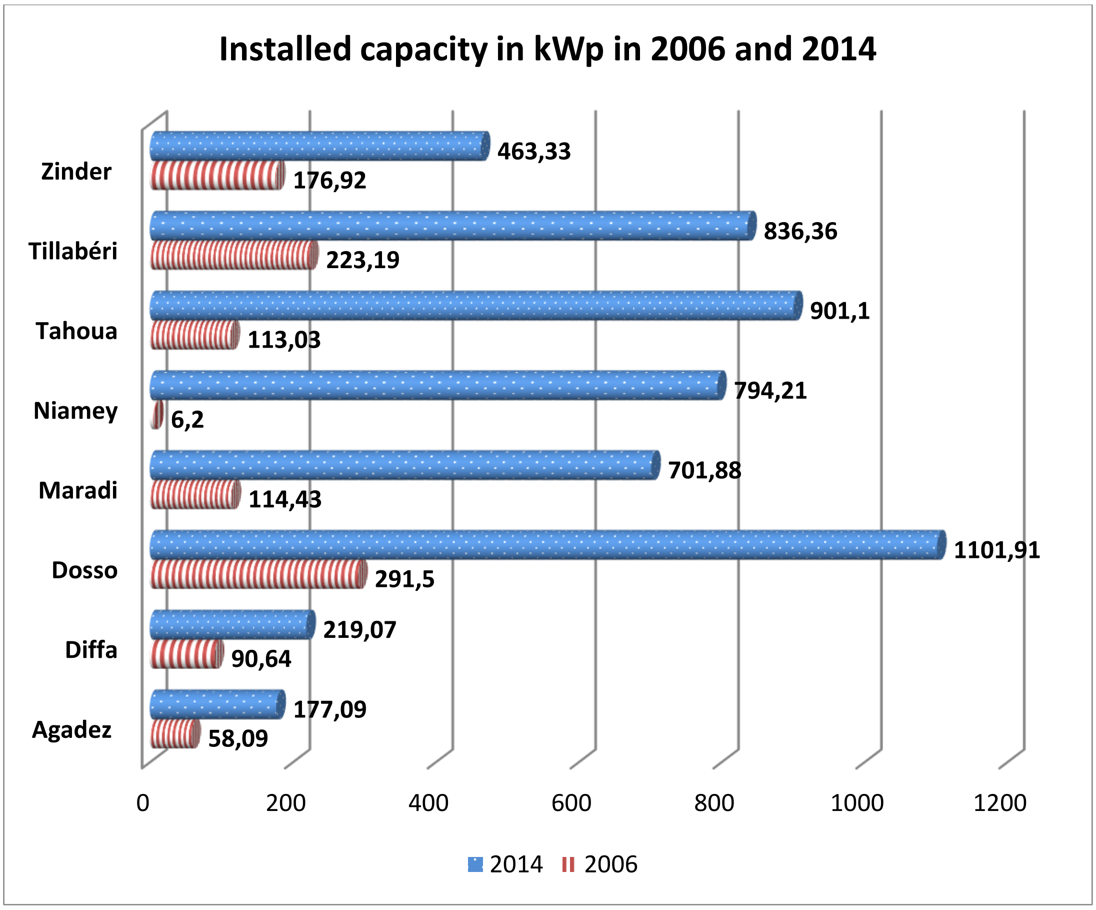


Fig. 2. 7: PV installed capacity in Niger in 2006 and 2014 (CNES, 2015)

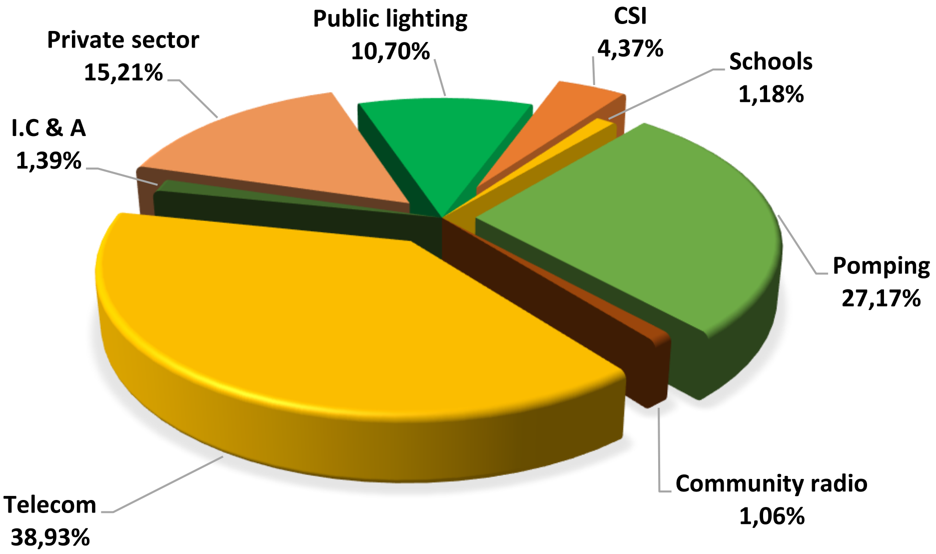


Fig. 2. 8: Solar energy share by different sectors in Niger (CNES, 2015); I.C& A= community and administrative infrastructure; CSI (Lighting, refrigeration, ventilation, Radio)

## 2.10. Climate Change Impacts on Solar Energy

According to Tampakis et al. (2013), solar energy is environmentally and socio-economically beneficial with a proper design, planning, sitting and management, it enjoys favorable public acceptance and is normally given a large theoretical solar potential. In addition to that according to IPCC, based on modeled projections of changes of climate in the long-term future, it will be attractive for investments considering large penetration of renewable energy generation in their energy mix.

In Africa, West Africa is particularly one of the most vulnerable to the effect of climate change (Tchotchou and Kamga, 2010). A study conducted by Li et al., (2012) demonstrates that climate changes can cause variabilities in weather patterns (wind speed, solar radiation, precipitation, temperature). This changes in resource potentials resulting from the impact or consequences of climate change may affect power generation from RE sources and can affect future electricity output. Also, changes in magnitude of several weather parameters (global solar radiation, relative humidity, precipitation, and wind speeds) are also to be expected (Ohunakin et al., 2013).

According to a study by Martin et al, (2017), in the coming decades the climate conditions related to the solar power production may change due to anthropogenic activities. While changes in air temperature are a widely acknowledged aspect of climate change, the study revealed that potential changes in surface solar radiation have been discussed to a much lesser degree. For simplicity or lack of better knowledge, surface solar radiation is often assumed to remain constant over time. However, according to the same study there is a growing evidence that surface solar radiation undergoes substantial multi-decadal variations, which should be considered in solar resource assessments. Coherent periods and regions with prevailing declines (known as "global dimming ") and inclines (known as "brightening ") in surface solar radiation have been detected in the worldwide observational networks, often in accordance with anthropogenic air pollution patterns. This suggests that anthropogenic air pollution and associated accumulation of aerosols in the atmosphere may have substantially contributed to the decadal variations in surface solar radiation. Specifically, the decline in surface solar radiation at widespread observation sites from the 1950s to the 1980s is in line with the strongly increasing air pollution during this period, whereas the subsequent partial recovery of surface solar resources since the 1980s fits well with the successive implementation of effective air pollution regulations, leading to decline in aerosol burdens and more transparent atmospheres particularly in industrialized countries since the 1980s.

The socio-economic sectors too could be affected by the effect of climate change at seasonal time scales. Thus, changes in solar radiation in future climate is of considerable interest (Pan et al., 2004).

Others studies like (Vardavas & Taylor, 2011) determined that cloud cover could strongly affect the radiation budget in the earth-atmosphere system due to sensitivity of the climate to cloud distributions and cloud radiative properties associated with anthropogenic forcing arising from changes in greenhouse gases and aerosols. Also, studies such as (Benson et al. 1984; Harry, Bowden & Hollands, 2013) analyzed that the cloud cover and sunshine are correlated to the global, direct and diffuse irradiance.

It is well evident that we no longer use past observations alone to estimate potential future changes in surface solar radiation and related meteorological quantities relevant for solar power production. Projections from comprehensive climate models are used. The climate models are the primary tools for the development of climate change scenarios for the 21$^{st}$ century, such as those for the latest IPCC assessment report five (AR5), with the latest model generation known as the Coupled Model Inter-comparison Project Phase 5 (CMIP5) models (Martin et al., 2017).

(Pal et al., 2007) discussed that Climate models (global and regional circulation models) can help to understand processes that govern the climate systems and (Olayinka et al., 2015) revealed that besides the the fact many simulations are carried out using Global circulation models (GCMs), it is difficult for GCMs to reproduce various atmospheric variables of interest at a reasonable spatial resolution and thus cannot generate realistic outputs.

In Greece, a study conducted by Iona et al. (2014) that assessed the impacts of projected changes in irradiance and temperature on the performance of photovoltaic system, revealed that the RCM data presented systematic errors against observed values, resulting in the need for bias adjustment. Climate projections used were obtained from 5 regional climate models (RCMs) under the A1B emissions scenario, for two future periods. The spatiotemporal analysis showed significant increase in mean annual temperature (up to 3.5°C) and mean total radiation (up to 5W/m2) by 2100. The performance of photovoltaic systems exhibited a negative linear dependence on the projected temperature increase which was outweighed by the expected increase of total radiation resulting in an up to 4% increase in energy output.

With respect to the role of the solar radiation in the design of solar PV systems, the study conducted by (Page, 2012) examines that there is a need for long-term time series of solar-radiation data and temperature data for each specific site at the hourly level especially for sizing and modeling of stand-alone systems. The study suggested that effective statistical approaches have to recognize the links between solar-radiation data and temperature data.

Another study by (Cleugh & Grimmond, 2012) on urban climate and global climate change indicated that urbanization is an agent of climate change at multiple scales such as local, regional, and even globally. The study analyzed that the conversion to urban landcover of landscape is causing large changes to the local and regional energy, carbon, and water balances. These also affect the quality of the air and climate. The study revealed as well that urban areas have a much greater environmental impact than the 2% of the total global land area they occupy. The significant contribution that cities make to anthropogenic climate change through large net emissions of Green House Gas gives however more evidence of the global impact of urban areas, which is why understanding the interactions between the urban environment and global climate change is so important.

# CHAPTER 3

# METHODOLOGY

## 3.1. Study Area

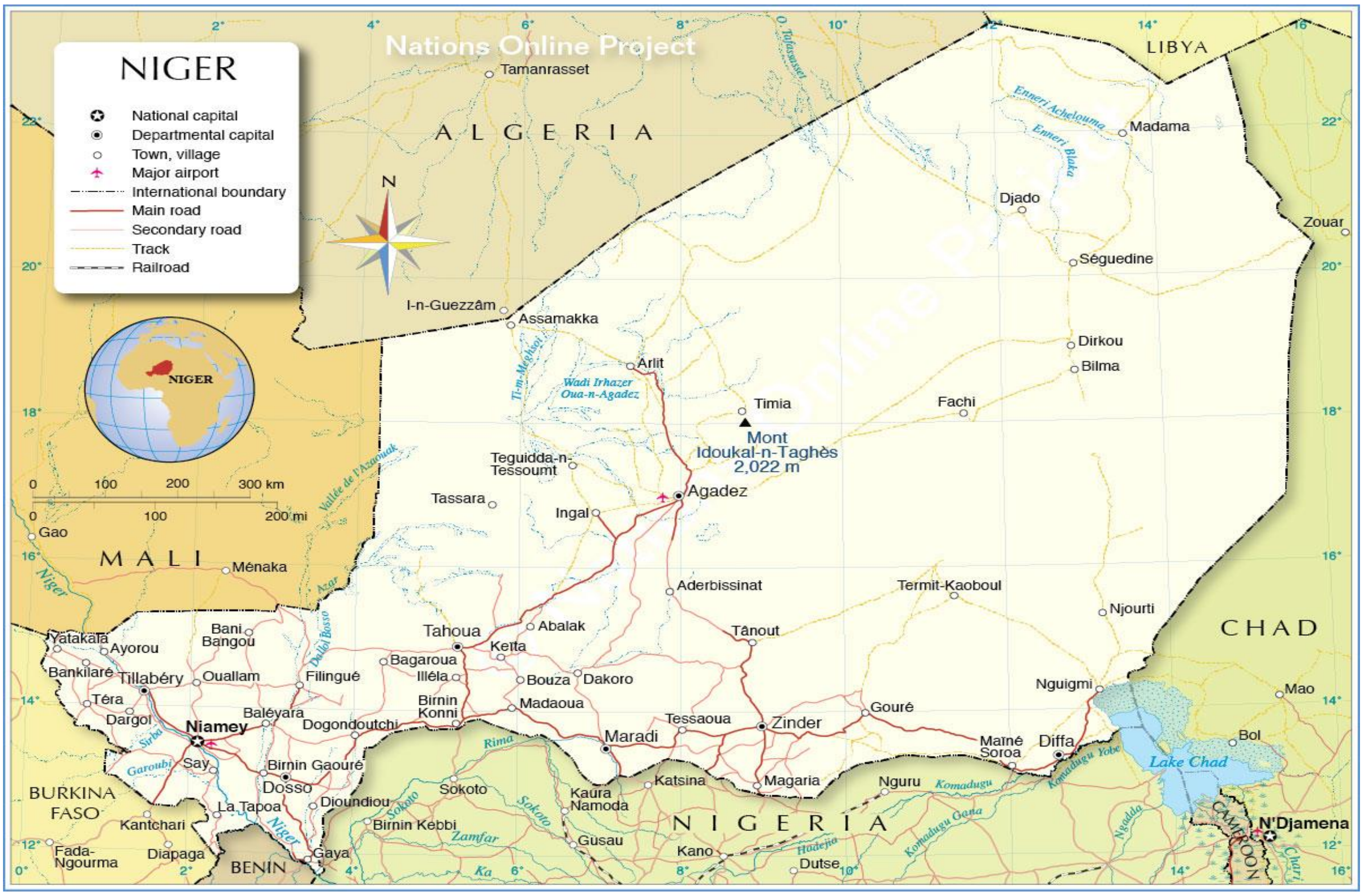


Fig. 3. 1: Map of Niger

Source : http://www.nationsonline.org/oneworld/map/niger-political-map.htm

Niger is a landlocked country in West Africa located just to the south of the Sahara Desert. The country is bounded on the North by Algeria and Libya, on the West by Burkina Faso and Mali, on the South by Benin and Nigeria and on the East by Chad. Niger is the largest country in West Africa with a land mass of 1,267,000 km² (490,000 sq. mi). Most of the territory lies in the semi-arid and arid areas such as the Sahel and the Sahara. The population of Niger was around 21 million in 2017 (UN-DESA, 2017) and had a growth rate of 3.9% in 2012 as shown in the table 3.1 below. Niger has a tropical climate with two main seasons which are the

dry season extending from October to May and the rainy season from May to September. The humid regions are mainly located in the southern part of the country and around the Niger river valley which the largest river in the country and extend to 500 km across the country.
Niger is a hot country with temperatures up to 44° C at certain times of the year, especially around the months of April and May. It is divided in three climatic zones:

- In the northern part of the country is the Saharan zone representing 3/5 of the land surface which is dry and rich in mineral resources;
- In the central a Sahelian pastoral zone with an average rainfall of 200-300 mm of rain per year;
- In the southern part, there is the Sudanian zone which is very suitable for both agriculture and livestock breeding. The rainfall in this zone is around 350-600 mm annually.

The cities of Niamey in the south-western zone and Agadez in the northern zone were the focus of this study.

Table 3. 1: General Information about Niger

| | |
|---|---|
| Country | Republic of Niger |
| Geographical location | West Africa |
| Time zone | GMT + 1 |
| Political system | Democratic and pluralistic |
| Constitutional regime | Semi-Presidential system |
| Official language | French |
| Change | Le Francs CFA (XOF) convertible: 1 € = 655.957 F CFA |
| Capital | Niamey |
| Main cities | Agadez, Diffa, Dosso, Maradi, Tahoua, Tillabéry, Zinder |
| Administrative subdivisions | 8 regions, 66 departments and 265 municipalities |
| Area | 1 267 000 $km^2$ |
| Population | 17 138 707 (General Census 2012) |
| Population growth rate | 3.9% (General Census 2012) |
| Life expectancy | 58.4 years (UNDP 2014) |
| GDP | $ 7.4 billion (IMF, 2013) |
| GDP per capita | $ 443 (IMF, 2013) |
| Growth rate | 4.1% (IMF, 2013) |
| Share of sectors in GDP | Agriculture 38%, industry 20%, services 41% (WB, 2012) |
| Inflation rate | 2.3% (IMF, 2013) |
| Public debit | 34% of GDP (IMF, 2013) |
| Trade balance | $ - 1.3 billion (WTO, 2012) |
| Unemployment rate | 5% (ILO, 2012) |

Source: (Salifou, 2015)

Niger is very rich in terms of energy potential from varied sources ranging from biomass (firewood and agricultural residues), mineral coal, oil, natural gas, uranium, hydroelectricity and of course solar energy as shown in the table 3.2 below.

