# CONCENTRATING SOLAR POWER IN WEST AFRICA: SITE SELECTION AND POTENTIAL ASSESSMENT

Doctoral Thesis

by

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Sandwich programme

between

Ecole doctorale

Sciences et technologies de l'Eau, l'Energie et l'Environnement

Institut international d'ingénierie de l'eau et de l'environnement-2iE, Ouagadougou

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Kwame Nkrumah University of Science and Technology, Kumasi

September 2013

## CERTIFICATION

I hereby declare that this submission is my own work towards the PhD and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any degree of the University, except where due acknowledgment has been made in the text.

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# ABSTRACT

The Economic Community of West African States (ECOWAS) which is a regional group of fifteen countries has some of the lowest modern energy consumption rates in the world. Concentrating Solar Power (CSP) could be an attractive renewable energy option for increasing access to electricity, for diversifying sources of energy and for reducing oil bill in the region. However, to date, no CSP plant has been installed in the region and none is under construction. Moreover, with the exception of some few isolated cases in some countries like Ghana where the feasibility of a 20 MW central receiver Plant was investigated, to the best of our knowledge no site evaluation or capacity assessment pertaining to CSP plant has ever been performed for the whole Community. The overall objective of this thesis was to fill that gap by carrying out a potential assessment for large-scale CSP projects in the region.

A first step in the methodology consisted in identifying key parameters as criteria for the proper siting of CSP plants. The second step was to develop maps of ECOWAS illustrating spatial distribution of some of the key parameters. The maps were to be subsequently laid over each other with given criteria and using Geographical Information System's techniques. The intersected area was assumed to be suitable for CSP implementation. The third step was to develop a method for the calculation of both the nominal potential and the corresponding energy yield and apply the method in the ECOWAS region.

Three maps of ECOWAS were developed illustrating spatial distribution of solar radiation resources (DNI), land slope and transmission lines respectively. The study considered only 1 % of the suitable land area which met certain criteria and found for example that West Africa has a potential nominal capacity of 21.3 GW for Parabolic trough technology. This greatly exceeds the projected electricity demand of 17 GW by 2023 for the region. Results in this thesis are expected to serve the basis for project development and further research within the field of Concentrating Solar Power, specifically in West Africa. The suggested method could also be used in other parts of the World.



**Keywords:** ECOWAS, Concentrating Solar Power, capacity assessment, site ranking

# RESUME DE LA THESE

La Communauté économique des États de l'Afrique de l'Ouest (CEDEAO) qui est un regroupement régional de 15 pays est parmi les régions du monde qui ont les taux les plus bas de consommation d'énergie moderne. Les centrales solaires à concentration pourraient être une option attrayante d'énergie renouvelable pour accroitre le taux d'accès à l'électricité, pour diversifier les sources d'énergie et pour réduire la facture pétrolière dans la communauté. Toutefois, à ce jour, aucune centrale solaire à concentration n'ait été installée dans la sous-région et aucune n'est en cours de construction. De plus, à l'exception de quelques études isolées dans certains pays comme le Ghana où la faisabilité d'une centrale à tour de 20 MW a été étudiée, aucune prospection ou évaluation du potentiel couvrant toute la région CEDEAO et liée aux centrales solaires à concentration n'ait été réalisée (à notre connaissance).

L'objectif général de cette thèse était de combler cette lacune en procédant à une évaluation du potentiel des centrales solaires à concentration dans la sous-région.

Une première étape dans la méthodologie a consisté à identifier les paramètres clés servant de critères pour le choix de sites potentiels pour l'implantation des centrales solaires à concentration. La deuxième étape consistait à établir des cartes de la CEDEAO illustrant la répartition spatiale de certains des paramètres clés. Les cartes devraient ensuite être superposées avec des critères donnés en utilisant des techniques SIG (Système d'information géographique). La zone d'intersection a été supposée convenable pour l'implantation des centrales solaires à concentration. La troisième étape a consisté à proposer une méthode de calcul de la puissance nominale potentielle et de l'énergie correspondante. La méthode devrait ensuite être utilisée pour prédire le potentiel CSP dans l'espace CEDEAO.

Trois cartes de la CEDEAO ont été développées. Ces cartes illustrent la répartition spatiale du rayonnement solaire direct, la topographie du terrain et des lignes de transmission, respectivement. Ayant ensuite considéré 1 % seulement de la superficie convenable, l'étude conclue entre autre que la CEDEAO dispose d'une capacité nominale potentielle d'environ 22 GW pour la technologie cylindro-parabolique. Cela dépasse largement la projection de la demande en électricité qui sera de 17 GW pour la région en 2023.

Les résultats de cette recherche sont censés servir de base non seulement à des projets de développement des centrales solaires à concentration mais aussi à des recherches plus poussées dans le domaine, en particulier en Afrique de l'Ouest. La méthode proposée pourrait être appliquée dans d'autres parties du monde.

**Mots clés :** CEDEAO, centrales solaires à concentration, évaluation de la capacité, classification des sites

**DEDICATION**

*I*

*dedicate this thesis*

*to the memory of the Late Professor Abeeku Brew-Hammond.*

**DEDICATION**

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*I*

*dedicate this thesis*



*to the memory of the Late Professor Abeeku Brew-Hammond.*

# ACKNOWLEDGEMENT

This thesis was made possible through support from many people. I would like to express my sincere gratitude for the support and help from everyone. In particular, I truly acknowledge the valuable time, patience, support of my supervisory team throughout the whole thesis research (Late Professor Abeeku Brew-Hammond, Professor Yao Azoumah and Dr Kwame Owusu-Achaw). Thanks to Professor Kannatey-Asibu who has been my mentor during my 6-month stay at the University of Michigan and who has been very supportive of this work.

I acknowledge the assistance of Gildas Tapsoba and Anselme Rungundu, both at «Laboratoire Energie Solaire et Economie d'Energie-2iE» in the use of the GIS tools in my research. I am very grateful to the Kwame Nkrumah University of Science and technology (KNUST), the International Institute for Water and Environmental Engineering (2iE), the African Studies Center of the University of Michigan and the German Academic Exchange Service (DAAD), for their support;

I would like to express gratitude to my colleagues at KNUST and also to my PhD colleagues at 2iE: Pascal, Daniel, Stéphanie, Malick, Ibrahim, Mounirou, Tadjouwa and Noellie.

To my wife, Rakisyoaba, my dauther Wendemi and my son Rakiswendé, I say "Bark woussogo": your love, care and moral support have been key in completing this thesis. Also, I have the immense pleasure to acknowledge my parents, my brothers and sisters for their support during my academic progression.

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## ACRONYMS

| | |
|---|---|
| CLFR: | Compact Linear Fresnel Reflector |
| CR: | Central Receiver |
| CSP: | Concentrating Solar Power |
| CSR: | Climatological Solar Radiation |
| DEM: | Digital Elevation Model |
| DNI: | Direct Normal Irradiation |
| DSG: | Direct Steam Generation |
| ECOWAS: | Economic Community of West African States |
| ECREEE: | ECOWAS Regional Centre for Renewable Energy and Energy Efficiency |
| GIS: | Geographic Information System |
| HTF: | Heat Transfer Fluid |
| ISG: | Indirect Steam Generation |
| kWh: | Kilowatt hour |
| LF: | Linear Fresnel |
| NREL: | National Renewable Energy Laboratory (USA) |
| ORC: | Organic Rankine Cycle |
| PCU: | Power Conversion Unit |
| PT: | Parabolic Trough |
| SEGS: | Solar Energy Generating Stations |
| SRTM: | Shuttle Radar Topography Mission |
| WAPP: | West African Power Pool |

# CHAPTER 1: GENERAL INTRODUCTION

This chapter is the introduction to the thesis and contains the background of the research, statement of the problem, research methodology, objectives, and structure of the thesis.

## 1.1. Background of the study



Environmental concerns associated with conventional thermal power plants, the rising prices for fossil fuel, the issues of energy poverty and energy security have led researchers to look for alternative sources for the production of electricity. In that regard, solar energy appears as an attractive renewable energy option for the production of electricity. Solar photovoltaic is the direct conversion of solar radiation into electricity while concentrating solar power produces electricity through thermodynamic cycles. Efficiencies of commercially available photovoltaic modules are on the order of 6 to 15 percent [1]. However, in concentrating solar thermal systems, efficiencies can reach 30 percent or more [2]. Concentrating solar power (CSP) plants are therefore good candidates for addressing some of the above-mentioned issues. A concentrating solar power plant uses reflective materials such as mirrors to concentrate the direct component of solar radiation onto a receiver. Concentration of the direct solar radiation reduces the receiver surface area with respect to the collector aperture area and thus significantly decreases the overall thermal losses. The receiver is a high-absorptance and low-reflectance, radiative/convective heat exchanger that absorbs the solar energy and converts it into high-temperature thermal energy. The thermal energy is subsequently converted into mechanical power through thermodynamic cycles which later, is converted into electricity via a generator.

## 1.2. Statement of the problem

Energy is central to improved social and economic well-being, and is indispensable to most industrial and commercial wealth generation. It is key for relieving poverty, improving human welfare and raising living standards. Unfortunately, the Economic Community of West African States (ECOWAS) which is a regional group of fifteen countries, has some of the lowest modern energy consumption rates in the world with average electricity consumption of 120 kWh/capita compared to the continental and global averages of 529 and 2570 kWh/capita respectively [3]. In 2010, the highest electricity access rate in the region was recorded in Cape Verde with 95 % but this rapidly dropped to about 72 % in Ghana, 50 % in Senegal, 30 % in Mali, 29 % in Burkina Faso, and 9 % in Niger [4]. Household access to electricity across the region was reported in 2010 to be about 20 % but wide differences exist between the access rates in urban areas that average 43 % while rates in rural areas range between 6 % and 8 % [5]. Figure 1.1 presents some indicators in the electricity sector for each country of the region and compares them with the regional and continental averages.

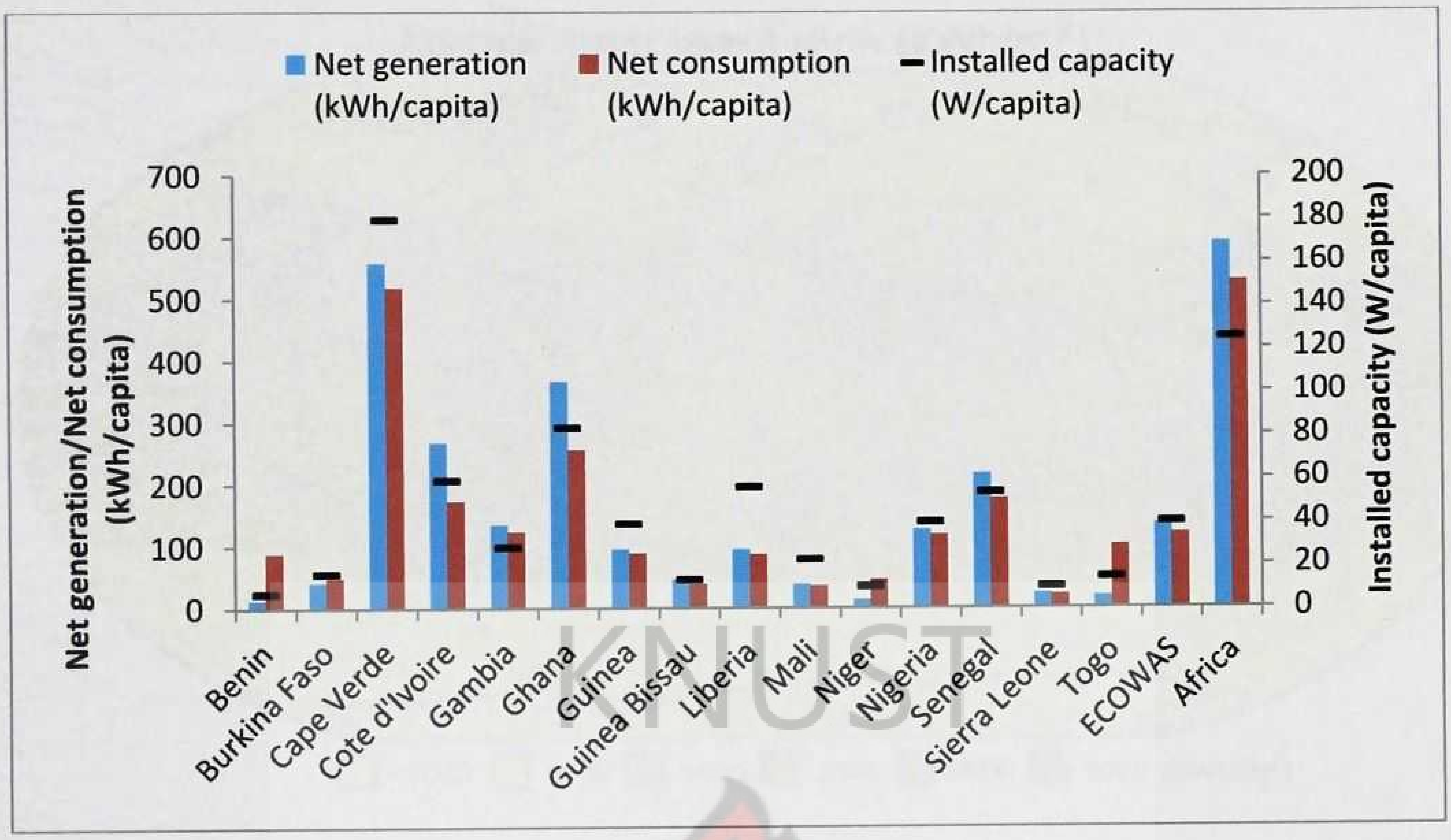


**Figure 1.1: Electricity indicators in the ECOWAS region (2009 data)**

Source of data: [3]

Except Cape Verde which compares relatively well with the continental averages, the other countries perform poorly in terms of net electricity generation per capita, net electricity consumption per capita and the total installed capacity per capita.

Although the share of oil products in ECOWAS' energy balance remains modest, commercial energy consumption (electricity, oil products and gas) is highly oil-dependent. Power generation depends on 65% of fossil fuel [6]. If the total energy situation is considered, traditional biomass (wood and charcoal) represents the bulk of the final energy consumption, reaching up to 70-85% in some of the countries [7].

Since West African countries receive abundant solar energy all year round (see Figure 1.2 [8]), solar power plants present opportunities to increase access to electricity in a sustainable manner and reduce oil bill.

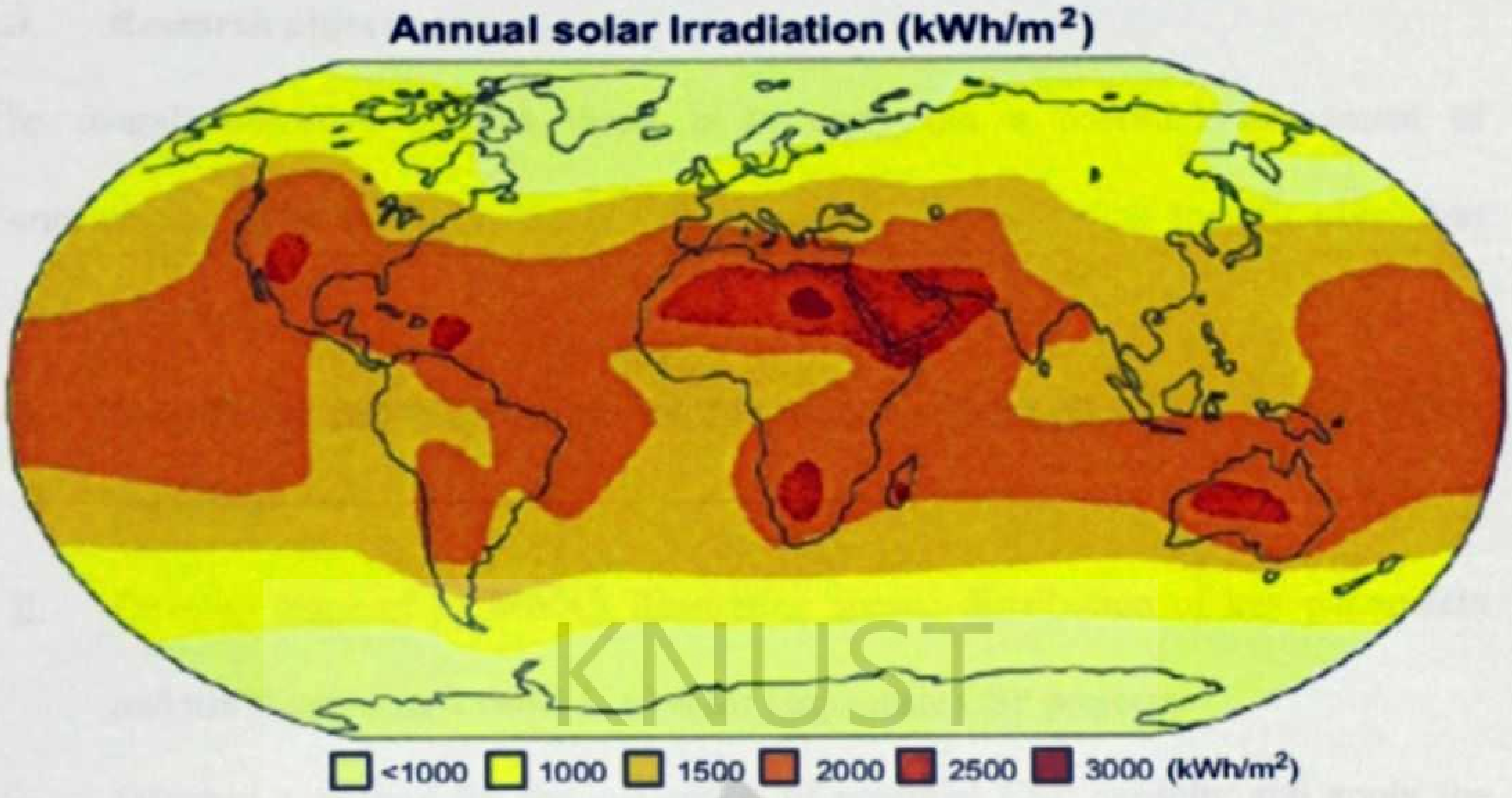


**Figure 1.2: Annual solar irradiation**

ECOWAS could be divided into three main climatic zones: the humid tropical southern coastal zone, the Sahel and the Sahara desert. Direct Normal Irradiation (DNI) which is the 'fuel' for Concentrating Solar Power (CSP), is relatively high in the Sahara and the Sahel zone. Hence CSP could present an opportunity for increasing access to electricity and for diversifying sources of energy in the ECOWAS region. However, to date, no CSP plant has been installed in the region and none is under construction. Moreover, Moreover, with the exception of some few isolated studies in some countries like Ghana where the feasibility of a 20 MW central receiver Plant was investigated [9], to the best of our knowledge no site evaluation or capacity assessment pertaining to CSP plant has ever been performed for the whole Community.

### 1.3. Research objectives

The overall objective of this thesis is to carry out a potential assessment of Concentrating Solar Power in the ECOWAS region. The following specific objectives will be pursued:

i. Identify key parameters in the implementation of CSP plants and provide siting-guidelines.
ii. Develop maps of ECOWAS illustrating spatial distribution of key parameters and use these to rank suitable sites for large-scale CSP projects.
iii. Develop a method for the evaluation of potential CSP capacity and apply the method in the ECOWAS region.



### 1.4. Research methodology

This research therefore started with a literature review in order to give a detailed picture of the four main Concentrating Solar Power technologies. CSP technologies are many with regard to the collector type, the receiver type, the heat transfer fluid, the working fluid and the thermodynamic cycles. The review also covered previous studies pertaining to site selection and potential assessment for concentrating solar power. Guidelines for the selection of suitable sites for CSP plants were also developed. Subsequently, maps of ECOWAS illustrating spatial distribution of some key parameters, previously suggested in the guidelines, were developed using Geographical Information Systems. This was then followed by site evaluation and ranking for large-

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### 1.5. Significance of the research

Concentrating Solar Power could present an opportunity for increasing access to electricity and for diversifying sources of energy in the ECOWAS region. The potential of CSP in the region however was not well known at the time this research began. This research provided siting-guidelines and contributed to the assessment of the potential, by evaluating and ranking suitable sites for large-scale CSP projects. Findings from this research are expected to pave the way for the design and construction of concentrating solar power plants in West Africa.

### 1.6. Structure and scope of the thesis

This thesis is organized into five Chapters. Chapter one serves as a general introduction to the study. It provides a background, states the objectives and describes the research methodology of the study. Chapter two provides a detailed picture of the four main Concentrating Solar Power technologies, which have reached commercial or near-commercial stage. It discusses the key components, the technological challenges, and the research and development activities for each technology. Chapter three provides technical guidelines for the selection of suitable sites for CSP plants with special focus to Sahelian countries. As a case study, the guidelines are applied in selecting a candidate site in Burkina Faso, an ECOWAS country.

Chapter four performs a site evaluation of the ECOWAS region for CSP. It evaluates and ranks suitable sites for large-scale CSP projects. It further proposes a new method for computing the nominal potential power and applies it to predict the potential in the ECOWAS region. Finally, the main conclusions drawn from this investigation and recommendations for future research are presented in Chapter Five.

The scope of the thesis is limited to assessing the potential for large scale Concentrating Solar Power in the ECOWAS region. The results achieved may not therefore be applicable to small-scale CSP plants.

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# CHAPTER 2: LITERATURE REVIEW ON CSP TECHNOLOGIES: MAJOR CHALLENGES AND ISSUES

This chapter provides a review of Concentrating Solar Power technologies for electricity generation. Attention is also given to previous work pertaining to siting guidelines and potential assessment for concentrating solar power.



## 2.1. FIRST PART: REVIEW OF CSP TECHNOLOGIES FOR ELECTRICITY GENERATION

### 2.1.1. Introduction

Since the last two decades, Concentrating Solar Power technologies have been successfully implemented in many countries but mostly in USA, Southern Europe, Asia and Northern Africa. In fact, about 11 GW of CSP plants are planned or under construction in the United States (4800 MW), Spain (1850 MW), China (900 MW), Israel (250 MW), Egypt (150 MW), South Africa (150 MW), Abu Dhabi (100 MW) and smaller plants in Australia, Algeria, Morocco, Iran, and Mexico [10]. All these projects suggest that CSP technologies are becoming more and more matures and widely spread. Concentrating Solar Power technologies are many with regard to the collector type, the receiver type, the heat transfer fluid, the working fluid and the thermodynamic cycle. Figure 2.1 is a flow diagram for concentrating solar power plant [11].

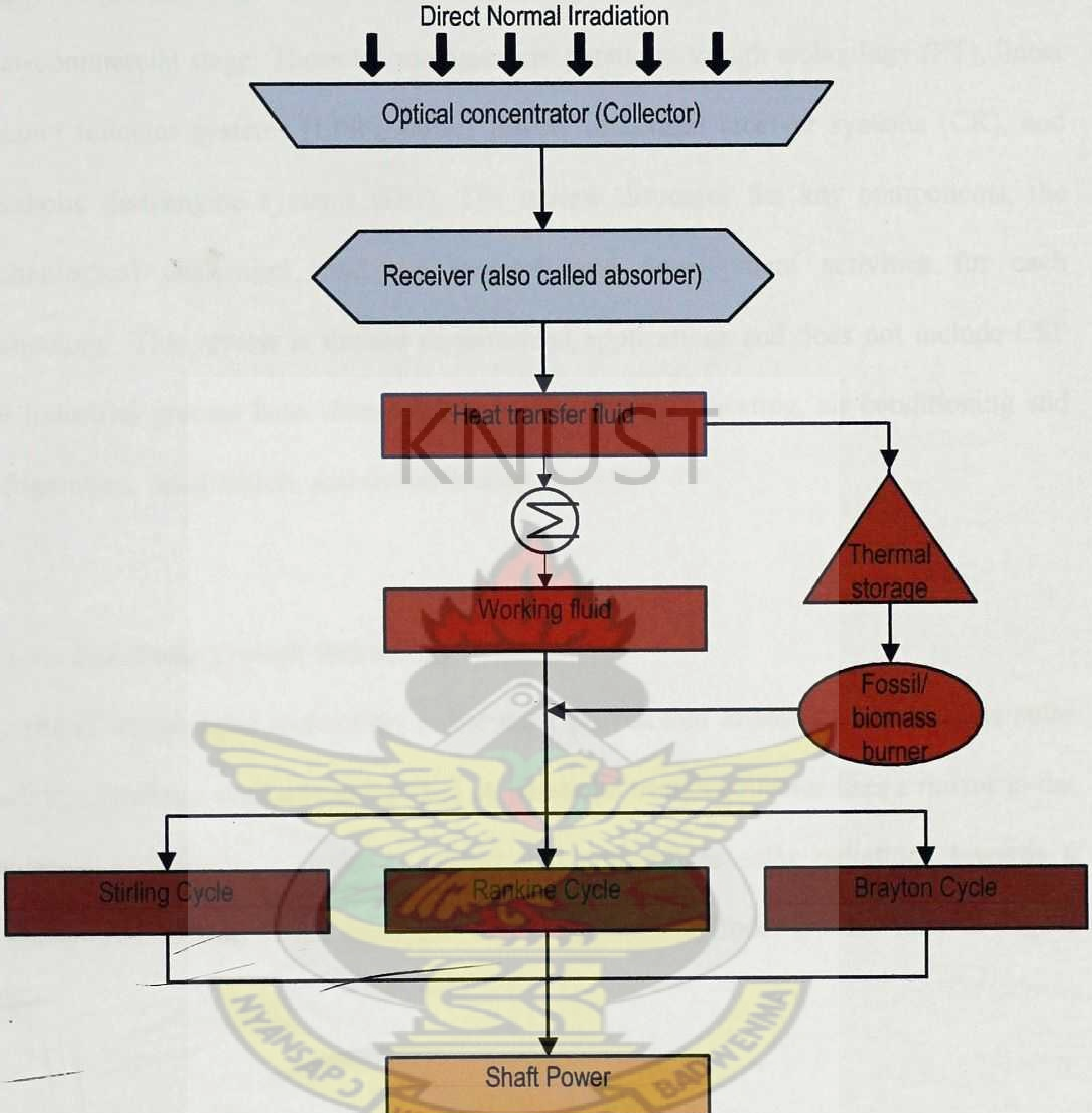



**Figure 2.1 Flow diagram for concentrating solar power plant [11]**

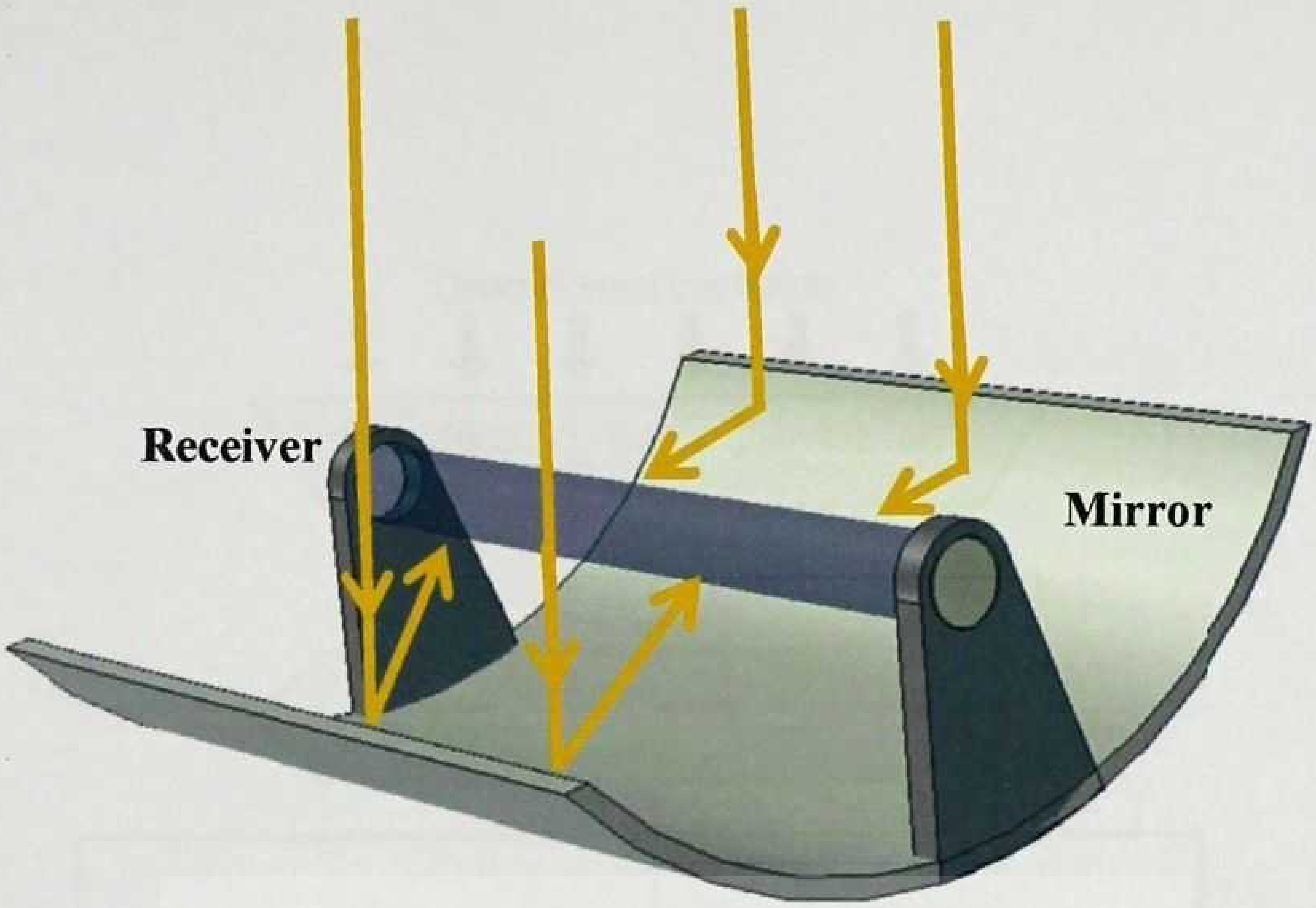
Figure 2.1 clearly suggests that the main thermodynamic cycles used in concentrating solar power plants are the Brayton cycle, the Rankine cycle and the Stirling cycle. A combined Brayton-Rankine cycle is also possible.

This section will review the four main technologies which have reached commercial or near-commercial stage. These technologies are parabolic trough technology (PT), linear Fresnel reflector systems (LFR), power towers or central receiver systems (CR), and parabolic dish/engine systems (DE). The review discusses the key components, the technological challenges, and the research and development activities for each technology. This review is limited to terrestrial applications and does not include CSP for industrial process heat, domestic hot water and space heating, air conditioning and refrigeration, desalination, and detoxification.



### 2.1.2. Parabolic Trough technology

Parabolic trough solar technology is the most proven and lowest cost large-scale solar power technology available today [12]. A parabolic trough collector uses a mirror in the shape of a parabolic cylinder to reflect and concentrate solar radiations towards a receiver tube located at the focal line of the parabolic cylinder (Please refer to Figure 2.2).






The receiver absorbs the incoming Direct Normal Irradiations (DNI) and transforms it into thermal energy, the latter being transported and collected by a Heat Transfer Fluid (HTF) circulating within the receiver tube. A parabolic trough collector is able to concentrate the solar radiation flux 30–80 times, with power conversion unit (PCU) sizes of 30–80 MW [11, 13-15]. Figure 2.3 illustrates the parabolic trough technology.

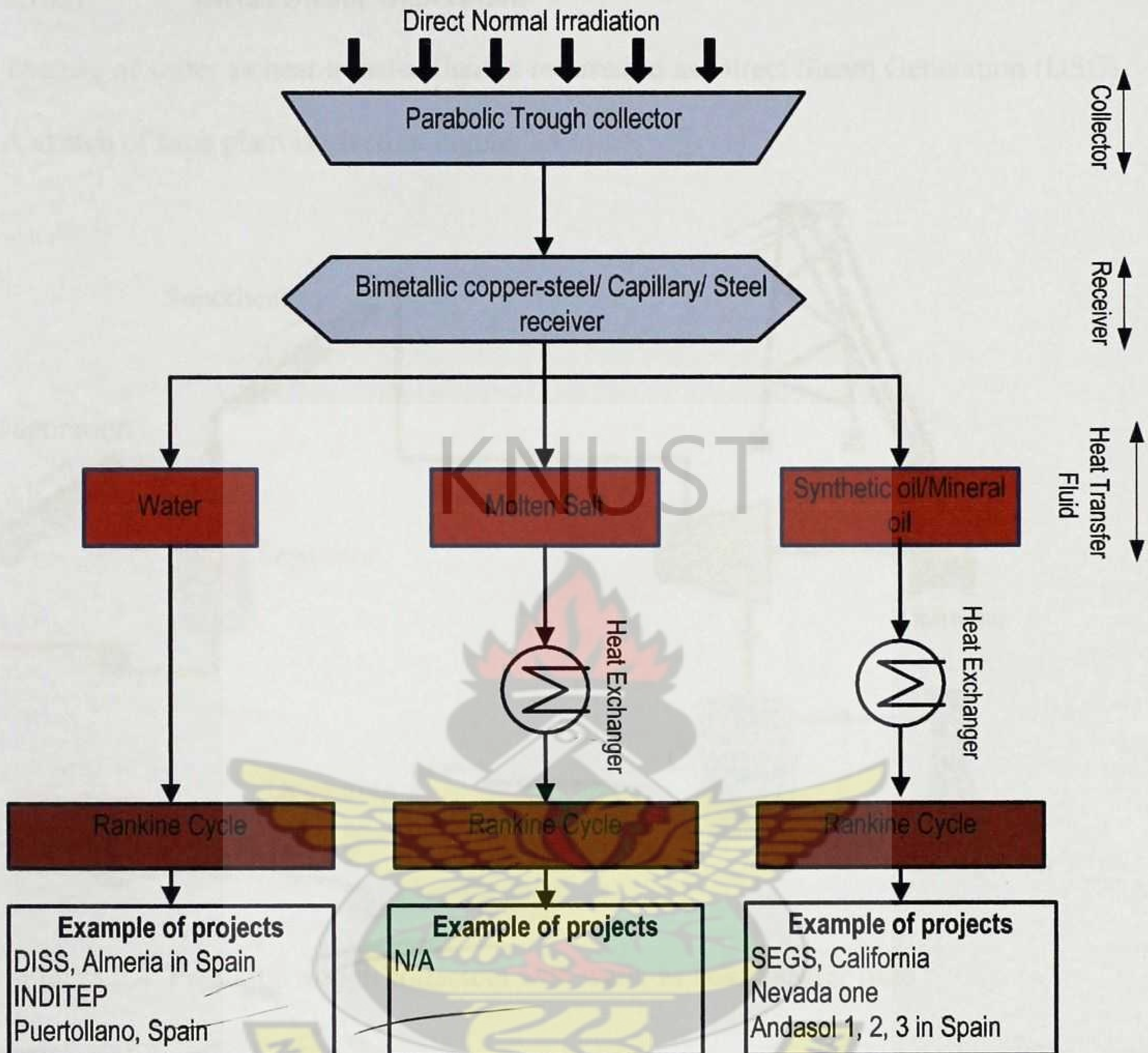



**Figure 2.3: Flow chart for parabolic trough technology**

.Heat transfer fluid in parabolic trough is either water for Direct Steam Generation (DSG), thermal oil or molten salt for Indirect Steam Generation (ISG). The type of heat transfer fluid determines the operational temperature range of the solar field and consequently the maximum power cycle efficiency that can be obtained; it also affects the corrosion of the receiver, the heat transfer rates and the type of thermal storage technologies that can be used in the plant.

#### 2.1.2.1. Direct Steam Generation

The use of water as heat transfer fluid is referred to as Direct Steam Generation (DSG). A sketch of such plant is given in Figure 2.4.

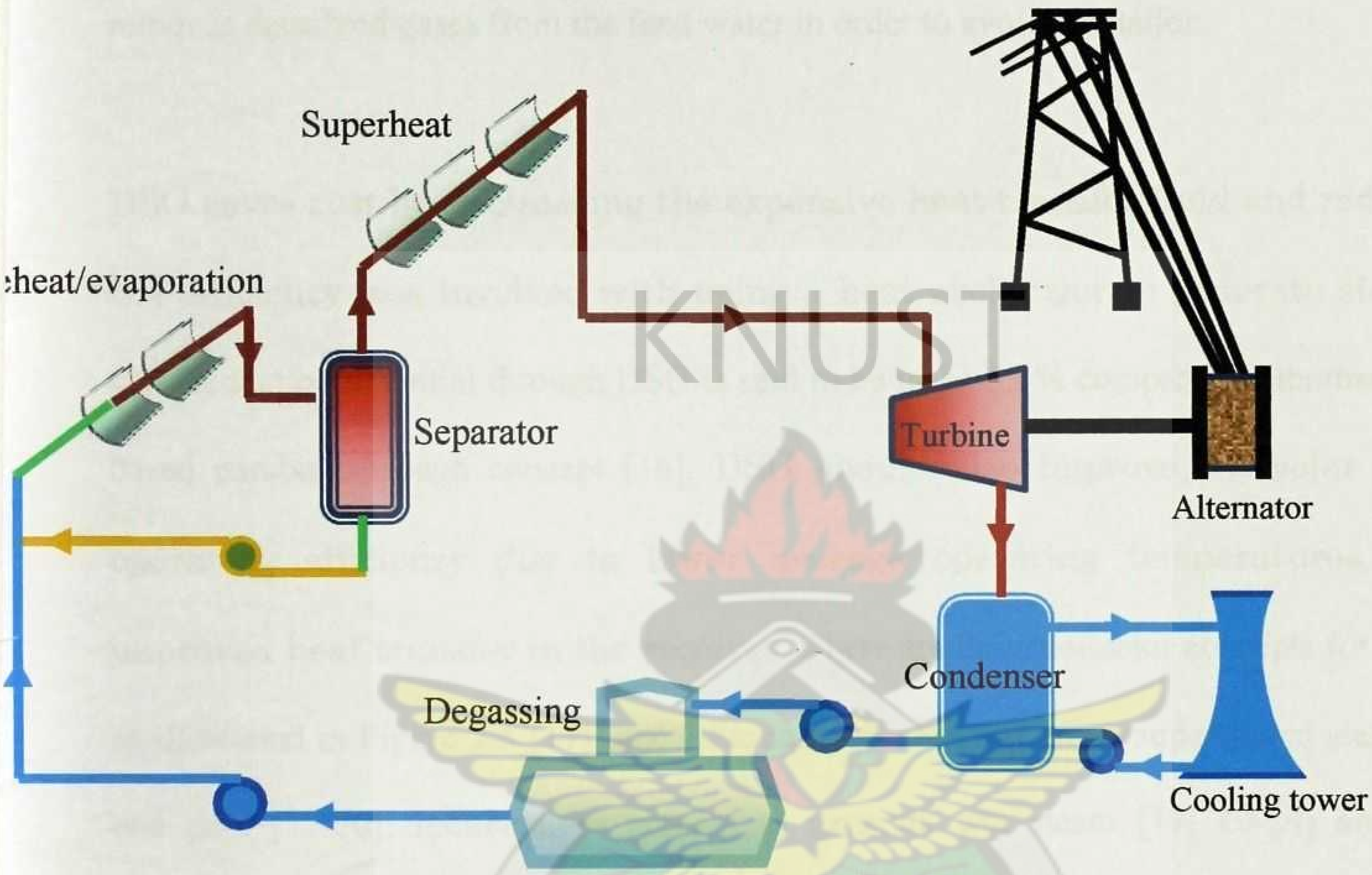



Figure 2.4: Parabolic trough collectors with water as heat transfer fluid

In Figure 2.4, the separator removes water droplets from the steam since they can cause stratification in the receivers due to the two-phase flow (liquid water and steam). Moreover, the water droplets can erode the turbine blades. The degassing system removes dissolved gases from the feed water in order to avoid cavitation.

