International Journal of Computational and Experimental Science and ENgineering (IJCESEN)

Vol. 11-No.4 (2025) pp. 9004-9014
http://www.ijcesen.com

ISSN: 2149-9144

Research Article

Inherited Urbanism and Energy Transition: An Approach Based on Artificial Intelligence and GIS

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Article Info:

DOI: 10.22399/ijcesen.4346
Received : 21 June 2025
Revised : 20 October 2025
Accepted : 27 October 2025

Keywords

Urban planning,
Colonial legacy,
Energy transition,
Photovoltaic potential.

Abstract:

This study aims to analyze the impact of urban planning in cities marked by an unequal distribution of neighbourhoods — particularly those that were colonized by foreign powers, such as the city of Sidi Bel Abbès in Algeria — on the current energy transition. The study area includes 277 rooftops suitable for solar panel installation and located near electricity distribution substations. The results revealed a disparity in annual individual photovoltaic energy production between neighborhoods once inhabited by colonizers and those designated for the indigenous population, a contrast still evident today due to the preservation of the same urban structure. Deep learning techniques (U-Net and Attention U-Net) were used to detect rooftops, yielding good results despite limited data availability. Geographic Information Systems (GIS) were also employed to assess the solar potential and analyze the proximity of rooftops to the distribution substations.

1. Introduction

The building sector stands as one of the primary consumers of energy and sources of CO_2 emissions, accounting for nearly one-third of global energy use. These figures are projected to rise significantly, potentially exceeding half by 2060. This trajectory highlights the urgent need to embrace sustainable approaches in both construction and renovation to reduce the sector's environmental footprint [1]. In this context, smart energy management has become a key lever, crucial for new constructions and existing buildings. Integrating renewable energy sources and enhancing energy efficiency are essential measures to address today's climate challenges and support the ecological transition [2]. Renewable energy sources (RES) play a crucial role in the transition toward net-zero carbon buildings by significantly reducing energy demand [3]. Among these, photovoltaic energy stands out for its high potential, particularly due to its ease of integration on rooftops and building facades [4]. Beyond its role in energy supply, solar power offers substantial long-term environmental and economic benefits, making it a key solution for the buildings of the future. From a sustainable development perspective, photovoltaic integration should extend beyond the individual scale and be adapted to urban environments [5]. Urban areas, with their distinct characteristics, offer a prime opportunity to optimize existing infrastructure and improve building energy efficiency, especially through tailored solutions that respect architectural heritage and local context. Cultural heritage sites hold a vital place in the built environment, serving a wide range of functions, monumental, social, religious, symbolic, cultural, and economic, for the communities they belong to. Most of these buildings, constructed before 1945, typically exhibit limited energy performance due to the materials and construction techniques used at the time [6]. Energy retrofitting of heritage buildings is particularly challenging, as the integration of modern technologies must be carefully aligned with conservation requirements. Historic buildings make up roughly 30 to 40% of the total building stock in European countries [7]. In Italy, for instance, heritage structures built before 1919 represent around 19% of the total, while those constructed between 1919 and 1945 account for approximately 12%. In the United Kingdom, it is estimated that about 1% of the existing buildings can be classified as heritage properties [3]. Despite their cultural significance, heritage buildings often lack the environmental upgrades commonly implemented in other types of infrastructure [8]. The construction standards under which these structures were built differ markedly from current regulations and frequently fall short of today’s expectations for energy efficiency and comfort. This gap between modern needs and the characteristics of historic buildings highlights the urgent need for renovation solutions that respect their historical value. Modifying the building envelope of protected structures is rarely an option, as it would compromise their aesthetic integrity—even though these components play a crucial role in thermal insulation [9]. Retrofitting heritage buildings for energy efficiency is a complex endeavor [2]. Beyond the usual technical challenges, the main barrier lies in the reluctance of stakeholders in the heritage sector to reconcile energy performance with the preservation of historical value. This challenge is further complicated by the lack of a unified approach between conservation professionals and technological innovators. One of the most significant hurdles to improving the energy efficiency of historic buildings is the concern among heritage stakeholders that retrofit measures might be incompatible with the conservation of architectural and cultural integrity [3]. To optimize the energy performance of these structures, several studies have explored the feasibility of different interventions, ensuring they comply with existing regulations [10]. Key steps in an effective renovation process include conducting an energy audit, assessing building performance, estimating potential energy savings, carrying out economic analysis, evaluating risks, and monitoring the results achieved [11].Many historic buildings have successfully integrated solar panels while preserving their visual identity. The Guggenheim Museum in Bilbao, for example, installed 300 panels to combine energy production with architectural conservation. Other sites have opted for more discreet approaches, such as Chippenham Hall in England, where 32 panels are subtly hidden within the landscape, or the archaeological park of Pompeii, where tile-shaped panels blend seamlessly into the ancient ruins. However, not all initiatives go unnoticed. The installation of 438 visible panels on the chapel of King’s College in Cambridge sparked controversy, as the panels are visible from the street. Despite opposition, the project was approved, with some viewing it as a symbol of progress and adaptation to today’s environmental challenges [12]. These debates highlight the ongoing tension between the urgent need for energy transition and the preservation of the visual and historical identity of heritage buildings.The main criteria for integrating photovoltaic systems into historic buildings are as follows [13]:

Visual compatibility: Preserving the original appearance by respecting proportions, colors, and architectural features.
Material compatibility: Maintaining original materials and construction techniques, while minimizing material loss.
Minimal intervention: Reducing the impact of photovoltaic installations on existing surfaces, ensuring the building’s aesthetics and materials are preserved.
Reversibility: Ensuring that the photovoltaic systems can be removed without altering the original structure.
Durability: Preventing structural, hygrothermal, electrical, and energy-related risks associated with the installation.
Balance between conservation and energy production: Sizing photovoltaic systems to meet the building’s energy needs while safeguarding its heritage integrity.

This study aims to determine the photovoltaic potential of the rooftops of buildings in the city of Sidi Bel Abbès, which has experienced a stratification in architectural and residential distribution (colonial and indigenous populations), and to evaluate its impact on the current energy transition. This is done by identifying the most efficient rooftops, based on criteria for integration into the current electrical grid, and projecting them onto a map based on population density data in the city's old neighborhoods. The goal is to analyze the distribution of these rooftops across neighborhoods and their individual annual electricity production during that time. This scenario allows for an analysis of urban planning and the extent of energy transition implementation in cities that witnessed two social layers (colonizers and indigenous people), as well as its influence on the current energy situation.

The study will focus on the city of Sidi Bel Abbès, founded in 1842, which is characterized by an urban plan based on a grid inspired by the French bastide cities of the Renaissance and Spanish colonial cities in Latin America during the 16th century. This rigid plan, marked by the absence of visual sequences and the homogeneity of buildings, gave the city a character of system and rationality. The plan was designed for military and logistical purposes, leading to an uneven distribution of neighborhoods, as seen in areas such as "Séniclose" (a lower-income neighborhood) and "Marso" (a working-class neighborhood). The colonial legacy is also visible in the city’s homogeneous architectural landscape. The identification of the original public buildings in the city began with the definition of the colonial space of Bel Abbès, using two successive maps from 1949 and 1962, as shown in Figure 1 [14].

Covering an area of over 811 hectares, this zone highlights more than 78 public buildings from the French colonial period, evenly distributed throughout the city. Administrative offices account for approximately 17.9% of all public buildings, while educational and training facilities make up the largest share at over 37%. Religious buildings represent around 6.4%, and commercial functions account for 9% of the total. Cultural, sports and recreational facilities, along with healthcare and social assistance services, each represent about 5.1% of the public building stock. Lastly, supply-related infrastructure—similar in share to commercial buildings—also constitutes around 9% [14].This study adopts a practical and low-cost approach to address the lack of detailed cadastral data and the high cost of advanced technologies like LIDAR. It leverages Artificial Intelligence (AI) to automatically identify suitable rooftops using free satellite imagery and high-performance image segmentation models. Once these rooftops are detected, Geographic Information Systems (GIS) are employed to assess their solar potential and analyze their proximity to electricity distribution substations an essential step toward integrating them into a smart grid framework.

2. Methodology

2.1 Automatic Detection of Rooftops Using Artificial Intelligence

The U-Net [15] and Attention U-Net [16] models were used to automatically detect rooftops from satellite images of Sidi Bel Abbès. Binary segmentation was employed to differentiate the rooftops (in white) from the rest of the image (in black). The images, sourced from Google Earth, were divided into 360 blocks, each measuring 250 × 250 pixels.