The national average annual production of uranium is around 5000 tons which makes Niger the biggest uranium producer in Africa and the fourth in the world behind Australia, Canada and Kazakhstan.

According to (Salifou, 2015) the mineral coal is over 90 million tons. Its exploitation has already started since 1976 in Agadez region. It is used mainly for electricity production in an on-site thermal power plant. In the Tahoua region, an exploitation project will start soon for the purpose of power generation as well as for the production of coal briquettes for cooking and other services.

The country is also rich in oil reserves estimated at over one billion barrels. The oil production started in 2011 in the Agadem block located in the east-northern part of the country. The oil is of lightweight type with a density higher than 30° API. The oil is piped to Zinder which is 420 km from the production site to be processed into final products at a refinery with a capacity of 20 000 barrels per day. The final product is distributed through the country by the Hydrocarbon Company of Niger (SONIDEP). The refined products consist of diesel oil, gasoline and LPG (44 000/year). The other part of the crude oil is mainly for export to China. Regarding the natural gas, the estimated reserves are around 18.6 billion $m^3$.

Table 3. 2 : Niger Energy Ressources

| Resources | Reserves |
|---|---|
| Uranium | 450 000 tonnes (Reserves proven) |
| Mineral coal | 90 million tons |
| Crude oil | 1.18 billion barrels oil in place |
| Natural gas | 18.6 billion $m^3$ |
| Hydropower | 280 MW |
| Solar energy | 6 to 7 $kWh/m^2/day$ |

Source : (Salifou, 2015).

### 3.1.1. Renewable Energy Sector

The national renewable energy sector is largely dominated by the use of biomass which account for up to 97 % of household energy consumption as shown by the Fig. 3.2 below. That is due, in part to the insufficient access to conventional and modern energy for the households despite the fact that Butane gas or LPG are currently sufficiently available in Niger (44 000 tons per year) and which should be the solution to replace firewood as cooking fuel used by households. However, the acquisition of accessories for its use (although available on the market) is still out of the reach of low-income households. Thus, many have no choice than to make use of traditional energy sources. Obviously, the large use of the biomass especially firewood for energy needs, as the case is, currently, creates an overexploitation of wood resources which leads to forest deterioration.

Other renewable energy sources include hydropower, with hydroelectric potential estimated at approximately 280.5 MW, including 130 MW in Kandadji, 122.5 MW on the River Niger in Gambou and 26 MW in Dyondyonga on Mekrou. In addition, many sites suitable for micro hydropower are identified on seasonal rivers (Goulbi Maradi and Tahoua Maggia) and tributaries of the Niger River (Sirba, Goroubi, Dargol).

Solar energy is one of the largest renewable energy sources throughout the territory where the average insolation level is 5 to 7 kW/m2/day with an average of 8.5 hours per day according to the National Center of Solar Energy (CNES).

Wind speeds, ranging from 2.5 m/s in the south to 5 m/s in the north, are in favor of many applications especially wind turbines for water pumping.

The renewable energy sector in Niger is still lacking specific legislations. However, the law on electrical code covers issues related to renewable energy in order to create enabling conditions for renewable energy development in the country.

### 3.1.2. Electricity Supply

In Niger, the power transmission and distribution segment is monopolized by the National Electricity Company (NIGELEC) founded in 1968 and the Coal Company of Anou-Araren (SONICHAR), which produces electricity in a thermal coal power plant. The electricity produced by SONICHAR is in part used to supply the northern region of the country and the remaining sold to mining companies. The country is highly dependent on imports from Nigeria through the West African Power Pool (WAPP) to fully cover its electricity needs (Salifou, 2015).

Although the transportation segment and distribution of electricity remains a State monopoly in Niger, the country adopted the Law 2003-004 of 31 January 2003 and the Electricity Code that liberalized the power production sector in Niger in its article 31. The purpose of the law is to allow the development of independent power production from national and foreign investors.

According to the world Bank, the national electricity access rate of Niger was 16.2% in 2016. The electricity access rate is around 65.4 % in urban areas, but only 5 % in rural areas.

### 3.2. Global Solar Energy Potential

Well established studies (e.g. Julian, 2011) have demonstrated that the average power density of solar radiation just outside the atmosphere of the Earth is 1366 W/m$^2$ which is widely known as the *solar constant* (solar flux intercepted by the earth). The length of the meridian of Earth, according to the definition of the meter, is 10,000,000 m from the North Pole to the equator, see Fig. 3.3. This definition is still pretty accurate according to modern measurements. Therefore, the radius of the Earth is $(2/\pi) \times 10^7$m.

The total power of solar radiation reaching Earth is then:

$$\text{Solar power} = 1366\times\frac{4}{\pi}\times10^{14} \cong 1.73\times10^{17}\text{W}$$

Each day has 86,400 s, and on average, each year has 365.2422 days. The total energy of solar radiation reaching Earth per year is:

$$\text{Annual solar energy} = 1.7310^{17}\times86400\times365.2422\cong 5.4610^{24}\text{J} = 5{,}460{,}000\ \text{EJ/year}$$

To have an idea of how much energy that is, compare it with annual global energy consumption. In the years 2005–2010, the annual energy consumption of the entire world was about 500 EJ. A mere 0.01% of the annual solar energy reaching Earth can satisfy the energy need of the entire world. The total solar energy that arrives at the surface of Earth per year is 5,460,000 EJ (Julian, 2011).

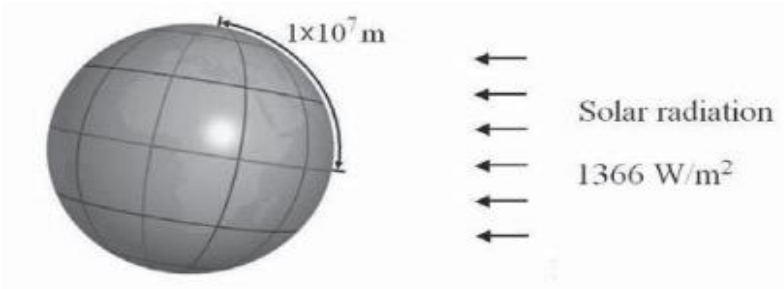


Fig. 3. 2: Annual solar energy arriving at surface of Earth (Julian, 2011).

### 3.3. Data Analysis and Model

#### 3.3.1. ECMWF Reanalysis Data (ERA-interim)

The European Centre for Medium-Range Weather Forecast (ECMWF) has produced ERA-interim to replace of ERA 40 which is a second generation reanalysis and the first reanalysis that directly assimilate satellite radiance data (TOVS, ATOVS, SSM/I and ERS). The ERA-interim is the latest global atmospheric reanalysis which covers the period from 1989 onwards and continues to be extended. ERA-interim comprises gridded data product consisting of a variety of 3-hourly surface parameters which gives description of weather and ocean waves and land surface conditions and also 6-hourly upper-air conditions. Monthly averages for many of the parameters including atmospheric flux and other related field have also been produced (Dee, et al., 2011). ERA-Interim or MERRA is the most recommended to be used for new research. In this study, the MERRA data was considered.

#### 3.3.2. Global Climate Models

Global climate models also called Global Circulation Models (GCMS) are computer-driven models of climate used to forecast weather, understand climate in general and also project climate change.

They are systems of differentials equations based on the basic laws of physics, chemistry and fluid motion. In order to run the model, the planet is divided into a 3-dimensional grid, the basic equations are applied for the results evaluations as shown in the Fig. 3.4 below.

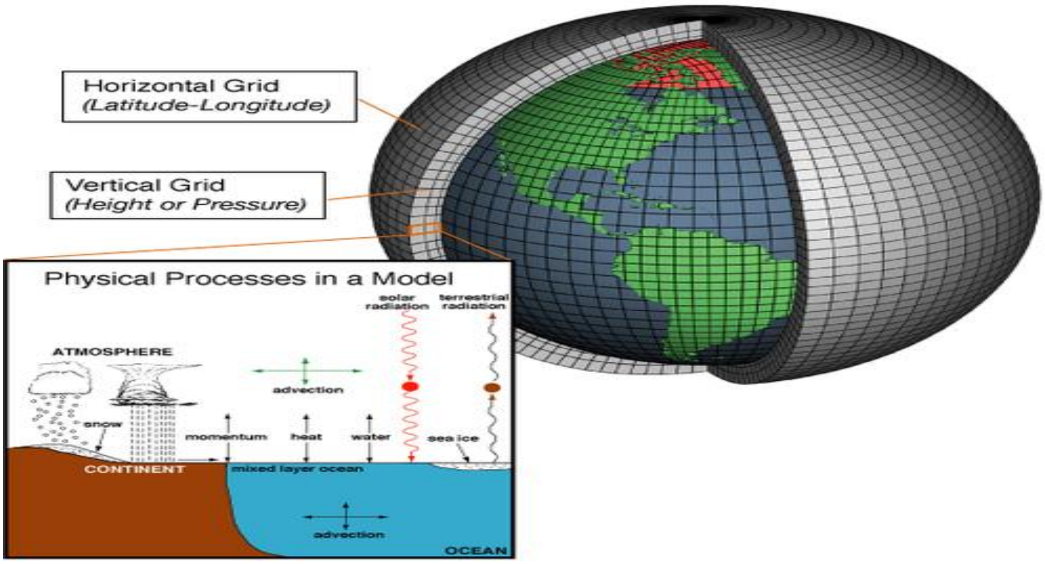


Fig. 3. 3: The 3-dimensional division of the earth for climate models (NOAA, 2017)

Table 3. 3: GCMs and the institutions that developed them. (Bazyomo et all, 2016).

| Institute ID | Global Climate Model Name | Model Short Name |
|---|---|---|
| NOAA–GFDL | GFDL–ESM2M | NOAA |
| NCC | NorESM1–M | NCC |
| MPI–M | MPI-ESM–LR | MPI |
| MIROC | MIROC5 | MIROC |
| IPSL | IPSL–CM5A–MR | IPSL |
| ICHEC | EC–EARTH | ICHEC |
| CNRM–CERFACS | CNRM–CM5 | CNRM |
| CCCma | CanESM2 | CCCMA |

Table 3. 4: Global Climate Models Used to drive the Weather Research and Forecasting (WRF) model used in this study (Fatoumata, 2018)

| **Modelling Centre** | **Institution** | **Model** |
|---|---|---|
| NOAA GFDL | Geophysical Fluid Dynamics Laboratory | GFDL-ESM2M |
| MOHC (additional Realizations by INPE) | Met Office Hadley Centre (additional HadGEM2-ES realizations contributed By Instituto Nacional de Pesquisas Espaciais) | HadGEM2-ES |
| MPI-M | Max Planck Institute for Meteorology (MPI-M) | MPI-ESM MR |

### 3.3.3. Regional Climate Models -WRF

Numerical models solving equations of atmospheric processes are often used for the purpose of predicting future climates. On a global scale, GCMs are most used to assess the general circulation patterns on the earth. However, the Regional Climate Models are the most appropriate for high resolution regional or local scale features. The RCMs are usually driven by the GCMs and this process is called nested modeling technic.

The Weather Research and Forecasting (WRF) model is an example of a numerical model used for limited area weather prediction and climate simulations. WRF can be used in both research and operations. The version 3 of the Advanced Research WRF has been available since 2008. WRF is a state-of-the-art atmospheric simulation system that is portable and efficient on parallel computing platforms. It is suitable for a large number of applications across scales up to thousands of km such us Idealized simulations, Data assimilation research, parameterization research, forecast research, Hurricane research, regional climate research and many others. The WRF modeling system software is in the public domain and is freely available for community use.

## 3.4. Experiment

### 3.4.1. Ensemble Experiment Design

In this study a combination of three GCMs (MPI, GFDL, HAD-GEM) with one RCM (WRF) were obtained from the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL). The Representative Concentration Pathway Scenario RCP 4.5 (Van Vuuren, et al., 2011) was considered for the study. RCPs are climate change scenarios that describe alternative trajectories of $CO_2$ emissions and the resulting concentration in the atmosphere from 2000 to 2100 established by the IPCC in its fifth Assessment Report (AR5) in 2014. The RCP 4.5 scenario is considered because of limited computational resources and on the basis of the fact it is a more reasonable scenario in the light of Paris' COP21 climate agreement in December 2015.

The temperature and precipitation extremes are also covered by the selected GCMs including those in the GCM ensemble used in the Coordinated Downscaling Experiment (CORDEX) and span large range of conditions until about 2060 than the two scenarios (i.e. RCP 4.5 and RCP 8.5) and are able to reproduce the dominant, large-scale atmospheric features over West Africa (Elguindi et al., 2014 and Nikulin et al. , 2013). Furthermore, to a control run using reanalysis data used to verify the models and for correction. The control run using the reanalysis forcing data (instead of a GCM) to drive the WRF model, is conducted for the period ranging from 1979 to 2014 and for the historical on the period 1979-2005 and extended until 2100 by the RCP 4.5 (Fig. 3.5). Statistics are derived from climatological reference period from 1980-2010 using the approach as described by the World Meteorological Organization (2011). For the future climates the calculations are made for periods ranging from 2019-2050 and 2069-2100 until the end of the 21st century.

High-performance Computing Centers (HPC) are required to generate an ensemble of climate projections at a resolution of 12 km and for around 90 years which is a process over many years.

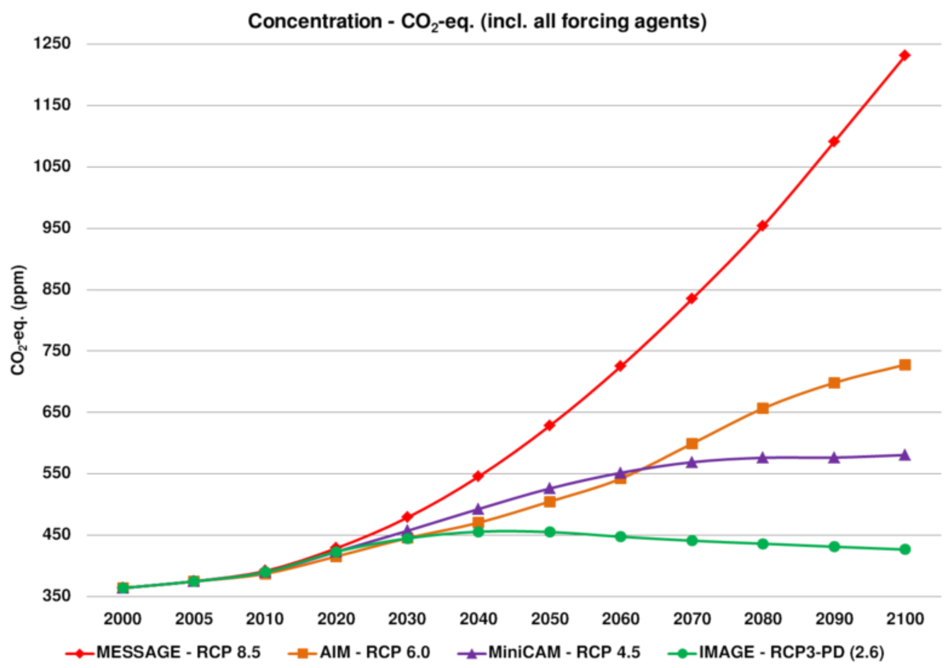


Fig. 3. 4: Representative Concentration Path Scenarios -RCPs (Richard et al., 2008)

### 3.4.2. WRF Model Configuration

Studies like (Browne & Sylla, 2012) has shown that, the ability of Regional Climate Models (RCM) to determine the regional and large-scale patterns related to West African monsoon flow, is largely dependent on the RCM domain extent. The nested domain configuration is displayed on the figure (Fig. 3.6) for the ensemble experiment. An outer domain of 60 km resolution is used in order to downscale the coarse global forcing datasets and an inner domain of 12 km horizontal resolution is nested within the 60 km domain so that the initial and boundary conditions for the inner domain are from the outer domain. Moreover, the figure also highlights additional parameters such as the agro-climatologic zones in West Africa. A common standard for the model output was defined for all model runs to make it easy to use the results and that is in addition to the configuration of the models. All data is gathered in a net-CDF CF-1.6 compliant format on a regular latitude-longitude grid for a pre-defined set of variables and pressure levels.