DSG saves cost by eliminating the expensive heat transfer fluid and reduces the efficiency loss involved with using a heat exchanger to generate steam. Cost-reduction potential through DSG is said to be up to 35 % compared to thermal oil-based parabolic trough concept [16]. DSG should also improve the solar field operating efficiency due to lower average operating temperatures and improved heat transfer in the receiver. There are three collector concepts for DSG as illustrated in Figure 2.5 [17]: once-through process to generate superheated steam in one pass [17-20]; recirculation process to generate wet steam [17, 20-24] and the injected water system to control steam quality and flow instability along the absorber tube. DSG has been the main research line in parabolic through technology [25]. The PSA DISS facility in Spain serves as the main test bed for investigating the DSG process in parabolic trough solar collectors.

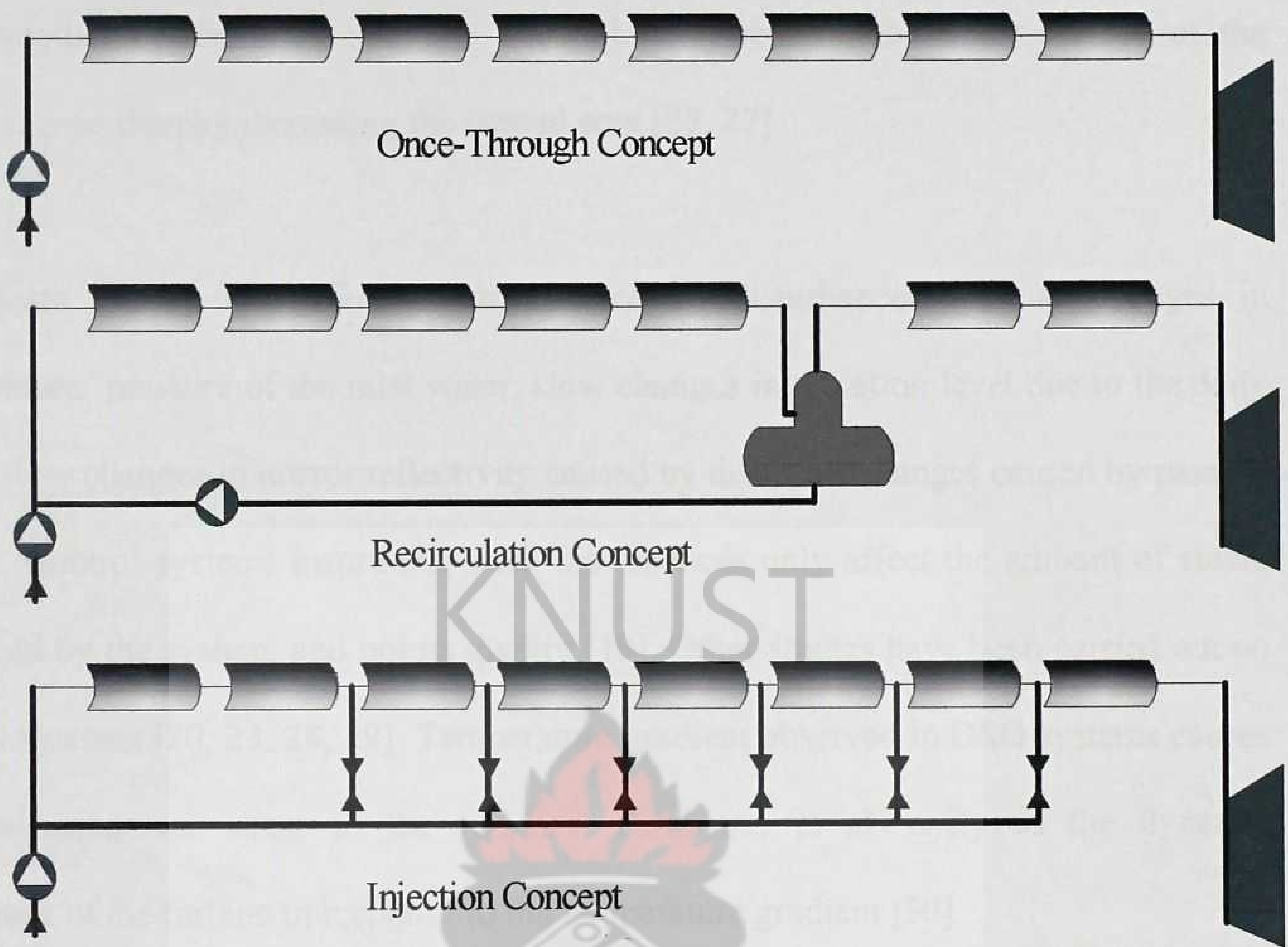



**Figure 2.5: Operation modes of DSG collectors [17]**

Studies on DSG have been mainly focussed on controlling the steam quality and flow pattern along the absorber tube. Control of the flow pattern in the absorber tube is critical since the existence of flow stratification may induce large temperature gradients in the absorber tube wall and possibly cause damage to the absorber module [18]. Stratification occurs in DSG receivers due to the two-phase flow (liquid water and steam). This phenomenon is not experienced in single-phase flow receivers i.e. oil or molten salt receivers. It is even more pronounced at low flow rates since the two phases tend to separate and to stratify, leading to very different heat transfer coefficients in the absorbers' cross-section [25]. One possible solution to stratification issue is having an absorber pipe with a high thermal conductivity such as bimetallic copper-steel receiver

[26]; another option is to integrate a capillary system on the inner surface of the absorber pipe thereby increasing the wetted area [25, 27].

The steam quality in DSG plant is affected by disturbances such as changes in temperature/ pressure of the inlet water, slow changes in radiation level due to the daily cycle, slow changes in mirror reflectivity caused by dust, fast changes caused by passing clouds. Control systems insure that such disturbances only affect the amount of steam produced by the system, and not its quality [19]. Other studies have been carried out on control systems [20, 23, 28, 29]. Temperature gradient observed in DSG systems causes thermo-mechanical stress to the turbines. Birnbaum et al. analyzed the dynamic behaviour of the turbine in response to the temperature gradient [30].

In addition to the issue of controlling the steam quality, thermal storage for DSG systems has also been the subject of many studies. Thermal storage in direct steam generation plants must be adapted to the special characteristics of the two-phase fluid water/steam. This issue was addressed by [31-36].

#### 2.1.2.2. Oil as heat transfer fluid

SEGS I used Caloria, a mineral oil, as heat transfer fluid (HTF); SEGS I is one of the nine Solar Electric Generating Station (SEGS) plants in the Mojave Desert in California. The maximum operating temperature for Caloria is 310 °C. Because power plants later moved to higher operating temperatures for improving power cycle efficiency, mineral oil was replaced by Therminol VP-1, an organic heat transfer fluid [37]. VP-1 is a synthetic heat transfer fluid which remains thermally stable up to 400 °C and freezes at

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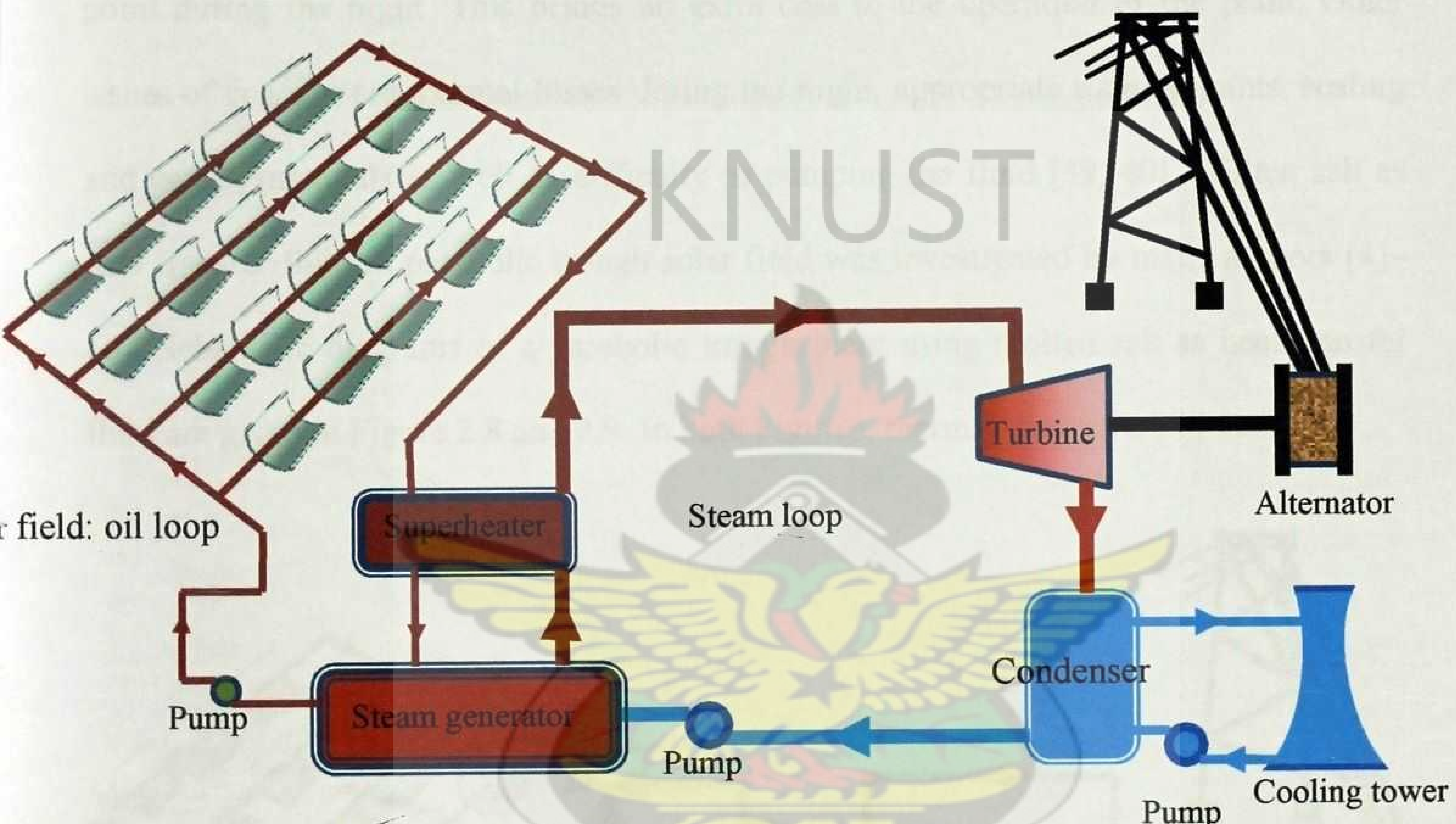


Figure 2.6: Parabolic trough plant with oil as heat transfer fluid

### 2.1.2.3. Molten salt as heat transfer fluid

Molten salts are common fertilizers. They have good thermal properties; they are also cheap, non-toxic and non-flammable, as opposed to synthetic oils. Moreover, molten salt is advantageous when thermal storage is being envisaged. In that case, molten salt serves both as HTF and storage medium. This obviously has the advantage of eliminating the expensive heat exchanger.

With salt, it may be possible to raise the solar field output temperature to 450-500 °C (Currently 393°C with oil as HTF); thereby increasing the thermodynamic efficiency of the plant. The main concern with molten salt as HTF is its high freezing point (120 to 220°C). The solar field of the plant must therefore be maintained above the freezing point during the night. This brings an extra cost to the operation of the plant. Other issues of concern are thermal losses during the night, appropriate rotating joints, sealing and gasket materials as well as difficulty in pumping the fluid [39, 40]. Molten salt as heat transfer fluid in parabolic trough solar field was investigated by many authors [41-46]. Schematic diagrams of a parabolic trough plant using molten salt as heat transfer fluid are given in Figure 2.8 and 2.9. In both Figures, thermal storage are included.



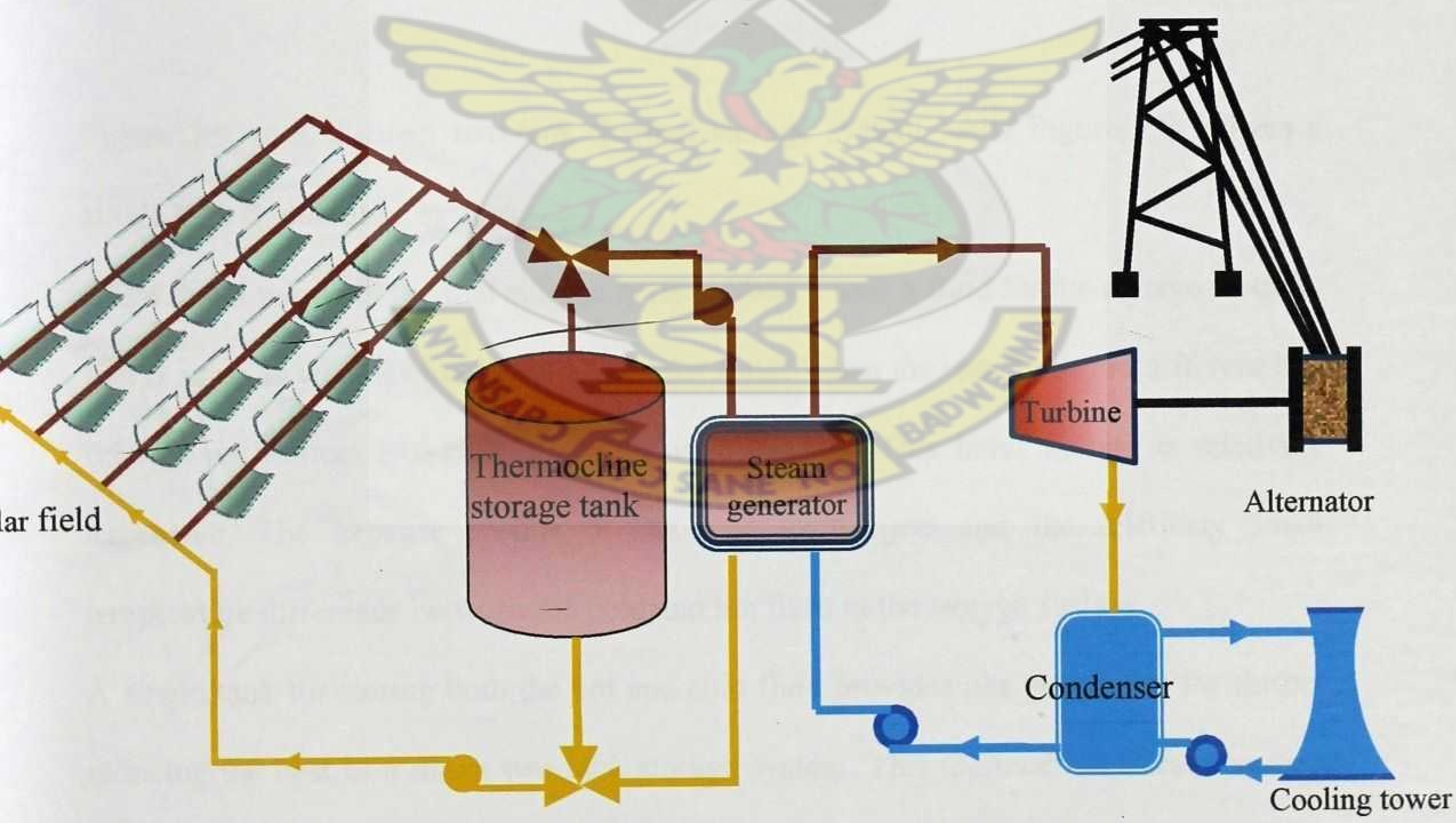


Figure 2.8: Parabolic trough with molten salt as HTF and thermocline thermal storage

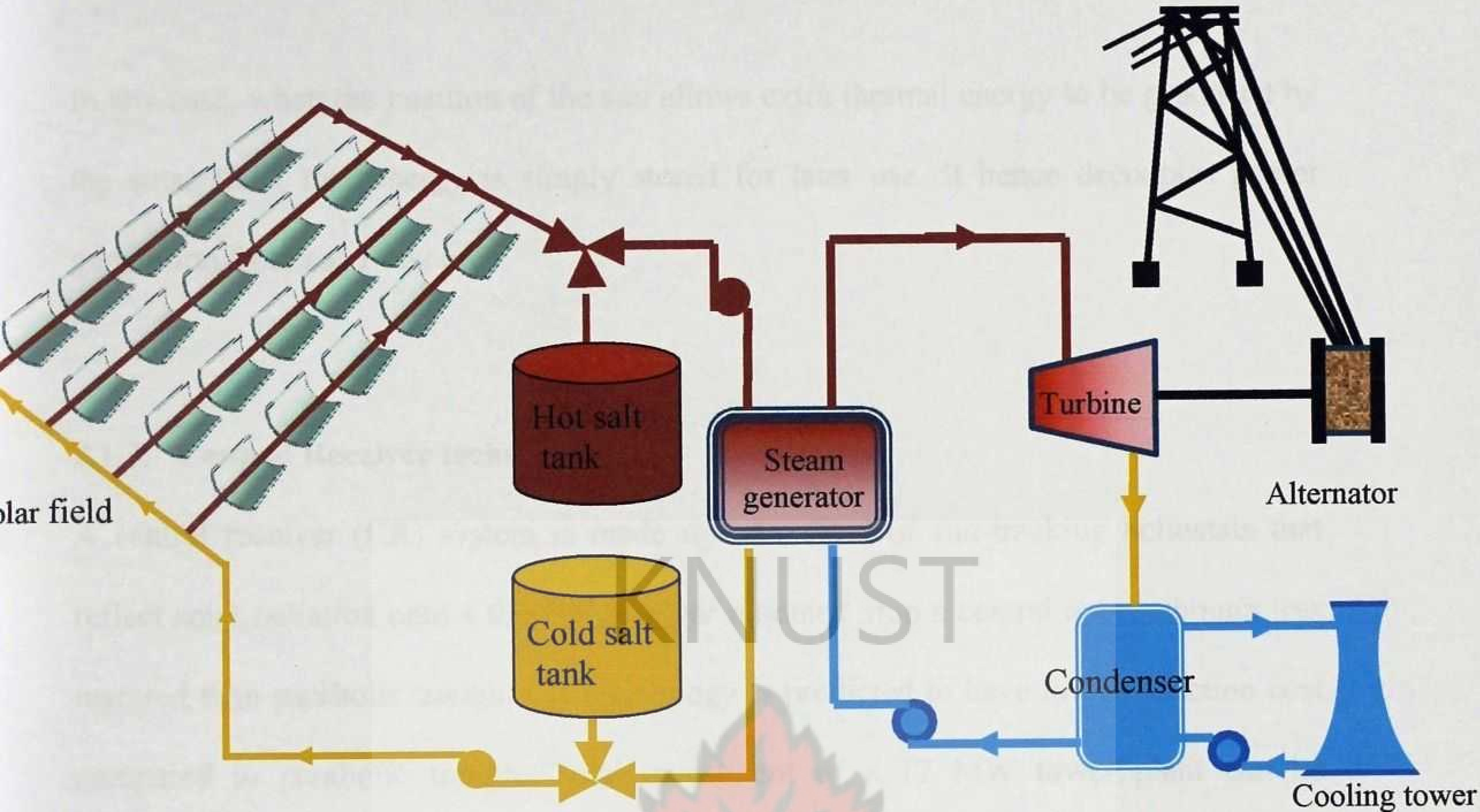


Figure 2.9: Parabolic trough with molten salt as HTF and two-tank thermal storage

Figure 2.9, uses a direct two-tank thermal storage system while Figure 2.8 utilizes a single tank thermocline system.

It is a direct two-tank thermal storage system when it uses a fluid for the storage medium that is same as what is circulated in the solar field. When the two fluids are different it is referred as indirect two-tank thermal storage system. This latter system is relatively expensive. The expense is due to the heat exchangers and the relatively small temperature difference between the cold and hot fluid in the storage system.

A single tank for storing both the hot and cold fluid provides one possibility for further reducing the cost of a direct two-tank storage system. This thermocline storage system features the hot fluid on top and the cold fluid on the bottom. The zone between the hot and cold fluids is called the thermocline.

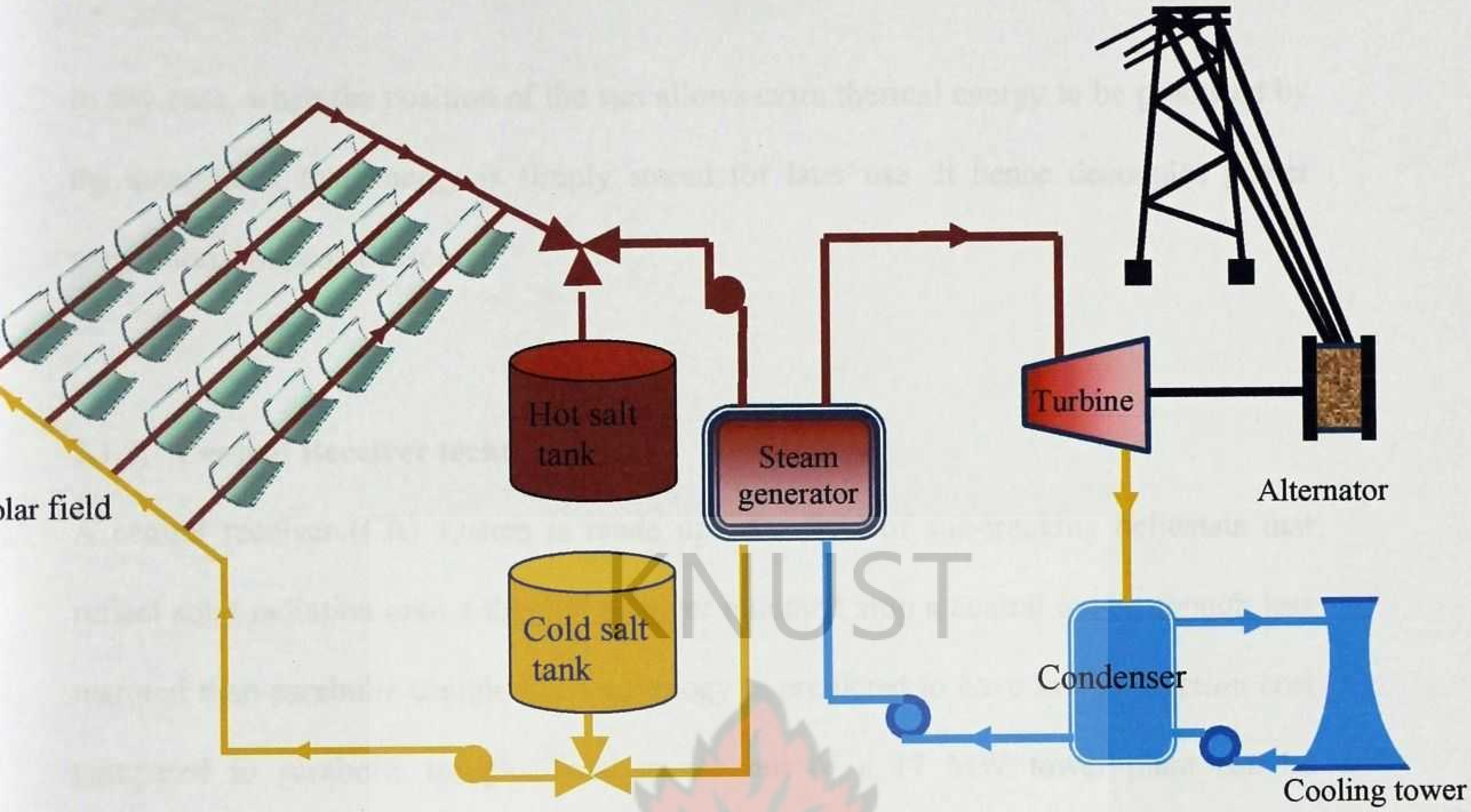


Figure 2.9: Parabolic trough with molten salt as HTF and two-tank thermal storage

Figure 2.9, uses a direct two-tank thermal storage system while Figure 2.8 utilizes a single tank thermocline system.

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In any case, when the position of the sun allows extra thermal energy to be produced by the solar field, that energy is simply stored for later use. It hence decouples power generation from solar resource.

### 2.1.3. Central Receiver technology

A central receiver (CR) system is made up of a field of sun-tracking heliostats that reflect solar radiation onto a thermal receiver mounted atop a central tower; though less matured than parabolic trough, CR technology is predicted to have low production cost compared to parabolic trough. Total investment of a 17 MW tower plant can be disaggregated in the following manner: solar field accounts for 42 % of the investment, power block for 20 %, tower and receptor for 16 %, storage system for 6 %,construction for 6 %, and the remaining 8 % accounts for engineering and contingencies costs [47].

Central receiver (CR) solar thermal power plants can reach higher temperatures and therefore achieve higher thermal efficiencies; however as pointed out by Segal [48], there is an optimum value after which the overall efficiency of the plant drops due to increasing losses in the receiver.

There are many alternatives when it comes to central receiver. CR can be classified with regards to the heat transfer fluid (HTF). To date, three main HTF have been experimented. These are air, water and molten salt (See Figure 2.10). Carbon dioxide in a Brayton cycle was proposed by Chacartegui et al. [49] but has not yet experimentally been developed. Nanofluids were also discussed in some studies. In order to experimentally demonstrate the concept of nanofluid-based receivers, Lenert [50] designed and built a volumetric receiver, a type of receiver for CR. Taylor et al. [51] equally showed that nanofluids have excellent potential for central receiver power plants.

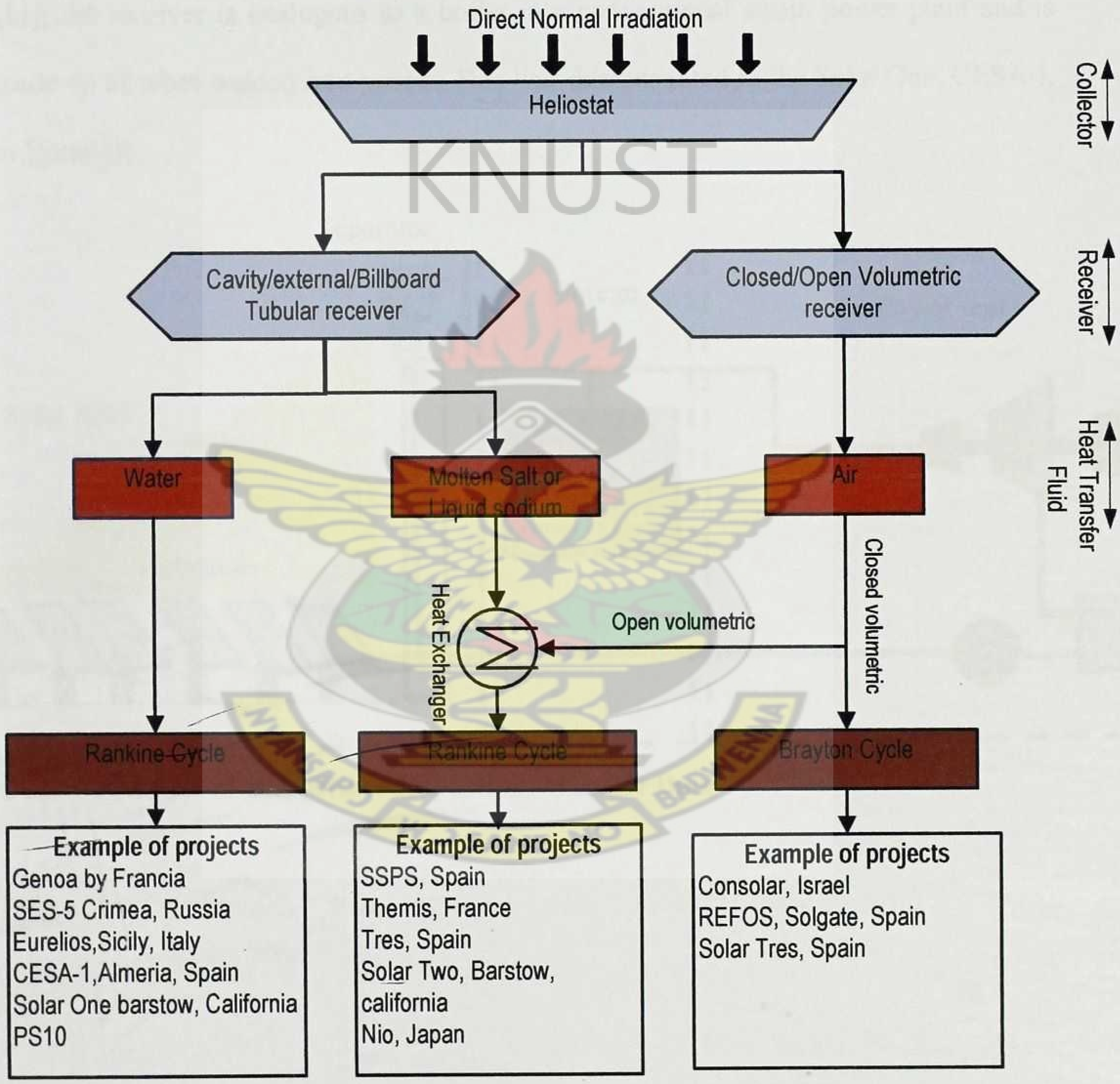


**Figure 2.10: Flow chart for central receiver technology**

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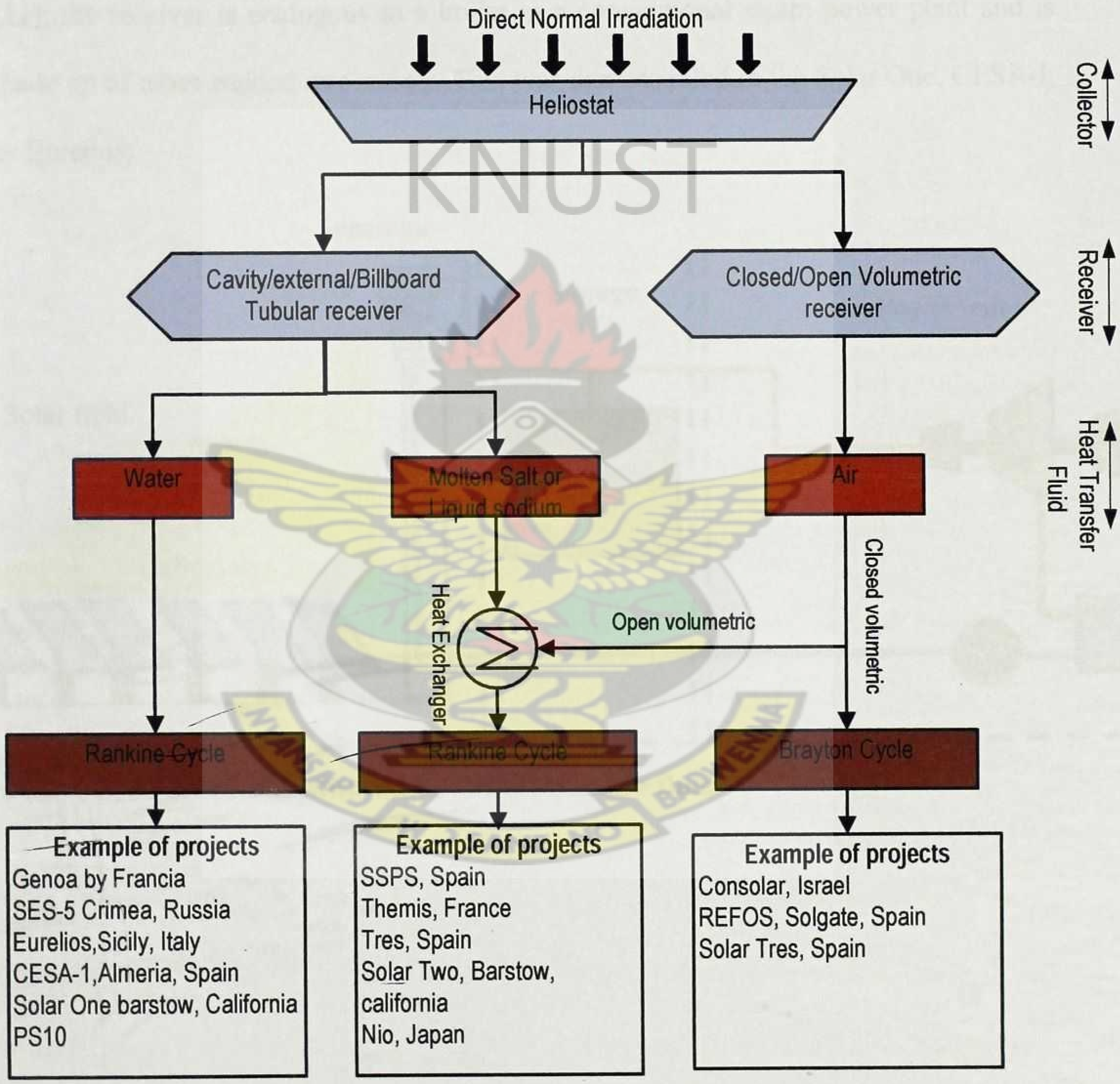


**Figure 2.10: Flow chart for central receiver technology**

#### 2.1.3.1. Central receiver with molten salt or water as heat transfer fluid

When the HTF is water, it is referred to as direct steam generation (DSG) system. Central receiver with water as heat transfer fluid is illustrated in Figure 2.11.

Types of receivers are cavity tubular, external tubular cylindrical, and billboard tubular [11]; the receiver is analogous to a boiler in a conventional steam power plant and is made up of tubes welded into panels. This was demonstrated in the Solar One, CESA-I, or Eurelios;



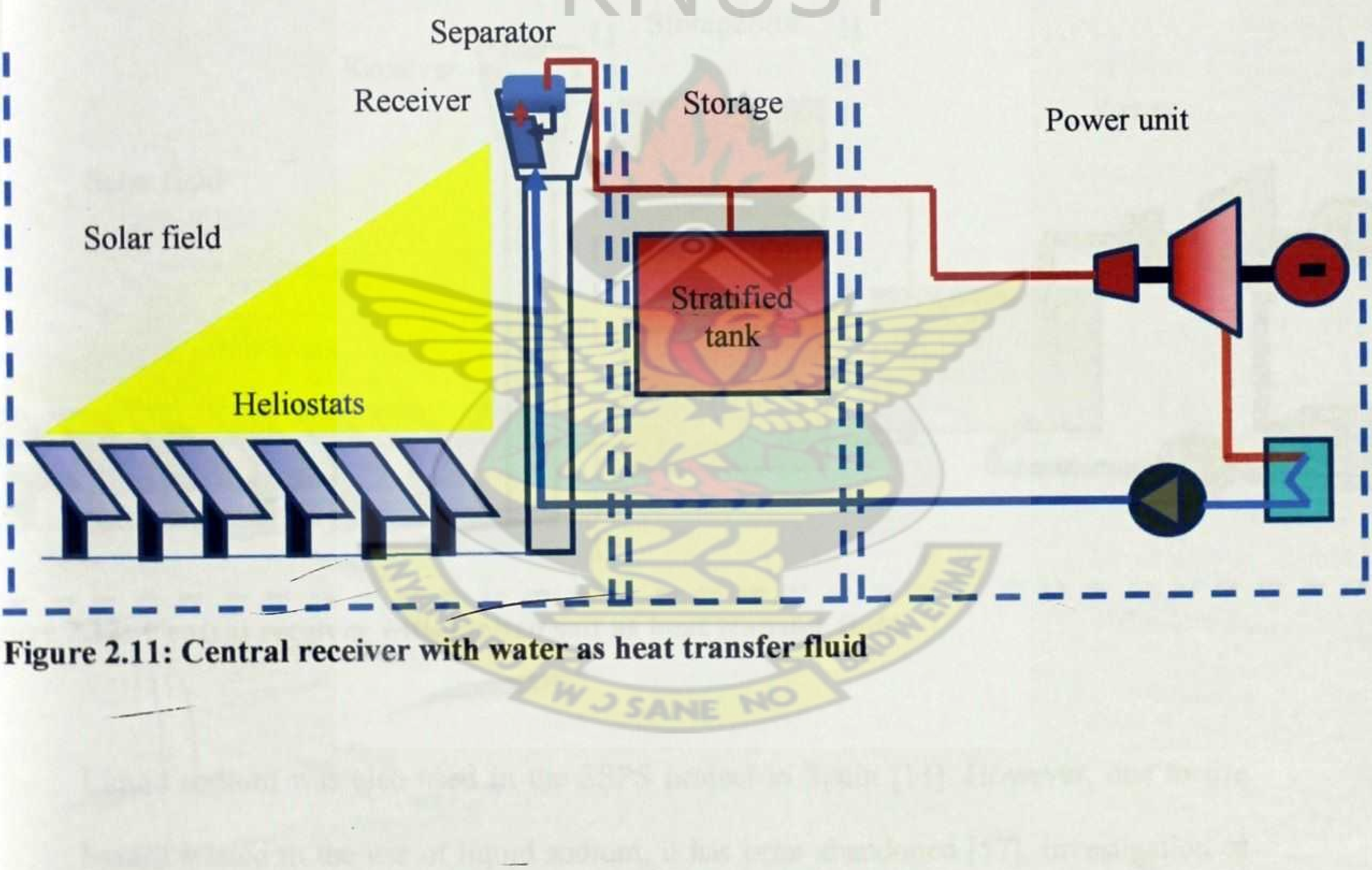


**Figure 2.11: Central receiver with water as heat transfer fluid**

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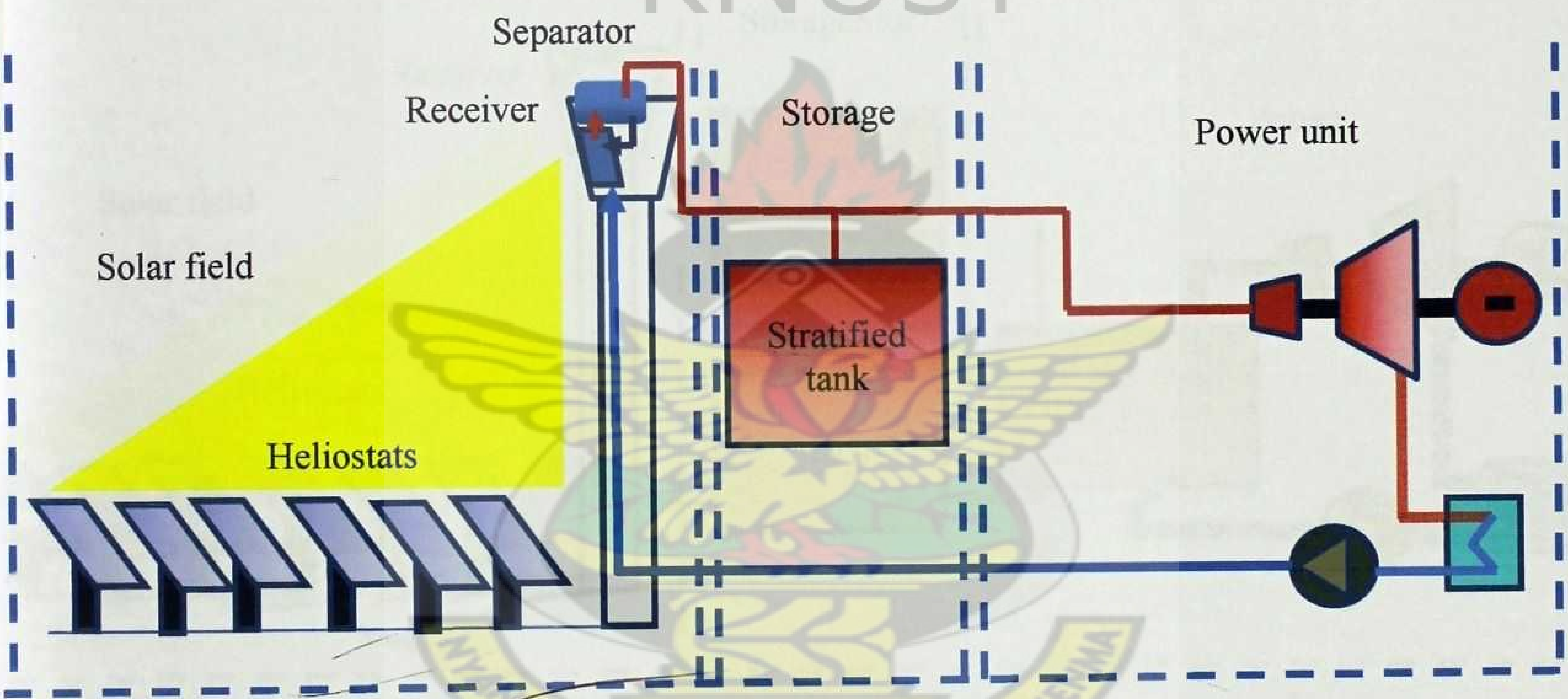
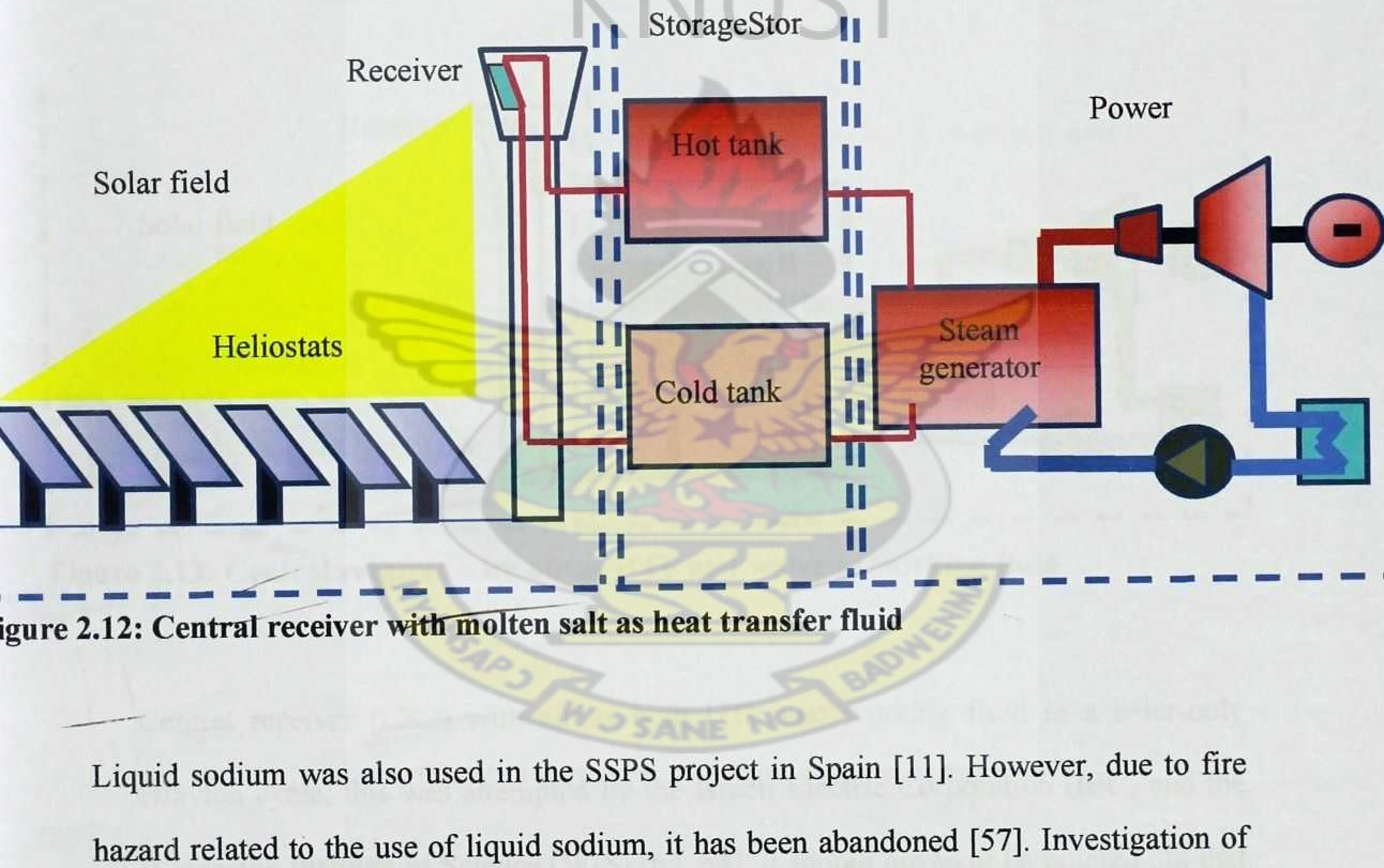



**Figure 2.11: Central receiver with water as heat transfer fluid**

However, problems such as tubes' leakage and deformations in the superheated zone were reported [52].

