Title:

Comprehensive Review of Building-Integrated Photovoltaics in the Renovation of Heritage Buildings

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Abstract:

The escalating global climate crisis necessitates immediate action to mitigate its adverse impacts on societal and environmental systems, particularly through reducing emissions associated with the built environment. Traditional and historic buildings, which often exhibit significantly higher energy consumption compared to modern standards, pose a unique challenge in meeting emission reduction targets. Building-integrated photovoltaic (BIPV) systems present a promising solution, combining renewable energy generation with the preservation of historical and cultural heritage.

This study examines 41 case studies of historic buildings that have integrated BIPV systems, with a focus on achieving harmonious integration within their built environments. The findings reveal that the majority of these projects are located in Europe, with rooftops serving as the predominant site for system installations. Additionally, the analysis underscores a significant correlation between a building's heritage protection status and the placement of photovoltaic systems.

The objective of this research is to broaden awareness and increase the visibility of BIPV systems as a viable approach for the sustainable renovation of historic and traditional buildings. The results

demonstrate that it is both feasible and effective to balance heritage conservation with the integration of photovoltaic technology, offering a sustainable pathway to enhance energy efficiency in culturally significant structures.

Keywords: Renovation, Building-Integrated Photovoltaic, BIPV, Historic building, Traditional building, Renewable energy sources, Distributed generation

1. Introduction

Buildings have a pivotal role to play in the energy transition, given that they account for 40% of total energy consumption and are responsible for 36% of both, direct and indirect greenhouse gas emissions [1–3]. To address this, the European Union (EU) has introduced the Green Deal, aiming to make Europe the first climate-neutral continent by 2050 [4], thereby contributing to the objectives established under the Paris Agreement [5]. One potential avenue for achieving the Green Deal is Objective 55, a legislative initiative mandating a minimum 55% reduction in greenhouse gas emissions by 2030, compared to 1990 levels [2].

To achieve the objectives of the EU's climate strategy, the "Fit for 55" package has been introduced. This comprehensive package includes proposals aimed at revising existing legislation and launching new initiatives to align EU policies with climate goals. It establishes a coherent and balanced reference framework to position the EU as a global leader in combating climate change.

A central focus of the package is the enhancement of energy efficiency in buildings, targeting the transition of existing structures to zero-emission status by 2050 [2,6]. Specifically, the EU aims to reduce average residential building energy consumption by 16% by 2030 and by 20–22% by 2035 [7]. In particular, the revised Energy Performance of Buildings Directive (EPBD) [3], adopted in May 2024, explicitly defines the role of solar energy in buildings. Furthermore, it progressively mandates the installation of solar systems in all new and existing buildings, provided it is technically feasible.

The package also includes amendments to the Renewable Energy Sources (RES) Directive. Initially, the 2018 target sought to increase the share of RES to 32% of the energy mix by 2030 [2,8,9]. However, recognizing the inadequacy of this target, the EU revised it in 2023, increasing the RES target to 42.5% with an ambition to reach 45% by 2030 [10,11]. RES integration in buildings is expected to significantly reduce energy-related emissions, supporting sustainability goals. Additionally, the EU set a new energy efficiency improvement target of 11.7% by 2030 [12]. These measures align with the United Nations' Sustainable Development Goals, which underscore the critical role of RES in the energy transition [13–15]. At the Conference of Parties (COP-28), the annual meeting of the United Nations Framework Convention on Climate Change (UNFCCC), it was further emphasized that renewable energy capacity must triple, and energy efficiency must double by 2030 to meet global climate objectives [16].

To support Fit for 55, the Renovation Wave strategy has been developed, aiming to renovate 35 million buildings by 2030. This strategy addresses the significant energy consumption of older buildings, which are typically less efficient [3,7,17]. Interventions targeting these structures are essential to reducing energy demand, consumption, and emissions, thus mitigating climate change. Despite this urgency, the current renovation rate in EU countries remains low, averaging 1–2% annually, and often falls short of maximizing energy efficiency potential [18,19]. Accelerating the renovation rate and ensuring comprehensive improvements are imperative to achieving the EU's climate goals.

There is significant potential for the renovation of historic buildings in Europe, with approximately 110 million buildings requiring such interventions [18,20]. Data indicate that a considerable portion of the building stock holds historical significance due to its age. An analysis of residential buildings reveals that the largest proportion, 31%, was constructed before 1945, with 14% predating 1919. Buildings erected between 1946 and 1969 constitute the second-largest category, representing 20% of the total. Consequently, more than half (51%) of Europe's residential buildings were constructed before 1969, underlining their historical significance [21–25]. In the service sector, the highest proportion of buildings (29%) was also constructed before 1945 [23]. The number of historically significant buildings varies depending on the geographical area and its historical context. Compared to other regions globally, Europe has a larger concentration of heritage buildings requiring preservation. However, significant variation exists within Europe itself. For instance, in the United Kingdom, only 1% of buildings are officially designated as historic and protected [26], whereas in Italy, 30–31% of the total building stock comprises heritage buildings constructed before 1945 [25,27,28]. This prevalence of historic buildings across different regions highlights the substantial opportunity for targeted interventions to improve their energy efficiency while preserving their cultural and architectural value.

The necessity of renovating existing buildings to reduce energy consumption presents a unique opportunity to enhance energy efficiency through the integration of renewable energy sources. Building renovation allows for the implementation of comprehensive solutions, including improved insulation, high-performance glazing systems, advanced ventilation, and modern heating and cooling systems, alongside renewable energy technologies [12]. Incorporating renewable energy sources in renovation projects is critical within the global climate framework. This approach can significantly impact the transition to emission-free cities by reducing buildings' energy demand, facilitating their renovation, and generating clean energy. Moreover, it contributes to societal well-being by improving indoor comfort and reducing environmental emissions [29].