Limited area modelling sometimes encounters problems especially when giving lateral boundaries to nested models. This could even make the RCM solution to become inconsistent with the data forcing. For long-term transient simulations this can be problematic especially when associated with large computational domain (Warner et al., 1997; Harris & Durran, 2010; Park et al., 2014). Different approaches to address the problem include more frequent re-initialization suitable for simulations of individual weather event whereas for climatic application, longer re-initialization is more appropriate.

The ERA-interim driven control run where the data from 1980 to 2014 obtained comprise four-time slices as follows: 1979-1990, 1989-2000, 1999-2010 and 2009-2014. For the purpose of this study, the simulation was done from say 1979 but the first year was discarded and the averaging done from 1990 to 2000. This approach allows the WRF model to spin up and evolve the necessary fine-scale structures, embedded in the large-scale features of the forcing global model, without departing too far from the global conditions. For the studies of climate change impact, an optimal configuration of the WRF model is paramount.

For the case of West Africa, the accurate representation of the West African Monsoon (WAM) features is important in the model. Many studies such as Klein et al. (2015) has shown that physical parameterization available in WRF, namely those measured in the near temperature and precipitation accuracy, can have a great influence on the model's quality. This setup is based on the Klein et al. (2015) WRF parameter study of 27 combinations of microphysics, planetary boundary layer and cumulus schemes for two extreme years (dry and wet), forced by ERA-Interim re-analysis data. To account for the different characteristics and resolutions of re-analysis data and GCM data, we extended their study and tested their most promising configurations using MPI-ESM MR (close to the CMIP5 multi model mean; Nikulin et al., 2013) as forcing data. The resulting optimal setup of WRF used in the WASCAL high-resolution ensemble experiment is thus a compromise to obtain good performance for both ERA-Interim and MPI-ESM MR forcing. The output of the coarser resolution, D1(60 km) model runs as forcing data set is used to carry out the high-resolution, D2 runs (12 km) as a nested simulation. The coarser resolution model runs are forced by the different re-analysis and GCM data sets described above. An offline-nesting approach is adopted, which implies no feedback from the 12 km experiments to the 60 km experiments. Thus, the 60 km experiments can be considered as standalone experiments at a relatively coarse resolution.

The experiments are conducted as time-sliced runs of 11-year duration each, where the first year is considered as spin up period and should not be used in the analysis. The historical run 1999-2006 is carried over into the projection run 2006– 2010 to be able to provide model data for the WMO reference period 1980–2010 by combining the three-decadal time-slice experiments 1979–1990, 1989–2000, 1999–2010 the average from the 1979-1990 to 1989-2000 were used in this work and neglecting the spin up year for each of them (Dieng, et al., 2017) and also accounts for the higher resolution (12 km versus 24 km in Klein et al., 2015) according to a study conducted by Fatoumata (2018).

Table 3. 5: Output variables of the WASCAL WRF climate simulations. (Fatoumata, 2018)

| WRF name | Output name | Units | Stream | Type | Description (long name) |
|---|---|---|---|---|---|
| ACLWDNB | rlds | J m-2 | wrfsfc | acc | Accumulated surface downwelling longwave radiation |
| ACLWDNT | rldt | J m-2 | wrfsfc | acc | Accumulated TOA incident longwave radiation |
| ACLWUPB | rlus | J m-2 | wrfsfc | acc | Accumulated surface upwelling longwave radiation |
| ACLWUPT | rlut | J m-2 | wrfsfc | acc | Accumulated TOA outgoing longwave radiation |
| ACSWDNB | rsds | J m-2 | wrfsfc | acc | Accumulated surface downwelling shortwave radiation |
| ACSWDNT | rsdt | J m-2 | wrfsfc | acc | Accumulated TOA incident shortwave radiation |
| ACSWUPB | rsus | J m-2 | wrfsfc | acc | Accumulated surface upwelling shortwave radiation |
| ACSWUPT | rsut | J m-2 | wrfsfc | acc | Accumulated TOA outgoing shortwave radiation |
| ALBEDO | alb | 1 | wrfsfc | inst | Albedo |
| CANWAT | canwat | kg m-2 | wrfsfc | inst | Canopy water |
| CLDFRA | cl | 1 | wrfprs | inst | Cloud area fraction |
| DEPTH | depth | m | wrfsfc | coord | Depth |
| EMISS | ems | 1 | wrfsfc | inst | Surface emissivity |
| GHT | zg | m | wrfprs | inst | Geopotential height |
| GRDFLX | hfg | W m-2 | wrfsfc | inst | Ground heat flux |
| HFX | hfss | W m-2 | wrfsfc | inst | Surface upward sensible heat flux |
| HGT | orog | m | wrfsta | inst | Terrain height |
| ISLTYP | sltype | 1 | wrfsta | const | Dominant soil category |
| IVGTYP | vegtype | 1 | wrfsta | const | Dominant vegetation category |
| LANDMASK | sftlf | 1 | wrfsta | const | Land binary mask (1 for land, 0 for water) |
| LAT | lat | degrees_north | wrfclm, wrfprs, wrfsfc, wrfsta | coord | Latitude, south is negative |
| LH | hfls | W m-2 | wrfsfc | inst | Surface upward latent heat flux |
| LON | lon | degrees_east | wrfclm, wrfprs, wrfsfc, wrfsta | coord | Longitude, west is negative |
| MU | amdry | Pa | wrfsfc | inst | Dry air mass in column |
| PBLH | zmla | m | wrfsfc | inst | Atmosphere boundary layer thickness |
| PLEV | plev | hPa | wrfprs | coord | Pressure |

| | | | | | |
|---|---|---|---|---|---|
| PMSL | psl | Pa | wrfsfc | inst | Sea level pressure |
| PSFC | ps | Pa | wrfsfc | inst | Surface air pressure |
| Q2 | vaps | kg kg-1 | wrfsfc | inst | Near-surface water vapor mixing ratio |
| QCLOUD | clw | kg kg-1 | wrfprs | inst | Cloud water mixing ratio |
| QFX | mfs | kg m-2 s-1 | wrfsfc | inst | Surface upward moisture flux |
| QICE | cli | kg kg-1 | wrfprs | inst | Ice mixing ratio |
| QRAIN | clr | kg kg-1 | wrfprs | inst | Rain water mixing ratio |
| QSNOW | cls | kg kg-1 | wrfprs | inst | Snow mixing ratio |
| QVAPOR | vap | kg kg-1 | wrfprs | inst | Water vapor mixing ratio |
| RAIN | pr | mm | wrfsfc | acc | Accumulated precipitation |
| RH | hur | % | wrfprs | inst | Relative humidity |
| RH2 | hurs | % | wrfsfc | inst | Near-surface relative humidity |
| SEAICE | sic | 1 | wrfsfc | inst | Sea ice binary mask (1 for sea ice, 0 for water) |
| SHDMAX | vegmax | 1 | wrfsta | const | Annual max vegetation fraction |
| SHDMIN | vegmin | 1 | wrfsta | const | Annual min vegetation fraction |
| SKINTEMPMAX | tsmax | K | wrfclm | max | Daily maximum surface skin temperature |
| SKINTEMPMIN | tsmin | K | wrfclm | min | Daily minimum surface skin temperature |
| SMCREL | mrrlsl | 1 | wrfsfc | inst | Relative soil moisture |
| SMOIS | mrlsl | m3 m-3 | wrfsfc | inst | Water content of soil layer |
| SMOIST | mrso | m3 m-3 | wrfsfc | inst | Total soil moisture content |
| SNOALB | albmax | 1 | wrfsta | const | Annual max snow albedo in fraction |
| SNOW | snw | kg m-2 | wrfsfc | inst | Snow water equivalent |
| SNOWH | snd | m | wrfsfc | inst | Physical snow depth |
| SPDUV | wind | m s-1 | wrfprs | inst | Wind speed |
| SPDUV10 | sfcWind | m s-1 | wrfsfc | inst | Near-surface wind speed |
| SPDUV10MAX | sfcWindmax | m s-1 | wrfclm | max | Daily maxmimum near-surface wind speed |
| SR | prfz | 1 | wrfsfc | inst | Fraction of frozen precipitation |
| SST | tso | K | wrfsfc | inst | Sea surface temperature |
| SWDDIF | swddif | W m-2 | wrfsfc | inst | Shortwave surface downward diffuse irradiance |
| SWDDIR | swddir | W m-2 | wrfsfc | inst | Shortwave surface downward direct irradiance |
| SWDDNI | swddni | W m-2 | wrfsfc | inst | Shortwave surface downward direct normal irradiance |
| T | ta | K | wrfprs | inst | Air temperature |
| T2 | tas | K | wrfsfc | inst | Near-surface air temperature |
| T2MAX | tasmax | K | wrfclm | max | Daily maximum near-surface air temperature |
| T2MIN | tasmin | K | wrfclm | min | Daily minimum near-surface air temperature |

| | | | | | |
|---|---|---|---|---|---|
| TCLDFRA | clt | 1 | wrfsfc | inst | Total cloud fraction |
| TD | td | K | wrfprs | inst | Dew point temperature |
| TD2 | tds | K | wrfsfc | inst | Near-surface dew point temperature |
| TH2 | thetas | K | wrfsfc | inst | Near-surface potential temperature |
| TIME | time | hours since 1970-01-01 | wrfclm, wrfprs, wrfsfc, wrfsta | inst | Time |
| TMN | tsll | K | wrfsfc | inst | Temperature of soil at lower boundary |
| TSK | ts | K | wrfsfc | inst | Surface skin temperature |
| TSLB | tsl | K | wrfsfc | inst | Temperature of soil |
| U | ua | m s-1 | wrfprs | inst | Eastward wind |
| U10 | uas | m s-1 | wrfsfc | inst | Eastward near-surface wind |
| U10MAX | uasmax | m s-1 | wrfclm | max | Daily maximum eastward near-surface wind |
| V | va | m s-1 | wrfprs | inst | Northward wind |
| V10 | vas | m s-1 | wrfsfc | inst | Northward near-surface wind |
| V10MAX | vasmax | m s-1 | wrfclm | max | Daily maximum northward near-surface wind |
| VEGFRA | veg | 1 | wrfsfc | inst | Vegetation fraction |
| W | wa | m s-1 | wrfprs | inst | Upward wind |

The variable types are "acc" (accumulated values), "coord" (coordinate variables), "const" (constant values), "min" (minimum over last output interval), "max" (maximum over last output interval)

### 3.4.3. Description of Nesting Strategy

A higher resolution domain D2 with a spatial resolution of 12 km is nested within a coarser 60km resolution domain D1. The re-analysis and GCM datasets described earlier, were used as forcing datasets. An offline-nesting approach is adopted, which means there is no feedback from the 12 km domain to the 60 km domain. Thus, the 60 km (D1) domain data can be considered as an independent experiment at a relatively coarse resolution.

Time-sliced runs of 11 years' duration each were used for the experiment. In every time-slice, the first year is considered as a spin up period and is not used in the analysis. Three-decadal time-slice experiments 1979–1990, 1989–2000, 1999–2010 and an average from the 1979-1990 and 1989-2000 were used (Fatoumata, 2018).

The figure (Fig. 3.6) below displays the 60 km outer domain and the 12 km inner domain. It also shows the three distinct agro-climatological regions of West Africa.

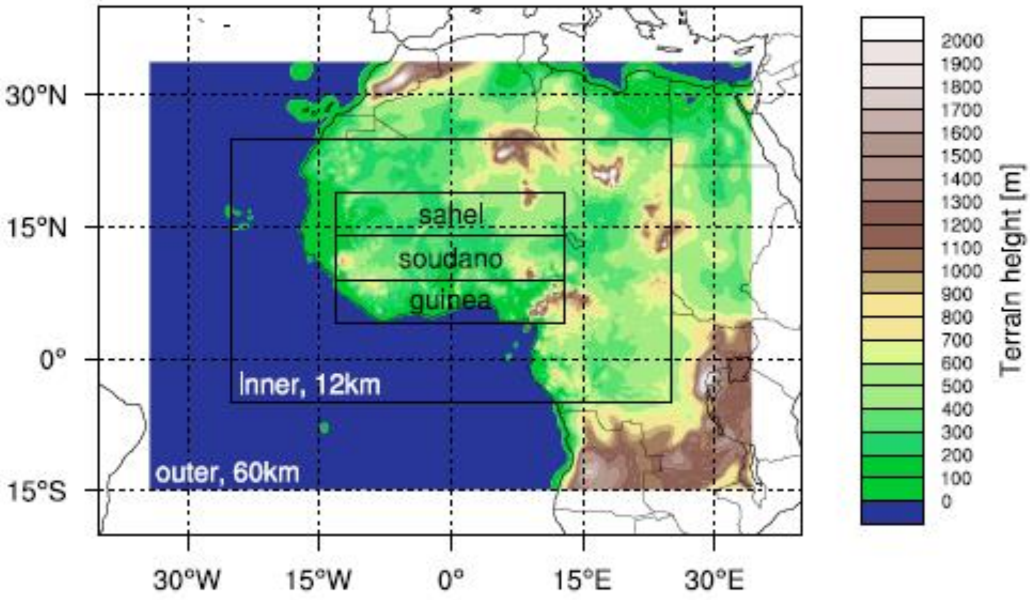


Fig. 3. 5: Nested domain configuration (Dieng, 2017).

Table 3. 6: Time-slices generated in the WASCAL WRF ensemble experiment (Fatoumata, 2018).

| Scenario | Time-slices |
|---|---|
| Control (ctrl) | 1979–1990, 1989–2000, 1999–2010, 2009–2014 |
| Historical (hist) | 1979–1990, 1989–2000, 1999–2005 (continued by 2006–2010) |
| Projection (rcp4.5) | 2006–2010 (continued from 1999–2005), 2019–2030, 2029–2040, 2039–2050, 2069–2080, 2079–2090, 2089–2100 |

Table 3. 7: Re-analyses and global circulation models (earth system models) used as forcing data for the long-term regional climate simulations and model used to conduct the ensemble experiment. (Fatoumata, 2018).

| GCM/ESM | Characteristics for West Africa | CCS | Reference |
|---|---|---|---|
| ERA-Interim | re-analysis, "perfect atmosphere" | — | Dee et al. (2011) |
| MPI-ESM MR | temp. close to OBS/MMM | medium | Stevens et al. (2013) |
| HadGEM2-ES | precip. close to OBS/MMM | large | Jones et al. (2011) |
| GFDL-ESM2M | both differ from OBS/MMM | small | Anon (2012) |
| **RCM** | **Model configuration for West Africa** | | **Reference** |
| WRFV3.5.1 | see Table 9 | | Skamarock et al. (2008) |

The characteristics of the forcing models for Africa and their Climate Change Signal (CCS) are taken from Elguindi et al. (2014); OBS means observations, MMM the CMIP5 Multi-model ensemble Mean.

Table 3. 8: Computational resources used for the WASCAL high-resolution regional climate ensemble experiment

| GCM/ESM | RCM | Experiment | HPC |
|---|---|---|---|
| ERA-Interim | WRFV3.5.1 | control | DKRZ Blizzard |
| MPI-ESM MR | WRFV3.5.1 | hist./proj. | JSC Juropa |
| GFDL-ESM2M | WRFV3.5.1 | hist./proj. | JSC Juropa |
| HadGEM2-ES | WRFV3.5.1 | hist./proj. | JSC Jureca |
| Preprocessing | | | KIT/IMK-IFU Kea |
| Postprocessing | | | DKRZ Mistral |

Control runs are conducted for the period 1979–2014, historical runs for the period 1979–2010 and RCP4.5 projection runs for the periods 2019–2050 and 2069–2100.

### 3.5. Methodology

In order to carry out the study, the 12km horizontal resolution WRF Model simulations from https://cera-www.dkrz.de/WDCC/ui/Project.jsp?acronym=WASCAL.WRF was used to get three-hourly data of temperature (ts), shortwave surface downward direct radiation (*swddir*) and shortwave surface downward diffuse radiation (*swddif*). The WRF model was forced by the ERA-Interim as control experiment and the Coupled Model Inter-comparison Project Phase 5 (CMIP5) GCMs. For the historical and control, data from 1979-2006 were used, whereas for the climate change projection the RCP 4,5 was considered for the period of 2019-2050 and 2069-2100. Statistical calculations are used to test the changes in the different physical parameters mentioned above.

