SOLAR ENERGY POTENTIAL ASSESSMENT ON HERITAGE PROTECTED VENETIAN OLD TOWN ROOFTOPS BASED ON LIDAR DATA, CLOUD COMPUTING AND RADIATION MODELING: AN AGENT-BASED USE-CASE IN SLOVENIA

Summary

The Mediterranean region has significant solar energy potential but also extensive protected built heritage, which creates challenges for integrating photovoltaics (PV) on historic rooftops. National guidelines are often general, allowing inconsistent interpretation by heritage authorities and resulting in uncertainties for homeowners and communities undertaking retrofitting. Solar potential mapping typically overlooks heritage restrictions and lacks building-scale precision, leading to unrealistic expectations. This study is particularly relevant in North Adriatic Venetian old towns, characterized by specific urban morphology. Focusing on the old town of Koper–Capodistria, where rooftop PV is largely prohibited to preserve the medieval character, this study applies LiDAR data, cloud computing, and solar radiation modelling to assess realistic solar scenarios that comply with heritage guidelines. These scenarios are used to inform an agent-based decision-making model, creating a feedback loop and enabling the development of a more precise solar zoning map to support energy-positive districts in the region.

Keywords: Solar Energy Potential, Solar Radiation Modelling, Energy Positive Districts, Built Heritage, Agent-Based Modelling

Field of application for the findings: Sustainable and Efficient Districts

1. Introduction

The Mediterranean is one of Europe's sunniest regions, offering significant solar energy potential (Perpiña Castillo et al., 2016), while also containing a rich and often strictly protected built heritage. The integration of photovoltaics (PV) on historic rooftops is therefore complex. National guidelines are typically broad and not adapted to specific urban morphologies, which can lead to inconsistent interpretations among heritage officials involved in the approval process. This creates uncertainty for homeowners and communities considering investment in PV systems. Moreover, solar potential mapping frequently fails to distinguish between heritage-restricted and unrestricted areas (Kojaković & Vaskalis, 2022; SOLAR ADRIA Project, 2021), generating expectations that may not be achievable in practice. Available cadaster data are often limited in geographic scope and resolution, suitable for general assessments but insufficient at the building scale (*CEU | Solarni Kataster DEDIS*, n.d.). North Adriatic Venetian towns present additional challenges due to their specific morphology: pitched roofs with traditional tiles, dominant vertical elements such as bell towers, narrow streets, and coastal or island settings. These features significantly influence solar exposure and urban radiation patterns (Morganti et al., 2017). The Old Town of Koper–Capodistria, protected as a cultural monument, currently prohibits rooftop PV installations primarily to preserve its medieval character. Nevertheless, some residents informally install PV systems, reflecting the tension between heritage protection and the urgent need for sustainable energy solutions. This study addresses the gap between conservation and energy transition through a detailed building-scale solar potential assessment based on LiDAR data, cloud computing, and radiation modelling, aligned with the most recent heritage guidelines (Gantar et al., 2025; Tomšič et al., 2025). Scenarios were developed in collaboration with the heritage department and include the application of PV tiles, exclusion of buildings under special heritage treatment (monuments of regional or national importance), and visibility analyses from sea level, street level, and bell tower viewpoints. The results inform an agent-based decision-making model for energy-efficient renovation and retrofitting, supporting multiple stakeholders. In addition to technical solar potential, the model incorporates socio-economic conditions, dwelling characteristics, and subsidy availability, generating a feedback loop for the development of a precise solar zoning map similar to that implemented in Prague (Odbor památkové Péce, 2022). This approach enables the identification of rooftop sections that can accommodate PV—fully or partially—without compromising the visual integrity of the historic urban fabric. Ultimately, the proposed workflow supports the establishment of Positive Energy Districts (PEDs) within Monument-Protected Areas (MPAs) across the Northern Adriatic, including Venetian historic towns such as Piran, Rovinj or Venice.

2. Methodology

Data Collection, Preprocessing and Model Establishment

The methodology relies on high-resolution spatial data and advanced radiation modelling to achieve building-scale accuracy in a heritage-sensitive context. Airborne Laser Scanning (ALS) data formed the primary dataset. Ground and segmented building points were extracted from the LiDAR point cloud and combined with 2D building outlines following (Bizjak et al., 2021), enabling precise three-dimensional reconstruction of rooftop geometries. The LiDAR-based 3D models were calibrated in a GIS environment to ensure geometric and positional accuracy. Each rooftop surface was assigned a unique identifier linked to its cadastral lot ID, allowing integration with ownership, socio-economic, and heritage protection data. A parametric workflow developed in Grasshopper automated geometry processing and solar radiation simulations. Annual solar irradiation values were calculated for each rooftop surface, and results were calibrated against previous regional solar potential studies to ensure consistency and reliability.

