



Full-length article

Harnessing rooftop photovoltaic potential: Adoption disparities across building types in Tarragona Province, Spain [☆]

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ABSTRACT

In recent decades, climate change and the global energy transition have prioritised renewable energy adoption. Rooftop photovoltaic (PV) systems have emerged as a promising solution, aligning with sustainability, decentralisation, and local energy production while efficiently using built spaces. Despite their potential, rooftop PV systems are still unevenly adopted due to technical and economic barriers. A lack of consistent data limits the ability to track adoption and support energy transition planning. This study focuses on Tarragona province (Spain) and assesses the solar PV potential of public and private buildings, including town halls, schools, libraries, and residential properties. Using GIS-based modelling and high-resolution geospatial data, including LiDAR-derived elevation models and cadastral records, we estimate that 38.72% of rooftops in the province meet suitable technical conditions for PV installation under a conservative scenario. A key contribution is the creation of a geolocated database of 18,577 rooftop PV installations through detailed photointerpretation, enabling spatial assessment of where systems have been deployed and how adoption varies by building type. Statistical analysis reveals contrasts in adoption, with residential buildings showing higher uptake, while public buildings adopted PV later. Results confirm that adoption is shaped by technical potential and sector-specific policy barriers. Findings suggest public buildings could foster broader PV uptake, leveraging peer effects and targeted incentives. This study highlights the need for accurate, publicly accessible PV installation databases to support energy planning, especially in urban and mixed-use areas. By clarifying PV adoption dynamics, this research supports informed policymaking for a more equitable, effective energy transition.

1. Introduction

Climate change and the need to decarbonise energy systems are global challenges requiring urgent action, as highlighted by the Paris Agreement and IPCC reports (United Nations Framework Convention on Climate Change, 2015). The energy sector is central to reducing greenhouse gas emissions, making renewable energy adoption essential for limiting global warming while enhancing energy security. Among the available pathways, renewables are key to achieving a sustainable, low-carbon future, reducing dependence on fossil fuels, and promoting both resilience and energy equity. In Europe, the European Green Deal has set ambitious targets to achieve climate neutrality by 2050, placing renewable energy at the core of the region's decarbonisation strategy (European Commission, 2022; Escobar et al., 2020). Within this framework, increasing the deployment of renewables is seen as critical for reducing emissions, enhancing energy security, and fostering resilience across member states.

Among renewable energy sources, solar photovoltaic (PV) systems have emerged as particularly promising due to their scalability, declining costs, and suitability for decentralised generation using existing built spaces (Vargas-Salgado et al., 2022). Rooftop PV installations support local energy production, reduce transmission losses, and enable citizen participation in the energy transition (Toboso-Chavero et al., 2019). Despite this potential, widespread rooftop PV adoption faces challenges. High upfront investment costs, regulatory complexities, and insufficient data on rooftop suitability and ownership structures continue to limit deployment rates (Rosales-Asensio et al., 2019). Addressing these barriers is essential for unlocking the potential of decentralised solar energy within climate and energy transition frameworks.

Spain, with its high solar potential, is well-positioned to advance rooftop PV adoption within the European energy transition (López Prol

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and Steininger, 2020; Ministerio para la Transición Ecológica y el Reto Demográfico, 2020). The regulatory reform introduced in 2019 (Royal Decree 244/2019) marked a turning point by promoting self-consumption and decentralised energy generation, aligning with national and EU sustainability goals (Ministerio para la Transición Ecológica y el Reto Demográfico, 2020, 2021; Rosales-Asensio *et al.*, 2019). However, adoption remains uneven across sectors and regions due to economic and administrative barriers, policy uncertainty, and persistent challenges in accessing reliable data on rooftop potential and PV deployment (Mérica-Rodríguez *et al.*, 2015; Gallego-Castillo *et al.*, 2021). The non-residential sector also plays a key role in PV deployment globally, as shown by studies in Spain, Australia, and the United States examining adoption drivers and policy impacts (San-Martín and Elizalde, 2024; Best and Burke, 2023; Crago and Koegler, 2018).

While large-scale solar projects contribute significantly to renewable energy targets, they require substantial land areas and can conflict with agriculture, ecosystem services, and cultural values (Kienast *et al.*, 2017; Obane *et al.*, 2020; Serrano *et al.*, 2020). In Spain, many projects encroach upon valuable agricultural and forest lands or target ecologically sensitive areas, raising concerns over the environmental and social sustainability of utility-scale renewable expansion (Serrano *et al.*, 2020). Integrating PV into existing infrastructure and urban environments can mitigate these land-use conflicts, contributing to climate goals while preserving essential land uses (Shiraishi *et al.*, 2019).

Effective energy planning requires reliable, up-to-date data; however, the energy transition often lacks consistent data frameworks, contributing to uncertainty and exacerbating social inequalities and energy poverty (Moreno-Munoz, 2021; Yin and Zhou, 2022; Liang *et al.*, 2025). Public administrations play a critical role in ensuring equitable PV deployment through informed local planning, supported by initiatives such as NextGenerationEU funding and recent incentives that have accelerated rooftop PV adoption (European Commission, 2020).

In this context, this study uses the province of Tarragona as a case study to assess the technical potential of rooftop PV systems and to analyse current adoption patterns within Spain's energy transition. In this study, we define the public sector as public service buildings (e.g., town halls, libraries, schools) owned and operated by public administrations, whereas the private sector includes both residential and non-residential private users, such as households, retail, offices, industry, and agriculture. We align with the literature, distinguishing between residential (private) and non-residential (public and private) sectors to maintain consistency throughout the analysis.

The main objectives of this study are:

1. To assess the technical PV potential in rooftop areas in the Tarragona province.
2. To examine the sectoral (in)equality in rooftop PV adoption within the province.
3. To provide detailed information on the energy potential of these spaces to promote informed planning and social debate.

This document is organised as follows: Section 2 provides the theoretical background and key factors, along with an overview of the research gaps identified in this study. Section 3 describes the study area and its characteristics. Section 4 details the design and analysis of the available data. Section 5 presents a comprehensive description of the results. Section 6 discusses the findings relative to existing research and their implications. Finally, Section 7 offers conclusions.

2. Background

2.1. Key factors affecting solar photovoltaic adoption

Decisions about the adoption or rejection of solar photovoltaic systems (PV) are influenced by a variety of factors, both endogenous and exogenous (Ahmad *et al.*, 2024; Zhang *et al.*, 2023; Bekti *et al.*,

2022; Alrawi *et al.*, 2022; Jiang *et al.*, 2022). Endogenous factors include household income, environmental awareness, energy consumption habits, and socio-demographic characteristics such as education level, age, and homeownership status. Exogenous factors include incentive systems, market structures, regulatory frameworks, electricity prices, and the exclusion of climate change externalities from energy prices, factors that have all been identified as either barriers or drivers of renewable energy adoption. These endogenous and exogenous factors often interact, as the willingness to adopt and pay for PV systems is shaped by the capacities, attitudes, and financial readiness of residential and private non-residential users (endogenous) while also being shaped by external conditions such as available incentives and market structures. For example, some households are willing to pay more for better and more reliable services, suggesting that perceived value plays a role in adoption (Qureshi *et al.*, 2017). Multiple studies have shown that higher income and educational attainment are positively correlated with the decision to adopt PV (Vaishnav *et al.*, 2017; Alipour *et al.*, 2020).

In some cases, the factors influencing adoption are highly context-dependent; for example, in developing countries, the inaccessibility of grid connections has been identified as a primary driver of PV adoption (Muntasser *et al.*, 2000). While many studies have focused on residential adoption, research has increasingly explored the non-residential sector, identifying specific drivers and barriers in various contexts, such as in India, Mexico, and Hong Kong (Dhingra *et al.*, 2023; Mah *et al.*, 2018; Hancevic and Sandoval, 2023). A recent study conducted in the Netherlands identified four key factors influencing the adoption of photovoltaic technology: the perceived relative advantage of the technology, innovation complexity, social influence, and knowledge of subsidies and costs (Vasseur and Kemp, 2015), concluding that the cost of photovoltaic systems is the most significant determinant of adoption decisions for both adopters and non-adopters.

Several studies have found that consumers prioritise cost over environmental or other concerns when deciding to adopt solar PV systems (Palm, 2016). Lack of technological awareness among users has also been identified as a significant barrier, particularly in developing countries, often leading to the spread of misinformation about the benefits of the technology (Muntasser *et al.*, 2000). A recent study conducted in Norway classified nine key barriers to PV adoption, structured across three perspectives: (1) the residential users' perspective, (2) the private sector's perspective, and (3) the public sector's perspective (Xue *et al.*, 2021). From the residential users' perspective, the main barriers include high initial investment costs, limited access to financing, and a general lack of awareness or misinformation about the potential benefits of PV systems. From the private sector's perspective, barriers primarily stem from limited funding opportunities, a lack of pilot projects to demonstrate feasibility, and uncertainty regarding return on investment. From the public sector's perspective, challenges include underutilisation of existing incentive schemes, bureaucratic hurdles, and inconsistencies in regulatory frameworks.

These barriers can be broadly categorised into financial constraints, information-sharing challenges, and risk and uncertainty issues, all of which significantly impact the adoption rates of PV systems (Xue *et al.*, 2021). The differences between public and private sector adoption are particularly relevant, as they reflect varying levels of resource availability and regulatory challenges. While the public sector often struggles with bureaucratic inefficiencies and budget constraints, the private sector (residential and non-residential) is more affected by market conditions and financial limitations. Addressing these disparities is critical to ensure a more equitable and effective energy transition.

