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Evaluation of the Solar Photovoltaic Potential for Electrification of Rural Areas off the National Grid in Mali

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Abstract

Mali, like many countries in the Sahel-Saharan strip, faces critical challenges in terms of access to electricity, particularly in rural areas where a large proportion of the population remains without power. This situation seriously hampers the economic and social development of these regions. Conventional energy solutions, such as thermal power plants, prove unsuitable for remote areas due to the high costs associated with transport and infrastructure. However, with abundant year-round sunshine and some of the highest solar irradiance levels in the world, Mali has remarkable potential to harness solar energy as a promising alternative for electrifying rural areas that have no access to electricity. This study aims to analyze the extent to which photovoltaic solar energy can be a viable solution for electrifying Mali's rural areas not connected to the national grid, based on an assessment of the country's solar potential. The aim is to promote the optimal installation of solar photovoltaic power plants in these rural areas deprived of electricity. In the first stage, the suitability of rural communes for hosting solar power plants was studied using a combination of the Geographic Information System (GIS) and the Analytical Hierarchy Method (AHP) to identify suitable communes. In a second step, the electrical energy production generated at each site was evaluated using a formula, integrating data on electricity requirements per commune, solar radiation, surface area available for installation and number of hours of sunshine. The estimated solar potential to cover the electricity needs of the 435 communes selected by the qualitative analysis is 341397.1732 MWH, and the estimated electricity production capacity is 3496960.355 KWh. The evaluation of the available electrical energy potential involved four hundred and nine (409) communes, identified and deemed suitable for solar photovoltaic installations following a quantitative analysis. The results obtained are evaluated at 8.50571*10 + 11 MWh as the theoretical solar potential available in all the selected communes, with an electricity production capacity of 8.5102*10 + 12 kWh. The technical potential represents 50% of the available potential. Overall, the recorded solar potential amounts to 4.25285*10 + 11 MWh, corresponding to a total annual electricity production of 4.2551*10 + 12 kWh. The analysis reveals that the available solar production potential far exceeds the identified electricity needs, leading to the conclusion that Mali has significant potential in terms of solar resources, capable of meeting its energy needs over the long term.

Keywords

Analysis, Suitability, Installation, Solar, Photovoltaic, Site

1. Introduction

Renewable energies such as wind power, solar power, biomass and hydroelectric power are promising solutions for competing with mass energy sources such as fossil fuels and nuclear power [1]. The concept of renewable energy refers to energy that is constantly circulating in the environment, including solar energy. Photovoltaic conversion involves the production of directly usable electrical energy from light. The energy produced in this way is said to be "clean". This is really the case when compared with other sources of production such as coal, gas or fuel oil, which are real sources of pollution through the emission of greenhouse gases, particularly carbon dioxide [2]. Many countries are turning to renewable energies to combat climate change, with photovoltaic (PV) energy being a leading option due to its advantages. Many countries are turning to renewable energies to combat climate change, with photovoltaics (PV) being a leading option due to its advantages.

Assessment of the potential for electricity generation dates back to the early 20th century, when the first hydroelectric power stations were developed. This marked the beginning of the use of natural resources for electricity generation, which led to a growing interest in assessing the potential of different renewable sources. This period saw the development of methodologies for assessing energy potential, focusing on factors such as solar radiation and geographical location [3]. Mali is a country in the Sahel-Saharan strip, with a slightly low electrification rate. The gap between demand and supply of electricity continues to widen every year, and power cuts are becoming more frequent and longer, particularly during the dry periods from March to June [4]. For this reason, the government of Mali created policies in 2006 to diversify energy sources and ensure affordable, reliable and sustainable energy for its development. Although the country has enormous potential in terms of solar energy sources, the rate of access to electricity is still low. According to figures for 2021, the rate of access to electricity is estimated at 51% nationally (24% in rural areas and 86% in urban areas), with an increase of around 4% per year (DNE, 2021) [5]. Electricity demand in Mali has historically increased by 10% per year (7.8% per year on average between 2005-2015, due to the marked impact of the crisis period 2012) [5]. In 2018, Mali's energy capacity was 720 MW, with thermal power plants accounting for 72% and solar power less than 1% [6], highlighting the need for better management of photovoltaic (PV) systems. Assessing the solar photovoltaic (PV) potential in sub-Saharan Africa is crucial to understanding the viability of solar energy systems in the region [7], and will enable Mali to plan and implement solar-based electrification projects. Understanding the amount of energy that can be produced from sources such as solar power allows informed decisions to be made about energy investment and infrastructure development. Mali's energy situation is characterised by an energy balance in which biomass accounts for 76% of primary energy, followed by 20% for hydrocarbon imports and 4% for electricity [8]. Mali is potentially rich in renewable energy sources, such as solar energy, the exploitation of which could strengthen the electricity supply to meet the electricity needs of all sectors of activity. The availability of abundant sunshine in Mali offers significant potential for the deployment of solar power plants and other renewable energy solutions.

In terms of solar thermal and photovoltaic energy, the country has 6 to 7 kWh/m^2/d of sunshine, with sunshine reaching around 10 hours a day at certain times of the year [9]. Generally speaking, these figures show that Mali has significant solar potential capable of generating electricity. Mali is home to many rural communities, some of which are unfortunately often deprived of reliable access to electricity. Mali's electricity generation strategy relies solely on hydroelectricity and thermal (diesel) power, although other sources, such as solar power, can be exploited to supplement the electricity supply. Electricity is generated from hydro (48%) and thermal (52%) sources [10]. The largest and most promising renewable energy source (RES) is solar energy (SE). Other renewable energy sources, including wind, water and bioenergy, are directly linked to solar energy. As science and technology develop, the potential for direct solar power generation and heating increases [11]. However, little empirical research has been carried out in Mali to identify the potential of solar photovoltaic resources in these areas. In this context, where there are no clear rules on how to use energy reserves, it is crucial to identify suitable locations for installing photovoltaic solar panels. This makes it possible to determine the amount of solar-generated electricity that can be produced in these specific locations. In this situation, it has been necessary to focus on identifying and assessing the potential for electricity generation because of the pivotal role it has played in developed countries and in technological advances. The use of GIS information systems was necessary in this study given its role in determining solar resources in appropriate locations. These information systems make it possible to analyse spatial data and visualise the relationship between geographical features and energy resources. Given that Mali has a large amount of sunshine for electricity production, solar energy offers a potential source of energy. Solar energy offers an opportunity for the efficient and sustainable development of electricity thanks to its radiation.

