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Assessment of the Photovoltaic Solar Potential of Buildings for the Electrification of Communities Not Connected to the National Grid in Mali

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Abstract

The assessment of solar energy potential in the Sahel region, particularly in Mali, has made significant progress due to various geographic, environmental, and socioeconomic factors. This study focuses on assessing the solar potential of buildings in rural areas of Mali, specifically excluding grid-connected electrification systems. It highlights the transition from initial feasibility studies to comprehensive assessments that take into account the lack of electrification services and the region's abundant solar resources. The study identifies optimal rooftop sites for the installation of solar photovoltaic systems in rural municipalities in Mali that are in need of electricity. The methodology uses the Analytic Hierarchy Process (AHP) to prioritize key criteria, such as the absence of reliable electrification services, the availability of solar resources, and space for installing solar panels. In this study, the assessment of the solar potential of buildings covered 547 municipalities, which were identified and deemed suitable using the Analytic Hierarchy Process (AHP) method for solar photovoltaic installation. These municipalities are spread across the entire country, specifically in rural and peri-urban areas of Mali with varying levels of solar radiation. The theoretical surface area potential of available and unused buildings is estimated at 84697.17 hectares. After taking other land uses into account, the technical potential is estimated at 50% of this area. The available solar potential is quantified at 819445297.61 MWh, representing an estimated annual electricity generation of 348601162.21 kWh. These results highlight the viability of solar projects in these areas, with an installed capacity of 3.17 kWp capable of

replacing carbon-based energy sources, thereby helping to reduce negative environmental impacts. The study concludes that the region has strong potential for solar energy projects, particularly on building rooftops, which can effectively replace carbon-based energy sources that have a negative impact on the environment. This represents a significant opportunity for sustainable energy development in rural areas of Mali.

Subject Areas

Electric Engineering

Keywords

Assessment, Potential, Photovoltaic Solar Energy, Rural Areas, Buildings

1. Introduction

An analysis of the electricity generation mix reveals a strong dominance of hydropower, which accounts for 57.86% of total generation. This dominance reflects a significant dependence on water resources, often driven by the availability of waterways and existing hydropower infrastructure. This situation offers advantages in terms of low greenhouse gas emissions, but also exposes the energy system to risks associated with climate variability, particularly in the event of drought. In second place, thermal power generation accounts for 42.04%. This significant share reflects the crucial role of thermal power plants in balancing the electricity grid, particularly to compensate for the intermittency or shortfalls in hydroelectric generation. However, this reliance on thermal sources—which are generally based on fossil fuels—poses major environmental challenges due to CO_2 emissions and the costs associated with fuel imports. In contrast, solar energy sources other than PV remain marginal, contributing only 0.10 percent. This low proportion highlights a largely untapped potential, particularly for resources such as solar energy, which is especially abundant in many Sahelian regions. Developing this energy source could help diversify the energy mix, strengthen the resilience of the electricity system, and reduce dependence on fossil fuels [1].

According to 2021 figures, the electricity access rate is estimated at 51% nationwide (24% in rural areas and 86% in urban areas), with an annual increase of approximately 4% [2].

In Mali, electricity generation capacity relies on various power plants, with a total capacity of 540.2 MW. This capacity, derived from various power plants, meets a large portion of the country's energy needs. During the period under review, these facilities generated a total of 1441.21 GWh of electricity (EDM-SA Report, report of the Electricity and Water Regulatory Commission).

Electricity demand in Mali has increased by 10% per year, or an average of 7.8% per year between 2005 and 2015 [3]. The country receives 6 to 7 kWh/m^2/day of

solar radiation, reaching approximately 10 hours per day during certain times of the year [4] [5]. In 2018, Mali's total energy capacity was 720 MW, with thermal power plants accounting for 72% and solar energy for less than 1% [6]. To ensure the effective operation of a solar system, it is necessary to assess solar radiation at the site where it will be installed; therefore, this study sets the following objectives:

First, to present a methodology designed to identify suitable locations for solar installations in rural areas not connected to the national grid. Second, to assess the photovoltaic solar potential in these rural areas to meet electricity needs.

