Estimation of Solar Potential in Senegal Using GIS Application

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Abstract
Senegal is one of the most developing countries and does not have a reliable network of surface observation stations for collecting solar data. This has been a major drawback to estimate the accurate potential of solar energy for the generation of photovoltaic systems in Senegal. Therefore, in this paper, the potential of solar for photovoltaic systems has been estimated using annual average of global horizontal solar irradiation from National Aeronautics and Space Administration (NASA) data with 65 locations spread around fourteen regions in Senegal and generated solar potential map by using Geographic Information Systems (GIS). GIS models are used to find out the annual solar energy potential in the Country. The resultant solar map observed that western and northern part of the country have the highest radiation with the value of 2233kWh/m²/year and 2179kWh/m²/year respectively. Calculation results of Annual Energy Production (AEP) and potential estimation investigated that solar potential might be around 63919 MW. Thus, the result shows that PV solar system can support major part of country's energy demand.

Keywords
Radiation, Solar Potential, GIS, AEP, GHI.

I. Introduction

Utilization of energy systems across the world can be classified into three main areas: fossil fuels, nuclear power and renewable energy. Renewable energy resources are easily accessible to mankind around the world. Solar, wind, biomass and wave energies are not only available in a wide range, but are also abundant in nature. Solar power is one of the most promising renewable energy [1]**.** Annual average solar energy on entire planet may produce 1.3 - 1.4 kW/m^2 electric energy [2]. In one day, the sun sends 10,000 to 15,000 times more energy to the earth than we all collectively use. From which, Africa enjoys 51% of Earth's most concentrated sunlight [3]. One of the African countries, Senegal has abundant sunshine, which about 3000h/year [4].The rapid development of solar energy in Senegal has appeared gradually. Various studies have been done on this field: [5] and [6]. [5] compared four empirical models across four localities in Cameroon and Senegal and obtained the solar radiation values measured by the meteorological stations. [6] has evaluated the solar potential in 4 regions of Senegal and 29 localities for each month, however the uncertainty data can be considered and still weak for using these data.

Another aspect which is underlined, government is trying to find out all ways for electricity generation. The government operates effectively for a fast fulfillment of independence of energy in Senegal and aims to make energy a key factor for economic and social development, as indicated in the Emerging Senegal Plan. Senegal's ambition is to achieve the objective of universal access to electricity by 2025 [7].

Lack of solar data and deficiency of meteorological stations are some of the problems for the sustainable development of Senegal and on the other hand, Senegal has scarcity of electricity and frequent power cuts. The unexpected cuts in electricity are slowing considerably the economic activities in Senegal. Government is trying to find out all the possible ways for the generation of electricity. To resolve this problem, solar energy can be used as an alternative source. However, many projects fail due to lack of information about the amount of solar potential available in a particular location. Therefore, this paper proposes to estimate the solar potential over the territory. And also, this can help the decision-makers to determine the suitable land for the development of solar energy plants and to fulfill the electricity generation in the country.

II. Material and Method

1. Study Area

Senegal is a country in West Africa located at latitude 14°43'29N, longitude 17°28'24"W as shown in Fig. 1, the capital is Dakar. The country is a flat surface that lies in the depression known as the Senegal-Mauritanian basin elevation of more than about 330 feet (100 meters) are found only on the Cape Verde Peninsula and Southeast of the country. The population is estimated around 15,286,346 [9]. The consumption of electricity per person is around 219.25 kWh/person in 2013 [10]. The country as a whole falls into three structural divisions: the Cape Verde headland, which form the western extremity and consists of a grouping of small plateaus made of volcanic origin, the southeastern and the eastern parts of the country, which consist of the fringes of ancient massifs (mountain masses) contiguous with those buttressing the massif of Fouta Djallon on the Guinea frontier and which include the highest point in the country, reaching an elevation of 1,906 feet (581 meters) near Népen Diakha; and a large but shallow landmass lying between Cape Verde to the west and the edges of the mountainous to the east [11]. It has a tropical climate with varying temperatures from 26°C to 17°C from December to April, and from 30°C to 20°C from May to November. Temperature is found to be the lowest along the coast [12]. The country has more forest reserves. About 45 percent of the country is occupied with forests. While Senegal lost some 675,000 hectares and forest between 1990 and 2005, the country's deforestation rate has only increased by 5 percent since the 1990s [13].