Solar energy has the potential to be an economically viable and sustainable source of electricity for the inhabitants of a given geographical area, indicating that the use of solar energy can help to alleviate p However, if the solar system is to be used properly, the solar radiation in the area where it is exposed must be assessed. The aim of this study is to present the methodology used to identify and assess the potential for photovoltaic solar power sources in the appropriate communes in Mali. To do this, we have divided the country into its various communes. The AHP method was used to identify potential sites for solar installation, then evaluated with GIS data including electricity needs per commune, solar radiation and available surface area. Theoretical and technical evaluations were carried out on the basis of this data and the digital terrain model of the study area.

The main objective of the study is to identify and determine the potential for electricity production in rural areas of Mali suitable for the installation of solar photovoltaic systems [12].

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2. Materials and Methods

2.1. Study Area

Mali is a landlocked country in West Africa with a rich history and marked cultural diversity. It is bordered by Algeria to the north, Niger to the east, Burkina Faso and Côte d'Ivoire to the south, Guinea to the south-west, and Senegal and Mauritania to the west. Its capital is Bamako, in the south-west of the country. The country is located in the Sahel-Saharan strip, as part of an alliance known as the Alliance of Sahel States, with a surface area of 1,240,192 km^2. The study area concerns the localities identified for solar PV installation, spread across the territory. The study covers a total of 368 localities deemed suitable for solar PV installations. Figure 1 shows the geographical and administrative location of the localities concerned.

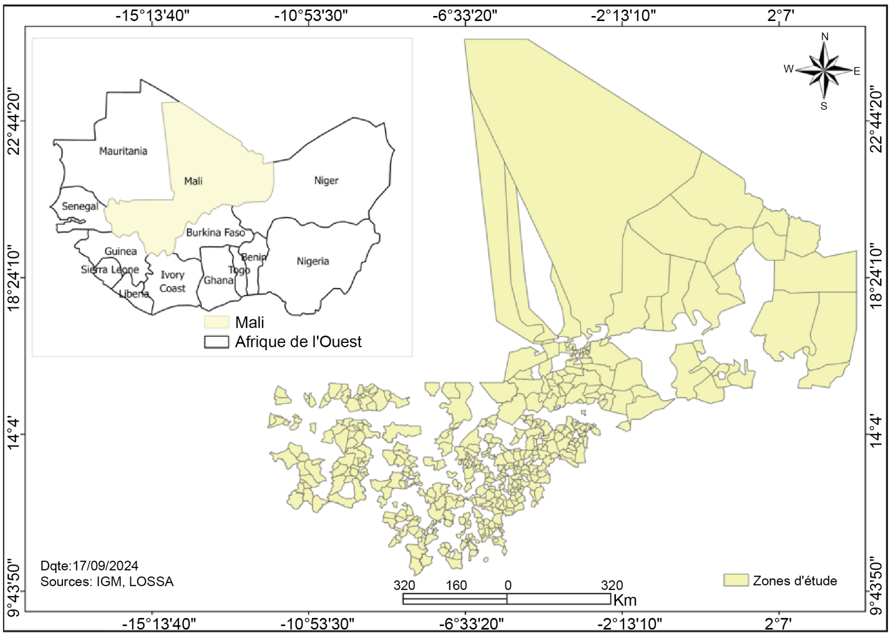

Figure 1. Study area.

2.2. Data and Materials

2.2.1. Materials

Table 1 describes the equipment and software used to generate the necessary information in these municipalities, analyse the data and generate maps.

Table 1. Equipment used.

Names	Utilities
	Devices
GPS	To determine the coordinates of a number of points in the municipalities concerned
Laptop computers	For data analysis and report writing
	Software
PVSyst	Software used in photovoltaic modelling. It provides access to the database based on image processing by the Meteosat Second Generation satellite. It was therefore used as part of this research to process satellite images of the various municipalities concerned.
Microsoft office	The company's proprietary office suite
Excel	used to organise, analyse, view and manipulate data using its spreadsheet, formula and graph functions
PVGIS	Software used in photovoltaic modelling. It provides access to the database built from satellite image processing.
ArcGIS 10.3 and QGIS 3.32.3	This Geographic Information Systems software was used for digitisation (digitisation of maps), file conversion, data editing and modelling, visualisation of the spatial data created, management of spatial information and spatial analysis

2.2.2. Data

For a proper analysis of the errors associated with the data used, in situ values are more reliable. However, it was impossible to obtain IN-SUTI data for solar irradiance and the number of sunshine errors for the entire study area from the Direction de la Météorologie Nationale, due not only to their non-existence, but also to the high cost of the data available for certain sites. Thus, given the inaccessibility of reliable climatic data, satellite data were exploited insofar as, "since the 1960s, meteorological satellites have become one of the preferred instruments for studying the atmosphere".

In order to assess the potential for solar electricity generation in the individual municipalities selected, the data in **Table 2** relating to in situ electricity requirements, solar insolation, solar radiation intensity from the World Solar Atlas and the number of hours of sunshine from the Deutsche Wetterdienst (German Meteorological Service; DWD; https://www.dwd.de), which this institution collected from the national meteorological services reporting on these localities in the country, were used.

Table 2. Data used.