The barriers to PV adoption in Norway and Sweden share common challenges, particularly regarding high initial costs and limited public awareness. However, while Norway's barriers are distinctly categorised by public, private, and individual perspectives, Sweden's adoption challenges are more influenced by regulatory uncertainties and subsidy inconsistencies. Additionally, social influence and peer effects appear

Table 1
Roger's five perceived attributes of innovations (Qureshi et al., 2017).

Attribute	Definition
Relative advantage	The degree to which an innovation is perceived as superior to the idea or technology it replaces, based on factors such as economic benefit, social prestige, convenience, or satisfaction.
Compatibility	The extent to which an innovation aligns with the existing values, past experiences, and needs of potential adopters.
Complexity	The perceived difficulty in understanding and using the innovation.
Trialability	The extent to which an innovation can be tested or experimented with before making long-term commitments or incurring significant costs.
Observability	The degree to which the outcomes of an innovation are visible and apparent to others.

to play a greater role in Sweden's PV adoption dynamics compared to Norway (Xue et al., 2021; Palm, 2017).

According to Roger's theoretical model (2003), potential users go through different phases when deciding whether to adopt an innovation. This model explains that the adoption of new technologies is communicated over time through various channels, with interest among potential adopters growing as they acquire sufficient knowledge about innovation. Pre-knowledge characteristics, such as personality, communicative behaviour, and socioeconomic conditions, also play a significant role. The model identifies five key attributes of innovation that can ultimately determine whether it succeeds or fails: (1) relative advantage, (2) compatibility, (3) complexity, (4) trialability, and (5) observability. The public sector, through policy leadership and large-scale projects, can demonstrate the practical benefits of PV energy, encouraging adoption by implementing visible PV projects and offering incentives and favourable regulations. In contrast, adoption within the private sector is primarily driven by cost considerations and perceived direct benefits. Table 1 provides descriptions of each attribute and its influence on the adoption rate of innovations (Qureshi et al., 2017).

In the context of Rogers' theoretical model, the adoption of PV systems is dependent not only on the inherent qualities of the technology but also on how potential users acquire and interpret information about the innovation. Knowledge plays an essential role in determining the success or failure of adoption, as potential adopters, including residential and private non-residential users, must be sufficiently informed to recognise the relative advantage, compatibility, and other critical attributes of PV systems. Case studies, surveys, and interviews have suggested that providing information can stimulate the adoption of PV systems. For example, it was found that when local actors actively promoted PV systems, they likely triggered an increase in localised adoption rates (Palm, 2016). Adopters perceived informative seminars as having a positive influence on their decisions to adopt PV systems (Palm, 2016). Furthermore, various studies have shown that the effects of neighbourhood equality contribute to higher adoption rates of PV systems (Morrisey and Scheller, 2024; Palm, 2017). In Sweden, interviews with PV adopters and non-adopters revealed that finding and understanding relevant information about PV adoption remains a challenge (Palm and Lantz, 2020). Understanding what types of information are most effective for potential PV adopters could provide valuable information. For example, a benchmark study on the performance of solar installers in California was conducted in 2017, uncovering evidence and relationships between installer sizes, geographic distribution of operations, and vertical types of installations, revealing significant differences in system efficiency (Wang, 2017).

Few studies have explicitly examined the barriers and enablers of PV installation as perceived by non-residential property owners (Reindl and Palm, 2021). Reindl and Palm (2021) conducted a literature review and an empirical study in which non-residential property owners in Sweden were asked to identify barriers and enablers they encountered

when considering PV installations. Table 2 presents the barriers identified in previous research, which were also observed in their empirical study. Like the findings for residential property owners, these barriers include financial, knowledge-related, and administrative challenges. On the other hand, specific economic enablers were identified, such as the ability to sell self-produced electricity (Reindl and Palm, 2021). Interestingly, while solar maps have been cited as enablers in international studies, their absence was perceived as a barrier in the Swedish context. The authors argue that the institutional context of each country influences the relevance of specific barriers and enablers, highlighting the importance of understanding the adoption of PV within its institutional and cultural environment. Thus, the barriers and enablers to the adoption of PV are dynamic and vary between different contexts (Reindl and Palm, 2021; Alrawi et al., 2022).

Additionally, social influence and peer effects have been identified as relevant factors in the adoption of PV systems, especially during the early stages of diffusion. Several studies have shown that the presence of visible PV installations in a neighbourhood can encourage further adoption among nearby residents, while the involvement of community organisations can amplify these effects in some contexts (Palm, 2016, 2017; Curtius et al., 2018). Some research suggests that adopting a snowball strategy, where initial installations serve to trigger further uptake, can be more effective in promoting PV adoption than uniform nationwide incentives (Curtius et al., 2018). Although the present study does not directly analyse peer or snowball effects, recognising their potential role provides important context for interpreting the dynamics of PV adoption, especially regarding the potential of public buildings to catalyse broader PV deployment in urban areas.

2.2. Methods for rooftop PV potential estimation

Decentralised energy systems based on PV energy are promising in urban environments. However, before any further planning or implementation of PV systems can proceed, it is essential first to evaluate the physical and technical potential. This step provides a reliable and accurate baseline for assessing the feasibility of PV energy generation. Achieving optimal performance for PV systems also requires accurate estimates of energy supply, as well as the development of intelligent distribution systems that can be seamlessly integrated with electrical networks.

The specific type of information to be modelled depends mainly on the chosen approach, with careful consideration of the technical potential being crucial in this process (Hasan et al., 2024; Fakhraian et al., 2021).

Depending on the scale and objectives of the analysis, studies may aim for highly detailed rooftop-level assessments or adopt broader, aggregate estimates based on statistical assumptions. For instance, national-level assessments such as Instituto para la Diversificación y Ahorro de la Energía (IDAE) (2021) do not incorporate geospatial modelling of rooftop-level solar potential.

Fig. 1 illustrates a top-down approach to estimating the solar energy potential, progressing from theoretical to economic potential. The theoretical potential represents the maximum available energy without any constraints, encompassing all incoming solar radiation. The subsequent layer, territorial/technical potential, refines this estimate by accounting for factors such as land use, rooftop suitability, shading, and technical feasibility. This stage includes the use of geospatial data and modelling to identify areas realistically available for photovoltaic (PV) installations. Finally, the economic potential narrows the estimate further by considering financial feasibility, including installation costs, maintenance, and the potential return on investment. This hierarchical structure emphasises the increasing level of detail and the constraints applied as the potential is refined from theoretical to practical applications.

We emphasise that the technical potential represents the energy that could be generated if all suitable roof areas were equipped with

Table 2
Barriers to PV installation mentioned by the Swedish respondents (Reindl and Palm, 2021).

Often mentioned	Moderately often	Only once
<ul style="list-style-type: none"> • Economic barriers • Taxation • Lack of subsidies • Regulatory barriers • Administrative and organisational barriers • Design barriers • Maintenance barriers • Building construction barriers 	<ul style="list-style-type: none"> • Information/knowledge barriers • Technological barriers • Security and insurance • Lack of electricity storage • Tenants' electricity supply contracts 	<ul style="list-style-type: none"> • Just installed district heating • National political instability • Only viable for residential buildings • Conservative construction industry • No detailed calculations of solar radiation, no solar map • Time consuming

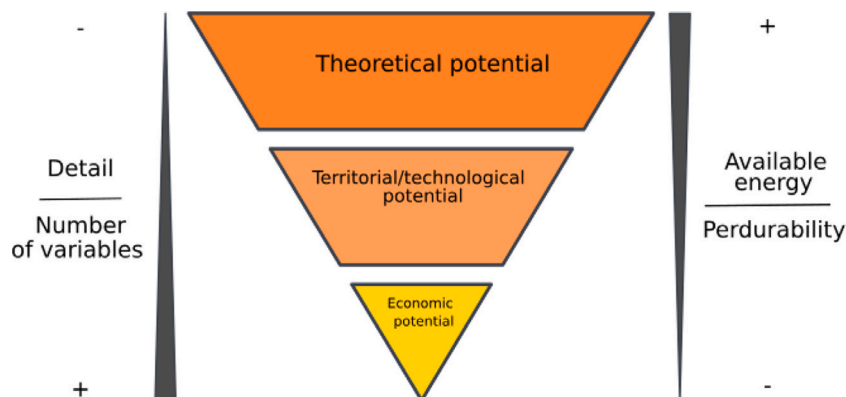


Fig. 1. Top-down approach to estimating solar energy potential. Based on Hao et al. (2022).

solar photovoltaic systems (see Fig. 1). It serves as an established reference point to quantify the potential generation of PV, considering the availability and quality of the resources, the performance of the technology in capturing the resource and the physical area suitable for development (Bódis et al., 2019; Gagnon et al., 2018). Importantly, the technical potential does not consider economic factors, growth potential, or grid integration considerations. It is not intended to represent a specific deployment plan or predict future deployment, but rather to define the upper limit of the energy generation potential of a technology under current conditions. In this study, only physical, geographic (urban), and technical potentials are considered and modelled (Fakhraian et al., 2021).

In recent years, methods for estimating solar PV potential have evolved. Initially, approaches such as statistical sampling and mathematical modelling were widely used. However, there has been a significant shift towards more advanced techniques, such as artificial intelligence (AI) and machine learning, driven by the increasing availability of high-resolution Geographic Information System (GIS) data and remote sensing technologies, such as LiDAR and high-resolution aerial imagery (Malof et al., 2016; Fakhraian et al., 2021; Hu et al., 2023). The integration of AI with GIS and remote sensing technologies offers more accurate and detailed estimates of rooftop solar potential, making it possible to generate precise, large-scale solar energy potential maps. These advances have become particularly important for urban planning and sustainable city design, where integrating solar potential into planning processes is crucial for the development of smart cities.