Among renewable energy sources, solar energy demonstrates the greatest growth within the EU. Its advantages include cleanliness, flexibility, and affordability, evidenced by an 82% reduction in cost between 2010 and 2020 [30]. Solar energy is a key driver in the transition to clean and sustainable energy, offering broad accessibility to users. Incorporating photovoltaic (PV) technologies into building renovations provides a transformative solution to climate change and a critical step toward decarbonization. PV systems offer numerous benefits, including the ability for users to self-consume the electricity generated on-site, reducing dependence on the electrical grid, bringing energy closer to citizens, making them more aware of it, and, in many cases, changing their consumption habits [31]. Recent advancements in PV module aesthetics—such as enhanced flexibility, modularity, and diverse colour and size options—have further facilitated their integration into buildings.

Two primary typologies of photovoltaic systems are employed in building applications:

Building-Attached Photovoltaics (BAPV). BAPV systems use standard, opaque photovoltaic modules with exposed cells and frames, prioritizing performance and energy production over aesthetics. These systems are mounted onto building envelopes, such as roofs and façades, using guides and uprights for support. Since they are not integrated into the structure, BAPV systems function solely as energy-generating elements and do not contribute to the structural or aesthetic integrity of the building [32,33].

Building-Integrated Photovoltaics (BIPV). BIPV technology represents an emerging segment of the photovoltaic market experiencing rapid growth. These systems are fully integrated into the building envelope, serving multiple functions beyond electricity generation, such as weather protection, insulation, noise reduction, shading, and structural reinforcement. Unlike BAPV systems, BIPV elements constitute an integral part of the building structure, without which the building would not be complete and functional. BIPV systems offer enhanced aesthetic versatility through customized sizes, shapes, colours, and textures, allowing them to mimic traditional building materials. Applications include roofs, façades, parapets, and skylights, enabling seamless structural and aesthetic integration. These innovations mark a significant advancement in photovoltaic technology, demonstrating adaptability and multifunctionality in diverse building contexts [32,34–39].

A comparison of the two technologies and their applications in buildings reveals that BAPV systems are the most widely recognized and have the longest history in the solar market. However, BIPV systems are currently experiencing exponential growth due to their unique characteristics. This is evidenced by the fact that, in Europe, one in three renovations of existing buildings has incorporated BIPV in recent years [40,41]. The use of BIPV systems presents an optimal opportunity for integration into historical buildings, given their adaptability and compatibility with the inherent values and specifications of such structures. Understanding the specific criteria for determining a building's heritage value and the permissible extent of intervention is essential for ensuring compliance with established guidelines. In the context of constructed heritage, the United Nations Educational, Scientific and Cultural Organization (UNESCO) defines cultural heritage as comprising buildings with various qualities, including artistic, historical, aesthetic, symbolic, social, and scientific significance [42,43].

The concept of "cultural heritage" encompasses a range of building groups, sites, and monuments, including architectural works. These are further categorized into two main types: historic buildings and traditional buildings. The term "historic buildings" refers to structures typically protected and catalogued as having significant heritage value, necessitating preservation. According to the European Union, this value is determined by a structure's age, which must exceed 50 years [44]. Conversely, "traditional buildings" are characterized by their construction using local materials and techniques, reflecting the cultural identity and history of their region. However, these buildings do not necessarily possess intrinsic heritage value [29,44].

As stipulated in current environmental frameworks, historic buildings must undergo modifications to address contemporary environmental challenges and demands. These renovations should enable the structures to meet sustainability and energy efficiency standards, and even generate energy, while safeguarding their heritage values [45].

Therefore, when designing the renovation of a building of this magnitude, regardless of its protected status, the focus should be on preserving its defining characteristics while balancing conservation with renovation. This approach will enhance the building's energy efficiency, aligning with both sustainability goals and heritage preservation.

In the case of historic and traditional buildings, any proposed intervention must respect the existing structure and integrate with the overall design. BIPV systems offer a promising solution for preserving the building's original values through their aesthetic capabilities, while simultaneously enhancing energy efficiency. By employing products that can be carefully tuned in shape, colour, and texture, and manufactured in accordance with the specifications of the project, they can closely align with the aesthetic characteristics of the original materials, even reproducing them.

Nevertheless, the utilisation of these systems in the restoration of historic edifices is not a common practice, largely due to a notable reluctance to employ them. This is primarily attributable to the existence of political, technical, economic and social barriers. The lack of a legislative framework, specialized labour, financial support, and the high initial cost of these systems compared to other conventional passive solutions pose substantial obstacles to their adoption [31]. Regarding BIPV systems and historic buildings, one of the primary challenges is the social perception surrounding their use. A lack of understanding of these technologies often leads to the belief that installing modern photovoltaic modules on historically significant structures is an inappropriate or regressive approach. This misconception contributes to concerns that such installations may negatively impact the building’s historical appearance. As a result, integrated solar systems are frequently rejected [37,46]. While BIPV technologies are not original building materials, they offer the potential to adapt and closely replicate the building's aesthetic characteristics. Therefore, a comprehensive evaluation is crucial to assess the potential impacts and feasibility of incorporating these systems into renovation projects [40].

In summary, data highlights the need for intervention in the built environment to reduce emissions and support the energy transition, with a significant portion of the building stock possessing historical value due to its age. One of the most effective strategies to achieve this goal is integrating renewable energy sources, such as solar energy, into the renovation process. In this context, the objective of the present research is to review and analyse the process of renovating old, historic, and protected buildings with integrated photovoltaic systems. The aim is to demonstrate, through built examples, how it is possible to renovate historic buildings, including listed structures, using integrated solar systems in a way that respects their intrinsic value and preserves the built environment. A total of 41 case studies have been selected, encompassing a variety of solutions and building typologies, with the goal of providing visibility and promoting this type of renovation as a means of advancing the energy transition.