The search for a potential site for a photovoltaic installation is based on a multi-criteria approach, which requires a good balance between economic, social, and environmental criteria. This approach makes it possible to identify the most favorable sites by taking into account all the constraints and opportunities associated with their operation [7]. The use of solar energy at the building level remains limited, particularly by the available surface area of the building envelope. Thus, solar potential corresponds to the portion of solar energy received by the building envelope that can actually be harnessed to meet the building's energy needs [8].

Knowing the solar potential of a roof provides an estimate of the electrical power—and thus the amount of electricity—that the future photovoltaic system can generate.

2. Methodology

2.1. Study Area

However, for the purposes of this study, the administrative structure of Mali is analyzed based on data from the RPGH-5, which has a slightly different structure than the RPGH-4. The study area consists of 815 municipalities, 29 of which are urban (**Figure 1**) [9].

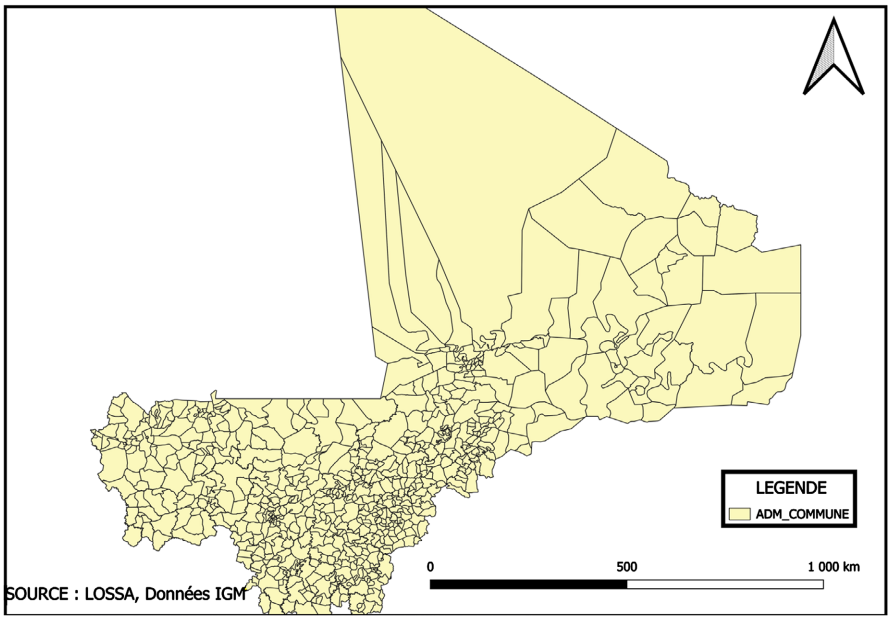


Figure 1. Study area.

2.2. Equipment

Conducting this study required the use of various pieces of equipment and computer tools, including a GPS device for collecting and geolocating field data, as well as Excel, PVGIS, ArcGIS 10.3, and QGIS 3.32 for processing, analyzing, and visualizing the data.

2.3. Data

The study draws on several sources of geographic, meteorological, satellite, and statistical data necessary for analyzing photovoltaic solar potential and identifying areas suitable for electrification. The main data used are as follows: the administrative boundaries of municipalities from the IGM vector database; data on electricity demand in rural areas, derived from INSAT electrification data; global solar irradiance data from satellite databases such as Global Solar Atlas/GIS; land-use data obtained from NASA's Landsat satellite imagery; sunshine duration data from national meteorological service stations; data on average monthly solar radiation intensity derived from satellite data; data on the number of hours of sunshine, extracted from the German Weather Service (DWD) satellite database; and data on built-up areas in the various municipalities, provided in shapefile format by the Geographic Institute of Mali.

2.4. Methodological Approach

2.4.1. Qualitative Analysis

Assessing the geographic distribution of access to electricity is an essential step in effective electrification planning. In this context, the Analytic Hierarchy Process (AHP), combined with geographic information systems (GIS), is a relevant method for identifying and prioritizing the areas with the greatest needs for photovoltaic electrification [10]. To facilitate decision-making, selection options and evaluation criteria were defined.

Municipality Selection Options:

The selected options make it possible to distinguish municipalities based on their level of access to electrification services and, consequently, their priority level for the deployment of decentralized photovoltaic systems:

- Option 1: priority municipalities, corresponding to those with no access to electrification services;
- Option 2: Lower-priority municipalities, comprising those that have at least one electricity service.