As an alternative to water, molten salt was used in projects such as Themis in France [53], solar two in USA [54] and Solar Tres in Spain [55, 56]. Figure 2.12 is a sketch of a central receiver with molten salt as heat transfer fluid.




**igure 2.12: Central receiver with molten salt as heat transfer fluid**

Liquid sodium was also used in the SSPS project in Spain [11]. However, due to fire hazard related to the use of liquid sodium, it has been abandoned [57]. Investigation of molten salt in central receivers was carried out by Li et al., Kolb, Yang et al. and Hasuike et al. [58-61].

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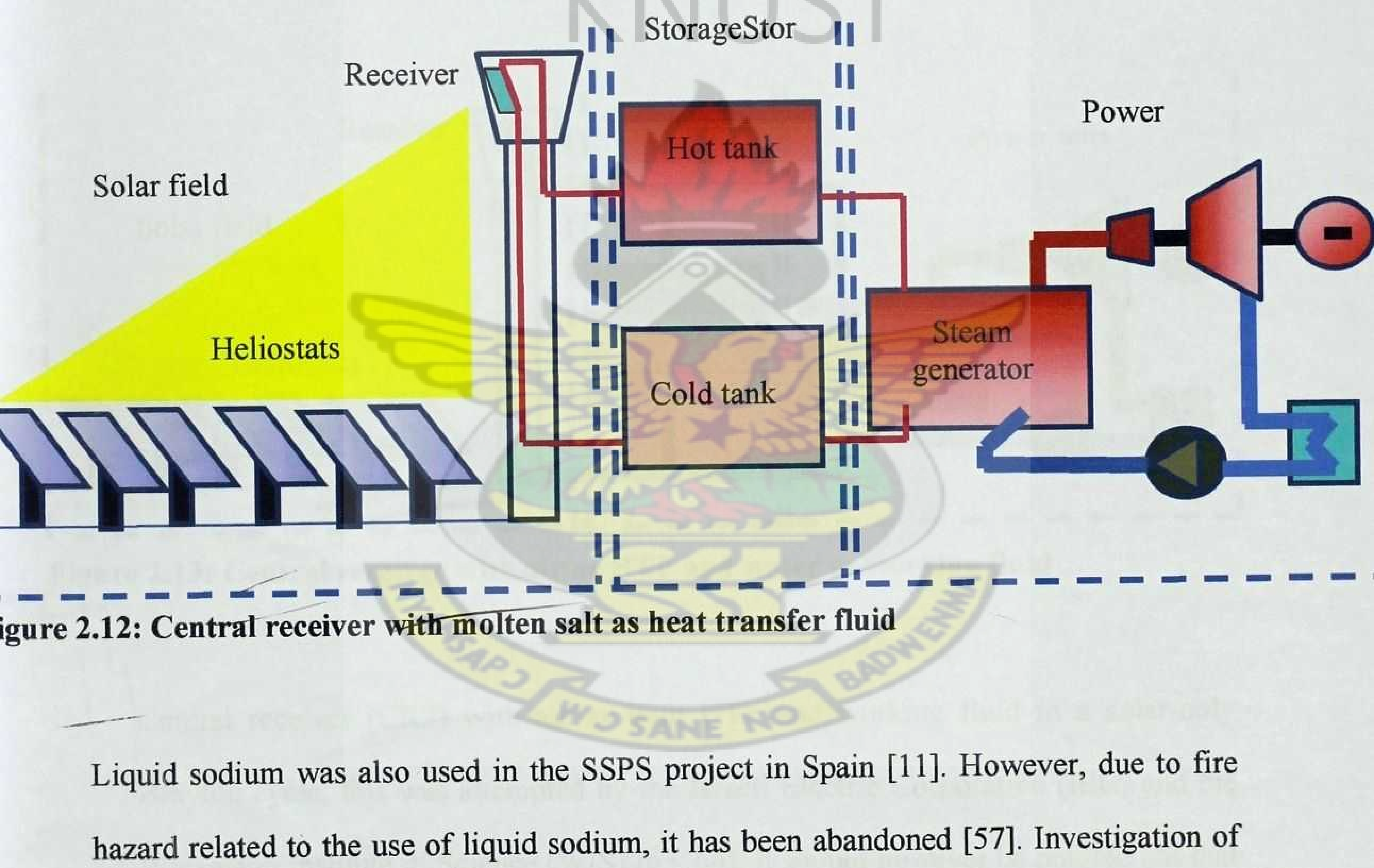


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#### 2.1.3.2. Central receiver with air as heat transfer fluid

Air has the advantage of being safe, available everywhere and easy to handle. When the HTF is air, the following options apply:

- Central receiver (CR1) with air as heat transfer fluid and water as working fluid [62]. Please refer to Figure 2.13 for a sketch. Such plant was illustrated in the Phoebus/TSA/Solair power plant concept [63].



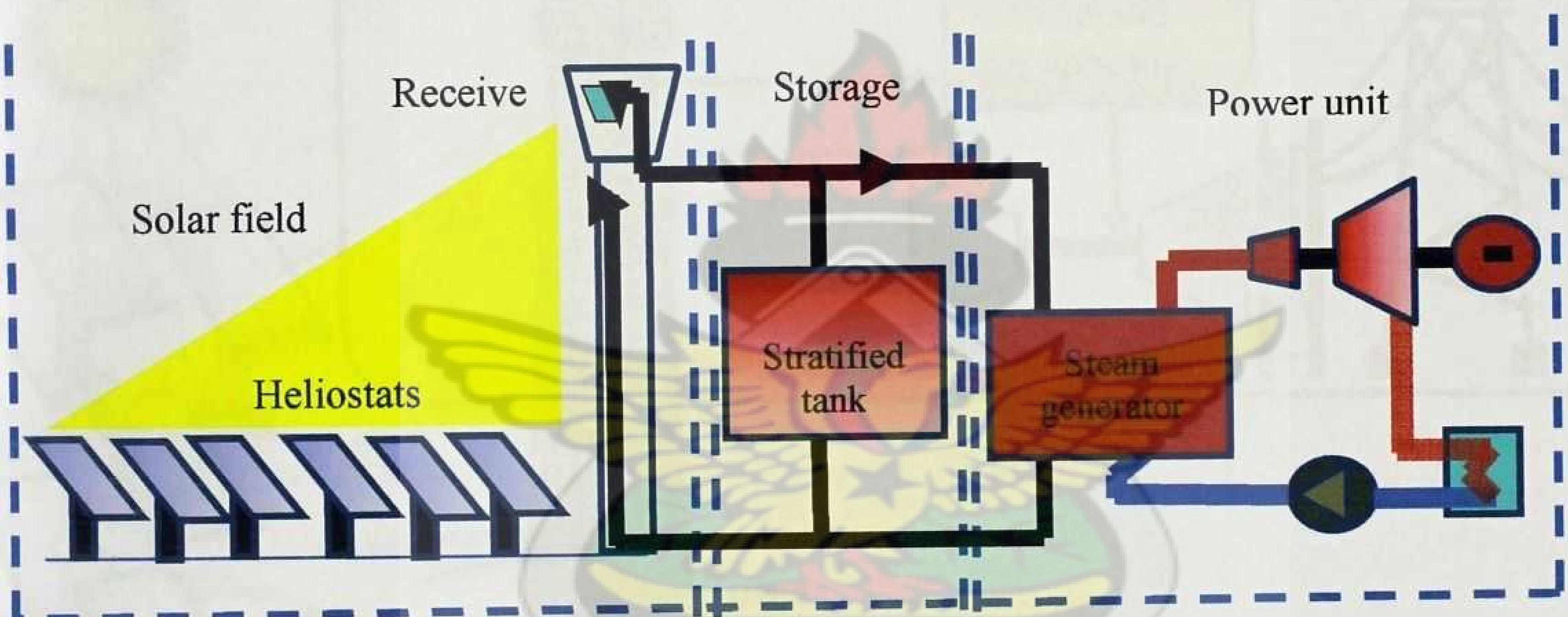


**Figure 2.13: Central receiver with air as HTF and water as working fluid**

- Central receiver (CR2) with air as both HTF and working fluid in a solar-only Brayton cycle; this was attempted by the Israeli Electric Corporation (IEC) and the Weizmann Institute of Science (WIS) [63, 64]. It should however be pointed out that the turbine in a solar-only Brayton cycle is likely to suffer thermal stresses due to the variation of its inlet temperature related to the radiation fluctuations.

- Central receiver (CR3) with air as HTF in a hybrid solar-gas/fuel oil Brayton cycle. A sketch of CR3 is given in Figure 2.14. Air leaving the compressor is preheated in the solar receiver before mixing with gas/fuel oil in the combustion chamber [63-66]; this is referred in the literature as hybrid systems as compared to solar-only systems.



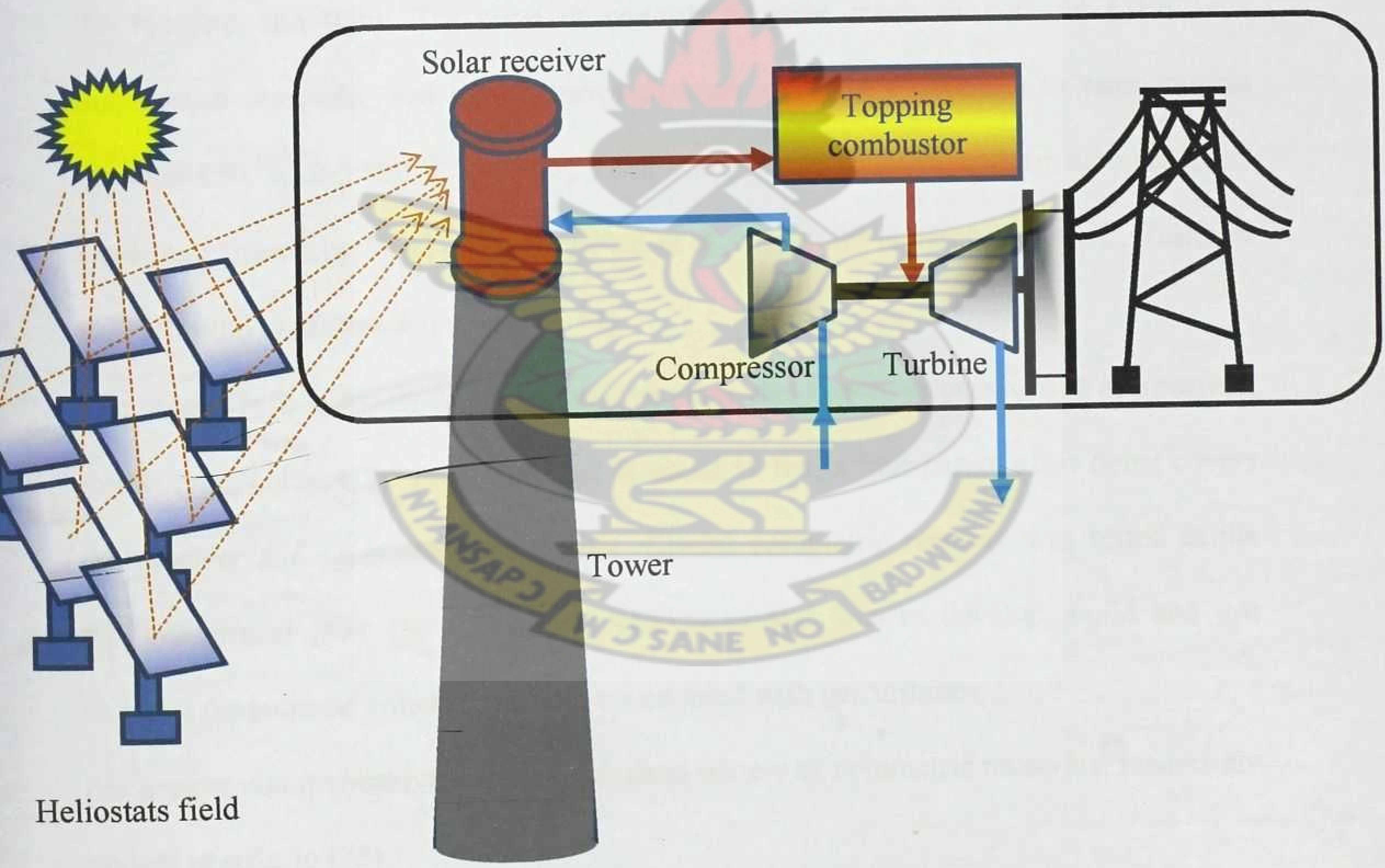


**Figure 2.14: Central receiver with air as HTF in a hybrid solar-gas Brayton cycle**

As any Brayton cycle, overall efficiency of CR2 and CR3 can be improved by bottoming them up with Rankine cycle [67]; organic fluid or steam serves as working fluid of the

- Central receiver (CR3) with air as HTF in a hybrid solar-gas/fuel oil Brayton cycle. A sketch of CR3 is given in Figure 2.14. Air leaving the compressor is preheated in the solar receiver before mixing with gas/fuel oil in the combustion chamber [63-66]; this is referred in the literature as hybrid systems as compared to solar-only systems.



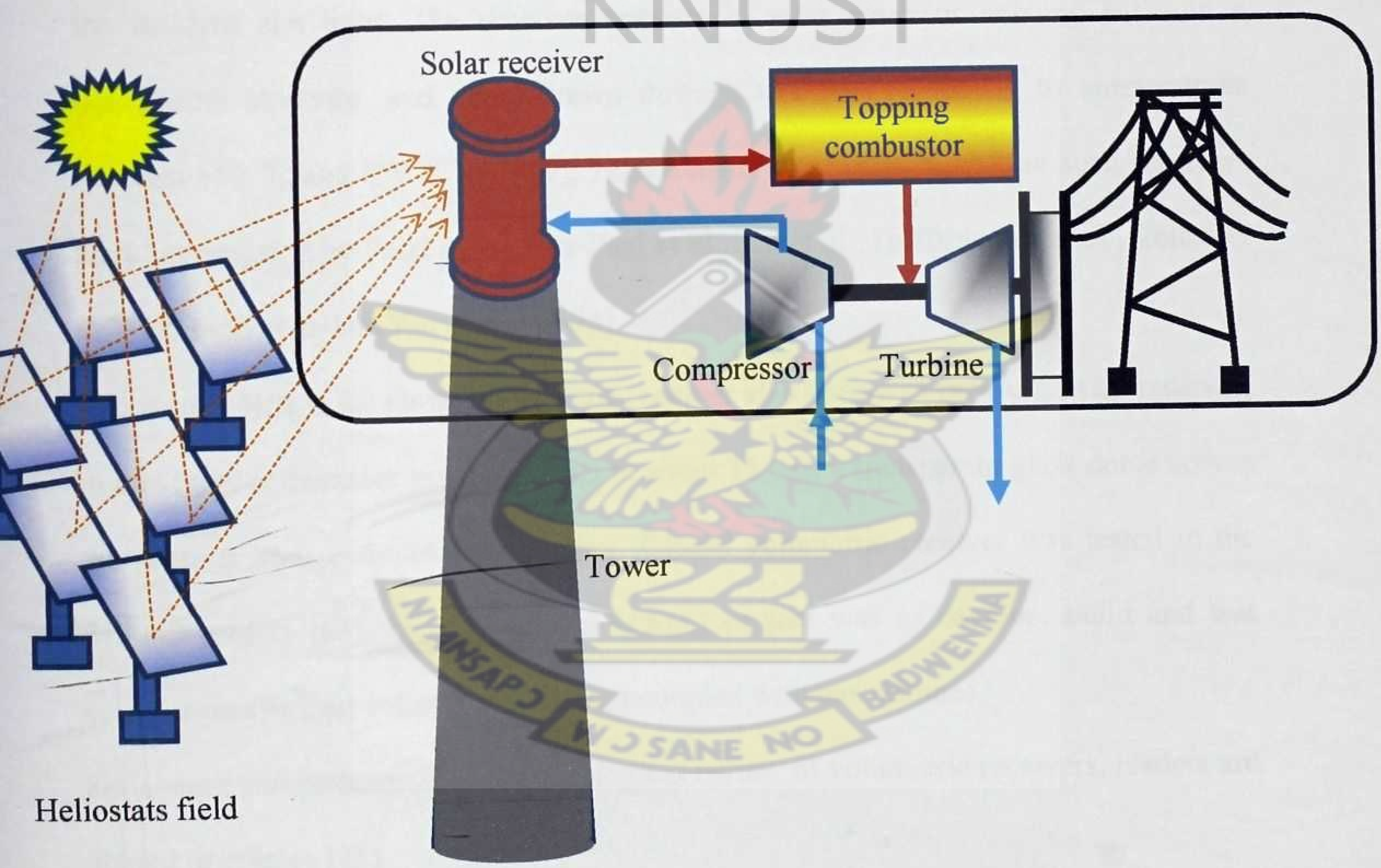


**Figure 2.14: Central receiver with air as HTF in a hybrid solar-gas Brayton cycle**

As any Brayton cycle, overall efficiency of CR2 and CR3 can be improved by bottoming them up with Rankine cycle [67]; organic fluid or steam serves as working fluid of the bottom cycle. When organic fluid is used, the bottom cycle is referred to as Organic Rankine Cycle (ORC).

#### 2.1.3.3. Air receiver technology

Two types of air receivers have so far emerged in CR Systems. One type is the open volumetric receiver also known as atmospheric air receivers. In this type of air receiver, atmospheric air is transported by a blower through the receiver, which is then heated by the incident sun light. The receiver consists of wire mesh or ceramic foam in a honeycomb structure, and air is drawn through this and heated up to temperatures between 650 °C and 850 °C [68, 69]. Heat transfer and performances in such receivers were investigated by Fend et al., Pitz-Paal et al., Xu et al., Hoffschmidt et al., Tellez et al., Hellmuth et al. and Wu et al. [68-74].

The second type is the closed volumetric receiver also known as pressurised air receiver; in this type, compressor pressurizes air to about 15 bar; a transparent glass dome covers the receiver and separates the absorber. Closed volumetric receiver was tested in the REFOS project [63]; the aim of the REFOS project was to develop, build and test modular pressurized volumetric receivers coupled with gas turbines.

For a more comprehensive and chronological review of volumetric receivers, readers are invited to refer to [75].

### 2.1.4. Linear Fresnel reflector technology

Linear Fresnel Reflector (LFR) is less matured compared to parabolic trough, and central receiver; it however shows great potential since it aims at offering lower overall costs by sharing a receiver between several mirrors and also by avoiding the cost of flexible high pressure lines. LFR system is similar to parabolic trough systems, since it has simple line-focus geometry with one axis for tracking; the main difference resides in the fact that it employs flat mirror segments and a stationary receiver which is fixed in space above the mirror field. Figure 2.15 is a layout of this technology. Puerto Errado 1 (PE 1) in Spain is the first grid-connected linear Fresnel power plant. It started operation in March 2009.



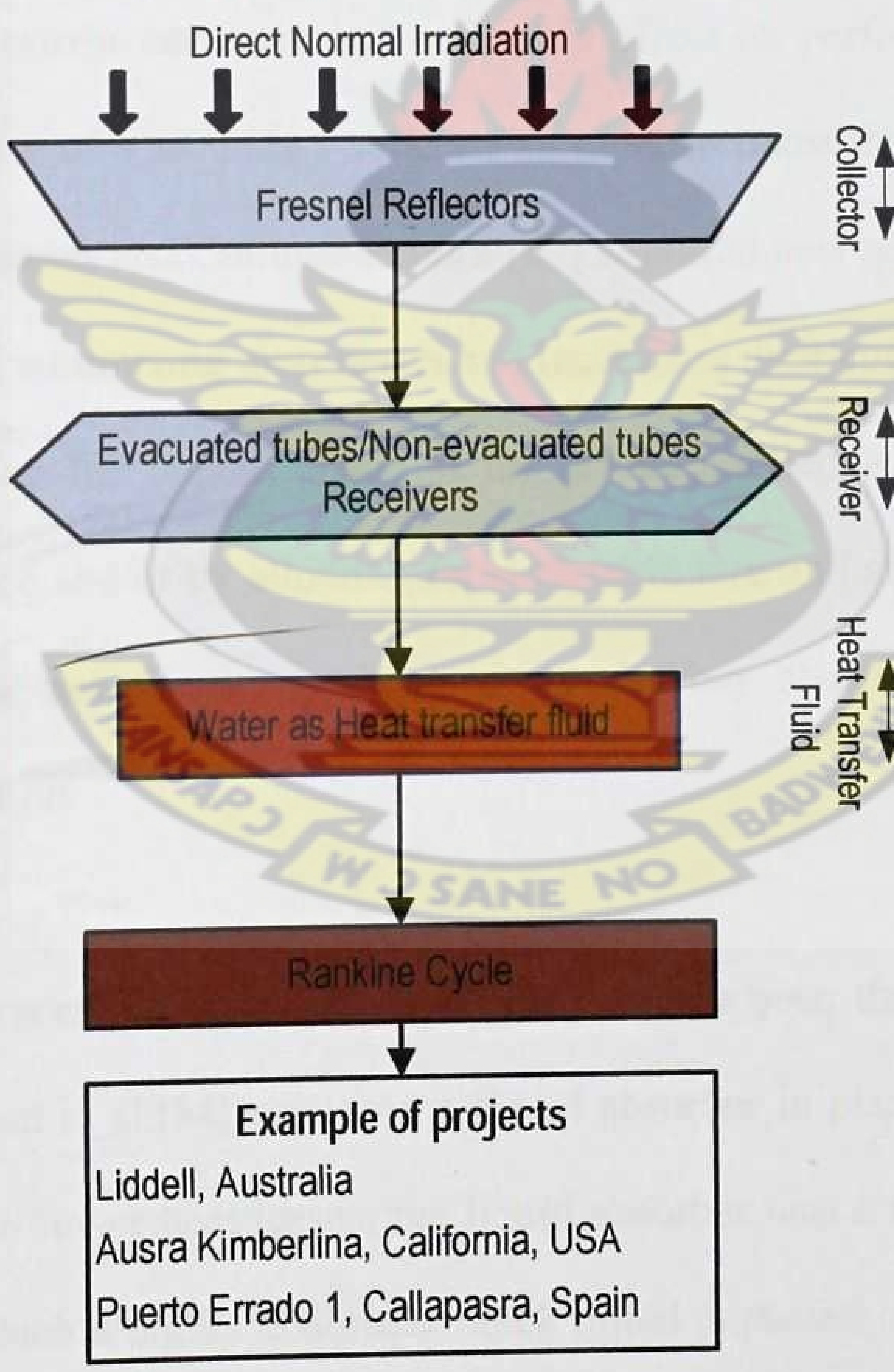


**Figure 2.15: Flow chart for Fresnel reflector technology**

Work on Linear Fresnel reflectors started in France with Francia [76]. But one fundamental difficulty with the LFR technology is the avoidance of shading of incoming solar radiation and blocking of reflected solar radiation by adjacent reflectors. Blocking and shading can be reduced by either increasing the height of the absorber towers or by the use of Compact Linear Fresnel Reflector (CLFR) technology. CLFR has been recently developed at Sydney University in Australia [77, 78]. Research on CLFR has been conducted by many authors. Mills and Morrison [79] investigated CLFR systems and found that the best orientation for the evacuated absorber tube was horizontal and the use of standard mirror curvature has negligible effect on performance; in addition, they suggested the use of a secondary reflector in order to boost the concentration to its theoretical limits. Chaves and Collares-Pereira [80] explored new geometries for Fresnel reflectors in view of minimizing their losses and increasing their concentration. This was achieved by changing the overall shape of the primary reflector, making it a wave-shaped trough surface and/or by allowing for a variable size and shape of the reflectors as a function of the position in the heliostat field. They also suggested the use of secondary concentrators.

Thermal losses on receivers for CLFR systems have also been the subject for various studies [81-86]. Islam et al.[84] proposed a liquid absorber in place of glazed metallic absorbers in order to lower heat losses; the liquid absorber was a tubular corning glass absorber through which a highly absorbent black liquid is passed. Khan [83] carried an experiment in order to measure the overall heat loss coefficients, the optical efficiency and the stagnation temperature of the concentrator-absorber. The results obtained for a copper oxide-coated rectangular absorber were compared with that of an identical black painted absorber. The experiment showed better performance for the copper oxide-coated absorber. Dey [82] described aspects of a design methodology and presented heat transfer calculations for an elevated linear absorber. Reynolds et al. [81] developed a computer model in order to study heat losses from a trapezoidal cavity absorber. The absorber was called so because the cross-section of the cavity is an isosceles trapezium. Experiment showed good agreement with the model.



Singh et al. [85, 86] in studying experimentally the effect of concentration ratio, absorber's shape and surface coating on the thermal performance of a Fresnel reflecting device, found that the thermal efficiency decreases with the increase in the concentration ratio of the Fresnel collector; they also noted that the thermal efficiency of the collector with black-nickel coated absorbers was about 10 % higher as compared to ordinary dull-black painted absorbers; round pipes (multi-tube) absorbers were also found to have 2–8 % efficiency higher as compared to rectangular pipes absorber.

Direct steam generation has been used so far in linear Fresnel technology but applicability of molten salt as heat transfer fluid has been considered by Grena and Tarquini [87].



### 2.1.5. Parabolic Dish technology

Parabolic dish offers the highest thermal and optical efficiencies compared to the other technologies. A parabolic dish is a large reflector that concentrates thermal energy into a single focal point; when the focal point contains a Stirling engine, the technology is called dish- Stirling [88-92]; it is also termed dish-Brayton [90, 93, 94] or dish-Rankine [88, 89, 95-97] when the focused thermal energy is used in a Brayton or a Rankine cycle respectively. Figure 2.16 illustrates the working principle of parabolic dish technology. Direct electrochemical conversion of heat to electricity using parabolic dish technology was also proposed by [98].

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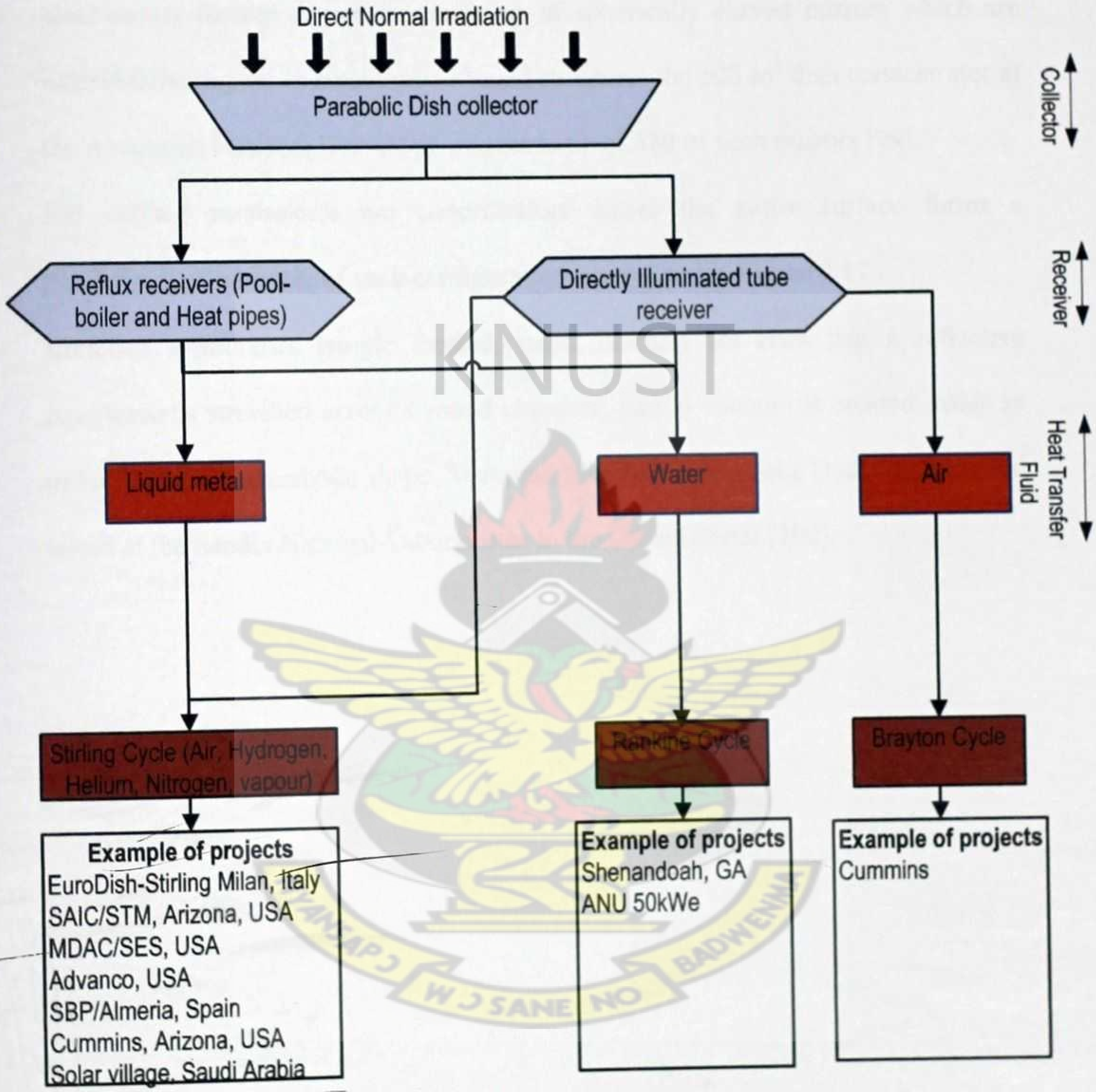


**Figure 2.16: Flow chart for Parabolic dish technology**

#### 2.1.5.1. Dish concentrators

There are many configurations when it comes to dish concentrators:

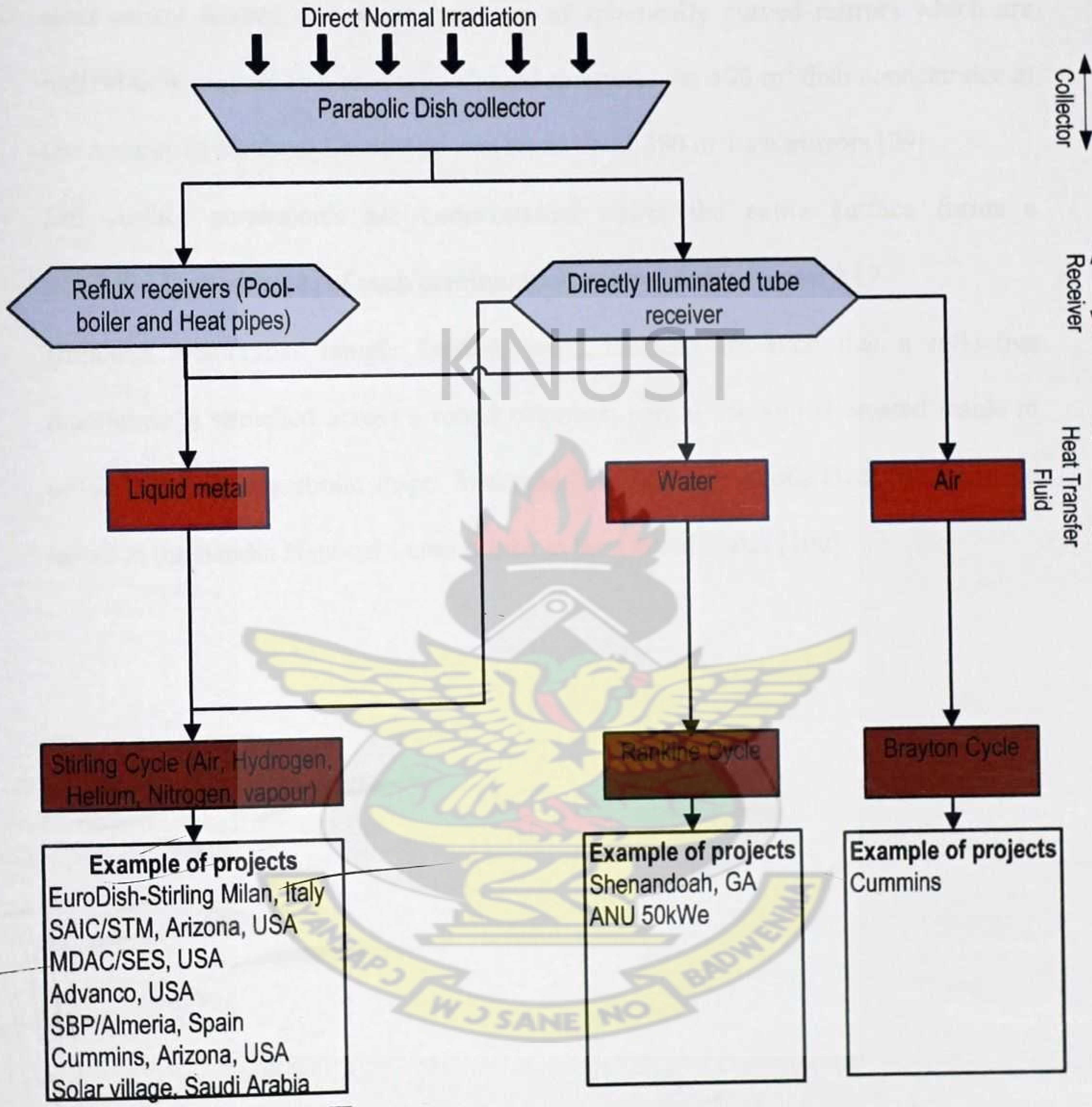


**Figure 2.16: Flow chart for Parabolic dish technology**

### 2.1.5.1. Dish concentrators

There are many configurations when it comes to dish concentrators:

- glass mirror-faceted dishes are made up of spherically curved mirrors which are individually aligned in a parabolic shaped structure; the 500 $m^2$ dish concentrator at the Australian National University was made up of 380 of such mirrors [99].
- full surface paraboloids are concentrators where the entire surface forms a paraboloid; an example of such configuration is provided in Figure 2.17.
- stretched membranes (single faceted, multi faceted) are such that a reflective membrane is stretched across a round chamber; partial vacuum is created inside in order to induce a parabolic shape. Stretched-Membrane Parabolic Dish was built and tested at the Sandia National Laboratories in the United States [100].