2. Methodology

The objective of this research is to highlight renovation interventions in traditional and historic buildings, some of which are protected, using integrated solar photovoltaic systems. To achieve this, a series of steps were undertaken. Firstly, it was essential to assess the current state of knowledge on studies addressing this topic. A literature review was conducted to this end. The search for relevant studies was carried out on two platforms, ScienceDirect [47] and MDPI [48], using the following keywords: 'BIPV', 'renovation', 'historic building', 'historical building', 'heritage', and 'sensitive areas'. To narrow the focus and maximise the accuracy of the results, queries were conducted by combining these keywords, yielding a total of 193 results. Each research study was then analysed in detail to determine its relevance to the objectives of this article. The following exclusion criteria were applied in the selection process: studies that did not directly address the research topic; studies focusing on add-on solar systems; studies published prior to 2012; studies that did not reflect the current BIPV market, as they failed to incorporate advancements in module treatment to facilitate integration into the building; and studies examining the use of BIPV systems in existing buildings without historical significance. This process resulted in the selection of 27 studies, which formed the initial bibliographic basis for this article. These studies enabled the identification of various articles, studies, and examples relevant to the research. The results of this search demonstrate that the use of BIPV systems in protected buildings has not been extensively explored. However, it is an emerging field, driven by prevailing climatic conditions, and there is considerable potential for further theoretical contributions. The analysis of the selected studies provided insights into the current state of this research area, the types of analyses and approaches employed, the topics explored in greater depth, and those less explored. Additionally, it offered valuable information on case studies of completed projects, as well as the platforms and initiatives referenced in these studies.

Following this first review, the next stage involves identifying traditional and historic buildings where renovation has been carried out using BIPV in a manner that integrates seamlessly with the existing built environment, while respecting and preserving its historical values.

A variety of information sources have been employed to address and select a diverse range of completed cases. One of the key research projects used is entitled *BIPV Meets History* [49], a study investigating the use of BIPV systems in historic buildings as part of a broader research initiative led by EURAC Research [50], which also developed the platforms IPV Integrated Photovoltaic [51] and HiBER Atlas [52], bringing together international case studies where renovations have focused on improving the energy efficiency of older buildings. In addition, *Solarchitecture* website [53], promoted by the University of Applied Sciences and Arts of Southern Switzerland (SUPSI), the Federal Institute of Technology Zurich (ETHZ), the Swiss professional association for solar energy (Swissolar) and the Swiss energy program, was also used to gather relevant information.

Moreover, publications from the International Energy Agency`s Tasks 15 – *Enabling Framework for the Development of BIPV* (IEA PVSP) [54] and 59 – *Renovation of Historic Buildings Towards Zero Energy* (IEA SHC) [55] have also been reviewed.

To gain deeper insights, a review was conducted of projects undertaken by leading manufacturers of integrated PV modules, complementing the searches on platforms, projects, and research programmes.

The final stage of the investigation involved reviewing various awards recognising successful renovations utilising solar systems in historic buildings. Selected awards include the Swiss Solar

Prize [56], the European Solar Prize [57], the Norman Foster Solar Award [58], and the CasaClima Award [59], among others. These awards serve to promote the use of solar systems and highlight best practices, thus establishing reference points for future projects [31].

From this selection, projects involving the renovation of historic buildings, where visual, aesthetic, and technical integration with the existing structure was optimised, were chosen. Each example provides detailed data on the interventions made during the renovation process, with the aim of enhancing the building's energy efficiency. The data presented is the most representative of each building, thereby facilitating a comprehensive understanding of its historical and current energy efficiency.

The outcome is the selection of 41 case studies, representative of various BIPV typologies and solutions, identified through a comprehensive analysis of the examples presented in the information sources. These examples are then subjected to a detailed examination in a series of tables, summarising the most relevant data to facilitate understanding and comparison. This information facilitates the identification of discernible patterns and characteristics, which are then addressed in the discussion. Additionally, all the data gathered throughout the research is contextualised within the prevailing political, social, and economic framework.

3. Case studies

In order to narrow the search focus and obtain a complete set of examples for analysis, all the interventions available on the different source information mentioned above were filtered. The selection process was based on four key phases. First, all interventions that were not renovations of existing buildings were excluded. Next, interventions aimed at improving energy efficiency including photovoltaic solar systems were identified. Within this context, those employing BAPV systems were excluded, and only renovations involving integrated photovoltaic systems were considered. Finally, each intervention was thoroughly assessed selecting those where the principal design objective was integration with the existing building, ensuring the preservation of its traditional and heritage values. This process resulted in 41 international case studies, which provide a comprehensive overview of BIPV interventions in both protected and unprotected historic buildings and serve as exemplars for future projects.

The selected buildings are presented in Table 1, which summarizes fundamental data to provide both an individual perspective on each building and its BIPV intervention, as well as a comprehensive overview of all the case studies. This information is accompanied by references where each example can be accessed and analysed in depth, with the aim of promoting further study and increasing the visibility of these interventions.