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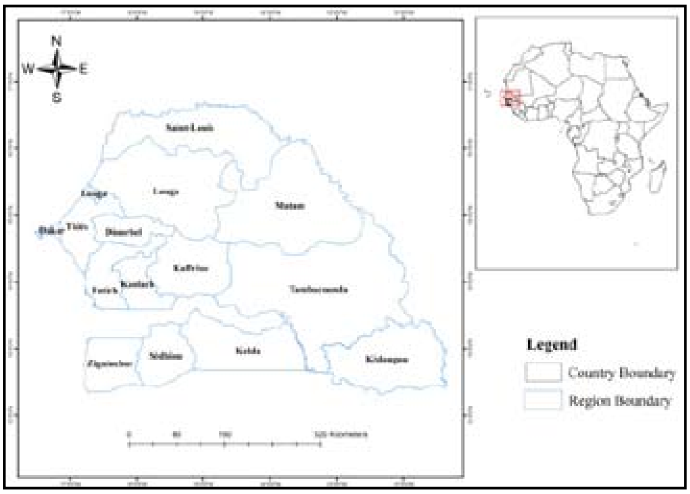


Fig. 1: Study area representing the regions of Senegal

2. Description of the data

NASA Surface meteorology and Solar Energy (NASA-SSE) database is used to collect the information on solar parameters (GHI, DHI, DNI) and Meteorological parameters (Temperature) for Senegal. This database has been most extensively used for national estimations of solar radiation intensity, solar electricity generation potential, etc. The NASA-SSE is an online database of over 200 climate parameters obtained from geo-stationary satellite observations and from the Goddard Earth Observing System (GEOS) of NASA's Global Modeling and Assimilation Office (GMAO) [14]. These parameters are presented as 22-year averages with a spatial resolution of 1° longitude by 1° latitude over the entire surface of the globe.

Global horizontal irradiance (GHI): global horizontal irradiance is the total amount of shortwave radiation received from the sun on a horizontal surface. GHI is of particular interest to non tracking photovoltaic installations and includes both Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI) [15].

Direct Normal Irradiance (DNI) travels unobstructed through space and the atmosphere to the surface [16]. DNI is the amount of solar radiation received per unit area by a surface that is always held perpendicular (or normal) to the rays that come in a straight line from the direction of the sun at its current position in the sky [15].

Diffuse Horizontal Irradiance (DHI) is scattered by atmospheric components such as gases, molecules, aerosols, dust and clouds [16]. It is the amount of radiation received per unit area by a surface (not subject to any shade or shadow) that does not arrive on a direct path from the sun, but has been scattered by molecules and particles in the atmosphere and comes equally from all directions [15].

Administrative boundaries, railroad, roads from DIVAGIS [17], protected area from World Database for Protected Area [18], elevation from SRTM (Shuttle Radar Topography Mission) [19], and airport from Google earth are gathered using these various open source websites. All data were projected to WGS-84 of the Universal Transverse Mercator (UTM) zone 28N to make the calculations easier. SRTM (Shuttle Radar Topography Mission) provides elevation data at a spatial resolution of 90m. This data is used for the preparation of slope map. Land Use and Land Cover (LULC) data has been taken from ESA (European Space Agency). World database on Protected Areas (WDPA) gives the information on protected areas for Senegal. The airport data is plotted in Google earth and downloaded as KML files. These KML files are then converted in to shapefiles in ArcGIS-10.5.

The summary of the data sets used and their source are described in Table (1).

Table (1): Datasets

Data set	Source	Resolution	Time Period
Roads	www.diva-gis.org/dataTown	-	2011
Railroads	www.diva-gis.org/dataTown	-	2011
Protected areas	WDPA	-	2014-2016
Land Use Land Cover (LULC)	ESA glob cover	300 meter	2009
Solar data (GHI)	NASA-SSE	1°X1°	Jul 1983 - Jun 2005
Digital Elevation Model	SRTM	90 meter	2004 -2017
Airport	Google Earth	-	2016