Data	Types	Sources
Administrative boundaries of Mali's communes	Vector	Mali Geographic Institute (IGM) database
Data on electricity requirements	statistis	INSAT data on electrification obtained using the World Bank electricity consumption reports, in rural areas in the Sahel-Saharan strip of West Africa
Solar irradiation potential	raster	Global Solar GIS
Land use	raster	Produced by processing satellite images from the Landsat satellite launched by NASA
Sunshine	in-situ	National weather service station
Irradiance	satellite	From the NASA satellite database
Number of hours of sunshine	raster	Satellite database of the German Meteorological Service; DWD; www.dwd.de

Methodological approach:

The methodological approach used in this study is both qualitative and quantitative.

2.3. Qualitative Analysis to Identify Communes outside the Coverage Network

The qualitative analysis of this study aims to identify communes not covered by existing national electrification services. To do this, we examined areas served by Energie du Mali (EDM-SA) and the Malian Agency for the Development of Domestic Energy and Rural Electrification (AMADER), as well as areas crossed by national power lines but lacking a reliable source of electricity. The aim is to maximize the yield of solar power plants while minimizing the negative impacts associated with their installation. The optimal choice of location for solar photovoltaic (PV) panels is crucial, and several studies have already addressed this issue. In this context, the hierarchical analytical process (HAP), coupled with geographic information systems (GIS), has proven to be an effective method for identifying the most suitable sites for solar installations [13].

GIS was used to analyze spatial data and identify optimal sites for solar photovoltaic installations. AHP, on the other hand, is a structured decision-making tool that enables several criteria to be ranked and evaluated in a systematic way. In this study, the AHP was applied to assess the factors influencing site selection for solar photovoltaic projects. The method is based on the creation of a hierarchy of criteria and alternatives, using binary comparisons and expert opinions to establish priority scales [14].

The selected criteria were standardized according to a continuous scale of suitability ranging from 1 (least suitable or least important) to 9 (most suitable or most important). The process of calculating the relative importance of each criterion, known as criterion normalization [15], created pairwise comparison matrices based on expert opinions. To apply the AHP method, a pairwise comparison matrix was established for the following criteria:

- EDM-SA coverage
- Coverage by AMADER
- Proximity to national power lines

This matrix allows us to determine the relative importance of the criteria by comparing them two by two, using a scale from 1 to 9. The degree of importance of each criterion was determined by comparing the factors and assigning them a weighting coefficient. The pair-wise comparison matrix is shown in **Table 3** below:

Table 3. The pair-wise comparison matrix.

Criteria	EDM-SA	AMADER	Power line
EDM-SA	1	3	5
AMADER	1/3	1	3
Power line	1/5	1/3	1

Relative weights were calculated in two stages:

1. Matrix normalization: Each element of the matrix was divided by the sum of its column.

2. Calculation of weights: The rows of the normalized matrix were averaged to obtain the relative weights.

The results of normalization and weighting are shown in **Table 4** below.

The weights obtained indicate the relative importance of the criteria:

- Areas covered by EDM-SA: 0.633 (most important criterion)
- Areas covered by AMADER: 0.260
- Areas crossed by power lines: 0.106

Table 4. The results of normalization and weighting.

Criteria	EDM-SA	AMADER	Power line	Weight
EDM-SA	0.652	0.692	0.556	0.633
AMADER	0.217	0.231	0.333	0.260
Power line	0.130	0.077	0.111	0.106

Each site (A, B, C, D, E) was then evaluated against these criteria. A binary score was assigned to each criterion:

- 0: Site is covered by service (not desirable for PV installation).
- 1: Site is not covered by the service (desirable for PV installation).

The following matrix results from this evaluation:

Site	EDM-SA	AMADER	Power line
A	0	1	0
B	1	0	1
C	0	0	0
D	1	1	0
E	1	1	1

The scores were weighted by multiplying each score by the weight of the corresponding criterion. For example, for site E:

EDM-SA: $1 \times 0.633 = 0.633$

AMADER: $1 \times 0.260 = 0.260$

Power line: $1 \times 0.106 = 0.106$

Total score: $0.633 + 0.260 + 0.106 = 1.000$

The weighted scores for all sites are as follows:

Site A: 0.260

Site B: 0.739

Site C: 0.000

Site D: 0.893

Site E: 1.000

Site E obtained the highest score (1,000), confirming that it is the most suitable for PV installation, as it is not covered by any of the national energy services. The other sites (A, B, C, D) have lower scores, as they are partially or fully covered by at least one service. Site E was therefore selected for the solar photovoltaic installation due to its "non-coverage" status by EDM-SA, AMADER and the national power lines. The selection criteria used were adapted from renewable energy potential guidelines and Environmental Protection Agency (EPA) location maps.

2.4. Quantitative Analysis

The second stage consists of evaluating the solar production potential of the municipalities selected in the first stage. To do this, we carried out a theoretical assessment on the one hand and a technical assessment on the other.

2.5. Theoretical Evaluation

The theoretical assessment was carried out from two angles: on the one hand, it consisted of determining the solar potential that could cover the needs of the communes, and on the other, the potential available in these locations. In this way, it is possible to determine the extent to which the available resources can meet the study objective.

2.6. Solar Production Potential of the Planned Installation in the Communes to Cover Electricity Needs

Various methods are used to assess the potential for producing photovoltaic solar electricity. The solar resource potential in any specific area is the amount of energy generated by solar radiation in that geographical area. This volume is measured in kilowatt hours (kWh); however, in order to assess the production of solar photovoltaic electricity for a given period, data on the electricity requirement per municipality, solar radiation and GIS data on the useful surface areas for the installation were required in this study.

To assess the need for electricity in the areas concerned, INSAT data on electrification is more reliable. These data are obtained from World Bank reports on electricity consumption in rural areas in the Sahelo-Saharan band of West Africa.

