

Assessment of Hybrid Concentrated Solar Power-Biomass Plant Generation Potential in Sahel: Case Study of Senegal

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Abstract

Concentrating Solar Power (CSP) is non-existent in Sahel. Such a situation arises from the high investment costs required by these energy infrastructures and from a lack of information on the identification of suitable sites to accommodate them. Conversely, CSP-biomass plants due to lower investment may be an option for CSP penetration in Sahel where Direct Normal Irradiation (DNI) is between 1400 kWh/m²/year and 2000 kWh/m²/year and significant biomass potential. This work presents the results of an identification of suitable sites for hybrid CSP-Biomass in the Sahel, case study of Senegal, taking into account the Direct Normal Irradiation, the availability of water, space and biomass potential. The identified sites have a DNI > 1600 kWh/m²/year. The biogas production capacity is equivalent to 5,096,563 m³/year. The quantity of *Typha Australis*, invasive plant in Senegal river valley available is estimated at more than 3 million tons. The capacity of electrical energy in this zone is estimated at 6.89 GWe for an installation surface estimated at 275.61 km². The establishment of CSP/hybrid plants can also contribute to combat the proliferation of *Typha Australis*.

Keywords

Biomass, Concentrating Solar Power (CSP), Direct Normal Irradiation (DNI), Hybrid, *Typha Australis*

1. Introduction

The Sahel, a transitional zone between the Sahara desert and the equatorial fo-

rests, is a semi-arid region that extends from West Africa to East Africa. With an area of 7.3 million km², the Sahel covers the following countries: Burkina Faso, Eritrea, Gambia, Guinea-Bissau, Mali, Mauritania, Niger, Senegal, Sudan and Chad. The total population of the Sahelian countries was estimated at 125 million habitants in 2013. Their natural growth rates are among the highest in the world, about 2.5% to 3.8% [1].

Like other countries in sub-Saharan Africa, access to electricity in the Sahelian countries is limited. Around 32% of the population has access to energy in 2013 [2]. Among people having no access to electricity, 80% live in rural areas and remain distant from distribution networks.

In front of this situation, off grids are one of the means of access to electricity for rural communities in the Sahel. The main technologies available for off grids are generators and renewable energy technologies (solar technologies, small hydropower and small wind turbines).

The economic cost and the environmental impact of the use of generators make the choice of off grids fueled by renewable energy sources in the rural areas of the Sahel.

Solar technologies are more suitable in the Sahelian zone because of a high solar potential of around 5.5 kWh/m² [3] and low hydroelectricity as well as wind potential. Wind speeds are indeed low with national averages ranging from 2 to 3 m/s with some peaks of 4 to 5 m/s in some localities [4].

Among solar production technologies, thermodynamic solar power plants (CSPs) could be an alternative to decentralized production and contribute to the fight against climate change. Thermodynamic solar power plants (CSPs) concentrate solar rays to heat, a fluid that is directed directly or indirectly to a turbine coupled to an alternator. CSPs offer the ability to store heat that facilitates the management and distribution of electricity. They can be hybridized with a fossil or biomass energy source to ensure continuous production.

In addition to their capacity to generate electricity, CSPs can also meet heating, desalination and cold requirements. Since 2009, the CSPs have grown steadily. Between 2009 and 2013, installed capacity increased from 600 MWe to 3959 MWe [5].

Despite its advantages and progress, CSPs are not yet competitive with other renewable energy technologies. As comparison, the standardized cost of electricity for CSPs is (0.20 - 0.35) USD/kWh for (0.11 - 0.28) USD/kWh to photovoltaic solar energy and (0.06 - 0.12) USD/kWh to wind turbine [6].

Hybridization with lower-cost fuels (biomass or waste) is also a strategy that could help reduce production costs and make CSPs competitive. In addition, while facilitating the management and distribution of electricity with cost advantages, hybrid plants can extend the siting of CSP plants from arid zones to semi-arid or temperate zones.

In addition, while standard CSP plants generally require direct irradiation (DNI) of 2000 kWh /m²/year or more, CSP hybrid plants can be located in areas where the DNI reaches 1700 kWh/m²/year [7]. This brings CSP plants closer to

agricultural regions with high biomass potential and waste disposal areas.

Among hybrid plants at lower cost, hybrid CSP-biomass plants are a well-accepted solution for low-cost, base-load and renewable energy [8] and are a niche for areas with a DNI and Biomass resources.

CSP hybrid plants are beginning to be a reality. In 2012, the first CSP-biomass “Termosolar Borges” hybrid plant is operational in Spain, demonstrating the technical and economic viability of this technology. In 2014, India also launched a project for a 3 MW hybrid CSP-biomass plant equipped with biomass-integrated gasification (SCOPEBIG) [9].

Hybrid plants continue to be the focus of many research activities. Different configurations have been studied. Peterseim *et al.* [10] evaluated 17 CSP-biomass hybrid configurations in relation to their technical, commercial and environmental performance. Other work has focused on the hybridization of cylindrical parabolic (PTC) plants with biomass [11] [12] [13]. The Linear Fresnel Reflectors (LFRs) have been studied for hybridization with biomass [14]. The hybridization of solar towers with biomass was also discussed [15] [16].