Selection Criteria

The selection of municipalities is based on three criteria related to the current or projected availability of electricity services:

- Criterion 1: Electricity service coverage by EDM-SA;
- Criterion 2: Electricity service coverage by AMADER;
- Criterion 3: Plans for an expansion of the national power grid.

For each of these criteria, a binary score was assigned to characterize the situa-

tion in each municipality:

- ✓ 0: Access to electricity is not guaranteed in the municipality;
- ✓ 1: Access to electricity is guaranteed or planned in the municipality according to the criterion in question.

Based on this classification, municipalities that lack any electrification services and are not included in grid expansion plans were identified as the highest priority areas for the deployment of decentralized photovoltaic systems. These municipalities thus constitute the set selected for the analysis of photovoltaic potential.

The location, boundaries, and spatial classification of the municipalities were determined using QGIS software, which allowed for the cross-referencing of various geographic layers and the categorization of municipalities according to their priority level. The results of this classification are presented in Table 1 and Table 2.

Table 1. Evaluation matrix for localities.

Locations	EDM-SA	AMADER	RI Extension
Location A	1	0	1
Location B	0	1	0
Location C	1	1	1
Location D	0	0	1
Location E	0	0	0

Table 2. Site selection criteria table.

Localities	Covered by EDM-SA	Covered by AMADER	RI Expansion Plan	Status
Sites A	yes	No	yes	**Covered**
Sites B	No	yes	No	**Covered**
Sites C	yes	yes	yes	**Covered**
Sites D	No	No	yes	**Connection**
Sites E	No	No		**Off-grid**

Using QGIS 3.36.3 software, we identified the various municipalities that met these criteria and classified them by locality, for a total of 547 municipalities.

2.4.2. Quantitative Analysis

- Estimation of Photovoltaic Energy to Be Generated:

A municipality's electricity demand is calculated by multiplying the daily, monthly, or annual consumption of a typical person (Bji) by the total population (Pt) of that municipality. This method is based on a linear approach to energy

demand grounded in individual needs. This method is particularly well-suited for rural areas where detailed consumption data are not always available. It was used by Ebhota & Tabakov (2022) to model local energy needs based on demographic parameters [11]:

- ✓ $B_T = B_{ji} * P_t$ **(Eq1)**; where B_T is the municipality's electricity demand, which is 116 kWh in Mali;

- The planned installation area for each municipality [12]:
  - ✓ $S_p = \frac{B_T}{I_S}$ **(Eq2)**; or:
  - ❖ B_T (in kWh): Electricity demand per municipality
  - ❖ I_S (in kWh/m²): the average global solar irradiance
- The available solar potential for each municipality [13]:
  - ✓ $RPge = S_p * H_r * T_s$, where H_r is the average monthly irradiance (MW/km²)
- Electricity generation by municipality [13]:
  - ✓ $EA = S_p * H_R * \eta_p * (1-\lambda_p) * (1-\lambda_C)$

or

- ❖ H_R : total solar irradiance (in kWh/m²/year)

- Solar and electricity generation potential of buildings for each municipality [13]:
  - ✓ $RPge = S_B * H_r * T_s$
  - ✓ $EA = S_B * H_R * \eta_p * (1-\lambda_p) * (1-\lambda_C)$
- Potential availability: The availability of built-up areas is equal to 50% of the solar potential of the built-up areas for each municipality.
  - ➢ $RPge_D = 50\% * RPge$
  - ➢ $EA_D = 50\% * E_A$

3. Results and Discussion

3.1. Maps of Localities Not Served by Electric Utilities

Figure 2 below shows the geographical distribution, by municipality, of the various localities served and not served by the national electrification services. The area colored black consists of localities with access to electricity, totaling 268 localities. In contrast, the area colored yellow consists of localities with no access to any electrification services, totaling 547 municipalities spread across the entire national territory.

Figure 2 below highlights an uneven spatial distribution of access to electricity nationwide. The 268 municipalities that are currently served or scheduled for service are shown in black, while the 547 municipalities that are not served are shown in yellow. This high proportion of unserved municipalities underscores the persistence of regional disparities in electrification and highlights the need to develop decentralized solutions—particularly solar photovoltaics—for off-grid areas. In other words, 67% of rural localities are not served by the two national electrification services.