### 3.6 Analysis Procedure

From the three-hourly data obtained, the monthly and yearly mean of ts, swddir, swddif were calculated. The computed mean values of monthly and yearly solar radiations and temperature were used for the analysis in this study. Simulations of WRF12KM-GFDLESM, WRF12KM-HADGEM2, WRF12KM-MPI were used for the historical simulations and WRF12KM-ERA-INT for the control simulations or run.

Firstly, monthly mean data of the considered physical parameters from the three Global climate model historical simulations (WRF12KM-GFDLESM, WRF12KM-HADGEM2, WRF12KM-MPI) from 1979 to 2006 were compared to the control simulation (WRF12KM-ERA-INT) for the same period. Identifying which of the three previous model simulations is best correlated with the control simulation, was the objective of the procedure. For this purpose, the study conducted by Fatoumata (2018) was considered. She constructed Taylor diagrams of all the variables over three West African regions (Savana, Sahel and Guinea Cost) with the NCL software in order to select the suitable GCMs for the study.

Taylor diagrams (Taylor, 2001) are generally used to provide a way of graphically summarizing how closely a pattern (or a set of patterns) matches observations. The correlation of the patterns and observation, their centered root-mean-square difference and the amplitude of their variations (represented by their standard deviations) are used to quantify the similarities between the patterns. Taylor diagrams are especially useful in evaluating multiple aspects of complex models or in gauging the relative skill of many different models.

Secondly, an analysis of the trend and variability of temperature (ts), shortwave surface downward direct radiation (*swddir*) and shortwave surface downward diffuse radiation (*swddif*) over the cities of Niamey and Agadez was done and the future evolution of these parameters explored, using rcp4.5 scenarios for the period of 2019-2050 and 2079-2100. Based on the analysis, a comparison was carried out to assess the suitability of the two locations to solar PV. The analysis was done using NCAR Command Language (NCL) which is a programming software very suitable for atmospheric related data processing and visualization as well as Climate Data Operator (CDO) for data manipulation and analysis.

Additionally, investigation was done to determine the existing renewable energy in Niger and some policy recommendations were made in order to scale up the deployment of solar energy.

### 3.6.1. Statistics

**Linear regression of the trend analysis for significance test**

Regression analysis is a process of predicting the values of one response or dependent variable from known values of a predictor or independent variable. The strength of the relationship between the dependent and independent variables is often clear when a scatter plot is drawn. A least square line can be fitted to describe the relationship. The strength of the relationship between the dependent and independent variables is determined by the coefficient of determination, *R*-square, which measures the reproducibility of the response variable from the predictor values. The *R*-square values range from 0 (for no relationship) to 1 (for very strong relationship). The relationship between the response variable y, and the predictor variable x is summarized by a linear equation $\mathbf{y = bx + a}$, where **b** and **a** are respectively the slope of the least square regression line and its intercept on the y axis. Normal distribution is a requirement for optimal regression analysis. Where the data is other than normal, a transformation scheme is applied to rectify it. A log transformation is frequently used to correct data that is not normally distributed.

$$y_i = \alpha + \beta * x_i + \varepsilon_i$$

Where Epsilon describes the random component of the linear relationship between X and Y.

The probability value (p-value) is the most important concept of statistical significance and therefore an applicability of the results of a (trend) test.

The p-value represents the probability of an error when considering how the real value of an estimated parameter differs from the computed (or static) one. For example, that the null hypothesis holds although we considered the alternative one. Usually, if the p-value is under 5%, we accept the alternative hypothesis, because the risk of its invalidity is relatively low.

# CHAPTER 4

# RESULTS AND DISCUSSIONS

## 4.1. Introduction

In this chapter, the variability and trends of the shortwave downward direct irradiance, shortwave downward diffuse irradiance and the surface temperature, for present and future climates, are discussed. In addition to that, existing energy policies of Niger which include the renewable energy policy are also presented. The results are illustrated as graphs, tables and maps.

## 4.2. Global Climate Models Selection (GCMs)

In order to identify which GCM is most suitable for driving the WRF12km model in the Sahel, the results of Fatoumata (2018) was used. Her work was on the simulation of solar energy potential over Bamako and Mopti in Mali, where the WRF-GCM driven (i.e. GFDL, MPI, HADGEM) simulations were compared to the WRF-ERA-Interim driven simulation over the Guinea-Coast, Sahel and Savanna of West Africa.

The study used statistics obtained from Taylor diagram such as correlation, root mean square error (RMSE) and standard deviation to identify GCMs that drive WRF to best simulate shortwave downward direct irradiance, shortwave downward diffuse irradiance and surface temperature over the previously cited regions. To this end, a comparison is made with the ERA-Interim driven simulation for each GCM used to drive the WRF at 12 km horizontal resolution.

Niger, just like Mali, is located in the Sahel region. Therefore, the GCM forcing that gave the best results Obtained from the WRF 12 km simulation for the Sahel in the Fatoumata (2018) study, was used for this study over Niger. As stated earlier, the trend and variability of shortwave surface downward direct irradiance, shortwave surface downward diffuse irradiance and surface temperature obtained from WRF 12 KM simulation were analyzed. The RCP4.5 scenario was used to project the different parameters for the middle of the twenty first century (2019-2050) and the end of twenty first century (2069-2100) for Niamey and Agadez.

It should be noted, that due to, lack of data coverage until the end of the century (period from 2069-2100) for shortwave-surface-downward-direct-irradiance and shortwave-surface-downward-diffuse-irradiance, reference was made to the study conducted by Fatoumata (2018), where the trends and variability of these parameters were projected over Bamako and Mopti which are Sahelian cities too.

According to the study conducted by Fatoumata (2018), the best GCMs for driving the WRF model to simulate each parameter is the one with highest correlation and lowest RMSE. Therefore, the study came up with the following results:

- All the forced GCMs (i.e. GFDL, MPI, HADGEM) have well estimated *swddif* over the Sahel regions but from of the three models MPI has the highest correlation and lowest RMSE.
- All the forced GCMs have underestimated *swddir* over the Sahel regions but of the three models MPI has the highest correlation and lowest RMSE.
- All the GCMs estimated *ts* well. MPI and HADGEM were selected over this region. In this study MPI was considered.

## 4.3. Variability and Trend of Projected Solar Radiation

### 4.3.1. Variability and Trend of Projected Shortwave-Surface-Downward-Direct-Irradiance over Niamey and Agadez

The figure 4.1 below shows inter-annual evolution of shortwave downward direct irradiance for the historical period (1979-2005) to the near future (2019-2050) over Niamey and Agadez under RCP4.5 Scenario.

For the period of 2019-2050 compared to the historical period of 1979-2005, a decrease in swiddir is observed for most of the months of the year, except for the months of July, August and October for Niamey (Fig. 4.1, (c)) and April, July and August for Agadez (Fig. 4.1, (d)) where an increase is observed. The increase could be due to the rainy season and hence more cloud cover during these months. The increase in April in Agadez is due to particles in the environment caused by harmattan winds. From (Fig. 4.1, (a), (b)), peaks are observed in the months of May, June and September for Niamey and in April, July and September in Agadez. However, increase in direct irradiation is higher in Agadez than Niamey. The value, up to +6W/m$^2$, observed in August for both localities compared to the reference years (Fig. 4.1, (c), (d)). The minimum is observed in the month of August for both Niamey and Agadez (Fig. 4.1, (a), (b)). Compared to the reference years, a decrease of up to -4W/m$^2$ is observed in September (Fig. 4.1, (c), (d). This could be due to increased cloud cover as August and September are within the rainy season.

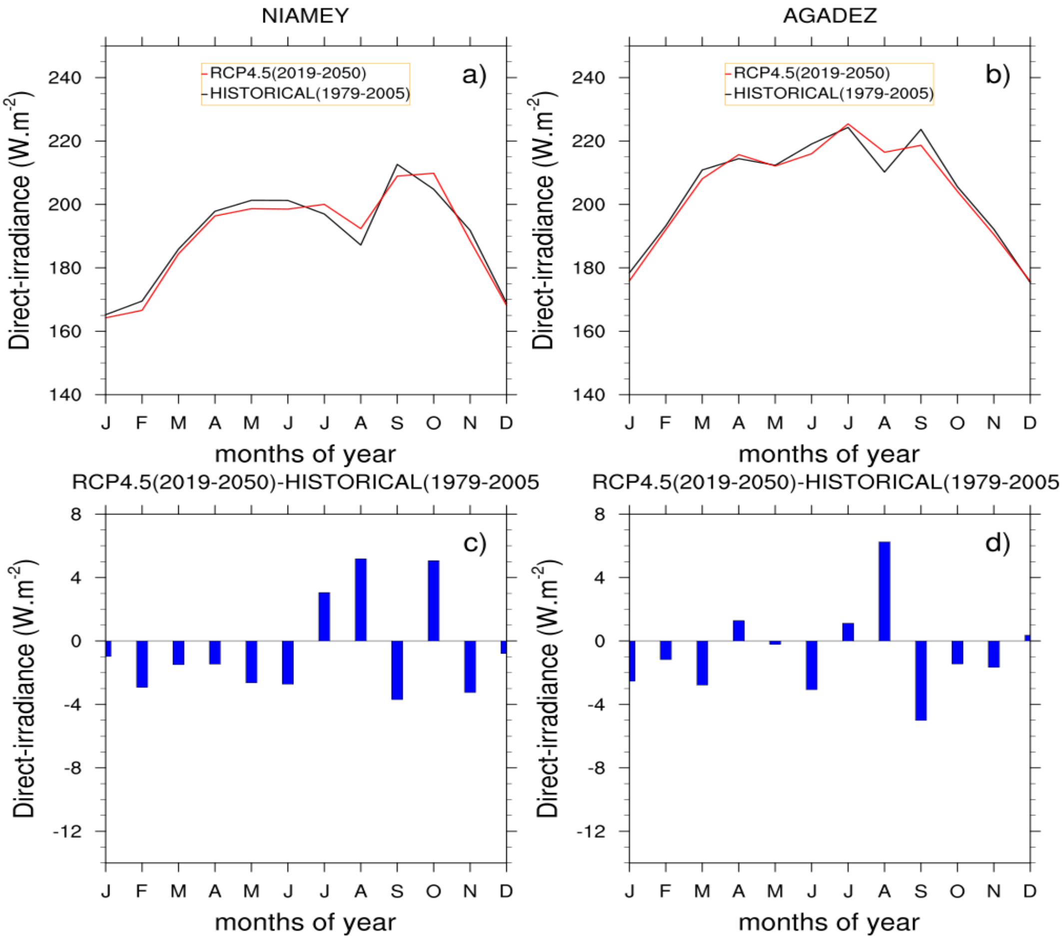


Fig. 4. 1: Time series of the inter-annual evolution of shortwave downward direct irradiance for the reference period to the near future over Niamey and Agadez under RCP4.5 Scenario; (a) rcp4.5 (2019-2050) and historical (1979-2005) for Niamey, (b) rcp4.5 (2019-2050) and historical (1979-2005) for Agadez, (c) rcp4.5 (2019-2050) minus historical (1979-2005) for Niamey, (d) rcp4.5 (2019-2050) minus historical (1979-2005) for Agadez.

Figure 4.2 and table 4.1 show a decrease of swiddir during the historical period (1979-2005) and the near future (2019-2050) for both Niamey and Agadez.

The analysis for both cities, showed a negative trend of direct irradiance for the reference period (1979-2005) as well as for the near future (2019-2050) (Fig. 4.2). Those negative trends are not statistically significant for both periods and for both Niamey and Agadez.

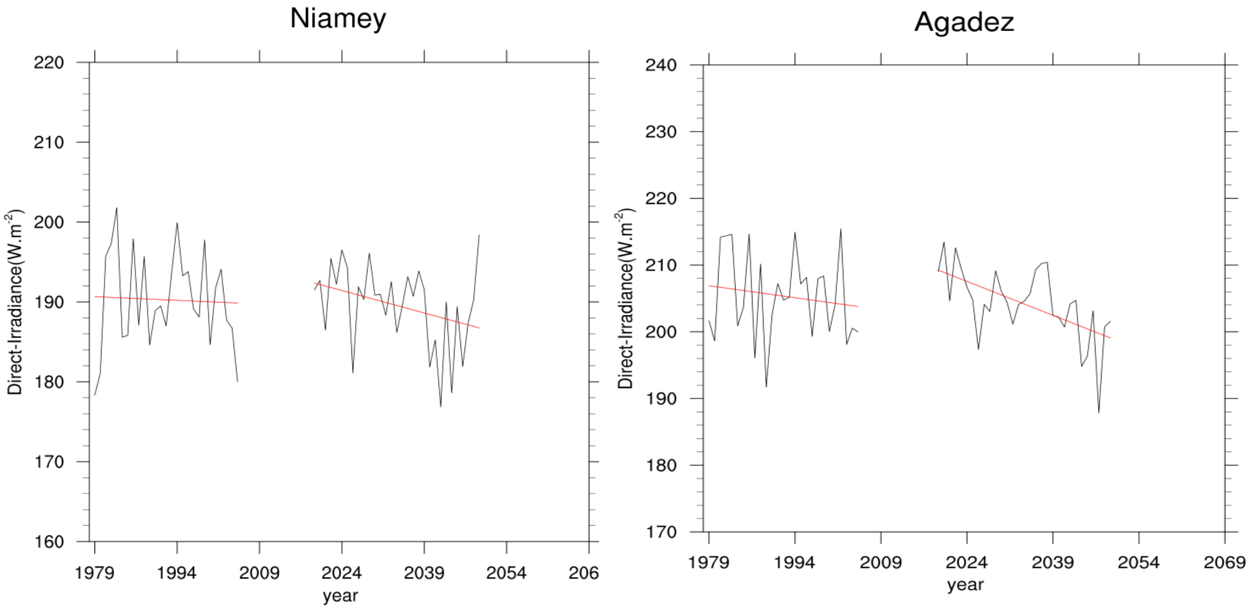


Fig. 4. 2: Time series of the inter-annual evolution of shortwave downward direct irradiance or the reference period to the near future of Niamey and Agadez under RCP4.5 Scenario.

Table 4. 1: Values of regression coefficient and probability values for swiddir

| | Period | Reg-coefficient | P-Value |
|---|---|---|---|
| **Niamey** | Historical (1979-2005) | 0.8464 | -0.0303 |
| | RCP4.5 (2019-2050) | 0.0732 | -0.1874 |
| **Agadez** | Historical (1979-2005) | 0.4684 | -0.1200 |
| | RCP4.5 (2019-2050) | 0.0007 | -0.3388 |

### 4.3.2. Variability and Trend of Projected Shortwave-Surface-Downward-Diffuse-Irradiance over Niamey and Agadez

Fig. 4.3 below shows the intra-annual plots of shortwave-surface-downward-diffuse-irradiance over Niamey and Agadez from the reference period (1979-2005) to near future (2019-2050) and the far future (2069-2100) under RCP4.5 scenario.

For the period of (2019-2050), compared to the reference period (1979-2005), there was a decrease of swiddif for all the months of the year for the two localities, except for the month of November for Niamey and June for Agadez (Fig. 4.3. c) d)). The increase of diffuse irradiance in November in Niamey could be due to increased dust in the environment caused by the Harmattan winds starting around that time and the increase in June in Agadez could be due to the increase in the cloud cover as the rainy season starts around that time of year in that locality. Two peaks in diffuse irradiance are observed during the year for both Niamey and Agadez. The peaks are observed in the months of March and August for Niamey, while in Agadez, the peaks are observed in April, May and August (Fig. 4.3. a) b)). The peaks in March for Niamey and April and May for Agadez is due to the increase in dust caused by Hamattan winds and the peak in August for both cities is due to the period of rain. The peaks in Niamey are almost the same compared to the reference years and for Agadez there was slight decrease than the reference years. However, the increase in Agadez is higher than Niamey. It is around 2 $W/m^2$ and less than 1 $W/m^2$ for Niamey, the increases are observed in June in the first and in November for the second (Fig. 4.3. c) d)). The minimum values of the diffuse irradiation are observed in the month of November for both regions (Fig. 4.3. a) b)).