The lack of information on the identification of potential sites with an acceptable DNI and the availability of biomass constitutes an obstacle to the deployment of hybrid CSP-biomass plants in the Sahelian zone. To our knowledge, the identification of potential sites for hybrid CSP/biomass plants has been done only for Australia [17], India [14] and Brazil [18]. There are no studies on the identification of potential sites for CSP/biomass hybrid systems in the Sahelian zone.

This study aims to fill this gap by focusing on the identification of suitable sites for the implementation of hybrid CSP/biomass plants in the Sahel for decentralized electricity generation. The case of Senegal, located at West Africa between 12°08'N and 16°41'N latitude and 11°21'W and 17°32'W longitude, is studied because of the high potential for biogas production in areas with high DNI and the presence of large quantities of *Typha Australis* in the valley of the Senegal River, which is an invasive plant that colonizes cultivated land.

2. Review of Hybrid CSP-Biomass System Requirement

2.1. Direct Normal Irradiation (DNI)

Like the standard CSP installations, hybrid plants require a high level of direct sunlight. While the threshold value of the DNI of a site for the implantation of a standard CSP installation proposed by some researchers varies from 2000 to 1800 kWh/m²/year [8] [9], hybrid systems can be implanted in sites of which The DNI > 1700 kWh/m²/year [11]. According to Peterseim *et al.* [19], sites with a DNI > 1500 kWh/m²/year can be considered acceptable for the implementation of CSP hybrid plants.

2.2. Land Slope

CSP plant sites must have limit slopes. Cylindrical Parabolic Trough and Linear

Fresnel Reflectors require zones with a slope of less than 2%. Solar towers and Dish can be installed in sites with a slope of less than 5%, but installation on sites with slopes greater than 2% can lead to additional installations.

2.3. Land Requirement

CSP plants require large areas of earth for the installation of the solar collectors field, the thermal storage system and the power block. The required area varies from one technology to another. For a given technology, the land requirement varies depending on the presence or absence of the thermal storage system and the cooling method of the power block. In this regard, authors have provided values on the areas required by MW in **Table 1**.

The availability of land and possibly its cost are important issues to consider in choosing a site. In Senegal, land belongs to the state that distributes it to local communities. CSP plant sites should not be in competition with agricultural land, nature reserves, residential and industrial land.

2.4. Water Requirement

Water requirements vary from one technology to another. For water-cooled parabolic (PTC) plants, water consumption is 3000 - 3500 L/MWh [22], water requirements are approximately 2300 L/MWh for Fresnel Linear Reflector (LFR) [22] and the needs of a solar tower are of the order of 2800 L/MWh [23].

The majority of CSP-biomass hybrid systems operate with the Rankine cycle (steam generators) in which 90% of the water is used to cool the steam cycle and the remaining 10% is used to clean the mirrors. Dry cooling systems can dramatically reduce water consumption but can result in additional costs. In the Sahel, a semi-arid zone, water cooling is more efficient because the outdoor temperature can reach a maximum of 40°C. The efficiency of air cooling decreases when the outdoor temperature is high. Moreover, the Sahel is marked by a strong presence of dust. Therefore, the hybrid plant site must always have water availability.

Table 1. Field requirements for various solar thermodynamic technologies.

CSP technologies	Land requirement (m ² /MW)
Parabolic Trough	18,000 including power block [20]
	40,000 [21]
	45,000 [20]
Solar Tower	83,600 [21]
	19,166 [20]
Linear Fresnel Reflector	25,555 (1 h of thermal storage capacity) [20]
	34,000 (wet cooling) [20]
Parabolic Dish	16,000 [21]
	40,460 [20]

2.5. Biomass Potential

The availability of long-term biomass is an important criterion for the implementation of CSP-Biomass hybrid plants. The biomass taken or used must not have a negative impact on the environment. Biomass can be used as a back-up to a CSP when solar radiation is not sufficient to produce electricity. Alternatively, biomass can also be used to increase the amount of vapor produced or the temperature of the working gas.

Due to environmental constraints and funding opportunities, the share of biomass in a hybrid plant should be less than 30%.

2.6. Availability of Power Lines

As with all power generation systems, hybrid CSPs require access to electrical transmission lines to link supply to demand and roads to transport heavy elements from the CSP central office. According to Kirby *et al.* [24], the distance from the power grid should not exceed 80.5 km and the site should be accessible by road or rail over 80 km.

3. Methodology

Geographic information system (GIS) tools were used to map the availability of direct sunlight in a specific region. This parameter was used as a general indication of areas favorable to the installation of hybrid CSP-biomass plants and analysis of the cooling constraints, slope and availability of biomass. We are also interested in the economic impact of a 1 MWe cylindrical parabolic CSP.

3.1. Location of Potential Areas Suitable for Hybrid CSP Plants/ Biomass

This study concerns areas potentially suitable for the installation of hybrid CSP-Biomass plants for decentralized electricity generation (<1 MWe) if they comply with the following requirements:

- $\text{DNI} \geq 1600 \text{ kWh/m}^2/\text{year}$
- Terrain slopes $\leq 2^\circ$
- The land should not be located on crop areas, protected areas or reserves
- The land should not be located in residential areas
- The land must be in areas with high biomass potential
- The land must be in an area with a source of water (river or river) or a water source (boreholes and / or wells)

It is important to note that the boreholes provide water for households and for livestock. Moreover, water points polarize many economic activities and benefit from an economic dynamism linked to the access to this precious liquid.