The Bt-electricity requirement per commune, equal to the annual electricity consumption of a single Solar production potential of the planned installation in the communes to cover electricity needs: inhabitant, *i.e.* 116 KWh in Mali (source INSTAT-Mali, 2021) multiplied by the number of inhabitants per commune.

$$BT = BJI*Pt \quad [16] \tag{1}$$

where:

BT-Electricity demand per municipality

BJI-daily electricity consumption per person

Pt-total population per municipality

The Geographic Information System tool, through the administrative shapefile of the study areas, was used to generate the graph representing the need in each commune (**Figure 2**).

In-situ data was used to characterise sunshine. These data were available from various national weather service stations throughout the country. As for solar irradiation data, the Global solarGIS satellite databases were used because, since the 1960s, meteorological satellites have become one of the preferred instruments for studying the atmosphere [17]. Based on the digital terrain model of the study area, the ArcGis Solar Radiation tool was used to model solar irradiation.

Based on this data and the digital terrain model of the study area, we carried out the following assessment: a theoretical evaluation of the surface potential of the planned installation.

The exploitable surface area S- for photovoltaic solar installations per municipality is equal to the ratio between the electricity consumption Bt-(in kWh) and the annual solar irradiation per municipality is expressed (in kWh/m^2).

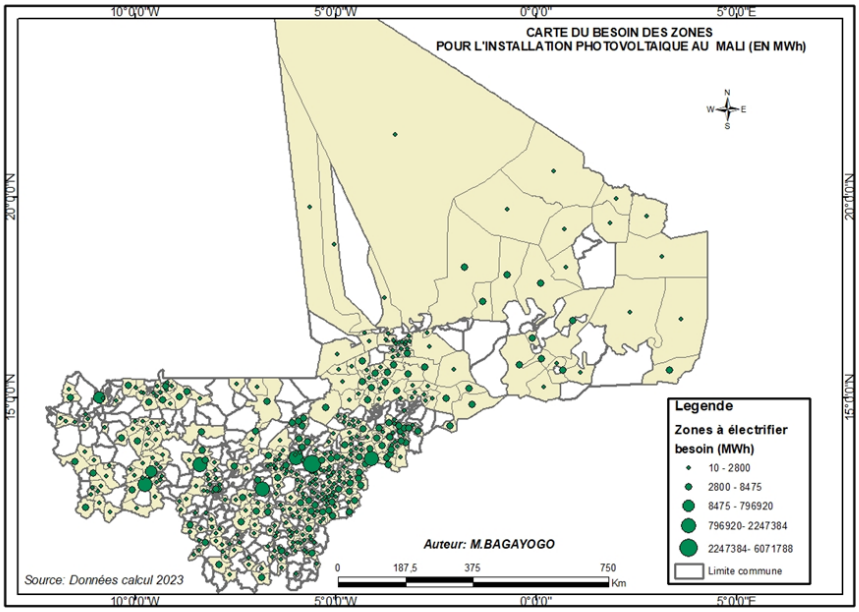

Figure 2. Electricity consumption by municipality.

The exploitable area for solar PV installations of any specific zone expressed in square metres is the area reserved for the solar field of that zone.

The annual solar irradiation per municipality Is-expressed (in kWh/m^2) obtained from the Global solar GIS satellite databases was used.

Theoretically, the surface area of the installation by the various municipalities concerned can be expressed as follows:

$$S_p = \frac{B_T}{I_S} \tag{2}$$

or:

S_p : exploitable surface area of the local authority's solar installation

B_T : Electricity requirement of the municipality concerned in the study area (in kWh).

I_S : Solar irradiation intensity of the municipality concerned in the study area (in kWh/m^2).

We determined the solar potential of the installation planned to cover the B_T requirement using the theoretical formula:

$$RPge = S * Hr * Ts \text{ [11]} \tag{3}$$

or:

RPge- theoretical natural resource potential

S- exploitable surface area of the facility

Hr- average monthly solar radiation intensity per (MW/km^2)

Ts - the number of hours of sunshine per municipality over the year.

The amount of photovoltaic solar energy produced by PV technology per commune is evaluated by the formula:

$$EA = APV * HR * \eta P * (1 - \lambda p) * (1 - \lambda C) \quad \text{[11]} \tag{4}$$

or:

EA - is the annual production capacity of the PV system (in kWh/year)

APV - is the exploitable surface area of the installation concerned (in m^2)

HR - the value of solar radiation in one year or irradiation (in kWh/m^2)

ηP - Module efficiency

λp - module loss due to various causes (10%),

λC - losses due to PV battery cooling (5%).

Assessment of available potential per site (surface potential):

Only municipalities (communes) with sufficient available area for solar fields and with the potential to meet their electricity needs through solar energy will be selected in this phase for more detailed assessments.

The available potential per site, or surface potential, refers to the surface resources that can be used to produce solar electricity. To assess this potential, we have considered two types of surface: the roofs of buildings and undeveloped areas.

Building roofs: The theoretical potential for roof space was calculated on the basis of the total surface area of buildings in 2023 in each municipality. Data from digital building files, obtained from satellite images, was used to extract the roof surfaces available for the installation of solar panels. These areas were then mapped using ArcGIS.

Undeveloped land: With regard to undeveloped land, the focus was on land that is not used for any purpose, such as agricultural land (**Figure 2**), watercourses (**Figure 3**) and built-up areas (**Figure 4**).

Once these land uses have been extracted from the available area, the remainder is undeveloped land. As a result, the surface area of roofs will be added to that of undeveloped areas, giving an overall total of available surface area per site.