3. Methodology

All GHI data has been downloaded for 65 locations in and around Senegal and saved as an excel sheet. This excel sheet is then converted into shapefile in ArcGIS environment. GHI data is a point shapefile and interpolated using IDW (Inverse Distance Weight) technique to prepare the solar map. IDW under 3D Analyst tool is the procedure this map is then validated using the 3Tier GHI map. Airport locations throughout Senegal are identified using Google Earth and saved as KML files. These KML files are converted to layer files with KML to layer conversion tool. LULC map is processed and certain areas where solar power plants cannot be established (Exclusion area) are removed. Digital Elevation Model (DEM) data from SRTM is used to prepare the slope map using the slope tool under 3D Analyst extension. Slope map is converted from raster to polygon and areas above 3° have been removed. Buffer analysis tool is used and a buffer of around 5km for airport, 1km for railroads, and 1km for roads is performed. Protected areas, LULC, roads, railroads, airport, slope maps are integrated and a single exclusion zones map is prepared. This exclusion zones map is overlaid on the GHI map and the exclusion areas are erased using the erase tool under Analysis tool extension. Thus, a final solar resource map of Senegal was prepared. A fishnet model under Data Management extension with a spatial resolution of 2kmX2km is created. Point features created from fishnet model are used to extract GHI data from the solar resource map after removing the exclusion areas. These point features are joined to the fishnet using join tool. Available area, energy estimation studies like Annual Energy Production (AEP), solar plant capacity that can be accommodated in the available area are calculated using this model. Fig. 2 represents the Methodology involved in preparing the solar resource map of Senegal.

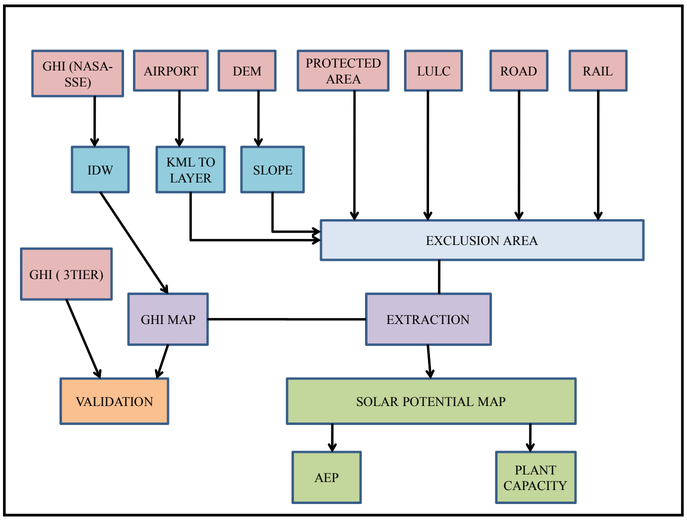
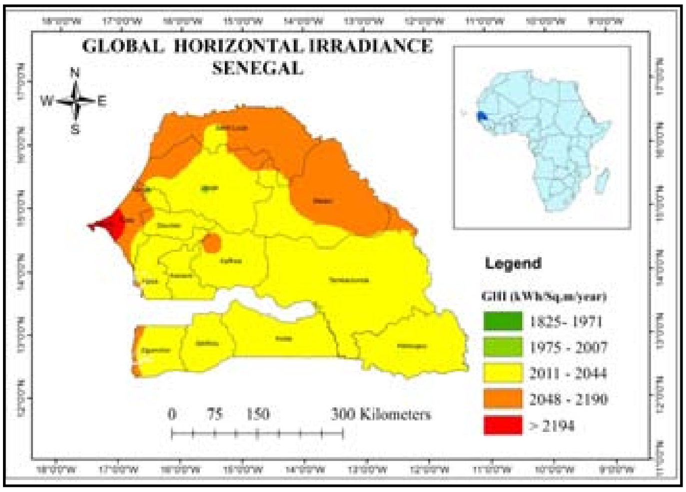


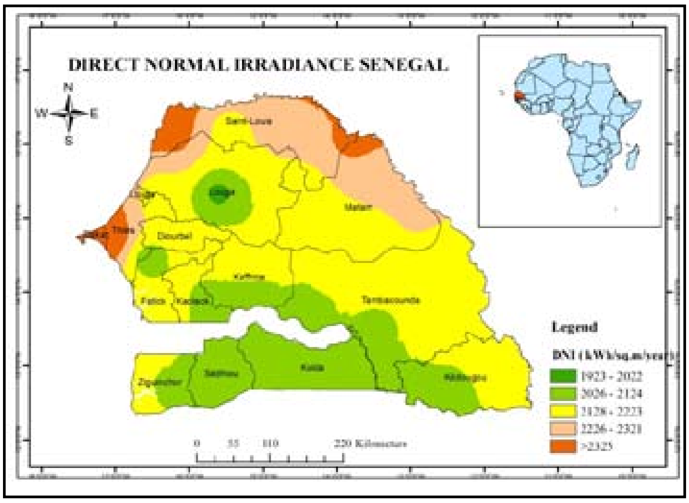
Fig. 2: Methodology for mapping Solar Resource in Senegal

III. Result

1. Solar Map in Senegal

Solar map of Senegal was obtained and shown in the Fig. 3. There are three maps to represent the solar map. It was observed from the GHI map the range is 1825 - 2194 kWh/m²/year and the DNI map, the range is 1923 - 2325 kWh/m²/year. For DHI map the range is 613 – 686 kWh/m²/year.