During the period 2019-2050, compared to the reference period of 1979-2005, a large decrease in diffuse irradiance is observed during the month of October in Niamey and in August for Agadez (-4 $W/m^2$). These could be due to less cloud cover in those months for the two cities.

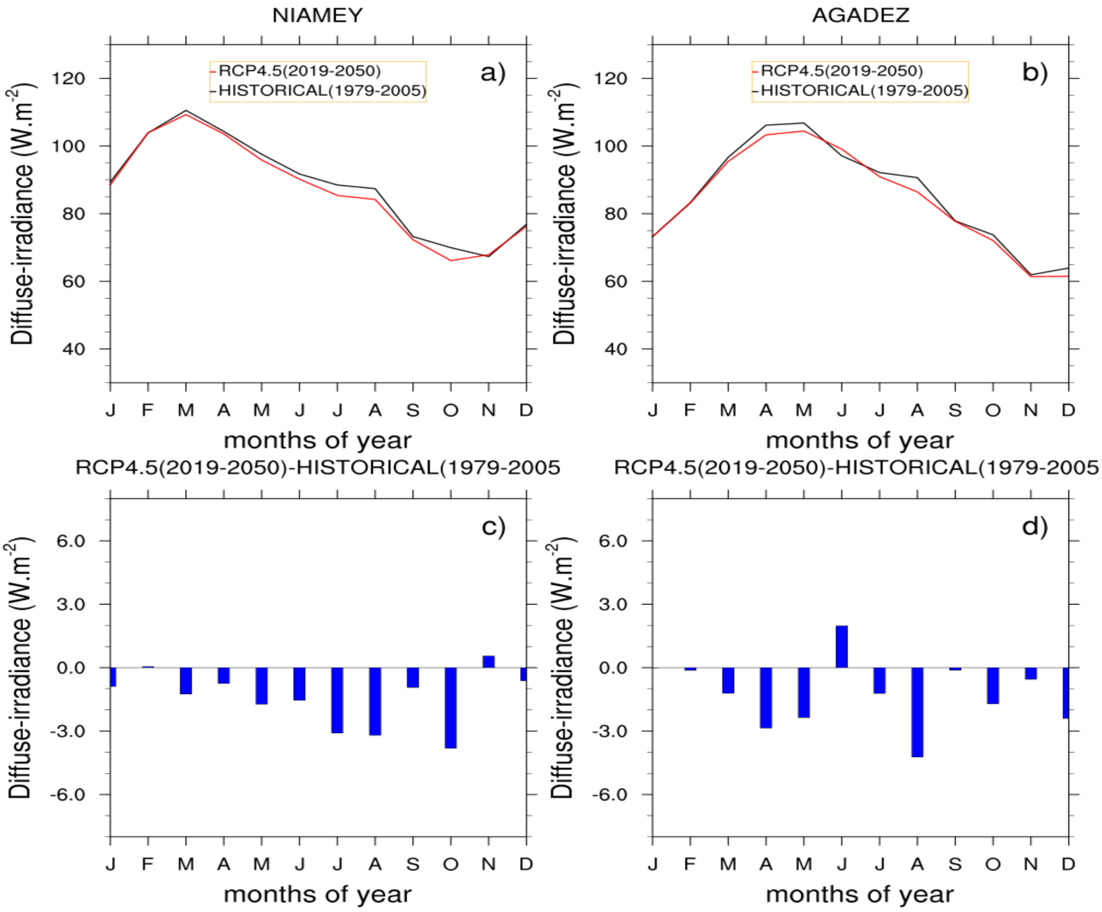


Fig. 4. 3: Time series of shortwave downward diffuse irradiance for the reference period to the near future; (a) rcp4.5 (2019-2050) and historical 1979-2005 for Niamey, (b) rcp4.5 (2019-2050) and historical (1979-2005) for Agadez, (c) rcp4.5 (2019-2050) minus historical (1979-2005) for Niamey, (d) rcp4.5 (2019-2050) minus historical (1979-2005) for Agadez.

From Fig. 4.4 and table 4.2, a decreasing trend in *swddif* is observed during the reference period (1979-2005) and an increasing trend during the near future for both cities. These increasing trends may be due to the enhanced greenhouse gases in the atmosphere. Greenhouse gases absorb some of solar radiation in the atmosphere and the remains are reflected in the earth surface as diffuse radiation. Analysis shows that a negative trend of diffuse irradiance is observed for both cities. The negative trend in Niamey is not statistically significant at all and the positive trend is statistically significant at 75% confidence level. As for Agadez, the negative trend in diffuse irradiance is not statistically significant at 99% confidence level and the positive trend is statistically significant at 58 % confidence level.

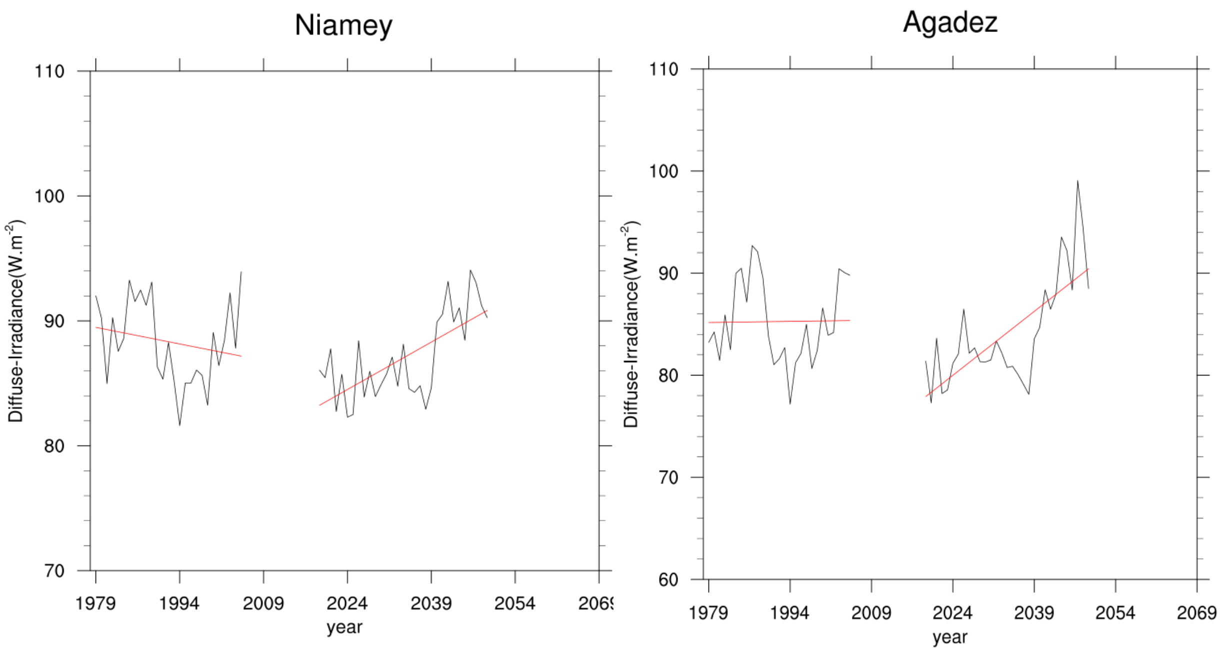


Fig. 4. 4: Time series of the inter-annual evolution of shortwave downward diffuse irradiance for the reference period to the near future over Niamey and Agadez under RCP4.5 Scenario.

Table 4. 2: Values of regression coefficient and probability values for swiddif

| | Period | Reg-coefficient | P-Value |
|---|---|---|---|
| **Niamey** | Historical (1979-2005) | 0.2969 | -0.0884 |
| | RCP4.5 (2019-2050) | 2.19e-5 | 0.2531 |
| **Agadez** | Historical (1979-2005) | 0.9438 | 0.0073 |
| | RCP4.5 (2019-2050) | 4.23e-6 | 0.4172 |

### 4.3.3. Variability and Trend of Projected Surface Temperature over Niamey and Agadez

The figure (Fig. 4.5) shows the intra-annual plots of surface temperature over Niamey and Agadez from, the reference period (1979-2005) to near future (2019-2050) and the far future (2069-2100) for RCP4.5 scenario.

A continuous increase in surface temperature is clearly observed for the near and far future over both Niamey and Agadez (Fig. 4.5; a, b, c, d). The peaks over both localities are observed in May, June, and September. A high augmentation is observed during the month of February for both near and far future (Fig. 4.5; e, f, g, h). The augmentation is up to 2° C for the near future for both cities and more than 3° C for Niamey and 2.6 °C for Agadez in the far future.

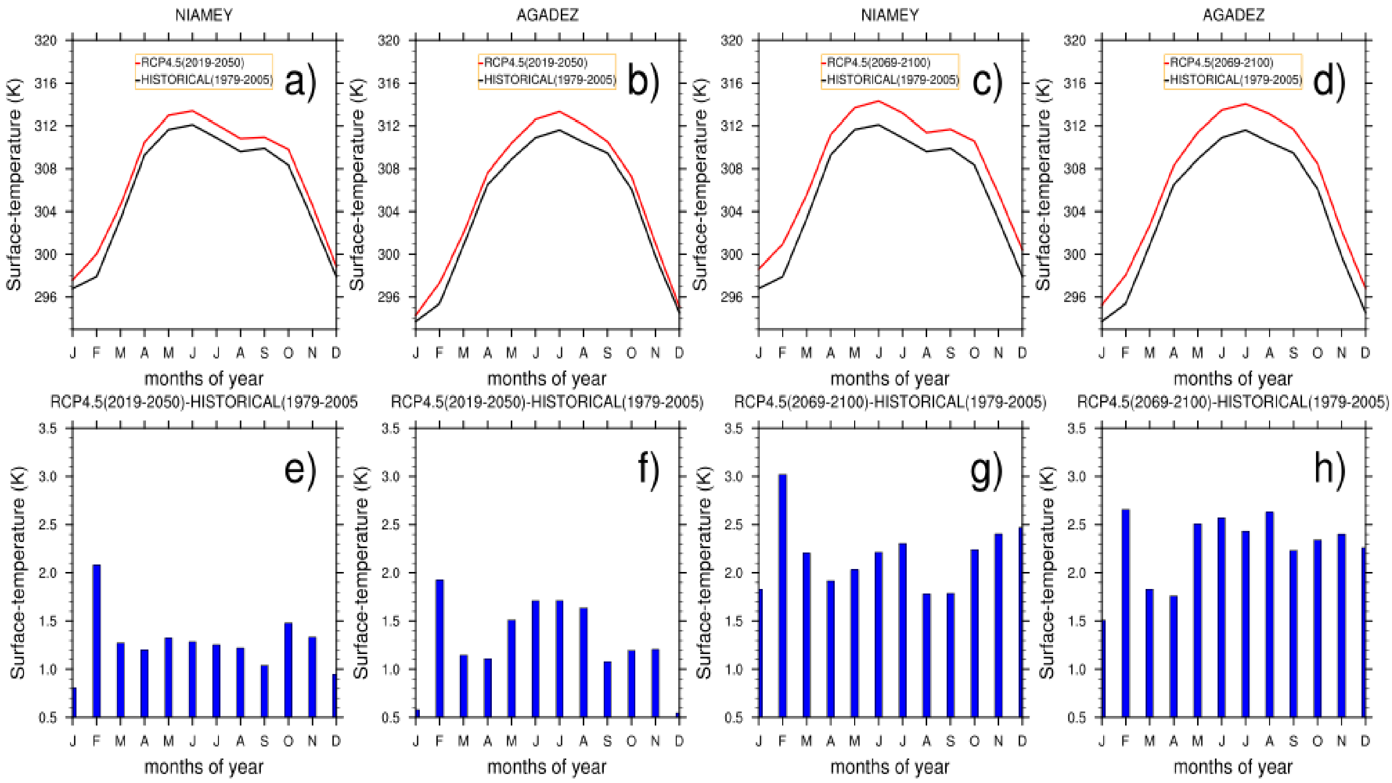


Fig. 4. 5: Time series of the inter-annual evolution of surface Temperature for the reference period to the near future and far future over Niamey and Agadez under RCP4.5 Scenario (a) rcp4.5 (2019-2050) and historical (1979-2005) for Niamey, (b) rcp4.5 (2019-2050) and historical (1979-2005) for Agadez, (c) rcp4.5 (2069-2100) and historical (1979-2005) for Niamey, (d ) rcp4.5 (2069-2100) and historical (1979-2005) for Agadez, (e) rcp4.5 (2019-2050) minus historical (1979-2005) for Niamey, (f) rcp4.5 (2019-2050) minus historical (1979-2005) for Agadez, (g) rcp4.5 (2069-2050) minus historical (1979-2005) for Niamey, (h) rcp4.5 (2019-2050) minus historical (1979-2005) for Agadez.

Fig. 4.6 shows the time series of the inter-annual evolution of trends in surface Temperature for the reference period to the near future and far future over Niamey and Agadez under RCP4.5 Scenario.

The Niamey analysis shows a positive trend in the reference period and it is not statistically significant at 95 % confidence level. The same positive trends are observed for the near and far future but are not statistically significant. The trend is positive in Agadez for the reference period (1979-2005) and it is statistically significant at 95 % confidence level. The negative trends in the near and far future are not statistically significant at 98 % confidence level.

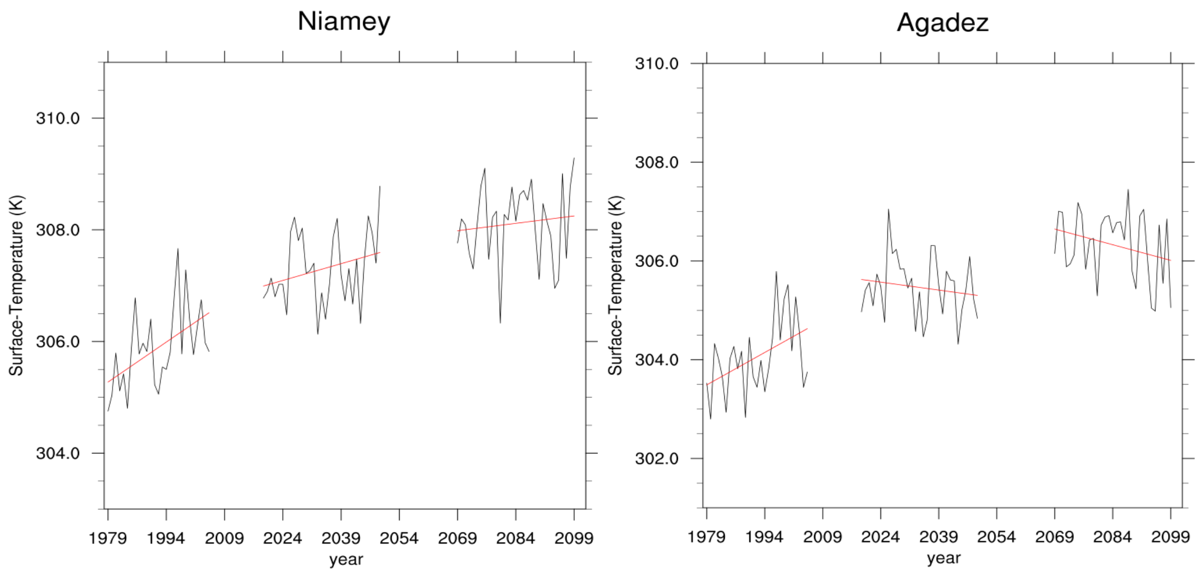


Fig. 4. 6: Time series of the inter-annual evolution of trends in surface temperature for the reference period to the near future and far future over Niamey and Agadez under RCP4.5 Scenario.

Table 4. 3: Values of regression coefficient and probability values for Surface Temperature (ts)

| | Period | Reg-coefficient | P-Value |
|---|---|---|---|
| **Niamey** | Historical (1979-2005) | 0.0048 | 0.0477 |
| | RCP4.5(2019-2050) | 0.1243 | 0.0200 |
| | RCP4.5(2069-2100) | 0.5389 | 0.0088 |
| **Agadez** | Historical (1979-2005) | 0.0168 | 0.0438 |
| | RCP4.5(2019-2050) | 0.3943 | -0.0107 |
| | RCP4.5(2069-2100) | 0.1317 | -0.0211 |

The previous results of this study were completed by investigation on the existing energy policies of Niger and policy recommendations in the last part of this study.

## 4.4. National Energy Sector

In Niger, the Ministry of Energy and Petroleum (MoEP) among others stakeholders, is in charge of the development of the national renewable energy policy, regulations, finance and action plans in the energy sector as well as defines the guidelines for the utilization of the country's RE potential especially solar and wind which are being seen as reliable energy sources that can contribute to reducing dependence vis-à-vis imported electricity.