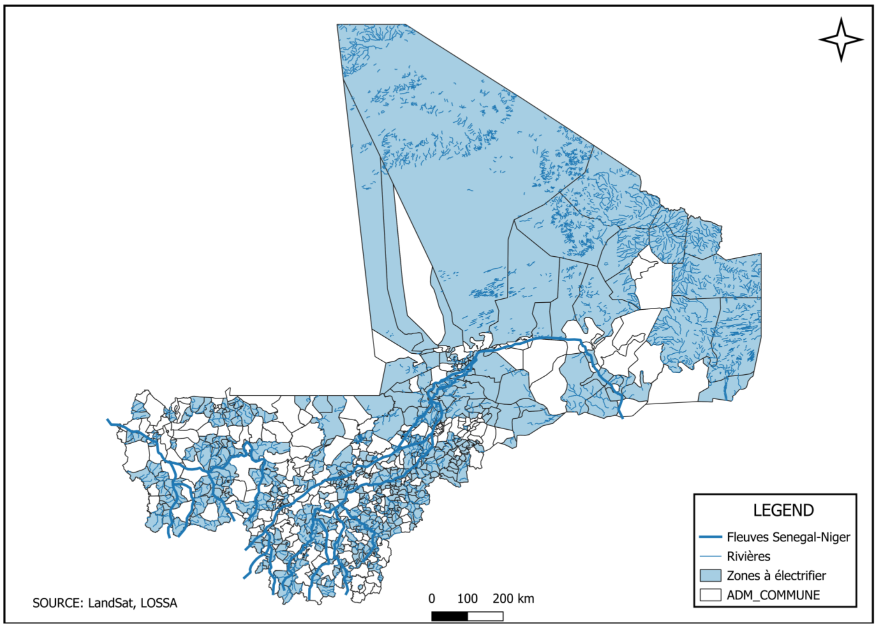

Figure 3. Distribution of surface area occupied by watercourses by municipality.

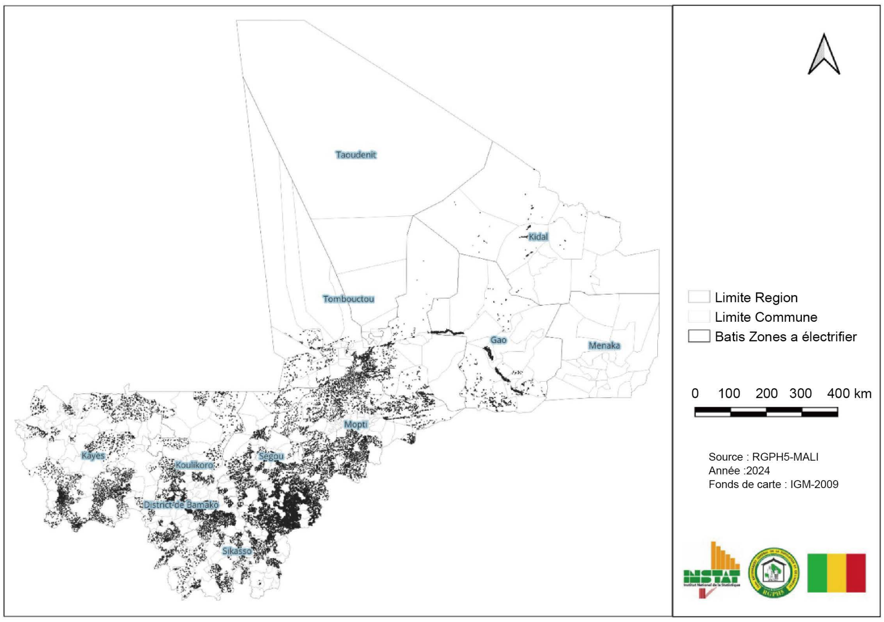

Figure 4. Breakdown of surface area occupied by buildings in communes for PV installations.

The availability of land for solar installations is strongly influenced by existing land uses, such as built-up areas, watercourses and cultivated areas. A methodical approach using GIS and a careful assessment of land use conflicts was carried out to identify the areas available and suitable for solar installations. For the assessment of solar and electricity generation potential, we selected sites that met these various criteria.

The solar potential and the available electricity generation potential are calculated using the theoretical formulae (5) and (6) respectively:

$$RPge_D = S_D * Hr * Ts \quad [11] \tag{5}$$

or:

$RPge_D$ - theoretical natural resource potential available per location.

S_D - area available per site.

Hr - solar radiation intensity per municipality or average monthly insolation (MW/km^2).

Ts - number of hours of sunshine per municipality over the year.

$$EA_D = APV_D * HR * \eta P * (1 - \lambda p) * (1 - \lambda C) \quad [11] \tag{6}$$

or:

EA_D - is the annual production capacity available per site (in kWh/year)

APV - is the available surface area per site (in m2)

HR - the value of solar radiation in one year or irradiation (in kWh/m2)

ηP - module efficiency

λp - module loss due to various causes (10%),

λC - losses due to PV battery cooling (5%).

Technical assessment: Technically, to assess the potential available for solar photovoltaic installations, we took into account 50% of the total available built and unbuilt surface area of each municipality. This approach enabled us to obtain a realistic estimate of the solar potential, taking into account the practical constraints linked to the use of the surfaces. As a result, the technical potential for electricity production has been assessed on the basis of 50% of the theoretical potential of the available surface areas per municipality.

3. Result

3.1. Maps of Localities Not Served by Electricity Companies

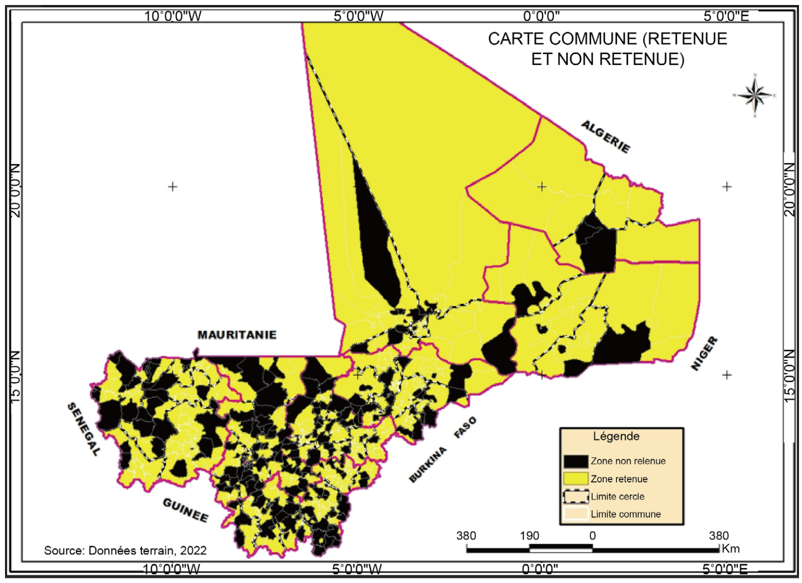

Figure 5. Zones selected for solar photovoltaic installations.