2.2 Estimation of Solar Potential Using GIS

The solar potential analysis was conducted using the Solar Radiation tool in ArcGIS Pro, which estimates the solar irradiation received on each rooftop based on factors such as slope, orientation, and geographical position. The tool relies on Digital Surface Models (DSM) to calculate the incident solar energy at the pixel level. The estimation followed the guidelines outlined in the Esri technical manual [17], which is widely used in urban energy planning. This method enabled the identification of rooftops that are most exposed to solar radiation, and therefore, the most suitable for photovoltaic installations.

2.3 Linear Analysis of Energy Production

To assess the relationship between annual electricity production, rooftop area, and solar irradiation, a multiple linear regression analysis was conducted using SPSS software. The dependent variable is the estimated annual energy production (MWh/year), while the independent variables are the rooftop area (m^2) and the average annual solar irradiation (kWh/m^2).

2.4 Proximity Analysis to Distribution Substations

A layer representing the electricity distribution substations was integrated into ArcGIS. Using the Buffer tool, a 100-meter buffer zone was created around each substation to identify rooftops located within proximity to the electrical grid. This distance is considered optimal for potential integration into a smart grid system.The city of Sidi Bel Abbès is served by three main electricity distribution substations: SBV, MAKAM, and MEKKERA (see figure 3). Each substation supplies a specific sector of the city and includes several secondary distribution points. For the purposes of this analysis, special focus is placed on the MEKKERA substation (80 MVA), which supplies the area covered in the analyzed map.

2.5 Distribution of Solar Rooftops and Population Density

After identifying the rooftops located within 100 meters of the electrical grid, which showed stability and a slight increase in the average annual electricity production, and which we considered the most efficient for integration into the electrical grid, we will project them onto a historical map of the city of Sidi Bel Abbès from 1960. The objective is to simulate a scenario that links rooftops suitable for integration into the current electrical grid with the annual energy production per individual across the different neighborhoods of the city during that period.

3. Results

This section presents the results obtained through the automatic detection of rooftops, the estimation of their energy production, their proximity to electricity distribution substations, as well as their demographic distribution within the historical neighborhoods of the city.

3.1 Detection and Classification of Rooftops

Based on various evaluation criteria, such as accuracy, precision, recall, F1 score, and Intersection over Union (IoU), Table 1 presents the performance metrics of the two classifiers: U-Net and Attention U-Net.From the results presented in the table above, we observe that the U-Net model performs better than the Attention U-Net model in our case study. This contrasts with previous comparisons, such as [18], which suggest that U-Net is generally less effective than Attention U-Net. This discrepancy can be attributed to the specific nature of our dataset and objectives. In our case, we used only 342 images, which is not enough to properly train a model. Additionally, image quality plays a critical role in influencing the performance of segmentation models. The aerial images we used from Google Earth, focused on a city in Algeria (Sidi Bel Abbes), contain various factors that could affect the results, such as resolution, lighting, and shadows. Depending on these factors, U-Net seems to be better suited for our context, while more complex models like Attention U-Net may struggle to process these images. Therefore, it is important to note that the choice between U-Net and Attention U-Net largely depends on the specific characteristics of the data and the objectives at hand.

3.2 Global Photovoltaic Potential

Our preliminary analysis identified a total of 10856 rooftops in the study area. The integration of this data into ArcGIS generated a new map, revealing that 3804 rooftops, or 35.04% of the total, have optimal characteristics for solar panel installation. These rooftops offer significant energy potential for solar power generation in the region, with a total area of 610,072.60 m² and an estimated annual production of 114543,42 MWh/year.
On the map, each color corresponds to a category of annual energy production (in MWh/year), linked to a specific surface area range:

- Light yellow (≤ 14.73 MWh/year): 30.66 – 78.44 m²
- Yellow (≤ 49.85 MWh/year): 80.91 – 265.38 m²
- Light orange (≤ 130.01 MWh/year): 266.62 – 694.75 m²
- Orange (≤ 303.59 MWh/year): 698.75 – 1,563.50 m²
- Red (≤ 456.36 MWh/year): 1,626.54 – 2,404.05 m²