Although AI and machine learning provide powerful tools for PV estimation, traditional modelling approaches are still widely used. These models are effective for quantifying the effects of multiple variables that influence rooftop PV potential, such as roof geometry, solar radiation estimates, and shading factors. They are useful for small-scale studies, such as those at the neighbourhood or city level, especially when using LiDAR datasets. However, these models become computationally intensive when applied to large-scale assessments, such as for entire countries. Machine learning, on the other hand, offers a promising alternative because it can handle large amounts of data efficiently, allowing it to be applied to large-scale analyses, helping

to inform policies that promote the adoption of photovoltaic systems in broader regions, including cities and countries (Wang et al., 2023; Trigo-González et al., 2023).

The integration of GIS and machine learning techniques enables researchers to develop more accurate and less computationally demanding methods for estimating rooftop PV potential, particularly on a larger scale. These approaches address key uncertainties and help to produce reliable estimates of solar energy production on rooftops, from neighbourhood to national levels (Mohajeri et al., 2018; Yin and Zhou, 2022; Li et al., 2021; Mayer et al., 2022).

Despite the progress made, GIS modelling still has limitations that need further development (Freitas et al., 2015). One key issue is ensuring that the input data used for simulations is consistent and precise. For example, while LiDAR data provides detailed information, it can have limitations, particularly near building façades, where errors are more pronounced. Some radiation models still rely on simplified methodologies to balance computation time and accuracy. In addition, continuous updates of LiDAR data may generate several problems. More advanced tools, such as RADIANCE and SOLENE, are capable of detailed simulations but still face limitations when basic models overlook important features such as the slope or aspect of the roof (Freitas et al., 2015). Moreover, challenges remain with accurately converting solar radiation data into electrical output, and model validation is critical, often requiring field data to ensure accuracy and reliability.

To address these challenges, many researchers are working to refine solar mapping techniques (Gassar and Cha, 2021). Examples include studies estimating PV potential for neighbourhoods or cities (Quirós et al., 2018; Gooding et al., 2015; Palmer et al., 2018), entire countries (Luković et al., 2015; Huld, 2017), and even the European Union (Bódis et al., 2019).

Building on these technological advances, the development of short-term solar forecasting (or nowcasting) is gaining attention due to its ability to predict solar irradiance and balance energy systems in real time (Trigo-González et al., 2023). Nowcasting methods help address uncertainties in solar energy generation by using real-time data to improve predictions. For example, a method for nowcasting PV power from satellite-derived data was proposed, which uses real-time power

data from reference PV systems to improve forecast precision (Bright *et al.*, 2018). Although nowcasting offers immediate insight, it does not replace the need to assess physical and technical potential as the foundational step in long-term planning. Accurate and timely estimates, supported by AI and nowcasting, can provide effective tools to promote the adoption of PV on various scales, from individual buildings to entire cities and countries.

In any of the methods presented, quality data are essential for training or testing models. Several attempts have been made to develop better inventories of PV solar energy generation units (Kruitwagen *et al.*, 2021). Despite these advances, estimates of current capacity remain uncertain. Even determining the installed capacity of a single country is often prone to inaccuracies and omissions due to market fragmentation and evolving regulations. This issue is non-trivial, as complete and accurate data are essential for advancing the energy transition (Stowell *et al.*, 2020).

2.3. Research opportunities

By comparing the proposed research with the existing literature, several research gaps have been identified. First, knowledge of the peer effects that influence PV adoption rates comes primarily from countries with mature photovoltaic markets. Since local factors are believed to play an important role during the early stages of PV dissemination, studying different contexts could help to create more robust and generalisable theories. Furthermore, few studies have directly compared the importance of neighbours, local organisations promoting photovoltaic energy, and other local factors, such as regional variations in the implementation of national policies. Recent research in China, Spain and other contexts has begun to address these gaps, providing insights into spatial spillovers and relational peer effects in PV adoption (Irwin, 2021; Qiu *et al.*, 2025; Zhang *et al.*, 2023; San-Martín and Elizalde, 2024). In this regard, technical potential estimates and case studies are key as a first step towards developing robust economic potential models. Future research could further explore non-residential PV adoption, leveraging insights from studies in Chile and Jordan that reveal sector-specific barriers and policy enablers (Nasirov and Agostini, 2018; Hamed *et al.*, 2023).

Additionally, GIS-based modelling remains computationally intensive, particularly for large study areas, including models based on machine learning. Sharing code and elaborated datasets would facilitate collaboration, improve reproducibility, and accelerate the development of more efficient algorithms. Open access to these resources would enable researchers to build upon each other's work, allowing for the validation of models across different regions and enhancing the accuracy of rooftop PV potential estimations at larger scales. Moreover, it could help reduce redundant efforts, making the research process more efficient and fostering innovation in the field.

Another critical gap concerns the lack of detailed GIS databases that incorporate various data types, such as digital elevation models (DEMs), 3D models, cadastral information, installed PV locations, and energy consumption. Addressing this scarcity is essential because numerous applications related to energy transition rely on such data. Comprehensive and up-to-date GIS databases enable more accurate modelling of rooftop solar potential, better decision-making in urban planning, and more effective energy policy development. Additionally, these datasets are fundamental for assessing the feasibility of large-scale renewable energy projects and optimising energy distribution networks. Expanding access to such data would significantly improve the precision of renewable energy assessments and help identify the most suitable areas for PV installation, thus accelerating the transition to sustainable energy systems.

Building on the previous point, it is important to note that in most studies, modelling techniques do not account for the current use of buildings. Although some research has focused on estimating potential in residential, commercial, and industrial areas (López Prol

and Steininger, 2020), others have focused on specific locations such as airports, train stations, educational centres, and other infrastructures (Sreenath *et al.*, 2020; Zhong *et al.*, 2020; Chen *et al.*, 2022; Ordóñez Mendieta and Hernández, 2021; Thai and Brouwer, 2021; Julieta *et al.*, 2022; Hurtado-Pérez *et al.*, 2024). Incorporating data on the current use of buildings in these models is indispensable, as it enables more accurate assessments of the available space for PV installation and the energy generation potential in different sectors. Integrating land use data would significantly enhance model accuracy, ensuring that predictions reflect real-world constraints and opportunities for PV deployment. Furthermore, this approach would support more targeted policy recommendations and investments, guiding the adoption of PV in sectors with the highest potential for sustainability.

Considering these research gaps, our study aims to address them through several contributions.

1. This study addresses the lack of streamlined methods for integrating public data by developing an automated workflow. This workflow creates a potential solar irradiance model, identifies the most suitable rooftop areas for PV installation, analyses overlap with existing PV installations, and extracts new insights. This methodology is applied on a relatively large scale, focusing on the province of Tarragona (Catalonia, Spain), which provides a replicable model for similar regions.
2. Although qualitative approaches are often used, this study uniquely compares different building uses, classified under residential, private non-residential (retail, offices, industry, agriculture), and public services, to assess the share of rooftops and rooftop sections where PV systems have been installed, addressing a gap in the understanding of sector-specific adoption trends.
3. To our knowledge, this is the first study to directly compare the adoption of photovoltaic technologies between the public sector (public service buildings) and the private sector (residential and private non-residential uses). The study provides initial insights into the significance of peer- and snowball effects driven by the public sector, which are overlooked in current literature.
4. Addressing the limited reproducibility in similar studies, this research exclusively uses publicly available data from Spanish and Catalan administrations and processes it with FOSS GIS tools. By sharing derived datasets and models, the study promotes collaboration, transparency, and reproducibility in investigating the adoption of PV.

3. Study area

The Tarragona province, located in northeastern Spain within the region of Catalonia, forms part of the Mediterranean Corridor, a key economic region in southern Europe. The province covers an area of 6303 km² (19.64% of Catalonia) and has a population of 861,744 inhabitants (10.7% of Catalonia; INE 2024). It comprises 184 municipalities with varying geographic, demographic, and economic characteristics, affecting electricity consumption patterns and the availability of suitable areas for photovoltaic (PV) installations. Tarragona was selected not only for its strategic role in the Spanish energy system, but also due to the active support from local authorities for renewable energy initiatives. In addition, the scheduled decommissioning of its three nuclear power stations reinforces the urgency of accelerating the deployment of renewable alternatives in the area. Finally, the availability of high-quality GIS data at both the national (Spain) and regional (Catalonia) levels facilitates the replication of this methodology in other municipalities or regions with comparable data availability.

The province holds a strategic position in the energy infrastructure of both Spain and Catalonia, in terms of electricity production and consumption. On the consumption side, Tarragona province is home to a large petrochemical complex and several energy-intensive industries.