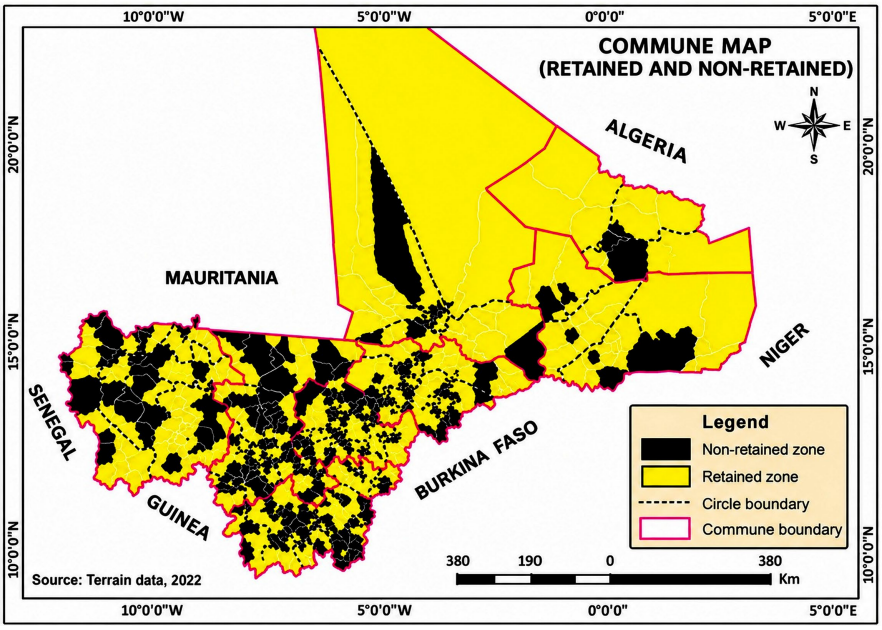


Figure 2. Off-grid communities suitable for photovoltaic systems.

3.2. Estimating the Amount of Photovoltaic Energy to Be Generated

The map shown in Figure 3 illustrates a positive correlation between electricity demand (orange/dawn areas) and the solar potential to be harnessed (red pie charts).

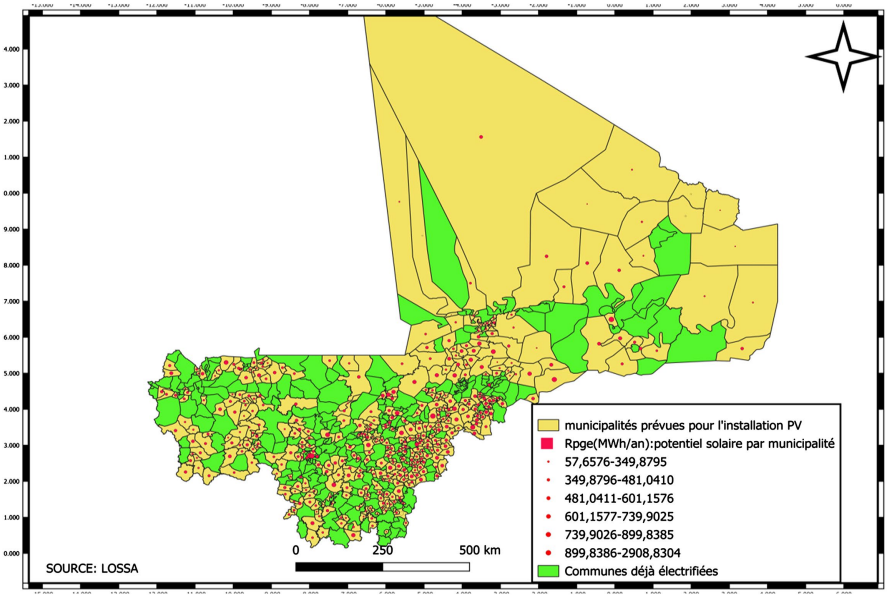


Figure 3. Estimated solar potential by municipality to meet demand.

The map in Figure 3 reveals a proportional relationship between the energy needs of municipalities (orange areas) and their exploitable solar potential (red diagrams). This trend suggests that the localities with the greatest electricity defi-

cits also have favorable solar resources, making photovoltaic energy a suitable solution. Thus, the higher the demand for electricity, the greater the projected solar potential, which justifies targeted investments in these areas. A total of 341397.17 MWh can be generated across the region. This relationship suggests that localities (municipalities) not served by national energy services but suitable for solar PV installations are also those where sunlight levels are sufficient to justify investments in solar photovoltaic solutions.