The analysis of rooftops suitable for solar panel installation reveals an uneven distribution based on annual production capacity. The majority of rooftops fall into the low or medium production categories (light yellow and yellow), representing more than 85% of the identified areas. These rooftops, often small or medium-sized, show modest individual production, but their large number plays a significant role in the overall solar potential of the city. In contrast, rooftops in higher production categories (light orange, orange, and red), although far fewer in number, stand out due to their high individual output. For example, red category rooftops, despite making up only a small fraction of the sample, contribute significantly to total energy production because of their larger surface area and favorable orientation. These findings highlight a complementary logic: on one hand, a large base of rooftops spread throughout the urban fabric provides distributed production, and on the other, there are high-energy concentration points that could play a strategic role in a smart grid. This configuration underscores the untapped potential of Sidi Bel Abbes' urban fabric to support a decentralized, efficient energy infrastructure, in line with the goals of the energy transition.

3.3 Regression Analysis

Regression is a statistical technique used to examine the relationship between a dependent variable (in this case, annual electricity production) and one or more independent variables (roof surface area and annual solar irradiation).

a) Constant
B(cst) = −128.907: This coefficient represents the value of the annual energy production when all

other variables (surface area and irradiation) are equal to zero. It is the intercept of the regression line with the dependent variable axis, indicating the theoretical starting point with no influence from the independent variables.

b) Annual Average Solar Irradiation
B = 0.094: This means that for each unit increase in the annual average solar irradiation, the annual energy production increases by 0.094 MWh.

c) Roof Surface Area
B = 0.187: This indicates that for each unit increase in roof surface area, the annual energy production increases by 0.187 MWh.

The results suggest that the available roof surface area has a more significant impact on annual energy production than solar irradiation. This observation implies that focusing on increasing available roof area may be a more effective strategy for maximizing the efficiency of solar installations, rather than concentrating solely on optimizing solar exposure.

3.4 Analysis of Proximity to Distribution Substations

After applying the Buffer method with a radius of 100 meters in ArcGIS, we identified the suitable rooftops for solar panel installation located near 10 electricity distribution substations. The feeder areas impacted by these rooftops are as follows: Baghli Substation, Bremer Substation, Batis Substation, ISM Substation, Amarnas Substation, Saira Substation, Casoran Substation, CFTE Substation, Posté Substation, and A. Ramdane Substation.These rooftops are considered optimal for solar panel installation due to their proximity to the MEKKERA distribution substations, which minimizes energy losses and reduces the infrastructure costs required to connect the panels to the electrical grid.The table provides a detailed breakdown of the rooftops suitable for solar panel installation and located near the electrical grid. The data reveals the identification of 2,117 rooftops, representing a decrease of 55.65%, as illustrated in the chart (Figure 7). These rooftops cover a total area of 374,570.68 square meters and generate a total annual energy output of 70,291.6 MWh.The differences in the average production reduction are generally small across the categories, with an average decrease of less than 2%. However, the "Light Orange" category stands out with an increase of +1.86%. In addition to its proximity to the electrical grid, it also demonstrated a higher average annual energy production, making it the most suitable candidate to represent a scenario of integrating renewable energy into historical buildings.

