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Energy Transition and Heritage in Anthropocene Era—Proposal for a Methodological Analysis at Local Scale

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Abstract: In the Anthropocene era, climate change highlights the need to abandon the centralized energy generation model using large installations located far from consumption centers, and to move towards an urban energy transition based on decentralized self-consumption models—both individual and collective—and local energy communities. These approaches reduce emissions and external dependency, strengthening resilience, urban sustainability, and promoting energy justice and citizen participation. This work aims to develop a model for integrating photovoltaic solar systems in urban centers of high heritage value, combining the protection of cultural legacy with climate change adaptation strategies. A methodology is designed to integrate solar energy into urban areas while respecting cultural heritage in the most reasonable way possible. The proposed methodology consists of carrying out a characterization of the municipalities under study, considering legal, demographic, energy, and heritage aspects. Next, a territorial zoning is proposed that differentiates between protected and unprotected areas in each municipality. Visibility maps are developed to assess the impact of the installations by sector from the main visual consumption points, facilitating differentiated decisions to protect the most sensitive environments. In addition, specific measures are proposed, such as locating the installations in non-visible areas and using materials and techniques adapted to the construction typology, to preserve areas of higher cultural value and to implement energy communities and collective self-consumption outside culturally protected zones. This methodology is applied to two urban areas in the province of Jaén (South of Andalusia): Alcalá la Real and Cazorla, which, due to their different characteristics, demonstrate its versatility and adaptability. It is concluded that the transition toward decentralized models is an effective way to adapt cities to climate change, reinforcing social cohesion, contributing to the fight against energy vulnerability, and protecting historical heritage.

Keywords: anthropocene; cultural heritage; solar energy; local scale; energy self-consumption; energy communities; visibility maps

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1. Introduction

Since the Industrial Revolution, multiple processes have progressively unfolded, giving rise to the Anthropocene, with the rate of urbanization considered a key indicator [1]. Thus, cities have been crucial for the development of this new era [2] and possess the potential to reduce the current human impact on the environment [3] to help mitigate present risks and overcome future challenges [4,5]. There is a need for resilient cities that overcome their dependence on fossil fuels—in fact, increasing urban resilience in

anticipation of an energy shock due to the decline of non-renewable sources-, is a defining challenge of our time [6,7]. Therefore, a sustainable management of cities is essential to alleviate the effects of climate change [8].

Furthermore, in the current international context with armed conflicts such as the Russia-Ukraine war or the escalating hostilities in the Middle East, which are destabilizing the economy and the energy market, the EU27 faces the necessity of transitioning towards a model that increases energy independence and is low in CO_2 emissions to meet climate commitments. Although this transition is mainly based on the proliferation of renewable energy projects in rural areas, an increasing number of voices argue that renewable energy installations in urban areas and transformed spaces should be prioritized as a key aspect of a fair and balanced energy transition, while maintaining a balance with the necessary protection of cultural heritage and/or its integration [9–11].

In fact, Directive 2023/2413 of the European Parliament and of the Council, dated 18 October 2023, requires Member States to adopt plans by 21 February 2026 at the latest, formally designating Renewable Energy Acceleration Zones (REAZ). These zones refer to homogeneous areas where the deployment of renewable energy sources is not expected to have a significant environmental impact. Article 15.1(a) of the Directive mandates that priority should be given to artificial and built surfaces, including rooftops, building facades, transport infrastructure and their immediate surroundings, parking areas, agricultural holdings, landfills, industrial zones, and mines, among others.

Nevertheless, the necessary integration of renewable energies—specifically photovoltaic solar energy—in urban environments is supported by the EU Directive 2018/2001 [12], which recognizes energy communities, and the EU Directive 2019/944 [13], which regulates Local Energy Communities (LECs) within the EU27, introducing two new legal entities: "citizen energy communities" and "renewable energy communities" as active players in the energy system. In Spain, Royal Decree-Law (RDL) 15/2018 [14] and Royal Decree (RD) 244/2019 [15] regulate self-consumption with surplus and set its conditions. Although the transposition of these EU directives in Spain has so far been partial, they are accompanied by quite restrictive distance limitations for sharing energy, reaching a 2 km radius as per RDL 20/2022 [16].

Hence, solar energy in heritage buildings and landscapes has emerged as an interdisciplinary field of study seeking innovative solutions to overcome these limitations [17,18]. In fact, solar energy is one of the most promising technologies for integration into heritage environments due to its versatility and adaptability to different architectural contexts. In Europe, where 14% of buildings date from before 1919 and an additional 12% from between 1919 and 1945, options must be explored to implement photovoltaic solutions that do not compromise historical values [18].

While the integration of solar systems in historical buildings presents significant challenges in terms of aesthetic and technical compatibility—since conventional solar technologies, such as standard photovoltaic panels, can cause a negative visual impact and generate tensions between prevailing energy transition models and conservation [19]—advanced technologies, such as solar tiles and architecturally integrated photovoltaic systems (BIPV), have been developed and demonstrated as viable solutions to preserve the key characteristics of heritage assets. These technologies combine energy efficiency with respect for aesthetics and original materials, allowing for a visually discreet and functional integration [17–20].

Local and international regulations impose restrictions to ensure that interventions in cultural assets do not affect their authenticity. In this regard, the approval process for renewable energy projects in protected environments can be complex and lengthy, which often discourages the implementation of these technologies [18]. Integration represents

a technical, regulatory, and social challenge that requires interdisciplinary approaches. These challenges can be addressed through the implementation of advanced technologies, the adaptation of regulations, and the use of spatial analysis tools—such as Geographic Information Systems (GIS). GIS can be used to integrate variables of different types, as well as to create visibility maps that assess the visual impact of solar installations from key heritage points. All of this facilitates progress towards a sustainable energy model that respects and enhances the cultural value of heritage assets.