Several factors are taken into account when setting up a project to select suitable sites that contribute to the efficiency and yield of solar energy production. The Sahel-Saharan strip in general, and Mali in particular, benefits from significant solar radiation. Therefore, the most important factor to consider in our selection criteria was the inaccessibility of the sites to national energy services. The qualitative analysis revealed that the most suitable sites for the installation of solar photovoltaic panels were sites located in areas not covered by the national electrification services, namely EDM-SA and AMADER. These surveys have enabled us to identify the areas covered by these services and the areas not covered by the electrification services. Localities that meet the standards for the installation of solar power plants are selected on the basis of various selection criteria. In the light of these criteria, it emerges that of the 703 communes in Mali, 70 are served by EDM-SA, 117 are served by AMADER and 81 communes are crossed by the national power line. In all, 435 communes or localities have no reliable access to electricity. Given the criteria for selecting sites for solar photovoltaic installations, namely the abundance of solar resources and the inaccessibility of the sites to electrification services, these communes are deemed suitable for the installation of solar power plants (**Figure 5**).

In **Figure 5**, the municipalities selected for solar photovoltaic installations are highlighted in yellow. These municipalities are potential sites for solar photovoltaic installations provided they meet the selection criteria. We can see that, 61% of localities are not served by national electrification services.

3.2. Estimation of Photovoltaic Energy to Be Produced

In Mali, energy consumption and electricity production have never been balanced due to rapid population growth and dependence on two energy sources: hydroelectricity and thermal energy. To meet these challenges, assessing the surface area and solar potential of the proposed installation for each municipality is an important step in setting up a solar photovoltaic project.

The exploitable surface area planned for solar photovoltaic installations in a given area, expressed in square metres, is the surface area reserved for the solar array. This area represents the surface area of the solar array for all the municipalities included in the qualitative analysis. The solar potential of an area is proportional to the number of hours of sunshine and the intensity of solar radiation in the area, and is 341397.173 MWh for all areas. As for the electricity production potential, it is proportional to the solar production capacity per zone, irradiation (in kWh/m^2), the efficiency of the modules and the various losses in the system and is equivalent to 3496960.35 KWh. **Figure 6** and **Figure 7** show the predicted solar potential and the predicted electricity production potential respectively.

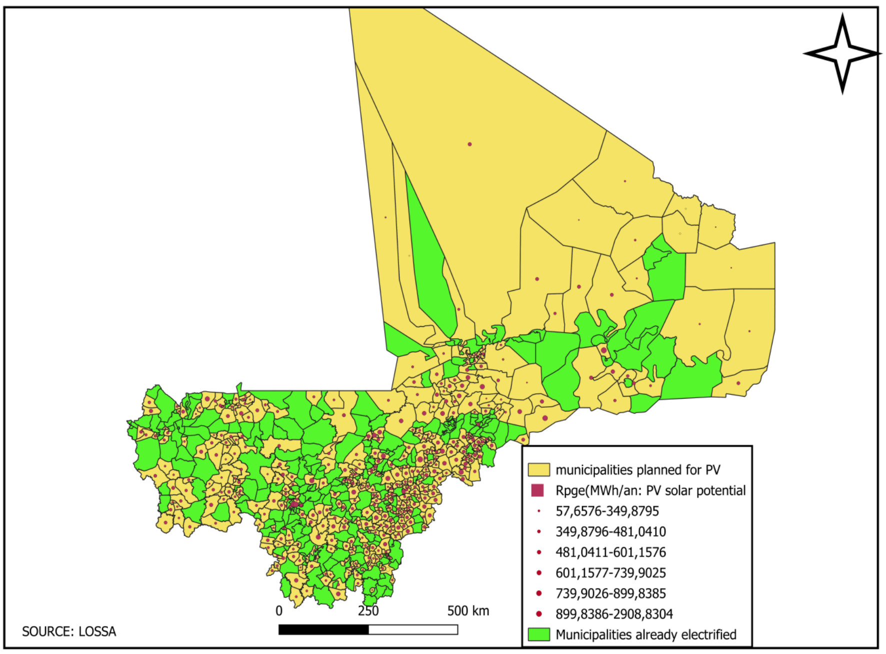

Figure 6. Breakdown of projected solar potential by municipality to cover electricity needs.

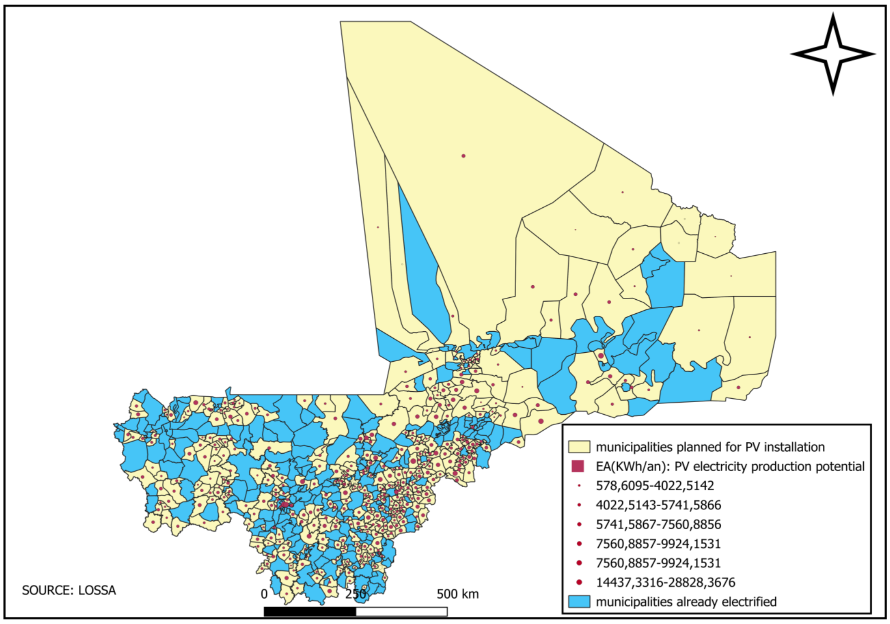

Figure 7. Breakdown of electricity generation potential by municipality to cover demand.