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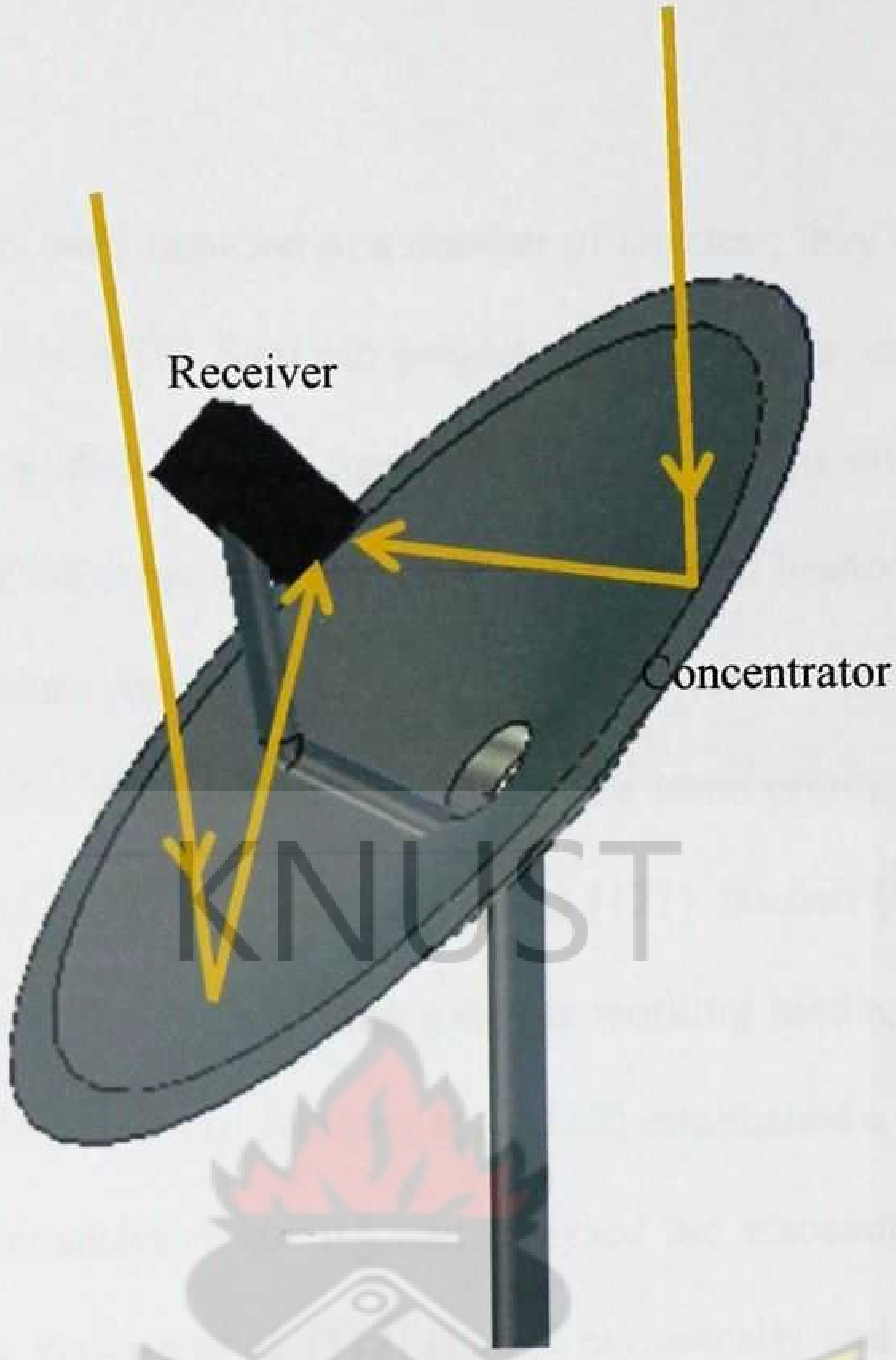


#### 2.1.5.2. Receivers in parabolic dish

The function of the receiver (or absorber) in parabolic dish systems, as in any other CSP system, is twofold: firstly, it absorbs the solar radiation reflected by the mirrored collector and secondly transfers it as heat into the engine working fluid. Receivers for dish Stirling systems are cavity receivers with a small opening (aperture) through which concentrated sunlight enters. They are of two types [101]: the first type is the directly illuminated tube receiver; it is made up of small tubes placed directly in the concentrated solar flux region and through which the working fluid flows. The second type is the reflux receiver. It uses a liquid-metal intermediate heat-transfer fluid in a heat pipe or in a pool-boiler.

Direct illumination receivers were reported in a number of articles ; they were also used in some projects such as SAIC/STM SunDish project, ADDS system and SES System all in the USA, and the Eurodish SBP in Spain [102]; however, as noted by Adkins [103], direct illumination of the tubes created high stress areas that limited the life of the solar receiver. Reflux receivers were then introduced. Many works were carried out on reflux receivers [103-120] and were mainly focussed on the more prominent heat losses which are reported to be radiative and convective losses [121]. Bienert [119] noted that heat pipe receivers were best suited to heating gaseous working media, such as air or helium in Brayton and Stirling systems. Jianfeng et al.[110] established a physical model of a solar receiver pipe with selective coating and analysed the associated heat transfer and exergetic performance. Prakash et al. [113] studied numerically and experimentally the effects of fluid inlet temperature, receiver inclination angle and external wind on the total thermal loss and the convective losses for a downward facing cavity receiver. Reddy and Kumar [115, 120] successively presented a 2-D and a 3-D numerical model for investigating natural convection heat losses from modified cavity receivers with and without insulation. Nusselt number correlations were developed. They had in a previous study [121] compared the natural convective heat loss from three types of receivers (cavity receiver, semi-cavity receiver and modified cavity receiver) and concluded that modified cavity receiver performs better for fuzzy-focal solar dish collector. Shuai et al.[116] studied the flux distribution on the aperture plane of different geometries of cavity receivers (cylindrical, dome, heteroconical, elliptical, spherical and conical); spherical receiver showed relatively good radiation performance. Design and modelling guidelines were proposed. A more comprehensive review on convection heat losses from cavity receivers in parabolic dish systems was provided by Kalogirou [122]; the review presented correlations that have been developed for predicting cavity receiver convection heat loss.

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## 2.2. SECOND PART: REVIEW OF LITERATURE ON SITING CRITERIA AND POTENTIAL ASSESSMENT FOR CSP

CSP implementation requires some preliminary studies in order to choose the right site which will host the plant.

### 2.2.1. Review of siting criteria

Broesamle et al. [123] used STEPS (Evaluation system for Solar Thermal Power Stations) to assess the potential of solar electricity in North Africa. STEPS provides sites ranking with respect to the potential and cost of solar thermal electricity for a particular power plant configuration based on Direct Normal Irradiation (DNI), geographical conditions (land slope, land cover, distance from cooling water resources, etc.), infrastructure (pipelines, electricity grids, streets etc.). The US Department of Energy identified some criteria in assessing the potential of CSP on public lands [124]; criteria included minimum DNI of 5kWh/$m^2$/day, a land slope of less than 5 %, ideally less than 1 % for central receiver systems and 10 % for distributed generation, a minimum parcel size of 0.16 $km^2$, availability of transmission lines (69-345kV) and access road/rail within 80 km. Hang et al [125] also studied the potential of CSP in China and presented strategies for promoting the technology. They noted that, except for solar energy resources, land use and land cover, the other siting factors are not much different compared with those of the conventional steam power plant.

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### 2.2.2. Site selection and potential assessment for Concentrating Solar Power

Selecting an appropriate site for concentrating power plant has been the subject of many studies. Broesamle et al. [123] made use of satellite data and Geographic Information System (GIS) to rank potential sites for CSP in North Africa. Bravo et al. [126] in considering parabolic trough plants with 6 hours thermal storage, used GIS and found a generation ceiling of 9,897 TWh/y for Spain. After taking just 1 % of the whole wasteland in China as potential site for solar thermal power plant and assuming a land area requirement of 20.2 km²/GW of installed capacity for power tower technology, Hang et al. [125] showed that 1,300 GW of electricity generation capacity could be installed. Fluri [127] also used GIS to identify potential areas for the implementation of large scale CSP plant in South Africa; assuming parabolic trough technology with an average capacity factor of 38.8 %, he found that the identified areas could yield a total nominal capacity of 547.6 GW corresponding to a net annual energy generation of 1,861 TWh. Charabi and Gastli [128] used GIS tools to first evaluate the solar resource and to select a candidate site for large CSP plants for Duqum in the Sultanate of Oman; they also calculated the electricity generation potential for different CSP technologies and for concentrated PV (CPV). The same methodology was used by Clifton and Boruff [129] in order to classify potential CSP sites in the Wheatbelt region of Western Australia.

Criteria used in these studies include sufficient DNI, suitable land use profile, availability of water, closeness to transmission lines, proximity to pipelines, low slope value, access to highways for maintenance and repair, population density etc.

Similar assessments were also performed in the United States and for some renewable energy technologies [124, 130-134], but none has ever been performed in the ECOWAS region for CSP technology. Moreover, the method used in some of the aforementioned studies for computing the nominal potential power is questionable since it does not take into account the actual value of the DNI of the site. For instance, in these studies, the land demand per unit power was assumed constant for predicting the nominal potential capacity of CSP. The studies rather assumed the DNI to be higher than or equal to a certain threshold value which they consider to be the minimum for a CSP plant to be economically viable. Land demand however, strongly depends on the level of DNI.



## 2.3. Conclusion

The four main CSP technologies, which have reached commercial or near-commercial stage, were reviewed in this chapter. They were parabolic trough technology, power towers or central receiver system, linear Fresnel reflector systems and parabolic dish/engine systems.

Substantial research and development issues are being addressed for concentrating solar power technologies. The review highlighted key components in each technology and discussed the innovations, the technological challenges and the research and development activities for each system. Interest was also granted to previous studies pertaining to site selection for concentrating solar power. Areas of research that still need strong focus are the solar resource assessment, dust-proof collectors, waterless and dry cooling CSP systems and small-scale CSP. Small-scale CSP systems are relevant in developing countries where the power demand does not necessarily always match the output of large-scale power systems and where high voltage transmission lines are yet to be built.

The review revealed that no site selection and potential assessment have ever been carried out for Concentrating Solar Power for West Africa. It also questioned the method used for predicting the CSP Capacity. The following chapters in this thesis attempt to address these issues.

# CHAPTER 3: SITING GUIDELINES FOR CONCENTRATING SOLAR POWER PLANTS: CASE STUDY OF BURKINA FASO

## 3.1. Introduction

This chapter provides technical guidelines for selecting a suitable site for Concentrating Solar Power (CSP) Plants. The guidelines are then applied in selecting a candidate site in Burkina Faso. Section 3.2 develops the guidelines and section 3.3 applies them to Burkina Faso, insights gained from this exercise are then summarized in Section 3.4, the conclusion for this Chapter.

It is worthy nothing that the content of this chapter has been published in June 2010 in the Solar Energy Journal [135].

## 3.2. Guidelines for CSP site selection

Selecting a site that meets the technical requirements for the implementation of a CSP plant requires a thorough study of some key parameters. Six of such parameters are highlighted in this section; they are solar resource, water resources, soil structure and the geology, the availability of land, the topography, and the energy demand.

### 3.2.1. Solar resource assessment

The electricity production by a CSP plant is approximately proportional to the annual solar radiation of the site, hence inversely proportional to the cost of electricity. A solar resource assessment of the site is therefore necessary [136] in order to allow proper sizing of the plant. For instance, 1 % uncertainty in estimating the solar resource can vary the annual revenues of a 50 MW CSP plant in Spain in the order of 310, 000 Euros (at 0.20 Euro/ $kWh_{el}$) [137].

The Direct Normal Irradiance (DNI) constitutes approximately between 50 % and 90 % of the global radiation in many parts of the world [138]. DNI varies highly in time and space. Indeed, the annual DNI can vary up to 30 % from one year to the other. Radiation data should therefore be measured over a period of five years or 10 years in order to reduce long-term averaging errors to less than 10 % or 5 % respectively [139]. Furthermore, the strong spatial unpredictability of the DNI requires the necessity of less than 5 km resolution or even 1 km for costal and mountainous areas [137]. Moreover, the cost of electricity is 31 % less for a CSP plant operating in a site where daily DNI amounts to 7.9 $kWh/m^2$ than that of a CSP plant operating in a site of 5.5 $kWh/m^2$ [138]. With regards to the above, irradiation is crucial in selecting candidate site for a CSP project.

### 3.2.2. Availability of water and cooling mode

When CSP technology uses Rankine cycle, water is needed for cooling unless dry cooling technology is adopted. The cooling uses approximately 90 % of the water. The steam cycle uses approximately 8% and mirror washing uses the remaining 2% [132]. A combination of both wet and dry cooling is another alternative. This option is comparable to dry cooling in terms of water consumption and in terms of plant efficiency drop. Al-Soud and Hrayshat [140] in studying the technical and economic feasibility of a 50 MW CSP plant for Jordan, compared the two modes of cooling in Table 3.1.

It is worth noting that dry cooling is at the expense of plant efficiency and investment costs. Kearney et al. [141] also noted that dry cooling increases the cost of electricity by 10 %. He added that CSP plants in California consume 3.4 $m^3$ of water per megawatt-hour of electricity produced. In 2006, Kelly [142] compared wet and dry Rankine Cycle heat Rejection. He concluded that the dry heat rejection systems deliver 91 to 96 % of the annual electric energy supplied by the wet heat rejection system, and have annual solar-to-electric efficiencies 0.5 to 0.7 percentage points lower. He however noted that the annual water use for the dry cases is only about 8 % of that for the wet case.



**Table 3-1: Comparison of cooling technology for a 50 MW CSP plant [140]**

| Cooling technology | Wet | Dry |
|---|---|---|
| Steam cycle efficiency % | 37 | 35 |
| Parasitic electricity consumption MW | 5 | 7 |
| Energy yield GWh | 117 | 109 |
| Evaporated water $m^3$/MW | 180 | - |
| Investment Million US$ | 2.1 | 6.8 |

The demand in water is minimal when gas cycles are used; even in that case, water is still required for cleaning the mirrors from dust deposits.

Water resource assessment of a candidate site for CSP plant is paramount in deciding on the mode of cooling.

efficiency drop. Al-Soud and Hrayshat [140] in studying the technical and economic feasibility of a 50 MW CSP plant for Jordan, compared the two modes of cooling in Table 3.1.

It is worth noting that dry cooling is at the expense of plant efficiency and investment costs. Kearney et al. [141] also noted that dry cooling increases the cost of electricity by 10 %. He added that CSP plants in California consume 3.4 $m^3$ of water per megawatt-hour of electricity produced. In 2006, Kelly [142] compared wet and dry Rankine Cycle heat Rejection. He concluded that the dry heat rejection systems deliver 91 to 96 % of the annual electric energy supplied by the wet heat rejection system, and have annual solar-to-electric efficiencies 0.5 to 0.7 percentage points lower. He however noted that the annual water use for the dry cases is only about 8 % of that for the wet case.

**Table 3-1: Comparison of cooling technology for a 50 MW CSP plant [140]**

| Cooling technology | Wet | Dry |
|---|---|---|
| Steam cycle efficiency % | 37 | 35 |
| Parasitic electricity consumption MW | 5 | 7 |
| Energy yield GWh | 117 | 109 |
| Evaporated water $m^3$/MW | 180 | - |
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The demand in water is minimal when gas cycles are used; even in that case, water is still required for cleaning the mirrors from dust deposits.

Water resource assessment of a candidate site for CSP plant is paramount in deciding on the mode of cooling.

### 3.2.3. Soil structure and the geology

The nature of the soil has effects on the type of civil work to be carried out on the site especially the foundation and the earthwork. Loose and sandy soils are to be avoided.

When considering storage system in a CSP plant, due to the intermittence of the solar resource, it is very important to study the nature of the local rocks and/or sands. Local rocks or sands could be used in constructing storage systems, thus reducing costs. Caldes et al. [143] noted that storage could cost as much as 12 % of total cost for parabolic through power plant and 6 % for power tower.



In case, studies show oil deposits (case of Mali, Niger and Chad) hybrid CSP/Diesel thermal plants could be implemented. Indeed, hybrid CSP/Diesel thermal plant will guaranty continuous production of electricity. That will avoid building fossil-fired power plants in parallel with 100 % CSP and spare the construction of expensive diurnal and seasonal storage system. A 100 % capacity factor can be obtained with a solar fraction of 10-20 % with a mean daily DNI of 5.51 kWh/m$^2$ (e.g. Seville in Spain). It can also be obtained with 10-28 % solar fraction when daily DNI attains 7.64 kWh/m$^2$ (e.g. Daggett in California) [66].



### 3.2.4. Land issues

CSP plants occupy large areas of land; therefore land tenure, land use and cost are other important issues to be considered in the choice of the appropriate site for a CSP plant. Land ownership varies from country to country; for instance in Burkina, land belongs to the state. The cost of land must also be taken into consideration since it contributes to

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### 3.2.5. Geography and topography of the site (Latitude, Altitude and slope)



Higher altitude leads to much clearer sky and subsequently to more direct normal irradiance (DNI) which is good for sizing CSP plant. Furthermore, because of large land area requirement and in order to avoid excessive cost from land preparation, a small slope is desirable. 1 % gradient was taken by [127, 128, 132, 133, 145] as most economical slope for CSP plant. An average slope of less than 3 % was suggested by Hang et al. for all CSP technologies [125] while Broesamle et al. [123] considered even higher slope of up to 5 % for parabolic trough. Above these values, the ground needs to be levelled and that will elevate the capital cost.



### 3.2.6. Energy demand profile of the site and connection to transmission lines

Finally, the electricity demand profile for the selected site and/or surrounding areas must be established. When demand is low compared to the potential energy yield of the CSP plant, connection to transmission lines has to be considered. Transmission lines will therefore be needed for transporting the electricity produced to much larger electricity consumption centres. In that case, access to transmission lines is definitely a key criterion for the selection of the site. The closeness of the site to a high voltage line will reduce not only power losses but also transmission cost. In order to illustrate the cost of transmission lines in West Africa, the 225-kV line connecting Bobo-Dioulasso to Ouagadougou with a load carrying capacity of 120 MW has cost about US$290,000 per kilometre [146].

## 3.3. Application to case study of Burkina Faso



### 3.3.1. About Burkina Faso

Burkina Faso is landlocked and has a high population density with few natural resources and a fragile soil. Approximately 90 % of the population is engaged in agriculture (mainly subsistence) which is highly vulnerable to variations in rainfall. The country is divided into 13 administrative regions.

### 3.3.2. Energy context of Burkina Faso

Burkina Faso has no known fossil resources. Consumption of petroleum products is entirely dependent on imports. The majority of the population (80 %) still relies on wood fuel for heating and cooking purposes (firewood and charcoal). The total energy consumption per capita was 0.17 toe (tonne of oil equivalent) in 2008. The net electricity consumption per capita, in 2009, was 48 kWh, compared to 120 kWh in the ECOWAS region and 529 kWh in the continent. The country has four hydroelectric plants of total installed capacity of about 32 MW [3]. The national electrification rate was about 25 % in 2009 (approximately 70 % in urban areas and about 3 % in rural areas) [147].

Burkina Faso is very limited in energy resources. However, the country receives abundant solar radiation all year round; data obtained from the national meteorological office suggest a mean annual global irradiation of 5.5 kWh/ $m^2$ per day and an average sunshine duration of over 3000 hours per year. This could be propitious for CSP plants' implementation.

### 3.3.3. Solar map of Burkina Faso

The solar resource is abundant in Africa but the assessment of this resource remains a problem because of lack of synoptic weather stations which have solar irradiation measurement equipments such us pyranometers (for total or diffuse radiation) or pyrheliometers (for beam radiation). As a consequence, most of solar plant's designs are based on satellite data or extrapolated correlations which, most of the time, are not very accurate.

Burkina Faso, like most of sub-saharan countries, is facing the problem of lack of accurate ground data. Data considered in this study are therefore satellite data.

Figure 3.2 is a solar map of Burkina Faso showing daily mean direct normal irradiation. The data were obtained using the Solar Radiation Data (SoDa) Model [148]. From the map, daily DNI values range from 3.9 kWh/$m^2$ to 4.5 kWh/$m^2$. The higher values in this range are recorded in the region bordering the Sahara desert, namely the Sahel region (see Figure 3.1). The region could therefore be considered as one of the best candidate sites for CSP plants, pending investigation of other criteria.

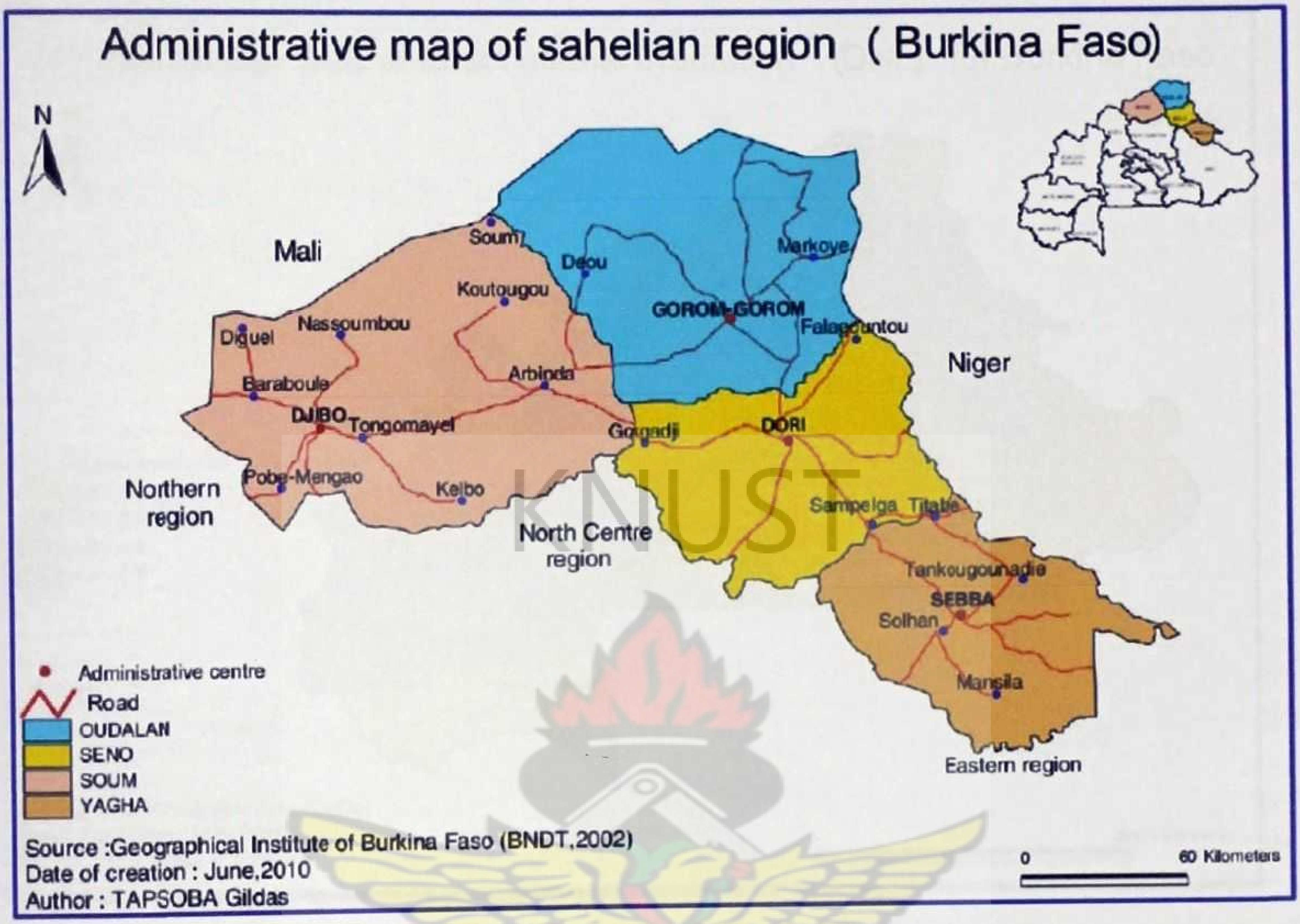



**Figure 3.1: Administrative map of Sahel region (North of Burkina Faso)**

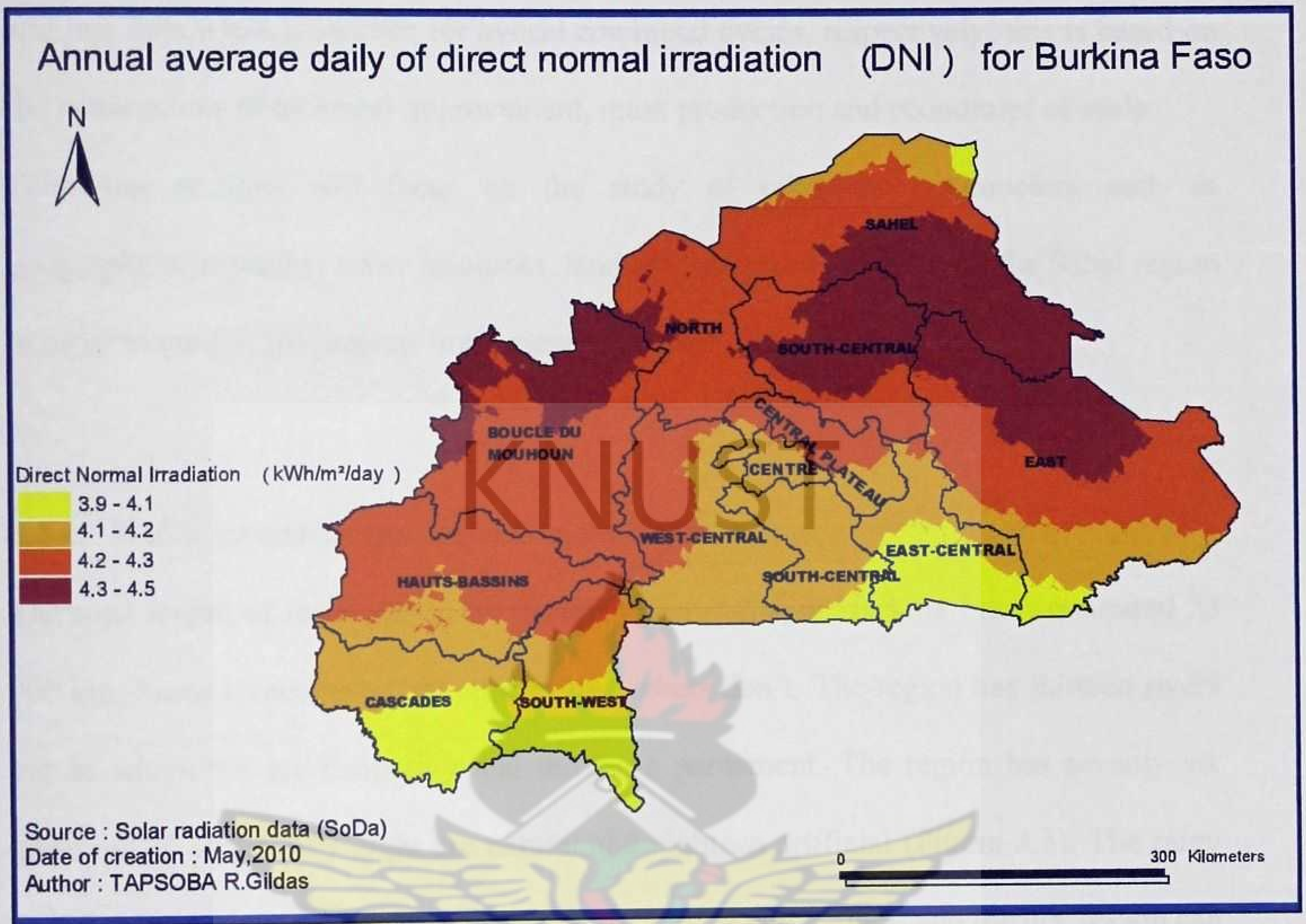
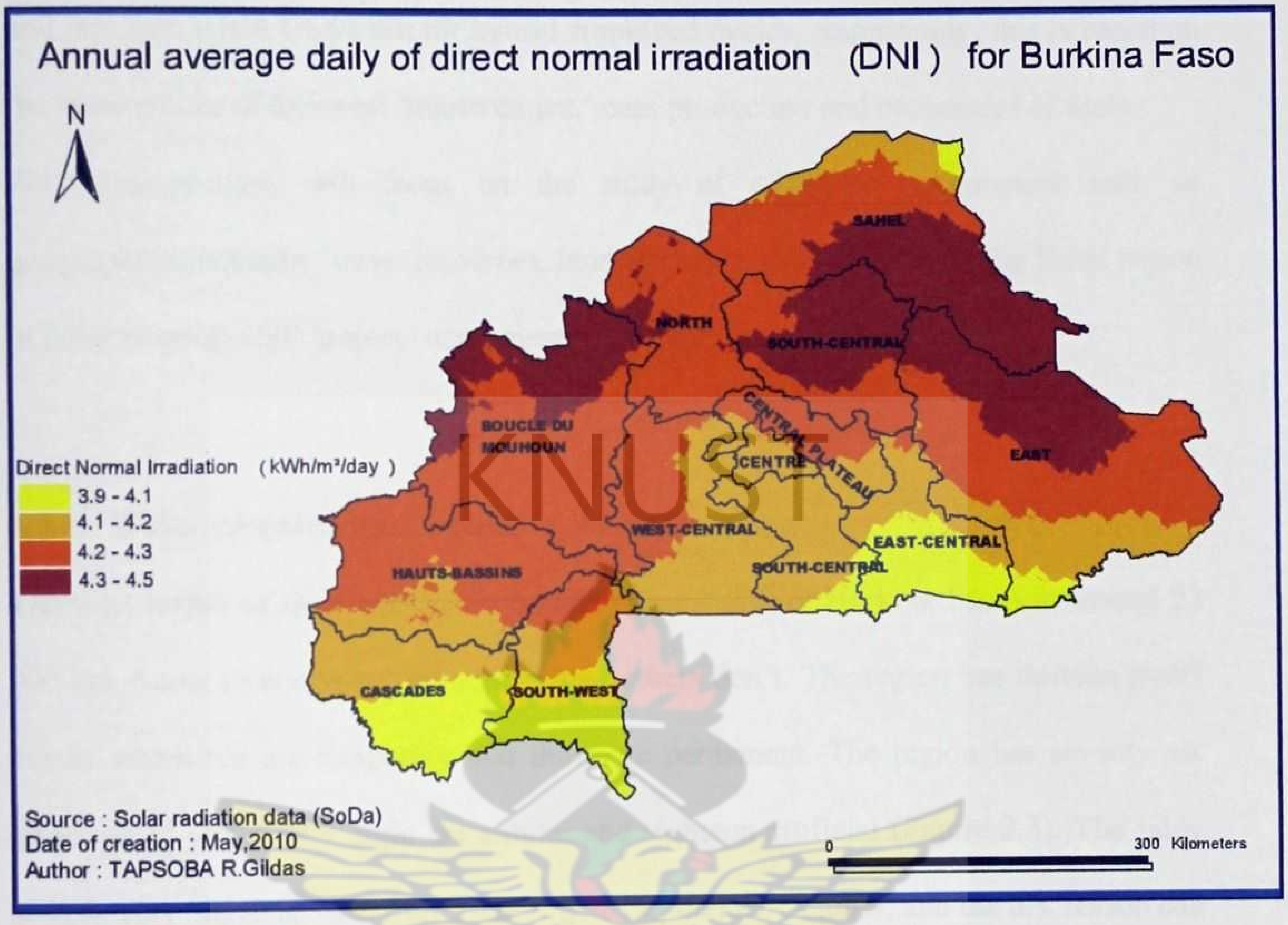



**Figure 3.2: Solar map of Burkina Faso, Annual mean daily DNI**

Economically viable minimum DNI has been suggested in the literature to be 5 $kWh/m^2$ [123, 149]; however Bravo et al. considered lower DNI values [126]. Moreover, as noted by Ramde et al. [150], the cost of electricity in Burkina Faso is one of the most expensive in the world (average in US$ of 24 cents/kWh) since it is mostly produced from diesel plants; hence, more prospective studies could be conducted in order to assess the economics of CSP in both the Sahel and Northern regions. Tsoutsos et al. [151] even proposed a CSP-based stirling engine to be operated at Crete in Greece with daily total irradiation of about 4.73 $kWh/m^2$. Trieb [152] predicted a cost reduction of 50 % for CSP plants and an electricity costs of less than 0.06 US$/kWh for hybrid steam cycles

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Following sections will focus on the study of other key parameters such as geography/topography, water resources, land use and energy demand of the Sahel region in order to guide CSP projects implementers in their design choices.



### 3.3.4. Water resources and rainfall in the Sahel region

The total length of the rivers in the Sahel region (north of Burkina Faso) is around 23 000 km. Some rivers have continuous flow, others don't. The region has thirteen rivers out of which ten are temporary and three are permanent. The region has seventy six lakes out of which fifty eight are natural and eighteen artificial (Figure 3.3). The rainy season, very unstable, runs from June/July to September/October; and the dry season can last nine (9) to ten (10) months with temperatures that vary between 10 °C to 43 °C. Figure 3.4 shows the inter-annual mean rainfalls of the Sahel region from 1989 to 1992. It is worth noting that the towns of Dori, Bani and Sebba are the rainiest ones of the region with a mean over 500 mm for the selected period.

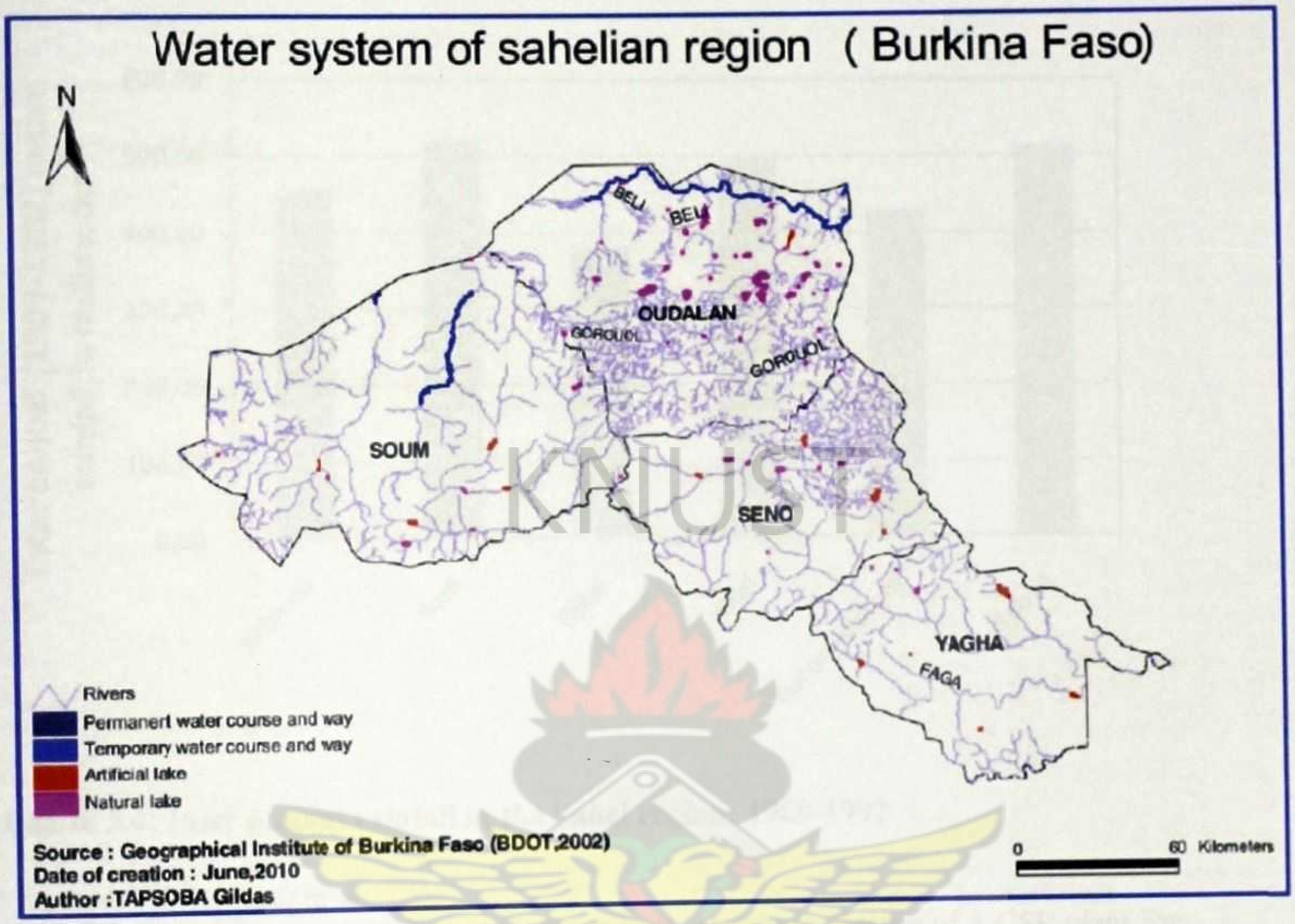
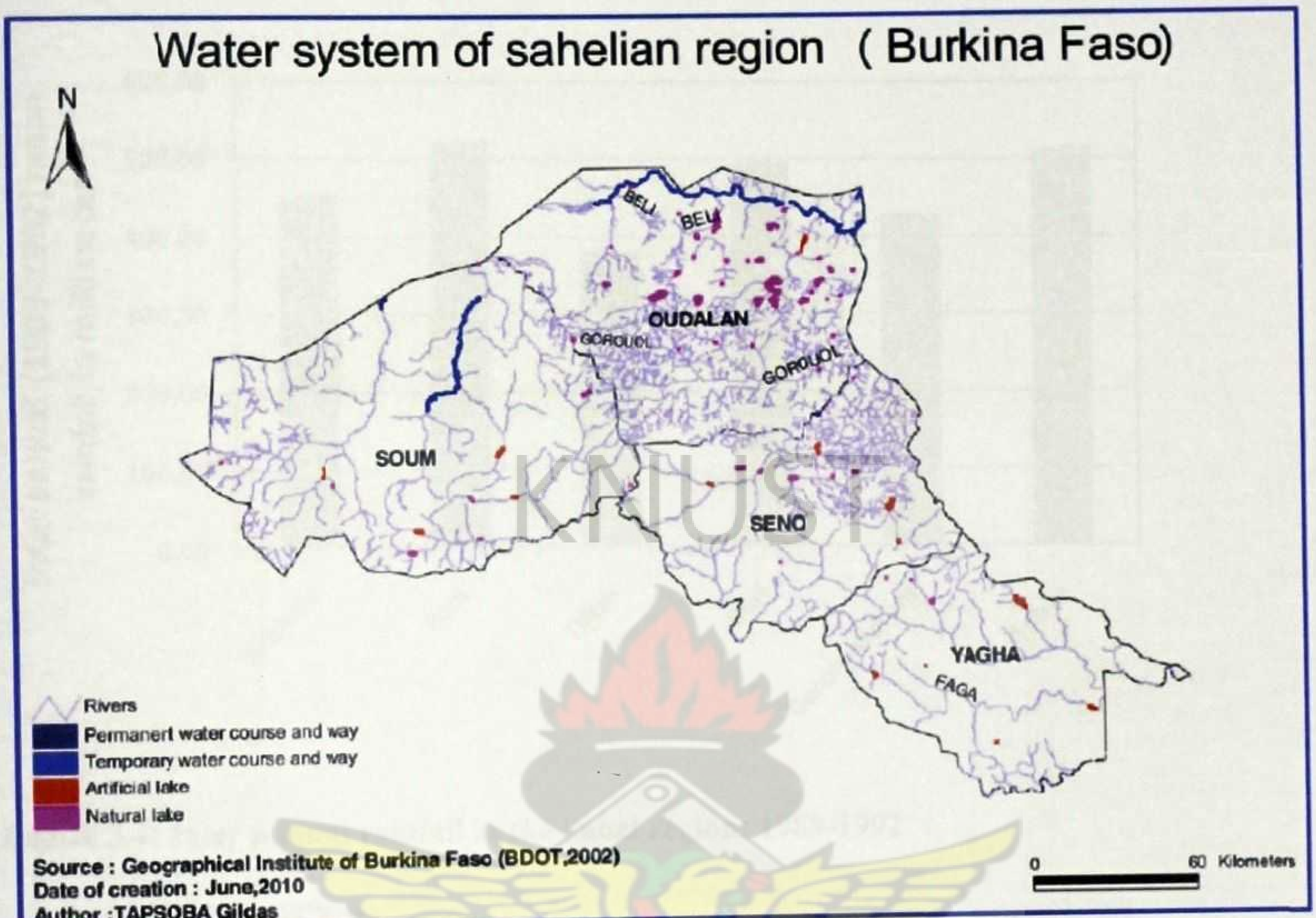



**Figure 3.3: Hydrographic map of the Sahel region (Burkina Faso)**

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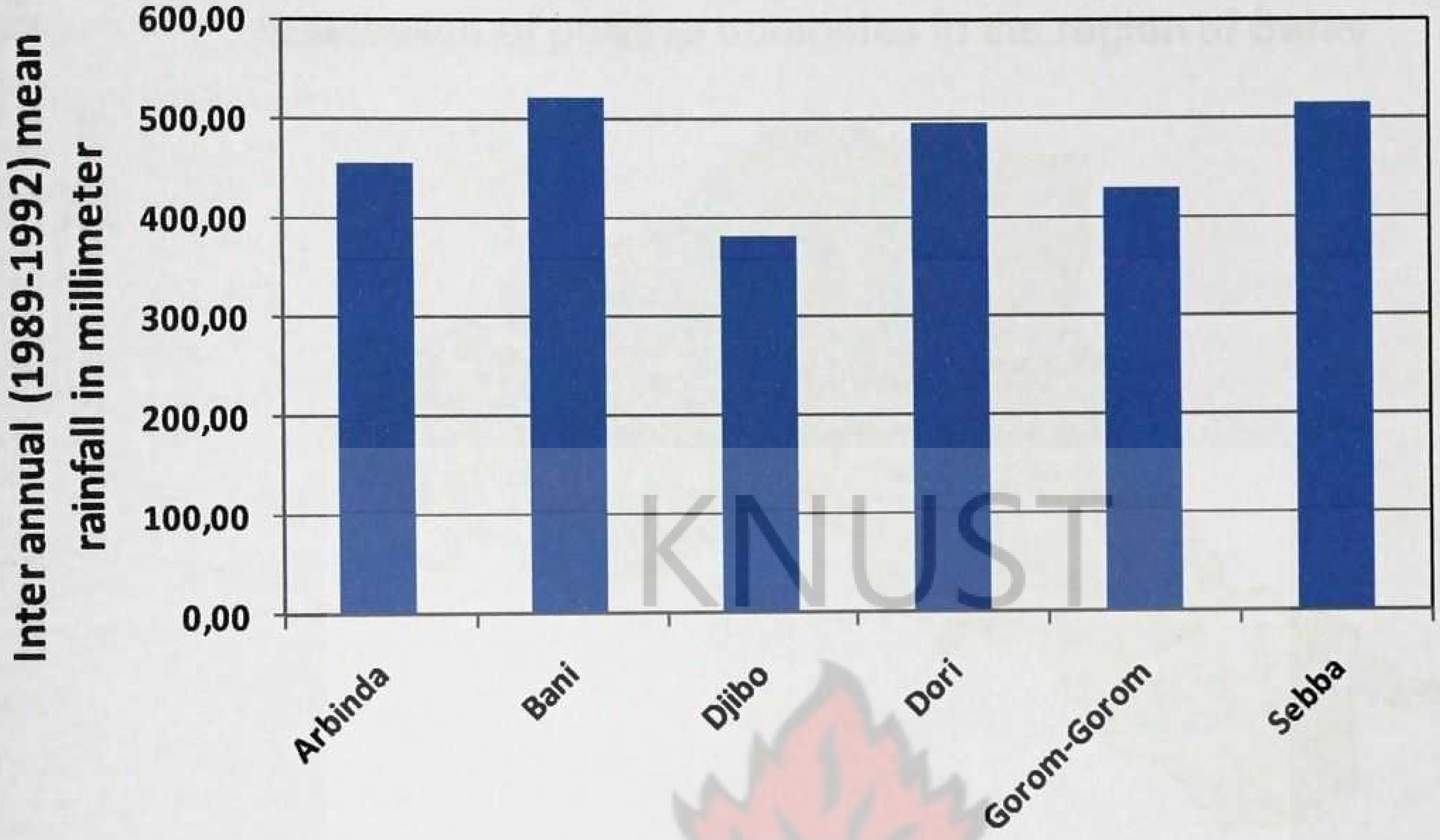


**Figure 3.4: Inter annual rainfall in the Sahel region: 1989-1992**

It is clear that this area is poor in water resources. However, design of a CSP plant for this area could explore dry cooling, rain harvesting technology or underground water technology. Figures 3.5 and 3.6 provide a clue about underground water availability in the region. Out of the 2111 boreholes which were drilled between 1986 and 1996, 67 % were positive (e.g. flow rate greater than 0.7 $m^3/h$) against 33 %. Table 3.2 shows that 53 % have flow rates between 1 and 5 $m^3/h$ while only 5 % have flow rate greater than 10 $m^3/h$.