There are several examples of integration in the literature on the integration of solar panels in urban areas. For example, in the case of Ceramic-tiled roofs, characteristic of traditional Andalusian towns (the subject of this study), present a particular aesthetic challenge in the integration of renewable energies. For these environments, solar tiles have emerged as a key solution, mimicking the color, texture, and dimensions of the original tiles while incorporating photovoltaic technology internally [17–19]. Moreover, their placement on south-facing slopes maximizes energy efficiency without altering the original structure. Some studies highlight that these systems are especially suitable for protected areas, as they comply with the reversibility and structural compatibility regulations required by Law 14/2007 [21] on the Historical Heritage of Andalusia. Por su parte, Slate roofs, common in northern regions of Spain and Europe, represent another construction typology that requires specific solutions. The integration of thin, frameless solar panels has proven effective in preserving the texture and tone of these roofs [20]. In cases such as the municipality of Catania, Italy, solar panels have been installed on slate roofs with visual patterns designed to mimic the original framework [18]. These technologies adapt to the irregular format of slates and can be installed in parallel to ensure visual continuity and prevent overheating-induced short circuits. Por el contrario, flat roofs, common in historic public buildings, offer greater flexibility for solar system installations. In these cases, low-height inclined supports are used to maximize solar capture without interfering with the ground-level visual perception [19]. This approach has been implemented in buildings such as the Real Albergo de Poveri in Naples, where opaque photovoltaic modules were installed on flat roofs in accordance with the original architectural lines [22].

Another innovation in this context is the use of semi-transparent modules in skylights, which not only generate energy but also allow natural light to penetrate the building. These solutions have proven particularly effective in structures with strict visibility and aesthetic restrictions [20]. The use of custom-colored photovoltaic modules adjusts the reflectivity and hue of the panels, enhancing their visual integration [20], and is an emerging trend. These panels allow the tonal adjustment and texture to harmonize with the original finishes of the facades, a particularly useful solution in urban buildings with visual restrictions [19].

In the other hand, facades and vertical elements, such as balconies and shutters, represent an additional opportunity for integrating solar energy in heritage buildings. Semi-transparent photovoltaic panels have been successfully used on glass facades, as in Casa Anatta in Monte Verità, Switzerland, where a functional and aesthetic integration was achieved in a high-value cultural environment [17].

Integrating solar energy into heritage buildings requires a tailored approach adapted to the construction typology. From solar tiles in traditional Andalusian towns to semi-transparent panels on urban facades, current technological solutions enable a combination of energy sustainability and cultural preservation. Cases such as those in Monte Verità, Catania, and Naples demonstrate that it is possible to achieve a harmony between innovation and conservation, laying the foundation for a sustainable and respectful energy model. In some cases, to preserve cultural heritage, the best solution is to propose collective installations outside protected areas through shared self-consumption and renewable energy

communities [23], which can take various forms in terms of ownership and governance [24], where energy democracy and justice become key aspects [25,26].

The objective of this research is to develop a methodological proposal to adequately integrate solar energy in urban environments with cultural heritage protection in two urban areas located in municipalities of the province of Jaén (Southern Spain). Differentiated strategies will be proposed based on the characteristics of the urban core, the type of heritage protection, and its visual exposure. Emphasis will be placed on the importance of architectural characterization to determine the most suitable solution, and examples of urban areas with different typologies where the proposed methodology has been applied will be presented. So far, partial research has been carried out to integrate solar energy into cultural heritage, but the contribution of the present research is crucial as it addresses the urban area as a whole and provides an integrated analysis of it with differentiated solutions according to architectural characteristics, cultural protection and visual exposure. In addition, this research offers community solutions for each case in search of democratisation and energy sovereignty.

2. Materials and Methods

This work focuses on developing a methodological proposal to integrate solar energy into urban centers with heritage protection. The methodology was carried out through an interdisciplinary approach that combines technical, regulatory, aesthetic, demographic, and social criteria, following several phases.

Firstly, a documentary and regulatory analysis is conducted to identify the legal frameworks and current cultural protection guidelines applicable to the supralocal context of the urban area to be analysed, establishing the limits and opportunities for installing solar systems in heritage environments. Compatibility with conservation regulations and the preservation of historical legacy are prioritized. Secondly, a comprehensive characterization of the municipality or urban area under study is carried out, considering demographic and energy aspects. This analysis enables an understanding of the specificities of each environment, their energy needs, and the definition of specific regulatory criteria. Finally, an analysis of the cultural heritage and architectural history of the urban core is performed to seek solutions that allow for the most appropriate integration of solar energy.

Regarding the study areas, the developed methodology was applied to various urban centers in the province of Jaén, where an investigation was conducted to reconcile the use of solar energy with the protection of cultural heritage. Some aspects of which have been tested with local stakeholders. Two urban areas were selected:

One municipality, Alcalá la Real, whose main urban area includes a culturally significant asset on a hill that overlooks much of the urban area—featuring both a traditionally protected core and an extensive unprotected zone that includes a sector for tertiary, commercial, and industrial uses. The other municipality, Cazorla, has a culturally protected section and a newer, unprotected section, with cultural assets at higher elevations and an equipment zone distinct from the traditional core. Moreover, the entire environment is protected by environmental regulations, as it is located within the Natural Park of Cazorla, Segura y las Villas. The different characteristics of the selected municipalities allow for determining whether the proposed methodology is adaptable to urban centers of various types and, therefore, generalizable to contexts beyond the referenced province, region, or even countries. Ultimately, the result of this work is the methodology itself, which is designed as a practical and replicable tool to guide the integration of solar energy in heritage contexts, balancing sustainability, climate adaptation, and cultural preservation.

3. Results

As a result, the proposed methodological phases for integrating solar energy into cultural heritage are presented, along with examples from the municipalities where the methodology has been applied.