	Location	**Building age**	**Protection**	**BIPV application**	**References**
Doragno Castle	Rovio, Switzerland	11th century	Listed building	Opaque roof	[49,51,52,55]
Single family house	Bern, Switzerland	1898	Listed building	Opaque roof	[49,52,55]
PalaCinema Lorcano	Lorcano, Switzerland	1850-1899	Protected area	Roof	[49,52,55]
Glaserhaus	Emmental, Switzerland	1765	Listed building	Opaque roof	[49,52,55]
Solar Silo	Basel, Switzerland	1850	Conservation area	Opaque roof and facade	[49,51–55]
La Certosa Island	Venezia, Italy	unknown	Listed building	Opaque roof	[49,51]
Rural building	Seegräben, Switzerland	unknown	None	Opaque roof	[49,51]
House Breuer	Schruns, Austria	1900-1944	None	Opaque roof	[52,55]
St Franziskus Church	Ebmatingen, Switzerland	1989	None	Opaque roof	[52,53,55]
Kindergarten and apartments	Chur, Switzerland	1914	None	Opaque roof	[52,55]
Single-family house	Gstaad, Switzerland	1700-1800	Listed Building	Opaque roof	[52,55]
Villa Castelli	Bellano, Italy	1850-1899	Listed Building	Opaque roof	[49,51,52,55]
Saint Andrew's Cathedral	Sydney, Australia	1817	Listed Building	Skylight	[49,51]
Linares Town Hall	Jaén, Spain	19th century	Listed Building	Skylight	[49,51]
Béjar Market	Salamanca, Spain	Unknown	Listed Building	Skylight	[49,51]
San Antón Market	Madrid, Spain	1879-1882	Conservation area	Skylight	[51,54]
Alzira Town Hall	Valencia, Spain	16-17th century	Listed Building	Skylight	[49,51]
Student housing	Slagelse, Denmark	1970	None	Facade / Balaustrade	[51,54]
Single-family house	Ulestraten, Netherlands	Unknown	None	Opaque roof	[51,54]
Milland Church	Bressanone, Italy	1984-1985	Listed Building	Opaque roof	[50,51]
Farm building	San Genesio, Italy	Unknown	None	Skylight	[50,51]
Office building	Miltenberg, Germany	Unknown	None	Facade	[51]
Energy Tower Aktiv	Wels, Austria	Unknown	None	Facade semi-transparent	[49,51,54]
Weyerguet farm	Köniz, Switzerland	1842	Listed Building	Opaque roof	[49,51]
Farmhouse Galley	Ecuvillens, Switzerland	1859	Listed Building	Opaque roof	[49,51]
Harbourfront Centre Theatre	Toronto, Canada	1926	None	BIPV curtain wall	[51,54]
COOP TH12 Headquarters	Basel, Switzerland	1978	None	Facade	[49,53]
Villa Carlotta	Orselina, Switzerland	1939	Unknown	Opaque roof	[56]
Residential building	Zürich, Switzerland	1982	None	Ventilated facade	[49,53,54]
Wattbuck Tower	Effretikon, Switzerland	1968	None	Ventilated facade-parapet	[49,53]
Historic Building	Montecrestese, Italy	Unknown	Landscape protection	Opaque roof	[49,51]
Single-family house Bianda	Losone, Switzerland	1930	None	Opaque roof	[49,51]
Ütia da Ju	San Martino di Badia, Italy	Unknown	Conservation area	Semi-transparent conopy	[50,51]
Die Mobiliar	Bern, Switzerland	1980s	None	Semi-transparent brise-soleil	[49,53]

Colterenzio Winery	Appiano, Italy	1980s	None	Semi-transparent conopy	[51]
Bell Works Labs	New Jersey, United States	1962	Listed building	Skylight	[60,61]
Ombú Acciona	Madrid, Spain	1905	Listed building	Skylight	[60,62]
Domaine de La Plume	La Penn, France	18th century	None	Opaque roof	[63]
The Predikheren	Mechelen, Belgium	1600-1650	Listed building	Opaque roof	[64]
Essen's old customs	Essen, Belgium	1902	Listed monument	Skylight	[60]
Lakefront Villa	Lavaux, Switzerland	Unknown	Listed building	Opaque roof	[65]

Table 1. All case studies were analyzed along with their main characteristics.

Each intervention underwent a comprehensive examination, with all relevant data compiled into individual fact sheets for each building. This approach allowed for in-depth analysis of each case, enabling comparisons between examples and the identification of key similarities. The following fact sheet illustrates the format used to compile information for each case study. Two examples from the 41 selected cases are presented, as they effectively represent the different types of interventions analysed and the integration of the solar system withing the built environment. While the two BIPV interventions are distinct, both involve rooftop installations, the most common approach in this type of renovation. Additionally, both interventions were carried out in protected European buildings, although they originated in different countries.

Case study: Weyerguet farm	
	BIPV application: Opaque roof
	Stakeholders: 3S Swiss Solar Solutions AG (Switzerland)
	System power: 37 kWp
	Annual electricity production: 37 600 kWh
Location: Köniz, Switzerland	BIPV area: 261 m^2
Building age: 1842	BIPV Renovation: The installation makes use of the slope of the original roof structure, employing opaque matte glass modules, hidden PV cells and a terracotta colour. This approach ensures that the installation integrates harmoniously with the surrounding buildings. The BIPV system was part of a compressive renovation.
Typology: Farm House	
Use: Residential	
Protection level: Listed Building	References: BIPV meets History / IPV Integrated Photovoltaic (eurac research)
Renovation year: 2016-2020	Other data: 2020 Swiss Solar Prize

Table 2. Weyerguet farm, case study selected to showcase its in-depth analysis. Image of the building's exterior showcasing the BIPV roof, sourced from the IPV Integrated Photovoltaic website [51].

Case study: Alzira Town Hall	
	BIPV application: Skylight
	Stakeholders: Onyx Solar (Spain)
	System power: 5.1 kWp
	Annual electricity production: 7 402 kWh
Location: Valencia, Spain	BIPV area: 112 m^2
Building age: 16-17th century	BIPV Renovation: The skylight is situated in the inner courtyard and features amorphous silicon modules with a glass-glass configuration and 10% transparency. This design allows natural light to enter the interior while regulating its intensity. The PV cells are hidden, ensuring aesthetic integration with the surrounding complex.
Typology: Town Hall	
Use: Institutional	
Protection level: Listed Building	References: BIPV meets History / IPV Integrated Photovoltaic (eurac research)
Renovation year: 2011-2015	Other data: Building with the highest level of protection in Spanish territory, as it is a BIC (Bien de Interes Cultural)

Table 3. Alzira Town Hall, second case of study selected to showcase its in-depth analysis. Images of the building's exterior and the BIPV skylight, sourced from the IPV Integrated Photovoltaic website [51].