Consequently, the map shown in Figure 4 provides a breakdown of projected electricity production by municipality.

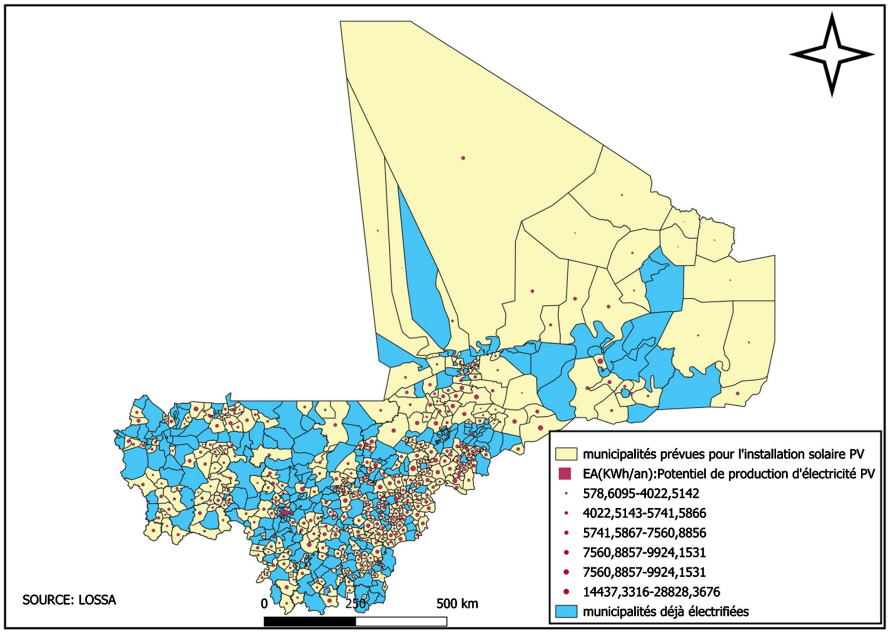


Figure 4. Projected electricity generation potential by municipality.

The map shown in Figure 4 highlights a direct correlation between high solar potential (red pie charts) and actual solar electricity generation in the municipalities (pink/beige areas). This relationship confirms that areas with high levels of sunshine have greater energy conversion capacity, resulting in higher electricity generation. High demand for electricity requires greater utilization of solar resources, thereby increasing production. This dynamic demonstrates the relevance of decentralized solutions in areas of Mali not covered by the electricity grid, where sunlight is abundant.

3.3. Solar Potential on Built-Up Areas for Each Municipality

The solar potential on built-up areas is estimated at 84,697 ha. Taking into account the 50% available area, this potential amounts to 42348.59 ha. The map shown in Figure 5 below provides a municipal breakdown of the available solar potential on built-up areas.

The solar potential of built-up areas is estimated at 84,697 ha across the municipalities studied. Assuming that 50% of this area is actually available and suitable

for the installation of photovoltaic systems, the usable area is estimated at 42348.59 ha. This area represents considerable spatial potential for the development of photovoltaic power generation, particularly in municipalities that are not served or are inadequately served by the national power grid.