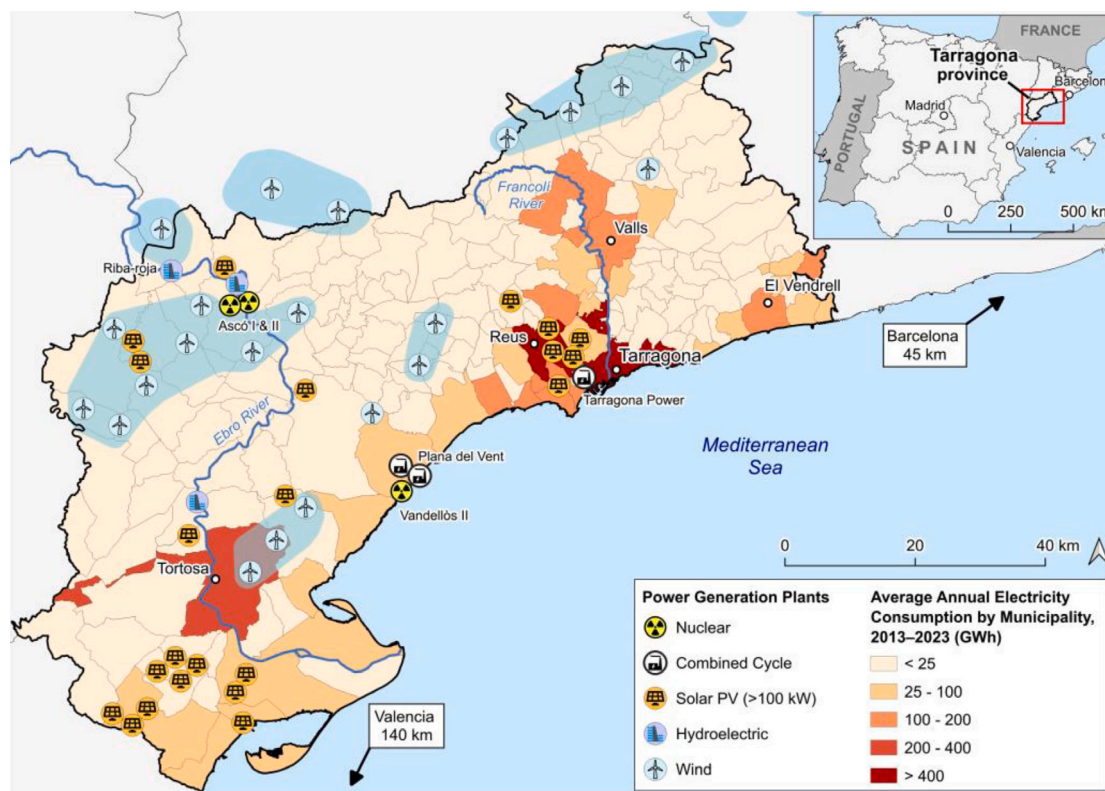


Fig. 2. Location map of the province of Tarragona.

These facilities significantly shape the spatial distribution of electricity demand, with only a few municipalities accounting for most of the electricity consumption. The total annual electricity demand in Tarragona province is 6437.73 GWh (16.2% of Catalonia's total consumption). Notably, only four municipalities — Tarragona, Reus, El Morell, and La Pobla de Mafumet — consume more than 50% of the province's electricity, driven by industrial activities.

On the electricity production side, Tarragona hosts three nuclear reactors (Ascó I, Ascó II, and Vandellòs II), with a combined installed capacity of 3064 MWe. In 2024, these reactors generated 59.1% of the electricity produced in Catalonia and 8.9% of the electricity generated in mainland Spain's power system. This power is particularly relevant within the broader context of the ongoing energy transition in Spain and Catalonia, as these reactors are scheduled for definitive shutdown in the coming years (Ascó I in October 2030; Ascó II in September 2032; Vandellòs II in February 2035). In addition to the nuclear plants, the province also concentrates a significant portion of Catalonia's wind power capacity (814 MW, 57.8% of the total installed in Catalonia), as well as a smaller proportion of gas-fired power plants (1251 MW, 33%) and ground-mounted photovoltaic installations (42.3 MW, 22.7%) (Fig. 2; Red Eléctrica de España (2025)).

The adoption of PV systems for self-consumption varies across the province. While urban centres such as Tarragona and Reus show a strong correlation between electricity demand and PV adoption, other regions, particularly in agricultural areas, have also experienced considerable growth in PV installations. This pattern suggests that both industrial and rural sectors are leveraging renewable energy opportunities, influenced by economic incentives and local policies (Fig. 3).

The evolution of PV adoption in Tarragona reveals a transition from small-scale residential installations to larger commercial and industrial systems. Before 2019, growth was modest, but following regulatory changes, the number of installations increased sharply. Since 2022, installed capacity has grown at a faster rate than the number of

installations, indicating that newer projects are larger in scale. This shift reflects changing market dynamics, improved economic viability and evolving policy frameworks that have encouraged both residential and commercial sectors to invest in PV technology (Fig. 3).

4. Methods

This section outlines the methodology used to calculate the PV potential for electricity generation on building rooftops and to analyse the distribution of actual installations, based on geolocated records from the official database of the Catalan Energy Institute (ICAEN). The methodology for determining potential follows an approach like that described by Gagnon et al. (2018). First, the solar potential radiation was calculated, followed by the estimation of the potential for electricity generation using PV systems, considering technical constraints such as available rooftop space, the conversion efficiency of the technology, and other relevant factors. This research does not address the economic or social potential (e.g., costs, social organisation, legal constraints).

This paper follows a five-step procedure in the analysis of the available rooftop photovoltaic potential:

1. Compilation and systematisation of relevant regulatory, theoretical and other experiences regarding electricity generation through renewable sources in urban environments. In this initial phase, the bibliography on the generation of electricity through solar PV is systematised to develop the specific methodology for research.
2. Gathering statistical information and generating cartography for calculating the potential for renewable source installations (solar) in urban environments. In this phase, maps of solar resources for the province of Tarragona are first generated. The statistical and cartographic databases are then collected from various sources to identify suitable areas for installing rooftop photovoltaic systems in urban areas (see Table 3).

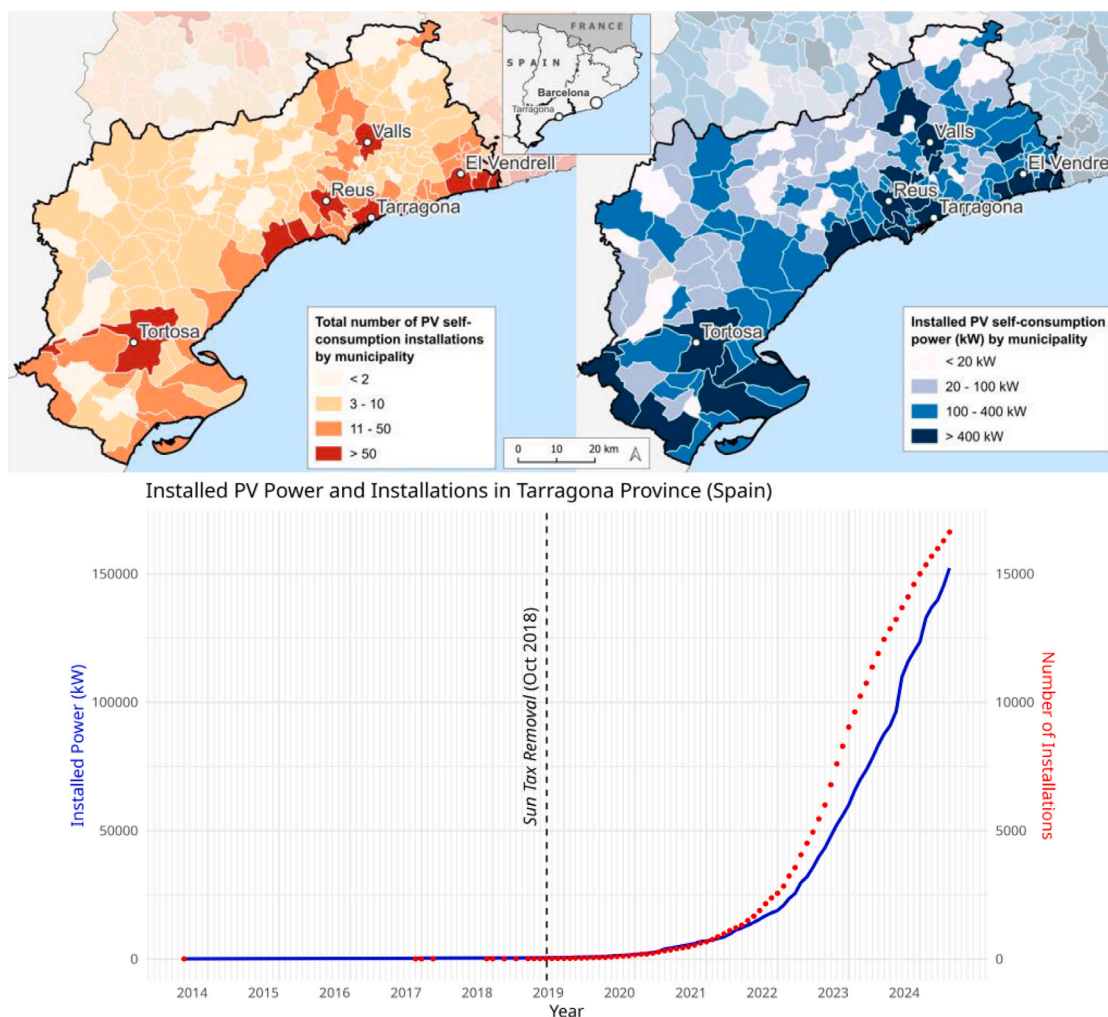


Fig. 3. Evolution of self-consumption PV in Tarragona province until June 2024. Top left: Number of PV installations per municipality. Top right: Total installed capacity (kW) per municipality. Bottom: Cumulative installed PV capacity and number of installations in the province. Source: Catalan Energy Institute (ICAEN).

3. Calculation of the potential and mapping of electricity generation from rooftop solar photovoltaic systems.
4. Classification of buildings or building parts according to their suitability for PV adoption. Those meeting optimal conditions (defined by high solar radiation exposure, sufficient rooftop area, and structural feasibility) are labelled as *Scenario 1*, while the rest are assigned to *Scenario 0*.
5. Finally, a statistical analysis is performed to determine if there are significant differences in the realisation of the PV potential based on building usage, grouped as residential, private non-residential (including commercial, industrial, agricultural, and office space), and public services.

The specific procedures for calculating solar radiation and the installation potential are detailed in 4.2. Fig. 4 illustrates the workflow throughout this process.

