GIS-based assessment of photovoltaic (PV) and concentrated solar power (CSP) generation potential in Cameroon using a Boolean method

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Abstract:

The negative environmental effects of traditional methods of electricity generation have created the need to plan and strategically develop renewable and sustainable energy production systems. This document presents the analysis of the suitability of solar park sites using a Boolean decision-making approach based on geographic information system (GIS) modeling. This analysis is based on different climatic, geographic, economic, and environmental criteria such as wind resource, slope, accessibility by roads, and proximity to the power grid. The land suitable for the installation of SPV solar parks is approximately 10.17% corresponding to an area of 47,331.18 km². However, when we include the condition that an SPV solar park must have at least 0.4km² of surface area, we go from 10.17% to 9.74% (i.e 47331.18 km² to 45329.96km²), a reduction in the area of approximately 2001.22 km². From this point, we note that SPV solar power plants can be installed in all regions of Cameroon. In addition, the regions of the Far North, the North, the Centre, the West, and the Coast abound with as many sites as possible for the establishment of SPV farms connected to the electricity grid. In addition, the land suitable for the installation of CPS solar parks is approximately 0.56% corresponding to an area of 2606.24 km². However, when we include the condition that a CPS solar park must have at least 2.2km² of surface, we go from (47,331.18 km² to 45,329.96km²), a reduction in the area of around 2,001.22 km². We note that only the northern regions (Far North, North, Adamawa) and a small area of the North-West and West regions are suitable for the installation of CPS plants in Cameroon. We recall that we have only evaluated the CSP and SPV solar power plants connected to the electricity grid and the various criteria and socio-economic constraints are valid for this scenario. We will soon be looking at the identification of suitable solar sites connected or not to the electricity grid with a multi-criteria analysis method.

Keywords: **photovoltaic (SPV), concentrated solar power (CSP), boolean, GIS, socio-economic parameter.**

1- Introduction

More than one billion people still live without access to electricity today. More than half of the people living without access to electricity are located in sub-Saharan Africa. There is an apparent shortage of energy information in Africa, particularly for renewable energy, due to lack of studies and research on the integration of renewable energy technologies *[1]*.Although renewable energies represent a significant part of the sources of electric power production in Cameroon (hydro-electricity), unconventional sources such as solar or wind energy did not represent a large part of their electric energy systems. The first step in promoting the use of these sources in the region is to identify the potential of each energy source, a task that can be completed using spatial tools such as geographic information systems (GIS) *[2].* There are many renewable energy supply strategies available for development and expansion, but for many countries the idea of possibly switching to fully renewable energy supply using domestic resources currently seems unworkable *[3].* Furthermore, it is well established that solar energy is a reliable alternative to reduce greenhouse gas emissions and mitigate the effects of climate change *[4]*Burning fossil fuels produces about three-quarters of the world's energy supply. However, the combustion of these fuels produces a considerable amount of pollutants, which will eventually harm the environment *[5]* Achieving the goal of temperature control requires a transition from the overall low-carbon energy structure *[6].* Nowadays, renewable energies are preferable to fossil fuels, because they are free, widely available, and produce minimal pollution. In addition, they are not accessible in all geographic positions. It is clear that renewable energy systems can be used to their full potential if used in the right place *[7]* As the global growth of renewable energy projects accelerates, site identification will become a priority, and a key element is to minimize the impact of development on the environment *[8].* Renewable energy sources are currently considered as alternatives to fossil fuels, because they are perpetual, respectful of the environment and emit only negligible quantities of greenhouse gases into the atmosphere while producing energy. A disadvantage of renewable energy sources is that they are not available in all geographic areas. Their use is mainly advantageous in remote places, often of great ecological value. Thus, the identification of preferable locations for renewable energy systems is a decisional problem that requires an assessment of the resource potential as well as economic and environmental constraints [9].

There is a huge shortage of solar resource assessments in Cameroon. As a result, the geographic adequacy of solar energy installations has hardly been studied in this region of the world. This is why the current study is tackling such a research gap by asking the following question: "What are the most suitable locations in Cameroon to build large-scale solar energy installations?". Answering to this research question will potentially help introduce solar energy as a renewable resource for extending electrification to millions of people who still do not have access to electricity.

Electrical installations are one of the most significant challenges faced by public service utilities and developers when it comes to the introduction and development of large-scale renewable energy production. This study aims to help decision-makers assess the areas suitable for large-scale solar energy installations by adapting a GIS-Bolean approach. The study contributes to existing knowledge in this area by introducing:
- the first study on the adequacy of large-scale solar energy based on the integrated GIS-Bolean approach in Cameroon,
- solar energy suitability maps (CSP and SPV) specific for a Cameroon-like technology, with a high resolution of 1 km * 1km, which represents the highest resolution for all large-scale solar energy suitability maps available in Cameroon.
- separate decision and criteria groups based on an in-depth knowledge of the local context in Cameroon.
- an easily approach applicable to other technologies using renewable energies once the corresponding criteria (representing the respective technology) has been carefully identified.

The objective of this study is therefore to find suitable areas for the establishment of SPV and CSP solar parks using Boolean method and socio-economic, technical and environmental criteria.

2. Literature review

Several studies have been done to identify suitable sites for the installation of renewable energy solar power plants in different countries.
[7] Use the Boolean method of GIS software to identify ideal locations for building wind power plants in the Middle East. They conclude that the results of their study could be useful in creating prospects for sustainable energy development for natural resource-based systems and in facilitating national policies on energy transport and the environment.
[1] Examine the spatial adequacy of large-scale solar installations in Tanzania using geographic information system (GIS) analysis combined with multi-criteria decision-making (MCDM) technique. The study identifies six exclusion criteria to shade inappropriate areas. A final technology specific suitability map classifies all of the non-excluded areas into the most suitable, suitable, moderately suitable and least suitable areas. The study also suggests four specific locations recommended for concentrated solar energy (CSP) installations and four locations for photovoltaic (PV) installations.
[10] Assess the usable potential of wind and solar energy for Afghanistan using a multi-criteria GIS decision analysis. Based on the zones, they estimated the wind and solar potential taking into account the technologies and conditions of the site. The total calculated annual production potential would be 342,521 GWh of wind energy, 140,982 GWh of solar photovoltaic energy and about 6,000 GWh of CSP (concentrated solar energy) representing 160 times the power supply in Afghanistan.
[11] Present estimates of geographic and technical potential for solar electricity production in rural areas of West Africa (ECOWAS region). The study is carried out by applying the methods of geographic information systems (GIS) and multi-criteria decision-making (MCDM). They are studying both the possibilities offered by large-scale solar systems connected to the grid (photovoltaic and concentrated solar technologies) and by off-grid solar systems (photovoltaic). The locations are assessed according to their suitability for deploying solar systems according to topographical, legal and social constraints, as well as factors likely to facilitate or prevent the development of solar production. They conclude that the results can be used to identify areas of potential interest for the deployment of solar production and to support integration between grid extension and off-grid electrification policies.
[12] Use a bottom-up approach taking into account the availability of solar energy and land resource constraints to assess the technical potential of CSP in Botswana. The potential of the CSP is estimated using land exclusion criteria based on a detailed geographic information system (GIS), and data on land use allowing to determine land suitability in the ten districts of the country. On the basis of the national solar map, information on direct normal irradiance (DNI) derived from satellites and data observed on DNI combined with human-induced biogeophysical and land use constraints, it is shown that Botswana has approximately 220,016 km2 of land to support CSP plants. They conclude

that an estimated nominal capacity of 3,389.54 TWh-1 or 363.86 GW could be adapted to the available area. They conclude that Botswana has a relatively large potential for CSP, capable of far exceeding current peak energy demand.
*[4] U*se the multi-criteria evaluation method to identify suitable sites for hosting photovoltaic projects in southern Morocco. Geographic information systems and analytical hierarchy process methods were combined to represent a high-resolution map comparing the potential of the study area to host large-scale photovoltaic projects. HOMER software was then used to model and simulate a PV system connected to the 10 MW network. The results of this study confirm that 24.08% of the study area offers suitable sites for hosting photovoltaic farms. The HOMER simulation clearly showed that the grid-connected photovoltaic system is beneficial in the long term, although its initial capital is greater than that of the grid supply. In addition, the cost of electricity generated by photovoltaic panels is affordable.