3.2. Economic Impact of Hybrid CSP Plants Install

This is a preliminary study to evaluate the construction and maintenance costs, the revenue generated and the number of jobs that can be created with the in-

stallation of a 1 MW thermodynamic plant from the tool Jobs Economic Development Impact (JEDI) developed by NREL [25]. This model is widely used in the literature to evaluate the benefits of the construction of renewable energy plants [18].

4. Results and Discussion

According to the previous methodology, calculations were made to evaluate potential sites for the installation of hybrid CSP-Biomass plants for decentralized electricity generation.

4.1. Identification of Areas with an Acceptable DNI

In sub-Saharan Africa except South Africa, weather stations do not have pyranometers and pyrhemometers. Satellite data are generally used to select favorable areas.

Analysis of the Africa's DNI solar map (Figure 1) [26] shows that the DNI in Sahel ranges from 1600 kWh/m²/year to 2000 kWh/m²/year. The most favorable areas remain in the eastern part.

As a Sahelian country, the case of Senegal is studied. The most favorable zones in Senegal have a DNI > 1600 kWh/m²/year according to their solar map are

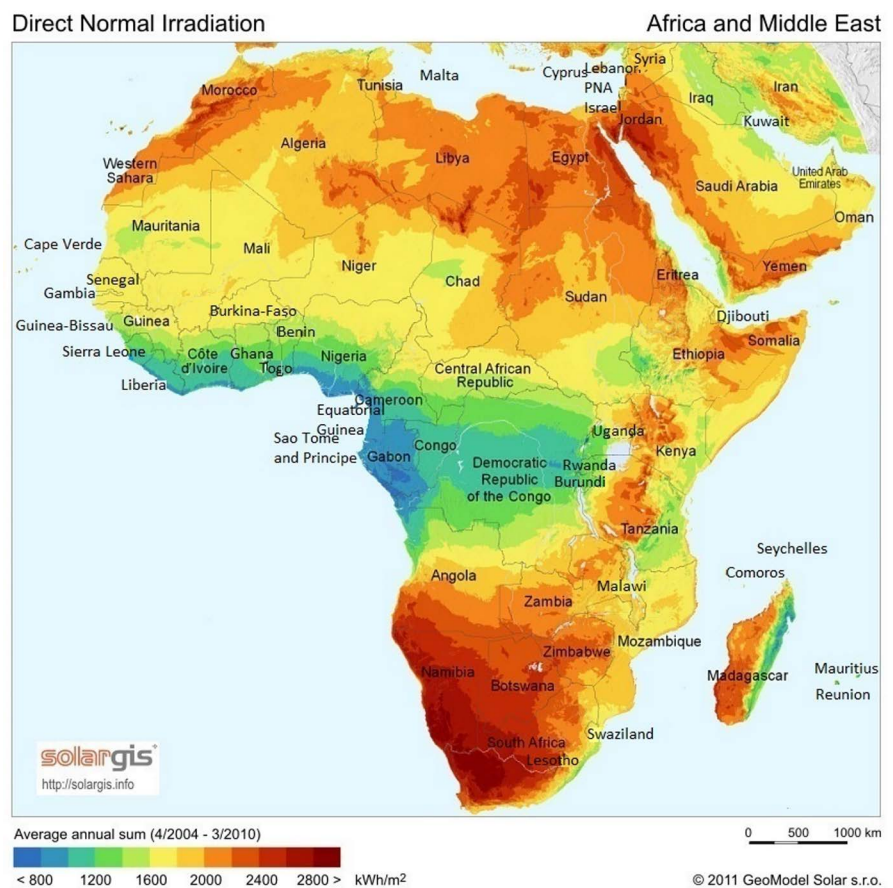


Figure 1. Solar map of Africa.

located in the North and extend over the administrative regions of Saint-Louis, Louga and Matam and to a lesser extent the regions of Thiès and Diourbel (**Figure 2**). They cover an area of 73,497 km² or 37.4% of the national territory.

4.2. Estimated DNI and Other Climate Parameters

The mean monthly values of the direct daily radiation of the departments concerned are obtained from PVGIS [27]. The external temperature and the wind speed come from the six stations of measurement of the climatological data of the national agency of the civil aviation and meteorology of Senegal from 2013 to 2015. Details are shown in **Table 2**.

Analysis of these data shows that the sites chosen from the solar map have a daily direct radiation greater than 5 kWh/m²/d. This is the minimum value required for the operation of a CSP. In addition to DNI, the outdoor temperature influences the performance of CSP power stations, particularly on receivers. With the exception of Matam and Ranerou, the average temperature is below 30°C. It should also be pointed out that the outdoor temperature reaches maxima of 40°C during the months of April, May and June in all the localities of the North zone. The average wind speed is relatively low (<4 m/s).