3.3. Availability of Electricity Generation Potential

Of the 435 municipalities (communes) deemed suitable by the analysis, a subsequent quantitative analysis was carried out to further refine the selection. This analysis focused on assessing the surface area actually available for solar installations. The quantitative analysis, through the assessment of the area actually available apart from other land uses, revealed that 26 communes, although deemed suitable during the qualitative assessment, did not have sufficient usable area to cover the estimated electricity needs in these communes. Following this rigorous assessment of the available surface area through quantitative analysis, 409 communes remained suitable for photovoltaic installation. We can see that, 68% of localities are not served by national electrification services. These communes were further analysed to determine their potential for producing solar energy and electricity, to ensure that the sites selected could not only accommodate solar panels, but also generate enough energy to meet local demand.

In order to calculate the theoretical potential of buildings, data on the total surface area of buildings by 2023 in all of the municipalities concerned by the solar photovoltaic installation was used. Using data from the digital raster file of buildings in the study area (source INSAT), geographic information system software was used to extract the surface area of the buildings. The map generated by the ArcGIS geographic information system software represents the built-up area in the municipalities concerned. This value varies from one municipality to another and is equivalent to 84697.17 ha for all the municipalities.

For undeveloped areas suitable for solar photovoltaic installations, the surface area covered by watercourses, estimated at 3611054.11 ha, and that occupied by agricultural areas, estimated at 11,137,097 ha, were evaluated. This represents a total of 14,748,151 ha, once extracted, the remainder is added to the potential surface area of built-up areas to find the surface area actually available as a theoretical potential surface area for solar photovoltaic installation. This available surface area suitable for solar installations is 83750721.5 ha. This represents the potential surface area available and suitable for photovoltaic solar installations.

Figure 8 and Figure 9 show, respectively, the solar potential and electricity production available in the municipalities selected after the various analyses. The solar potential of the communes is estimated at 8.50571*10 + 11 MWh and the electricity production potential at 8.5102*10 + 12 KWh.

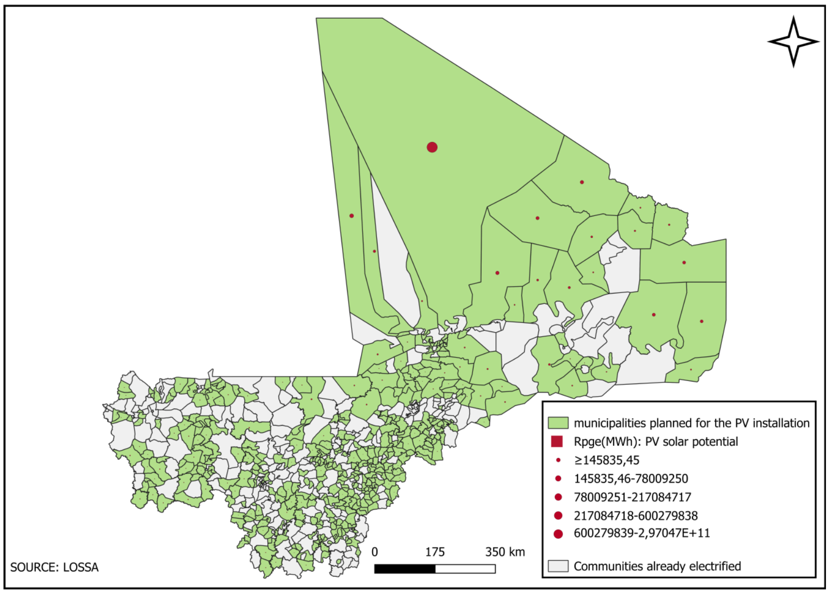

Figure 8. Available solar potential by municipality in the study area.

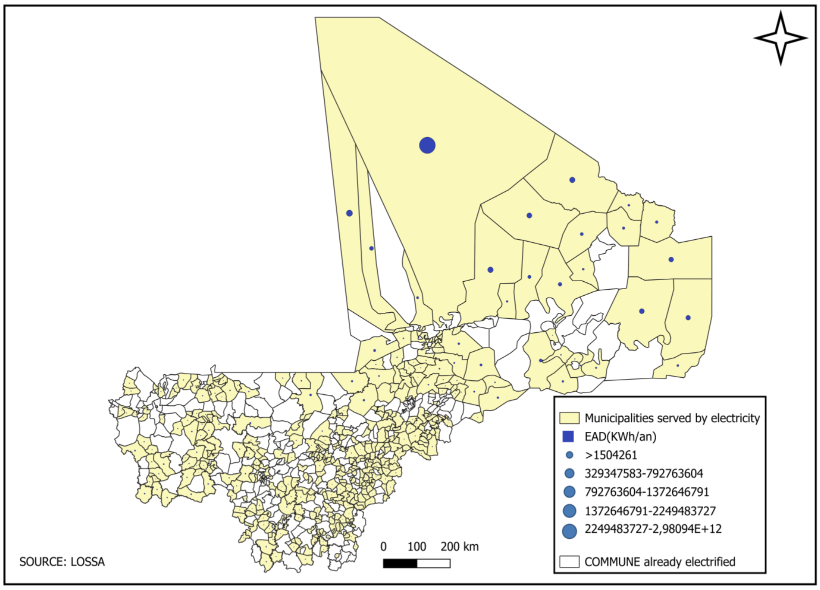

Figure 9. Available electricity generation potential by municipality in the study area.