3.5 Rooftop solar potential about population density

The rooftops in the light orange category are distributed across the city's five historic districts " Centre-Ville, Negrier, Eugène Etienne, Point du Jour, and Bugeaud" by the data presented in the following table. These results are based on the historical map used in the methodology section (see Figure 4, Section III-5), where the selected rooftops were overlaid onto a population density map from 1960.From the table above, we can deduce the electricity generation potential of the neighbourhoods covered by rooftops in the light orange category. The data shows the number of rooftops, their total surface area, annual energy production, and the population density for each district. The historic city center (Centre-Ville) stands out with the highest annual energy production (7,209.49 MWh) spread across 38,374.63 m² of rooftop area. With a population density of 97 inhabitants per hectare, it also records the highest production per inhabitant per hectare (74.32 MWh/year/inh/ha), indicating very high energy efficiency in a moderately dense urban context. In contrast, the Point du Jour district, despite its very high population density (354 inh/ha), shows a low value of energy production per inhabitant per hectare (3.67 MWh/year/inh/ha). This is due to the limited rooftop surface area and lower total energy output (1,301.41 MWh). The Negrier and Eugène Etienne districts record values of 29.15 and 24.86 MWh/year/inh/ha, respectively. While their specific energy production (MWh/m²) is comparable, the higher population density in Eugène Etienne further dilutes the production per inhabitant. Finally, the Bugeaud district, with a population density of 382 inh/ha, generates 2,426.43 MWh/year, equivalent to 6.35 MWh/year/inh/ha. This highlights how population density significantly influences the availability of rooftop area and, consequently, the energy yield per inhabitant. The figure above illustrates the individual annual solar energy production, expressed in MWh/year/inhabitant/hectare, for various historic districts. To analyze the urban energy structure of the time, we simulated a hypothetical solar production scenario for the year 1960, although this technology was not yet available at that period. This retrospective approach aimed to assess, in a forward-looking manner, whether an implicit energy strategy could have been identified based on the existing urban layout. The results reveal significant disparities between neighborhoods. Areas such as Centre-Ville, Négrier, and Eugène Étienne—historically inhabited predominantly by settler populations—show markedly higher levels of per capita energy production compared to Point du Jour and Bugeaud, which were traditionally home to the indigenous population. This distribution suggests the existence of a spatial organization that, even indirectly, favored greater energy capture potential in some neighborhoods over others, as a result of the urban, architectural, and social planning choices of the time.Thus, although no explicit energy strategy had been developed around solar power in 1960, our simulation highlights that historical urban structures could have created unequal opportunities in terms of energy transition—an imbalance still visible today in urban development and energy dynamics.

4. Discussion

Recent studies, such as that of Smith (2024) [20], highlight the importance of integrating photovoltaic (PV) technologies into heritage buildings through the development of a multi-criteria assessment framework that combines architectural, cultural, and climatic factors. The aim is to achieve a balance between environmental sustainability and the preservation of historical values. In a similar vein, Johnson et al. (2023) [21] proposed a methodology for estimating photovoltaic potential in environmentally and culturally sensitive areas, in collaboration with relevant authorities. This underlines the need to adapt energy technologies to the specific characteristics of heritage contexts. Furthermore, Martinez (2018) [22] analyzed various strategies aimed at improving energy efficiency in historical buildings by incorporating renewable energy sources without compromising their architectural value. Likewise, Lucchi et al. (2016) [23] demonstrated that enhancing energy performance and thermal comfort in heritage buildings can be achieved through meticulous restoration strategies that account for the architectural and functional heterogeneity of these structures. In contrast to these studies, which rely primarily on manual qualitative analyses or conventional modeling approaches, our research focuses on a specific urban context composed of architectural structures built between 1842 and 1960. These neighborhoods experienced an unequal spatial distribution. In order to evaluate the homogeneity of energy distribution across these districts, we adopted a simple and cost-effective methodological approach aimed at assessing the feasibility of integrating PV systems on heritage rooftops and connecting them to the electrical grid. To achieve this, we employed automatic rooftop detection techniques based on deep learning, combined with Geographic Information Systems (GIS).The results reveal that rooftops classified in the “light orange” category represent the most optimal choice for efficient integration with the existing power grid, with an estimated annual energy production of 31,373.48 MWh. These rooftops were distributed across five urban units defined using the 1960 urban fabric map. Among these units, three historically colonial districts showed significantly higher energy production levels (38.374,63; 18928,2; and 38792,14 MWh), while the other two districts, traditionally inhabited by the indigenous population, had much lower production levels (6760,25 and 12920,71 MWh).However, this disparity in energy potential is offset by a low population density in the colonial districts, limiting the feasibility of large-scale energy exploitation. Conversely, the densely populated indigenous neighborhoods possess lower energy potential. Although the buildings were constructed with durable materials and followed a rational urban plan, the historical development of the city prioritized comfort standards that were unevenly distributed. This has resulted in a structural imbalance in the context of the current energy transition, especially since the city has retained its historical urban and cultural organization post-independence.