4.3. Eco-Geographical Zones

The area has little or no difference in elevation (**Figure 3**), just like the entire Senegalese territory. It can be considered as an important low plateau (slope

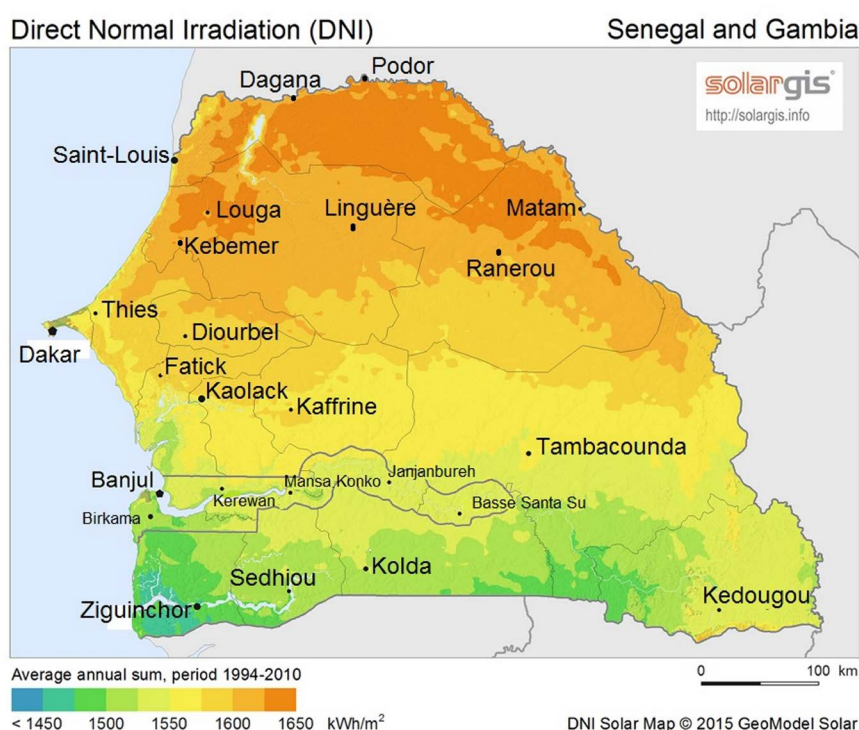


Figure 2. Solar map of Senegal.

Table 2. Average values of direct normal irradiation, temperature and wind speed.

Departments	Latitude (°N)	Longitude (°W)	DNI (kWh/m ² /d)	Temperature (°C)	Wind speed (m/s)
Saint-Louis	16.21	14.8	5.55	26.5	3.26
Dagana	16.46	15.58	5.53	nd	nd
Podor	16.66	14.95	5.52	29.7	1.34
Louga	15.61	16.21	5.64	27.9	3.00
Kebemer	15.37	16.44	5.69	Nd	nd
Linguère	15.38	15.22	5.59	29.8	1.99
Matam	15.66	13.25	5.78	31.0	1.60
Ranerou	15.29	13.95	5.60	30.3	2.25
Kanel	15.49	13.18	5.60	Nd	nd

**Figure 3.** Map of the eco-geographical zones of senegal.

ideally equal to 1%) and consists of 4 large eco-geographical zones namely the valley of the river, the Niayes, the groundnut basin, and the sylvo-pastoral zone [28].

- Valley of the river: wet ecosystem due to an important hydrographic network. It has hydromorphic, halomorphic, alkaline, saline, acidified soils and weakly leached ferruginous soils.
- Sylvopastoral zone: it is characterized by an arid climate, the presence of a lake and vast areas of pasture. It has hydromorphic, ferruginous soils with little leaching, reddish brown sandy sub-sandy clay and interbred brown soils.
- Niayes zone: Wet zone due to shallow aquifers with hydromorphic, halomorphic, alkaline, saline, acidified soil and weakly leached ferruginous soils.
- Groundnut Basin: In the old groundnut basin, tropical ferruginous soils are

leached and degraded on the surface because of intense rainfed crops without fallow. The vegetation cover has become a very rare element and the sand dunes are replenished with the winds strong enough for a good period of the year.

4.4. Land Availability

The area with a DNI greater than 1600 kWh/m²/d extends mainly to the administrative regions of Saint-Louis, Matam and Louga. It covers an area of 73,497 km², with housing occupying 2%, protected areas occupying 3.6% and arable land extending over 19%. The remainder, about 75%, consists of steppes, savannas and fossil valleys (**Figure 4**).

A more conservative estimate suggests that 0.5% of this available area can be used to accommodate CSP plants to preserve livestock activities about 2375.6 km².

4.5. Water Availability and Rain Fall

The region has an important potential in water resources distributed in surface water and groundwater.