*[13] U*se geographic information systems and the analytical hierarchy process (AHP) to identify the location of solar farms in the Mediterranean. The methodology identifies the areas available for the location of solar farms, based on exclusion criteria defined in the legislation in force. The methodology developed uses different types of criteria, such as techno-economic and socio-environmental criteria, it takes into account the distinct opinions of different stakeholders and allows the evaluation of different scenarios. They are doing a case study of the Rethymno region. The results in terms of maximum potential power that can be produced from areas of maximum priority are estimated at 530 MWp for photovoltaic systems and 30 MW for concentrated solar energy systems.
*[14] U*se site suitability analysis to identify UK solar park locations to help achieve climate change goals. A set of maps, each representing a given relevance criterion, is created using geographic information system (GIS) software. These are combined to give a Boolean map of the areas suitable for the installation of a large-scale solar farm. Several scenarios are studied by varying the criteria, which include geographic factors (land use), solar energy resources and the constraints of the electricity distribution network. Some are dictated by the physical and technical requirements of large-scale solar construction and others by government or the policy of the distribution system operator. They note that any suitability card that does not respect planning authorizations and network constraints would overexploit up to 97% of the potential area of a solar farm. This study made it possible to find enough room suitable for future energy scenarios (the main lines of the British national network for the future energy landscape).
*[2] E*xamine a long list of GIS publications in order to select a methodology to identify areas suitable for the development of unconventional renewable energy projects (solar and wind) in the Republic of Ecuador (REP). The REP development potentials have been identified and classified into spatial layers according to their technology and location. These results show that solar photovoltaib is the most widely used technology in the country and has particularly significant potential in two regions: the Andes and the Insular region, in particular in the provinces of Loja, Pichincha and the Galapagos Islands.
[6] Build a GIS-based model with 600 land conversion factors incorporated to accurately estimate the potential for large-scale photovoltaic energy production in China. The results show a potential installed capacity of 1.41 × 105 GW, which corresponds to an annual energy production of 1.38874×10^{14} kWh, or 21.4 times the national electricity consumption in China in 2016. If this potential was fully exploited to replace the current energy based on fossil fuels in 2030, it would result in a reduction of the carbon intensity of China from 63% to 68% compared to 2005, which is enough to respect China's commitment to reduce CO2 emissions. At the provincial level, while the production potential of the northwest and inner Mongolia represents 86% of the total, the eight economically developed coastal provinces of China represent only 1%. To realize a maximum large-scale photovoltaic scenario in China in 2030, the capacity of interregional transport networks from the North West region and inner Mongolia to regions with insufficient potential should reach around 300 GW. Our study could provide policymakers with accurate information on China's large-scale photovoltaic energy map and on optimizing carbon reduction strategies and interregional energy transportation to achieve sustainable development.

[7] Are trying to find the ideal locations for the construction of hybrid solar-wind power plants in the Middle East using the Boolean model of GIS software. The Boolean method is somehow a stricter method compared to the other positioning methods. Consequently, the selected sites will certainly have a higher energy potential using the Boolean method. Data obtained by RETScreen4 software from 400 plants in the Middle East was used to collect monthly weather information. The results of this document could be useful for creating sustainable energy development perspectives for natural resource-based systems and for facilitating national energy transport and sustainable environmental policies.
[15] Use a GIS method combined with a multicriteria assessment to combine existing information on solar radiation with other geographic factors (slope, land use, urban area and population distribution, as well as proximity to electrical network) in order to generate a suitability map for photovoltaic (PV) power plants in the EU with high spatial

resolution. They do a matching exercise which shows that the resulting suitability map is a good predictor of suitable locations for the deployment of photovoltaic plants. They classify the regions according to their overall suitability for solar energy systems and solar investments allocated by the EU cohesion policy. Thanks to this study, they identify the potential mismatches between the allocation of funds and the current regional adequacy for solar energy. They recommend that future fund allocations take into account the criteria of adequacy of solar energy to optimize the results of public policies.

[8] Assess an area in the south of England (17,094 km2) in three stages to determine if it allows the development of wind and solar farms, using geographic information systems. A multi-criteria decision-making framework incorporating an analytical hierarchy process involving expert stakeholders was applied, which constitutes an innovative approach for this type of study. A binary constraint layer has been created, identifying totally inappropriate locations. A factor layer has been developed to indicate relevance to a range of variables. Layers of aptitude for the development of wind and solar parks were then created to cover the region. The environmental constraints used in the model represented more than 60% of the study area for wind and solar developments. Wind power adequacy was generally poor, with only 0.5 km^2 representing the "most suitable" category. The solar capacity was higher overall; and a larger area (294 km2) in the “most suitable” category, which suggests that the region is better suited to the development of solar farms. Stakeholder feedback resulted in a higher weighting of economic considerations for the solar model, which caused the most suitable areas to coincide with the locations of the national grid connections. A sensitivity analysis showed that the model was generally reliable. This method can be used to assist in the proper selection of sites for shore-based renewable energy projects in large geographic areas, helping to minimize their impact on the environment.
[16] Describe the development of a management and planning system on a GIS (Geographic Information System) platform for decision-makers, whether administrators, planners or consultants in renewable energy (solar systems) , biomass and wind turbines) in rural Brazil. The GIS tool covers an area of 183,500 km2 and is contains three blocks namely the management of installed renewable systems, the inclusion (planning) of new systems and the updating of databases. They are developing a PV system as a management and planning support tool to include large-scale solar photovoltaic energy in rural areas, led by the Ministry of Mines and Energy of Brazil.
[17] Develop a two-step framework for the analysis of land suitability for solar farm operation using GIS and the fuzzy analytical hierarchy process (FAHP) in Iran. In the first step, the map of inappropriate regions is extracted according to the defined constraints. In the next step, in order to identify the suitability of different regions, 11 criteria defined, including solar radiation, average annual temperatures, distance from power lines, distance from main roads, distance from residential area, elevation, slope, land use, mean annual cloudy days, mean annual humidity and mean annual dusty days are identified. The data obtained indicates that 14.7% (237,920 km2), 17.2% (278,270 km2), 19.2% (311,767 km2), 11.3% (183,057 km2), 1.8% (30,549 km2) and 35.8% (580,264 km2) of Iran's land area is positioned as excellent, good, fair, low, bad, and inappropriate areas, respectively.

[9] Present a methodology for the on-site selection of hybrid wind-solar-wind-photovoltaic energy systems in Turkey. First, the objectives of environmental acceptability and economic feasibility are identified by a full review of the Turkish literature, laws and legislation in force and interviews with the Director General of the Turkish Administration for Investigation and Electric Resource Development. Secondly, locations that are viable in terms of environmental acceptability and economic feasibility are determined by a fuzzy decision-making procedure that uses an orderly weighted average algorithm to aggregate multiple objectives. Then, priority sites are identified separately for wind and solar energy systems using a geographic information system (GIS). Finally, the associated maps are superimposed to obtain the most realistic locations for hybrid solar-PV wind systems.

2.Theoretical background

2.1. Photovoltaic technology overview Solar

The photovoltaic effect was discovered in 1839 by the French physicist Becquerel. A solar panel works by the photovoltaic effect, which is to say by the creation of an electromotive force linked to the absorption of light energy in a solid. The photovoltaic cell is the basic building block of photovoltaic solar panels. The development of solar photovoltaic technology has been progressing very rapidly in recent years due to technological improvements, lower material costs, and government support for the production of electricity from renewable energy. Photovoltaic technology plays an important role in the use of solar energy for power generation worldwide. The efficiency of solar cells is one of the important parameters for the establishment of this technology on the market.