Figure 4.7 shows the structure of the national electricity sector.

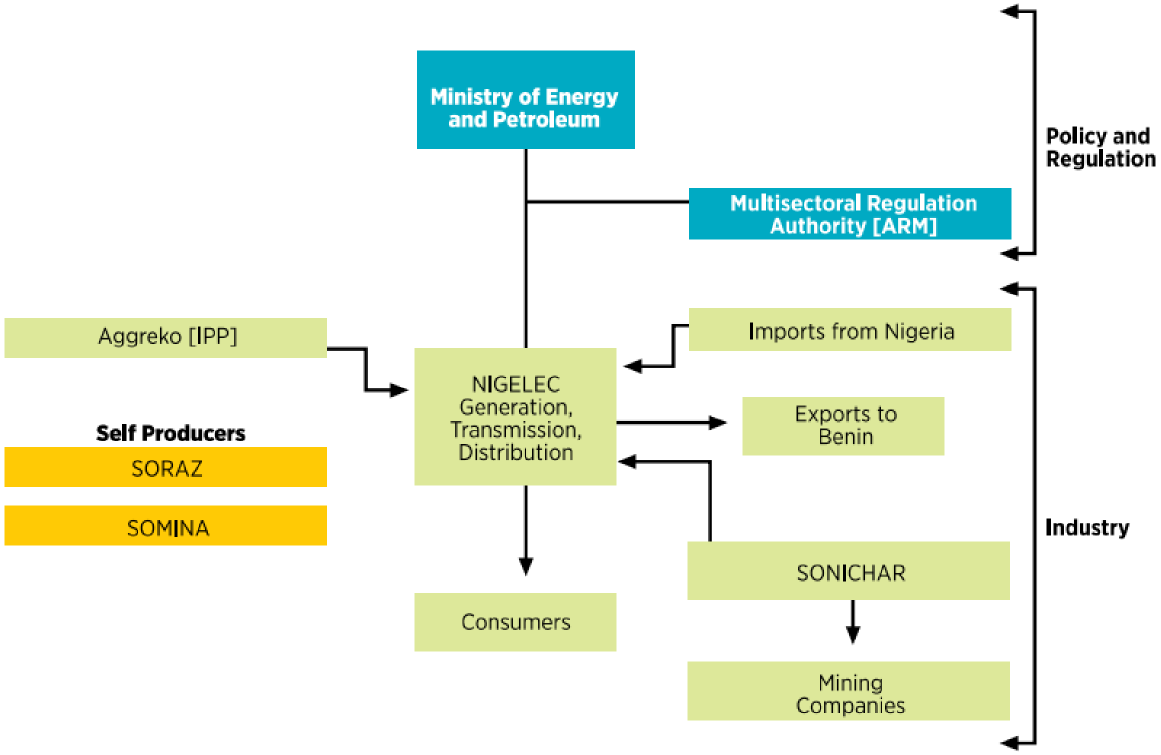


Fig. 4. 7: Niger electricity sector (IRENA, 2013)

### 4.4.1. Costs and Tariffs of Electricity in Niger

Like in a number of West African countries, electricity tariffs in Niger remains in the hands of the government and set by decree. The electricity tariff is set depending on many factors, such as the electricity production cost (including operation cost), social cost and other economic and political criteria. According to IRENA (2013), production costs in the country falls under tree categories consisting of the NIGELEC domestic power plants (USD 0.22/kWh), coal-fired plants (USD 0.12/kWh) and electricity imports from Nigeria (USD 0.04/kWh). The electricity utility (NIGELEC) purchases tax-free domestically produced diesel directly from the refinery at USD 0.70 per liter. It is worth noting that, the country will still remain dependent on cheap electricity from neighboring country, Nigeria unless the price is reviewed.

In 2012 the government initiated the creation of a social tariff in order to improve the national energy access. That social tariff is meant to support low income and low consumption citizens. Therefore, these households (3 kWh) are charged USD 0.11/kWh for the first 50 kWh consumed. Also, some plans are put in place to reduce the costs of electrical connections to low-income population (USD 102 for 3kW and USD 144 for 6 kW). Industries and agricultural facilities too, benefit of concessionary rates which are fixed at USD 0.11/kWh and USD 0.07/kWh respectively. All these tariff rates are put in place in order to achieve the social and economic development goals established by the government which require affordable and reliable energy services.

The cost of transmissions lines could amount from USD 20, 000 to 120,000/km (IRENA, 2013) which is financially not viable and unfortunately leaves a major part of the population unserved by the grid in areas far from the grid lines.

Furthermore, the national grid connection cost of USD 102 to 145 in Niger is too expensive for low-income households without adequate or appropriate financial support.

## 4.5. Solar Energy potential, Cost and Applications

Solar energy together with other renewable energy could be the solution to the unsustainable nature of the electricity generation in West Africa and particularly in Niger.

The country has adequate and sufficient solar radiation that can be utilized for power generation. The solar radiation ranges from 5 $KWh/m^2$ in the Southern part to 7 $KWh/m^2$ in the northern part of the country (Dankassoua et al., 2016). The solar energy technology could be used to expand the electricity supply in Niamey and Agadez and also other regions and most suitably for rural electrification.

Power shortage in most part of the country led to the utilization of solar energy for home power supply and street lightning. There is also solar PV-lighting in public places and hospitals. The installed capacity of solar PV in Niger was 5.2 MW in 2014 (CNES, 2015). It is used mainly for standalone power supply with no solar power plant connected to the grid system.

The following figures from the National Centre of Solar Energy (CNES) shows the use of solar energy by sectors in the country as well as in Niamey and Agadez in 2014.

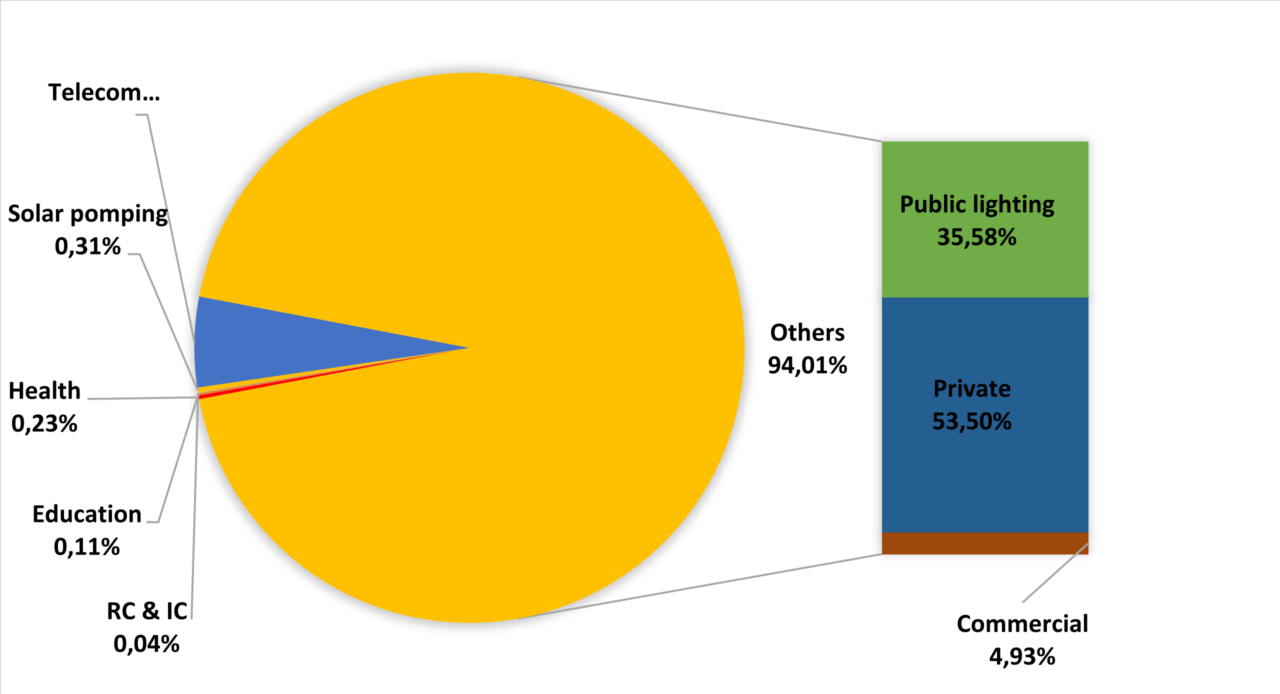


Fig. 4. 8: Solar energy share by different sectors in Niamey (CNES, 2015)

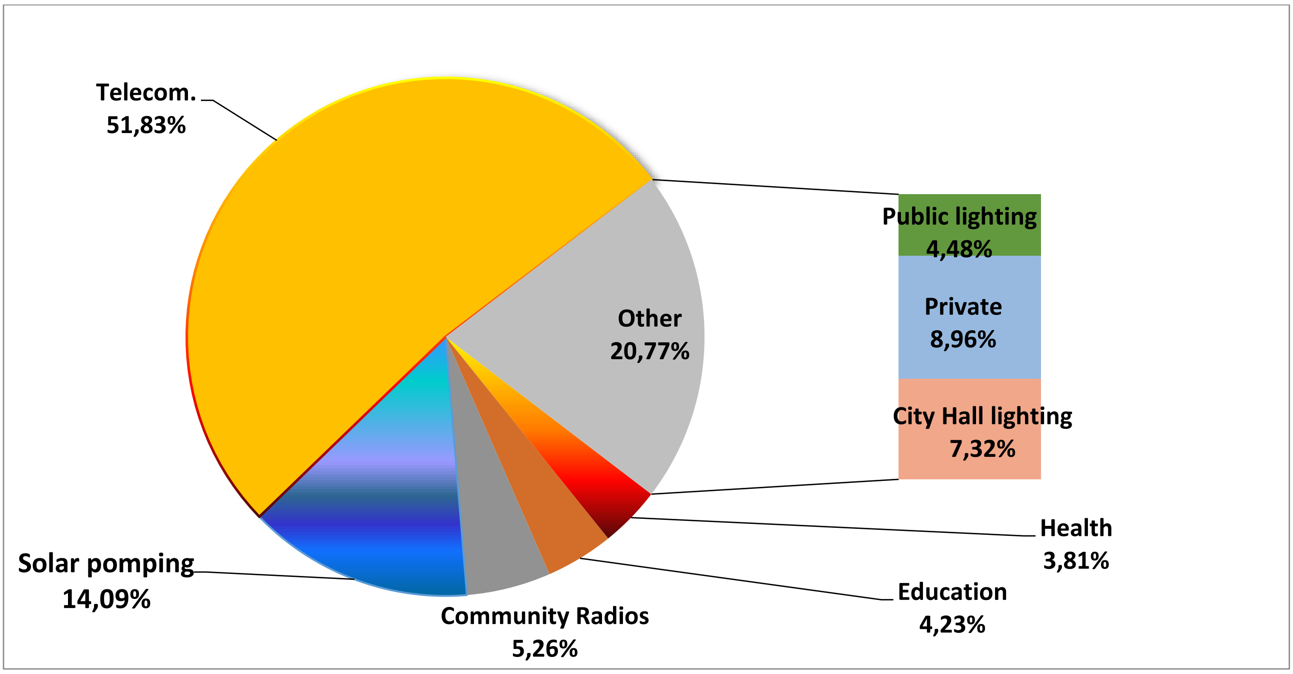


Fig. 4. 9: Solar energy share by different sectors in Agadez (CNES, 2015)

The figures 4.8 and 4.9 above are from 2014, but in recent times the contribution of solar has increased as result of the implementation of recent government public solar lighting projects countrywide. Additionally, a recent project was adopted by the government with the support of the European Union to construct a 13 MW solar power plant mixing power generation from solar PV and concentrating solar power (CSP) in Agadez.

However, the main challenges related to solar energy are among others the intermittency and variability of solar energy and the risk of overproduction and curtailment while the national grid systems are conventionally designed to operate on controllable generators rather than intermittent sources, but they still have some level of certainty.

On the other hand, the declining cost of the solar PV gives evidence that the high economic cost is not a constraint anymore to the deployment of solar PV but rather the challenge is the effective achievement of grid operations.

At the global scale, the weighted average of utility-scale installed solar PV decreased from $5/W in 2009, to about $2/W in 2015. In addition to that, the solar PV modules prices have also dropped significantly since 2009 to around $0.52/W to $0.72/W in 2015 (Nkiruka et al., 2017). In addition to the drop in the prices, the figure 4.10 shows the huge photovoltaic (PV) power potential of the country. The PV potential ranges from 1680 KWh in Niamey to 1860 KWh in Agadez annually.

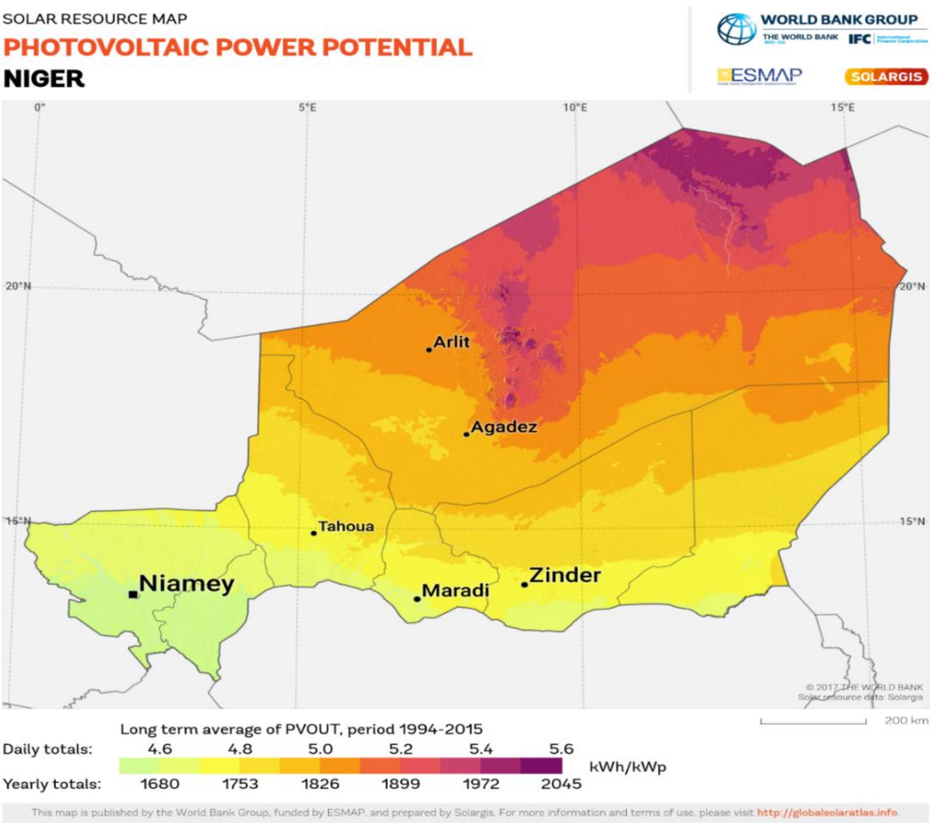


Fig. 4. 10: Photovoltaic power potential of Niger (SOLARGIS)

## 4.6. Enabling Environment for renewable energy

In general, the focus of the Niger's national Energy policies remains on conventional sources of power generation. The country is still lacking specific renewable energy policy. However, the law on electrical code review will cover issues related to renewable energy in order to create enabling conditions for the renewable energy development in the country.

### 4.6.1. Energy Policies of Niger

Niger needs to reconcile short-term imperatives for solving urgent concerns with long-term plans appropriate for the optimization of its natural and human resources for sustainable development. For that purpose, one of the important pillars of the national development is energy infrastructure to support the long-term economic growth. Renewable energy deployment through centralized or decentralized generation, will help to increase energy access for poverty reduction and local economic development. So, there is a need to create a specific supportive policy environment for renewable energy. To that end, Nigerien authorities have put in place four policies and strategies that directly governs the energy sector.

**Declaration de Politique Energétique (DPE)**

An Energy Policy Statement was adopted by Decree no. 2004-38/PRN/MME on 28 October 2004. It was created to ensure adequate and reliable energy supply at affordable prices which plays an important role in the social and economic development. DPE stipulate that Niger is endowed with its own important energy resources that need to be harnessed by the mobilization of national internal and external resources. The Energy Policy Statement advocates:

- the promotion of renewable energy and
- national energy resource improvement to help raise household energy access particularly in rural areas. National strategies on domestic and renewable energy, rural electrification, oil research promotion, and potential hydropower assessments would support this process (IRENA, 2013).