3.1. Bibliographic and Regulatory Review

A comprehensive review of the current regulations was conducted, covering historical and regulatory frameworks in the fields of heritage, energy, and urban planning. Within the cultural framework of the EU27, documents such as the 1964 Venice Charter [27], Article 167 of the Treaty on the Functioning of the EU [28], the Spanish Historical Heritage Law 16/1985 [29], and the Andalusian Historical Heritage Law 14/2007 [21] were reviewed. Since cultural competencies in Spain have been transferred to the autonomous communities, Andalusian legislation became particularly relevant for the practical examples illustrating the applied methodology. Andalusian law requires prior authorization for any intervention on protected assets, considering criteria of reversibility and aesthetic compatibility. Additionally, this legislation mandates that territorial planning instruments incorporate heritage analyses and introduces the concept of "visual or perceptual pollution", regulating any installation that degrades the values of cultural assets or interferes with their appreciation.

The review of urban planning documents revealed the general conditions for construction and permitted uses in different municipal areas. In protected areas, the implementation of an architectural compatibility project is required, which must be approved by the Department of Culture or the relevant municipal authority, along with an architectural integration project. Furthermore, the alteration of original building elements, such as traditional tiled roofs, is expressly prohibited. The analysis of the studied cases shows that:

Alcalá la Real: The General Urban Development Plan (PGOU) of Alcalá la Real [30] establishes the general conditions for construction and the permitted uses in the different areas of the municipality. Regarding renewable energy installations, such as solar panels, the PGOU regulates aspects such as visual integration and the materials to be used, especially in protected areas such as the historic centre. The regulation requires that applications be approved by the Department of Culture of the Andalusian Government, in addition to receiving municipal approval. An architectural integration project must be submitted and approved by the relevant authorities, and altering original building elements, such as traditional tiled roofs, is prohibited unless specifically authorized.

Cazorla: Has a partial adaptation of its Subsidiary Regulations (NNSS) to the General Urban Development Plan (PGOU) [31], in accordance with the Andalusian Urban Planning Law (LOUA) [32]. This adaptation means that, although it does not have a complete PGOU, it has partially incorporated the guidelines established by the LOUA [32] into its Subsidiary Regulations. The NNSS establish the general conditions for construction and permitted uses in different areas of the municipality. Additionally, the Planning Plan for the Sierras de Cazola, Segura y las Villas Natural Park adds an extra layer of environmental and urban planning regulation. Specific authorizations must be obtained, and visual impact studies must be conducted to ensure that installations do not significantly alter the historical environment's appearance.

3.2. Socioeconomic and Energy Consumption Analysis

To identify a solution that aligns with local needs, it is important to conduct a socioeconomic characterization of the municipality using available official information. This analysis should include the location and extent of the urban centers, as well as demographic and socioeconomic aspects, along with an evaluation of energy consumption patterns, with special attention to sector distribution and the evolution of residential consumption per in-

habitant. Energy solutions for the industrial sector include renewable installations designed to directly serve industrial needs, such as solar thermal plants for cooling and heating processes and agrivoltaic systems in the agricultural sector to reduce energy demand and electricity costs. In the residential and service sectors, it will be necessary to develop both individual and collective solutions to effectively address the specific requirements of each facility. These data allow for understanding the particularities of each territory and provide the basis for subsequent zoning.

For the examples addressed, data from the Multi-territorial Information System of Andalusia (SIMA) [33] were used. The population of these municipalities is 21,296 inhabitants in Alcalá la Real (SIMA, 2024) [34] and 7004 inhabitants in Cazorla (SIMA, 2024) [35]. Total electrical energy consumption is higher in Alcalá la Real than in Cazorla; in this municipality, industry is the main consumer, with a total consumption of 4.93 MWh per inhabitant and a residential consumption of 1.70 MWh per inhabitant. In the case of Cazorla, although the economy is more diversified, agriculture is the primary consumer, followed by the service and industrial sectors, with a total consumption of 3.52 MWh per inhabitant and a residential consumption of 1.66 MWh per inhabitant.

3.3. Analysis of Cultural Heritage and Historical-Architectural Characterization

To reconcile the conservation of cultural heritage with renewable energy installations, it is necessary to carry out a detailed analysis of the cultural heritage of the urban center under study using available official information sources, as well as a historical-architectural characterization to determine the dominant construction typologies of each area and thus identify the most suitable solutions. The cultural heritage of each urban center used to exemplify the methodology was examined in detail using the Andalusian Catalog of Historical Heritage [36]. Historic-artistic ensembles, walled enclosures, castles, viewpoints, archaeological sites, etc., were identified, from which high-value heritage areas were delineated. Based on this analysis, protected areas were mapped, and a historical and architectural characterization was established to determine the dominant construction typologies of each zone.

3.3.1. Alcalá la Real

Cultural Heritage

Alcalá la Real boasts a rich cultural heritage, led by the Fortaleza de la Mota and its historical ensemble. According to the Andalusian Historical Heritage Institute [36], it possesses 159 immovable assets, 15 of which are protected. Notable Cultural Interest Assets include the Ciudadela de la Mota with its Alcalá la Real Church, the most emblematic monumental ensemble located on Cerro de la Mota, which comprises a walled enclosure with defensive towers and the Major Abacial Church; the traditional urban core, which reflects its evolution since medieval times, with an intricate network of streets and plazas adapted to the relief of Cerro de la Mota; and other protected assets such as the Abacial Palace (General Cataloging), the ruins of the San Antón Church, the Nuestra Señora de las Mercedes Cemetery, and the Dominican Convent, among others. Additionally, in other centers within the same municipality, the Fuente Álamo Archaeological Zone and the Mesa Archaeological Site in Ribera Alta are highlighted as Cultural Interest Assets.