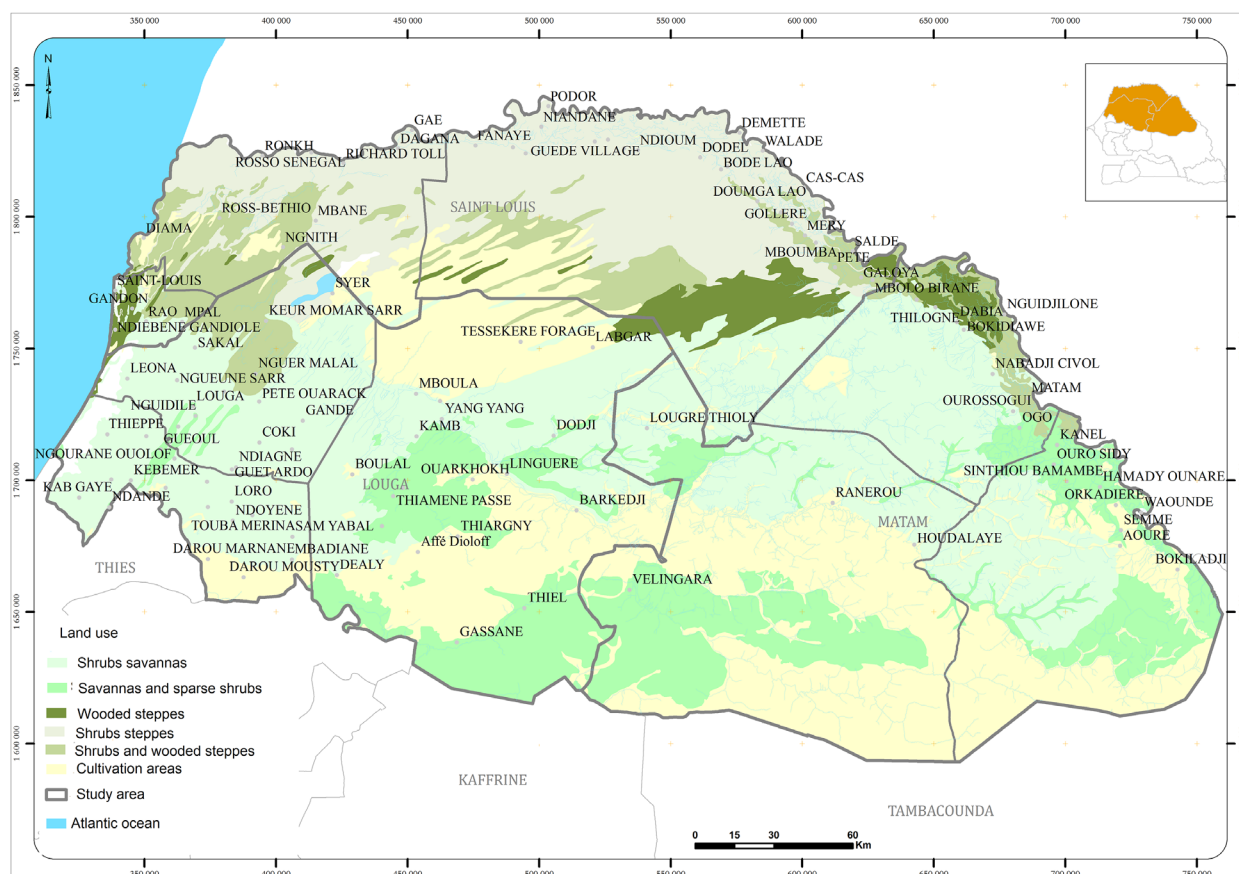


Figure 4. Occupancy map of the area.

4.5.1. Surface Water

The surface water potential is estimated at 23.656 billion m³, of which 23 billion m³ comes from the Senegal River (average annual volume) and 656 million m³ for Lake Guiers. They are mostly concentrated in the valley of the river (**Figure 5**).

4.5.2. Underground Water

The underground water potential of the region belongs to the country's aquifer system and is estimated at 1.66500 m³/d of which 1.105.000 m³/d is provided by shallow aquifers from wells or boreholes with a maximum depth of about 100 m and 550,000 m³/d for deep water tables with depths up to 500 m.

4.5.3. Rainfall

The average annual rainfall between 2013 and 2015 from weather stations in the area is presented in **Figure 5**. The rainy season goes from July to August. The rainfall collected shows that the region of the Sahel where isohyets are between 200 mm and 500 mm.

The year-to-date rainfall of the 6 meteorological stations in the region is shown in **Figure 6** [29]. The rainy season takes place during the months of July, August and September.