Solar photovoltaic (PV) technology is based on PV cells allowing the direct conversion of solar radiation into electricity. Nowadays, photovoltaics can be considered as a mature technology, from a technical and economic point of view. The photovoltaic market experiences an annual growth of 35% to 40%, making it one of the most expanding renewable energy technologies. The efficiency of PV technology has improved considerably in recent years. The nominal efficiency of a monocrystalline silicon solar cell was around 15% in the 1950s and is currently increasing to 28%. The performance ratio of modern PV systems exceeds 80% (with maximum values around 90%) but lower values between 70% and 85% for monocrystalline and polycrystalline systems are also reported. Photovoltaic technologies are implemented in systems connected and not connected to the network. Systems connected to the network can be widely distributed. Large-scale photovoltaic systems have a capacity ranging from 10 MW to more than 100 MW and generally require an area greater than 0.4 km². One of the advantages of these systems is the economy of scale. Distributed systems connected to the network make it possible to develop the potential of solar energy in built-up areas (i.e. systems mounted on the roof). Off-grid systems can supply energy to a single consumer or to several consumers via a midi network (without connection to the main lines of the electricity network). Off-grid systems provide opportunities for supplying electricity to remote areas while avoiding costly investments in distribution and transmission systems.

2.2. **Concentrated solar power technology overview**

Concentrated solar energy (CSP) technology use mirrors which transform solar energy into heat which is then converted into electricity using steam turbines, gas turbines or Stirling engines. The CSP market is currently developing, mainly in Europe (with Spain) and in the United States. Types of CSP installations include parabolic troughs, power towers, parabolic type systems, and Fresnel eggplant technology. These technologies differ in investment costs, land requirements and efficiency gains. Parabolic gutter systems dominate the CSP market. In 2010, parabolic trough technology represented 100% of the CSP plants in operation and under construction and 75% of the planned CSP plants. The “solar-electricity” yields of CSP technologies are linked to the evolution of CSP technologies and Field conditions. In particular, the efficiency of CSP plants strongly depends on the level of solar irradiance. One of the advantages of CSP technology is the presence of a thermal intermediary, which offers possibilities for thermal storage and hybridization with fossil fuels. Among the disadvantages are the high demands in land and water (except in case of dry cooling).

2.3. **Definitions of solar power potentials**

The solar production potential can be classified into 4 categories: geographic, technical, economic and environmental. The geographic potential of solar production in a selected area can be defined as the amount of total annual solar radiation available in that area, taking into account existing geographic constraints (for example, land covered by forests or bodies of water). The technical potential of solar production in a given area can be defined as the amount of geographic potential in that area that can be converted into electricity, taking into account the technologies available in solar energy. Economic potential represents the technical potential that could be realized in practice at a cost compatible with conventional sources of electricity. And the environmental potential helps protect our environment by respecting environmental criteria.

3. Description of study area, data and methodology

3.1. Study area

3.1.1. Presentation of Cameroon

Located between the equator and the tropics, Cameroon, situated at 6° north latitude and at a longitude of 12° E, has got the form of a triangle with an area of 475 650 km² (Land: 98.8%; Water: 1.2%) Surrounded by Lake Chad, the Atlantic Ocean, and the Congo Basin, it borders on Chad, the Central African Republic, Congo, Gabon, Equatorial Guinea and Nigeria. The relief of Cameroon is very diverse: We have in the western part of the country, wooded hills as well as a long chain of mountains dominated on all the Atlantic coast by Mount Cameroon (4095 m). In the center, altitude pastures in the Adamaoua massifs 2,500m high. In the North, the savannah is dominant as well as some mountain ranges (the Mandara Mountains) on the border with Nigeria. In the South, tropical forests and swamps. The country is subdivided into 10 administrative regions: the Far North (Maroua); the North (Garoua); Adamaoua (N'gaoundéré); the East (Bertoua); the Center (Yaoundé); North West (Bamenda); the South West (Buea); the West (Bafoussam); the Littoral (Douala); and the South (Ebolowa). Linguistically, the population is bilingual (English and French are the official languages), mostly French-speaking (80%) and an English-speaking minority (20%). It is estimated at just over 15 million souls. it is also unevenly distributed with an estimated density of about 10 inhabitants per km2 in the south-east and greater than 100, with peaks at 200 in the western area. 56% of the population is under 20 and around 50% of the total population live in urban areas, with around 50% in the cities of Douala (economic capital) and Yaoundé (administrative and political capital).

3.1.2. Context of electric power in Cameroon

The Cameroonian electricity production park includes three hydroelectric power stations, 9 thermal power stations connected to the network, and several isolated thermal power stations. Hydroelectric power generation accounts for the bulk of national production. *Fig.1* shows the energy map of Cameroon. A description of the data used in this study is listed in *Table 1* along with the type of format used and the different sources of this data.

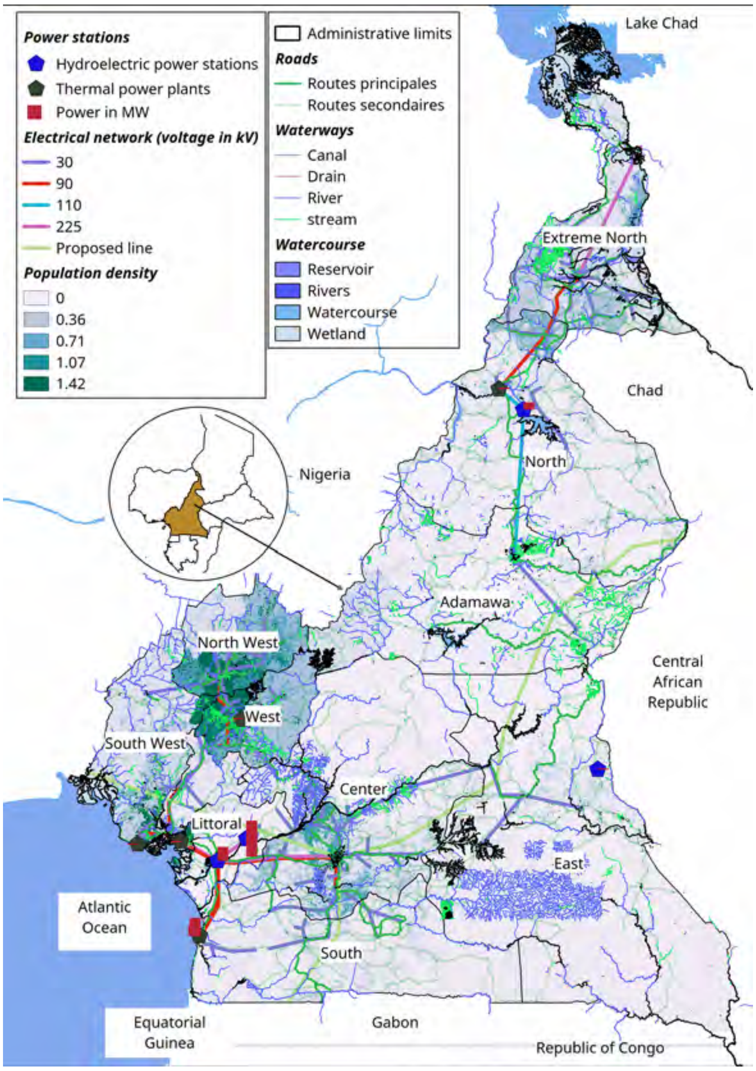

Fig.1: Energy map of Cameroon (Source: Worldpop 2010, OSM 2018, World Bank 2018, GADM 2018)

Table 1 : Description of study data

Data	Types (format)	Georeferenced	Sources
Administrative boundaries of Cameroon (regions, departments, districts)	Vector (shapefile)	yes	GADM
Long-term annual average of the global horizontal irradiation (GHI) and the normal irradiation (DNI) in kWh / m² / year, covering the period 1994-2015	Raster (1km²)	Oui	Solargis, World Bank, ESMAP
Population density map in Cameroon	Raster (1ha)	yes	Worldpop
Electric plants map in Cameroon	Vector (shapefile)	yes	World Bank

Hydrological map of Cameroon (water course, navigable water course, rivers, fleuves, wetlands, reservoirs…).	Vectoriel (shapefile)	yes	OSM
Lands occupation map in Cameroon	Vector (shapefile)	yes	OSM
Road network (inter-states, primary, secondary… roads) in Cameroon	Vector (shapefile)	yes	OSM
Electric network map in Cameroon	Vector (shapefile)	yes	World Bank
Evaluation map in Cameroon	Vector (shapefile) ou raster	yes	USGS/NASA SRTM data.
Monthly average temperature map over 12 months from 1970 to 2000 in Cameroon	Raster (1km²)	Yes	Worldclim version 2.0

3.2. Data description of solar farm

3.2.1. Solar resources

Solar radiation is the main resource for solar energy technologies. According to NASA's Surface Meteorology and Solar Energy Department, DNI is the primary resource for CSP technologies. GHI meanwhile includes both DNI and DIF (Horizontal Diffuse Irradiation), i.e. solar radiation which does not follow a direct path of the sun, but which has been dispersed by particles and molecules in the atmosphere and which therefore comes from all directions. Sites with high potential for solar resources will have a significant impact on the economic feasibility of large-scale solar energy installations. It is therefore essential to take into account the locations with high DNI for CSP installations and the locations with high GHI for PV installations Information on solar resources in Cameroon is based on data provided by the World Bank Group's Energy Sector Management Assistance Program (ESMAP). Solar irradiation data has a spatial resolution of 5 km*5 km. While CSP plants can operate at an annual level of 1,800 kWh/m^2 for DNI and large-scale photovoltaic plants can operate at an annual level of 1,700 kWh/m^2, the site of the plant becomes much more technically and economically favorable with increasing radiation levels. Table 2 shows the different thresholds for the DNI and the GHI.