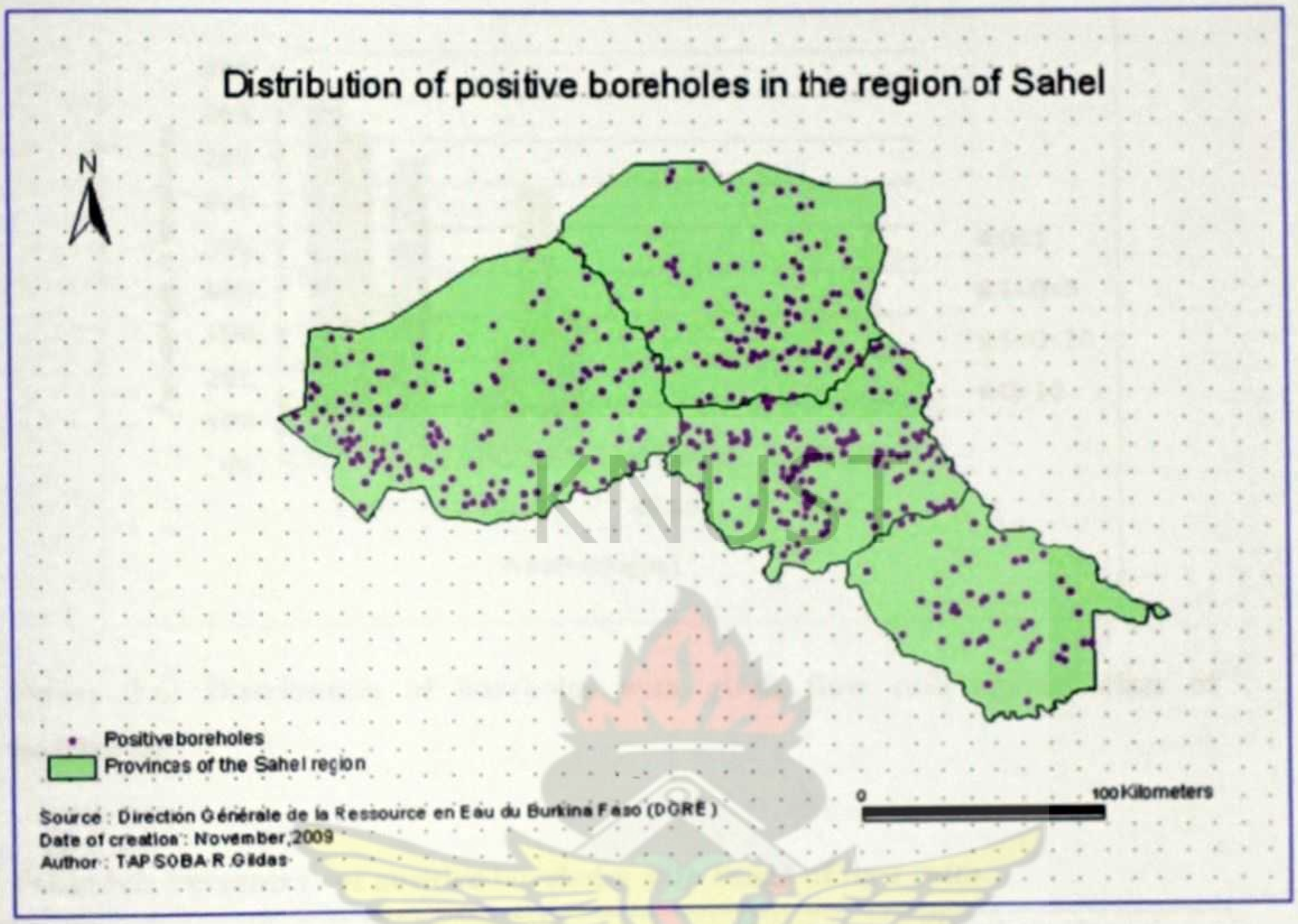


Figure 3.5: Distribution of positive boreholes in the region of Sahel

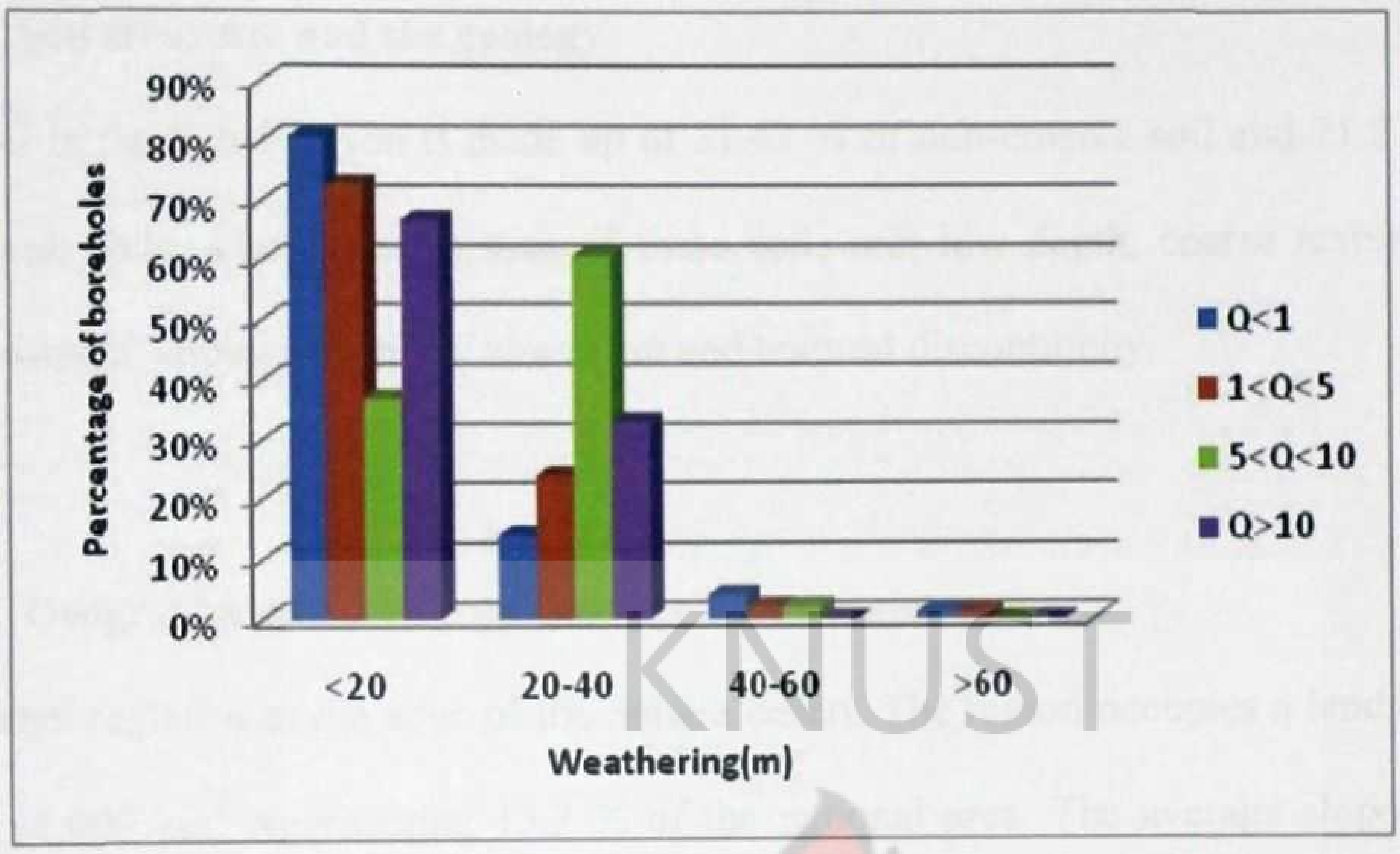


**Figure 3.6: Distribution of boreholes with given flow rate against class of weathering**

**Table 3-2: Percentage of positive boreholes with range of flow rates.**

| Flow rate range ($m^3/h$) | Percentage of boreholes % |
|---|---|
| Q <1 | 31 |
| 1< Q ≤ 5 | 53 |
| 5< Q <10 | 11 |
| Q > 10 | 5 |

Source: Ministry of agriculture; Burkina Faso.

### 3.3.5. Soil structure and the geology

The soil in the Sahel region is made up of 31.43 % of non-erosive soil and 21.21 % of allomorph soils. The characteristics of these soils are: low depth, coarse texture, low water content, strong sensitivity to erosion and textural discontinuity.

### 3.3.6. Geography and topography of the Sahel region

The Sahel region is at the edge of the Sahara desert. The region occupies a land area of about 36,000 $km^2$ representing 13.2 % of the national area. The average slope of the region is 0.12 % oriented towards east; this value is propitious for civil work. The altitude has an average value of 313.96 m with a highest value of 480 m in the localities of Deou and Koutougou; the lowest altitude is 200 m within the localities of Mansila, Boundore and Tin-Akoff. This is illustrated in Figure 3.7.

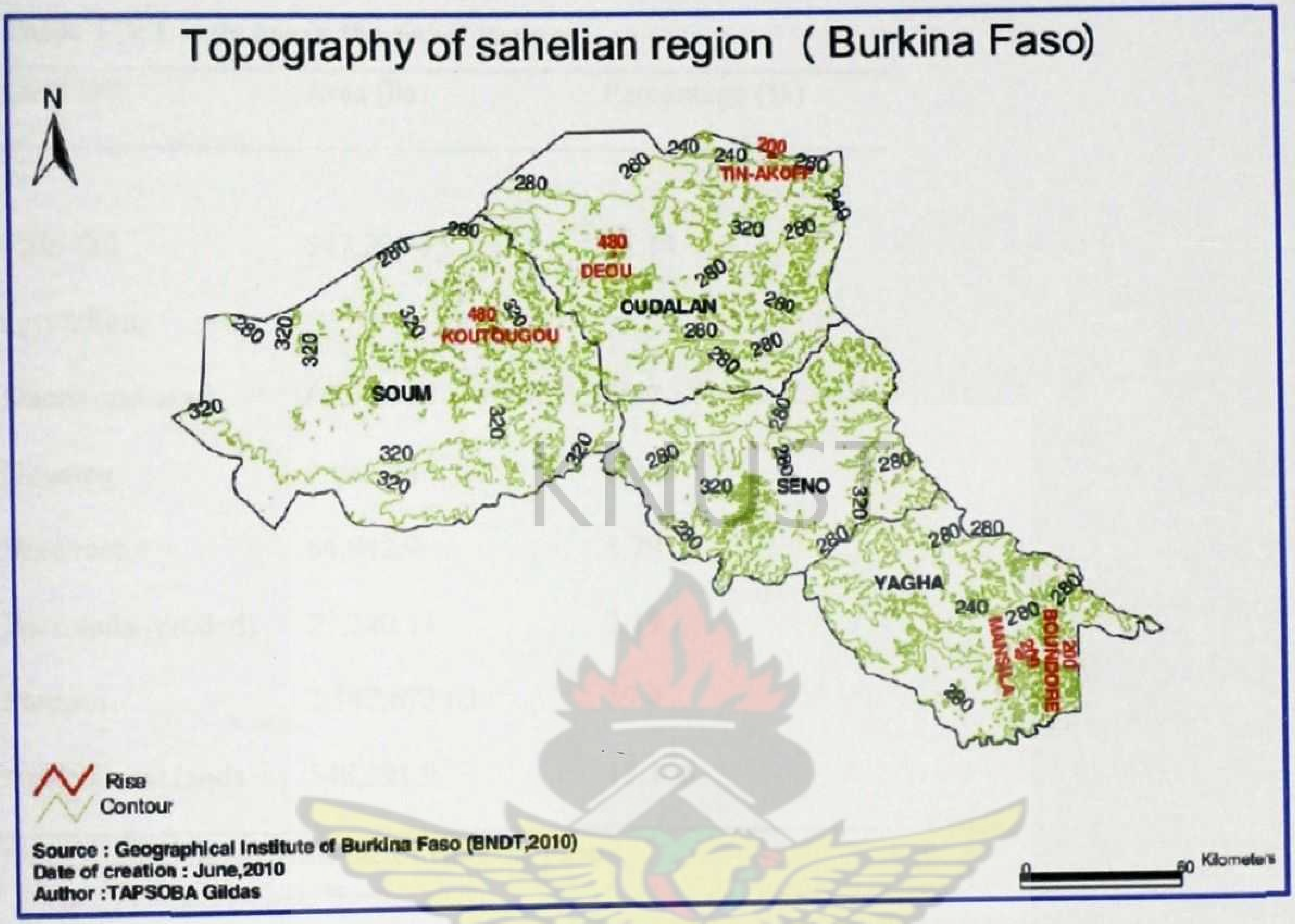


**Figure 3.7: Topographical map of the Sahel region (Burkina Faso)**

### 3.3.7. Land availability

Table 3.3 shows the of land use in the Sahel region. The total area concerned here is about 30 000 km$^2$. One can notice that the housing occupies less space with 0.045 % of the total area. The agricultural lands represent 15.14 % of the available area. The greatest part of the lands in the region of Sahel is occupied by the steppes.

Steppes represent almost 60 % of the total area of the region. This is somehow very interesting for CSP implementations in this area because there will be a priori no competition in land use.

**Table 3-3: Lands use in the Sahel region.**

| Land use | Area (ha) | Percentage (%) |
|---|---|---|
| Rain-fed agriculture | 547,396.75 | 15.14 |
| Dunes and sand | 6,302.54 | 0.17 |
| Housing | 1,662.44 | 0.045 |
| Bare rock | 64,942.9 | 1.79 |
| Bare soils (eroded) | 79,240.14 | 2.19 |
| Steppes | 2,147,673.63 | 59.4 |
| Agricultural lands | 548,391.9 | 15.168 |

*Source*: Geographic Institute of Burkina Faso

### 3.3.8. Energy demand profile of the site and proximity to transmission lines

In the Sahel region, electricity is produced by diesel thermal plants in three towns: Dori, Djibo and Gorom gorom. The demand in energy of the Sahel region is very low because of rural activities. As seen in Table 3.4, the total power installed in the Sahel region is 2970 kVA with 4758 subscribers.

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**Table 3-4: Electricity production of the Sahel region**

| Diesel thermal plant | Installed Power (KVA) | Number of subscribers |
|---|---|---|
| Dori | 1770 | 2252 |
| Djibo | 650 | 1800 |
| Gorom Gorom | 550 | 706 |
| Total | 2970 | 4758 |

*Source*: SONABEL (the electricity company of Burkina Faso).

Dori has the biggest number of subscribers (2252) and the biggest installed capacity (1770 kVA). It is clear noting here that the existing infrastructures in the Sahel region will not support any grid connection. This is confirmed by Figure 3.8 on which one can observe the actual state of the power lines and those at project stage not only in the Sahel region (North in the map) but for the whole country.

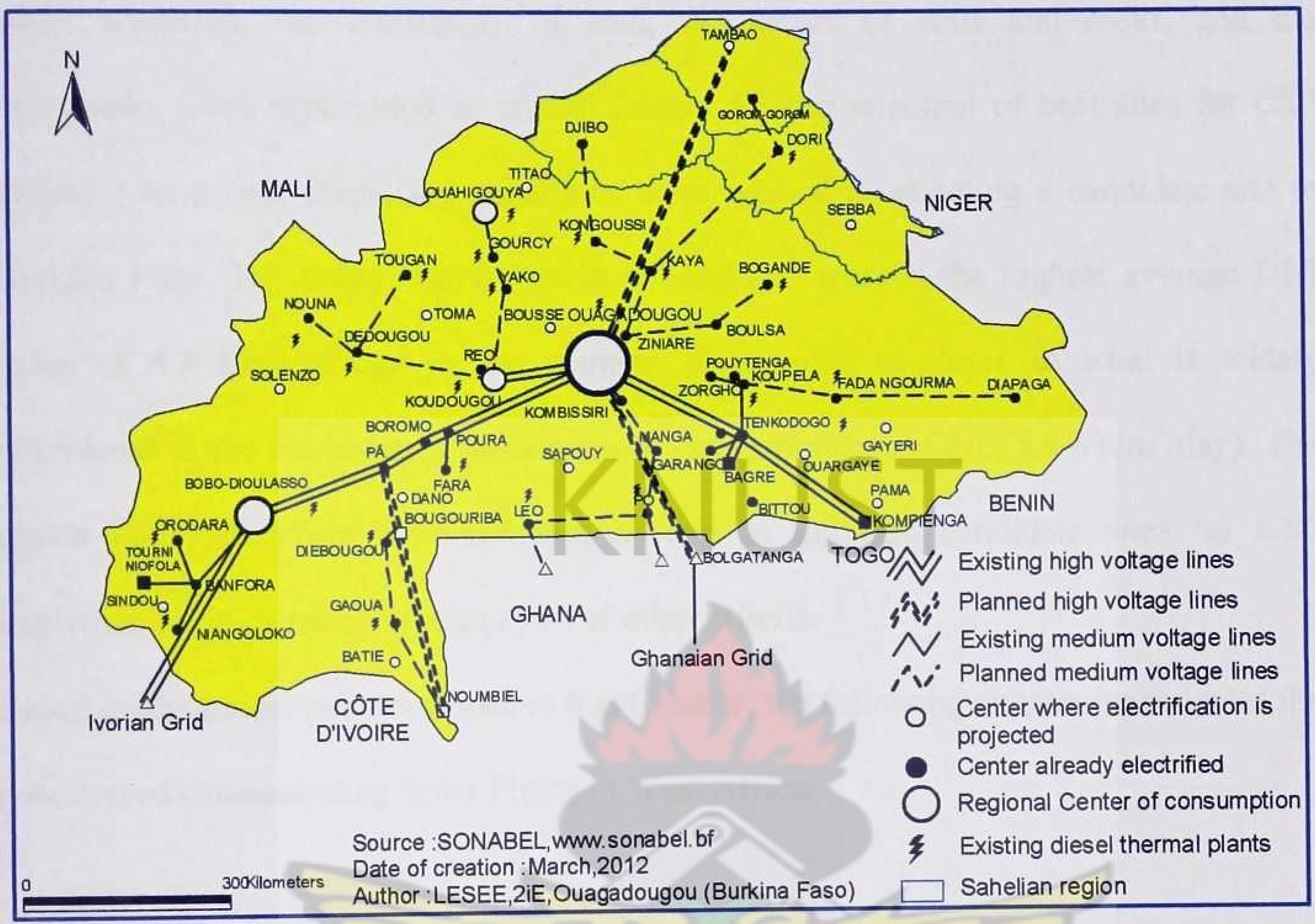


**Figure 3.8: Transmission lines map of Burkina Faso**

The interesting point when analyzing this figure is that some medium voltage lines projects are planned for Dori, Gorom-Gorom, Djibo and there is a big high voltage line project linking Tambao to Ouagadougou (the capital of Burkina Faso). The achievement of these projects will be an added advantage for the Sahel region since CSP plants can be built in the region without new investment in transmission lines.

### 3.4. Conclusion

This chapter provided technical guidelines for the selection of suitable sites for CSP plants. Six important parameters, namely the solar radiation, the energy demand, the water resources, the availability of land, the nature of soils and rocks, and the topography were highlighted as crucial factors for the selection of best sites for CSP projects. As a case study, the guidelines were applied in selecting a candidate site in Burkina Faso. The Sahel region (North of Burkina) records the highest average DNI value of 4.5 kWh/m$^2$/day in the country. This value is closer to what is widely considered in the literature as economically viable threshold DNI (5 kWh/m$^2$/day). The region could therefore be considered as one of the best candidate sites for CSP implementation, pending investigation of other criteria.

Based on the guidelines developed in this Chapter, the following chapter investigates the potential of Concentrating Solar Plants in West Africa.

# CHAPTER 4: SITE RANKING AND POTENTIAL ASSESSMENT FOR CONCENTRATING SOLAR POWER IN WEST AFRICA

## 4.1. Introduction

This Chapter is an extended version of a paper prepared by the author and his collaborators. The paper has been accepted for publication in the Journal Natural Resources and is scheduled to appear in March 2013 [153].

As mentioned in the general introduction, the Economic Community of West African States (ECOWAS) is a regional group of fifteen countries. In this chapter, maps of ECOWAS illustrating spatial distribution of Direct Normal Irradiation (DNI), land slope and transmission lines were respectively developed. The chapter also suggested a method for the calculation of potential capacity with given mean DNI and given CSP technology. The method was subsequently applied in the ECOWAS region to compute the potential nominal power and the corresponding energy yield with many scenarios. Sample maps ranking suitable sites for large-scale Concentrating Solar Power projects are also provided.

## 4.2. Overlaying in GIS

Overlaying is the method used in this study. It is an important procedure in GIS analysis. It involves superimposing two or more map layers to produce a new map layer by combining diverse data sets; Overlay analysis is used to investigate geographic patterns and to determine locations that meet specific criteria. Out of the six parameters which were highlighted in Chapter three as crucial factors for the selection of best sites for CSP projects, four are used in this Chapter in order to evaluate and rank suitable sites for large-scale CSP projects in West Africa. Sufficient DNI, proximity to transmission lines, low slope values and land occupation were considered. Land use profile for the region could not be established because of lack of data in GIS format. The study, however, made room for possible land occupation by surface water, forests, settlements, and arable land by assuming only 1 % of the total suitable land in order to compute the potential capacity and the energy yield. Data on water availability, the soil structure and the geology in GIS format for the ECOWAS region could not also be accessed and therefore were not factored in this study. This approach was previously used by [125, 127, 128]. Table 4.1 summarizes the criteria used in previous CSP potential assessment studies and compares with criteria in the present study. DNI and land slope were considered in all the studies while no study included water availability. The lack of detailed data in GIS format was pointed out by some of the authors as the main reason why the availability of water was not applied as a criterion.

**Table 4-1: Criteria used in previous CSP potential assessment studies**

| Author | Criteria: Minimum DNI ($kWh/m^2/d$) | Maximum Land slope (%) | Land consideration | Maximum distance to transmission lines (km) | Maximum distance to roads or railways (km) | Water availability | Location |
|---|---|---|---|---|---|---|---|
| Hang et al. (2008) | 5.00 | Not considered | 1% of wasteland | Not considered | Not considered | Not considered | China |
| Fluri (2009) | 7.00 | 1 | 'Least threatened areas' | 20 | Not considered | Not considered | South Africa |
| Charabi and Gastli (2010) | 6.40 | 1 | Not considered | Not considered | Not considered | Not considered | Oman |
| Bravo et al. (2007) | 4.10 | 7 | Low productivity lands[1] | Not considered | Not considered | Not considered | Spain |
| Pletka et al. (2007) | 6.75 | 1 | 'Solar park[2]' | 1.6 | Not considered | Not considered | USA |
| Dahle et al. (2008) | 5.00 | 3 | 'Legacy management sites[3]' | 40 | 40 | Not considered | USA |
| Clifton and Boruff (2010) | 5.50 | 4 | Not considered | Not considered | Not considered | Not considered | Australia |
| Present study | 4.00 | 5 | 1% of total suitable land | 100 | Not considered | Not considered | ECOWAS |

[1] Low productivity lands include Moorlands and bushes, big formations of dense bushes, scarce bushes, Subdesert Xerosteppe, high altitude spaces with scarce vegetation, burnt areas.

[2] "solar park" is designated land for solar plants in the Southwest, with a lease fee of $200/acre/year.

[3] Legacy of World War II and the Cold War which includes radioactive and chemical waste, environmental contamination, and hazardous material at over 100 sites across USA

In the present study, three maps of ECOWAS were developed illustrating spatial distribution of solar radiation resources (DNI), land slope and transmission lines respectively; these maps are illustrated in Figure 4.1 to 4.3. The maps were subsequently laid over each other with given set of criteria and three different scenarios were considered. Scenario 1 carried out the assessment considering DNI only; Scenario 2 took into consideration not only DNI but also land slope and existing transmission lines whereas Scenario 3 included planned transmissions lines in addition to the DNI, land slope and existing transmission lines.

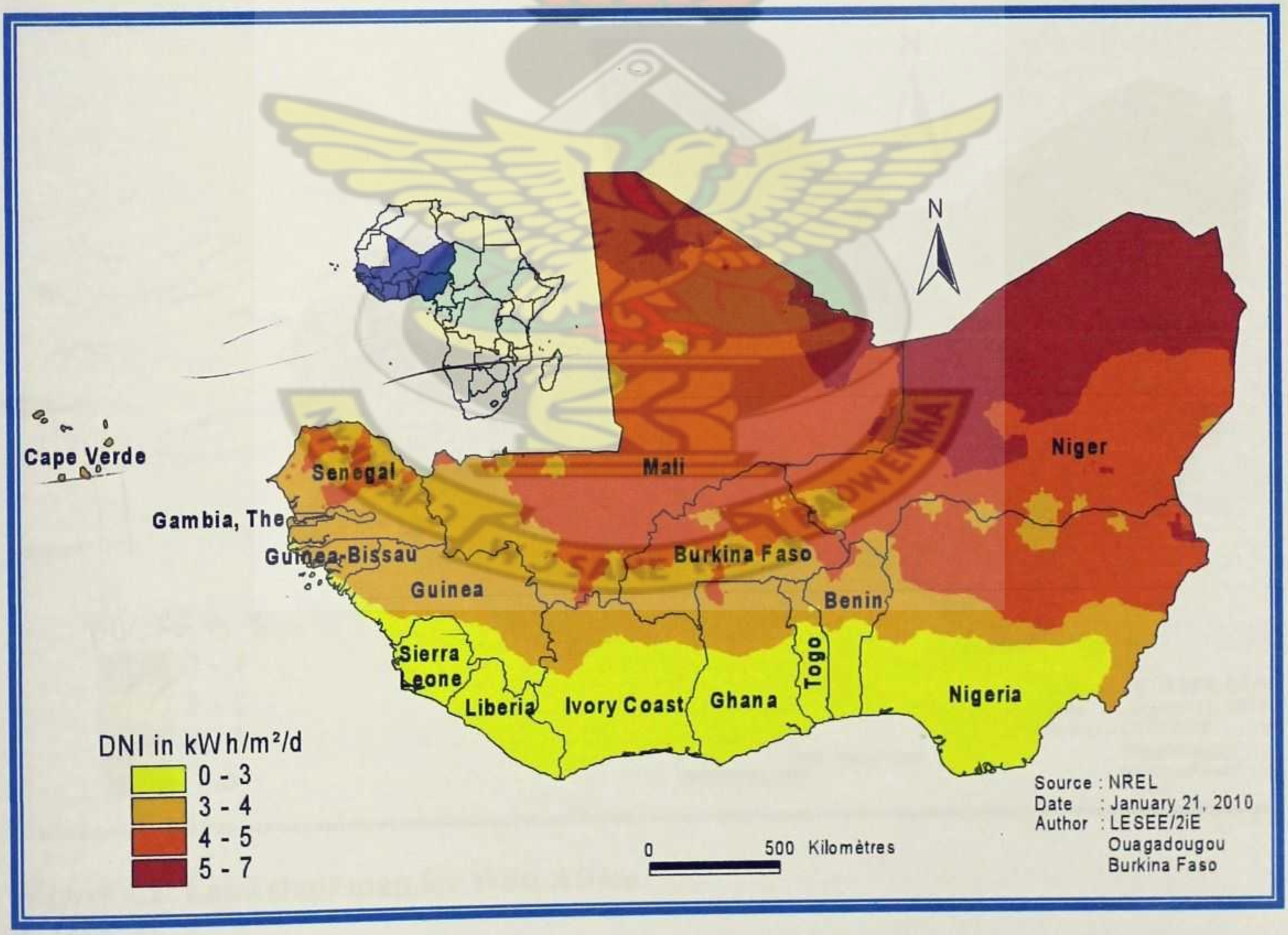


Figure 4.1: Map of annual mean daily Direct Normal Irradiation for West Africa

The DNI map in Figure 4.1 was obtained using data from the Climatological Solar Radiation (CSR) Model from the National Renewable Energy Laboratory (NREL, USA); the model according to Maxwell et al. is approximately 5 % accurate [154]. Description of the model is given in Appendix A.

Figure 4.2 illustrates the land slope in the ECOWAS region while Figure 4.3 shows the transmission map for the same region. Both existing and future transmission lines were taken into account. Existing transmission lines are illustrated with full lines while future transmission lines are shown in broken lines.

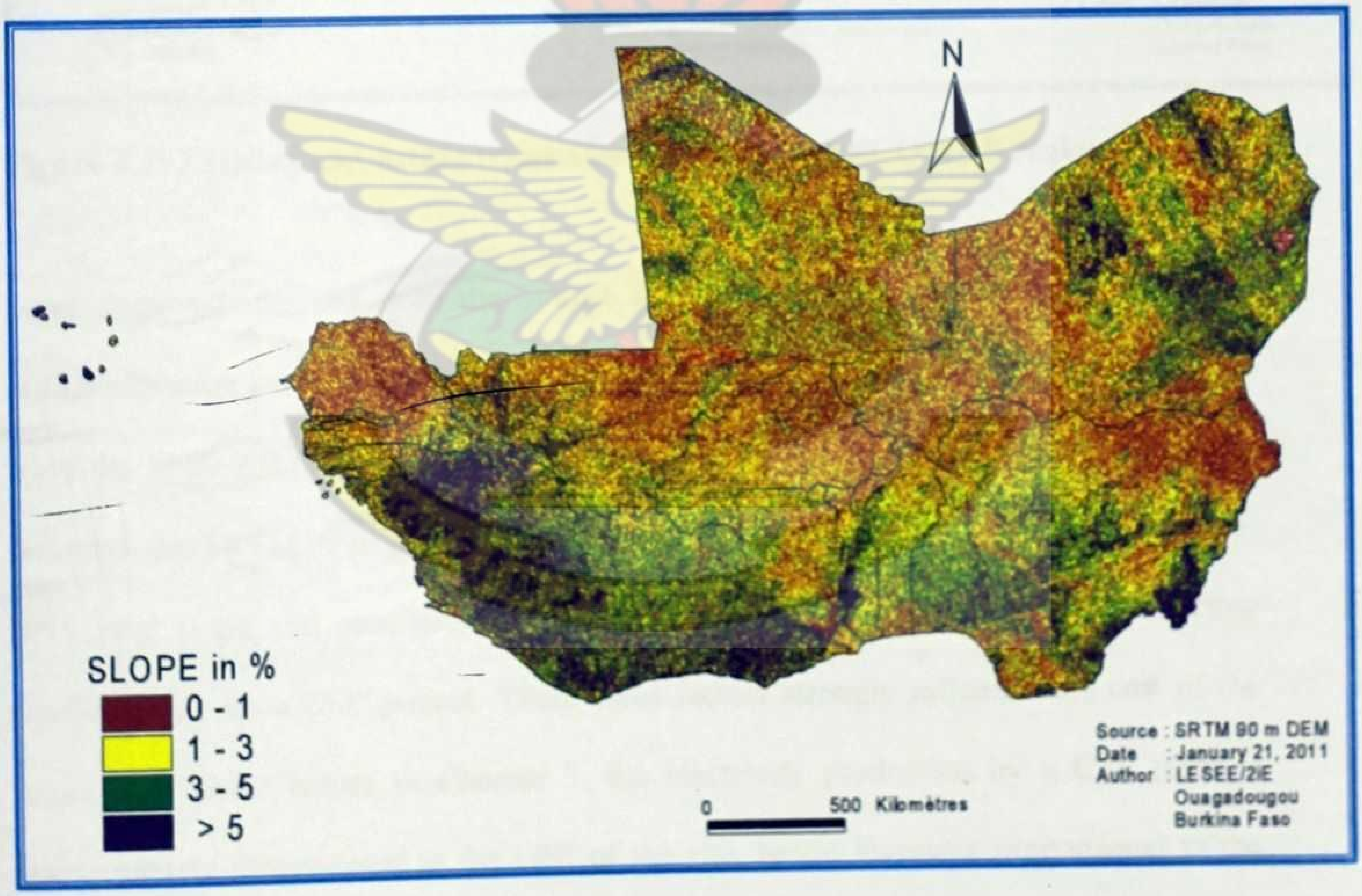


**Figure 4.2: Land slope map for West Africa**

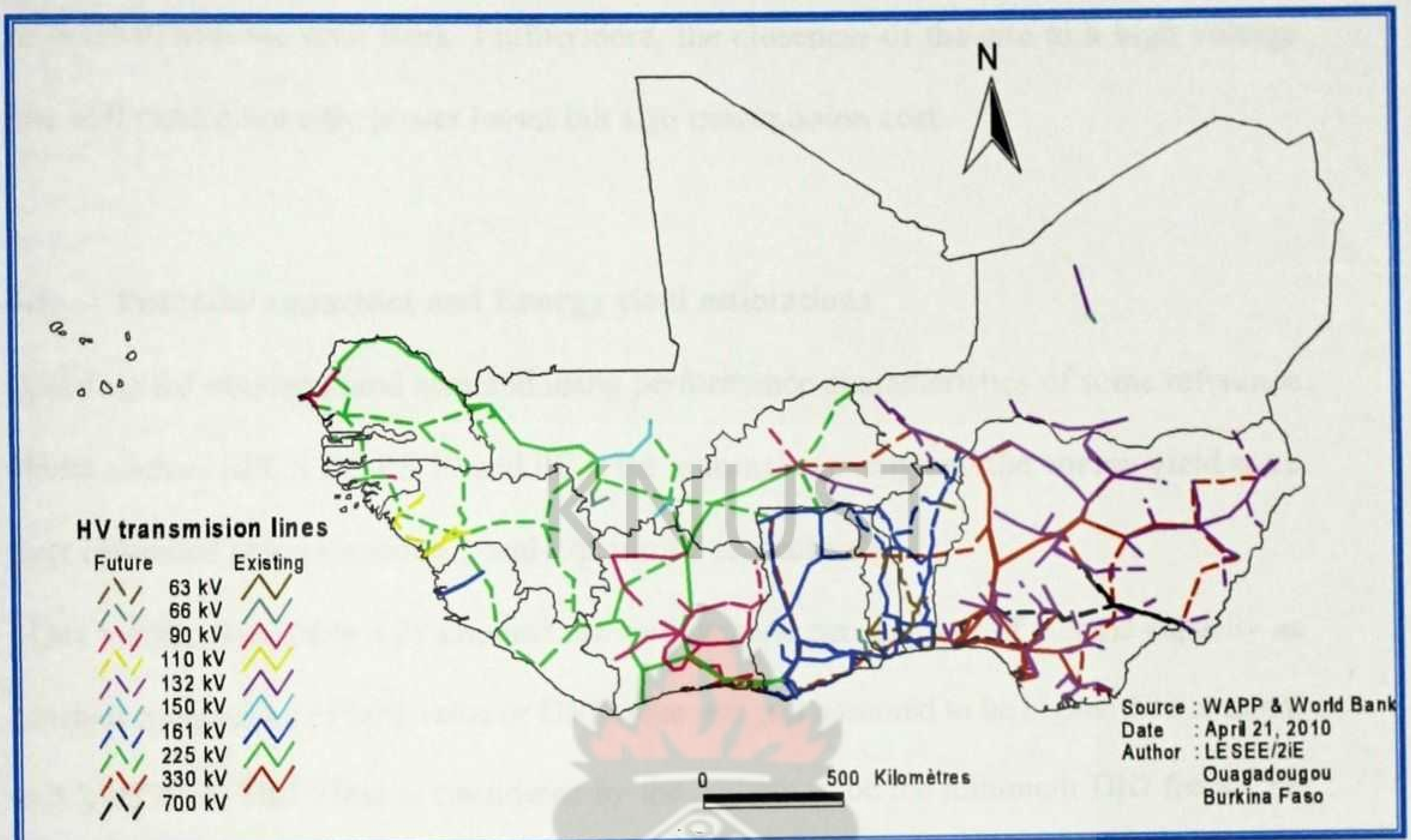


**Figure 4.3: Existing and future transmission lines of the ECOWAS region**

Land slope was derived from the Shuttle Radar Topography Mission (SRTM) 90 m digital elevation model [155] whereas transmission map was drawn with data obtained from the West African Power Pool[4] (WAPP) and from the World Bank. Appendix B describes the SRTM 90 m digital elevation model in details.