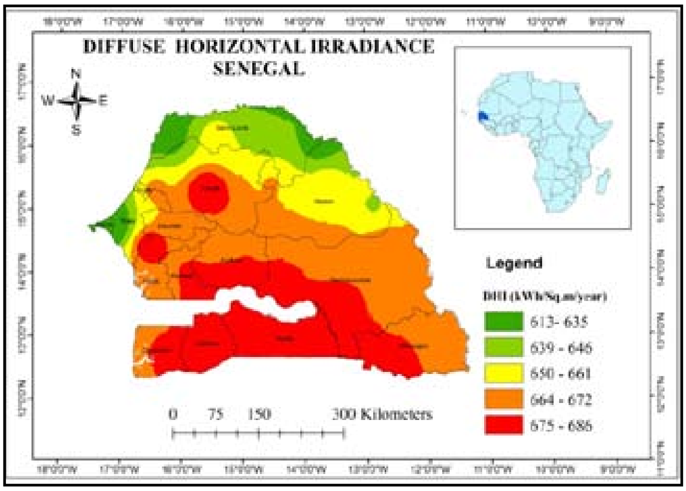


Fig. 3: Solar Map in Senegal

Title The result solar resource maps show that global horizontal irradiation (GHI) in annual daily average reaches around 2194 kWh/m² /year in western of the country (Dakar and some part of Thies region have the highest radiation around 2190 kWh/m²/year), around 2011 kWh/m² /year in the central, in the east and in the south, from 1825 to 1971 kWh/m² /year in the small part in central of Senegal (a part of Louga region). For direct normal irradiation (DNI), the annual average is around 2325 kWh/m² / day in the western of the country, from 2128 to 2223 kWh/m²/year in practically the whole of the country, from 2026 to 2124 kWh/m²/year in part of south and around from 1923 to 2022 in the small part of the central (Louga). For diffuse horizontal irradiation (DHI), the annual daily average is around 613 kWh/m²/day in extremely in Western side and small part in North, around 664 kWh/m²/year in the central and east side of the country (and small part in the south precisely in Ziguinchor). The root mean square error is ±5% for global irradiation on horizontal surface.
For this study, monocrystalline module (300 Watt capacity with 1.919 Sq.m size an efficiency of 15.64% having 75% performance ratio) was applied in the calculation (AEP per MW= Module Area* Efficiency of the Module * Performance Ratio * Radiation). Thus, the table (2) is obtained.

Table (2): Annual Energy Production per MW in MWh

S1. No	Category radiation (kWh/m²/day)	Area (km²)	Radiation (kWh/m²/yr)		Production (AEP) per MW in MWh radiation (kWh/m²/day)	
			min.	max.	min.	max.
1	5.00 to 5.40	0	1825	1971	1369	1458
2	5.41 to 5.50	148	1974	2007	1481	1506
3	5.51 to 5.60	8112	2011	2044	1509	1534
4	5.61 to 6.00	188532	2047	2190	1536	1643
5	>6.01	1796	2193		1645	

Total area of Senegal is 196,712 km². But, for present study area is considered to be 198,588 km² due to the presence of excess area at the boundaries of the country while performing the map processing. If suppose 1sq.km of area can accommodate 50MW and 1% to the total area has been taken then the solar potential estimated for entire Senegal would be around 99,294 MW.

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2. Solar Potential in Senegal

The solar potential map is obtained after removing the exclusion area as shown in the Fig. 4. Suitable areas with varying radiation are shown and exclusion areas are represented in white color.