Historical-Architectural Characterization

The historical core is distinguished by a combination of geographical, historical, and architectural factors. Its urban layout, with irregular and steep streets, reflects Andalusian heritage enriched by Renaissance and Baroque influences. The architectural style combines defensive and residential elements, with emblematic buildings such as the Fortaleza de la Mota. Traditional construction materials include local limestone, white lime render,

wooden carpentry, and artisanal forged iron. Roof Typologies: Predominantly, two-sloped roofs with moderate inclinations prevail. On the Facades, Renaissance and Baroque styles are present in representative buildings, in popular housing with simple and functional architecture, and in a colour palette of white and earthy tones.

3.3.2. Cazorla

Cultural Heritage

The Andalusian Historical Heritage Institute identifies 40 immovable assets in the municipality of Cazorla, four of which have special protection. Notable among them are the Castillo de la Yedra, of Arab origin and rebuilt during the Christian era, which houses the Museum of Arts and Popular Customs of Alto Guadalquivir; the Castillo de las Cinco Esquinas (or de Salvatierra), reflecting its defensive function and historical importance during both Arab and Christian dominations; and the Historic Ensemble of Cazorla, which includes the urban core and its landscape integration within the mountainous environment, highlighting its Arab origins and Renaissance and Baroque influences; as well as the ruins of the Santa María de Gracia Church, the Hermitage of the Virgin of the Cabezas, the Castillo de la Iruela, and various viewpoints.

Historical-Architectural Characterization

The urban core of Cazorla, located at an approximate altitude of 836 m above sea level in a mountainous environment with an urban layout adapted to the terrain, is marked by slopes and natural viewpoints that enhance its tourist appeal. Key elements include local limestone, Arab ceramic tiles, olive and pine wood, plaster and lime render, and forged iron, which define walls, sloping roofs, extended eaves, and whitewashed facades with simple moldings and ornamented windows with wrought-iron grilles, complemented by stone plinths. Additionally, interior courtyards with traditional paving, native vegetation, water features, and shading structures play a key role in thermal resilience, reducing energy needs during periods of high temperatures.

3.4. Protected/Unprotected Cultural Areas

Based on the prior characterization, a classification was developed to differentiate between protected and unprotected cultural areas, which are delineated with a black contour in Figures 1 and 2 for each of the example municipalities. Notably, Alcalá la Real has approximately one-fourth of its urban area protected, Cazorla has around one-third. This distinction underscores the necessity of adopting differentiated strategies tailored to the specific conditions of each municipality. Consequently, this classification represents a crucial preliminary step in establishing intervention criteria aimed at minimizing or preventing alterations to the aesthetic and historical values of protected assets caused by the installation of solar energy systems.

3.5. Visibility Study and Strategic Planning

This analysis primarily utilizes Digital Surface Models (DSM), specifically the use of 2 m DSM published by the National Geographic Institute [37], to generate detailed three-dimensional representations of the terrain and raised elements. The points for carrying out the visibility work will depend on the locations of heritage assets, viewpoints, and other visual consumption points, and must be carefully determined during fieldwork and tested with local stakeholders.

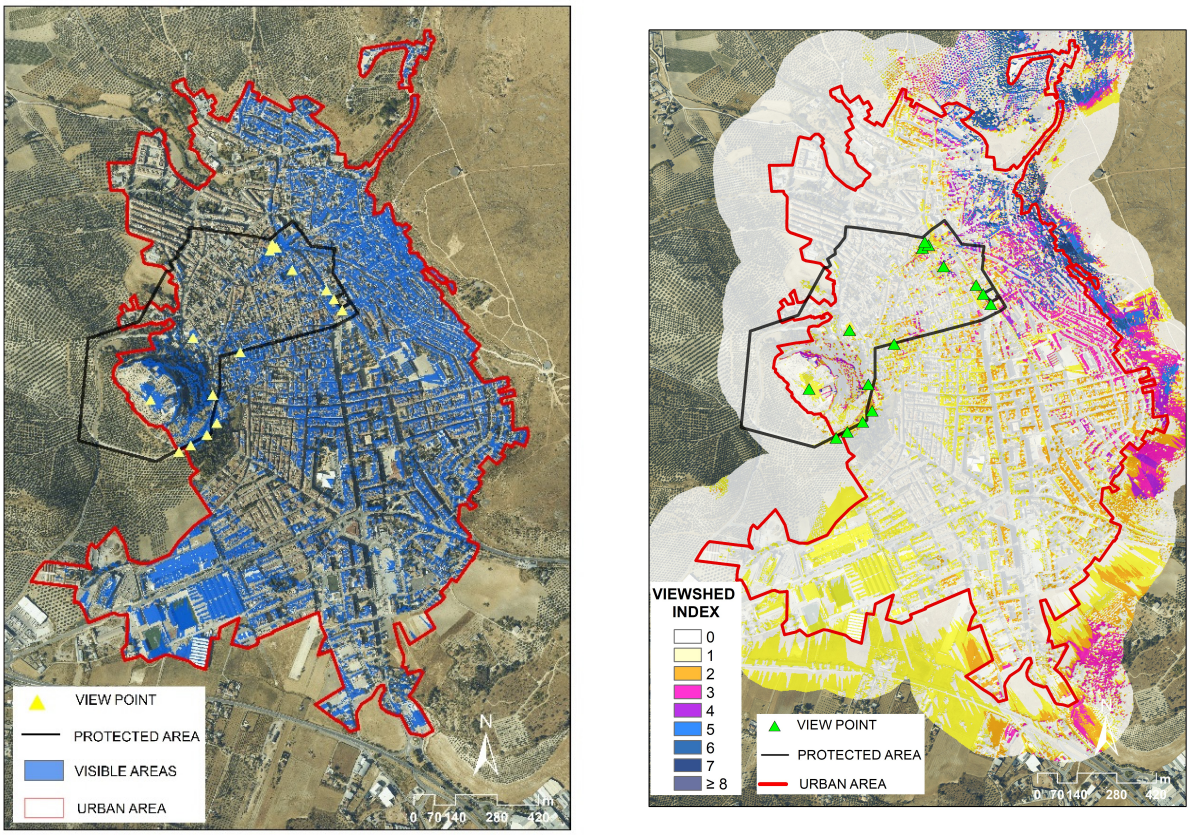


Figure 1. Maps of protection and visibility zones of Alcalá la Real (right: increasing viewshed index). Source: Own elaboration (2025).