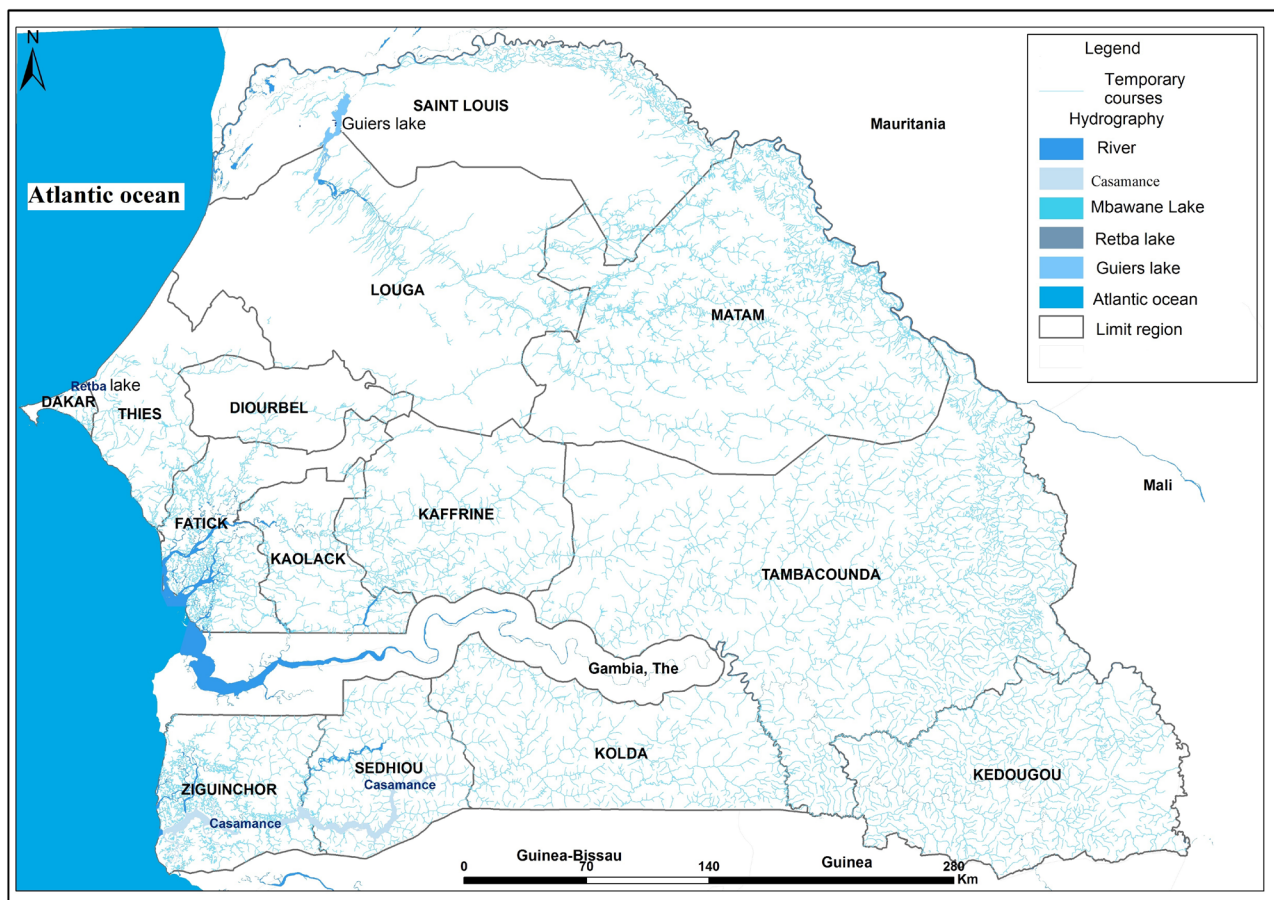


Figure 5. Hydrographic map of Senegal.

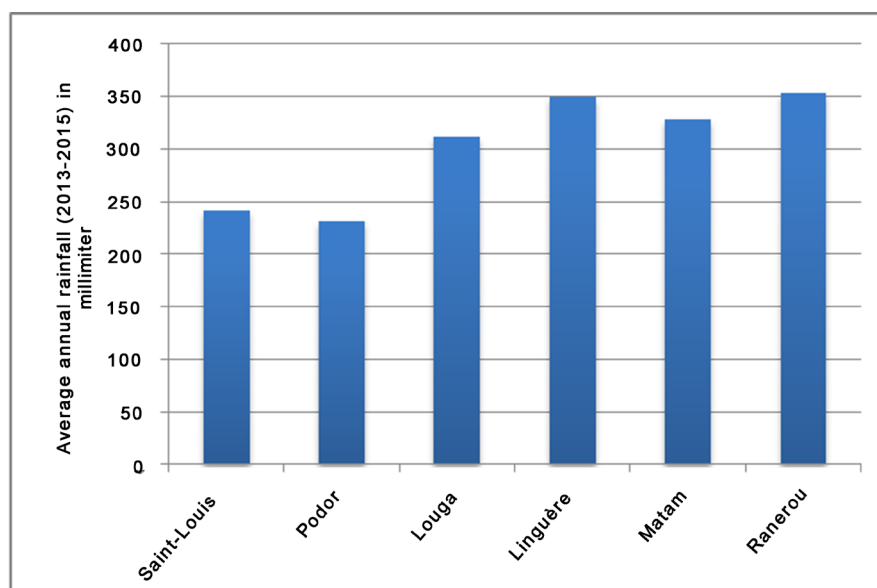


Figure 6. Average annual rainfall in the area with an acceptable DNI.

4.6. Boreholes

The region has a large park of boreholes and wells protected or motorized to allow populations and beasts to access to water. The details of the boreholes and pumps can be found in the following table obtained from the Senegal drilling and well directory [30] (Table 3).

In the sylvo-pastoral zone, boreholes provide water for both households and livestock. They polarize many economic activities and benefit from an economic dynamism linked to access to water. However, the drilling remains insufficient. In addition, insufficient water points for livestock watering also cause conflicts between livestock keepers and populations for water use.

4.7. Biomass Potential

4.7.1. Biogas

The anaerobic fermentation of animal waste produces biogas (about 65% of CH_4 , 34% of CO_2 and 1% of N_2). This zone is a breeding ground with a large livestock whose number of heads Cattle is approximately equal to 1,228,969 or at least 4,096,563,333 m^3/year of biogas. Livestock numbers in the region are shown in Table 4 [31] [32] and [33]. In addition, Senegal has a strong biogas production experience through the National Biogas Program. This agency promotes the production and use of biogas in rural areas.

4.7.2. Typha Australis Plant

Mali, Senegal and Mauritania are confronted with the phenomenon of the proliferation of *Typha Australis*. *Typha Australis* is a rapidly growing reed whose proliferation in the Senegal River basin has accelerated considerably after the construction of dams, notably the 1986 Diama anti-salt dam, which created favorable conditions for its development. Because of its rapid growth, *Typha*

Table 3. Distribution and characteristics of boreholes.

Departments	Number of boreholes	Debit (m ³ /h)	Depth (m)
Saint-Louis	3	39.6 - 79	80 - 558
Dagana	52	13.8 - 87.8	26 - 133
Podor	199	10.2 - 99	39 - 315
Louga	205	10.5 - 95.0	40 - 490
Kebemer	353	25 - 86	46 - 371
Linguère	196	10.8 - 82.8	60 - 637
Matam	177	10.4 - 90	50 - 225
Kanel	131	12.9 - 88	50 - 335
Ranerou	69	10.2 - 93.7	55 - 438

Table 4. Distribution of livestock species by department in 2013.