4.1. Data availability

The availability of high-quality public GIS data in Spain and Catalonia was key in determining the methodology used for this investigation (see Table 3). Several data sources were accessed and integrated into the model to estimate the photovoltaic (PV) potential on the roofs of buildings in the Tarragona province.

Data for this study were provided by the ICGC (Cartographic and Geological Institute of Catalonia). Base orthoimages, with a resolution of 0.25 m, were used to perform precise photointerpretation. These orthoimages corresponded to a developmental version of the official mosaic, incorporating more recent aerial imagery in areas where it was already available. Although originally produced and first published by the ICGC, these images are also integrated into the Spanish national spatial data infrastructure (IDE) and later made accessible through the CNIG platform.

SIOSE data (Spanish Land Cover and Use Information System), provided in vector format at a 1:25,000 scale, was used to identify land use types and inform decisions on the most likely building uses. Furthermore, GIS reference layers, including administrative boundaries and urban areas, were essential for structuring the spatial data used in the analysis. These datasets were crucial for accurately locating buildings and delineating urban areas. All these data sources are available for download from the CNIG platform (<https://centrodedescargas.cnig.es>).

A 5-m-resolution DEM, derived from LiDAR data, was used to compute all steps of the solar potential model (Böhner and Antoniá, 2009).

Cadastral data was used to identify available roof surfaces (https://inspire-geoportal.ec.europa.eu/srv/api/records/ES_SDGC_CP_ATOM). This dataset includes relevant attributes such as the number of dwellings, the number of floors above and below ground, the status of

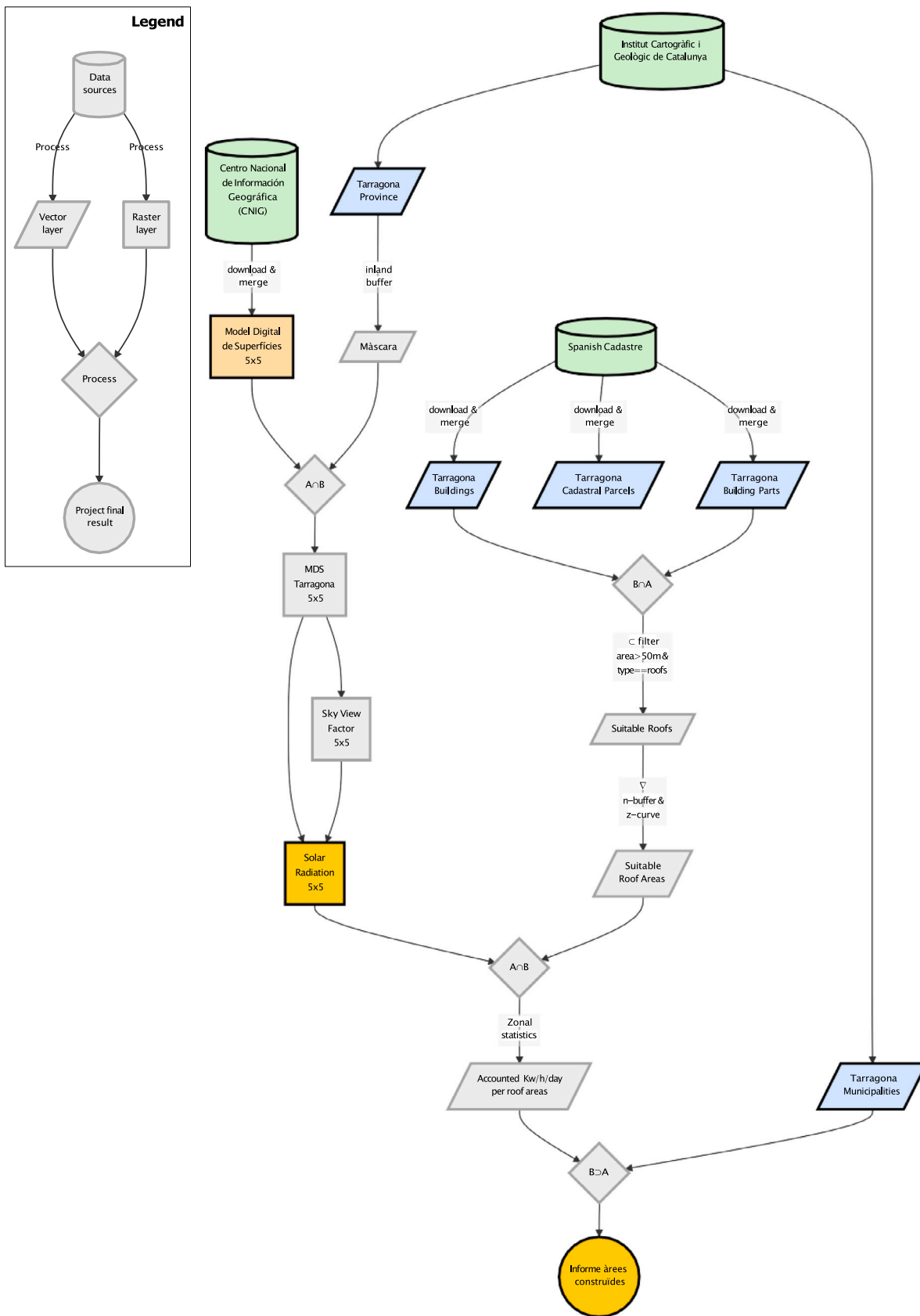


Fig. 4. General workflow to generate the PV potential model for the building rooftop.

Table 3
Source GIS data layers.

	Data layer	Format	Scale	Publication date
Base orthoimages ^a	PNOA (CNIG), orthophoto 2024 (ICGC, provisional)	Raster/WMS	0.25 m/pixel	2004–2024
Digital elevation model ^a	DEM (LiDAR)	Raster	5 m/pixel	2018
Land use ^a	Spanish Land Cover and Use Information System (SIOSE)	Vector	1:25,000	2005–2017
GIS reference layers ^a	Administrative boundaries	Vector	1:5000	2005–2017
	Urban areas	Vector	1:5000	2005–2017
Cadastral data ^b	Building parts	Vector	1:1000	2023
	Buildings	Vector	–	2023
	Parcels	Vector	–	2023
	Approximate addresses	Vector	Geocoded	2013–2024
Installed PV ^c	Approximate addresses	Vector	Geocoded	2013–2024
Heritage buildings ^d	BIC registry	Vector	–	2017

Notes:

^a National Centre of Geographic Information (CNIG).

^b Spanish Cadastre.

^c Catalan Institute of Energy (ICAEN).

^d Spain's Ministry of Culture.

^e Cartographic and Geological Institute of Catalonia (ICGC).



Fig. 5. Editing of approximate locations of solar PV installations in the province of Tarragona: (A) Most probable location, (B) Multiple PV locations geocoded at the electrical substation coordinates, and (C) Validation using Google Street View imagery, when available.

Source: ICAEN and photointerpretation.

the building (e.g., declined, functional), the date of construction, the current use, and the date of digitisation, which were ultimately used in the analysis. In total, the dataset contains information on 349,305 buildings, comprising 855,177 building parts.

The Database of Cultural Assets of Interest (BIC), a legal designation for the protection of Spanish historical heritage, includes 30,400 registered assets as of 2017, of which 382 are in the province of Tarragona.

Data for installed photovoltaic systems were retrieved from a static web map provided by the Catalan Institute of Energy (ICAEN). This dataset contains the locations of self-consumption photovoltaic installations in Catalonia between 2013 and 2024. The data were manually adjusted to improve accuracy and spatially linked to the cadastral data for further analysis. Photointerpretation and field validation led to a more accurate dataset (see Fig. 5). This dataset is publicly available on the ICAEN website¹ The ICAEN database collects approximate locations (points) and relevant data for PV installations in Catalonia.

These data layers were processed and merged into a single GIS database that was instrumental in identifying suitable rooftops for solar panel installation, estimating solar potential, and assessing the current usage of PV systems across the province. The integration of these data sources, including topographic, cadastral, and energy-related data layers, provided a comprehensive view of the rooftop areas available and their potential for solar energy production.

¹ <https://icaen.gencat.cat/ca/energia/autoconsum/Observatori-de-autoconsum-a-catalunya/localitzacio-dinstallacions/>.

4.2. Modelling solar PV potential

The potential for renewable energy installations, specifically solar photovoltaic (PV) systems, was determined through the development of physical models that considered the suitable use of land, while considering the current socioeconomic context to facilitate a transition towards sustainable energy. Calculating solar radiation and subsequent estimation of the PV potential were essential components of this approach.

A 5-m resolution Digital Elevation Model (DEM) was used to calculate the potential solar radiation for the entire province of Tarragona (see Fig. 6). The DEM was available in ESRI ASCII Grid (.asc) files, organised by sheets of the National Topographic Map (MTN). A custom script was written to automatically download a total of 24 sheets, covering the entire province and an additional 10 km buffer zone to account for shading from nearby mountains along the borders. The resulting DEM dataset, in Geopackage format, was approximately 3.4 GB in size.

For the calculation of solar radiation, SAGA GIS, an open-source software, was used, specifically employing the Potential Incoming Solar Radiation module. This module provides a range of input parameters necessary for modelling solar radiation, such as the angle of incidence of the sun's rays, solar flux in the upper atmosphere, atmospheric transmittance, angle of solar illumination on the slope, and the Sky View Factor (SVF). The SVF is used to quantify obstructions caused by “self-shading” from the slope itself or surrounding terrain. The SVF quantifies the portion of the sky visible from a point on the surface, normalised by the solid angle of the entire celestial hemisphere. Essentially, it measures the geometric aspect of available radiation from the sky, without accounting for atmospheric effects. While the SVF only accounts for direct radiation, the method proposed by Böhner and Antonić (2009) also estimates diffuse radiation, which is a significant aspect of solar energy available at the Earth's surface. The parameters for calculating radiation were applied using average values specific to the province of Tarragona.