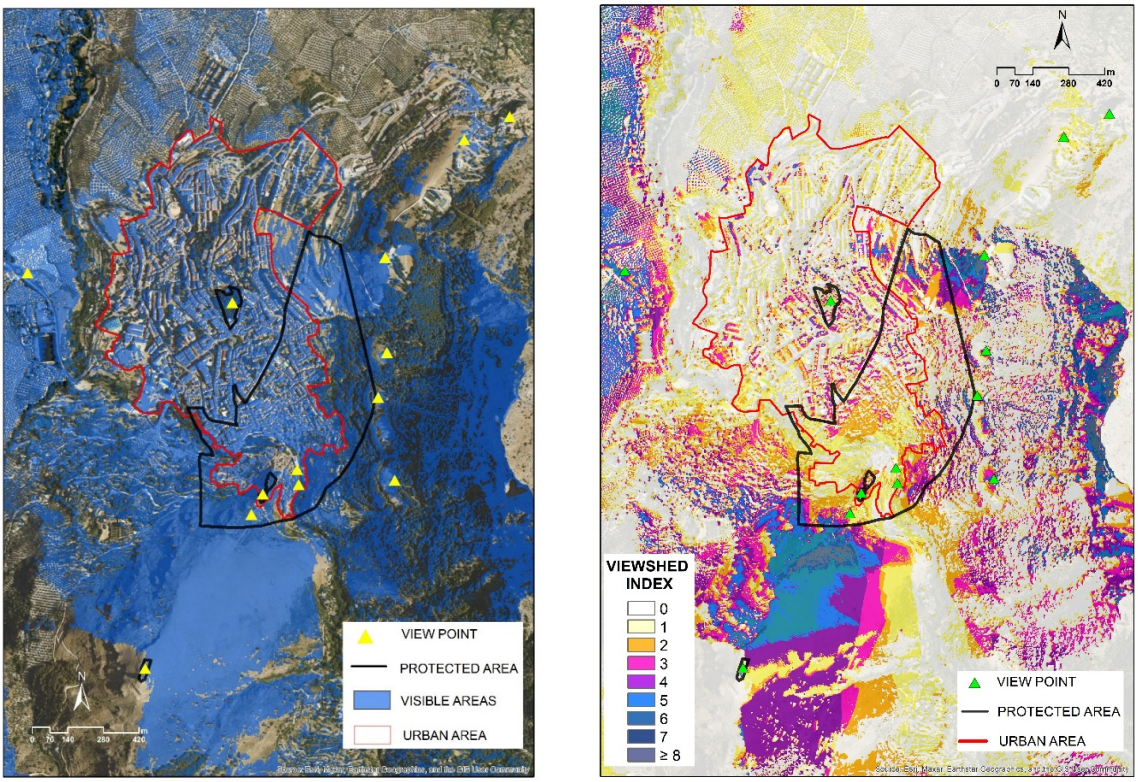


Figure 2. Maps of protection and visibility zones of Cazorla (right: increasing viewshed index); Source: Own elaboration (2025).

Regarding the GIS methodology, the analyses have been performed considering an average observer height of 1.80 m. Two types of analyses have been carried out:

- Characterization of visible and non-visible zones: This analysis allows for identifying which parts of the urban and heritage which areas can be seen from one of the key points, such as viewpoints or prominent monuments, as applicable. These points were checked with local stakeholders. This study is essential to determine locations where the integration of renewable energies, such as rooftop solar panels, can be carried out with minimal visual impact.
- Analysis of the number of points from which each area is visible: This analysis quantifies the visibility degree of each area by calculating the number of observation points from which it can be seen. The results enable the classification of zones according to their visual exposure facilitating the assessment of their suitability for rooftop renewable energy installations. Priority is given to areas with lower visual exposure to minimize potential interference with the urban and heritage landscape, ensuring a balanced integration of renewable energy solutions within culturally significant environments.

In Alcalá la Real, the entire urban area is situated at the foot of the Castillo de la Mota, with the most visually exposed zones concentrated in the eastern section of the urban core. These areas are located outside the traditionally protected zone, facing the Fortaleza de la Mota, as well as in certain parts of the historical ensemble (Figure 1). In Cazorla, the cultural heritage protection perimeter exhibits high visual exposure, along with the adjacent area. However, more distant sectors have lower visual exposure, and one particular area accommodates public-use facilities, including several sports buildings, a children's play area, and a parking lot. The architectural typology of this sector differs significantly from the traditional urban fabric (Figure 2).

4. Proposed Measures for Integration and Location of Energy Communities

Following the analysis of the characteristics of the protected heritage and the historical-architectural profile of each urban area under study, along with the possible recommendations and/or restrictions established by current cultural and urban planning regulations—and, crucially, in accordance with energy regulations—specific measures for the integration of solar energy will be proposed. These measures will not be uniform across all cases, as construction typologies, materials, and building characteristics vary depending on the country and the specific area under consideration. However, the measures will always be more restrictive in areas with protected heritage assets, where technologies and placements will be selected to minimize visual impact, and any potential integration of solar energy will require explicit approval from the relevant cultural authority. In the case of non-protected areas, guidelines will be proposed to minimize potential impacts on the brother urban environment. These areas will also serve as key locations for shared self-consumption installations linked to local energy communities, aiming to support protected zones where visual impact may be more significant. Additionally, they will provide opportunities for interested residents and business operators in non-protected areas to participate in renewable energy initiatives. The proposed solutions for each urban area under study are presented below.