3.2.2. Distance from electrical network

Long transmission lines between solar parks and the grid are associated with wiring costs and loss of electricity. The solar parks must be located near the electrical network. One of the biggest problems in reducing the cost of building solar parks is reducing the cost of building energy transmission infrastructure. When choosing the location, it is necessary to take into account the availability and access to the existing electrical network. For the current analysis, the maps of the national power grid and the power plant are extracted from the Eneo electrical data register. ENEO is a national electricity company responsible for managing electrical energy in Cameroon. In this study, a distance of 10km around the electrical network was taken as an area suitable for the establishment of solar parks. However, a safety distance of 250m is observed between the solar park and the power lines. The data relating to the electrical network comes from the World Bank 2018.

3.2.3. Distance from residences

Residential areas in general and areas located less than 2km from residential areas are not suitable for setting up a solar park. Due to the various adverse environmental impacts on populated centers and growing residential areas, distance from residential areas is considered to be one of the important criteria in the selection of PV and CSP solar park sites. In addition, regions more than 45km *(A. Aly et al.,2017) [1]* away from populated centers are considered inappropriate areas for establishing solar farms. However, these buffer distances are different in different studies and their selection must be justified on a case-by-case basis by the national planning authority. It is important that the locations of the solar parks are at a reasonable distance from the settlement areas in order to minimize transmission losses. Residential area data is obtained from Open Street Map (OSM, 2018). The safety distance is 2km around residential areas.

3.2.4. Distance from roads

To minimize the costs of building and maintaining solar parks, it is necessary that the distance between the location of the proposed solar park and the road network be as small as possible. In most solar park location assessments, the furthest areas from the roads are considered less suitable than those closer. However, there is no generally valid definition of a maximum distance between solar parks and the road network. The specific nature of transporting equipment for the installation and subsequent maintenance of solar panels is reflected in the need to secure the road network at the location of the solar park, by making the most of the existing road network. In order to reduce transport costs, it is preferable that the distance from the road be as small as possible. We took a distance of 10km around the roads as a suitable area for the installation of wind power plants. However, a safety distance of 500m is observed between the solar park and the road network. Road data is from Open Street Map 2018.

3.2.5. Population density

Since electrical energy is not stored and generates enormous losses during its transport, it would be desirable to locate solar sites not very far from densely populated areas. However, the dangers caused by solar parks require their construction far from densely populated areas. In this study, we have taken as suitable sites areas with less than 500 inhabitants per km² or less than 5 inhabitants per hectare.

3.2.6. Slope

Accessibility for installation and maintenance in solar parks is hampered by the steep slope of a plot. In the literature, the maximum authorized slope threshold ranges from 1% to 10% for the CSP and from 10% to 20% for the SPV. Due to the additional costs of construction and maintenance, the topography with steep slopes is generally considered unsuitable for the development of wind farms. In the physical sense, solar parks must be located in suitable locations. Areas with steep slopes are generally considered less suitable due to the additional construction and maintenance costs. In this study, slopes of 2% and 10% were respectively taken as the maximum threshold for the CSP and the SPV. The elevation map from which the slope is drawn is from USGS / NASA SRTM data.

3.2.7. Distance from protected areas

In order to avoid or reduce the negative impact on the environment, it is desirable to place solar parks outside protected areas. In this study, the protected areas are parks, forests, nature reserves, etc. A distance of 100m was also taken as a safety zone around lakes, rivers and wetlands for the SPV and CSP parks. However, CSP parks need to be at a maximum distance of 10km from watercourses because, we need water to maintain the CSP panels. Land cover data are from OSM 2018.

3.2.8. Altitude

In the physical sense, solar parks must be placed in suitable locations. Areas with high altitudes are generally considered to be less suitable due to the additional construction and maintenance costs. In this study, an altitude of maximum 4km was taken as the threshold. The elevation map is from USGS / NASA SRTM data.

3.2.9. Plant required

We remind here that we are installing solar power plants and not solar panels for the power supply of a house or other. These solar power plants will be connected to the national electricity grid in order to increase production. The areas required for the installation of an SPV and CSP solar park are areas of minimum 0.4km² and 2.2km² respectively.

3.2.10. Temperature

The solar panel is one of the components of photovoltaic systems. For the system to provide the required energy, it must be properly designed. One of the questions that influence the determination of the size of the required panel is its efficiency. The efficiency of solar panels depends on their temperature, and the temperature of the panel itself is a result of the ambient temperature and the intensity of the solar radiation. The performance of modules in PV systems decreases with increasing ambient temperature. For each 1°C increase in cell temperature at temperatures above 25°C, the amount of energy generated decreases from approximately 0.4% to 0.5% *[16]*. *Fig.3* shows the distribution of the different input data from our study. These are the spatial distribution of the electricity network, roads, the potential of the GHI and DNI solar resources, rivers, altitude, slope, protected areas, residential areas and the population density.

3.3.Methodology

3.3.1. Geographic Information System

GIS (Geographic Information System) have been used as a research and application tool since the 1970s. It relates to a number of academic fields, including wind technology. GIS are designed to store, retrieve, manipulate, analyze and map geographic data [18]. Raster and vector are the two types of coverage representation with which GIS work. The raster is represented by a rectangular grid called pixels which contains specific information based on a specific geographic location. The vectors manage a geometric figure (points, lines and polygons) defining the limits associated with a reference system. The storage of this information is presented in a geodatabase which provides order, structure and normalization of the data. All geographic information has been treated as a raster in this research, due to the continuous analysis of spatial variables such as wind speed, terrain altitude and vegetation cover, among others. GIS is a powerful tool for collecting and organizing spatial data, with many successful examples of potential sites for renewable energy production appearing [18] ,[19]. The raster processes are faster in evaluating problems, including mathematical combinations such as Boolean methods. The Boolean method in a GIS environment is based on criteria represented by a layer of geo-referenced cartographic information; therefore, each point of the territory received a value concerning the activity of the object of the decision which is 0 for not appropriating and 1 for appropriating. The free software GRASS GIS.7 and QGIS 2.18 were used to pixelate and normalize the data layers in this research. With this starting point and the generated entries, the statistical calculations were also made in GRASS and the layout of the figures in QGIS.

Fig.2 presents the design flowchart for our study with the various maps needed for this study as input and the maps obtained after applying GIS processing.