Previous models for solar radiation calculation, especially those in GIS environments, typically used topographic information from DEMs to estimate indices such as elevation, surface orientation, and shadow projection (Böhner and Antonić, 2009). However, the algorithm used in SAGA GIS differs in its approach, which can result in varying estimates of solar radiation, especially when using DEMs of different resolutions (Raaflaub and Collins, 2006). This discrepancy is particularly noticeable in regions with complex geomorphology. As a result, using a higher resolution DEM can lead to more accurate estimates, but at the cost of increased computational time and resources.

To improve the accuracy of solar radiation estimates on building rooftops, only pixels that were overlapped entirely by building polygons were considered in the zonal statistics analysis. This approach ensured that the calculated radiation values reflected only the

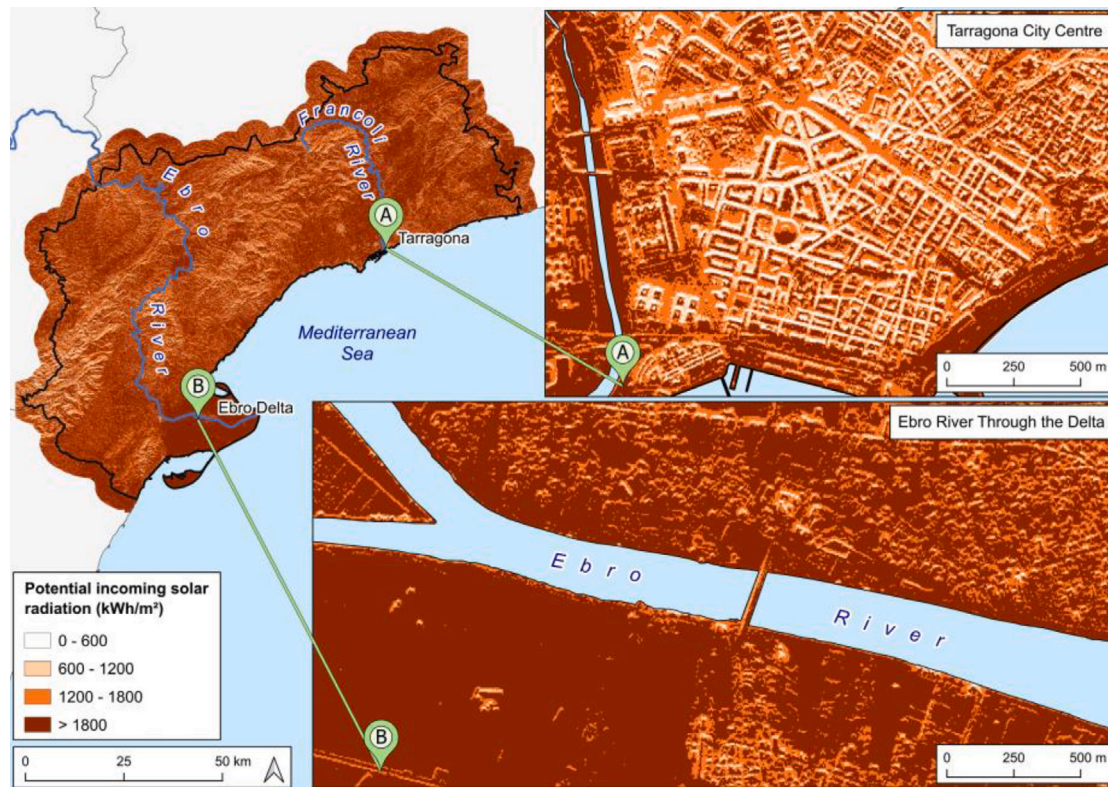


Fig. 6. Generated 5m-resolution model of total potential incoming solar radiation (direct + diffuse) for the province of Tarragona. Details in Section 5.1.

core areas of the rooftops, avoiding contamination from mixed pixels along building edges that may include façade information, surrounding ground, or adjacent structures. This filtering step reduced errors in estimating average solar radiation values per building part and improved the reliability of the dataset used for identifying suitable rooftop areas.

4.3. Available rooftop area

Once the radiation values for the entire Tarragona province were obtained, the roof surfaces of buildings suitable for the installation of photovoltaic panels were calculated. These data were downloaded in bulk through the ATOM download services of the Spatial Data Infrastructure of Spain (IDEE) catalogue (see Section 4.1). The downloaded data includes all buildings, building parts, and plots of the Tarragona province.

Using these data, two indicators related to the building's shape, including the fractal index and shape index (Zaragoza et al., 2012), were calculated. An indicator related to the vertical structure was also computed, specifically the median number of floors above ground in each part of the building and the remaining roofs. Additionally, the average annual total solar radiation for each building polygon was calculated using the solar radiation model described in the previous subsection. From the generated database, the following criteria have been applied to refine the cadastral layer by filtering out:

- Buildings classified as non-functional according to the Cadastre were excluded from the analysis. These buildings are either abandoned or in ruin, making them unsuitable for PV installation.
- Building parts that do not belong to a building (e.g., surrounding areas, gardens, etc.).
- Historic buildings constructed before 1800 were excluded to avoid interfering with heritage protection regulations. These buildings are often subject to legal restrictions that prevent modifications, such as installing solar panels.
- Buildings designated as Cultural Assets of Interest (BIC) were excluded to comply with legal protections for Spain's historical heritage. These buildings typically cannot undergo modifications, including the installation of rooftop solar panels.
- Rooftop areas less than 10 m² were excluded from the analysis, except for those that met the minimum legal requirements for safety and maintenance. This approach ensures that only rooftops with enough useable space for effective PV deployment are included.
- Building parts with intricate or highly irregular shapes were excluded, as these characteristics often hinder the effective installation of photovoltaic systems. A shape index ranging from 1.1 to 4 was considered suitable, as shapes outside this range are typically less efficient for PV installations. The Fractal Dimension Index, which quantifies the complexity of building shapes, was used to remove areas with an index greater than 1.9, indicating highly irregular forms that are not suitable for solar panel installation.
- Buildings with an average potential solar radiation of less than 1000 kWh/m². This threshold ensures that only rooftops with sufficient solar exposure are considered for PV installation, according to local installers. Although local installers commonly use the 1000 kWh/m² threshold to determine the viability of PV installations, it remains an arbitrary limit based on current technologies and practices in the study area. Future technological advancements and economic considerations may allow the deployment of PV systems on surfaces receiving lower annual solar radiation.
- Courtyards and sections of buildings located below the average roof height were excluded. These areas typically do not receive adequate sunlight for PV generation, even if their solar radiation potential is estimated to be sufficient.

A panel installation density is usually applied, typically ranging from 0.5 to 0.8 panels/m², depending on roof constraints (Phillips,

2024). This parameter is conservatively set to 0.6 panels/m² in this study. This factor is necessary to account for structural and spatial limitations such as ventilation gaps between panels, pathways for maintenance access, and required safety setbacks. Without applying this density factor, the estimated suitable area would overstate the actual deployable PV surface, leading to unrealistic projections of photovoltaic capacity.

While the suitable roof area was estimated based on these criteria, we did not attempt to calculate potential energy production due to methodological limitations. The 5 m resolution raster lacks the precision necessary to accurately derive roof slope and aspect, as many pixels contain mixed information, including portions of building façades, adjacent terrain, and varying rooftop heights. These inaccuracies lead to unreliable estimations of actual solar exposure on each surface. Additionally, energy production is influenced by dynamic factors such as localised shading, dirt accumulation, module degradation, and atmospheric conditions, which cannot be effectively accounted for at this scale.

For precise energy yield assessments, a more precise digital terrain model, more advanced simulation tools such as PVsyst, SAM (System Advisor Model), or real-time monitoring data should be used (Chepp et al., 2021; Milosavljević et al., 2022; Malvoni et al., 2017). Instead, this study focuses solely on identifying the proportion of rooftops that are physically suitable for solar panel installation, providing a basis for policy and urban planning considerations.

4.4. Statistical analysis

The combination of the factors identified in Section 4.3, including high solar radiation exposure, sufficient available rooftop area, and structural feasibility, was defined as *Scenario 1*. This scenario represented a subset of buildings or building parts with the greatest potential for photovoltaic (PV) deployment, ensuring that only the most suitable rooftops were considered for solar energy generation. Buildings not listed as *Scenario 1* were labelled as *Scenario 0*.

First, a Chi-Square test of independence was performed to determine whether the proportion of PV adoption was significantly associated with the building's primary use, classified under residential, private non-residential (retail, offices, industry, agriculture), and public services. Second, given that adoption rates and variances differed across categories, a Games–Howell post-hoc test was applied to identify pairwise differences in PV adoption. This analysis was conducted separately for *Scenario 1* and *Scenario 0*, allowing us to assess whether buildings with higher solar potential exhibited different adoption patterns. To capture temporal changes in adoption trends, we extended the analysis by applying the Games–Howell test to both 2024 and 2020, the latter representing the early phase of PV expansion. This comparison provided insight into whether the relationship between building use and PV adoption had evolved.

Statistical analyses were conducted using the R platform, which offers robust tools for data visualisation and analysis. Data distributions were visualised using the *ggplot* library, while the *rstatix* library was used for statistical computations.