DNI, land slope and proximity to transmission lines are crucial factors in selecting candidate site for a CSP project. These three factors strongly influence the cost of the project. As noted before in Chapter 3, the electricity production by a CSP plant is approximately proportional to the DNI of the site, hence inversely proportional to the cost of electricity. For the land slope, a small gradient is desirable since it reduces cost

[4] The West African Power Pool (WAPP) is a specialized Institution of ECOWAS which aims at addressing the issue of power supply deficiency within West Africa. http://www.ecowapp.org/

associated with the civil work. Furthermore, the closeness of the site to a high voltage line will reduce not only power losses but also transmission cost.

### 4.3. Potential capacities and Energy yield estimations

Based on the obtained land area and using performance characteristics of some reference plants such as SEGS IX, PS 10 and PE I, the nominal capacity and the energy yield were then estimated using Equation 1 and Equation 2 respectively.

Many studies (see Table 4.2) assumed the land demand per gigawatt of electric capacity as constant irrespective of DNI value or DNI value was just assumed to be higher than or equal to 5 $kWh/m^2/d$; This value is considered by the authors to be the minimum DNI for a CSP plant to be economically viable.

**Table 4-2: CSP land demand in $km^2/GW$ from literature**

| | Technology | Land demand $km^2/GW$ |
|---|---|---|
| Broesamle et al. [123] | Parabolic trough | 20 |
| Hang et al. [125] | Parabolic trough | 20.2 |
| Fluri [127] | Parabolic trough | 28 |
| Charabi and Gastli [128] | Parabolic trough without storage | 23 |
| | Parabolic trough with storage | 32 |
| | Power tower | 45 |
| | Dish Stirling | 20 |

Land demand however, strongly depends on DNI level. In the present study, land demand was assumed to be proportional to DNI and Equation 1 was deduced.

$$P_2 = P_1 \frac{A_2}{A_1} \frac{(DNI)_2}{(DNI)_1} \quad \text{(Eq. 1)}$$

$P_1$, $A_1$ and $(DNI)_1$ represent respectively, the installed capacity of the reference plant, the land cover in which it was built and the DNI of the area where it is located. $P_2$ and $A_2$ are correspondingly the potential power of the selected area, the land cover of that area with a Direct Normal Irradiation $(DNI)_2$.

Once potential power $P_2$ was known, the energy yield $E_2$ could then be computed through Equation 2 using the capacity factor of the reference plant.

$$E_2 = 365 \times 24 \times \text{Capacity Factor} \times P_2 \quad \text{(Eq. 2)}$$

The following section provides a description of the selected reference plants.

### 4.4. Description of the reference plants: SEGS IX, PS 10 and PE 1

SEGS IX, PS 10 and PE I were selected because of their commercial maturity.

SEGS IX is one of the nine Solar Electric Generating Station (SEGS) plants in the Mojave Desert in California. The combined electric generating capacity of these plants, which use parabolic trough technology, is more than 350 megawatts. SEGS IX which started operation in 1991, is the largest individual trough plant (along with SEGS VIII); it has an auxiliary natural gas heater which provides backup capability during low and non-solar hours [156].

PS10 (Planta Solar 10) is the first solar central-receiver system producing grid-connected electricity in a commercial basis. The plant started operation in March 2007. It is based on Direct Steam Generation (DSG) and makes use of well proven technologies, like glass-metal heliostats, a pressurized water thermal storage system, and a saturated steam receiver and turbine. The plant's thermal storage system has a 50-minute capacity at 50 % load to handle cloud transients. PS10 is located in Seville, Spain [157].



PE I (Puerto Errado 1) is a solar thermal power plant located in southern Spain. It is based on linear Fresnel collector technology and has an electrical capacity of 1.4 MW. Since March 2009, it has been connected to the local grid and selling electricity to the local network provider. It is also based on Direct Steam Generation (DSG) and produces saturated steam at temperatures of up to 300°C [158, 159].

Table 4.3 provides information about the selected reference plants.

**Table 4-3: Characteristics of selected reference plants**

| | Technology | Power MW $P_l$ | Land Area km² $A_l$ | Land demand MW/km² $(P_l/A_l)$ | Capacity factor (CF) | Location | DNI kWh/m²/day $(DNI)_l$ |
|---|---|---|---|---|---|---|---|
| **SEGS IX** | Parabolic Trough | 80 | 1.7 | 47.3 | 21 | California, USA | 7.5 |
| **PS 10** | Central Receiver | 11 | 0.6 | 20 | 24 | Sevilla, Spain | 5.5 |
| **PE I** | Linear Fresnel | 1.4 | 0.1 | 20 | 22 | Murcia, Spain | 4.7 |

## 4.5. Results and Discussion

### 4.5.1. Scenario 1: Potential assessment based on DNI only

In Scenario 1, the potential assessment is carried out based on DNI only.

**Table 4-4: Potential land area in high, medium and low DNI zones from scenario 1**

| DNI ($kWh/m^2$.day) | 1 % of land area in 1000 of ($km^2$) | Average DNI ($kWh/m^2$.day) |
|---|---|---|
| $DNI \geq 5$ | 8.5 | 5.6 |
| $4 \leq DNI \leq 5$ | 19.4 | 4.4 |
| $3 \leq DNI \leq 4$ | 11.9 | 3.7 |

ECOWAS has a total land area of 5,110,914 $km^2$. This study reveals that 17 % of that land area is endowed with an average daily DNI of 5.6 $kWh/m^2$ while 38 % enjoys an average daily DNI of 4.4 $kWh/m^2$. 23 % has an average daily DNI of 3.7 $kWh/m^2$ and the remaining 22 % records an average daily DNI value below 3 $kWh/m^2$.

Table 4.4 gives only 1 % of the land within certain range of DNI as an illustration.

Considering only 1 % of lands with daily DNI greater or equal to 5 $kWh/m^2$ (about 0.17 % of ECOWAS total land area), Figure 4.4 shows for example that the lowest potential capacity is about 170 GW with central receiver and the highest potential capacity is about 300 GW using parabolic through technology. These potential capacities highly exceed the current total installed capacities of 11.4 GW and 124 GW, respectively for the ECOWAS sub-region and for Africa (Refer to Figure 1.1).

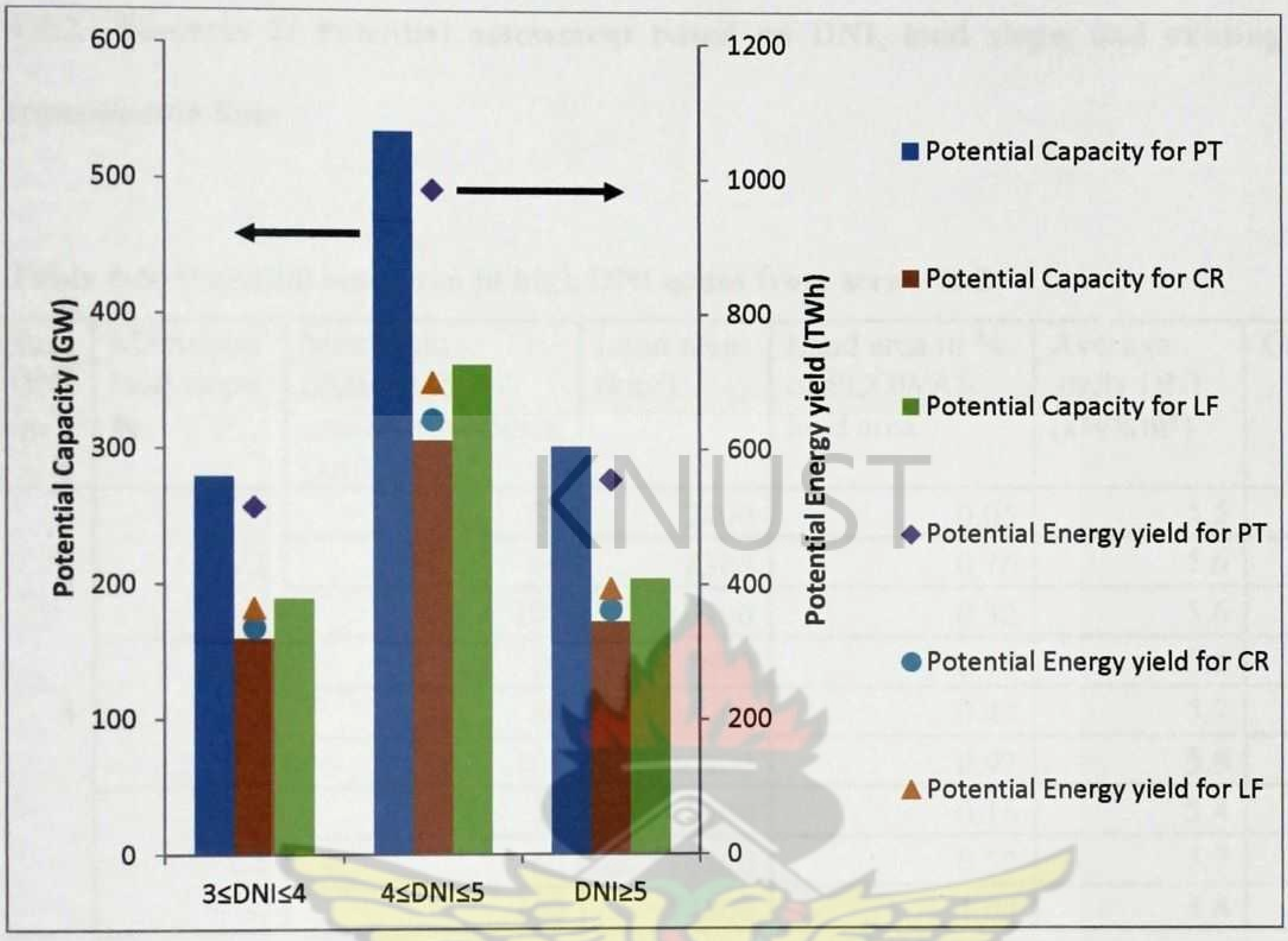


**Figure 4.4: Scenario 1 potential capacity and energy yield**

Of course, DNI is crucial in selecting candidate site for a CSP project but not sufficient. Other factors must be taken into account. Scenario 1 is therefore less informative but necessary to have a quick idea about the CSP potential of the area. In the following Sections, Scenarios 2 and 3 carry out the potential assessment by including land slope and transmission lines in addition to the DNI.

### 4.5.2. Scenario 2: Potential assessment based on DNI, land slope, and existing transmission lines

**Table 4-5: Potential land area in high DNI zones from scenario 2**

| Minimum daily DNI (kWh/m$^2$) | Maximum land slope % | Maximum distance to transmission lines (km) | Land area (km²) | Land area in % of ECOWAS land area | Average .daily DNI (kWh/m$^2$) | **Cases** |
|---|---|---|---|---|---|---|
| 5 | 1 | 20 | 2400 | 0.05 | 5.5 | **1** |
| | | 60 | 8300 | 0.16 | 5.6 | **2** |
| | | 100 | 16200 | 0.32 | 5.6 | **3** |
| | 3 | 20 | 7600 | 0.15 | 5.5 | **4** |
| | | 60 | 23900 | 0.47 | 5.7 | **5** |
| | | 100 | 46900 | 0.92 | 5.8 | **6** |
| | 5 | 20 | 8200 | 0.16 | 5.4 | **7** |
| | | 60 | 26800 | 0.52 | 5.7 | **8** |
| | | 100 | 52800 | 1.03 | 5.8 | **9** |

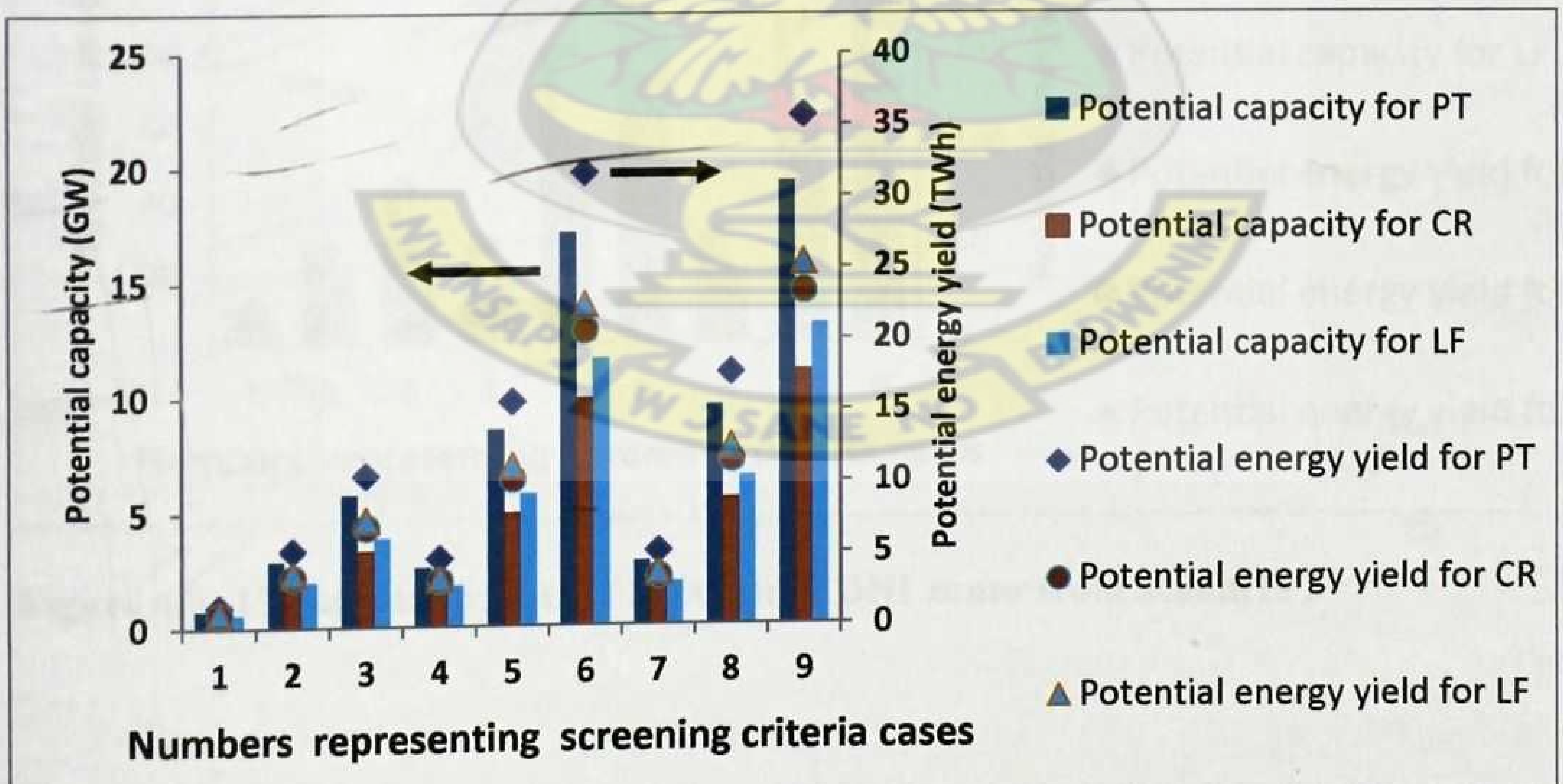


Figure 4.5: 1% of total potential in high DNI zones from scenario 2

**Table 4-6: Potential land area in medium DNI zones from scenario 2**

| Daily DNI range ($kWh/m^2$) | Maximum land slope % | Maximum distance to transmission lines (km) | Land area ($km^2$) | Land area in % of ECOWAS land area | Average .daily DNI ($kWh/m^2$) | **Cases** |
|---|---|---|---|---|---|---|
| 4≤DNI≤5 | 1 | 20 | 39600 | 0.77 | 4.2 | **1** |
| | | 60 | 98900 | 1.94 | 4.2 | **2** |
| | | 100 | 165900 | 3.25 | 4.3 | **3** |
| | 3 | 20 | 102500 | 2.01 | 4.2 | **4** |
| | | 60 | 301400 | 5.90 | 4.2 | **5** |
| | | 100 | 476200 | 9.32 | 4.2 | **6** |
| | 5 | 20 | 115100 | 2.25 | 4.2 | **7** |
| | | 60 | 334300 | 6.54 | 4.2 | **8** |
| | | 100 | 520700 | 10.19 | 4.2 | **9** |

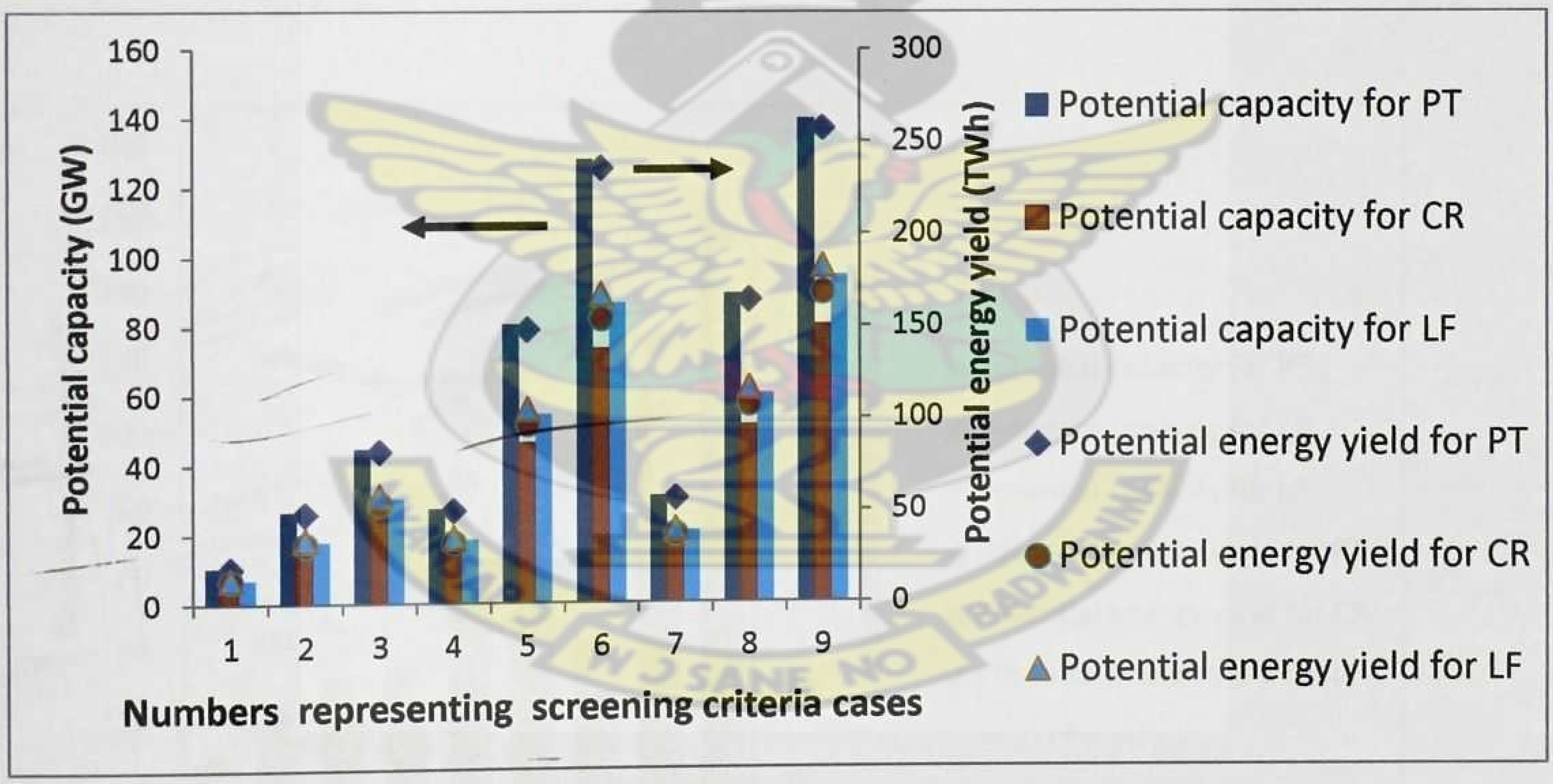


**Figure 4.6: 1% of total potential in medium DNI zones from scenario 2**

**Table 4-7: Potential land area in low DNI zones from scenario 2**

| DNI range (kWh/m²) | Maximum land slope % | Maximum distance to transmission lines (km) | Land area (km²) | Land area in % of ECOWAS land area | Average .daily DNI (kWh/m²) | Cases |
|---|---|---|---|---|---|---|
| 3≤DNI≤ 4 | 1 | 20 | 33100 | 0.65 | 3.6 | **1** |
| | | 60 | 89300 | 1.75 | 3.7 | **2** |
| | | 100 | 135100 | 2.64 | 3.7 | **3** |
| | 3 | 20 | 149900 | 2.93 | 3.5 | **4** |
| | | 60 | 400800 | 7.84 | 3.5 | **5** |
| | | 100 | 585600 | 11.46 | 3.6 | **6** |
| | 5 | 20 | 186000 | 3.64 | 3.5 | **7** |
| | | 60 | 493100 | 9.65 | 3.6 | **8** |
| | | 100 | 719500 | 14.08 | 3.6 | **9** |

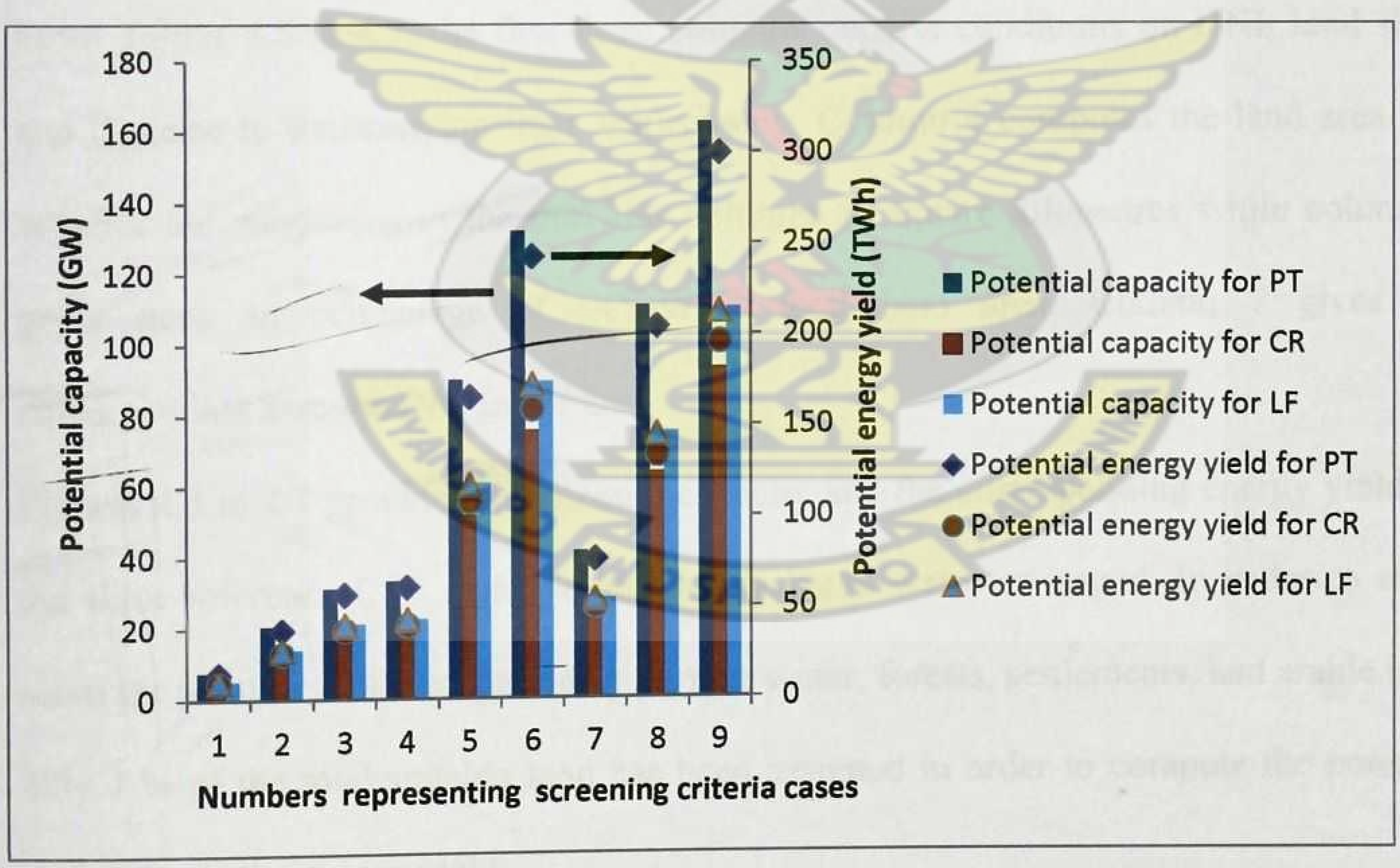


**Figure 4.7: 1% of total potential in low DNI zones from scenario 2**

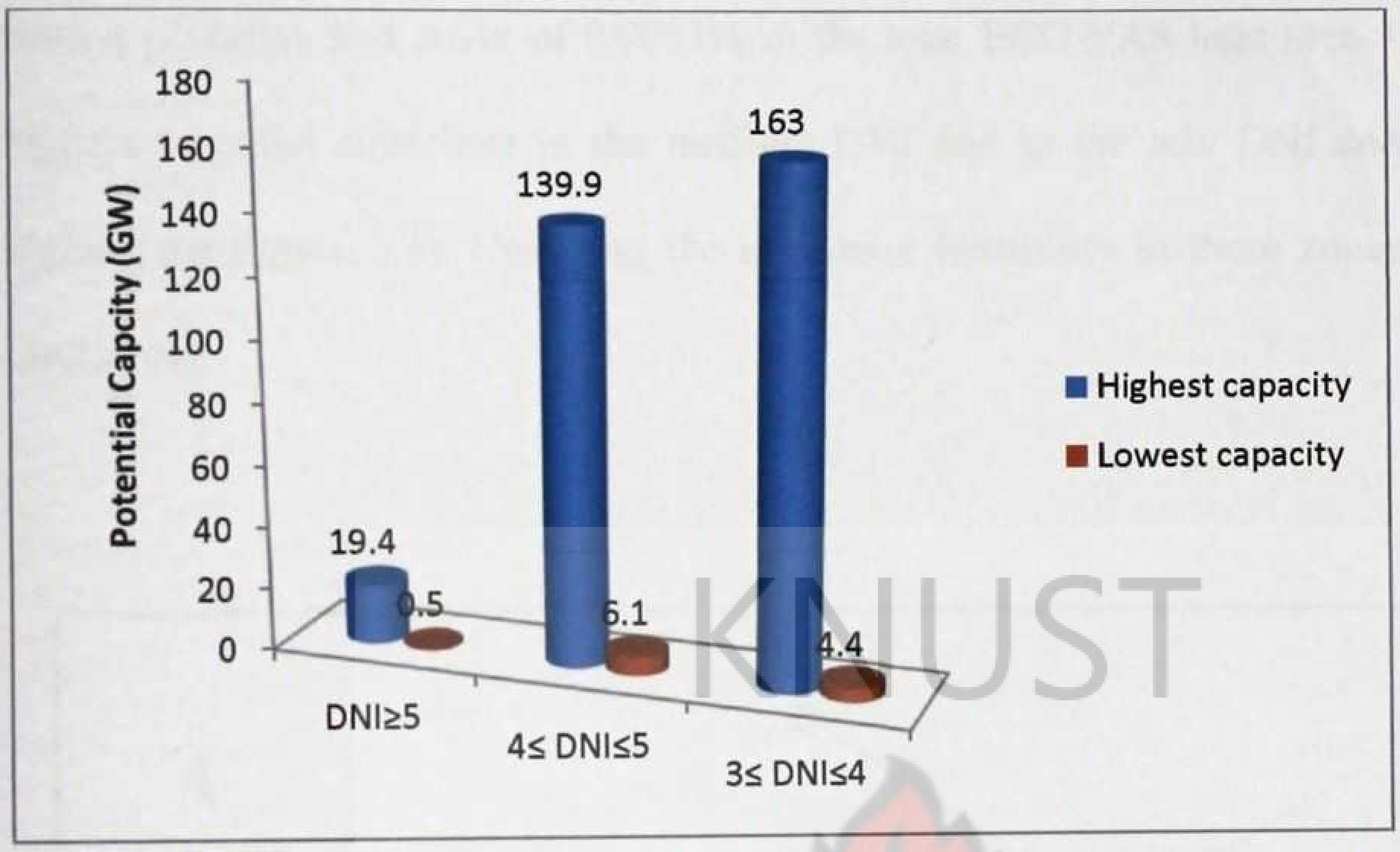


**Figure 4.8: Highest and lowest potential capacities from scenario 2**

From Tables 4.5 to 4.7, the first three columns contain conditions on DNI, land slope and distance to transmission lines respectively. Column 4 computes the land area that satisfies the conditions in the previous columns in square kilometres while column 6 gives same in percentage of ECOWAS total land area. Column 7 gives the corresponding average DNI in the area.

Figures 4.5 to 4.7 provide the potential capacity and the corresponding energy yield for the three reference CSP technologies. Many cases were envisaged. In order to make room for possible land occupation by surface water, forests, settlements, and arable land, only 1 % of the total suitable land has been assumed in order to compute the potential capacity and the energy yield.

Considering a daily DNI greater or equal to 5 kWh/m$^2$ and judging from Table 4.5 and from Figure 4.8, the highest potential capacity is about 19.4 GW which is calculated from a potential land cover of 0.0001% of the total ECOWAS land area. Likewise, the highest potential capacities in the medium DNI and in the low DNI zones are much higher (see Figure 4.8). However, the economic feasibility in these zones needs to be carried out.



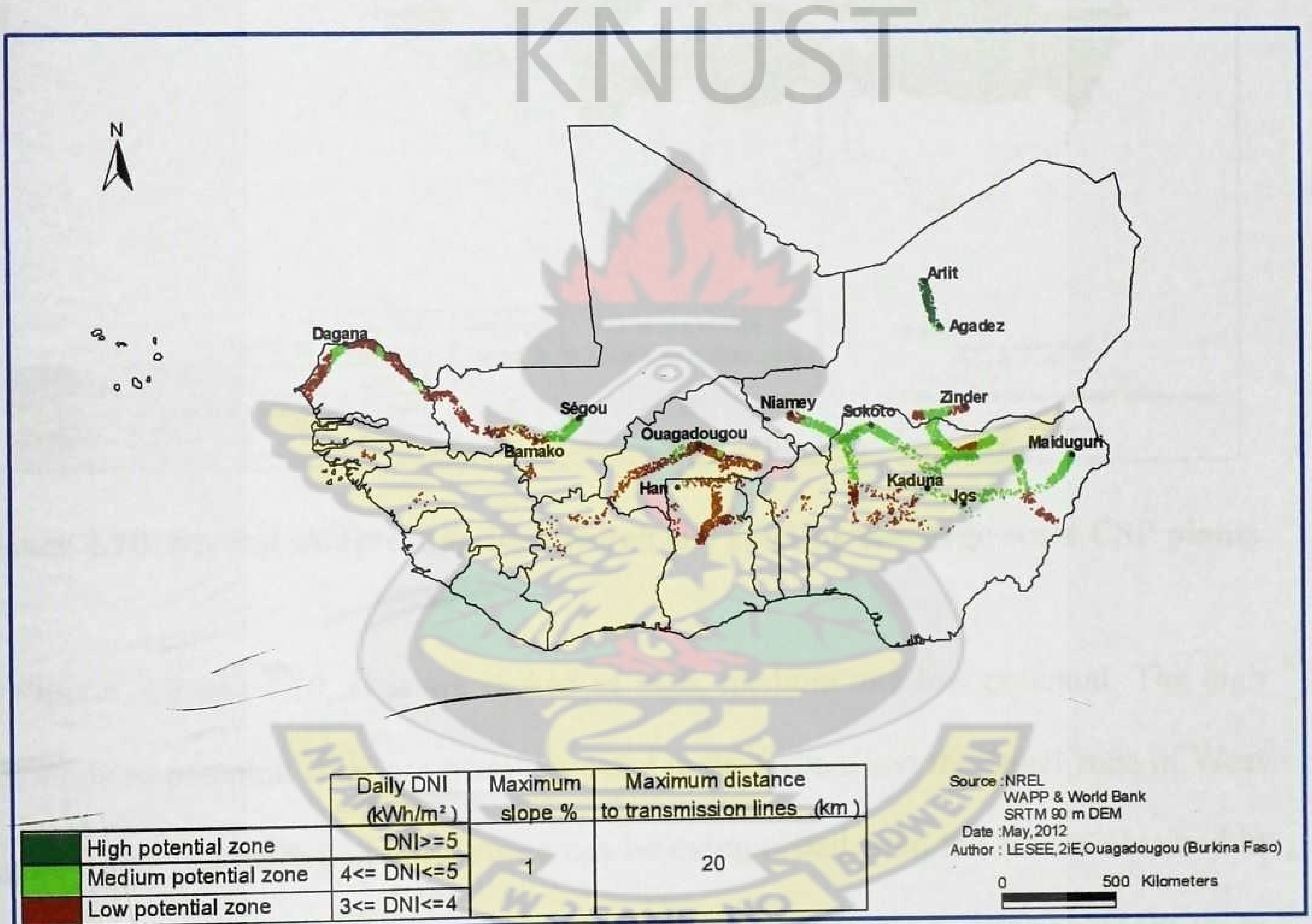


**Figure 4.9: First sample map illustrating site ranking for large-scale CSP plants**

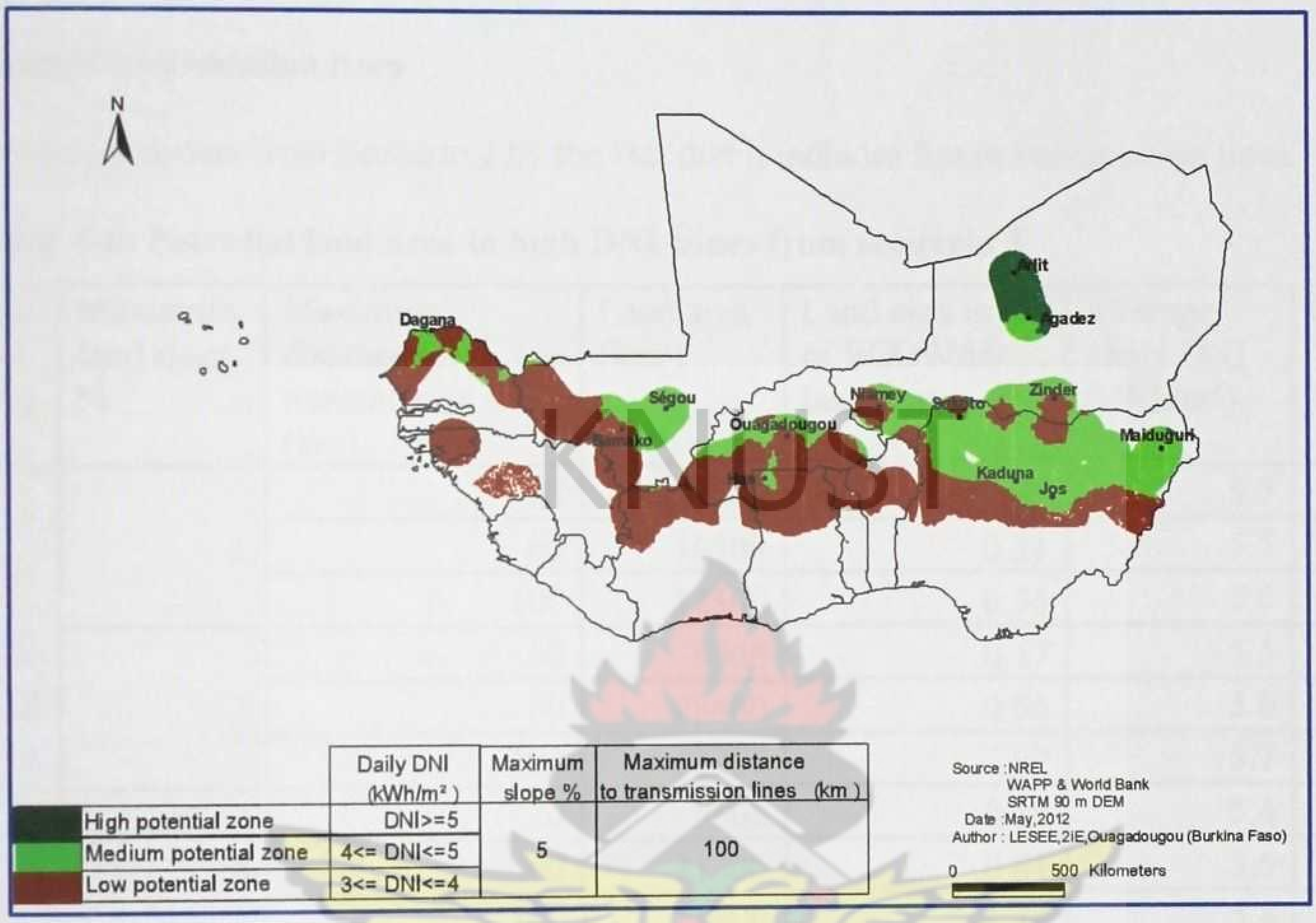


**Figure 4.10: Second sample map illustrating site ranking for large-scale CSP plants**

In Figures 4.9 and 4.10, sites are ranked as high, medium and low potential. The high and medium potential areas are mainly located in the Sahara and the Sahel zone of West Africa. Land use pattern in these zones can be extrapolated from the results obtained in Chapter 3 for Burkina Faso, since there is a strong similarity in climate. From these results, only 36 % of the land in the Sahel is occupied by housing, forest, rivers and agricultural farms with housing accounting for 0.04 %. There is therefore no competition in land use in the high potential and medium potential zones. However, as mentioned earlier, in order to make room for possible land occupation by surface water, forests, settlements, and arable land, only 1 % of the total suitable land has been assumed in order to compute the potential capacity and the energy yield.

#### 4.5.3. Scenario 3: Potential assessment based on DNI, land slope, existing and planned transmission lines

Scenario 3 differs from Scenario 2 by the fact that it includes future transmission lines.