The selected examples all contain the same information, which has been compiled on both the building and the intervention in question. Accordingly, should any research require this data, the authors of this article invite interested parties to contact them to share the conducted research without issue.

4. Results and discussion

4.1. Overview of general findings

The comparative analysis of the 41 case studies provides a comprehensive view of the status of Building-Integrated Photovoltaic (BIPV) systems in historic buildings. Geographic concentration in Europe, with 38 out of 41 case studies located in this region, highlights the centrality of Europe in adopting BIPV technologies. Outside of Europe, the number of case studies is far smaller, with notable exceptions in countries like the United States, Canada, and Australia. However, these non-European case studies are limited, and in the case of Australia, only one example of a protected building is observed, underscoring the challenge of implementing BIPV technologies in regions with less-established solar infrastructure and less stringent heritage conservation policies.

In terms of country-specific trends, Switzerland leads with 18 BIPV interventions in historic buildings, followed by Italy with 7 and Spain with 5. This distribution illustrates not only the geographical concentration of BIPV technologies in Europe but also reflects the influence of national legislative frameworks on the adoption of renewable energy systems. Switzerland, in particular, stands out due to its pioneering role in integrating photovoltaic technologies into heritage buildings, supported by a long-standing commitment to climate neutrality, which has significantly impacted the number and variety of BIPV installations.

Building typologies further demonstrate the versatility of BIPV systems. Case studies cover a wide range of building types, from single-family homes to churches, offices, and rural buildings, which highlights the adaptability of BIPV technology in accommodating diverse architectural styles and functional needs. This adaptability is vital when considering the preservation of the historical and cultural value of these buildings while also improving their energy efficiency.

Additionally, 23 of the 41 buildings are located within conservation areas or are protected, with varying levels of protection. This segmentation is crucial because it speaks to the delicate balance between heritage conservation and the need for sustainable building practices, where BIPV can play a crucial role. While the remaining 17 case studies are not formally protected, they still carry historical value, underscoring the importance of adopting solar technology in a way that respects and integrates the architectural significance of these structures.

In order to facilitate a more in-depth analysis of the data and its correlation with legislation, research, and current projects, the information has been systematically structured into discrete sections. This segmentation has been undertaken to ensure a comprehensive representation of the critical parameters that shape the application of BIPV systems in building renovation.

4.2 Geographical distribution and contributing factors

Europe is distinguished by the highest concentration of traditional and historic buildings that have undergone renovation with BIPV systems. This assertion is corroborated by the findings of the present study, which revealed that 38 of the 41 buildings analysed were located withing Europe.

Two key factors have been identified that explain the BIPV use in renovations, the location manufacturing companies specialized in BIPV solution, and the legislative framework.

In the current BIPV market, the greatest concentration of manufacturers of integrated solar systems is observed in Europe. With the exception of the Harbourfront Centre Theatre in Toronto, Canada, which utilises modules from a local manufacturer, all the manufacturing companies involved in the case studies analysed in this research are European. This indicated that modules produced by European manufacturers are not only utilised within the continent itself, but also have an international commercial reach. For example, in the case studies of Bell Works Labs in the USA and Saint Andrew's Cathedral in Australia, the BIPV systems were manufactured by a Spanish company [60]. Therefore, it can be inferred that the greater prevalence of integrated photovoltaic systems in European building renovations is, at least in part, attributable to the higher concentration of manufacturers and pioneers in the BIPV market within this region.

Conversely, another factor that may inhibit the wider integration of solar technologies in historic edifices is the legislative framework and associated guidelines. In Europe, the EN 16883:2017*Conservation of cultural heritage* standard [66] serves as a reference for conservation and renovation processes aimed at improving energy efficiency in historic buildings. This standard target users, professionals and administrative authorities responsible for heritage management. By employing this guide as a reference for each individual case, a comprehensive analysis of the building's relevant characteristics can be conducted, facilitating the formulation of intervention proposals that align with the building's specifications. This ensures that the proposed interventions enhance energy efficiency while maintaining the building's historical and architectural integrity [45,67]. It is important to note that the application of this standard must be in accordance with local regulations. EN 16883:2017 does not serve as a prescriptive standard, but rather provides a framework for best practices. At present, the utilisation of this standard in renovation projects is not particularly widespread primarily due to its generic nature, its non-mandatory status, and limited awareness of its existence, as it is relatively new [68]. Nonetheless, the existence of this standard is noteworthy, as it promotes visibility and for such interventions, despite not specifically addressing BIPV systems.

4.3 Country-specific trends and legislative frameworks

A focus on individual countries reveals that Switzerland and Italy have the highest number of renovations incorporating BIPV systems. This advancement can be also attributed to the influence of their legislative frameworks. Switzerland is a noteworthy case in Europe, exhibiting a comprehensive regulatory and procedural framework aimed at achieving climate neutrality by 2050. It is a pioneer in the utilisation of PV systems in buildings, with such technology being a legislative consideration since 1979 [69]. The legislative framework includes several laws that facilitate and regulate the deployment of integrated solar systems in heritage areas, subject to the required authorisations. Additionally, it encompasses guidelines and tools designed to promote the adoption of these systems. A significant feature of Switzerland's approach is the visibility and regulation of these systems. Federal legislation outlines guidelines for assessing the impact of solar installations in protected areas and provides general procedures for implementation [44]. One illustrative example is the Swiss government's establishment of a solar cadastre, which supplies data on building energy consumption and the potential for solar energy production on facades and roofs. This initiative aims to encourage the installation of such systems [45]. In contrast, Italian legislation recognizes solar systems as a key measure for descarbonisation, although BIPV systems are not explicitly included withing this framework. The incorporation of photovoltaic technologies is regarded as a potential strategy during the restoration of a historic building. However, a permitting procedure is mandated by the prevailing legislation, and the proposal will be evaluated by the pertinent commission. The implementation of BIPV systems in areas of cultural significance is a more complex process, requiring approval of multiple institutions and a comprehensive assessment. Consequently, in numerous instances, the initial phase does not proceed to the subsequent stages. Nonetheless, the guidelines issued by the Italian Ministry of Cultural Heritage and Activities and Tourism (MiBACT) provide several examples of the application of BIPV technology. This guidelines serve as a resource for assessing the energy performance of listed buildings and designing interventions that enhance energy efficiency while maintaining heritage value [69].