4.1. Alcalá la Real

For Alcalá la Real, differentiated measures were developed for the Protected and the Unprotected Zones, considering that only a small portion of the urban area is subject to high visual exposure. Additionally, viable locations within the urban core allow for the placement of solar energy installations without significantly disrupting the overall urban harmony.

4.1.1. Protected Zones

- General Restrictions: Photovoltaic solar installations are generally not permitted on protected assets, such as the Castillo de la Mota and the historical ensemble, unless detailed studies confirm their seamless integration and demonstrate no adverse effects on cultural heritage. In such cases, prior authorization from the competent cultural authority is required.
- Preferred Locations: Installations should be prioritized in interior courtyards, secondary or rear-facing roofs that are not visible from key viewpoints. Areas of low visual exposure, as identified through visibility analyses should be favored. Additionally, visual camouflage techniques should be employed to minimize the visibility of installations from elevated vantage points, ensuring that they do not disrupt the urban landscape's aesthetic coherence.
- Installation Characteristics: Solar tiles that replicate traditional materials should be used, while transparent solar panels may be considered for windows. Photovoltaic panels should have matte finishes and colors that blend with the municipality's conventional building materials.
- Protection of Original Elements: The alteration of original architectural features, such as traditional tiled roofs, is prohibited unless explicitly authorized in specific cases.
- Approval Process: All installation proposals must receive approval from the Andalusian Cultural Department or the relevant cultural authority, in addition to municipal authorization. Furthermore, an architectural integration project must be submitted for review by the appropriate bodies

4.1.2. Unprotected Zones

- Flexibility and Visibility: Although these areas offer greater flexibility, their visibility from elevated points, particularly from the Castillo de la Mota, necessitates he application of aesthetic compatibility criteria.
- Visual Harmony: Although more leniency is permitted, installations must be designed to maintain urban visual harmony. Greater flexibility is allowed in the industrial and commercial sector on the southwestern flank due to its ongoing transformation.
- Preferred Locations: Priority should be given to south or southwest-facing roofs with minimal visibility from major roads. Flat roofs and large surfaces on modern or industrial buildings, particularly those outside direct sightlines from key viewpoints, should also be considered. Installations should feature matte finishes and color tones that prevent strong reflections or stark contrasts with the surrounding environment.
- Community Solar Plants: Community solar plants should be installed on the roofs of public municipal buildings in unprotected areas with low visual exposure (e.g., near the Castle's viewpoints) to minimize their impact on heritage sites.
- Installation Characteristics: Aesthetic guidelines should be followed, ensuring that installations incorporate matte finishes and colors that blend with the surrounding landscape to prevent strong reflections or visual disruptions. Conventional solar panels should be used on flat roofs and modern structures, with designs adapted to the building's form and volume (3–5 cm) to minimize their visual impact. In protected areas, integrated technologies such as solar tiles, solar glass, or transparent panels that replicate traditional materials and respect the existing architectural typology are recommended.
- Strategic Planning and Feasibility Study: A feasibility study was conducted to identify strategic locations for collective self-consumption infrastructure mainly on the roofs of public municipal buildings outside the historical centre. The goal is to facilitate the development of local energy communities and concentrate installations in areas

where the visual perception of the heritage is not affected. One such location is the southwestern sector of the urban area that concentrates most of the public-use facilities (services, commercial, and industrial), characterized by a modern and functional construction typology distinct from the traditional protected urban core. Within this sector, the proposed installation site is the roof of an auxiliary building adjacent to the paddle courts, near the municipal swimming pool, as shown in Figure 3 (left). This location was selected to minimize both aesthetic and cultural impact while optimizing energy production and community benefits.