Figure 1: *Definition of the urban area of Bel Abbes based on the 1949 and 1962 maps [14].*

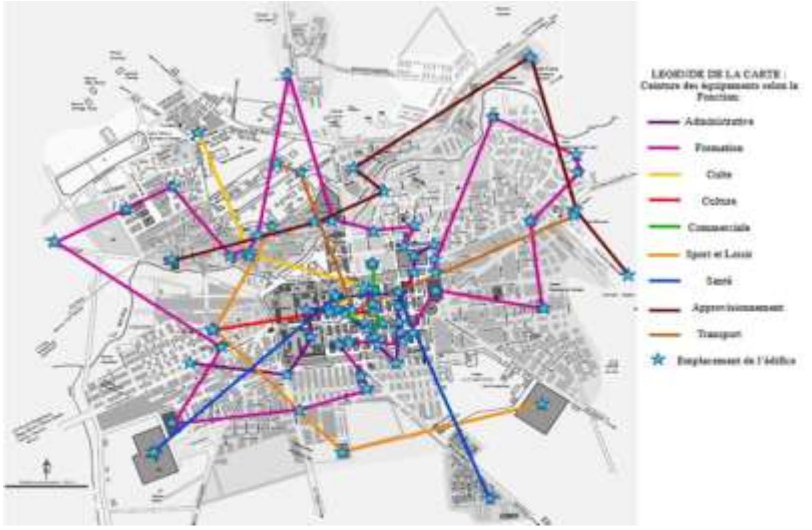

Figure 2: *Distribution of Public Building Types from the French Colonial Era in Sidi Bel Abbes [14].*

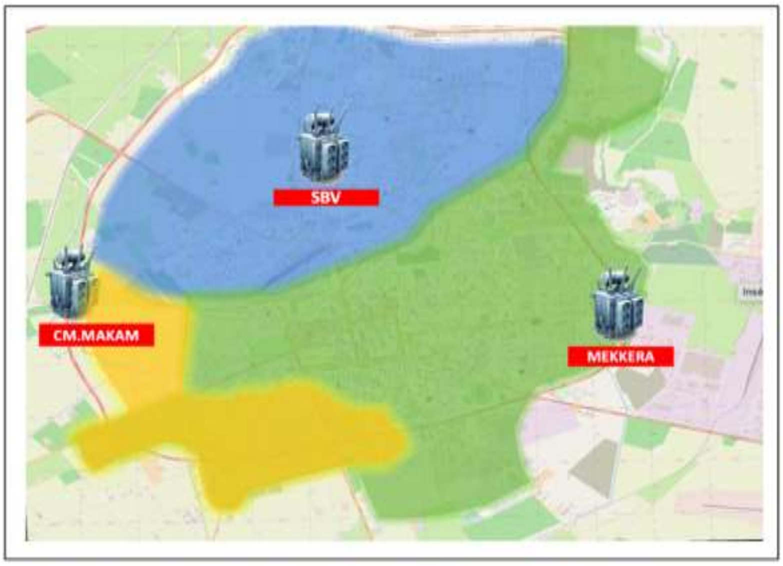

Figure 3: *Location of Electricity Distribution Substations in Sidi Bel Abbès [18].*

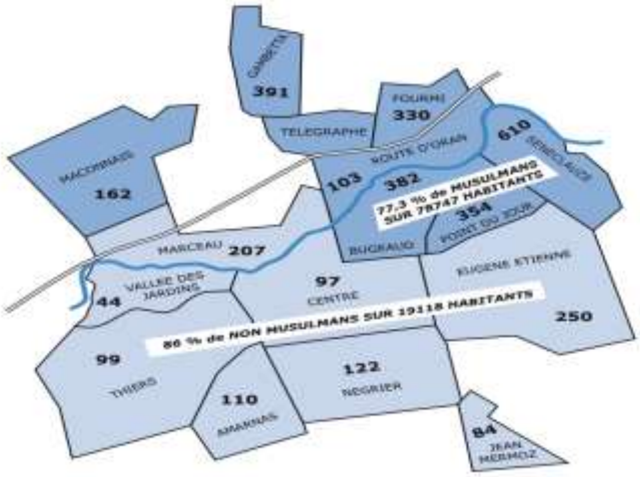

Figure 4: *Map of Sidi Bel Abbès Districts in 1960 with Population Density (inhabitants/ha) [19].*