In brief, Switzerland presents a more robust and accessible legislative framework for the deployment of BIPV systems, whereas Italy prioritises energy transition and the promotion of renewable energy sources, with less emphasis on integrated solar systems. Nevertheless, both countries serve as examples of effective renovation processes incorporating photovoltaic systems, aligning with the objectives set by the European Union. This is evident in the significant adoption of BIPV systems in the renovation of traditional and historic buildings. Furthermore, as highlighted in the introduction, Europe is home to a cultural and historical heritage, as evidenced by the considerable number of heritage-listed buildings. Consequently, the prevalence of historic buildings necessitating renovation has resulted in a higher frequency of BIPV interventions.

4.4 BIPV applications across building typologies and protection levels

A comparative analysis of the BIPV systems incorporated into the renovations undertaken in the case studies reveals that 80.5% are BIPV solutions mounted on the roof, while the remaining 19.5% are located on the facade. Regarding roof systems, the majority are opaque, employing coloured modules that replicate the tone of the original and adjacent roof tiles. This accounts for 66.67% of the total, while 33.33% utilise integrated photovoltaic skylights. For facade solutions, the findings indicate that they are relatively uncommon, with ventilated facade solutions and photovoltaic curtain walls representing the most prevalent types. It can thus be concluded that BIPV systems are typically situated on the roof of buildings with historical and protected value. This conclusion is supported by various studies examining these technologies in historic buildings [19,59,70–73].

Furthermore, this is intrinsically connected to buildings that are listed. Of the 41 case studies, 56% are subject to some form of protection, 42% are old buildings without any such protection, and only 2% (one case) could not be verified as listed. Of the case studies involving listed buildings, 23 have BIPV systems installed on the roof, while only one example has BIPV installed on the facade. This case study pertains to the Solar Silo, a building situated within the protected industrial zone of Basel. The structure is used for educational and research purposes, and it has been equipped with BIPV systems on both the roof and the facade. These systems comprise modules of varying colours, which are employed to monitor their performance. In comparison to unprotected buildings, the integrated PV solutions are more evenly distributed, with nine older buildings featuring BIPV systems on the roof and eight examples with these installations located on the facade. From these results, several conclusions can be drawn.

It is important to first note that the area for BIPV installation in listed buildings is the roof, and that these systems are not located on the façade, except in cases where the building is used for educational or research purposes. This is due to a few reasons. The primary rationale for this is that rooftop installations are less visible for buildings with historical value, thereby ensuring superior integration and reducing the risk of compromising the historical value of the building. Furthermore, the installation of such systems in these locations is more straightforward and meets with greater acceptance, both in technical and aesthetic terms [71]. The production of modules with customised dimensions and geometric configurations, combined with the existing advancements in photovoltaic module processing, allows the replication of the colouring of the original tiles through the imitation of terracotta tiles, slate and sheet metal roofs. This ensures the original appearance of the building is preserved. Furthermore, the roof is the area of the building with the highest absorption values. These factors collectively explain why roofs are the preferred area for BIPV installations, whereas facades are generally considered suboptimal for integrated PV solutions. The deployment of such technologies on facades presets a higher risk to heritage values due to the inherent complexity of integrating PV modules with original building materials. Although the photovoltaic market offers a variety of modules in different colours and textures, further development is needed to fully address these challenges. It is also crucial to emphasise that any partial intervention on facades is wholly unacceptable, as they would contravene the principles of heritage conservation. Additionally, solar resources on facades could be significantly reduced due to shading from adjacent buildings, and façade interventions are generally less socially accepted. Consequently, is most renovation projects, the possibility of integrating BIPV systems into the façade of listed buildings is often dismissed due to the associated risk and reduced benefits [74]. Nevertheless, research has indicated that such interventions may be conducted in protected buildings with a view to maintaining visibility of this type of renovation [75]. Conversely, the findings suggest that in buildings not designated as heritage sites or located within conservation areas, BIPV systems exhibit greater diversity. In these cases, wide range of BIPV solutions are available for retrofitting existing buildings, with a more balanced distribution between roof and facade installations. These solutions include opaque modules installed in ventilated facades, semi-transparent curtain walls, and installations featuring brise-soleil and PV parapets.

4.5 Challenges and barriers to BIPV adoption in Historic Buildings

The results of the research demonstrate that the use of BIPV systems in historic buildings is a viable option, regardless of the level of protection granted to them, as long as their heritage value is preserved. Current BIPV systems are flexible and can be adapted to various scenarios. Additionally, recent advancements in module treatments have made their integration into buildings more feasible [76].

It is crucial that any interventions in historic buildings respect and preserve their inherent characteristics. The objective is to prioritize minimal intervention, within the limitations imposed by the building's condition and regulatory constraints. This can be achieved through a thorough study of the building's history, which serves as a foundation for seamlessly integrating the BIPV intervention into the existing structure. However, this process is challenging, as it requires balancing the conservation of existing features with the need to enhance energy efficiency.

Given the complexity of integrating BIPV systems into historic buildings, it is essential for the design of such interventions to involve a multidisciplinary team. This ensures that all perspectives, benefits, and challenges are considered. Effective communication and active participation from local authorities responsible for heritage conservation are also crucial. The design phase of the intervention must ensure optimal integration of BIPV systems with the surrounding built environment. To achieve this, it is necessary to address three key aspects: technical, aesthetic, and energy integration.

Technical Integration refers to the system's ability to fulfill its multifunctional role by replacing components of the building's external envelope. When proposing such systems, it is essential to ensure compatibility and durability between all materials and the structure, as well as reversibility, allowing for the potential removal and replacement of the system.