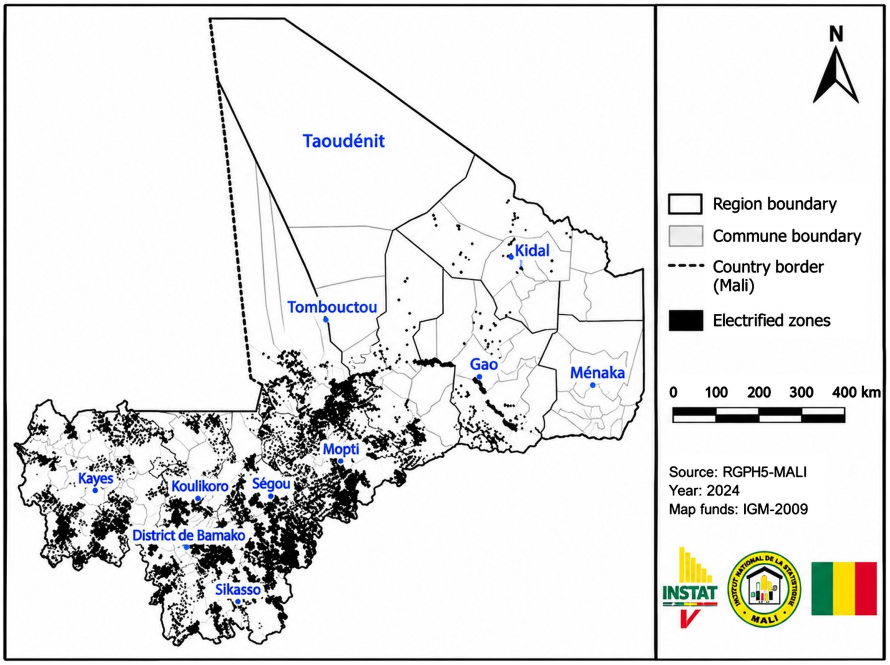


Figure 5. Solar potential on built-up areas by municipality.

3.4. Solar Potential per Built-Up Area

Figure 6 below shows the spatial distribution of photovoltaic solar potential across the various municipalities of Mali. It illustrates the regional disparities in potential and identifies the municipalities offering the most favorable conditions for the development of photovoltaic power generation.

This result highlights the considerable photovoltaic solar potential of built-up areas. Even when considering only 50% of the available surface area, the estimated potential reaches 311,921 × 10^3 MWh, which is approximately 914 times the electricity demand to be met. This significant margin between available potential and demand shows that built-up areas could serve as a major driver for the electrification of unserved communities, subject to technical, economic, and site accessibility constraints.

3.5. The Potential for Solar Electricity Generation on Built-Up Areas

Figure 7 shows the distribution of the theoretical and technically exploitable photovoltaic solar potential at the municipal level. The theoretical potential is estimated at 6397.75 × 10^6 kWh, and, assuming 50% of the available area is utilized, the technically exploitable potential is estimated at 3198.87 × 10^6 kWh—approximately 914 times the electricity demand to be met.

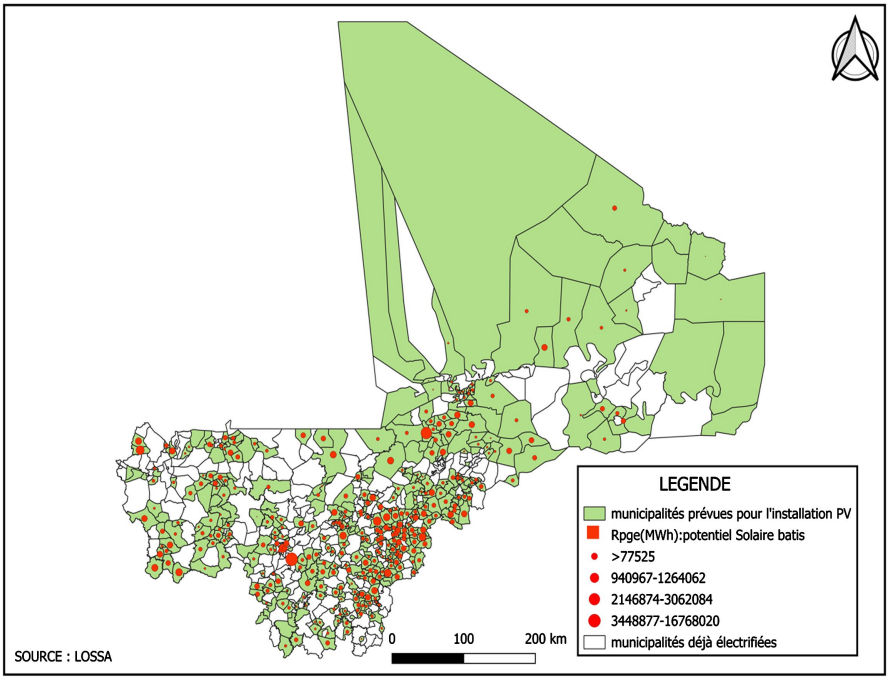


Figure 6. Available solar potential of built-up areas.