Table 1: *U-Net outperforms Attention U-Net in all evaluation measures.*

Classifier	Accuracy	Precision	Recall	F1-score	IoU
U-Net	**90.49%**	**90.97%**	**90.49%**	**90.73%**	**90.49%**
Attention U-Net	89.96 %	90.34%	89.96%	90.15%	89.96%

Table 2: *Summary of Rooftops by Color, Total Area, and Annual Energy Production in MWh/year.*

Categories	Number of Roofs	Total Area (m²)	Total Production (MWh/year)	Average Production (MWh/year)
Light yellow	1650	86670.64	16268.57	**9.85**
Yellow	1631	226403.97	42533.42	**26.07**
Light orange	409	166979.07	31373.48	**76.89**
Orange	99	100535.09	18826.87	**190.17**
Red	15	29489.83	5541.08	**369.40**

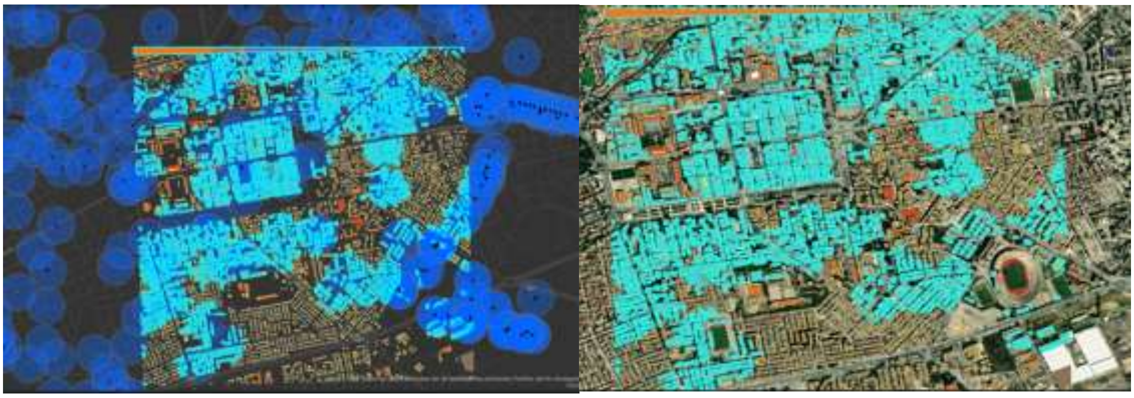

Figure 5: *Spatial Distribution of Rooftops Near the Electrical Grid.*

Table 3: *Rooftops Near Distribution Substations.*

Categories	Number of Roofs	Total Area (m²)	Total Production (MWh/year)	Average Production (MWh/year)
Light yellow	895	46840.39	8781.44	**9.81**
Yellow	881	123626.02	23224.24	**26.36**
Light orange	256	106724.09	20051.92	**78.32**
Orange	73	73604.83	13766.76	**188.58**
Red	12	23775.35	4467.24	**372.27**

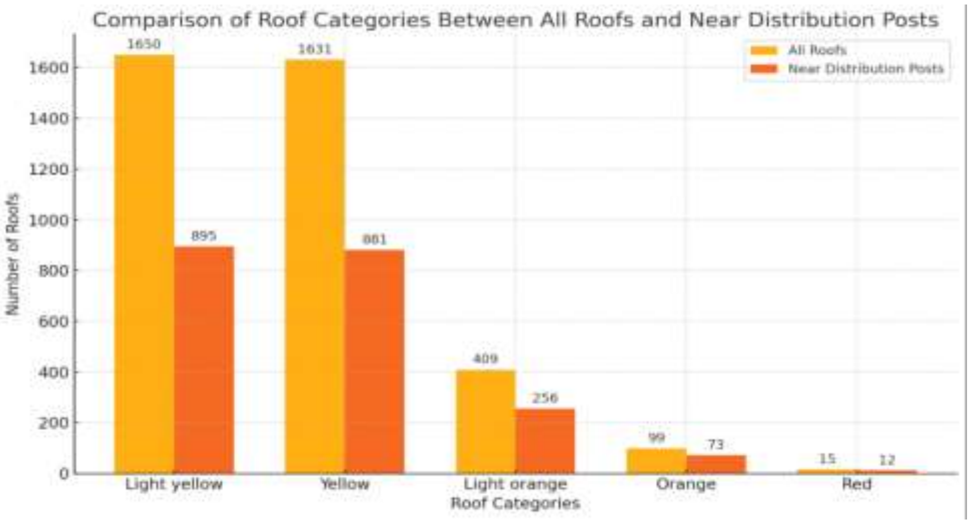

Figure 6: *Comparison of Suitable Rooftops for Solar Installation Based on Their Proximity to Distribution Substations (≤ 100 m).*