**Table 4-8: Potential land area in high DNI zones from scenario 3**

| Minimum daily DNI ($kWh/m^2$.) | Maximum land slope % | Maximum distance to transmission lines (km) | Land area ($km^2$) | Land area in % of ECOWAS land area | Average .daily DNI ($kWh/m^2$) | **Cases** |
|---|---|---|---|---|---|---|
| 5 | 1 | 20 | 3000 | 0.06 | 5.5 | **1** |
| | | 60 | 10500 | 0.21 | 5.5 | **2** |
| | | 100 | 18500 | 0.36 | 5.6 | **3** |
| | 3 | 20 | 8900 | 0.17 | 5.5 | **4** |
| | | 60 | 28400 | 0.56 | 5.6 | **5** |
| | | 100 | 52200 | 1.02 | 5.7 | **6** |
| | 5 | 20 | 9500 | 0.19 | 5.4 | **7** |
| | | 60 | 31300 | 0.61 | 5.6 | **8** |
| | | 100 | 58400 | 1.14 | 5.8 | **9** |

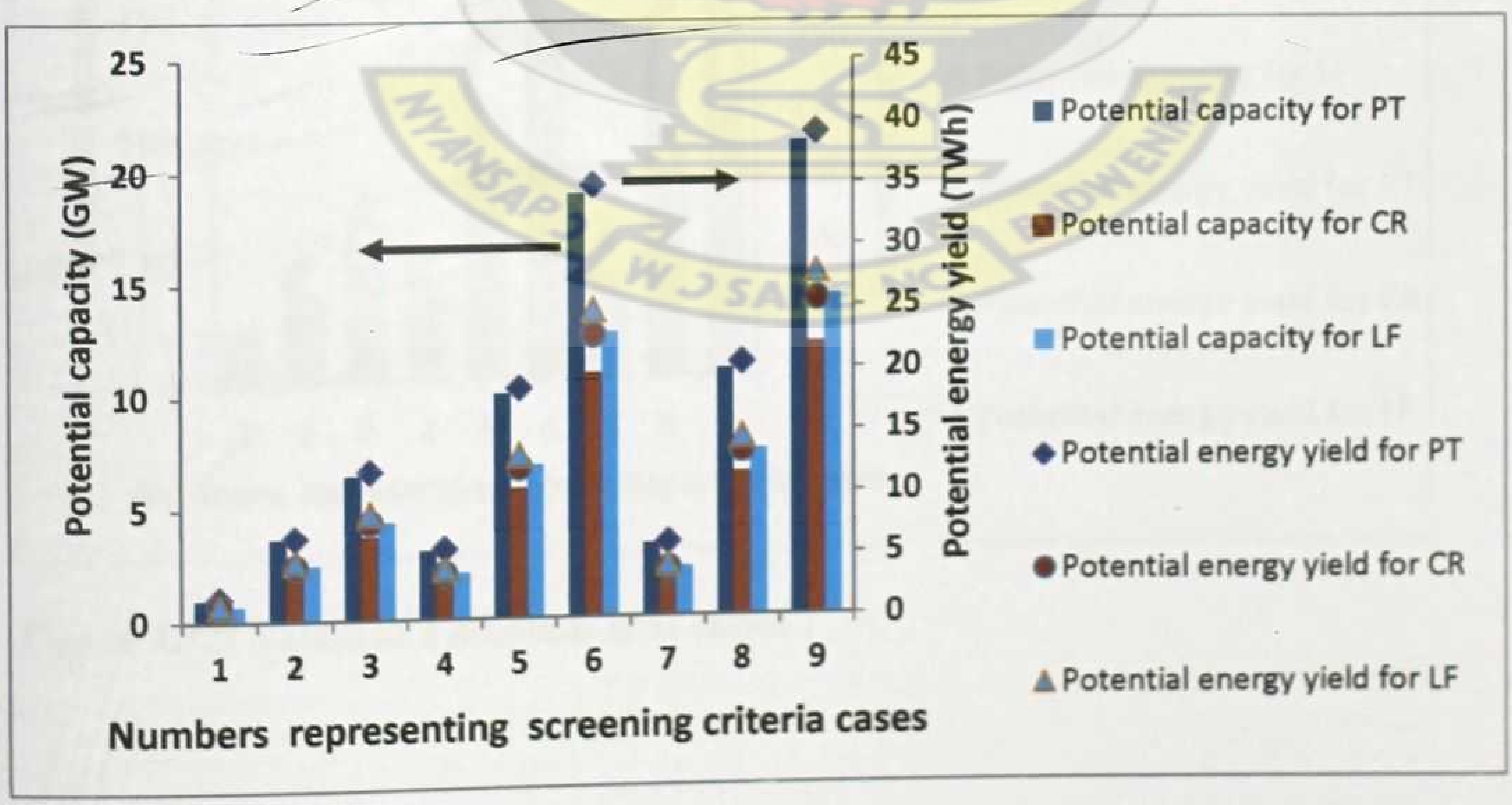


**Figure 4.11: Scenario 3 high DNI zones**

**Table 4-9: Potential land area in medium DNI zones from scenario 3**

| DNI range (kWh/m$^2$) | Maximum land slope % | Maximum distance to transmission lines (km) | Land area (km²) | Land area in % of ECOWAS land area | Average .daily DNI (kWh/m$^2$) | Cases |
|---|---|---|---|---|---|---|
| 4≤DNI≤ 5 | 1 | 20 | 67500 | 1.32 | 4.3 | 1 |
| | | 60 | 182900 | 3.58 | 4.3 | 2 |
| | | 100 | 268100 | 5.25 | 4.3 | 3 |
| | 3 | 20 | 189600 | 3.71 | 4.2 | 4 |
| | | 60 | 510800 | 9.99 | 4.3 | 5 |
| | | 100 | 724000 | 14.17 | 4.3 | 6 |
| | 5 | 20 | 206900 | 4.05 | 4.3 | 7 |
| | | 60 | 555300 | 10.86 | 4.3 | 8 |
| | | 100 | 780000 | 15.26 | 4.3 | 9 |



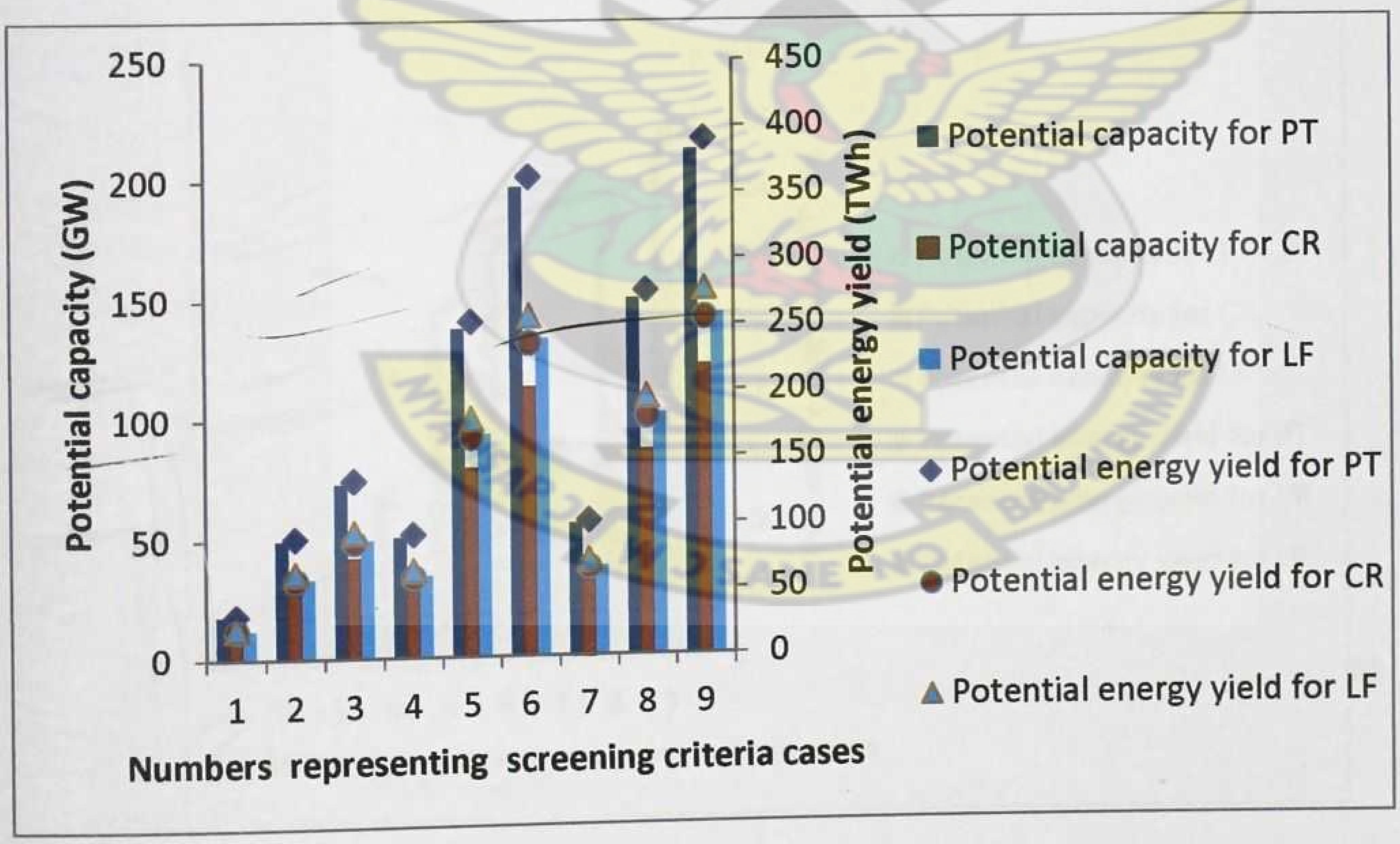


**Figure 4.12: Scenario 3 medium DNI zones**

**Table 4-10: Potential land area in low DNI zones from scenario 3**

| DNI range ($kWh/m^2$) | Maximum land slope % | Maximum distance to transmission lines (km) | Land area ($km^2$) | Land area in % of ECOWAS land area | Average .daily DNI ($kWh/m^2$) | Cases |
|---|---|---|---|---|---|---|
| 3≤DNI≤ 4 | 1 | 20 | 72100 | 1.41 | 3.6 | 1 |
| | | 60 | 154800 | 3.03 | 3.7 | 2 |
| | | 100 | 183000 | 3.58 | 3.7 | 3 |
| | 3 | 20 | 310700 | 6.08 | 3.5 | 4 |
| | | 60 | 654600 | 12.81 | 3.5 | 5 |
| | | 100 | 759300 | 14.86 | 3.5 | 6 |
| | 5 | 20 | 386100 | 7.55 | 3.5 | 7 |
| | | 60 | 809200 | 15.83 | 3.5 | 8 |
| | | 100 | 944700 | 18.48 | 3.5 | 9 |

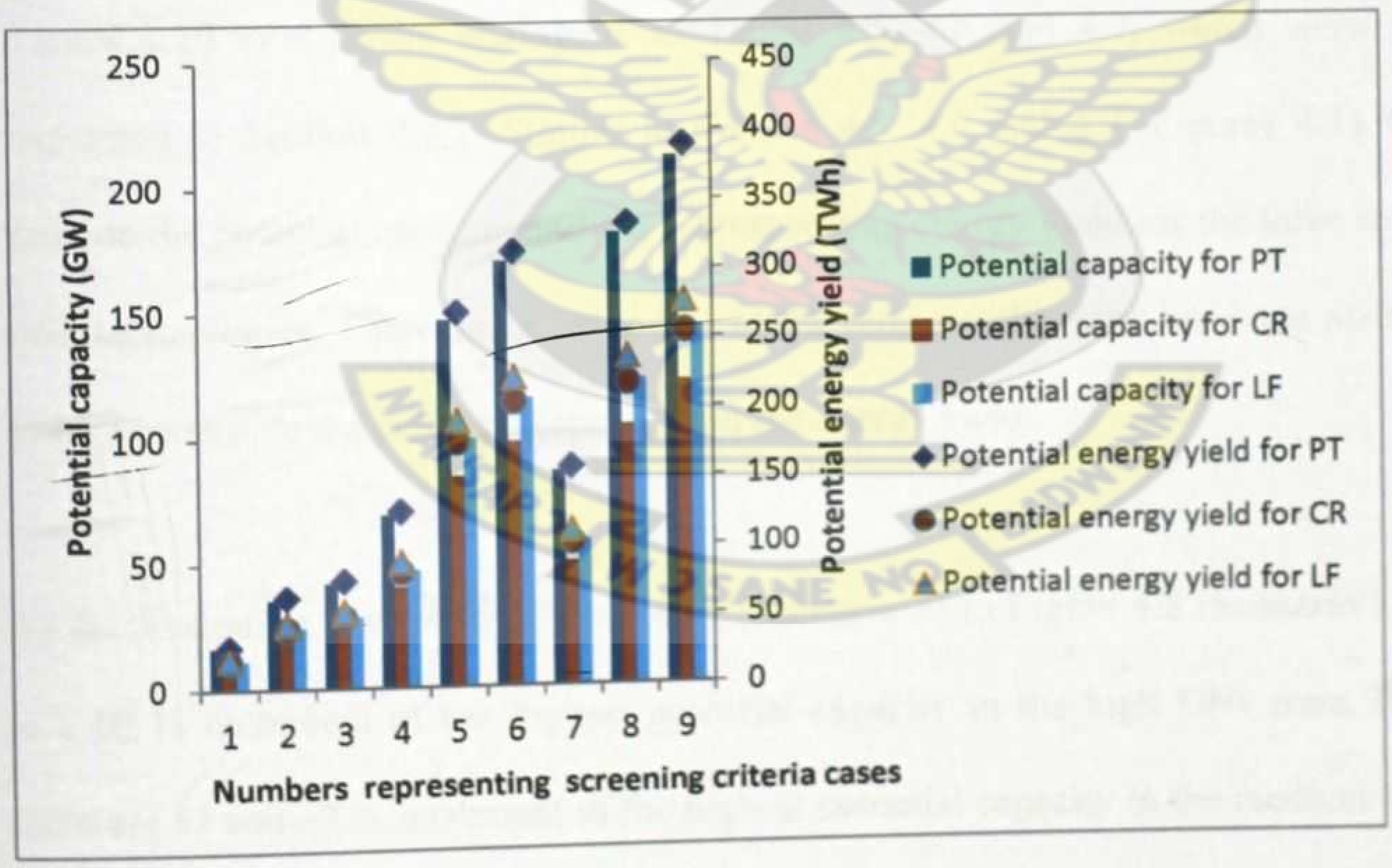


**Figure 4.13: Scenario 3 low DNI zones**

**Table 4-10: Potential land area in low DNI zones from scenario 3**

| DNI range ($kWh/m^2$) | Maximum land slope % | Maximum distance to transmission lines (km) | Land area ($km^2$) | Land area in % of ECOWAS land area | Average .daily DNI ($kWh/m^2$) | **Cases** |
|---|---|---|---|---|---|---|
| 3≤DNI≤ 4 | 1 | 20 | 72100 | 1.41 | 3.6 | **1** |
| | | 60 | 154800 | 3.03 | 3.7 | **2** |
| | | 100 | 183000 | 3.58 | 3.7 | **3** |
| | 3 | 20 | 310700 | 6.08 | 3.5 | **4** |
| | | 60 | 654600 | 12.81 | 3.5 | **5** |
| | | 100 | 759300 | 14.86 | 3.5 | **6** |
| | 5 | 20 | 386100 | 7.55 | 3.5 | **7** |
| | | 60 | 809200 | 15.83 | 3.5 | **8** |
| | | 100 | 944700 | 18.48 | 3.5 | **9** |

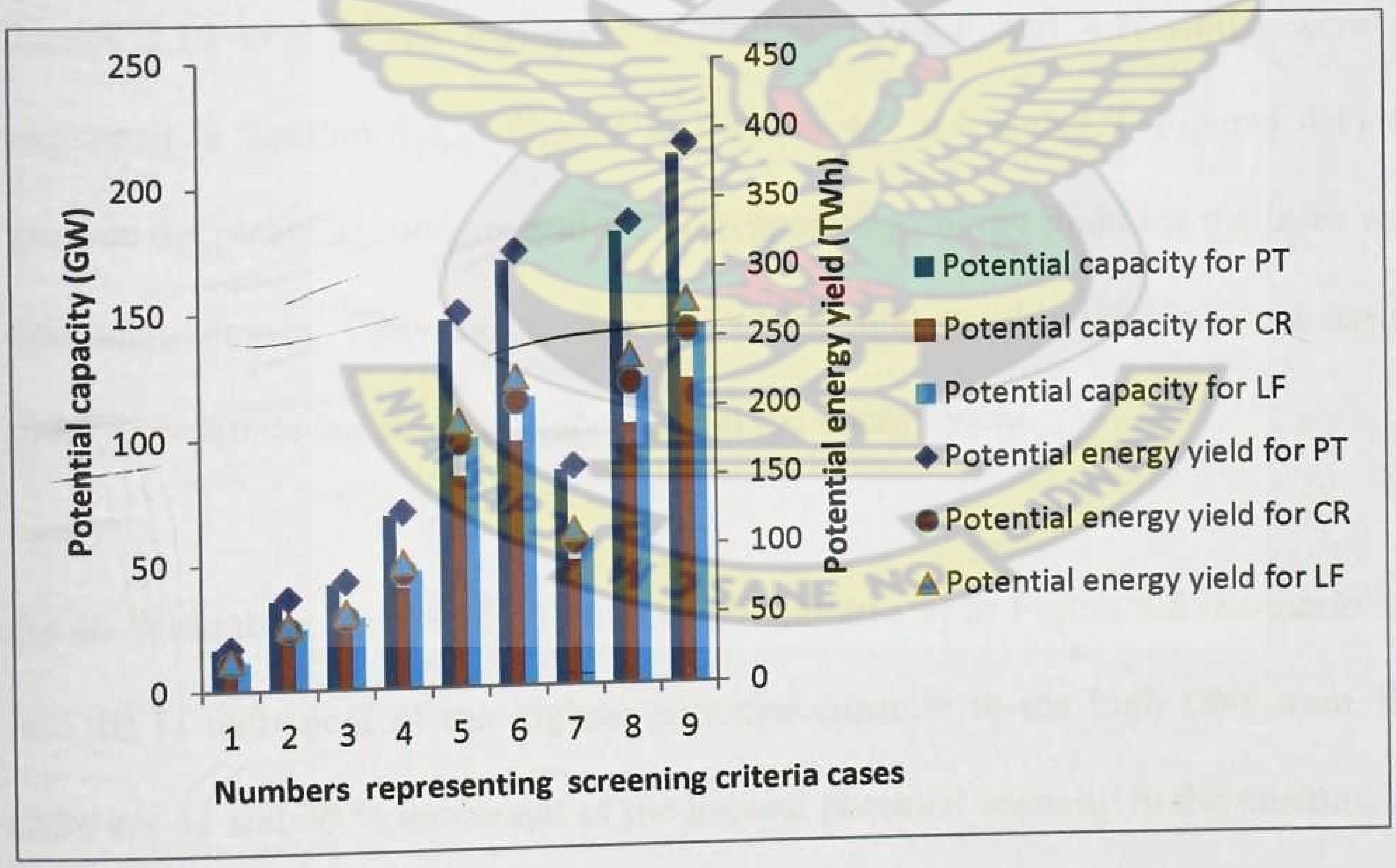


**Figure 4.13: Scenario 3 low DNI zones**

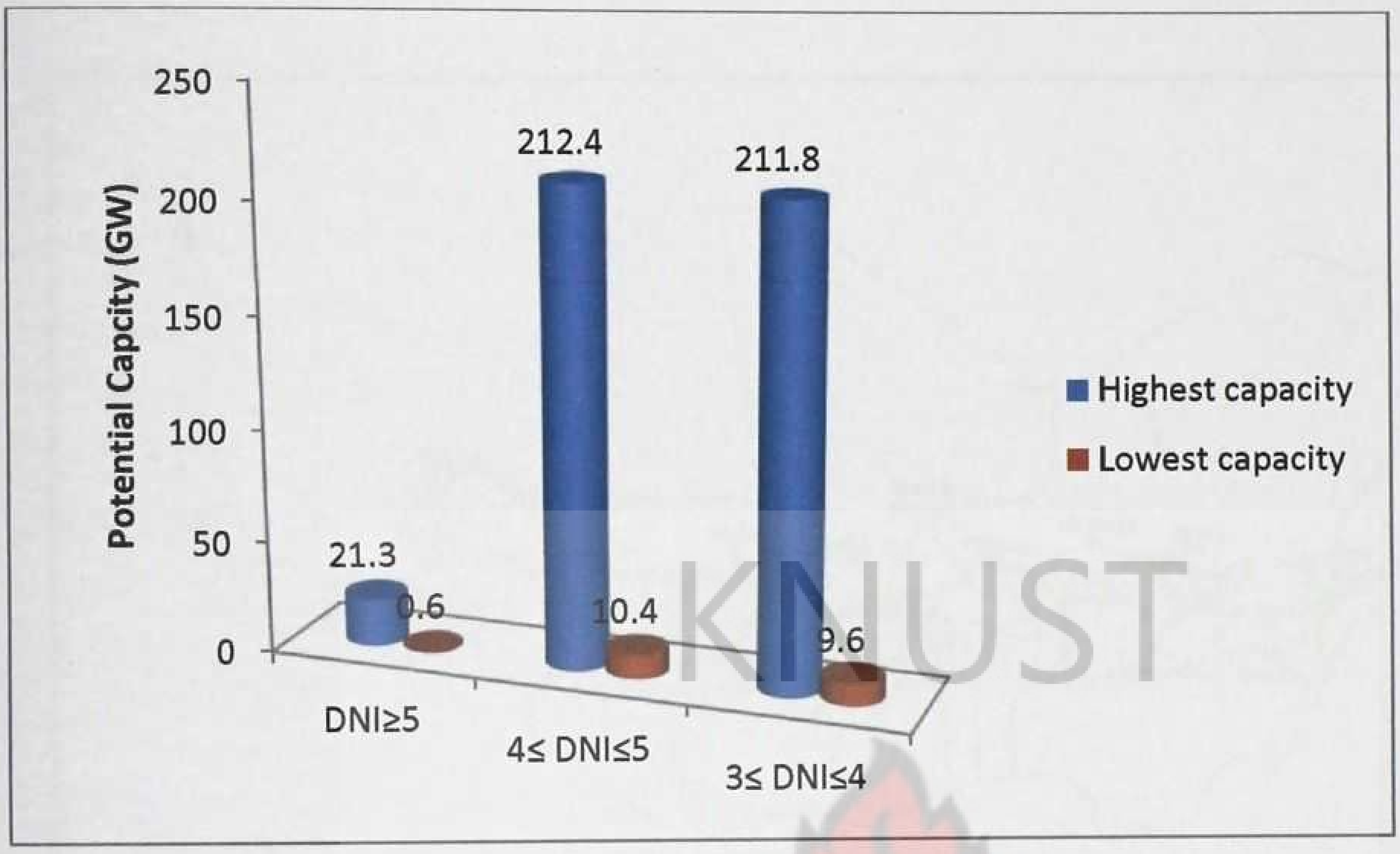


**Figure 4.14: Highest and lowest potential capacities from scenario 3**

Tables 4.10 to 4.12 are analogous to Tables 4.5, 4.6 and 4.7, which were already explained in Section 4.3.2. Similar to Figures 4.5, 4.6 and 4.7, Figures 4.11 to 4.13 provide the potential capacity and the corresponding energy yield for the three reference CSP technologies. There again, only 1 % of the total suitable land has been assumed in order to compute the potential capacity and the energy yield.

As an illustration, comparing Figure 4.14 (Scenario 3) to Figure 4.8 (Scenario 2), there is a 10 % increment of the highest potential capacity in the high DNI zone. Equally, there are 52 and 30 % increment of the highest potential capacity in the medium and low DNI zones respectively.

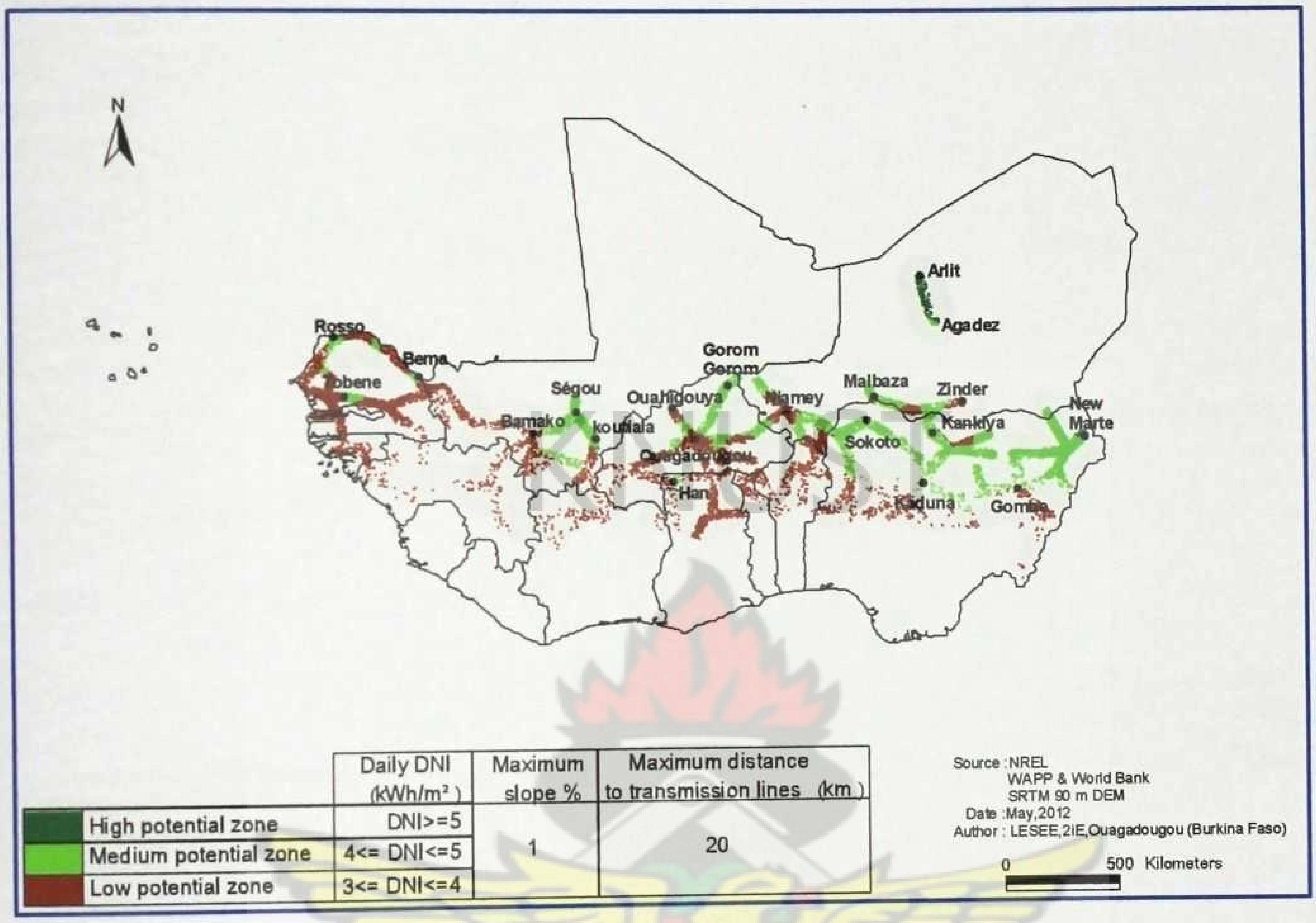


**Figure 4.15: Third sample map illustrating site ranking for large-scale CSP plants**

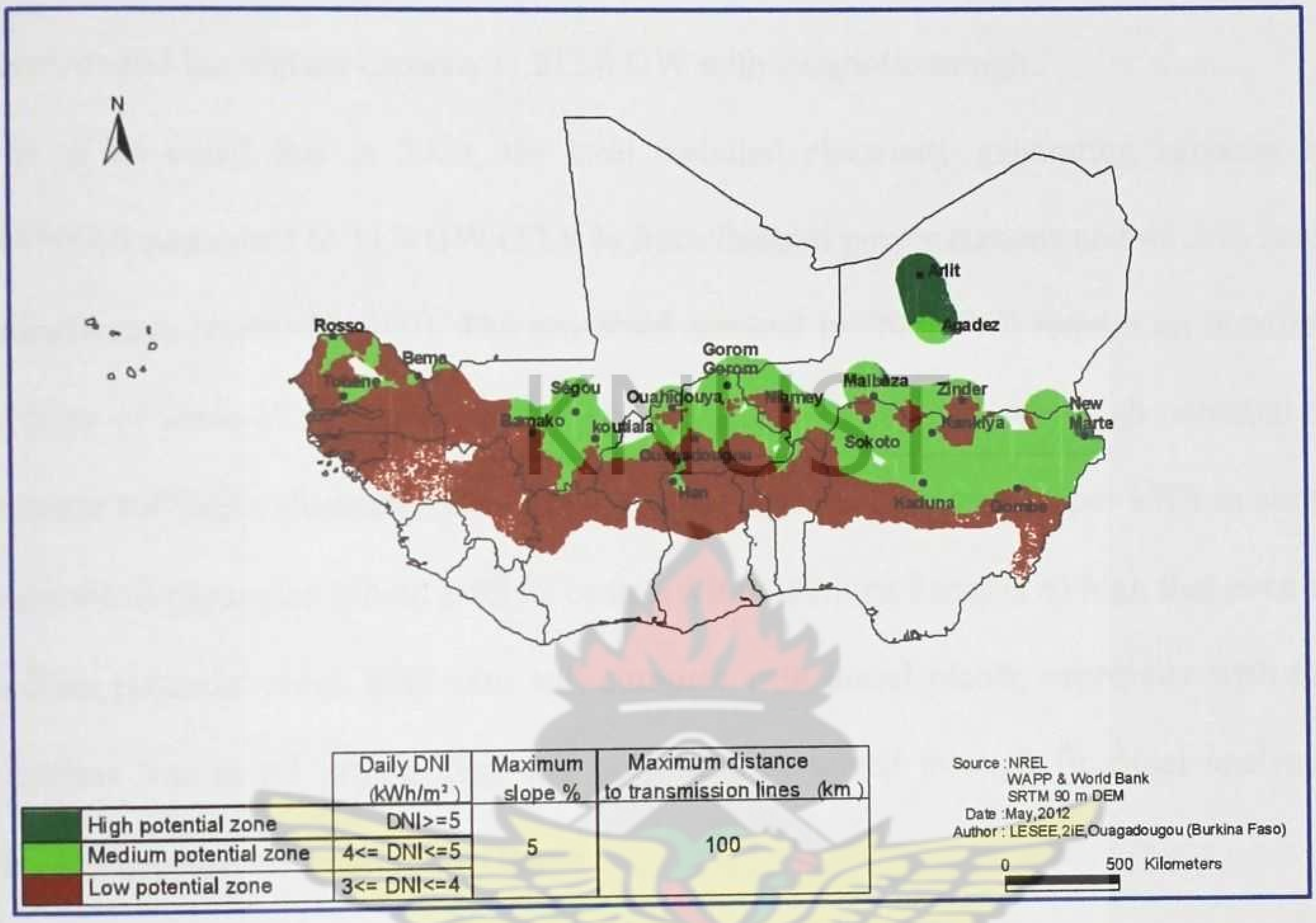


**Figure 4.16: Fourth sample map illustrating site ranking for large-scale CSP plants**

### 4.5.4. Discussion

In Scenario 2 where the assessment was done leaving out planned/future high voltage transmission lines, assuming 1 % of the suitable land area, the lowest capacity one could get in the high DNI zone (Figure 4.8) is 0.5 GW using Central Receiver and the highest capacity is 19.4 GW with Parabolic trough. Reading from the same Figure, the lowest capacity in the medium DNI zone is 6.1 GW using Central Receiver and the highest capacity is 139.9 GW with Parabolic trough.

With Scenario 3, the lowest capacity in the high DNI zone (Figure 4.12) is 0.6 GW using Central Receiver and the highest capacity is 21.3 GW with Parabolic trough. Still within

Scenario 3, the lowest capacity in the medium DNI zone is 10.4 GW using Central Receiver and the highest capacity is 212.4 GW with Parabolic trough.

It is to be noted that in 2009, the total installed electricity generating capacity in ECOWAS amounted to 11.4 GW (57.8 % from thermal power stations and 42.2 % from hydroelectric plants) [3, 160]. The projected demand by 2023 will require an installed capacity of some 17 GW [6]. For the region, there is therefore a very high potential to generate sufficient electricity from CSP. The average production cost per kWh in some countries of the region (about US$ 32 cents/kWh in Burkina Faso) is so high that even in medium potential areas, CSP may still compete with diesel plants, especially with the relentless rise in oil prices. This can only be ascertained through financial analysis, which is beyond the scope of this thesis.

Figures 4.9, 4.10, 4.15 and 4.16 are sample maps showing results from overlaying the three maps which illustrate the DNI, the land slope and the transmission lines in the ECOWAS region. Ranges of values for screening criteria used are given in Table 4.7. The sample maps serve as illustration; therefore, the maximum slope and the maximum distance to transmission lines were set to their lowest values of 1 % and 20 km respectively and to their highest values of 5 % and 100 km. In these Figures, sites are then ranked as high, medium and low potential zones depending on DNI level. The high potential zone lies between Agadez and Arlit in northern Niger. It is located in the Sahara desert and is also the host of an important uranium mining industry. There is an existing 132 kV voltage line in the region.

Scenario 3, the lowest capacity in the medium DNI zone is 10.4 GW using Central Receiver and the highest capacity is 212.4 GW with Parabolic trough.

It is to be noted that in 2009, the total installed electricity generating capacity in ECOWAS amounted to 11.4 GW (57.8 % from thermal power stations and 42.2 % from hydroelectric plants) [3, 160]. The projected demand by 2023 will require an installed capacity of some 17 GW [6]. For the region, there is therefore a very high potential to generate sufficient electricity from CSP. The average production cost per kWh in some countries of the region (about US$ 32 cents/kWh in Burkina Faso) is so high that even in medium potential areas, CSP may still compete with diesel plants, especially with the relentless rise in oil prices. This can only be ascertained through financial analysis, which is beyond the scope of this thesis.

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Northern Mali has good DNI but no transmission line is in existence or has been planned (refer to Fig. 1 and 3). As pointed out in Chapter 3, building new transmission line as part of a CSP project is capital intensive.

The high potential zone falls in the Sahara desert which is characterized by an important sand and dust deposit, lack of water and lack of transmission lines. Dust-resistant, Waterless, dry cooling and small-scale CSP technology could be envisaged in this zone. The medium potential zone coincides with the Sahel which is a transition between the Sahara desert and the humid tropical southern coastal zone. The low potential zone corresponds to the humid tropical southern coastal zone which, unlike the first two zones has better water resources, less dust deposit and a better transmission network. Dust and sand deposit affect optical efficiency of the mirrors thus causing overall output drop of the plant whilst high DNI implies better output. It must be interesting to conduct studies and to see whether the loss in overall plant performance due to deposition of dust in the high potential zone is not compensated with better optical efficiency in low-DNI but dust-free zone.

**Table 4-11: Land demand in various DNI zones for the three technologies**

| | **Land demand km²/GW** | | |
|---|---|---|---|
| **Technology** | High DNI zone Mean DNI 6 kWh/m²/d | Medium DNI zone Mean DNI 4.3 kWh/m²/d | Low DNI zone Mean DNI 3.6 kWh/m²/d |
| **Parabolic trough** | 28 | 37 | 44 |
| **Central receiver** | 49 | 64 | 77 |
| **Linear Fresnel** | 42 | 54 | 65 |

Table 4.11 clearly illustrates that the land demand increases as the DNI decreases. This was ignored in previous CSP potential assessments where the land demand was assumed constant (refer to Table 4.2). This has induced some percentage error which is for instance illustrated in Table 4.12 (High DNI zone for scenario 2).

**Table 4-12: Percentage error between previous method and new method**



| DNI kWh/m2.day | Land slope % | Proximity to transmission lines | Land area km² | Average DNI | Present method<br>Nominal Capacity GW for PT | Previous method<br>Nominal Capacity GW for PT | % Error |
|---|---|---|---|---|---|---|---|
| ≥ 5 | ≤1 | ≤20 | 24.0 | 5.5 | 0.8 | 1.1 | **25.8** |
| | | ≤60 | 82.9 | 5.6 | 2.9 | 3.9 | **25.1** |
| | | ≤100 | 161.7 | 5.6 | 5.8 | 7.6 | **24.5** |
| | ≤3 | ≤20 | 75.7 | 5.5 | 2.6 | 3.6 | **26.5** |
| | | ≤60 | 238.9 | 5.7 | 8.6 | 11.3 | **24.3** |
| | | ≤100 | 469.0 | 5.8 | 17.2 | 22.2 | **22.4** |
| | ≤5 | ≤20 | 81.5 | 5.4 | 2.8 | 3.9 | **27.1** |
| | | ≤60 | 267.7 | 5.7 | 9.6 | 12.7 | **24.2** |
| | | ≤100 | 528.1 | 5.8 | 19.4 | 25.0 | **22.2** |

### 4.6. Conclusion

Concentrating Solar Power (CSP) Plants appear to be good candidate for increasing access to electricity in Africa and to improve people's living conditions; however, with the exception of Northern Africa where extensive work is being conducted, potential assessment of CSP Plants in West Africa was yet to be done. This chapter presented results of the potential assessment of Concentrating Solar Power for electricity generation in West Africa. The study considered only 1 % of the suitable land area which met certain criteria and found for example that West Africa has a potential nominal capacity of 21.3 GW for Parabolic trough technology. This greatly exceeds the projected electricity demand of 17 GW by 2023 for the region. Of course, the study is constrained by the accuracy limits of the data used. Further studies need to be conducted in order to investigate the economic viability of such plants in the region.

# CHAPTER 5: SYNTHESIS, CONCLUSION AND RECOMMENDATIONS

## 5.1. Introduction

This Chapter brings together the study by providing a summary of the literature reviewed, a description of the methodology and the main results achieved. It thereafter suggests a set of recommendations for future research.

## 5.2. Overall objective of the study

The Economic Community of West African States (ECOWAS) which is a regional group of fifteen countries has some of the lowest modern energy consumption rates in the world. Concentrating Solar Power (CSP) could present better opportunities for increasing access to electricity and for diversifying sources of energy in the region. However, the potential of CSP in the region was not well known. The overall objective of this study was to carry out a potential assessment of Concentrating Solar Power in the ECOWAS region.

## 5.3. Summary of the related literature

Concentrating Solar Power for electricity generation has attracted the interest of many researchers. A concentrating solar power plant uses reflective materials such as mirrors to concentrate the direct component of solar radiation onto a receiver. Concentration of the direct solar radiation reduces the receiver surface area with respect to the collector aperture area and thus significantly decreases the overall thermal losses. The receiver is a high-absorptance and low-reflectance, radiative/convective heat exchanger that absorbs the solar energy and converts it into high-temperature thermal energy. The thermal energy is subsequently converted into mechanical power through thermodynamic cycles which later, is converted into electricity via a generator. The literature review discussed the key components, the technological challenges, and the research and development activities for each of the four main Concentrating Solar Power technologies, which have reached commercial or near-commercial stage. Interest was also granted to previous studies pertaining to site selection for concentrating solar power. In that regard, some studies were mainly performed in Northern Africa [123], Spain [126], China [125], South Africa [127], Oman [128], Australia [129] and USA [124, 130-134]. The review revealed that no site selection and potential assessment have ever been carried out for Concentrating Solar Power for West Africa. The review also revealed some shortfalls in the previous studies concerning the method used for predicting the potential capacity of large scale CSP.

## 5.4. Thesis organization and Methodology

This thesis was organized into five Chapters. Chapter one served as a general introduction to the study. It provided a background, stated the objectives and described the research methodology of the study. Chapter two provided a general picture of the four main Concentrating Solar Power technologies, which have reached commercial or near-commercial stage. It discussed the key components, the technological challenges, and the research and development activities for each technology. Literature on site selection and potential assessment was also reviewed. Chapter three proposed some guidelines for selecting suitable sites for CSP plants, with special focus to Sahelian countries. As a case study, the guidelines were applied in selecting a candidate site in Burkina Faso, an ECOWAS country. Chapter four performed a site evaluation of the ECOWAS region for CSP and Chapiter five draws the main conclusions from the investigation and presents recommendations for future research.