3.4. Assessment of the Technically Feasible Potential for Photovoltaic Solar Energy

However, the entire roof surface of a house cannot be used for solar installations because of the architectural configuration of the buildings, with some houses having flat roofs and others sloping roofs. Added to this is the space reserved for other uses, so we consider that only 50% of the surface area of buildings could be used, for each municipality. Given the competition with other land uses, it is also agreed that only 50% of the sloping surface is technically exploitable for each of the municipalities. Consequently, the technically available area is: 41875360.75 ha, making a total of the technically available area for each municipality. The technical solar potential generated by this surface is 4.25285*10 + 11 MWh for an electricity production of 4.2551*10 + 12 MWh.

4. Discussion

For the identification of suitable sites, the Analytical Hierarchy Method (AHP) was used to assess the suitability of the site for PV installations. The methodology used took into account factors such as the abundance of solar resources (sunshine, global horizontal irradiation, etc.), and the inaccessibility of national electrification services. The methodology used here highlights the challenges posed by inaccessibility to reliable electrification services that can hamper effective data collection and analysis. A similar methodology used by Wilson and Camile, in the study entitled "Identification of favourable sites for the installation of solar photovoltaic power plants using multicriteria analysis and GIS: the case of the Bélabo district, Cameroon", is consistent with the present study. Their work took into account factors such as irradiation, land use, topography, humidity and temperature. In addition, a study by Tunc *et al.* entitled "GIS-based site selection for solar power plants using the hierarchical analytical process (HAP) in Istanbul, Türkiye" [19], used the HAP approach to weight the different criteria and prioritise them according to their suitability for the project objectives. The results were then mapped using a Geographic Information System (GIS) to facilitate the selection of the optimal site for the installation of solar power plants in Istanbul. In order to determine the potential for solar photovoltaic electricity generation in our context, a theoretical and technical assessment was carried out, enabling the potential for electricity generation in the rural municipalities concerned to be evaluated. A similar study carried out by Poneabo and Tchawa, this time in Cameroon, on the "evaluation of the solar photovoltaic potential in the Littoral Sud-Camerounais" [19], used the same theoretical and technical evaluation method. It enabled the theoretical and technical potential of the Littoral Sud-Camerounais to be assessed.

On the other hand, other different methods are used to assess the production potential of solar photovoltaic resources, as in the case of the Ethiopian study "Feasibility and Assessment of Solar Resource Potential: A Case Study in the North Shewa Zone, Amhara, Ethiopia" [20], which uses advanced modelling techniques using HOMER (hybrid optimisation of multiple renewable energies) and Malab software. This approach allows a comprehensive analysis of the different renewable energy sources, optimising their integration and assessing their feasibility on the basis of extensive meteorological data collected from NASA and local meteorological centres. In summary, both assessment methods provide valuable methodologies in the field of solar energy assessment, adapted to their respective contexts. The Ethiopian study's use of advanced modelling techniques contrasts with the Malian study's focus on factors related to solar resources, land use and accessibility issues, highlighting the different approaches needed to address solar energy challenges in different communes. Together, they highlight the importance of context-specific methodologies to optimise the use of solar resources and address the unique challenges faced by communities in Ethiopia and Mali. This study focused on factors such as the abundance of identified solar resources (the intensity of solar irradiation), useful surface areas and the efficiency of solar systems in order to assess the theoretical potential for the installation of power plants. The same factors were taken into account in a similar study by Gulaliyev *et al.* on "Evaluation of solar energy potential and its ecological and economic efficiency: the case of Azerbaijan" [11], which mentions that the theoretical potential can be expressed, probably by means of a formula or mathematical model. This indicates a modelling stage, where the relevant parameters are taken into account, such as solar resources and the surface area suitable for installing small panels, in order to estimate the potential. The assessment of the available potential corresponds to 50% of the estimated potential to cover the need. It can be seen that the available electricity generation potential exceeds the estimated potential to cover electricity needs by 1.25 Gwh. The results indicate that the energy produced from the solar potential available in rural areas of Mali is more than sufficient to meet electricity demand, demonstrating the viability of solar installation projects for electrification.

5. Conclusions

In this study, the results obtained following the application of the methodological approach taken, both qualitatively and quantitatively, to the evaluation of solar potential and the potential for electricity production in rural areas of Mali in need of electrification, clearly demonstrate that the country has a strong solar potential which it must take advantage of to diversify its energy production sources in order to optimise its electricity production. The amount of solar production assessed in the various communes confirms the feasibility of solar projects. These results are consistent with previous research carried out in sub-Saharan Africa on the identification of optimal sites for the installation of solar photovoltaic systems. Indeed, these different results have enabled us to understand that the Sahelo-Saharan strip has sufficient solar potential to meet electricity needs, thus reinforcing the relevance of solar projects in Mali.

In this study, the results revealed that the theoretical potential for solar production to cover the needs of the municipalities deemed suitable for solar photovoltaic installations is estimated at 341397.1732 MWh, with an estimated electricity production capacity of 3496960.355 KWh. However, given the constraints associated with land use, the potential available to cover this requirement, in terms of surface area that can actually be exploited, is 52191222.5 hectares, generating a potential of 8.50571E+11 MWh for an electricity production of 8.5102E+12 KWh. The analysis of the project's technical feasibility, taking into account other surface uses, took into account 50 per cent of the available potential, *i.e.* 26095611.25 ha of technically exploitable surface with a solar potential of 4.25285E+11 MWh for an estimated electricity production capacity of 4.2551E+12 KWh. These technical results, which far exceed the estimated potential requirement, confirm the feasibility of solar installation in the areas identified, demonstrating that the technically available surface area is sufficient to meet the municipalities' energy production objectives.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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