Departments	Cattle	Ovine and Caprine animals	Horses	Asses	Poultry
Saint-Louis	12,490	37,570	300	nd	255,850
Dagana	78,420	118,480	1200	nd	885,800
Podor	307,670	53,500	108,00	nd	616,600
Louga	185,755	645,408	nd	nd	nd
Linguère	235,474	992,904	nd	nd	nd
Kebemer	52,160	640,060	nd	nd	nd
Matam	135,200	329,500	13,790	16,230	38,800
Kanel	126,300	264,000	9240	9880	28,500
Ranerou	95,500	302,000	15,570	14,000	53,500
Total	1,228,969	3,383,422	50,900	40,110	1,879,050

nd: not available.

Australis colonizes the flood zones of the Senegal River shared by these countries (**Figure 7**). It reduces the cultivable areas in the valley. Typha also hampers river navigation and provides a favorable environment for the development of carnivorous birds. In addition, it contributes to the infestation of the waters of the valley.

This invasive plant now covers an area estimated between 60,000 and 80,000 ha on the whole valley. Typha's surface progression in the river valley is 8% to 10% per year depending on the area (salinity level) and the biomass weight can reach 120 or 150T/ hectare [34]. Typha's green biomass was estimated by the Peracod (2012) [34] to be more than 3 million tons, giving about 520,000 tons of dry matter available per year. Typha has a calorific value of 17,000 kJ/kg throughout the Senegal River Valley, including Lake Guiers. However, to date

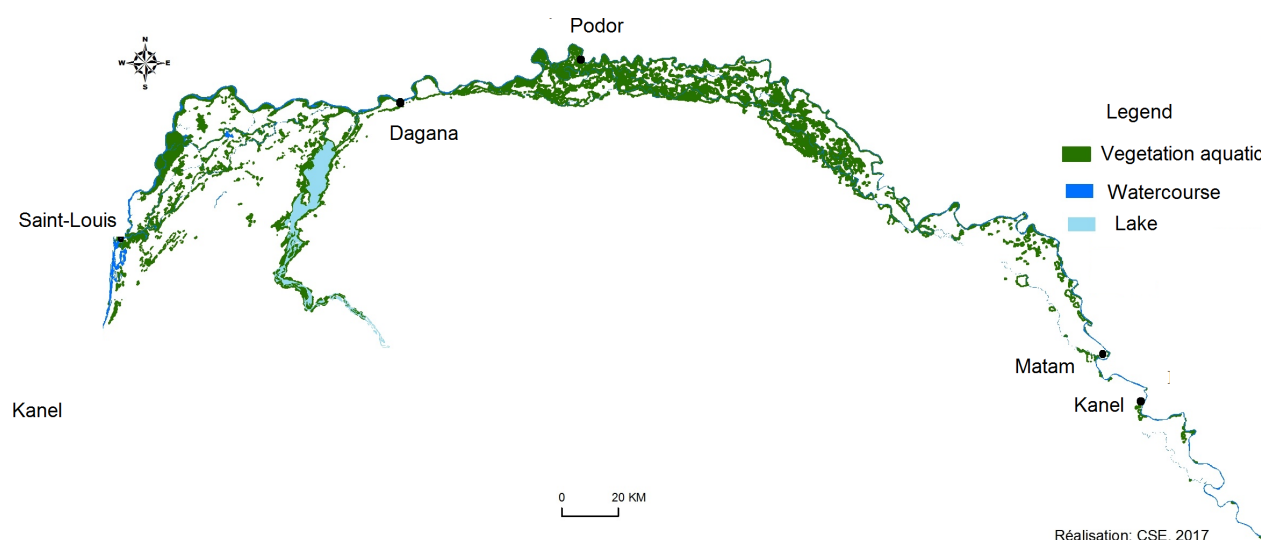


Figure 7. Distribution of aquatic vegetation in Senegal river valley.

there is no biological control. Typha upgrading programs have been explored since the early 2000 s. They involve the use of Typha as domestic fuels through carbonization of biomass into biological coal and as building materials [35].

4.8. Demand Profile and Grid Connection

In 2014, the urban electrification rate is 88% compared to 29% in rural areas in 2014. Most of the 39 municipalities are interconnected to the electricity grid (see **Figure 7**). The chief towns of the 80 communes in rural areas are not all electrified but they benefit from a program of equipment of small photovoltaic power plants and generators. In addition, a program led by the Senegalese agency for rural electrification (ASER) is equipping rural areas with PV plants and generators. At the same time, the Dagana department registered the commissioning of a 20 MW photovoltaic power plant in Bokhol, a locality near Dagana.

The rural world is evolving with the appearance of micro businesses consisting of mechanics workshops, bakeries, dairies, tailors and boreholes that impact on electricity consumption. Indeed, households consume a power of 100 W to 500 W while the micro companies (the carpenters, the tailors, the bakeries, the millers) consume more than 1 kW. The boreholes are large energy consumers (10 kW - 15 kW). In the sylvo-pastoral zone, it can run up to 20 hours a day during heat periods (**Figure 8**).