The methodology for this research included a literature review. Guidelines for the selection of suitable sites for CSP plants were also discussed. Subsequently, maps of ECOWAS illustrating spatial distribution of some key parameters, previously suggested in the guidelines, were developed using Geographical Information Systems. This was then followed by site evaluation and ranking for large-scale CSP plants in the ECOWAS region. Furthermore, a new method for computing the nominal potential power was proposed and afterwards applied to the ECOWAS region. Three scenarios were explored. In Scenario 1, the assessment was done based on DNI solely; Scenario 2 considered land slope, existing high voltage transmission lines in addition to the DNI. Scenario 3 took into account all criteria in Scenario 2 but included future high voltage transmission lines as well.

## 5.5. Synthesis of the results achieved

This research provided siting-guidelines and contributed to the assessment of the potential, by evaluating and ranking suitable sites for large-scale CSP projects in the

ECOWAS region. Findings from this research are expected to pave the way for the design and construction of concentrating solar power plants in West Africa.

In addition, the study proposed a new method that takes into account the actual value of the DNI of the site in predicting the nominal potential capacity. Indeed, many past studies assumed the land demand per unit power as constant in predicting the nominal potential capacity of CSP technology for some locations. These studies did not factor in the actual DNI value of the site but rather assumed it to be higher than or equal to a certain threshold value which they consider to be the minimum for a CSP plant to be economically viable. Land demand however, strongly depends on the level of DNI. The new method could be used to assess or re-assess the potential of CSP in other parts of the world. In order to illustrate the results obtained in this study, let's assume 1 % of the suitable land area in the high DNI zone (i.e daily DNI greater or equal to 5 $kWh/m^2$). Scenario 1 for example estimated the lowest potential capacity to be about 170 GW with central receiver and the highest potential capacity to be about 300 GW using parabolic through technology. Scenario 1 however was less informative since the assessment left out many other crucial factors. Under the same assumptions and with Scenario 2, the lowest capacity was 0.5 GW using central receiver and the highest capacity was 19.4 GW with parabolic trough. Likewise, Scenario 3 gave 0.6 GW as the lowest capacity and 21.3 GW as the highest capacity. These sample results suggest that CSP could meet entirely the current and future electricity demand of the ECOWAS region. The current total installed capacity in the ECOWAS regions amount to about 11.4 GW [3] and the projected demand by 2023 is said to be about 17 GW [6].

## 5.6. Recommendations

During the course of this study, some issues cropped up but were left out as a result of the delimitations of this research. They are therefore recommended for further investigation.

### 5.6.1. Water issues

As stated earlier, water resource assessment of a candidate site for CSP plant is paramount in deciding on the mode of cooling. However data on water availability in GIS format for the ECOWAS region could not be accessed and therefore was not factored in this study. The study could be repeated when data on water resources become available. Rain water, underground water as well as surface water could be included as criteria. A study should also look at the possibility of producing Water using CSP technologies as source of power.

### 5.6.2. Economic viability

The second topic that needs closer attention is the economic viability of CSP plants across the ECOWAS sub-region. Current electricity costs vary largely from country to country in the region due to varied sources of production. Though this study reveals a huge CSP potential in the region, a study comparing the economics of CSP with the current sources of production will be an added value.

### 5.6.3. Selection of an appropriate CSP technology

A third topic which is worth investigating is the selection of an appropriate CSP technology. Concentrating Solar Power technologies are many with regard to the collector type, the receiver type, the heat transfer fluid, the working fluid and the thermodynamic cycle. A study in this vain will help select the best technologies that suit West African conditions.

### 5.6.4. Small-scale stand alone versus large-scale grid connected systems

Judging from Scenario 1, the assessment based on DNI alone shows a huge potential however taking transmissions lines into account, this potential is, in some cases, divided by 300. Transmissions lines are capital incentive and therefore a comparative study could research on small-scale stand-alone CSP plants versus large-scale grid connected systems.

### 5.6.5. Solar radiation models

The models currently available for assessing the Direct Normal Irradiation are mainly based on satellite measurements. However, DNI ground data are more and more available thanks to some weather stations being installed in the ECOWAS region. For smaller grid resolution and better accuracy, the models will need to be re-adapted and corrected using the available ground data.

### 5.6.6. Dust deposit on mirrors

The last point that is recommended for further investigation is the dust issue. As pointed out before, the low potential zone corresponds to the humid tropical southern coastal zone which, unlike the remaining part of the region has better water resources, less dust deposit and a better transmission network. Dust and sand deposit affect optical efficiency of the mirrors thus causing overall output drop of the plant whilst high DNI implies better output. It must be interesting to conduct studies and to see whether the loss in overall plant performance due to deposition of dust in the high potential zone is not compensated with better optical efficiency in low-DNI but dust-free zone.

loss in overall plant performance due to deposition of dust in the high potential zone is not compensated with better optical efficiency in low-DNI but dust-free zone.

## References

[1] Kuo C, Shin H, Hong H, Wu C, Lee C, Lung I, et al. Development of the high concentration III-V photovoltaic system at INER, Taiwan. Renewable Energy. 2009;34:1931-3.

[2] Hong H, Jin H, Ji J, Wang Z, Cai R. Solar thermal power cycle with integration of methanol decomposition and middle-temperature solar thermal energy. Solar Energy. 2005;78:49-58.

[3] U.S. Energy Information Administration - EIA, 2009. International Energy Statistics Retrieved 27 March 2012 from http://www.eia.gov/countries/.

[4] Kemausuor F, Brew-Hammond A, Obeng GY, Duker A, Annor FO, Boamah F, et al. GIS-Based support for implementing policies and plans to increase access to energy services in Ghana. 2012.

[5] Quansah AD, Ramdé EW. Potentials, Opportunities and Barriers for the Deployment and Usage of Solar Energy Technologies and Services in West Africa. ECREEE; 2010.

[6] ECOWAS/UEMOA. White Paper for a Regional Policy on energy access. Abuja2005.

[7] ECREEE. ECOWAS Regional Policy on Renewable Energy. Praia, 2012.

[8] Kreith F, Kreider JF. Principles of solar engineering: McGraw-Hill; 1978.

[9] Opoku F. Feasibility Study of Thermal Electric-Power Generation in Northern Ghana [MSc]. Kumasi: Kwame Nkrumah University of Science and Technology; 2011.

## References

[1] Kuo C, Shin H, Hong H, Wu C, Lee C, Lung I, et al. Development of the high concentration III-V photovoltaic system at INER, Taiwan. Renewable Energy. 2009;34:1931-3.

[2] Hong H, Jin H, Ji J, Wang Z, Cai R. Solar thermal power cycle with integration of methanol decomposition and middle-temperature solar thermal energy. Solar Energy. 2005;78:49-58.

[3] U.S. Energy Information Administration - EIA, 2009. International Energy Statistics Retrieved 27 March 2012 from http://www.eia.gov/countries/.

[4] Kemausuor F, Brew-Hammond A, Obeng GY, Duker A, Annor FO, Boamah F, et al. GIS-Based support for implementing policies and plans to increase access to energy services in Ghana. 2012.

[5] Quansah AD, Ramdé EW. Potentials, Opportunities and Barriers for the Deployment and Usage of Solar Energy Technologies and Services in West Africa. ECREEE; 2010.

[6] ECOWAS/UEMOA. White Paper for a Regional Policy on energy access. Abuja2005.

[7] ECREEE. ECOWAS Regional Policy on Renewable Energy. Praia, 2012.

[8] Kreith F, Kreider JF. Principles of solar engineering: McGraw-Hill; 1978.

[9] Opoku F. Feasibility Study of Thermal Electric-Power Generation in Northern Ghana [MSc]. Kumasi: Kwame Nkrumah University of Science and Technology; 2011.

[10] Denholm P, Drury E, Margolis R, Mehos M. Solar Energy: The Largest Energy Resource. Generating Electricity in a Carbon-Constrained World. Boston: Academic Press; 2010. p. 271-302.

[11] Romero-Alvarez M, Zarza E. Concentrating Solar Thermal Power in Energy Convercion, Goswami, D.Y. and Kreith, F: CRC Press; 2008.

[12] Price H, Kearney D. Reducing the cost of energy from parabolic trough solar power plants. Citeseer; 2003.

[13] Mills D. Advances in solar thermal electricity technology. Solar Energy. 2004;76:19-31.

[14] Price H, Lupfert E, Kearney D, Zarza E, Cohen G, Gee R, et al. Advances in Parabolic Trough Solar Power Technology. Journal of Solar Energy Engineering. 2002;124:109-25.

[15] Fernández-García A, Zarza E, Valenzuela L, Pérez M. Parabolic-trough solar collectors and their applications. Renewable and Sustainable Energy Reviews.In Press, Uncorrected Proof.

[16] Pitz-Paal R, Dersch J, Milow B, Tellez F, Ferriere A, Langnickel U, et al. Development Steps for Parabolic Trough Solar Power Technologies With Maximum Impact on Cost Reduction. Journal of Solar Energy Engineering. 2007;129:371-7.

[17] Eck M, Eickhoff M, Zarza E, Rheinlander J, Valenzuela L. Applied research concerning the direct steam generation in parabolic troughs. Solar Energy. 2003;74:341-51.

[10] Denholm P, Drury E, Margolis R, Mehos M. Solar Energy: The Largest Energy Resource. Generating Electricity in a Carbon-Constrained World. Boston: Academic Press; 2010. p. 271-302.

[11] Romero-Alvarez M, Zarza E. Concentrating Solar Thermal Power in Energy Convercion, Goswami, D.Y. and Kreith, F: CRC Press; 2008.

[12] Price H, Kearney D. Reducing the cost of energy from parabolic trough solar power plants. Citeseer; 2003.

[13] Mills D. Advances in solar thermal electricity technology. Solar Energy. 2004;76:19-31.

[14] Price H, Lupfert E, Kearney D, Zarza E, Cohen G, Gee R, et al. Advances in Parabolic Trough Solar Power Technology. Journal of Solar Energy Engineering. 2002;124:109-25.

[15] Fernández-García A, Zarza E, Valenzuela L, Pérez M. Parabolic-trough solar collectors and their applications. Renewable and Sustainable Energy Reviews.In Press, Uncorrected Proof.

[16] Pitz-Paal R, Dersch J, Milow B, Tellez F, Ferriere A, Langnickel U, et al. Development Steps for Parabolic Trough Solar Power Technologies With Maximum Impact on Cost Reduction. Journal of Solar Energy Engineering. 2007;129:371-7.

[17] Eck M, Eickhoff M, Zarza E, Rheinlander J, Valenzuela L. Applied research concerning the direct steam generation in parabolic troughs. Solar Energy. 2003;74:341-51.

[18] Odeh SD, Behnia M, Morrison GL. Hydrodynamic analysis of direct steam generation solar collectors. Transactions of the ASME Journal of Solar Energy Engineering. 2000;122:14-22.

[19] Valenzuela L, Zarza E, Berenguel M, Camacho EF. Direct steam generation in solar boilers. IEEE Control Systems Magazine. 2004;24:15-29.

[20] Valenzuela L, Zarza E, Berenguel M, Camacho EF. Control concepts for direct steam generation in parabolic troughs. Solar Energy. 2005;78:301-11.

[21] Eck M, Schmidt H, Eickhoff M, Hirsch T. Field test of water-steam separators for direct steam generation in parabolic troughs. Journal of Solar Energy Engineering. 2008;130:011002-1.

[22] Montes MJ, Abanades A, Martinez-Val JM. Performance of a direct steam generation solar thermal power plant for electricity production as a function of the solar multiple. Solar Energy. 2009;83:679-89.

[23] Valenzuela L, Zarza E, Berenguel M, Camacho EF. Control scheme for direct steam generation in parabolic troughs under recirculation operation mode. Solar Energy. 2006;80:1-17.

[24] Zarza E, Rojas ME, Gonzalez L, Caballero JM, Rueda F. INDITEP: The first pre-commercial DSG solar power plant. Solar Energy. 2006;80:1270-6.

[25] Rojas ME, de Andres MC, Gonzalez L. Designing capillary systems to enhance heat transfer in LS3 parabolic trough collectors for direct steam generation (DSG). Solar Energy. 2008;82:53-60.

[26] Flores V, Almanza R. Behavior of the compound wall copper-steel receiver with stratified two-phase flow regimen in transient states when solar irradiance is arriving on one side of receiver. Solar Energy. 2004;76:195-8.

[27] Rojas M, E., Ajona J, I. Thermal gradient avoidance under stratified two-phase flow in DSG by capillar structures. J Phys IV France. 1999;09:Pr3-135-Pr3-40.

[28] Koch S, Eck M, Hirsch T. Modelling and Control of a Solar-Thermal Parabolic Trough DSG Superheater With Several Parallel Rows and Central Steam Separation. ASME Conference Proceedings. 2007;2007:1005-14.

[29] Eck M, Hirsch T. Dynamics and control of parabolic trough collector loops with direct steam generation. Solar Energy. 2007;81:268-79.

[30] Birnbaum J, Feldhoff JF, Fichtner M, Hirsch T, Jöcker M, Pitz-Paal R, et al. Steam temperature stability in a direct steam generation solar power plant. Solar Energy. 2011;85:660-8.

[31] Bayón R, Rojas E, Valenzuela L, Zarza E, León J. Analysis of the experimental behaviour of a 100 kWth latent heat storage system for direct steam generation in solar thermal power plants. Applied Thermal Engineering. 2010;30:2643-51.

[32] Birnbaum J, Hirsch T. A Concept for Future Parabolic Trough Based Solar Thermal Power Plants. 2008.

[33] Laing D, Bahl C, Bauer T, Lehmann D, Steinmann W-D. Thermal energy storage for direct steam generation. Solar Energy. 2011;85:627-33.

[34] Michels H, Pitz-Paal R. Cascaded latent heat storage for parabolic trough solar power plants. Solar Energy. 2007;81:829-37.

[26] Flores V, Almanza R. Behavior of the compound wall copper-steel receiver with stratified two-phase flow regimen in transient states when solar irradiance is arriving on one side of receiver. Solar Energy. 2004;76:195-8.

[27] Rojas M, E., Ajona J, I. Thermal gradient avoidance under stratified two-phase flow in DSG by capillar structures. J Phys IV France. 1999;09:Pr3-135-Pr3-40.

[28] Koch S, Eck M, Hirsch T. Modelling and Control of a Solar-Thermal Parabolic Trough DSG Superheater With Several Parallel Rows and Central Steam Separation. ASME Conference Proceedings. 2007;2007:1005-14.

[29] Eck M, Hirsch T. Dynamics and control of parabolic trough collector loops with direct steam generation. Solar Energy. 2007;81:268-79.

[30] Birnbaum J, Feldhoff JF, Fichtner M, Hirsch T, Jöcker M, Pitz-Paal R, et al. Steam temperature stability in a direct steam generation solar power plant. Solar Energy. 2011;85:660-8.

[31] Bayón R, Rojas E, Valenzuela L, Zarza E, León J. Analysis of the experimental behaviour of a 100 kWth latent heat storage system for direct steam generation in solar thermal power plants. Applied Thermal Engineering. 2010;30:2643-51.

[32] Birnbaum J, Hirsch T. A Concept for Future Parabolic Trough Based Solar Thermal Power Plants. 2008.

[33] Laing D, Bahl C, Bauer T, Lehmann D, Steinmann W-D. Thermal energy storage for direct steam generation. Solar Energy. 2011;85:627-33.

[34] Michels H, Pitz-Paal R. Cascaded latent heat storage for parabolic trough solar power plants. Solar Energy. 2007;81:829-37.

[35] Steinmann W-D, Eck M. Buffer storage for direct steam generation. Solar Energy. 2006;80:1277-82.

[36] Tamme R, Laing D, Steinmann WD. Advanced thermal energy storage technology for parabolic trough. Journal of Solar Energy Engineering. 2004;126:794.

[37] Medrano M, Gil A, Martorell I, Potau X, Cabeza LF. State of the art on high-temperature thermal energy storage for power generation. Part 2--Case studies. Renewable and Sustainable Energy Reviews. 2010;14:56-72.

[38] Therminol. Therminol VP-1 Vapor Phase/Liquid Phase Heat Transfer Fluid. 2011.

[39] Hunt J. Handling molten salt for sun power. World Pumps. 2011;2011:22-6.

[40] Etay J, Fireteanu V, Fautrelle Y, Roman C. Electromagnetic pumping of molten salts. IEEE. p. 264-72.

[41] Kearney D, Herrmann U, Nava P, Kelly B, Mahoney R, Pacheco J, et al. Evaluation of a Molten Salt Heat Transfer Fluid in a Parabolic Trough Solar Field. ASME Conference Proceedings. 2002;2002:293-9.

[42] Kearney D, Herrmann U, Nava P, Kelly B, Mahoney R, Pacheco J, et al. Assessment of a Molten Salt Heat Transfer Fluid in a Parabolic Trough Solar Field. Journal of Solar Energy Engineering. 2003;125:170-6.

[43] Kearney D, Kelly B, Herrmann U, Cable R, Pacheco J, Mahoney R, et al. Engineering aspects of a molten salt heat transfer fluid in a trough solar field. Energy. 2004;29:861-70.

[44] Blake DM, Moens L, Hale M, Price H, Kearney D, Hermann U. New Heat Transfer and Storage Fluids For Parabolic Trough Solar Thermal Electric Plants. 2002.

[45] Piemonte V, Falco MD, Tarquini P, Giaconia A. Life Cycle Assessment of a high temperature molten salt concentrated solar power plant. Solar Energy. 2011;85:1101-8.

[46] Pin G, Falchetta M, Fenu G. Adaptive time-warped control of molten salt distributed collector solar fields. Control Engineering Practice. 2008;16:813-23.

[47] Caldes N, Varela M, Santamaria M, Saez R. Economic impact of solar thermal electricity deployment in Spain. Energy Policy. 2009;37:1628-36.

[48] Segal A, Epstein M. Optimized working temperatures of a solar central receiver. Solar Energy. 2003;75:503-10.

[49] Chacartegui R, Muñoz de Escalona JM, Sánchez D, Monje B, Sánchez T. Alternative cycles based on carbon dioxide for central receiver solar power plants. Applied Thermal Engineering. 2011;31:872-9.

[50] Lenert A. Nanofluid-based receivers for high-temperature, high-flux direct solar collectors [MSc Thesis]: Massachusetts Institute of Technology; 2010.

[51] Taylor RA, Phelan PE, Otanicar TP, Walker CA, Nguyen M, Trimble S, et al. Applicability of nanofluids in high flux solar collectors. Journal of Renewable and Sustainable Energy. 2011;3:023104.

[52] Radosevich LG, Skinrood AC. The Power Production Operation of Solar One, the 10 MWe Solar Thermal Central Receiver Pilot Plant. Journal of Solar Energy Engineering. 1989;111:144-51.

[53] Ferriere A, Bonduelle B, Amouroux M. Development of an Optimal Control Strategy for the Themis Solar Plant: Part I---Themis Transient Model. Journal of Solar Energy Engineering. 1989;111:298-304.

[54] REILLY HE, KOLB GJ. An Evaluation of Molten-Salt Power Towers Including Results of the Solar Two Project. Other Information: PBD: 1 Nov 20012001. p. Medium: ED; Size: 100 pages.

[55] Lata JM, Rodriguez M, de Lara MA. High Flux Central Receivers of Molten Salts for the New Generation of Commercial Stand-Alone Solar Power Plants. Journal of Solar Energy Engineering. 2008;130:021002-5.

[56] Ortega JI, Burgaleta JI, Tellez FM. Central receiver system solar power plant using molten salt as heat transfer fluid. Journal of Solar Energy Engineering, Transactions of the ASME. 2008;130:0245011-6.

[57] Kaltschmitt M, Streicher W, Wiese A. Solar Thermal Power Plants. Renewable Energy2007. p. 171-228.

[58] Li X, Kong W, Wang Z, Chang C, Bai F. Thermal model and thermodynamic performance of molten salt cavity receiver. Renewable Energy. 2010;35:981-8.

[59] Kolb GJ. Economic evaluation of solar-only and hybrid power towers using molten-salt technology. Solar Energy. 1998;62:51-61.

[60] Yang M, Yang X, Yang X, Ding J. Heat transfer enhancement and performance of the molten salt receiver of a solar power tower. Applied Energy. 2010;87:2808-11.

[61] Hasuike H, Yoshizawa Y, Suzuki A, Tamaura Y. Study on design of molten salt solar receivers for beam-down solar concentrator. Solar Energy. 2006;80:1255-62.

[62] Buck R, Barth C, Eck M, Steinmann W-D. Dual-receiver concept for solar towers. Solar Energy. 2006;80:1249-54.

[63] Buck R, Brauning T, Denk T, Pfander M, Schwarzbozl P, Tellez F. Solar-hybrid gas turbine-based power tower systems (REFOS). Transactions of the ASME Journal of Solar Energy Engineering. 2002;124:2-9.

[64] Sinai J, Sugarmen C, Fisher U. Adaptation and modification of gas turbines for solar energy applications. Reno-Tahoe, NV, United states: American Society of Mechanical Engineers; 2005. p. 87-94.

[65] Heller P, Pfänder M, Denk T, Tellez F, Valverde A, Fernandez J, et al. Test and evaluation of a solar powered gas turbine system. Solar Energy. 2006;80:1225-30.

[66] Schwarzbözl P, Buck R, Sugarmen C, Ring A, Marcos Crespo MJ, Altwegg P, et al. Solar gas turbine systems: Design, cost and perspectives. Solar Energy. 2006;80:1231-40.

[67] Kribus A, Zaibel R, Carey D, Segal A, Karni J. A solar-driven combined cycle power plant. Solar Energy. 1998;62:121-9.

[68] Fend T, Hoffschmidt B, Pitz-Paal R, Reutter O, Rietbrock P. Porous materials as open volumetric solar receivers: Experimental determination of thermophysical and heat transfer properties. Energy. 2004;29:823-33.

[69] Pitz-Paal R, Hoffschmidt B, BÃ¶hmer M, Becker M. Experimental and numerical evaluation of the performance and flow stability of different types of open volumetric absorbers under non-homogeneous irradiation. Solar Energy. 1997;60:135-50.

[70] Xu C, Song Z, Chen L-d, Zhen Y. Numerical investigation on porous media heat transfer in a solar tower receiver. Renewable Energy. 2011;36:1138-44.

[71] Hoffschmidt B, Tellez FM, Valverde A, Fernandez J, Fernandez V. Performance Evaluation of the 200-kW[sub th] HiTRec-II Open Volumetric Air Receiver. Journal of Solar Energy Engineering. 2003;125:87-94.

[72] Téllez F, Romero M, Heller P, Valverde A, Dibowski G, Ulmer S. Thermal Performance of "SolAir 3000 kWth" Ceramic Volumetric Solar Receiver. Instituo de Investigaciones Electricas; 2004.

[73] Hellmuth T, Matthews L. Experimental characterization of a high-temperature, high-flux, solar volumetric receiver. Experimental heat transfer. 1997;10:141-63.

[74] Wu Z, Caliot C, Flamant G, Wang Z. Numerical simulation of convective heat transfer between air flow and ceramic foams to optimise volumetric solar air receiver performances. International Journal of Heat and Mass Transfer. 2011;54:1527-37.

[75] Ávila-Marín AL. Volumetric receivers in Solar Thermal Power Plants with Central Receiver System technology: A review. Solar Energy. 2011;85:891-910.

[76] Francia G. Pilot plants of solar steam generating stations. Solar Energy. 1968;12:51-8, IN3-IN5, 9-62, IN7-IN13, 63-4.

[77] Kalogirou SA. Solar thermal collectors and applications. Progress in Energy and Combustion Science. 2004;30:231-95.

[78] Mills DR, Morrison G, Pye J, Le Lievre P. Multi-tower line focus Fresnel array project. Transactions of the ASME Journal of Solar Energy Engineering. 2006;128:118-20.

[79] Mills DR, Morrison GL. Compact linear Fresnel reflector solar thermal powerplants. Solar Energy. 2000;68:263-83.

[80] Chaves J, Collares-Pereira M. Etendue-matched two-stage concentrators with multiple receivers. Solar Energy. 2010;84:196-207.

[81] Reynolds DJ, Jance MJ, Behnia M, Morrison GL. An experimental and computational study of the heat loss characteristics of a trapezoidal cavity absorber. Solar Energy. 2004;76:229-34.

[82] Dey CJ. Heat transfer aspects of an elevated linear absorber. Solar Energy. 2004;76:243-9.

[83] Khan MKA. Technical note Copper oxide coatings for use in a linear solar Fresnel reflecting concentrating collector. Renewable Energy. 1999;17:603-8.

[84] Islam MN, Negi BS, Kandpal TC. Thermal performance of a linear Fresnel reflector solar concentrator using a black liquid. Renewable Energy. 1992;2:533-5.

[85] Singh PL, Sarviya RM, Bhagoria JL. Thermal performance of linear Fresnel reflecting solar concentrator with trapezoidal cavity absorbers. Applied Energy. 2010;87:541-50.

[86] Singh PL, Sarviya RM, Bhagoria JL. Heat loss study of trapezoidal cavity absorbers for linear solar concentrating collector. Energy Conversion and Management. 2010;51:329-37.

[87] Grena R, Tarquini P. Solar linear Fresnel collector using molten nitrates as heat transfer fluid. Energy. 2011;36:1048-56.

[88] Pons RL. Optimization of a Point-Focusing, Distributed Receiver Solar Thermal Electric System. Journal of Solar Energy Engineering. 1980;102:272-80.

[89] Jaffe LD. Test results on parabolic dish concentrators for solar thermal power systems. Solar Energy. 1989;42:173-87.

[90] Jaffe LD. A Review of Test Results on Solar Thermal Power Modules With Dish-Mounted Stirling and Brayton Cycle Engines. Journal of Solar Energy Engineering. 1988;110:268-74.

[91] Abbas M, Boumeddane B, Said N, Chikouche A. Techno Economie Evaluation of Solar Dish Stirling System for Stand Alone Electricity Generation in Algeria. Journal of Engineering and Applied Sciences. 2009;4:258-67.

[92] Abbas M, Boumeddane B, Said N, Chikouche A. Dish Stirling technology: A 100 MW solar power plant using hydrogen for Algeria. International Journal of Hydrogen Energy. 2011;36:4305-14.

[93] Buck R, Heller P, Koch H. Receiver development for a Dish-Brayton system. San Antonio, TX, USA: ASME; 1996. p. 91-6.

[94] Heller P, Buck R, Biehler T. Development of a Volumetric Receiver for a Dish-Brayton System. Solar Engineering. 1994:561-.

[95] Siangsukone P, Lovegrove K. Modelling of a steam based Paraboloidal Dish concentrator using the computer source code TRNSYS. Proceedings of Solar 2002 - Australian and New Zealand Solar Energy Society.

[96] Lovegrove K, Taumoefolau T, Paitoonsurikarn S, Siangsukone P, Burgess G, Luzzi A, et al. Paraboloidal dish solar concentrators for multi-megawatt power generation. 2003.

[97] Schmidt G, Zewen H, Moustafa S. A solar farm with parabolic dishes (Kuwaiti-German project). Electric Power Systems Research.3:65-76.

[98] Wu S-Y, Xiao L, Cao Y, Li Y-R. A parabolic dish/AMTEC solar thermal power system and its performance evaluation. Applied Energy. 2010;87:452-62.

[99] Lovegrove K, Burgess G, Pye J. A new 500 m2 paraboloidal dish solar concentrator. Solar Energy. 2011;85:620-6.

[100] Mancini TR. Analysis and design of two stretched-membrane parabolic dish concentrators. ASME-JSES-JSME International Solar Energy Conference. 1991:201-8.

[101] Stine WB, Diver RB. Compendium of solar dish/Stirling technology. United States1994. p. 124p.

[102] Mancini T, Heller P, Butler B, Osborn B, Schiel W, Goldberg V, et al. Dish-Stirling Systems: An Overview of Development and Status. Journal of Solar Energy Engineering. 2003;125:135-51.

[103] Adkins D, Andraka C, Moss T. Development of a 75-kW heat-pipe receiver for solar heat-engines. 1995. p. 1-5.

[104] Andraka CE, Diver RB, Moreno JB, Moss TA, Adkins DR. Recent reflux receiver developments under the US DOE program1994.

[105] Andraka CE, Moreno JB. Pool boiler reflux solar receiver for Stirling dish-electric systems. Washington, DC, USA: Publ by IEEE; 1989. p. 2003-8.

[106] Cui H, Wang Z, Guo Y, Xu W, Yuan X. Thermal performance analysis on unit tube for heat pipe receiver. Solar Energy. 2006;80:875-82.

[107] Diver RB, Andraka CE, Moreno JB, Adkins DR, Moss TA. Trends in dish-Stirling solar receiver designs. New York, NY, USA: AIChE; 1990. p. 303-10.

[108] Fowler MM, Klett DE, Moreno JB, Heermann PD. Using artificial neural networks to predict the performance of a liquid sodium reflux pool boiler solar receiver. New York,NY, USA: ASME; 1997. p. 93-104.

[109] Hogan RE, Jr. AEETES-a solar reflux receiver thermal performance numerical model. Solar Energy. 1994;52:167-78.

[110] Jianfeng L, Jing D, Jianping Y. Heat transfer performance and exergetic optimization for solar receiver pipe. Renewable Energy. 2010;35:1477-83.

[111] Kaushika ND, Reddy KS. Performance of a low cost solar paraboloidal dish steam generating system. Energy Conversion and Management. 2000;41:713-26.

[112] Moreno J, Rawlinson S, Andraka C, Cordeiro P, Mehos M, Bohn M, et al. Dish/Stirling hybrid-heat-pipe-receiver design and test results. Energy Conversion Engineering Conference, 2002 IECEC '02 2002 37th Intersociety2002. p. 556-64.

[113] Prakash M, Kedare SB, Nayak JK. Investigations on heat losses from a solar cavity receiver. Solar Energy. 2009;83:157-70.

[114] Prakash M, Kedare SB, Nayak JK. Determination of stagnation and convective zones in a solar cavity receiver. International Journal of Thermal Sciences. 2010;49:680-91.

[115] Reddy KS, Sendhil Kumar N. An improved model for natural convection heat loss from modified cavity receiver of solar dish concentrator. Solar Energy. 2009;83:1884-92.

[116] Shuai Y, Xia X-L, Tan H-P. Radiation performance of dish solar concentrator/cavity receiver systems. Solar Energy. 2008;82:13-21.

[117] Reddy K, Kumar NS. Convection and surface radiation heat losses from modified cavity receiver of solar parabolic dish collector with two-stage concentration. Heat and Mass Transfer. 2009;45:363-73.

[118] Reddy KS, Sendhil Kumar N. Combined laminar natural convection and surface radiation heat transfer in a modified cavity receiver of solar parabolic dish. International Journal of Thermal Sciences. 2008;47:1647-57.

[119] Bienert WB. The heat pipe and its application to solar receivers. Electric Power Systems Research. 1980;3:111-23.

[120] Sendhil Kumar N, Reddy KS. Numerical investigation of natural convection heat loss in modified cavity receiver for fuzzy focal solar dish concentrator. Solar Energy. 2007;81:846-55.

[121] Sendhil Kumar N, Reddy KS. Comparison of receivers for solar dish collector system. Energy Conversion and Management. 2008;49:812-9.

[122] Wu S-Y, Xiao L, Cao Y, Li Y-R. Convection heat loss from cavity receiver in parabolic dish solar thermal power system: A review. Solar Energy. 2010;84:1342-55.

[123] Broesamle H, Mannstein H, Schillings C, Trieb F. Assessment of solar electricity potentials in North Africa based on satellite data and a geographic information system. Solar Energy. 2001;70:1-12.

[124] Kirby M, Dahle D, Heimiller D, Owens B. Assessing the potential for renewable energy on public lands. US Department of the Interior and US Department of Energy. DOE/GO-102003-1704, 27 p; 2003.

[125] Hang Q, Jun Z, Xiao Y, Junkui C. Prospect of concentrating solar power in China--the sustainable future. Renewable and Sustainable Energy Reviews. 2008;12:2505-14.

[126] Bravo JD, Casals XG, Pascua IP. GIS approach to the definition of capacity and generation ceilings of renewable energy technologies. Energy Policy. 2007;35:4879-92.

[127] Fluri TP. The potential of concentrating solar power in South Africa. Energy Policy. 2009;37:5075-80.

[128] Charabi Y, Gastli A. GIS assessment of large CSP plant in Duqum, Oman. Renewable and Sustainable Energy Reviews. 2010;14:835-41.

[129] Clifton J, Boruff BJ. Assessing the potential for concentrated solar power development in rural Australia. Energy Policy. 2010;38:5272-80.

[130] Janke JR. Multicriteria GIS modeling of wind and solar farms in Colorado. Renewable Energy. 2010;35:2228-34.

[131] Pletka R, Finn J. Western Renewable Energy Zones, Phase 1: QRA Identification Technical Report. National Renewable Energy Laboratory (NREL), Golden, CO.; 2009.

[132] Doug Dahle, Dennis Elliott, Donna Heimiller, Mark Mehos, Robi Robichaud, Marc Schwartz, et al. Assessing the Potential for Renewable Energy Developmenton DOE Legacy Management Lands. In: NREL G, Colorado, editor.2008.

[133] R. Pletka, S. Block, Keith Cummer, Kevin Gilton, Ric O'Connell, Bill Roush, et al. Arizona Renewable Energy Assessment. Arizona Public Service Company; Salt River Project; Tucson Electric Power Corporation; 2007.

[134] Karsteadt; R, Dahle; D, Heimiller; D, Nealon T. Assessing the potential for renewable Energy on National Forest System Lands. 2005.

[135] Azoumah Y, Ramdé EW, Tapsoba G, Thiam S. Siting guidelines for concentrating solar power plants in the Sahel: Case study of Burkina Faso. Solar Energy. 2010;84:1545-53.

[136] Garcia P. Outils d'évaluation technico-économique et d'aide à la conception des centrales solaires thermodynamiques du futur. France: University of Perpignan; 2007.

[137] Meyer R, Hoyer C, Diedrich E. Use of long-term solar irradiance products derived from satellite for solar power project development. ISES Solar World Congress. Orlando2005.

[138] Ferrière A. Les centrales solaires thermodynamiques. In: Sabonnadière J, editor. Nouvelles technologies de l'énergie: Les énergies renouvelables 2006.

[139] Meyer R, Hoyer C, Diedrich E, Schillings C, Lohmann S, Schroedter-Homscheidt M, et al. Solar energy mining: a high-quality satellite-based service to provide direct solar radiation for Europe, Brazil, Africa and Asia. 12th SolarPACES International Symposium. Oaxaca, Mexique2004.

[140] Al-Soud MS, Hrayshat ES. A 50 MW concentrating solar power plant for Jordan. Journal of Cleaner Production. 2009;17:625-35.

[141] Kearney D, Svoboda P, Nava P. Impact of design choices and site influences on solar thermal electric plant economics and performance. International Conference on Solar Energy, 27-30 April 1997. New York,NY, USA: ASME; 1997. p. 389-95.

[142] Kelly B. Nexant Parabolic Trough Solar Power Plant Systems Analysis. Task 2: Comparison of Wet and Dry Rankine Cycle Heat Rejection. Report for January 20, 2005 to December 31, 2005. United States2006. p. 32p.

[143] Caldés N, Varela M, Santamaría M, Sáez R. Economic impact of solar thermal electricity deployment in Spain. Energy Policy. 2009;37:1628-36.

[144] Müller-Steinhagen H, Trieb F. Concentrating solar power-a review of the technology'. Quarterly of the Royal Academy of Engineering Ingenia. 2004;18.

[145] Cohen G. SM, Cable R., Morse F. et al. Solar Thermal Parabolic Trough Electric Power Plants for Electric Utilities in California. California: Solargenix Energy; 2005.

[146] WAPP. West African Power Pool priority projects. 2011.

[147] Ouattara I, Yane NC, Traore B. Note sectorielle sur l'énergie au Burkina Faso. Ouagadougou, 2010.

[148] MINES ParisTech, 2009. Solar Radiation Data (SoDa). Retrieved May 2010 from http://www.soda-is.com/eng/index.html.

[149] Chung-Ling CJ. Concentrating Solar Thermal Power: A Viable Alternative in China's Energy Supply. China: Lauder Institute; 2009.

[150] Ramde EW, Bagre A, Azoumah Y. Solar energy in Burkina Faso: potential and barriers. ISES Solar World Congress. Johannesburg2009. p. 1781-95.

[151] Tsoutsos T, Gekas V, Marketaki K. Technical and economical evaluation of solar thermal power generation. Renewable Energy. 2003;28:873-86.

[152] Trieb F. Competitive solar thermal power stations until 2010--the challenge of market introduction. Renewable Energy. 2000;19:163-71.

[153] Ramde E, Azoumah Y, Brew-Hammond A, Rungundu A, Tapsoba G. Site ranking and potential assessment for Concentrating Solar Power in West Africa. Natural Resources. 2013;Special issue.

[154] Maxwell EL, George RL, Wilcox SM. A Climatological Solar Radiation Model. Annual Conference, American Solar Energy Society Albuquerque NM.1998

[155] CGIAR-CSI. SRTM 90m Digital Elevation Database v4.1. 2003.

[156] NREL. Solar Electric Generating Station IX. 2012.

[157] Solúcar. 10 MW Solar Thermal Power Plant for Southern Spain. 2006.

[158] Selig M. PE1 - First fresnel solar power plant in operation Experiences and Outlook. 2009.

[159] Novatec-Biosol. PE 1 – World's first Fresnel Solar Power Plant in commercial operation. 2011.

[160] Gnansounou E, Bayem H, Bednyagin D, Dong J. Strategies for regional integration of electricity supply in West Africa. Energy Policy. 2007;35:4142-53.

# APPENDIX A

The irradiation data were obtained from the Climatological Solar Radiation (CSR) Model developed by the National Renewable Energy Laboratory (USA). This model uses information on cloud cover, atmospheric water vapour and trace gases, and the amount of aerosols in the atmosphere to calculate the monthly average daily total irradiation (sun and sky) falling on a horizontal surface. Existing ground measurement stations are used to validate the data where possible. The modelled values are accurate to approximately 10% of a true measured value within the grid cell due to the uncertainties associated with meteorological input to the model. The local cloud cover can vary significantly even within a single grid cell as a result of terrain effects and other microclimate influences. Furthermore, the uncertainty of the model increases with distance from reliable measurement sources and with the complexity of the terrain. The data provides monthly average and annual average daily total solar resource averaged over surface cells of approximately 40 km by 40 km in size. The solar resource value is represented as watt-hours per square meter per day for each month.

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## APPENDIX B

The CGIAR-CSI[5] GeoPortal is able to provide SRTM (Shuttle Radar Topography Mission) 90m Digital Elevation Data for the entire world. The SRTM digital elevation data, produced by NASA originally, is a major breakthrough in digital mapping of the world, and provides a major advance in the accessibility of high quality elevation data for large portions of the tropics and other areas of the developing world. The SRTM digital elevation data provided on this site has been processed to fill data voids and to facilitate its ease of use by a wide group of potential users. This data is provided in an effort to promote the use of geospatial science and applications for sustainable development and resource conservation in the developing world. Digital elevation models (DEM) for the entire globe, covering all of the countries of the world, are available for download at ftp://srtm.csi.cgiar.org/. The SRTM 90m DEM's have a resolution of 90m at the equator.

[5] CGIAR-CSI: Consultative Group for International Agriculture Research- Consortium for Spatial Information