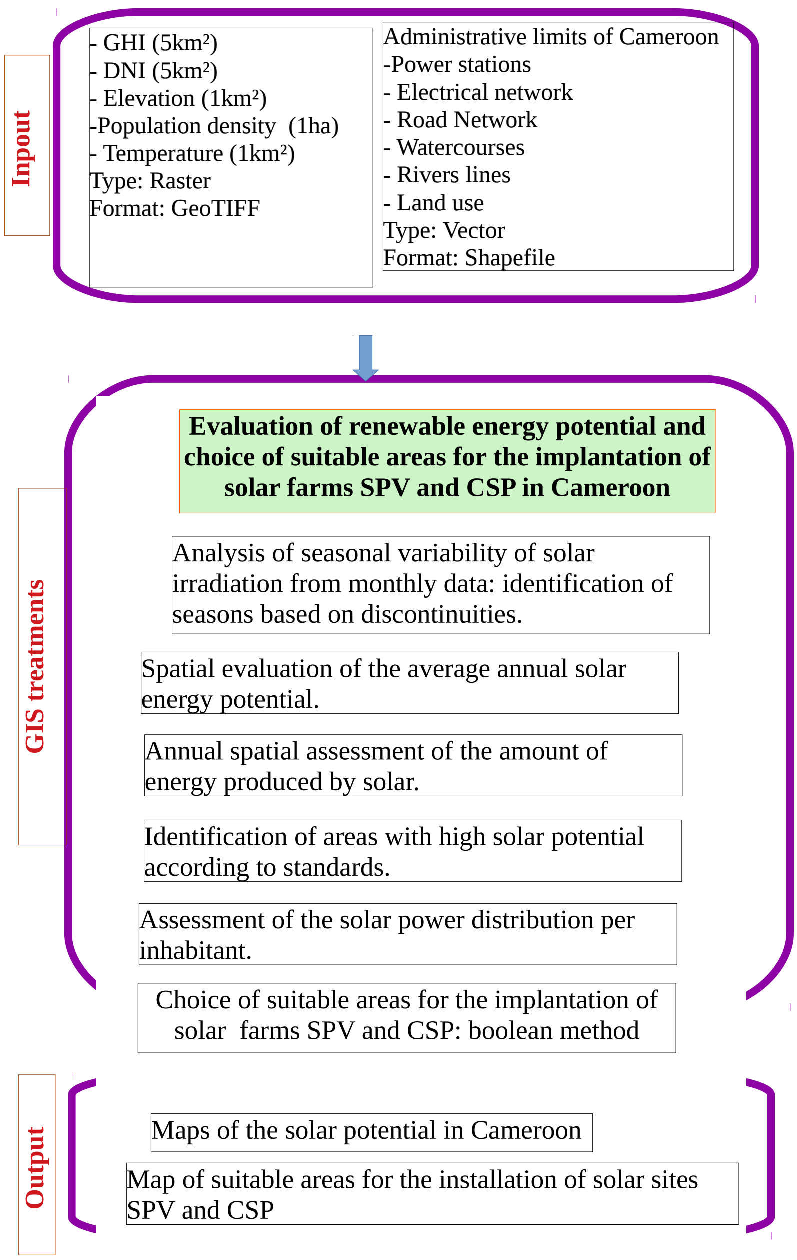

Fig.2: Design diagram

3.3.2. Boolean logic

The Boolean logic model is the easiest way to combine layers in a GIS. The combination of layers in this method is based on the zero-one law, and the final result of the model is a map divided into two classes that is totally appropriate (class 1) and totally inappropriate (class 0). This model has low flexibility and great rigor. Once the layers have been formed on the basis of the Boolean model, the layers obtained are combined using the AND operator by multiplying layers in raster layers. The AND operator, based on an intersection logic working in raster layers, is as follows: if the two input values are true, the output takes a value of 1 and if an input value is false and that the other is true, the relevant cell includes 0 in the output *[20]* .