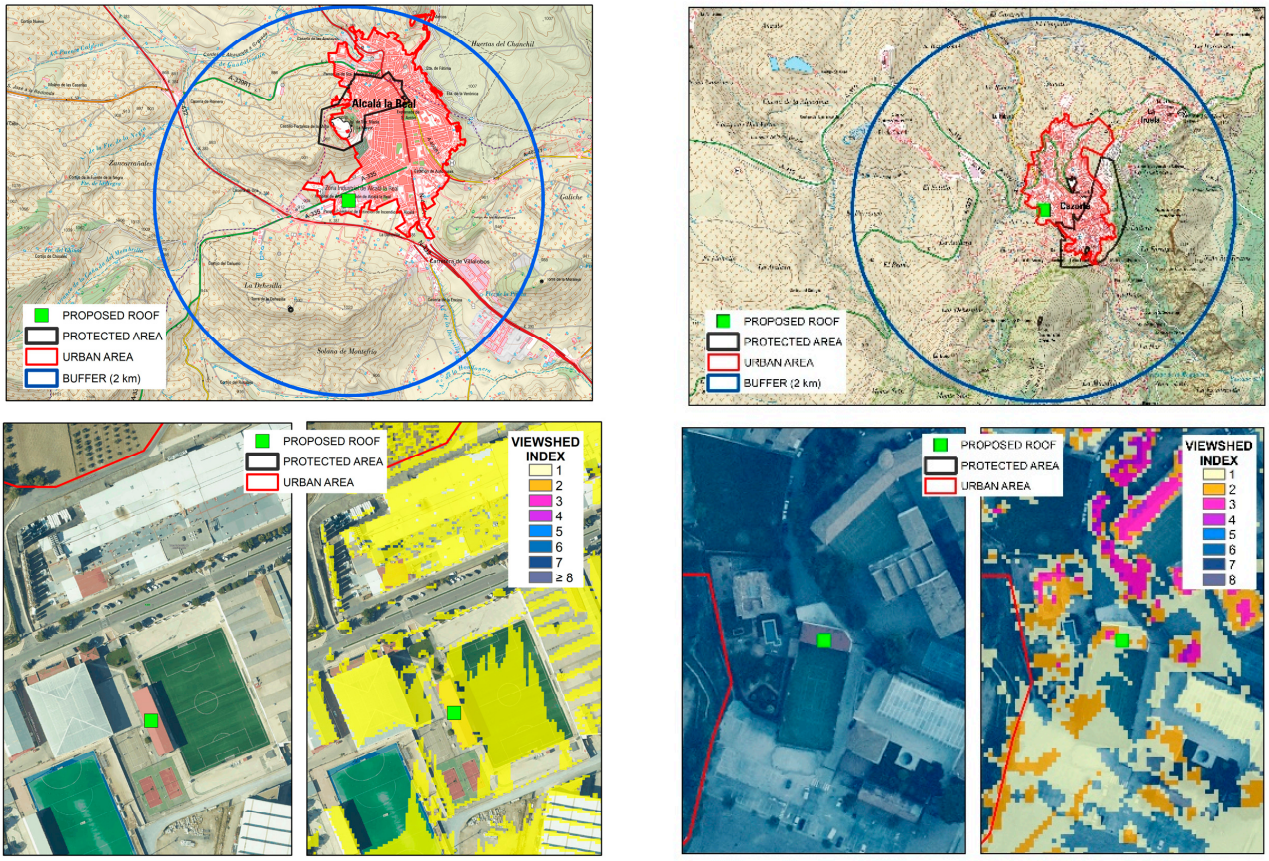


Figure 3. Proposal for shared self-consumption installations for LECs in Alcalá la Real and Cazorla. Source: Own elaboration (2025).

4.2. Cazorla

One third of Cazorla's urban core is culturally protected, situated in the Natural Park of Cazorla, Segura, and las Villas, an area characterized by steep slopes. Within this context, specific measures have been developed for both protected and unprotected zones.

4.2.1. Protected Zones

- General Restrictions: Photovoltaic solar installations are generally not permitted unless detailed studies demonstrate their proper integration and confirm the absence of any adverse impact on cultural heritage.
- Preferred Locations: Priority should be given to installing solar systems in interior courtyards, on secondary or rear-facing roofs that are not visible from key viewpoints. Installations should be avoided in areas with high visual exposure, as identified through visibility analysis. Additionally, efforts should be made to minimize the visibility of installations from tourist routes or viewpoints.

- Installation Characteristics: Use solar tiles that replicate the appearance for the original materials; integrates transparent solar panels into windows; and employ panels with matte finishes and colors hat closely match the municipality's traditional materials.
- Protection of Original Elements: Maintaining the visual integrity of the facades is essential, ensuring that the solar panels are not visible from main streets or plazas.
- Reversibility: Installation systems should be designed for easy removal without affecting the original structures.
- Approval Process: Any installation requires explicit approval from the relevant cultural authority, with a preference for collective installations located outside the protected zone.

4.2.2. Unprotected Zones

- Flexibility and visibility: Although the unprotected areas of Cazorla offer greater flexibility for solar installations, their visibility from elevated points—such as natural vantage points overlooking the historic centre—requires strict application of aesthetic compatibility criteria.
- Visual harmony: Although unprotected areas allow for greater design flexibility, installations should be designed to maintain the overall visual harmony of the urban environment, giving priority to the low visibility areas identified in the analysis. In areas characterised by modern, functional buildings that contrast with the historic core, a balance must be struck to avoid visual disturbance.
- Preferred locations: Priority should be given to south or south-west facing rooftops with minimal visibility from main roads and tourist viewpoints. Consideration should also be given to flat roofs and large areas of modern or industrial buildings located out of direct sightlines of major heritage sites. Installations should have matt finishes and colours that avoid strong reflections or sharp contrasts with the surrounding landscape.
- Community solar plants: It is recommended that community solar plants be installed on the roofs of municipal public buildings, in unprotected areas with low visual exposure, thus supplying both protected and unprotected areas and minimising the impact on heritage.
- Installation characteristics: Aesthetic guidelines should be followed, ensuring that installations incorporate matt finishes and colours that blend in with the surroundings. On flat roofs and modern structures, conventional solar panels should be used, with designs adapted to the shape and volume of the building (3–5 cm) to minimise visual impact. On the other hand, in protected areas, integrated technologies such as solar shingles, solar glass or transparent panels that mimic traditional materials and respect the existing architectural typology are recommended.
- Strategic Planning and Feasibility Study: A feasibility study should identify strategic locations for collective self-consumption infrastructure—especially on the roofs of public municipal buildings outside the historic center. In Cazorla, focusing on peripheral areas with lower visual exposure ensures that installations optimize energy production and community benefits while preserving the aesthetic and cultural integrity of the heritage sites.

As a proposed location for a shared self-consumption installation that can serve both the protected zones and other interested residents, the roof of the auxiliary building at the paddle courts, next to the municipal pool, is recommended for the energy community. This area is located outside the protected historic center and in a zone of low visual exposure, concentrating public-use facilities on the edge of the urban core (Figure 3, right), thereby minimizing the aesthetic and cultural impact.

5. Discussion

The methodology designed for the integration of solar energy into urban environments with heritage protection shares similarities with some previous studies but also presents certain differences. In any case, the application of all proposed guidelines results in a novel and useful tool for this type of intervention. While most studies focus on specific interventions at the scale of individual dwelling or buildings, this work adopts a holistic and multidisciplinary approach. It reinforces the idea that planning for solar energy integration must be based on an comprehensive analysis of visibility, territorial zoning, and the socioeconomic, energy, and cultural characteristics of urban centers. This aligns with the research of Lucchi [17], who proposes a conceptual framework in which solar energy integration is governed by aesthetic, functional, and regulatory compatibility criteria. However, our approach goes further by defining non-negotiable guidelines to ensure the preservation of cultural heritage.