4.9. Economic Impacts of Plant Construction

The production capacity is estimated at 50% of nominal output of a cylindrical parabolic power plant in an area where the annual DNI is equal to 2000 kWh/m²/year. Therefore, the capacity of production of electrical energy in the region is estimated at 3.45 GW, which largely covers the needs of the area.

This region is not very developed, but it has to milk production development potential and agriculture with the cultivation of rice in the river valley.

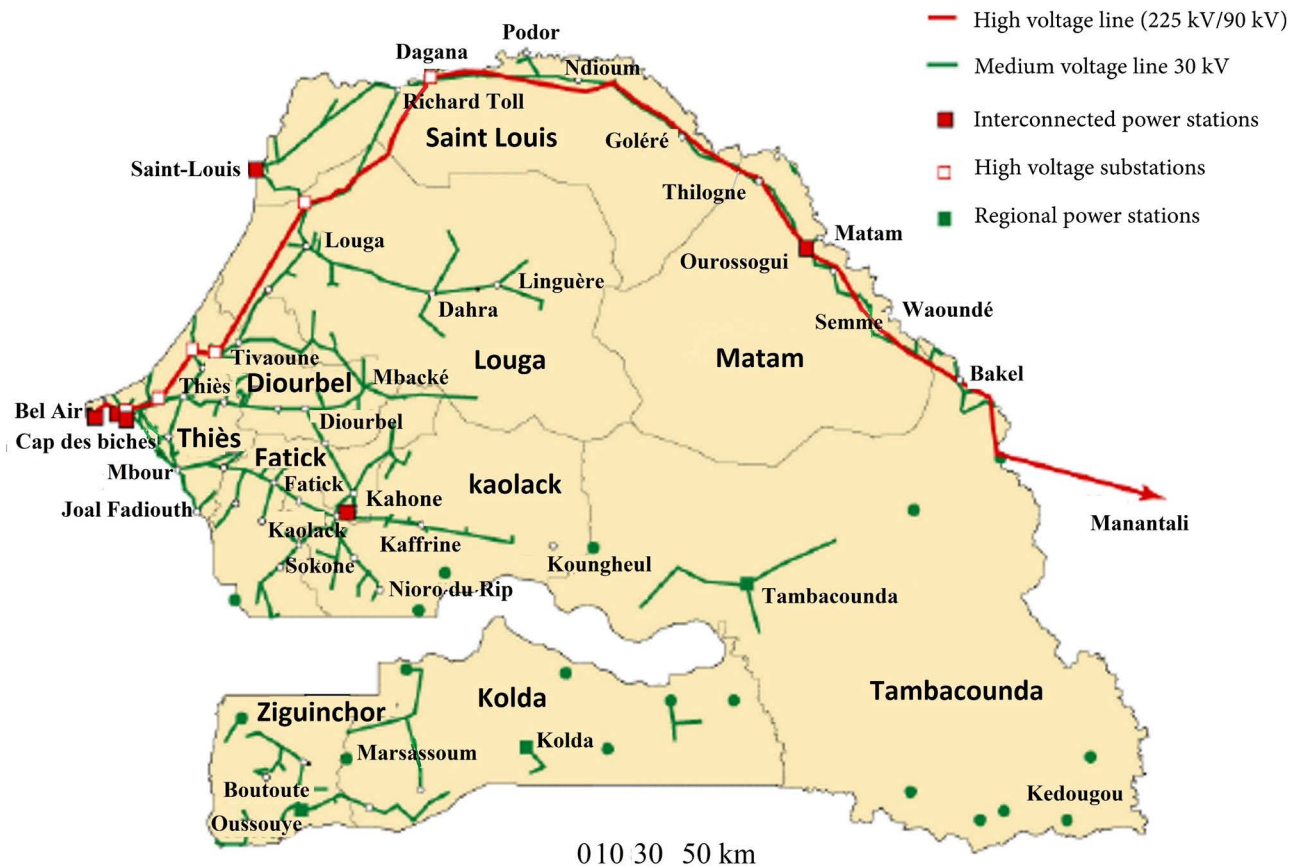


Figure 8. Map of High Voltage and Medium Voltage power lines.

The socioeconomic impact of installing a standard central CSP 1 MW was made using the Jedi tool [13], developed by the National Renewable Energy (NREL) was used to assess the socio-economic benefits Construction of renewable power generation projects in the USA.

The manufacturing cost of the plant is \$7,741,724 and maintenance costs of \$1,217,927. During operation, the plant can generate 1.52 million dollars and generate 21 full-time jobs. The construction cost is still high and a reduction in costs may be considering developing a small manufacturing industry. The production cost can significantly decrease if the plant is hybridized with biogas or *Typha Australis* plant.

5. Conclusion

This study shows the feasibility of hybrid CSP-biomass plants as a strategy of penetration into the Sahel. The area identified for the establishment of hybrid power plants in Senegal is located in the northern regions in which direct normal radiation is greater than 1600 kWh/m²/year. This area also has a significant biomass potential consisting of cow dung due to a large herd and extensive expanses of *Typha Australis*. The electricity generation potential is estimated at 6.89 GWe for 0.5% of the available surface area approximately 275.61 km². The

establishment of hybrid CSP-biomass plants can allow the development of the production of organic fertilizers from digestate derived from biodigesters and also combat the invasion of agricultural land by *Typha Australis*. In perspective, we plan to study different hybrid CSP/Biomass configuration according to solar and biomass potentials of the considered sites.

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