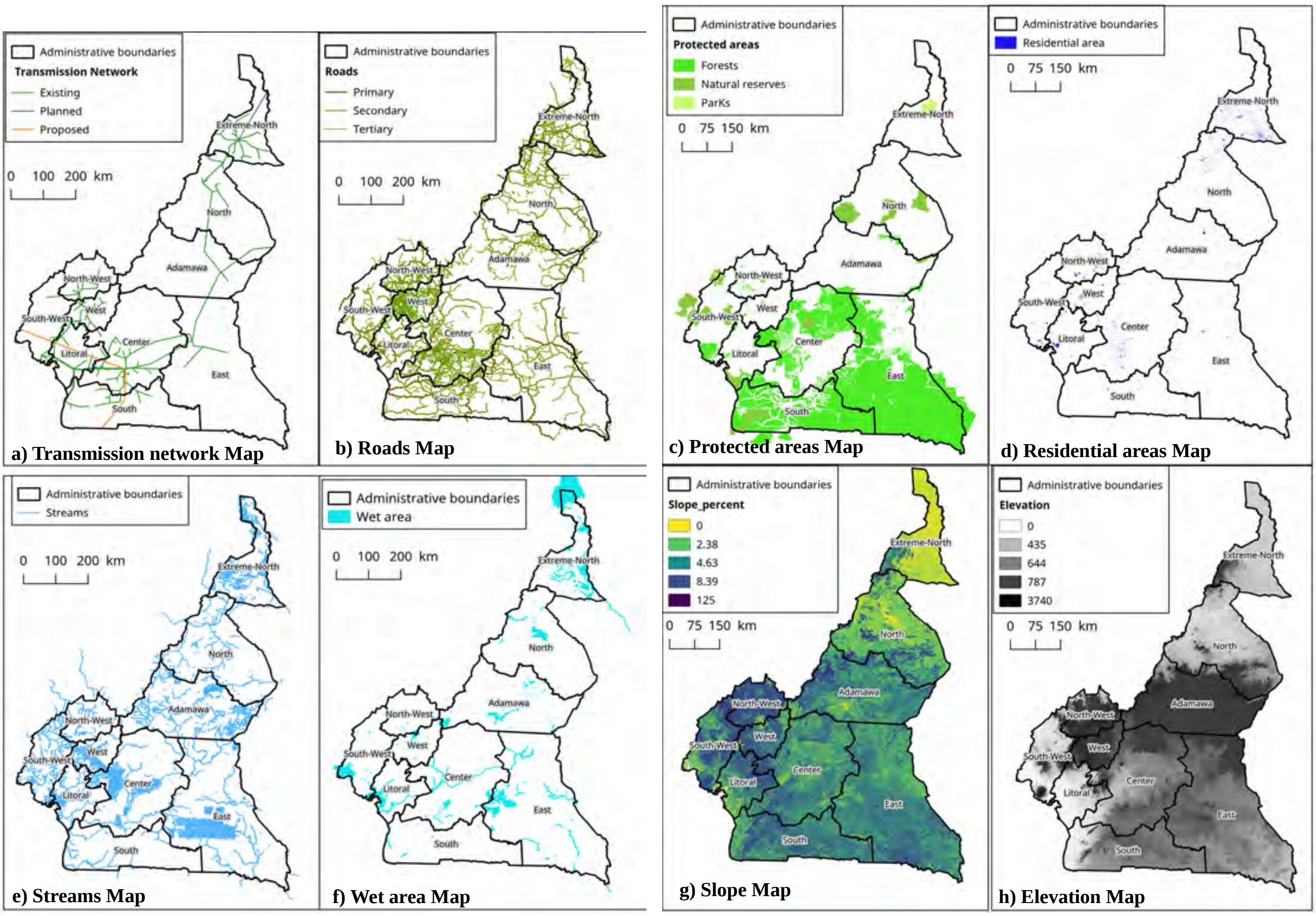

Fig.3: Evaluation Data

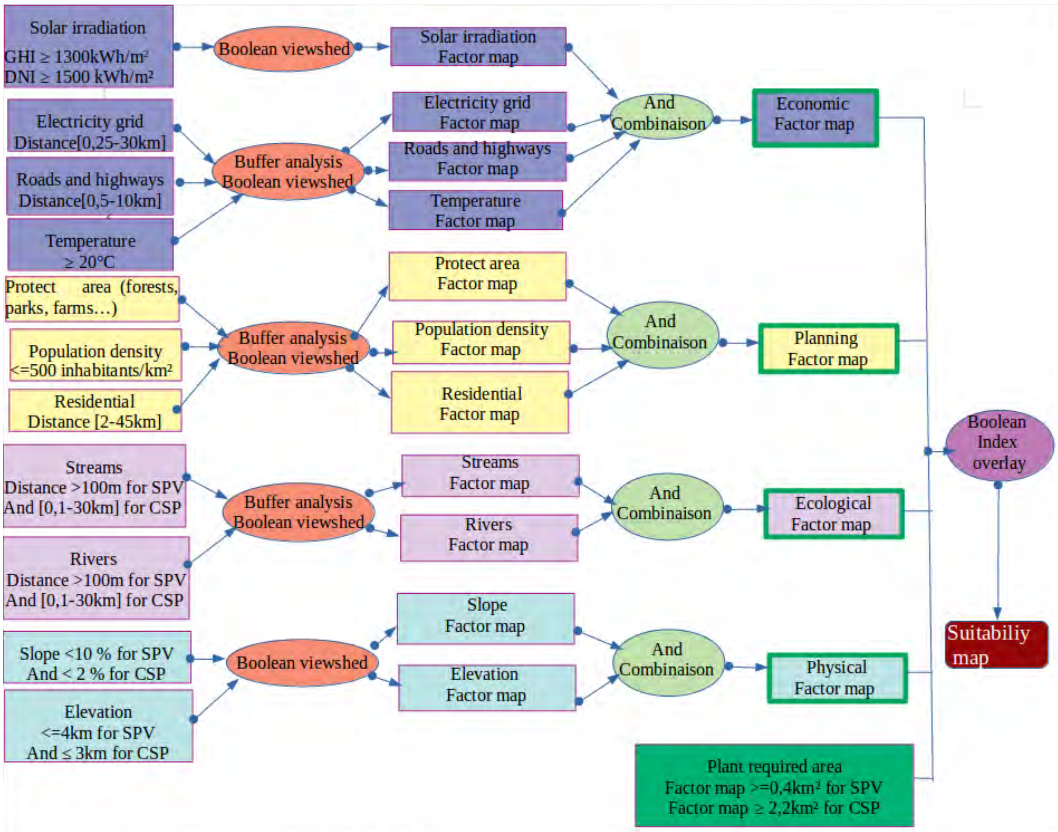

Fig.4: GIS based model solar SPV and CSP farm site selection

Fig.4 shows in a more detailed way the differents steps, and the related treatments to obtain appropriate sites for the implantation of SVP and CP solar using the SIG. *Table 2* displays necessary criteria for the present study and the sites appropriate for SVP and CSP.

Table 2 :Restriction criteria from chosen solar farm (SPV and CSP) site selection studies.

		Economic				Planning			Ecological		Physical	
	Plant required area	Ressources potential	Temperature	Buffer distance/ proximity from electricity grid	Proximity /buffer to roads & highways	Protect area (forests & parks…)	Population density, Minimize density	Buffer distance/ proximity from residential	Buffer distance from streams	Buffer distance from rivers	Slope	Altitude
SPV	>=0,4 km² [10]	Annual global horizontal irradiation (GHI) ≥ 1300 kWh/m² [10]	>=20°[17]	>250 m and <=30 km[2]	>500 m and ≤10 km [2]	Not within protect area [2]	<=500 inhabitants /km² (5 inhabitants/ha) [11]	>2 km and <45 km [1]	>=100 m [10]	>=100 m [10]	<10 % (5,71°) [11]	<=4km[2]
CSP	≥ 2,2 km² [10]	Annual direct normal irradiation (DNI) ≥ 1 500 kWh/m² [2]	>=20°[17]	>250 m and ≤30 km [2]	>500 m and ≤10 km [2]	Not within protect area [2]	<=500 inhabitants /km² ((5 inhabitants/ha) [11]	>2 km and <45 km [1]	>=100 m and ≤10 km [10]	>=100 m and ≤10 km [10]	<2 % (1,15°) [11]	<=3km[2]

4- Results and discussions

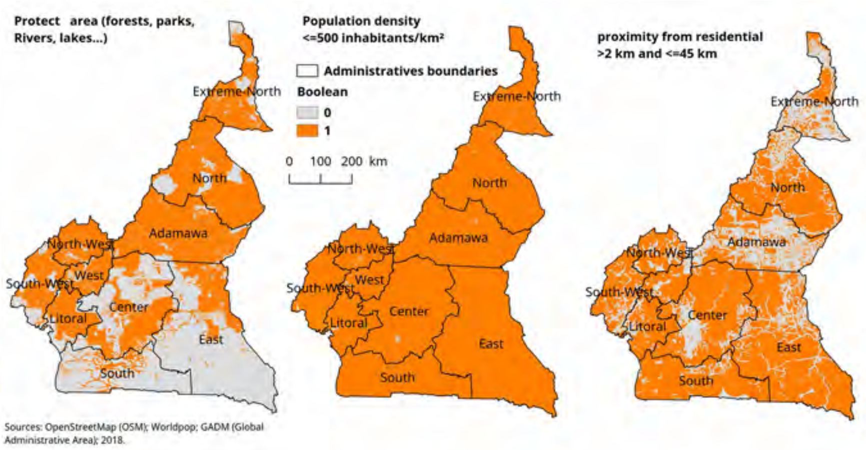

Fig.6: Planning criteria from chosen solar farm

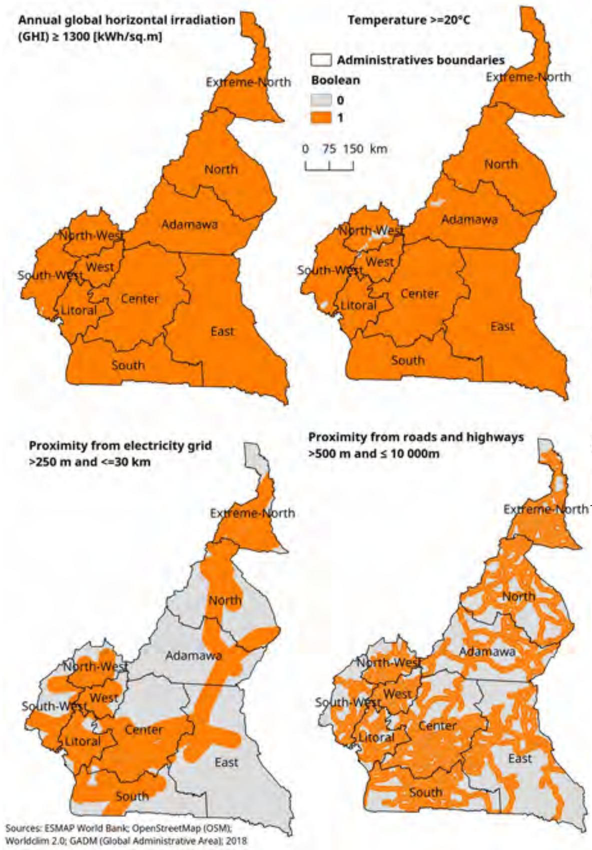

Fig.5: Economic criteria from chosen solar farm

Fig.5 presents the economic criteria grouping GHI solar irradiation ≥ 1300kWh / m², temperature> 20 ° C, safety buffers of 250m around road networks and a distance of 30km as an area suitable for the establishment of SPV and CSP solar power plants; in economic criteria, we also have proximity to road networks, ie 10,000m around road networks with a safety distance (buffer of 500m). We can also note from this F*ig.5* that all of Cameroon has the irradiation required for the installation of SPV solar power plants. However, to identify suitable sites for the installation of these SPV solar power plants, other criteria must be taken into account.

Fig.6 presents the planning criteria corresponding to suitable sites for SPV and CSP solar power plants. In this figure 6 we have the protected zones namely the forests, the parks, the rivers… we note that the regions of the South, the East and the Center are covered in great majority by the protected zones mainly the forests. These protected areas are not suitable for solar power plants. Since solar power plants must be built in the least populated areas, we note in *Fig.6* that a large area of Cameroon has less than 500 inhabitants per km². Furthermore, even if solar power plants are to be built in sparsely populated areas, they will still need not to be far from residential areas because, transporting electricity comes with additional costs and losses. We have then in F*ig.6* created a buffer of 2 km (safety distance) at the level of the residential zones, however, the solar power plants must be within a radius of 45 km of the residential zones in order to optimize the yield and reduce the costs.