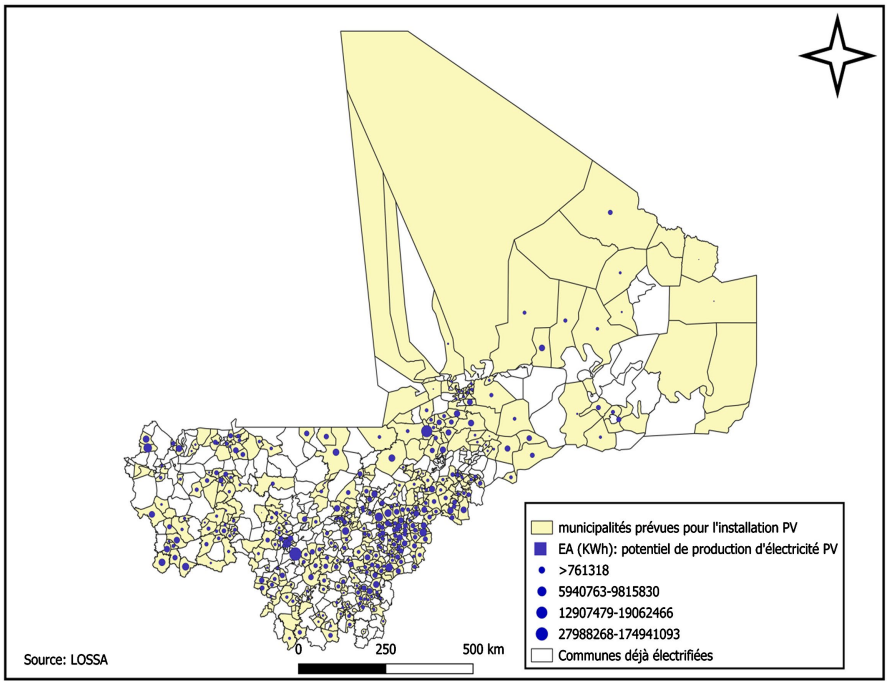


Figure 7. Solar electricity generation potential in built-up areas.

These results demonstrate the significant photovoltaic potential available to meet the electricity needs of the municipalities studied. Despite the 50% reduction resulting from the assumption that only 50% of the areas are available, the technically exploitable potential remains very high, at 3198.87×10^6 kWh—approximately 914 times the electricity demand. This significant surplus capacity under-

scores the value of solar photovoltaics as a sustainable solution for improving access to electricity, particularly in municipalities not connected to the national grid.

4. Discussion

Similar studies have been conducted: [14] in the Cameroonian Littoral region; [7] in Bélabo, also in Cameroon, on "the assessment of the photovoltaic solar potential of buildings", [15] in Istanbul, Turkey, on the selection of sites for solar power plants using a geographic information system and the analytic hierarchy process, employed the same evaluation method in these locations;

In addition, a study conducted along the same lines [16] assessed the solar potential of buildings in countries such as Algeria, South Africa, and Nigeria. These results indicate that areas in Sub-Saharan Africa have high potential.

In contrast, other methods are used to assess the potential of built-up areas, using LiDAR datasets and a GIS-based approach, as was the case [17]. In summary, these various assessment methods provide valuable methodologies in the field of solar energy evaluation, tailored to their respective contexts. The results indicate that the energy generated from the solar potential of buildings is more than sufficient to meet electricity demand, thereby demonstrating the viability of solar installation projects on built-up areas in sub-Saharan Africa.

5. Conclusions

Theoretically, the electricity generation potential of the buildings is estimated at 6397.75×10^6 kWh. Taking into account the 50% available surface area, this potential is technically reduced to 3198.87×10^6 kWh, which is 914 times the electricity demand in the municipalities concerned.

The results indicate that the energy generated from the solar potential of buildings is more than sufficient to meet electricity demand. However, the identified potential must be interpreted with certain limitations in mind. Roof orientation and shading, the structural suitability of buildings, seasonal variability in demand, and storage requirements can all affect the amount of photovoltaic power that can actually be generated. Similarly, existing distribution infrastructure and the affordability of photovoltaic solutions for households are key factors in implementation. Thus, while the estimated potential provides a solid foundation for planning and assessing the feasibility of photovoltaic deployment, its effective realization requires additional technical, economic, and social studies.

Conflicts of Interest

The authors declare no conflicts of interest.

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