Figure 7: *Percentage Reduction in Average Production by Category.*

Table 4: *Distribution of Rooftop Solar Energy Potential in Relation to Urban Density (1960 Map Overlay).*

District	Number of Rooftops	Rooftop Area (m²)	Production (MWh/year)	Population Density inhabitants per hectare	Specific Production (MWh/m²)	Production per Inhabitant per Hectare (MWh/(year·inh·hect))
Centre-Ville	87	38374,63	7209,49	97	0,188	74,32
Negrier	60	18928,2	3556,8	122	0,188	29,15
Eugène Etienne	82	38792,14	6216,99	250	0,160	24,86
Point du jour	17	6760,25	1301,41	354	0,192	3,67
Bugeaud	31	12920,71	2426,43	382	0,188	6,35

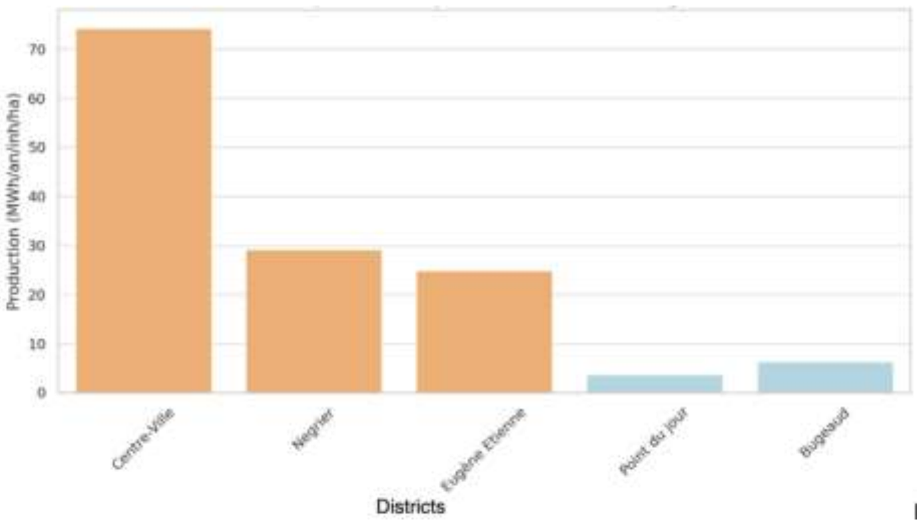

Figure 8: *Simulated Annual Individual Solar Energy Production by Historic District in 1960.*

5. Conclusions

The findings of our study, which focused on identifying suitable rooftops for solar energy integration in the old neighborhoods of Sidi Bel Abbès, fall within the broader dynamic of enhancing urban heritage through the energy transition, especially as the city has preserved its historical urban fabric. The selected rooftops from our sample—located in the southern part of the city (including the historical downtown and its surrounding neighborhoods)—demonstrated the potential to generate more electricity than the city's three main transformers. This highlights that the architectural style of the period between 1939 and 1960 currently offers excellent conditions for supporting the energy transition. During that era, buildings were constructed with large, well-spaced rooftops, minimizing shading effects and being oriented to maximize solar exposure and natural ventilation, thereby ensuring thermal comfort for residents. However, the disparity between neighborhoods with high and low energy potential indicates that, within the context of energy transition, some areas will face additional challenges in shifting to renewable energy sources. It may be difficult to direct investments uniformly across all neighborhoods, potentially leading to economic strain in areas lacking sufficient potential. Without effective measures to ensure the fair distribution of solar energy resources, low-potential neighborhoods may remain excluded from access to independent and secure renewable energy, thereby hindering a sustainable energy transition in these regions.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
- **Acknowledgement:** The authors declare that they have nobody or no-company to acknowledge.
- **Author contributions:** The authors declare that they have equal right on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.
- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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