5. Results

5.1. Solar PV technical potential in Scenario 1

The application of the defined criteria to refine the cadastral data identified 2823.8 ha of suitable rooftop area for PV installations, representing 38.72% of the total building area. The filtering process involved removing buildings classified as non-functional, those with complex shapes unsuitable for PV installation, and heritage-listed buildings, as well as excluding areas with insufficient potential solar radiation (less than 1000 kWh/m²) or insufficient rooftop space. Additional criteria, such as the exclusion of buildings constructed before 1800, rooftops

smaller than 10 m², and spaces located below the average height of buildings, further refined the dataset. Finally, a 0.6 density factor was applied, giving a very conservative estimation. These steps ensured that only the most appropriate and feasible rooftops were considered for the solar energy potential, providing a reliable basis for estimating potential PV energy output. The photointerpretation process identified a total of 18,577 rooftop PV installations across the study area. This dataset, which constitutes a high-resolution map of real installations, can serve as a valuable training set for developing automated models to accelerate the identification of PV systems in similar contexts.

Fig. 7 illustrates the distinction between the total rooftop PV potential and the refined selection of *Scenario 1*, where only the most suitable rooftop areas for photovoltaic deployment are considered. The filtering process excludes courtyards and enclosed inner spaces, which receive limited solar radiation due to obstruction from surrounding structures. Additionally, small buildings or rooftop sections that are significantly shaded by nearby taller buildings are removed, as their solar exposure is insufficient to support efficient PV generation. These areas, depicted in cooler tones, typically receive less than 1000 kWh/m² annually, which is below the viability threshold for most PV systems and thus not considered productive enough. Other exclusions include rooftops with heritage restrictions, complex geometries, or insufficient structural support. By refining the dataset in this manner, *Scenario 1* provides a more realistic assessment of the rooftop PV capacity that can be effectively utilised in urban environments.

5.2. Primary building use and PV adoption

In the Tarragona province, PV adoption varies significantly across different building use categories (residential, private non-residential, and public services), reflecting sector-specific constraints and incentives. To assess whether PV adoption rates differ significantly between building types; a Chi-Square test of independence was conducted using a Monte Carlo simulation to avoid approximation errors. The results confirm that the association between building use and PV adoption is statistically significant $\chi^2 = 14,790$; simulated p-value = 9.999×10^{-5} , indicating strong evidence that PV adoption patterns are not evenly distributed across building categories.

To further investigate which specific building categories differ in adoption rates, a Games–Howell post-hoc test was applied (Table 4). This test compares PV adoption rates between different building use types but does not account for whether buildings belong to *Scenario 1* (high solar potential) or not. The results indicate that in 2020, PV adoption was significantly higher in residential buildings compared to most other categories. Public services, office buildings, and industrial facilities exhibited lower adoption rates, likely due to economic constraints and administrative barriers. However, by 2024, the differences between residential and other building types had diminished, suggesting a more balanced adoption pattern across sectors.

Fig. 8 provides a visual comparison of PV adoption rates across building uses, distinguishing between installations calculated at the building level and the building part level. The left panel (A) shows that PV installations are concentrated in rooftops classified as *Scenario 1*, suggesting that owners prioritise rooftops with higher solar potential. In contrast, the right panel (B), which disaggregates adoption at the building part level, reveals that many buildings have only a portion of their rooftop suitable for PV installations, while other sections remain technically unsuitable or less productive. This disaggregation is important because it highlights how technical feasibility constraints within the same building footprint can limit further PV expansion or affect system performance. This comparison suggests that technical potential is a primary driver of early adoption, but awareness and operational experience may lead to further installations in suboptimal areas.

This analysis confirms that the category 'PV Installed, Not *Scenario 1*' represents a small fraction of rooftops across all building uses, rang-

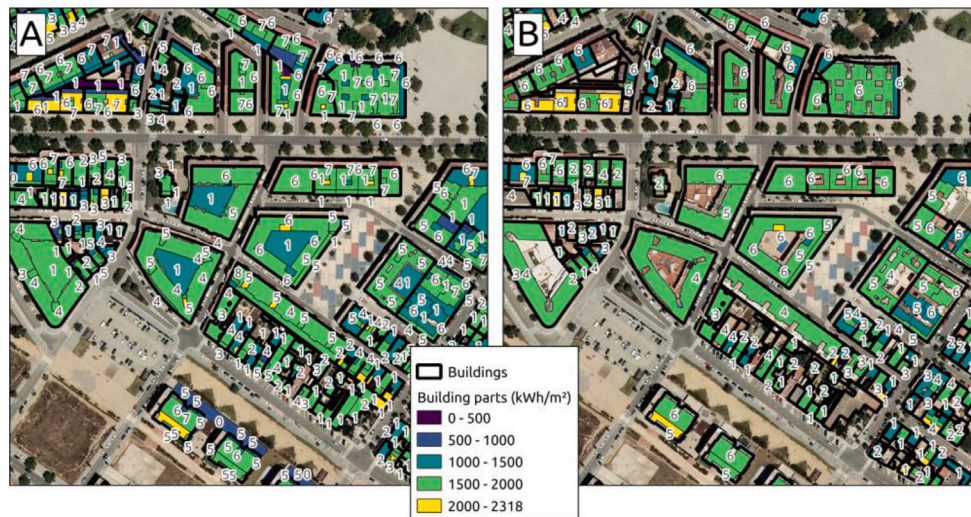


Fig. 7. Building rooftop PV potential. (A) Potential on all buildings; (B) Scenario discarding building parts according to Section 4.3 (Scenario 1). Numbers on each building part represent the number of floors above the ground.

Table 4
Games–Howell Post hoc test results for PV adoption by building type.

	group1	group2	estimate	conf.low	conf.high	p.adj	p.adj.signif
2020	Residential	Agriculture	-0.2792	-0.4085	-0.1498	0.00000171	****
	Residential	Industrial	-0.2454	-0.3615	-0.1293	0.000000382	****
	Residential	Office	-0.1504	-0.7199	0.4191	0.8570	ns
	Residential	Retail	-0.2102	-0.3279	-0.09257	0.000162	***
	Residential	Public services	-0.3437	-0.4855	-0.2020	0.00000357	****
	Agriculture	Industrial	0.03376	-0.1276	0.1951	0.9900	ns
	Agriculture	Office	0.1288	-0.4299	0.6874	0.9280	ns
	Agriculture	Retail	0.06891	-0.09114	0.2290	0.7950	ns
	Agriculture	Public Services	-0.06456	-0.2412	0.1121	0.8820	ns
	Industrial	Office	0.09499	-0.4651	0.6551	0.9770	ns
	Industrial	Retail	0.03515	-0.1159	0.1862	0.9830	ns
	Industrial	Public Services	-0.09833	-0.2673	0.07068	0.5170	ns
	Office	Retail	-0.05984	-0.6211	0.5014	0.9970	ns
	Office	Public Services	-0.1933	-0.7514	0.3648	0.7410	ns
	Retail	Public Services	-0.1335	-0.3014	0.03445	0.1830	ns
	2024	Agriculture	Industrial	0.0240	0.0206	0.0274	0.0000
Agriculture		Office	0.0783	0.0471	0.1096	0.0000	****
Agriculture		Publicservices	0.0881	0.0743	0.1019	0.0000	****
Agriculture		Residential	0.0571	0.0551	0.0592	0.0000	****
Agriculture		Retail	0.0772	0.0624	0.0920	0.0000	****
Industrial		Office	0.0543	0.0229	0.0857	0.0000	****
Industrial		Publicservices	0.0641	0.0500	0.0782	0.0000	****
Industrial		Residential	0.0331	0.0296	0.0366	0.0000	****
Industrial		Retail	0.0532	0.0381	0.0683	0.0000	****
Office		Publicservices	0.0098	-0.0243	0.0439	0.9640	ns
Office		Residential	-0.0212	-0.0525	0.0101	0.3800	ns
Office		Retail	-0.0011	-0.0356	0.0334	1.0000	ns
Publicservices		Residential	-0.0310	-0.0448	-0.0172	0.0000	****
Publicservices		Retail	-0.0109	-0.0310	0.0093	0.6380	ns
Residential		Retail	0.0201	0.0053	0.0349	0.0020	**

Significance levels: * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$, **** = $p < 0.0001$.

ing from 0.5% in offices to less than 0.05% in agricultural buildings. Specifically, the shares are 0.55% for offices, 0.46% for public services, 0.31% for residential, 0.24% for retail, 0.16% for industrial, and 0.04% for agriculture. These marginal proportions explain the barely visible dark red bars in Fig. 8, confirming that PV installations on rooftops that do not meet Scenario 1 technical suitability criteria remain rare exceptions in the province of Tarragona.

The differences in adoption rates across sectors also reflect sector-specific constraints. While residential buildings remain important, industrial and public service buildings have seen a considerable increase in PV installations. Public sector adoption tends to be slower, possibly

due to more complex administrative procedures, such as the need for political commitment, budgetary approval, and public procurement constraints. In contrast, private sector adoption is more agile, as businesses and homeowners can act more independently when economic incentives align.

These results highlight a transition in PV adoption patterns. While residential buildings dominated early installations, industrial and public service buildings have increasingly integrated PV systems in recent years. This shift underscores the role of policy changes, economic factors, and evolving market dynamics in shaping the distribution of PV adoption across different building types.