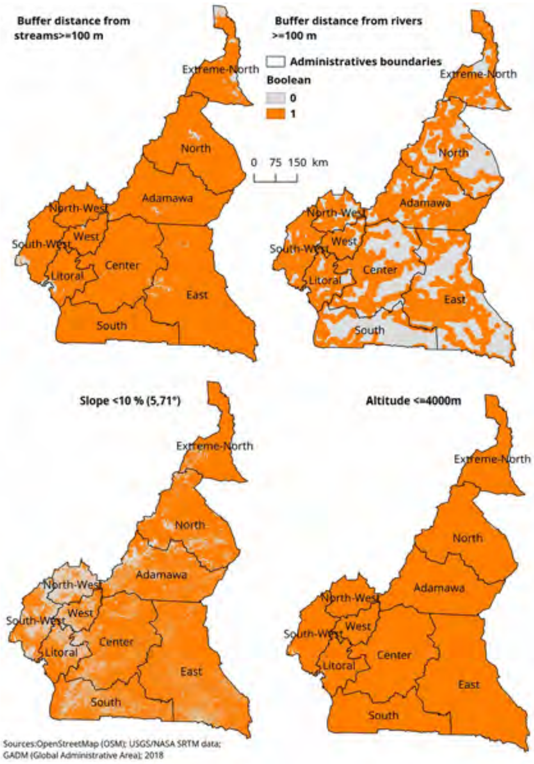

Fig.7: Ecological and physical criteria from chosen solar farm SPV

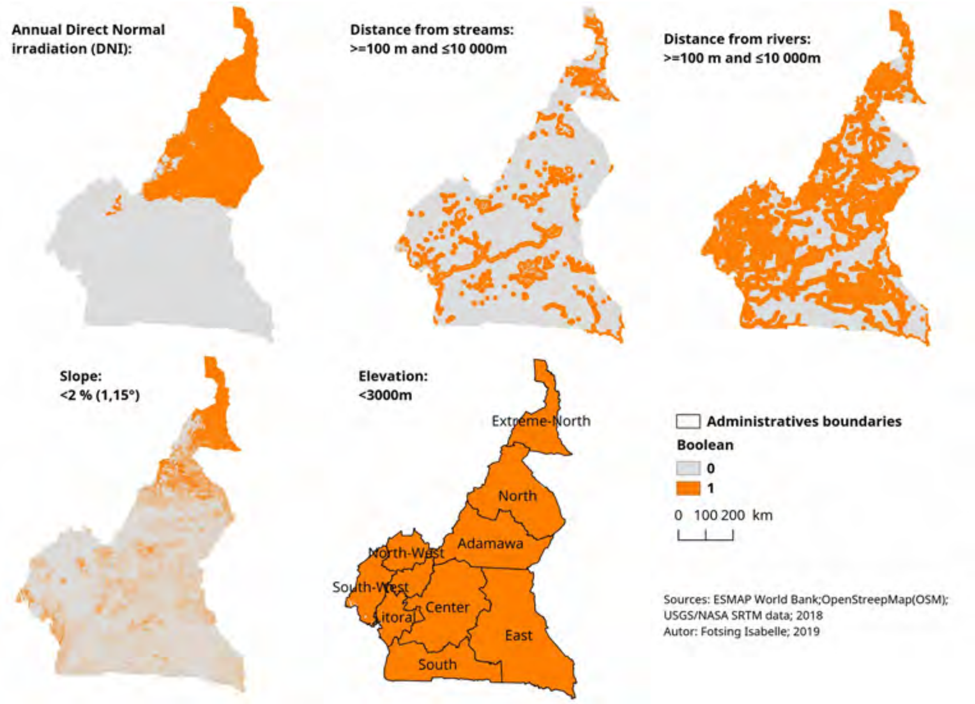

Fig.8: Economic, Ecological and physical criteria from chosen solar farm CSP

Fig.7 shows the physical and ecological criteria for the construction of SPV solar power plants. For rivers and streams, we have created a safety distance of 100m (buffer 100m) around them. Slopes <10% and altitudes <4000 m are also shown in this Fig.7. We can note that Cameroon has an altitude <4000m which suits perfectly for the construction of SPV solar power plants. Fig.8 presents the economic criteria (DNI solar irradiation), ecological and physical criteria for CSP solar power plants. We note that only the great North (Far North, North and Adamawa) and a small part of the North West are suitable for the establishment of CSP solar power plants. Furthermore, a safety distance of 100m must be observed for rivers and streams. However, CSP solar power plants need water for the maintenance of cylindrical-parabolic concentrators. They will therefore have to be at a maximum distance of 10km from streams and rivers. Speaking of physical parameters, we took a slope <2% and an elevation <3000m. We note in Fig.8 that Cameroon has an altitude of 3000m throughout its territory which is perfectly suitable for the construction of solar power plants. However, several techno-economic and environmental parameters are taken into account when choosing suitable sites.

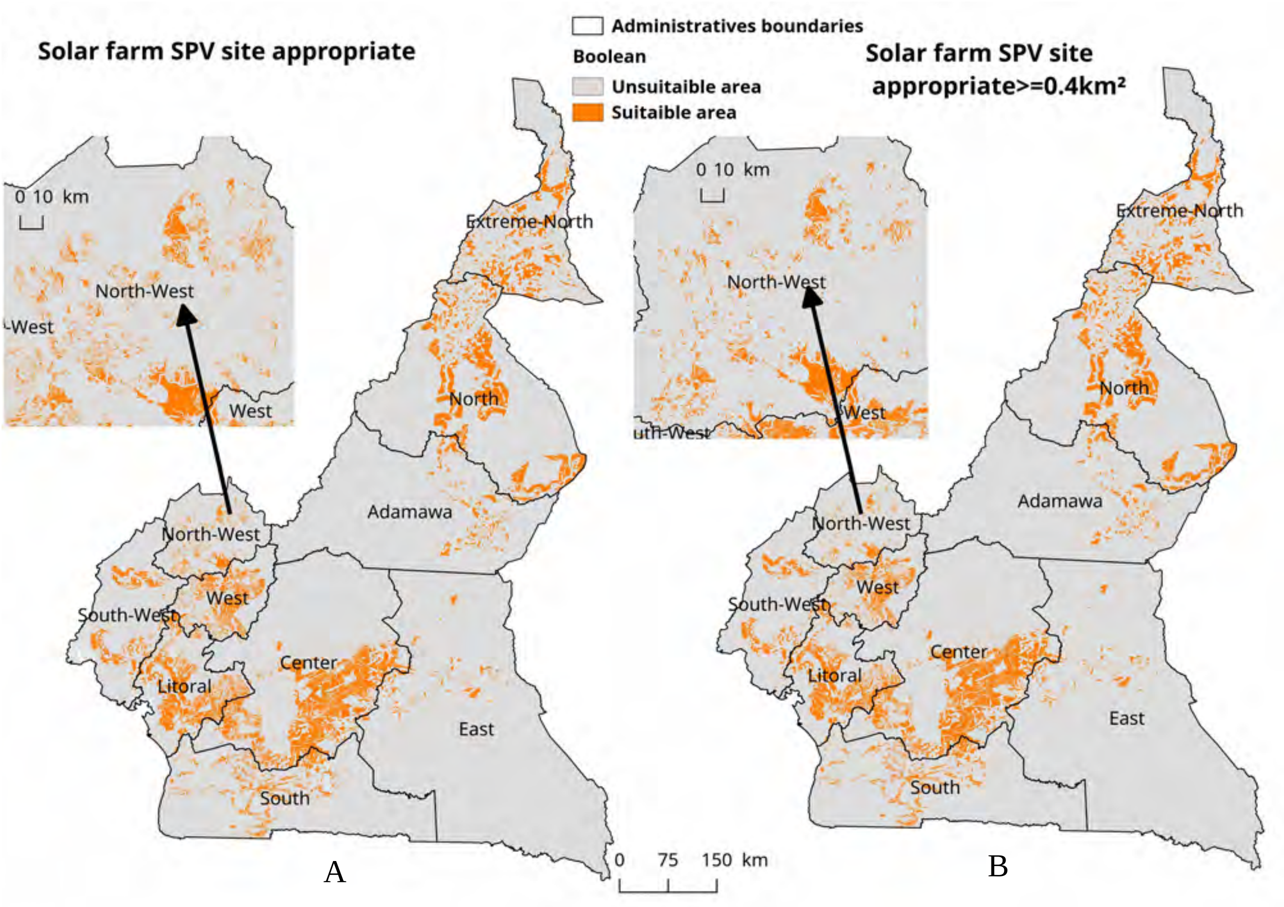

Fig.9: Suitability maps for Solar farm SPV (A) and Solar farm SPV ≥ 0.4km² (B)

Fig.9 presents the final map after combining the various economic, planning, physical and ecological maps for the sites suitable for the installation of SPV solar power plants.