The policy played a major role in the introduction of renewable energy systems in addition to a series of follow-up strategies that were developed.

**Electricity reform 2003-2004**.

The reform of the electricity sector was implemented in 2003-4 and the Electricity Code was introduced into law through Decree no. 2003-2004. It is intended to govern the production, transmission, distribution, import and export of power. The code assert that one or more natural persons or corporate entities are authorized to build and to operate private electrical installations to their satisfaction.

The intention behind this reform, was to allow news players into the electricity market and it also constitute an initial step towards power sector privatization. However, the country did not start the privatization process.

Three energy strategies back up the energy policy, which include:

a) **Stratégie Nationale sur les Énergies Renouvelables – SNER**, The National Strategy for Renewable Energies. This strategy intends to increase the renewable energy contribution to the national energy mix from less than 0.1% in 2003 to 10% by 2020 by:

- facilitating the promotion of renewable energy supply.
- reducing the impact on forest resources.
- use of renewable energy resources to promote rural electrification.
- promoting education, training, research and development related to renewable energy technologies.

b) **Stratégie Nationale d'Accès aux Services Energétiques Modernes -SNASEM**, National Strategy for Access to Modernized Energy Services. It is intended to increase the rate of the population with access to modernized energy services by 2015 through:

- access to modern cooking fuels.
- access to grid power for villages with 1,000–2,000 inhabitants.
- access to electricity for 66% of rural and semi-urban populations

c) **Stratégie Nationale des Energies Domestiques - SNED**, National Strategy for Household Energy. This was designed for the domestic energy subsector for the creation of a coherent framework by:

- ensuring the sustainable use of forest resources and better reforestation, promoting alternative energy sources (other than wood) and improving appliance efficiency.
- reinforcing the capacity of the main market players for better management of the sector.
- educating and communicating information to stakeholders on domestic energy production and use.

### 4.6.2. Legal and regulatory framework

In order to develop and expand the national RE market, a legal and regulatory framework is in place to create a favorable investment climate and reduce technical, legal and administrative barriers while increasing private sector confidence in the sector.

- The implementation of a policy of promoting Public and Private Partnerships (PPP), consecrated by the Ordinance No. 2011-07 of September 16, 2011 and ratified by law No. 2011-30 of 25 October 2011 and the establishment of a Supporting Cell to guide investors. The PPP Supporting Cell, established by Decree No. 2011-560 / PRN / PM of 9 November 2011, was attached to the Prime Minister's Cabinet, to affirm the commitment of the authorities to the matter;
- The creation of a very incentivized legal and fiscal framework that allows foreign companies to freely conduct business without discrimination;
- The Investment Code and other sectoral laws guaranteeing the transfer of capital and investor profits;
- The creation of a unique window for the implementation of the provisions of the Law (Investment Code) to facilitate business creation or installation of foreign companies in the Republic of Niger;
- The creation of a High Council for Investment in Niger (HCIN), an orientation organ, under the authority of the President of the Republic with a main mission to organize discussion and provide guidance on matters relating to the promotion and development of domestic and foreign investment.

### 4.6.3. Financing and Investment

#### 4.6.3.1. Financing

Finance and investment in the energy sector in Niger are primarily led by state-backed companies which include NIGELEC and SONICHAR and some self-generators such as SOMINA, SORAZ and IPP Aggreko. The major part of funding from state-backed companies is obtained through development partners and institutions. These include The World Bank, African Development Bank, Islamic Development Bank, West African Development Bank and other donors. Since the enactment of the Electricity Code that has opened the generation sector to private sector, only few IPPs such Aggreko (since 2012) has entered the market. The low cost of electricity imported from Nigeria (USD 0.04/KWh) according to IRENA (2013) is mainly responsible for the lack of investment in the power generation sector. This import account for a large part of the national electricity supply.

A study conducted on the renewable energy sector showed the country experienced between 2005-2010, a cumulative solar PV investment of USD 23.8 m of which more than 90 % is made by the development partners. Meanwhile the investment in solar thermal and energy efficiency amounted at less than USD 1m over the same period and were almost entirely by household and businesses.

For many years, Niger has relied on external financial resources (technical and financial partners) to develop its energy sector. However, since 2012 the government has begun to allocate national budget for the promotion of rural electrification. The budget amounted to USD 0.8 m for 2012-2013 and was about USD 6m in 2016.

Additionally, internal mechanisms to mobilize resources also exist. These include the Energy Fund and the tax on electricity. The Energy Fund consisted of money raised through a levy of USD 0.007 on every liter of oil product sold at the pump. The tax on electricity (TSE) established since 1972, was set at USD 0.004 per kWh consumed. It contributes to financing grid extension. The resources collected through this tax amount to approximately USD 2m annually.

Part of these funds is currently reallocated to fund renewable energy promotion as well as rural electrification together with other revenues generated by mineral resource exploitation.

A law on Public Private Partnerships (PPPs) was also adopted in 2012. It enables a public and private collaboration on the development of public infrastructure. The law aims to support public administration and technical ministries in elaborating and negotiating PPP projects.

#### 4.6.3.1. Incentives for Investment in Energy Sector

The investment code is intended to grant legal protection to private investors whose programs contribute to the social and economic development of the country. The code ensures foreign investment against expropriation and/or nationalization. It also provides tree (3) privileged regimes and advantages in the first five years, depending on the amount of investment:

1. Category A (also known as the promotional category) is for investments of USD (100,000-200,000) Exemptions are made for implementation and operations. During the implementation phase, investors are completely exempt from:
    - Duties and taxes including VAT on imported materials and equipment, provided that these are not available locally;
    - Duties and taxes including VAT on consulting work and services related to the implementation of the approved investment program.

    During the operational phase, investors are completely exempt from:
    - License;
    - Property tax or estate tax;
    - Tax on industrial and commercial profits and the minimum tax.
2. Category B (also known as the priority category) is for investments of USD 200,000-1,000,000. The advantages in this category are same as those in category A, but are also accorded the following:
    - Exemption from duties and taxes (excluding VAT) on raw materials, consumables and imported or locally produced packaging;
    - Exemption from taxes duties on product exports
3. Category C (also known as the conventional category) is for investments of over USD 1,000,000. In this category, investors may also have the same advantages as the previous category. In addition, they have the possibility of claiming a 50% reduction on fuel duties and taxes and any other source of energy used in fixed equipment based on an annual agreement.

# CHAPTER 5

# CONCLUSION AND POLICY RECOMMENDATIONS

## 5.1. General Conclusion

A number of studies have proven the fact that energy resources and services will be increasingly affected by climate trends, increasing variability, greater extremes and large inter-annual variations of climate parameters. Climate have been changing since the creation but what is alarming in this recent decade is the speed at which this change is produced.

The energy sector, through the greenhouse gas (GHG) emissions is to be considered responsible for this change but it is at the same time impacted by climate change across the entire energy supply chain. The most intuitive impacts are on the energy supply and demand but there are also direct effects on energy resource endowment, infrastructure and also transportations, and indirect effects through other economic sectors (e.g. water, agriculture).

Therefore, Changes in mean climate parameters such as surface temperature and solar radiation will have impacts on some renewable energy technologies such as solar PV and Concentrating Solar Power (CSP).

In this study, the solar energy potential was assessed over West Africa under a changing climate with a focus on the cities of Niamey and Agadez in Niger. Data used were the high resolution WRF12-km data from WASCAL. The WRF-12km model output selected is based on the study conducted by Fatoumata (2018) who evaluated which of the model members in the GCMs-WRF-12 km multi model ensemble was suitable over Guinea-coast, Sahel, Savanna regions of West-Africa for the parameters, shortwave downward diffuse radiation (swddif), shortwave downward direct radiation (*swddir)* and surface temperature (*ts*). The reason being to identify the best forcing GCM for WRF over these regions with regards to the three parameters mentioned earlier. Thus, the best forcing GCM over the Sahel region was used to analyze the trend and variability of the parameters over Niamey and Agadez.

Her analysis showed that, out of the three forcing GCMs (GFDL, HADGEM, MPI) used in the multi model ensemble, MPI is the one that best estimate the *swddif* and *swddir* over Sahel compared to the reference (ERA-Interim). As for surface temperature, both MPI and HADGEM were suitable over Sahel compared to the reference (ERA-Interim). For the case of this study MPI is considered.

The results of this study showed trend and variability of shortwave surface downward direct irradiance (*swddir*), shortwave surface downward diffuse irradiance (*swddif*) and surface temperature. There was an increase in swddif over both Agadez and Niamey. But the increase in *swddif* is more significant in the near future in Agadez than in Niamey. An increase of up to +2W/$m^2$ is observed in Agadez and around 1W/$m^2$ for Niamey. However, the increase in *swddir* is almost the same for Niamey and Agadez and is around to 6 W/$m^2$. The lowest radiation values are observed in December and January. The rainy season coincides with the high solar radiation summer months.

Compared to the reference period (1979-2005), there is an increase of temperature over both localities for the near future (2019-2050) where the it is up 2.1°C in Niamey and 1.9°C in Agadez. As for the far future (2069-2100), the increase is up to 3° C for Niamey and 2.6° C for Agadez. In general, April to August is the period of high insolation, where the month of January and December are the months where the three parameters are the lowest. These months coincide with the Northern Hemisphere winter.

Thus, based on the three parameters used in this study, both localities are suitable for installation of solar energy panels to satisfy the energy needs in the country. Regarding the siting of the solar panels (or solar farms), additional factors such as topography, land cover, price of the land, proximity to the transmissions lines, and the intended national grid expansion plans, are to be considered to determine the ideal locations to install solar power facilities.

## 5.2 Policy Recommendations to Scaling Up Solar Energy Deployment

In order, for Niger to develop its RE sector, favorable policies and strong political will from the government at all levels will be needed. Additionally, the country needs substantial investments in system modernization, but more importantly, in new generation plants, as well as transmission and distribution facilities.

Therefore, to accelerate solar energy development, the following recommendations are made to the government:

### Get Around Policy Stagnation

One of the remarkable problems in Niger, and indeed in Africa, is that energy policies are a static list of goals or laws. While, policies need to be dynamic to avoid side effects and unintended consequences. For that reason, they need to undergo periodic reviews to evaluate their effectiveness and help guide operational decisions.

Existing national policies and strategies should be reviewed and revised in order to be compatible with the national development goals of supporting social welfare and encouraging income-generation activities. The creation of renewable energy laws and a master plan will be of great importance to integrating modern energy service provision in the development needs. After the creation of the law, dialogue with all the stakeholders should maintained.

### Track Record in Auctions

The country is experimented in using auctions to select IPPs for providing conventional power at competitive prices to the grid. Renewable power generation could as well learn from that practice to design renewable energy auctions, which could be used for both large-scale grid-connected power plant as well as decentralized hybrid power plant. The knowledge of the intricacies of designing renewable auctions should be made available to executives and policy makers, who in turn should ensure the success of the auctions.

### Get Around Political Fragmentation

Energy as a prime support of development in any country should cut across ministerial and sector boundaries. In Niger, policy makers face not only the energy supply and cost challenges but also other challenges due to the fractured responsibilities within the energy policy which make the different government entities prone to turf battles. This is a sign of the lack of coordination among the departments involved. This fragmentation could easily arise with the discovery of oil and gas. It could lead to power struggles between those who see the transformative potential of renewables and those who supervise the fossil-fuel sector.

This indicates a need for a comprehensive energy policy that puts the energy sector requirements within a coherent framework. Policy makers are required to appreciate the fact that a mix of technologies at different scales is the foundation for healthy energy governance in Niger, and to act on that basis.

**Support mechanisms**

The country needs to develop renewable energy laws that will establish legal, economic and institutional basis for renewable energy and devise support mechanisms such as net metering or net billing, Feed in Tariff (FiT), competitive bidding, and standardized bankable PPAs. These performance-based incentives reduce risk and can drive rapid growth of the solar energy if designed well and implemented at the right level.

The support mechanisms should be optimized based on best practice and lessons learned, thus continuously improving the policy design (more effective than a switch to a different policy). It is also advisable to keep the financing of the support scheme outside the Government budget (no effects of changes in policy design and/or allocation of budgets).

**National Solar Energy Centre (CNES)**

The CNES should be allowed to flourish as lead technical institution for renewable energy research and development (R&D) in Niger. This should be done by strengthening the capacity of CNES to conduct detailed solar energy assessment throughout the country and establish a comprehensive database. Furthermore, the institution should spearhead R&D including standard development and quality control procedures for solar equipment in addition to developing installer certification schemes and facilitate training.

**Risk insurance**

Niger like most of the developing countries run a relatively high risk for economic, political or currency system instability and also, the creditworthiness of project partners is also often doubtful. Therefore, policy makers need to find ways to reduce the various risks of renewable energy projects in general in the country through international private and public insurances in order to improve credit conditions and attract private investment and that is in addition to direct financial support.

**Loan softening and guarantees**

Loan-softening programs and loan guarantees or reassuring of guarantees given by the governments have the advantage of reducing the costs of private lending and as result they could improve the project economics.

**Technical assistance and capacity building**

Policy design alone cannot address the various technical, administrative, legal and political barriers in Niger. In order to address these barriers, there is a need for technical assistance from partners countries and institutions and local and private capacity building. Any support program should try to involve massively the local institutions to encourage the renewable energy technology and policy learning in Niger and by the same, foster capacity building and expertise. The technical assistance and capacity building should achieve through:

- policy design for policy makers: e.g. feed-in tariff design, price and rate setting, as well as policy review and transitional decreasing of financial support over time;
- development, resource assessment and feasibility studies for governments and local partners;
- construction, operation and maintenance for local companies;
- grid expansion, management and integration strategies for utilities;
- financing and risk mitigation strategies for local financiers.

**Technology transfer**

In order for Niger to appropriately develop its energy sector, there is a need for a widespread transfer of sustainable energy technologies that match the national needs and priorities related to socio-economic development. This will sufficiently reduce $CO_2$ emissions and at the same time allow sustainable paths for development. For technology transfer to be possible on a larger scale, incentives have to be put in place for technology developers to cooperate and share technology knowledge.

**Consistent awareness creation**

A successful understanding and support of the public is very important for a countrywide implementation of solar energy or renewable energy in general. Therefore, the national authorities should put in place programs to increase awareness on benefits and opportunities associated with the development of solar energy and its inherent advantage for climate change mitigation. This will be important for a rapid and significant improvement on the desire and interest among the public in the country.

Increased awareness will assist in tackling the problem associated with insecurity of solar plant infrastructures. Awareness could be done through various promotions and dedicated communication efforts primarily through workshops and media (television and advertisement) and community meetings/forums. These meetings and advertisement will need financial support of the government and non-governmental organizations.

Finally, trough the results obtained on the solar radiations and there trends in the future over the two cities of Niamey and Agadez and the investigation on the energy policy of Niger, this study sought to provide some useful information for policy makers, private institutions and government organizations for them to understand the solar energy potential of the country and obtain more information regarding the national energy policies that could help for developing solar energy in the country. Policy recommendations are also made, that could help in disseminating the message that countries like Niger could cover large parts of their electricity demands by just developing a fraction of their solar potential, with appropriate policies in place.

## References


Adeoti, O., Oyewole, B. A., & Adegboyega, T. D. (2001). Solar photovoltaic-based home electrification system for rural development in Nigeria: Domestic Load Assessment. *Renewable Energy, 24,* 155–61. doi:https://doi.org/10.1016/S0960-1481(00)00188-9

AfDB, A. (2013). *Development of Wind Energy in Africa.* Tunis/Tunisia: AfDB.

Babatunde, E. B. (2012). *Solar Radiation.* Rijeka, Croatia: InTech.

Bazyomo, S. Y., Lawin, E. A., Coulibaly, O., & Ouedraogo, A. (2016). Forecasted Changes in West Africa Photovoltaic Energy Output by 2045. *Climate, 4,* 53. doi:doi:10.3390/cli4040053

Benoit, P. (2006). Africa is energizing itself. *sixth meeting of GFSE, 93.* Vienna, Austria.