Aesthetic Integration concerns the system's ability to maintain the architectural and morphological characteristics of the building. Several criteria must be met to assess this. Firstly, the modules must be integrated in terms of their size and surface area, ensuring they are coplanar with the structure and do not protrude. Secondly, the modules must match the color and texture of the existing building as closely as possible, with particular attention to reflectance.

Energy Integration focuses on the energy production of the BIPV system and its capacity to meet a portion of the building's interior energy demand. By addressing all three aspects—

technical, aesthetic, and energy integration—the proposed BIPV installation can be compatible with the building, preserving and perpetuating its heritage values while maintaining visual and material harmony [29,37,44,59,70,77–79].

It is important to note that achieving aesthetic integration may involve the use of specialized color and aesthetic treatments on the modules, which can reduce performance and increase manufacturing costs. To meet the diverse aesthetic requirements of historic buildings, PV cells may be concealed to achieve the desired colors, textures, and transparencies. In such cases, aesthetic considerations take precedence over performance, offering an optimal solution for interventions in historic buildings. Since each building is unique, it is essential to consider its specific characteristics and prioritize interventions, even if the energy production is lower. While BAPV (Building Applied Photovoltaics) systems generate more energy due to the absence of treatment on the PV cells, their installation is not suitable for historic buildings because they lack the integration required to fit into the existing structure.

The objective of this research is to promote the integration of BIPV systems in renovation projects. However, BIPV technology must be complemented with other strategies aimed at optimizing energy efficiency in historic buildings. Among the most common non-invasive interventions to ensure optimal comfort are improvements in insulation, airtightness, and modifications to original windows and doors [73]. These actions are minimal and non-invasive, focusing on the preservation of the building. When combined with BIPV systems, which contribute to energy generation, they are highly effective in reducing indoor energy demand. This combined approach can lead to significant improvements in energy efficiency, which is crucial for older buildings.

It is important to consider that several factors act as barriers to the adoption of BIPV systems. These include technical, policy, economic, and social barriers, as well as a lack of human resources and information [15]. In the early stages of BIPV systems' introduction to the PV market, economic constraints posed a significant challenge, primarily due to the high cost of the technology. However, costs have been substantially reduced and are expected to decline further. Despite these reductions, it is evident that increased government support is necessary to promote the widespread adoption of these systems and to enhance their affordability. At present, social and technical factors remain significant barriers to the advancement of BIPV technology. Social acceptance of BIPV systems in heritage buildings represents a particular challenge, with resistance often arising from a lack of knowledge, trust, and awareness, as well as insufficient commitment and communication. In many cases, this resistance stems from an outdated understanding of photovoltaic systems and the assumption that they are incompatible with the preservation of the architectural and historical values of listed buildings. In this context, the establishment of a political and legislative framework that supports the integration of solar systems is essential to promote and increase the visibility of such interventions. However, the absence of an adequate framework or the failure to address these systems effectively constitutes a significant obstacle [46,80,81].

5. Conclusions

The use of Building-Integrated Photovoltaic (BIPV) systems into historic buildings represents an emerging area of study with significant potential. This research aimed to evaluate the application of BIPV systems in such buildings by analysing a range of studies, projects, and case examples. The findings provide a valuable reference framework to support the broader adoption of these technologies and enhance understanding of their role in balancing heritage conservation with energy efficiency.

Promoting the use of BIPV systems requires addressing a major barrier: the lack of public and professional awareness. Insufficient knowledge about these systems often leads to their rejection. Efforts to overcome this challenge should include targeted educational programs, early incorporation of renewable energy concepts in curricula to foster awareness, and professional training to expand expertise within relevant fields.

While a unified legislative framework for integrating BIPV into historic buildings would be advantageous, the diversity of national regulations makes this impractical. Each historic building requires a bespoke approach, considering its unique historical context, cultural significance, and protection requirements. Existing resources, such as EN 16883:2017, provide valuable guidance for designing interventions that respect heritage values. However, further research is necessary to develop specific tools that can streamline the integration process and address the complexities inherent in such projects.

Historic buildings often exhibit high energy consumption, necessitating their adaptation to meet contemporary environmental standards. Exempting these structures from environmental regulations is increasingly unsustainable in light of the current climate crisis. Maintaining these buildings in their original state may require limiting their use, which reduces energy consumption but also diminishes their functional value. Instead, technological innovations such as BIPV systems present opportunities to enhance energy performance while preserving cultural heritage. These interventions, supported by comprehensive studies, can ensure seamless integration that respects both architectural and environmental objectives.

The preservation of historic buildings for future generations is of critical importance. Simultaneously, their adaptation to meet modern energy performance standards is essential in addressing climate challenges. The findings of this study demonstrate that BIPV systems can be effectively integrated into heritage-listed buildings, combining flexibility and adaptability to support their unique requirements. Continued research is crucial to improve the visibility, acceptance, and implementation of these solutions, facilitating their wider adoption and helping to overcome the negative perceptions that currently hinder their use.

6. CrediT authorship contribution statement

Irene Del Hierro López: Conceptualization, Formal analysis, Data curation Methodology, Investigation, Resources, Visualization, Writing – Original Draft, Writing – Review & Editing; **Lorenzo Olivieri**: Conceptualization, Data curation, Methodology, Validation, Writing – Review & Editing, Supervision, Project administration, Funding acquisition.

7. 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.