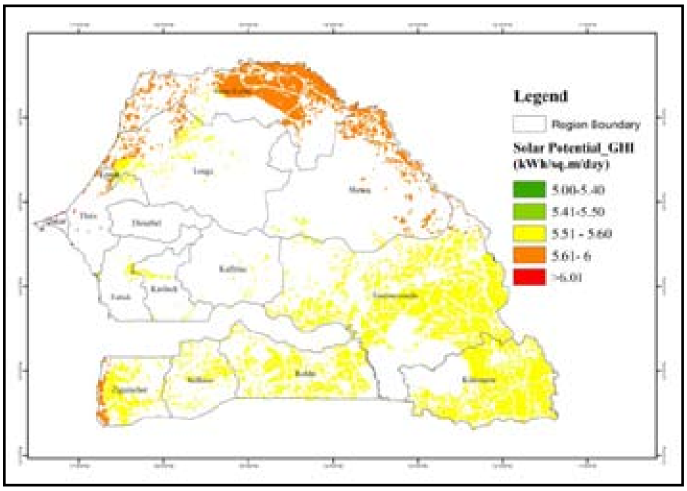

Fig. 4: Solar potential map of Senegal

Practically, solar potential for any photovoltaic system takes into consideration only the GHI parameter. Solar energy resource exploitation requires a shadow free area to tap the amount of solar energy available in a specific place. In the present research, to calculate the solar potential for open areas, assumption of 1 sq.km area can accommodate 50 MW of the plant was considered. The capacity of the solar plant that can be accommodated in the suitable/available area for each region in the country is calculated and shown in table II. Total suitable/available area for the development of solar power plants is around 42,613 km² which is 21% of the total available area. But, only 3% of the available area (1278 sq.km.) is taken and it is found that 63919.5MW of Solar PV plants can be installed throughout Senegal.

Table (3): Solar Radiation and potential for each region

Regions	Total Area (km²)	Available Area for PV (km²)	3% of Available Area (km²)	Solar PV Plant (MW)
Thies	6,640	332	9.96	498
Saint-Louis	20,257	7,085	212.55	10627.5
Matam	27,987	2,563	76.89	3844.5
Tambacounda	42,863	13,919	417.57	20878.5
Dakar	566	33	0.99	49.5
Ziguinchor	7,354	2,401	72.03	3601.5
Louga	24,659	1,965	58.95	2947.5
Kaffrine	11,314	154	4.62	231
Fatick	6,848	168	5.04	252
Sedhiou	7,351	1,268	38.04	1902
Kedougou	16,950	8,239	247.17	12358.5
Kolda	13,804	4,256	127.68	6384
Diourbel	4,860	0.8	0.024	1.2
Kaolack	5,407	229	6.87	343.5
Total	1,96,860	42,613	1278.39	63919.5

From the table it is evident that Tambacounda region has the highest land availability for setting up of the solar photovoltaic power plant. 20,878 MW can be installed as the area. The area is predominantly flat with some hills in the department of Bakel. Kedougou and Saint-Louis has an area of around 200sq.km where 10,000 MW plants can be installed. Diourbel region has very less available area to put up the solar plant due to the presence of vegetation. Dakar also has a lower solar potential around 49 MW because of highly populated areas. Matam, Ziguinchor has around 70 sq.km of the available area and 3500 MW solar plants can be installed. Kaffrine and Fatick have a solar potential of 200-250MW as the available area is only 4-5sq.km due to presence of vegetation.

IV. Validation

In the present study, the monthly average amount of the total solar radiation incident on a horizontal surface at the surface of the earth for a given month, averaged for that month over the 22-year period (Jul 1983 - Jun 2005) is considered. Each monthly averaged value is evaluated as the numerical average of 3-hourly values for the given month. NASA data is used for the preparation of solar radiation map of Senegal. It was observed from the map that the highest solar radiation is around 2233 kWh/m²/year, whereas Saint-Louis which is in the Northern part of the country has 2179 kWh/m²/year. Central part of the country has solar radiation of 2160 kWh/m²/year while eastern part receives 2127 kWh/m²/year.

The developed model is compared with 3Tier solar map of 2km spatial resolution downloaded from [20]. Data provides a 10 km Global horizontal solar irradiance map developed from 3Tier, with an annual temporal resolution, for the ECOWAS Region [20]. It was observed from the 3Tier solar map that the highest solar radiation is 2232 kWh/m²/year in the north side of Senegal. In the central side, the radiation is around 2188 kWh/m²/year (It should be noted that only a small part in the south side receives this radiation). In the west side, the solar radiation is around 2162 kWh/m²/year. By checking with the root mean square error method, the comparison result solar map is may be ±5% error throughout the country.

V. Conclusion and Discussion

In this paper, the solar radiation data for different coordinates in the country are obtained from the solar resource mapping from NASA surface meteorology and solar energy location. The GIS tool was used to generate the solar radiation map and solar potential map. The highest global horizontal irradiance is around 2190 and 1873 kWh/m²/year in Dakar and Thies respectively. After removing the exclusion areas from solar map, the solar potential of Senegal was estimated. The available solar potential is around 2,130,661 MW in Senegal. This result can fulfill electricity problems in Senegal.

Though the airport areas and railroad have been excluded from the present study, these areas can be used to install solar plant. Also the residential areas are removed in this study, but these areas can be used for setting up of solar rooftop systems. DNI and DHI aren't used in this study because DNI is appropriated to concentrate solar plant (CSP).

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