Scenario Development

Four scenarios were designed to evaluate solar potential under progressively refined heritage-related constraints, moving from a theoretical maximum toward a realistic and conservation-compatible outcome. The Base Case Scenario assesses total solar potential across all available rooftops within the protected Old Town of Koper, serving as a benchmark and comparison with earlier GIS-based estimations.

Scenario 1 explores the use of photovoltaic (PV) tiles as a replacement for traditional roofing materials. Simulations were initially applied to all rooftops and later refined to focus on surfaces visible from sea and street level, addressing visual sensitivity in historic settings.

Scenario 2 introduces stricter heritage constraints by excluding buildings under special protection (monuments of regional or national importance), reducing eligible buildings from 1,198 to 986.

Scenario 3 conducts a detailed visibility analysis from sea level, street level, and bell tower viewpoints, the latter representing a key tourist perspective. LiDAR-supported drone footage was used as a visual mask to improve identification of exposed roof areas.

Scenario 4 integrates all constraints—heritage exclusions, PV tile application, and visibility limits—to determine a realistic solar potential aligned with conservation principles.

Agent-Based Behavioural Model

An agent-based model simulates how property owners in heritage-protected districts decide on energy-related interventions, particularly rooftop retrofitting. The model includes one explicit agent type—the homeowner—while buildings are treated as aggregate entities whose state depends on collective owner decisions. Behavioral variables are derived from the Theory of Planned Behavior and small-world network dynamics (Preisler et al., 2017; Rai & Robinson, 2015), including attitude, perceived behavioral control, and intention. These are influenced by economic status, renovation history, intervention costs, subsidy levels, co-ownership structure, and social pressure. Social influence is modelled using the Relative Agreement algorithm within a neighborhood-based small-world network. If sufficient owners support an intervention, it is evaluated through a heritage protection module to determine eligibility. Solar potential estimates are incorporated as building-level attributes influencing adoption decisions. By aggregating simulated PV uptake, the model forecasts district-level solar production under varying policy and subsidy scenarios.

3. Results and Conclusion

The results indicate that two extreme scenarios should be avoided. The first is the imposition of overly rigid restrictions that completely prohibit PV installations on rooftops. In practice, individual homeowners may still install systems informally, resulting in uncoordinated interventions that neither respect heritage values nor allow proper adaptation of the technical infrastructure. Such a restrictive approach can also negatively affect broader renovation decisions. If energy retrofitting is perceived as impossible, residents may choose to relocate rather than invest in their properties, contributing to population decline and stagnation within the Old Town instead of supporting its revitalization. The second—equally problematic, though unrealistic—scenario is permitting PV systems on all rooftops without limitation. While this would maximize theoretical solar potential, it would compromise the historic urban landscape and require extensive infrastructure upgrades that may be incompatible with the protected fabric. This study demonstrates that both extremes can be avoided by integrating heritage constraints and homeowner decision-making within an agent-based model. Used as a strategic tool by heritage authorities, such a model can balance the protection of immovable cultural heritage with residents' energy needs in the process of establishing PEDs within MPAs. Furthermore, an interactive and detailed solar zoning map clarifying conditions and limitations enhances transparency, builds trust, and provides homeowners with greater certainty when planning long-term investments.

This study shows that integrating photovoltaics in strictly protected Mediterranean historic centers requires high spatial precision and strong contextual awareness. In the Old Town of Koper–Capodistria, extensive preprocessing was necessary due to limited digitalized building data. Accurate rooftop reconstruction from LiDAR and cadastral sources proved crucial for reliable building-scale solar assessment. Although data preparation is complex, the workflow allows partial automatization through parametric modelling and cloud-based radiation simulations. The findings suggest that heritage restrictions can become more flexible and transparent when supported by detailed, building-specific analyses. An interactive solar zoning map enables evaluation of individual rooftop sections, improving clarity for both homeowners and heritage authorities. While experiences from Prague highlight the value of visibility simulations, officials often still require on-site verification. Integrating drone photogrammetry with LiDAR visualization strengthens trust in digital results. The methodology is transferable to historic towns with LiDAR data but no digital twin, supporting Positive Energy District development within protected areas.

4. References

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