Benson, R. B., Paris, M. V., Sherry, J. E., & Justus, C. J. (1984). Estimation of daily and monthly direct, diffuse and global solar radiation from sunshine duration measurements. *Solar Energy, 32* (4), 523-535. doi:https://doi.org/10.1016/0038-092X(84)90267-6

Bonkaney, A., Madougou, S., & Adamou, R. (2017). Impacts of Cloud Cover and Dust on the Performance of Photovoltaic Module in Niamey. *Journal of Renewable Energy*, 9. doi:https://doi.org/10.1155/2017/9107502

Browne, N. A., & Sylla, M. B. (2012). Regional Climate Model Sensitivity to Domain Size for the Simulation of the West African Summer Monsoon Rainfall. *International Journal of Geophysics*, 17. doi:http://dx.doi.org/10.1155/2012/625831

Buys, P., Deichmann, U., Meisner, C., That, T. T., & Wheeler, D. (2007). *Country stakes in climate change negotiations: two dimensions of vulnerability.* Washington, DC: World Bank Policy Research Working Paper.

Cleugh, H., & Grimmond, S. (2012). Chapter 3 - Urban Climates and Global Climate Change. In *The Future of the World's Climate (Second Edition)* (pp. 47-76). Elsevier. doi:https://doi.org/10.1016/B978-0-12-386917-3.00003-8

CNES, (. (2015). Internal Report 2015.

Daniels, A. E., Morrison, J. F., Joyce, L. A., Crookston, N. L., Chen, S. C., & McNulty, S. G. (2012). *Climate projections FAQ. Gen. Tech. Rep. RMRS-GTR-277WWW. Fort Collins, CO:.* U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, .

Dankassoua, M., Madougou, S., & Yahaya, S. (2016). Evaluation of Solar Potential at Niamey: Study Data of Insolation from 2015 and 2016. *Smart Grid and Renewable Energy,* 394-411. doi:https://doi.org/10.4236/sgre.2017.812026

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., . . . Vitart, F. (2011). The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Q. J. R. Meteorol. Soc*, *137*, 553–597.

Dieng, D., Smiatek, G., Bliefernicht, J., Heinzeller, D., Sarr, A., Gaye, A. T., & Kunstmann, H. (2017). Evaluation of the COSMOCLM high-resolution climate simulations over West Africa. *Journal of Geophysical Research: Atmospheres, 122*, 1437–1455. doi:https://doi.org/10.1002/2016JD025457

Dieng, D; Smiatek, G; Bliefernicht, J; Heinzeller, D; Sarr, A; Gaye, A T; Kunstmann, H. (2017). Evaluation of the COSMO-CLM high-resolution climate simulations over West Africa. *Journal of Geophysical Research: Atmospheres*, *122*, 1437-1455. doi:https://doi.org/10.1002/2016JD025457

Ehsan, N. D., Mohsen, A. S., & Seyed, H. G. (2016). Land Suitability Analysis for Solar Farms Exploitation Using GIS and Fuzzy Analytic Hierarchy Process: A Case Study of Iran. *Energies, 9*, 643. doi: https://doi.org/10.3390/en9080643

Elguindi, N., Giorgi, F., & Turuncoglu, U. (2014). Assessment of CMIP5 global model simulations over the subset of CORDEX domains used in the Phase I CREMA. *Climatic Change*, *125*, 7-21. doi:https://doi.org/10.1007/s10584-013-0935-9

Fant, C., & Schlosser, C. A. (2016). The impact of climate change on wind and solar resources in southern Africa. *Appl Energy, 161*, 556–640.

Fatoumata, D. (2018). *Simulating the impact of solar energy potential over West Africa: A Case Study of Mali.* Niamey: Master thesis presented on March 7th, 2018 at University Abdou Moumouni (WASCAL).

Gebretsadik, Y., Schlosser, C. A., & Strzepek, K. A. (2014). Hybrid Approach to Incorporating Climate Change and Variability into Climate Scenarios for Impact Assessment. Retrieved from [Available online: http://www.wider.unu.edu/publications/ working-papers/2014/en_GB/wp2014-112/, accessed 2 October 15

Harris, L. M., & Durran, D. R. (2010). An Idealized Comparison of One-Way and Two-Way Grid Nesting. *Monthly Weather Review*, 2174– 2187. doi:https://doi.org/10.1175/2010MWR3080.1

Harry, S., Bowden, R. S., & Hollands, K. G. (2013). Relationship between sunshine duration and solar radiation. *Solar Energy*, *92*, 160-171. doi:https://doi.org/10.1016/j.solener.2013.02.026

Hassan, Z., Shamsudin, S., & Harun, S. (2013). Application of SDSM and LARS-WG for simulating and downscaling of rain-fall and temperature. *Theor Appl Climatol*, *116*, 43–257. doi:doi: 10.1007/s00704-013-0951-8

IEA. (2011). *Renewable Energy: Policy Considerations for deployment Renewables.* Paris, France.

IEA. (2014). *Africa Energy Outlook: A Focus on Energy Prospects in Sub-Saharan Africa.* Paris, France.

INS, N. (2016). *Tableau de Bord Social, Ministère de Plan, de l'Amenagement du territoire et du Développement Communautaire.* Niamey/Niger.

IPCC. (2001). Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. 881. Retrieved from (seehttp://www.grida.no/climate/ipcc_tar/wg1/317.htm#fig84)

IPCC. (2007). *Fourth Assessment Report Climate Change.*

IRENA. (2013). *Africa's renewable future: The Path to Sustainable energy Growth.* Abu Dhabi, United Arab Emirates.

IRENA, I. (2013). Niger Renewables Readiness Assessment.

Julian, C. C. (2011). *Physicsof Solar_Energy*. book.org.

Karekezi, S., & Kithyoma, W. (2003). *Renewable energy in Africa: prospects and limits.* Dakar/Senegal: NEPAD. Retrieved from 〈 http://www.un.org/esa/sustdev/sdissues/energy/op/nepadkarekezi.pdf〉

Kebede, E., Kagochi, J., & Jolly, C. M. (2010). Energy consumption and economic development in Sub-Sahara Africa. *Energy Economics*, *32*, 532–7.

Klein, C., Heinzeller, D., Bliefernicht, J., & Kunstmann, H. (2015). Variability of West African monsoon patterns generated by a WRF multiphysics ensemble. *Climate Dynamics*. doi:https://doi.org/10.1007/s00382-015-2505-5

Li, D. H., Yang, L., & Lam, J. C. (2012). Impact of climate change on energy use in the built environment in different climate zones – A review. *Energy, Elsevier, 42*(1), 103-112.

Martin, P. L., & Santigosa, R. L. (2016). Solar radiation forecasting with WRF model in the Iberian Peninsula. *https://www.researchgate.net/publication/290946564*.

Martin, W., Doris, F., & Florian, H. (2017). Impact of Climate Change on Future Concentrated Solar Power (CSP) Production. *AIP Conference Proceedings 1810, 100007* .

Min, E., Hazeleger, W., Oldenborgh, G. J., & Sterl, A. (2013). Evaluation of trends in high temperature extremes in north-western Europe in regional climate models. *Environ. Res. Lett*, 8. doi:doi:10.1088/1748-9326/8/1/014011

Mohammed, Y. S., Mustafa, M. W., & Bashir, N. (2013). Status of Renewable Energy Consumption and Developmental Challenges in Sub-Sahara Africa. *Renewable and Sustainable Energy Reviews, 27*, 453–463.

Nikiruka, A., Juan, P. C., Brittany, S., & Daniel, M. K. (2017). The energy challenges in Sub Saharan Africa: A Guide for Advocate and Policy Makers, Part 1: Generating Energy for Sustainable and Equitable Development. *OXFAM Research Backgrounder*, 35-50.

Nikulin, G., Jones, C., Kjellström, E., & Gboban, E. (2013). The West African Monsoon simulated by global and regional climate models. *EGU General Assembly 2013. 15*, p. 4581. Vienna, Austria: EGU. Retrieved from http://meetingorganizer.copernicus.org/EGU2013/EGU2013-4581.pdf

NOAA. (2017, May 12). *The First Climate Model*. Retrieved from National Oceanic and Atmospheric Administration Web site: https://celebrating200years.noaa.gov/breakthroughs/climate_model/welcome.html

OHUNAKIN, O. S., ADARAMOLA, M. S., OYEWOLA, O. M., & FAGBENLE, R. O. (2013). Correlations for estimating solar radiation using sunshine hours and temperature measurement in Osogbo, Osun State, Nigeria. *Front. Energy*. doi:DOI 10.1007/s11708-013-0241-2

Olayinka, O., Adaramola, M. S., Oyewola, O. M., & Fagbenle, R. O. (2015). Solar radiation variability in Nigeria based on multiyear RegCM3 simulations. *Renewable Energy: An International Journal, 74*, 195-207.

Ould Bilal, B., Sambou, V., Kébé, C. M., Ndongo, M., & Ndiaye, P. A. (2007). Study and Modeling of the Solar Potential of the Nouakchott and Dakar Sites. *Journal of Sciences, 7*, 57-66.

Page, J. (2012). Chapter IIA-1 - The Role of Solar-Radiation Climatology in the Design of Photovoltaic Systems. In A. MCEVOY, T. MARKVART, & L. CASTAÑER, *Practical Handbook of Photovoltaics (Second Edition): Fundamentals and Applications* (pp. 573-643). Elsevier. doi:https://doi.org/10.1016/B978-0-12-385934-1.00017-9

Pal, J. S., Giorgi, F., Xunqiang, B., & et al. (2007). Regional Climate Modeling for the Developing World: The ICTP RegCM3 and RegCNET. *American Meteorological Society*. doi:https://doi.org/10.1175/BAMS-88-9-1395

Pan, Z., Segal, M., Arritt, R. W., & Takle, E. S. (2004). On the potential change in solar radiation over the US due to increases of atmospheric greenhouse gases. *Renewable Energy 29,* 1923–1928.

Park, S. H., Klemp, J. B., & Skamarock, W. C. (2014). A Comparison of Mesh Refinement in the Global MPAS-A and WRF Models Using Idealized Normal-Mode Baroclinic Wave Simulation. *Monthly Weather Review, 142,* 3614–3634.

Richard, M., Mustafa, B., Sander, B., Eduardo, C., Tim, C., Jae, E., . . . Monika, Z. (2008). *Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies.* Geneva: Intergovernmental Panel on Climate Change.

Salifou, G. (2015). *The Energy Sector of Niger: Perpectives and Opportunities.* Energy Charter Secretariat Knowledge Centre.

Simiyu, S. M., & Keller, G. R. (2000). Seismic monitoring of the Olkaria Geothermal area, Kenya Rift Valley. *Journal of Volcanology and Geothermal Research, 95*, 197–208.

Stefano, M., Jacopo, B., Lorenzo, M., & Emanuela, C. (2014). Sustainable Energy in Africa: A Comprehensive Data and Policies Review. *Renewable and Sustainable Energy Reviews, 37*, 656-686.

Strobl, E. (2009). *The distributional Impact of Large Dams: Evidence from Cropland Productivity in Africa.* Centre Emile Bernheim. Brussel: Research Institute in Management Sciences.

Tampakis, S., Tsanpoulos, G., Arabatzis, G., & Rerras, I. (2013). Ctizens'views on various forms of energy and their contribution to the environment. *Renewable and Sustainable Energy Review, 20*, 473-482.

Tanimoune, L. I. (2018). *Study of Potential Sites for Solar PV Power Plant Implementation in the City of Niamey Using GIS Approach.* Niamey/Niger: Master thesis presnted on March 8th, 2018 at University Abdou Moumouni (WASCAL).

Taylor, K. E. (2001). Summarizing multiple aspects of model performance in a single diagram. *J. Geophys. Res., 106*, 7183–7192. doi:doi:10.1029/2000JD900719.

Tchotchou, L. A., & Kamga, F. M. (2010). Sensitivity of the simulated African monsoon of summers 1993 and 1999 to convective parameterization schemes in RegCM3. *Theor. Appl. Climatol., 100*, 207-220.

UN. (2015). *Adoption of the Paris Agreement. In Proceedings of the Conference of the Parties, Twenty-First Session.* Paris, France.

UN-DESA. (2017). *World Population Prospects: The 2017 Revision.* United Nations Department of Economic and Social Affairs, Population Division. UN-DESA. Retrieved from ESA.UN.org (custom data acquired via website)

UNFCC. (2015). *Adoption of the Paris Agreement.* Paris.

UNIDO, ECREEE, & REN21. (2014). *ECOWAS Renewable Energy and Energy Efficiency Status Report.* Paris, France.

Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Kram, C., . . . Rose, S. K. (2011). The representative concentration pathways: An overview. *Climatic Change, 109*, 5–31. doi:https://doi.org/10.1007/s10584-011-0148-z

Vardavas, I. M., & Taylor, F. W. (2011). Radiation and Climate: Atmospheric Energy Budget from Satellite Remote Sensing, International Series of Monographs on Physics 138. *Oxford University Press*.

Villegas, J. R., & Jarvis, A. (2010). *Downscaling global circulation model outputs: the delta method. Decision and Policy Analysis Working Paper No. 1.* Centro internacional de agricultura Tropical.

Wallace, J. w., & Hobbs, P. V. (1977). *Atmospheric Science: An Introductory Survey.* San Diego : Academic Press.

Warner, T. T., Peterson, R. A., & Treadon, R. E. (1997). A Tutorial on Lateral Boundary Conditions as a Basic and Potentially Serious Limitation to Regional Numerical Weather Prediction. *Bulletin of the American Meteorological Society, 78*, 2599–2617. doi:https://doi.org/10.1175/1520-5 0477(1997)078<2599:ATOLBC>2.0.CO;2

# Appendix

### Appendix: Research Internship Agreement

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**RESEARCH INTERNSHIP AGREEMENT**

Pan African University Institute of Water and Energy
Sciences (PAUWES) c/o Abou Bekr Belkaid University
of Tlemcen,
B.P. 119 13000 Tlemcen, Algeria

This is to Certify that **Mohamed Zodi Saddam**, Student at PAUWES in MA program in Energy Policy holder of passport number 09PC14100 has been accepted as intern at the African Center for Meteorological Applications for Development (ACMAD) from 26/03/2018 to 20/06/2018.

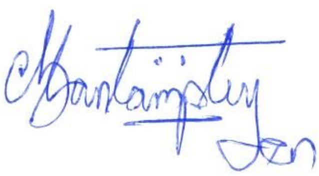
Mohamed will work with the Acting Director General.

During the internship, he/she will write a Master Thesis on Assessing solar energy potential over West Africa under changing climate: the case of Niger in our organization.

The Master Thesis supervisor is Dr. Benjamin L. Lamptey
The assigned internship supervisor is the supervisor himself, acting Director General of ACMAD.

Date: 22/03/2018

Place: Niamey/Niger

| | |
|---|---|
| Signatures:  |  |
| Director General of ACMAD | Student |

# I. Description on research grant use

The research grant amount received was **3000 USD.**

In following table are the different expenses made during the research.

| Research Duration | Tasks | Quantity | Estimated cost | | |
|---|---|---|---|---|---|
| | | | In Fr (F CFA) | In Dinar (DZ) | In USD |
| 6 MONTHS | **International flights** | Two ways | -- | 67,000 | 632.07 |
| | **Local flights** | One way + Penalty | -- | 5000 +1000 | 56.60 |
| | **Communication fees** | 6 months | 100, 000 | -- | 192.30 |
| | **Internet and related fees** | 6 months | 12, 000 | + 7,000 | 89.11 |
| | **Internet Rooter** | -- | 80, 000 | -- | 153.84 |
| | **Local Transport fees** | 2 months | 530, 000 | -- | 1019.20 |
| | **Trip to Agadez by bus (Second study area for data collection)** | Two ways | 41,176 | -- | 79.18 |
| | **Accommodations temporary for data collection** | 10 Days | 183,300 | | 352.50 |
| | **Printing and related fees** | Depend on the required | 15, 000 | + 2640 | 53.75 |
| | **Hard Disk for data storage** | 1 TB | 80, 000 | -- | 153.84 |
| | **Lost Data recovery from the Hard Disk fees** | -- | 7000+5000 | -- | 23.07 |
| | **Installation fees (Windows 10 + Linux+ NCL+ Office 2016)** | -- | 40,000 | -- | 76.92 |
| | **Supplementary costs** | Depend on the required | 55,000 | -- | 96.15 |
| **TOTAL** | | | **1,148,476** | **82,640** | **2,988.2** |

- The rate of conversion form Fr (CFA) to USD was at (1 USD=520 Fr) during the period of the research.
- The rate of conversion form Dinar (DZD) to USD was at (1 USD=106 DZD) during the period of the research.