Although this is an integrated tool, the use of digital surface models (DSM) processed through GIS allows the calculation of the visibility or across all sectors of a municipality with a precision of 2 m for an observer height of 180 cm. While some studies employ these techniques to calculate visual catchment areas [38] or asses solar performance based on light and shadow zones [39], they have not previously been applied to determine the visual exposure of urban areas in renewable energy integration projects within heritage contexts.

Furthermore, analyzing the architectural history of the urban area and the protected heritage allows for a better understanding of traditional materials used, thereby facilitating the identification of solutions adapted to the characteristics of the environment. In fact, recent research [40] highlights the need for the energy transition in historic cities to be articulated throug innovative solutions that integrate smart technologies. These solutins enable the implementation of building-integrated photovoltaic (BIPV) infrastructures which function synergistically with the existing urban fabric.

Additionally, guidelines and case studies from projects in Edinburgh and the United States demonstrate greater in integrating solar energy into heritage sites, providing examples of best practices that confirm the technical and regulatory feasibility of such interventions. However, Italian and Swiss guidelines emphasize the importance of applying micro-generation solutions that integrate solar energy discreetly and respectfully, using materials and techniques that adapt to the morphology of historic buildings.

In this context, the proposal to promote energy communities as a priority solution through collective self-consumption installations on municipal roofs to preserve cultural heritage represents a significant advancement. This approach encourages the adoption of sustainable energy alternatives by cultural and urban planning authorities while ensuring the protection of heritage values. Moreover, energy communities can serve as a bridge between energy efficiency and the protection of historical legacy preservation., promoting citizen participation and local governance in heritage neighborhoods [41]. This is particularly relevant in municipalities such as Granada, where an energy community under development in the historic neighborhoods of Albaicín and Realejo has been negotiating for two years with the city council, the university, and private institutions for two years to secure a roof for sharing photovoltaic solar energy generation qithouth compromising the conservation of cultural heritage [41].

Ultimately, the integration of renewable technologies into cultural heritage is feasible if specific design criteria are applied to ensure aesthetic and functional compatibility without compromising historical value. Collaboration among experts in energy, heritage, geography, and architecture is essential to develop solutions that, in addition to contributing to the energy transition and mitigating climate change—key aspects in cities in the Anthropocene—strengthen the identity and social cohesion of historic cities [42].

Although current regulations have been fundamental in promoting the integration of renewable energies in heritage environments, they present significant limitations in their practical application. Additionally, the existing regulations show insufficient adaptability to new technologies, making it difficult to incorporate improvements that optimize energy efficiency without compromising the authenticity of cultural heritage. Therefore, we propose that administrative procedures be reviewed and simplified, and that flexible, updated guidelines be established to respond to technological advances. Likewise, it is recommended to foster inter-institutional collaboration among cultural, urban planning, and energy authorities to ensure that future policies are more agile and tailored to the realities of integrating energy systems in historic settings. These improvements would help optimize the balance between preserving cultural legacy and transitioning toward a sustainable energy model.

6. Conclusions

The research demonstrates that it is possible to integrate solar energy into urban environments with heritage protection through a holistic and multidisciplinary methodology. The developed tool, which incorporates visibility criteria through Digital Surface Models (DSM), territorial zoning analysis, and the socioeconomic, energy, and cultural characterization of urban centers, offers a novel proposal compared to interventions that usually focus on the dwelling or buildings scale. Non-negotiable guidelines have been established to ensure that the installation of photovoltaic systems respects both aesthetics and historical value, based on recent research [17–40] and on a comparative analysis of international guidelines—both flexible and strict—from historic cities in Edinburgh, the United States, Italy, and Switzerland.

The use of geoinformation techniques to calculate visibility with a precision of 2 m for an observer height of 1.80 m constitutes a significant technical advancement, as it allows for accurately identifying low-visibility zones, thereby facilitating the strategic placement of solar installations [38,39]. Moreover, the analysis of architectural history and traditional materials enables the adaptation of technological solutions to the characteristics of the environment, resulting in an integration that respectfully preserves the visual composition of facades and interior courtyards.

Finally, promoting energy communities through collective self-consumption installations on municipal roofs emerges as a solution that bridges energy efficiency and cultural legacy protection, fostering citizen participation and local governance in heritage neighborhoods [41]. Ultimately, collaboration among experts in energy, heritage, geography, and architecture is essential to advance the energy transition in Anthropocene cities without compromising their identity and social cohesion.

In the context of uncertainty in the prices of energies such as gas, which have an impact on electricity prices, this type of solution can also help to alleviate situations of energy vulnerability, as priority is being given to subsidising energy communities whose objective is to cede part of the energy produced to cases of this type.

This research shows the difficulty of reconciling solar energy integration in heritage environments due to the insufficient adaptability of legislation to technological advances, which hinders the incorporation of improvements that optimize energy self-sufficiency, making it necessary to flexibly update and modernize the regulations to address these needs.

This research is focused on the incorporation of urban-scale tools that promote environmental, cultural, and social sustainability. These aspects are essential for enhancing energy self-sufficiency and sovereignty, adapting to climate change, and reducing energy vulnerability while improving social equity.

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Abbreviations

The following abbreviations are used in this manuscript:

CO_2	Carbon dioxide
EU	Europe
LECs	Local Energy Communities
RDL	Royal Decree-Law
RD	Royal Decree
BIPV	Architecturally Integrated Photovoltaic Systems
PGOU	General Urban Development Plan
NNSS	Subsidiary Regulations
LOUA	Andalusian Urban Planning Law
SIMA	Multi-territorial Information System of Andalusia
DSM	Digital Surface Models
GIS	Geographic Information Systems

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