The suitable land for the installation of SPV solar parks is approximately 10.17% corresponding to an area of 47,331.18km² F*ig.9.* However, when we include the condition that an SPV solar park must have at least 0.4km² of surface [10], we go from 10.17% to 9.74% (47,331.18 km² to 45,329.96km²), corresponding to a reduction in area of approximately 2001,22 km² from *Fig.9A* to *Fig.9B*. From *Fig.9*, we see that SPV solar power plants can be installed in all regions of Cameroon. In addition, the regions of the Far North, the North, the Center, the West and the coast have plenty of sites suitable for the establishment of SPV farms connected to the electricity grid. A study will be made soon by including sites not connected to the electricity network with a multi-criteria analysis methodology.

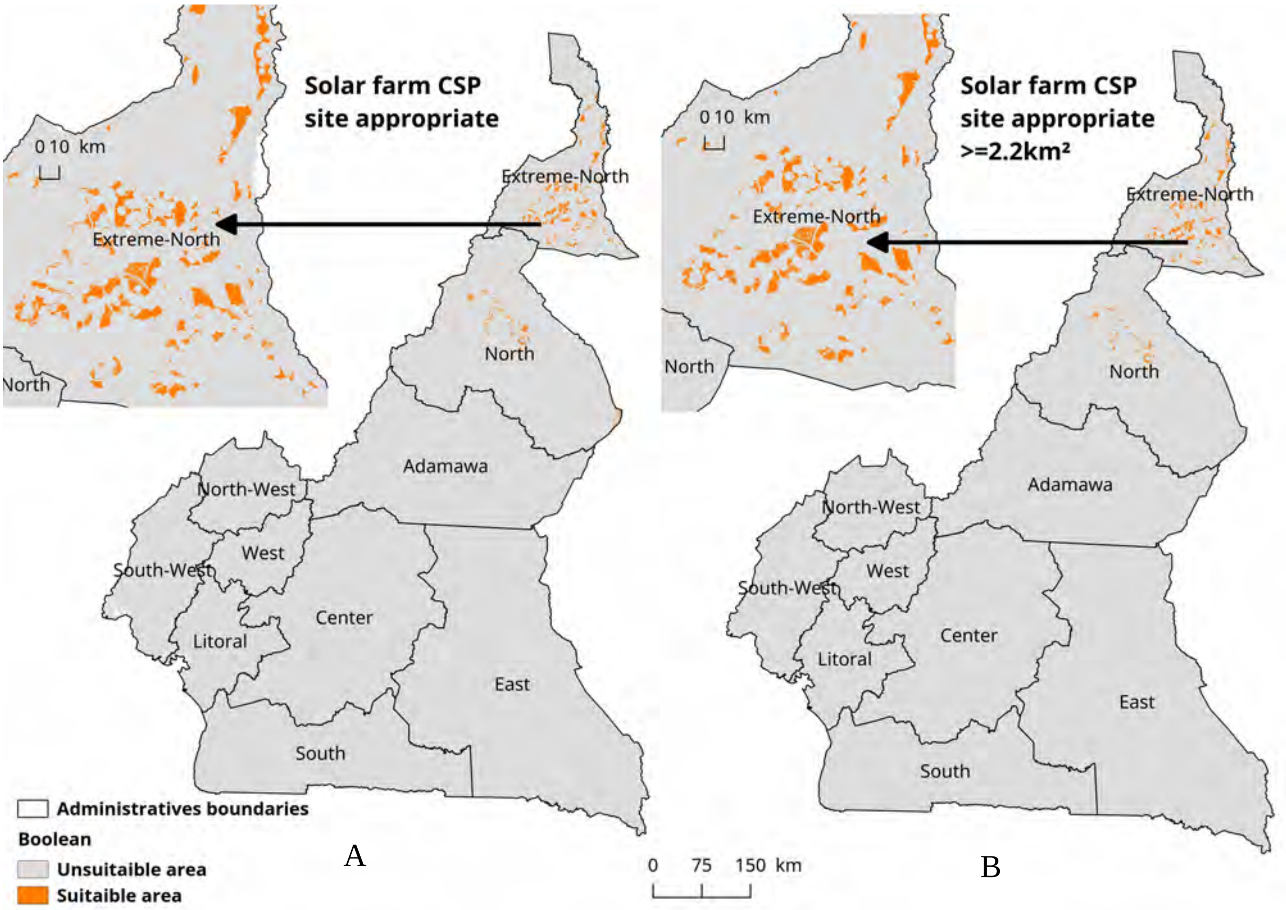

Fig.10: Suitability maps for Solar farm CSP and Solar farm CSP ≥ 2.2km²

Fig.10 presents the final map after the combination of the different economic, planning, physical and ecological maps for the sites suitable for the establishment of CPS solar power plants.

The land suitable for the installation of CPS solar parks is approximately 0.56% corresponding to an area of 2606.24 km² F*ig.10A*. However, when we include the condition that a CPS solar park must have at least 2.2km² of surface [10], we go from 47,331.18 km² to 45,329.96 km². Consider a reduction in area of around 2,001.22 km² from *Fig.10A* to *Fig.10B*. From *Fig.10*, we find that only the regions of the far North (Far North, North, Adamawa) and a small area of the North-West and West regions are suitable for the installation of CPS power plants in Cameroon. We recall that we have only evaluated the solar power plants connected to the electricity grid and the various criteria and socio-economic constraints are valid for this scenario. We will soon be looking at the identification of suitable solar sites connected or not to the electricity grid with a multi-criteria analysis method.

The problem of locating suitable sites for the installation of SPV and CSP solar power plants is its complex approach, because different and often contradictory criterion have to be taken into account in order to find the most suitable location zones. For example, an environmental criterion relating to the location of solar energy installations, such as the distance from areas of environmental interest, the purpose of which must be maximized, may in some cases contradict the criterion of distance from the road network, which is a techno-economic factor intended to be minimized. Therefore, the main objective of site selection studies suitable for the establishment of SPV and CSP solar sites is to find the most suitable locations to minimize impacts on the natural and human environment and maximize economic and technical potential.

This study addressed the problem of the location of solar energy installations, using GIS and the Boolean method. Therefore, a dynamic methodology has been developed to find sustainable settlements that can accommodate SPV and CSP farms. The adopted methodology was applied in the case study of the regional unit of Cameroon and allowed:

- the identification of legally available localization areas, after revision of the corresponding legislation
- the evaluation of the available sites of establishment, on the basis of technical-economic and socio-environmental criteria.

- the classification of each evaluation criterion in a two-category priority scale, after a rigorous bibliographic analysis, to determine the relative importance of the criteria, by implementing the Boolean method.
- the identification of sustainable implantation areas, after the production of priority maps with a Boolean method of the selected criteria

The results of the methodology adopted, for Cameroon, in terms of coverage of the most priority sustainable implantation areas are 9.74% for SPV photovoltaic parks and 0.56% for CSP parks. Therefore, the main advantages of the adopted methodology are as follows: it takes into account the three specters of sustainable development to ensure both the preservation of the environment and the landscape, and the feasibility of the investment, it takes into account the complexity of the choice of site. Therefore, economic evaluation criteria can be used to determine the economic potential and investors in the renewable energy field can participate in the survey, and thus contribute to their relative importance. Finally, the methodology developed is based on the quality and quantity of the data available for collection. In this study, a special effort was made to collect the necessary data from official authorities and scientific studies. However, despite the limitations due to the quality and unavailability of certain data, the methodology developed is dynamic and allows continuous updating of the data collected, which can lead to the use of additional evaluation criteria.

Fig.9A and *Fig.9B* respectively show the overall suitability of SPV power stations and SPVs with an area greater than 0.4km² in all regions of Cameroon, while *Fig.10A* and *Fig.10B* respectively show the suitability for CSP power stations and CSPs of area greater than 2.2km². For CSP, it is clear that the Far North and North regions are the most favorable. In addition, all regions favorable for CSP installations are also favorable for SPV installations.

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