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9. Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Open AI ChatGPT 3.5 in order to improve readability and language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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	Location	Building age	Protection	BIPV application	References
Doragno Castle	Rovio, Switzerland	11th century	Listed building	Opaque roof	[49,51,52,55]
Single family house	Bern, Switzerland	1898	Listed building	Opaque roof	[49,52,55]
PalaCinema Lorcano	Lorcano, Switzerland	1850-1899	Protected area	Roof	[49,52,55]
Glaserhaus	Emmental, Switzerland	1765	Listed building	Opaque roof	[49,52,55]
Solar Silo	Basel, Switzerland	1850	Conservation area	Opaque roof and facade	[49,51–55]
La Certosa Island	Venezia, Italy	unknown	Listed building	Opaque roof	[49,51]
Rural building	Seegräben, Switzerland	unknown	None	Opaque roof	[49,51]
House Breuer	Schruns, Austria	1900-1944	None	Opaque roof	[52,55]
St Franziskus Church	Ebmatingen, Switzerland	1989	None	Opaque roof	[52,53,55]
Kindergarten and apartments	Chur, Switzerland	1914	None	Opaque roof	[52,55]
Single-family house	Gstaad, Switzerland	1700-1800	Listed Building	Opaque roof	[52,55]
Villa Castelli	Bellano, Italy	1850-1899	Listed Building	Opaque roof	[49,51,52,55]
Saint Andrew's Cathedral	Sydney, Australia	1817	Listed Building	Skylight	[49,51]
Linares Town Hall	Jaén, Spain	19th century	Listed Building	Skylight	[49,51]
Béjar Market	Salamanca, Spain	Unknown	Listed Building	Skylight	[49,51]
San Antón Market	Madrid, Spain	1879-1882	Conservation area	Skylight	[51,54]
Alzira Town Hall	Valencia, Spain	16-17th century	Listed Building	Skylight	[49,51]
Student housing	Slagelse, Denmark	1970	None	Facade / Balaustrade	[51,54]
Single-family house	Ulestraten, Netherlands	Unknown	None	Opaque roof	[51,54]
Milland Church	Bressanone, Italy	1984-1985	Listed Building	Opaque roof	[50,51]
Farm building	San Genesio, Italy	Unknown	None	Skylight	[50,51]
Office building	Miltenberg, Germany	Unknown	None	Facade	[51]
Energy Tower Aktiv	Wels, Austria	Unknown	None	Facade semi-transparent	[49,51,54]
Weyerguet farm	Köniz, Switzerland	1842	Listed Building	Opaque roof	[49,51]
Farmhouse Galley	Ecuvillens, Switzerland	1859	Listed Building	Opaque roof	[49,51]
Harbourfront Centre Theatre	Toronto, Canada	1926	None	BIPV curtain wall	[51,54]
COOP TH12 Headquarters	Basel, Switzerland	1978	None	Facade	[49,53]
Villa Carlotta	Orselina, Switzerland	1939	Unknown	Opaque roof	[56]
Residential building	Zürich, Switzerland	1982	None	Ventilated facade	[49,53,54]
Wattbuck Tower	Effretikon, Switzerland	1968	None	Ventilated facade-parapet	[49,53]
Historic Building	Montecrestese, Italy	Unknown	Landscape protection	Opaque roof	[49,51]
Single-family house Bianda	Losone, Switzerland	1930	None	Opaque roof	[49,51]
Ütia da Ju	San Martino di Badia, Italy	Unknown	Conservation area	Semi-transparent conopy	[50,51]
Die Mobiliar	Bern, Switzerland	1980s	None	Semi-transparent brise-soleil	[49,53]
Colterenzio Winery	Appiano, Italy	1980s	None	Semi-transparent conopy	[51]
Bell Works Labs	New Jersey, United States	1962	Listed building	Skylight	[60,61]
Ombú Acciona	Madrid, Spain	1905	Listed building	Skylight	[60,62]
Domaine de La Plume	La Penn, France	18th century	None	Opaque roof	[63]
The Predikheren	Mechelen, Belgium	1600-1650	Listed building	Opaque roof	[64]
Essen's old customs	Essen, Belgium	1902	Listed monument	Skylight	[60]
Lakefront Villa	Lavaux, Switzerland	Unknown	Listed building	Opaque roof	[65]

Table 1. All case studies were analyzed along with their main characteristics.

Case study: Weyerguet farm	
	BIPV application: Opaque roof Stakeholders: 3S Swiss Solar Solutions AG (Switzerland) System power: 37 kWp Annual electricity production: 37 600 kWh
Location: Köniz, Switzerland	BIPV area: 261 m^2
Building age: 1842 Typology: Farm House Use: Residential	BIPV Renovation: The installation makes use of the slope of the original roof structure, employing opaque matte glass modules, hidden PV cells and a terracotta colour. This approach ensures that the installation integrates harmoniously with the surrounding buildings. The BIPV system was part of a compressive renovation.
Protection level: Listed Building	References: BIPV meets History / IPV Integrated Photovoltaic (eurac research)
Renovation year: 2016-2020	Other data: 2020 Swiss Solar Prize

Table 2. Weyerguet farm, case study selected to showcase its in-depth analysis. Image of the building's exterior showcasing the BIPV roof, sourced from the IPV Integrated Photovoltaic website [51].

Case study: Alzira Town Hall	
	BIPV application: Skylight Stakeholders: Onyx Solar (Spain) System power: 5.1 kWp Annual electricity production: 7 402 kWh
Location: Valencia, Spain	BIPV area: 112 m^2
Building age: 16-17th century Typology: Town Hall Use: Institutional	BIPV Renovation: The skylight is situated in the inner courtyard and features amorphous silicon modules with a glass-glass configuration and 10% transparency. This design allows natural light to enter the interior while regulating its intensity. The PV cells are hidden, ensuring aesthetic integration with the surrounding complex.
Protection level: Listed Building	References: BIPV meets History / IPV Integrated Photovoltaic (eurac research)
Renovation year: 2011-2015	Other data: Building with the highest level of protection in Spanish territory, as it is a BIC (Bien de Interes Cultural)

Table 3. Alzira Town Hall, second case of study selected to showcase its in-depth analysis. Images of the building's exterior and the BIPV skylight, sourced from the IPV Integrated Photovoltaic website [51].