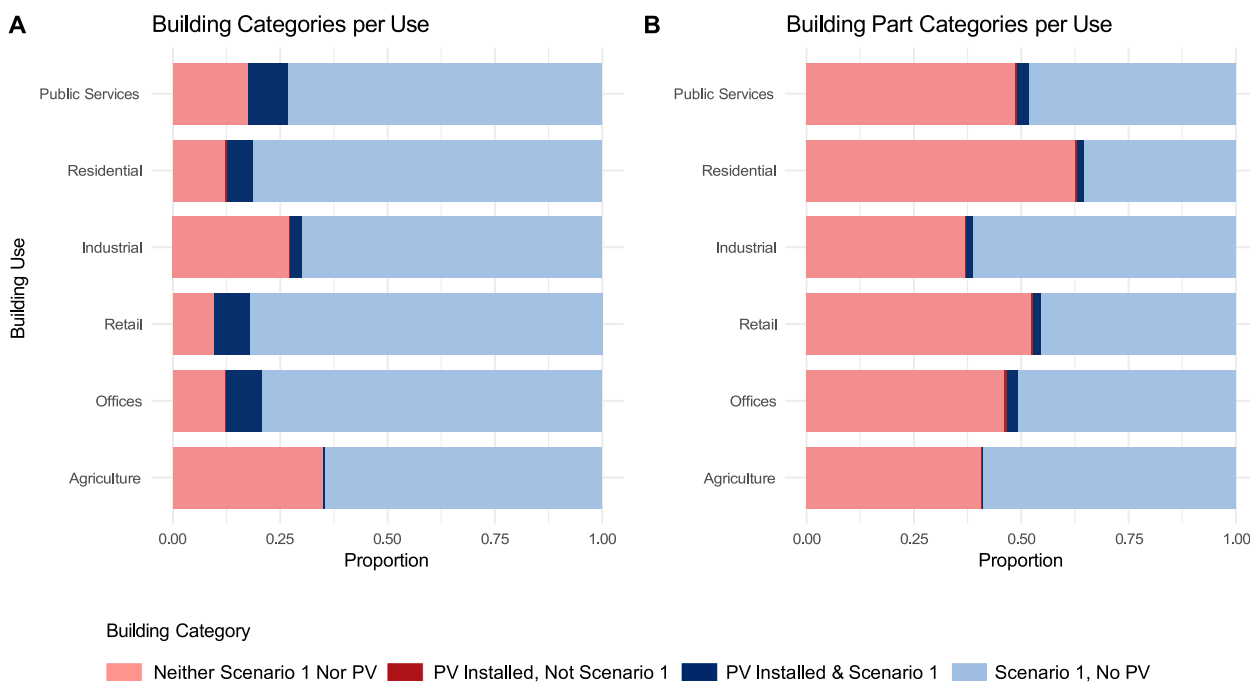


Fig. 8. Rooftop PV adoption by building use in Tarragona province (2024). (A) Proportions calculated at the building level. (B) Proportions calculated at the building part level. Categories distinguish rooftops with and without PV installations and whether they meet the *Scenario 1* technical suitability criteria (detailed in Section 4.3). Dark shades indicate PV adoption; light shades indicate absence of PV. This figure illustrates the concentration of PV installations in technically suitable rooftops (*Scenario 1*) across different building uses, facilitating comparison of adoption patterns between disaggregated and aggregated rooftop data.

6. Discussion

6.1. Implications of PV adoption trends

This study contributes to the understanding of rooftop photovoltaic (PV) adoption patterns, particularly in the context of public service buildings and engagement by the private sector (including residential and non-residential private uses). Our results confirm that residential buildings have played a leading role in early PV adoption, aligning with previous studies on self-consumption and decentralised energy models (Vaishnav et al., 2017; Gallego-Castillo et al., 2021). The expansion of PV installations in public service buildings, although progressing at a slower rate, reflects ongoing policy-driven efforts to enhance renewable energy deployment in institutional settings (Reindl and Palm, 2021).

The observed preference for installations on *Scenario 1* rooftops (those offering better solar conditions in our model) demonstrates that technical feasibility remains a primary determinant of PV adoption (Gassar and Cha, 2021; Freitas et al., 2015). However, the presence of installations in suboptimal areas (*Scenario 0*) suggests that technical criteria do not solely drive decision-making but is also shaped by financial incentives, peer effects, or evolving energy regulations (Curtius et al., 2018; Palm and Lantz, 2020; Irwin, 2021; Qiu et al., 2025; Zhang et al., 2023; San-Martín and Elizalde, 2024). This perspective aligns with studies showing that PV adoption is often shaped by both economic rationality and social influences (Palm, 2016).

6.2. Strengths, limitations, and data challenges

This study employs a systematic GIS-based methodology that integrates open-access spatial datasets, statistical modelling, and free and open-source software tools to estimate rooftop PV potential and adoption patterns. This approach is designed to be transparent, reproducible, and adaptable across different spatial scales, in line with current standards in open reproducible research (Zaragoza et al., 2020). It can also incorporate future advancements in modelling technical PV potential, as suggested by recent studies (Bhatta et al., 2025; Lucchi et al., 2022; Kutlu et al., 2022).

Despite these strengths, several challenges must be acknowledged. A key limitation is the accuracy of building use classification in cadastral databases, which may misrepresent actual use cases. Mixed-use buildings, typical in Spanish cities, often host commercial or office spaces on lower floors while remaining residential above. This situation can introduce inaccuracies when analysing adoption patterns by sector (Stowell et al., 2020). Future research could explore alternative datasets, including municipal land use registries or machine learning-based classification methods, to refine building function assessments.

Another limitation of this study is the availability and completeness of PV installation records; although the ICAEN database offers valuable insights, it may not fully capture all installed systems, particularly private self-consumption installations that do not require grid connection approvals. The reliance on photointerpretation improves data accuracy but introduces subjectivity and potential omissions. Addressing this gap requires improved data-sharing mechanisms between public institutions and private sector stakeholders (Kruitwagen et al., 2021).

Lastly, while our model accounts for technical suitability, it does not directly incorporate economic or behavioural factors influencing PV adoption. Financial incentives, awareness campaigns, and policy interventions play a critical role in determining actual deployment levels (Qureshi et al., 2017). Future studies could integrate socioeconomic data for further contextualisation of adoption trends.

6.3. Policy implications for PV adoption

The results of this study underscore the need for targeted policy interventions to accelerate PV adoption in public service buildings. Unlike the private sector (including residential and non-residential private buildings), where financial incentives and individual decision-making primarily drive adoption, public sector projects often require additional administrative steps, such as budget approvals, regulatory compliance, and political consensus. These barriers can significantly delay implementation, as observed in studies on institutional renewable energy adoption (Qureshi et al., 2017; Reindl and Palm, 2021).

One of the key policy takeaways is the potential for public sector buildings to serve as catalysts for broader PV adoption. Research suggests that peer effects play a significant role in technology diffusion, with visible installations encouraging further adoption among nearby users (Curtius *et al.*, 2018; Palm, 2017). Deploying PV systems in municipal buildings, schools, and libraries could have a demonstrable effect on local adoption rates, particularly in communities where renewable energy uptake remains low.

Additionally, policy frameworks should address sectoral disparities in PV adoption. While residential buildings have benefitted from self-consumption incentives, industrial and commercial sectors face more complex financial and regulatory barriers. Simplifying permitting processes and expanding financial support mechanisms for non-residential installations could enhance adoption rates in these sectors.

6.4. Future research directions

Based on the knowledge gaps identified in this study, several topics for future research emerge. First, future studies should examine whether administrators of public buildings, such as town halls, libraries, schools, sports centres, or cemeteries, are fully aware of their rooftop PV potential. Conducting surveys and interviews with facility managers could provide insights into the barriers and motivations for adoption. Additionally, while this study highlights adoption trends, further research could employ spatial diffusion models to analyse the influence of existing installations on nearby adoption, as studies in behavioural economics suggest that peer influence can sometimes be more effective than financial incentives (Curtius *et al.*, 2018).

Given the limitations of existing PV databases, it would also be valuable for future research to focus on remote sensing techniques, deep learning models, and community-driven data collection initiatives to improve the completeness and reliability of adoption data. Since mixed-use buildings present challenges for PV classification, further studies should explore custom classification models that integrate both cadastral and real-use data, enabling a better assessment of adoption trends in complex urban environments.

Moreover, in less densely populated regions, PV adoption dynamics differ because ground-mounted installations often replace the need for rooftop systems. Future studies should therefore make an explicit distinction between rooftop and ground-mounted PV adoption, considering land availability, grid connection constraints, and the potential for agrivoltaics in rural areas (Ferreira *et al.*, 2024; Kienast *et al.*, 2017; Toboso-Chavero *et al.*, 2019). Finally, further research should incorporate economic modelling and energy storage feasibility analyses to evaluate how financial returns, grid constraints, and storage capabilities influence long-term PV adoption.

7. Conclusions

Towns and cities will be key players in the global energy transition. In Spain, the 2019 law has reinstated the focus on promoting the adoption of new photovoltaic technologies, reducing the uncertainties that characterised the previous period.

The results of this research suggest that photovoltaic energy will play an important role, but the process must be carefully managed to avoid creating false expectations. Many roof surfaces will not be covered by solar panels, at least in the early stages. There are still technical gaps, and a lack of data needed to address the key questions of the energy transition. Our main contribution is to provide new evidence to help understand how the energy transition is being shaped across both public and private sectors. Public debate is essential to avoid repeating mistakes from past energy transitions and to ensure sustainability, equity, and rationality in the process.

Our target audience includes national authorities and regional and local land managers who can use this approach to: (1) strategically shape their energy transition with minimal impact on the landscape,

(2) design territorial and sectoral plans at the regional level, and (3) initiate a dialogue with the affected population using all available data in an operational context, such as stakeholder workshops or organising trialability and observability experiences.

CRedit authorship contribution statement

Benito Zaragoza: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lluís Salvat-Garcia:** Writing – review & editing, Visualization, Investigation, Formal analysis, Data curation. **Sergi Saladié-Gil:** Writing – review & editing, Investigation, Conceptualization. **Oscar Saladié:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing 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.

Data availability

The dataset supporting this study, including rooftop PV scenario modelling and photointerpreted installations in Tarragona (2024), is openly available at <https://doi.org/10.5281/zenodo.15000973>.

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