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A conceptual framework on the integration of solar energy systems in heritage sites and buildings

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Abstract. The integration between solar energy systems and building components is highly critical in sensitive heritage contexts. On the one hand there is the need for finding a balance between the preservation of the aesthetic appearance and the historical values, but on the other hand, finding the space where to effectively integrate the systems might be quite challenging. The solar systems can be divided in photovoltaic (PV) and solar thermal (ST) systems. Building Integrated Photovoltaics (BIPV) and Building Integrated Solar Thermal (BIST) are PV or ST panels integrated into the building envelope, combining the energy generation with other functions, such as noise, weather protection, thermal insulation, sun shadow, and other aspects. Nowadays, the dynamism of the market allows to design highly compatible products which look like traditional architecture materials. This situation fosters the integration of these products in the BIPV and BIST systems within the heritage sites, especially thanks to the use of advanced customisation processes, special and low-reflecting glasses, and innovative cost-competitive coatings. There is a limited number of studies on the application of these technologies in heritage contexts, due to the presence of architectonic, conservative, and cultural barriers. This paper aims to conduct a comprehensive review of the available literature on the integration of renewable energy sources (RES) in heritage sites and buildings, which would foster the preservation of their cultural and natural values as well as reducing primary energy consumption, increasing comfort levels, minimizing environmental impacts, and improving technical quality and economical outlays. A common framework will thus defined to support restorers, historic conservators, and energy experts and to facilitate the diffusion and application of RES in heritage contexts. This conceptual framework will provide industries and academics with operative strategies and will encourage their diffusion and application in sensible contexts.

1. Introduction

Historical buildings constitute a considerable part of the European stock. In numerical terms, more than 40% of the residential houses have been constructed before the 1960s [1] and more than 50% before the 1970s [2]. The constructions built before 1945 and worthy of being preserved represent 30-40% of the whole EU stock [3]. The EU households contribute to 68% of the total final energy use in houses, which is mainly related to heating, cooling, hot water, cooking, and appliances [1]. Existing buildings are the main cause of 30% of solid waste production, of about 35% of the total emission of pollutant emission in atmosphere, and 39% of the global energy consumption [4]. Most of these buildings were built in the past when proper technologies were not yet available. Some of them fell into disuse or have been abandoned. Energy-retrofit interventions aimed at the reuse of such spaces can provide comfort to their occupants [5]. On 30 May 2018, the European Parliament issued the Directive (EU) 2018/844 on the energy performance of buildings, introducing a specific legislative framework to cut carbon dioxide emissions (hereinafter, CO emissions) by 2020, to increase the share of renewable energy sources

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(hereinafter, RES), and to enhance the energy performances of existing buildings [7]. These exalted objectives seem difficult to achieve when renovating heritage buildings, where the energy saving measures are hindered by the restrictions on preservation [5; 6]. Although it is not always possible to comply with the current energy standards, trying to improve as much as possible the energy efficiency of heritage buildings is considered compulsory and essential [5]. RES can play a fundamental role in achieving this goal, allowing a rational use of energy (hereinafter, RUE). In case of major renovations, the EU legislation [7] requires RES to cover 50% of the energy produced for domestic hot water, heating and cooling. This measure is mandatory for existing buildings, contrary to listed buildings in the case that an aesthetic impact or a damage is generated [7]. This situation is very critical in heritage contexts, especially for the protection of their aesthetic appearance and historic values. In general, the installation of traditional photovoltaic (hereinafter, PV) and solar thermal (hereinafter, ST) systems is not recommendable for historic and vernacular buildings, in order to preserve their valuable fronts and roofs [8]. The use of integrated RES could be allowed using highly compatibility products designed to appear similar to traditional architectonic materials thanks to the advanced customisation and to the presence of several colours, patterns, special and low-reflecting glasses, and innovative cost-competitive coating [9; 10]. Building Integrated Photovoltaics (hereinafter, BIPV) and Building Integrated Solar Thermal (hereinafter, BIST) solutions are respectively PV and ST panels integrated into the building envelope, combining electricity generation with weather and noise protection, thermal insulation, and sun shadow [10]. The “integration” implies the substitution of the constructive element: BIPV or BIST elements have to be incorporated into the building as functional or constructive components, replacing the traditional building element (e.g. window, cladding or architectural element). Therefore, the new BIPV or BIST element becomes a functional and constructive element of the building envelope, similarly to a conventional material. The balance of technical and aesthetic aspects becomes a priority in terms of architectural functionalities and construction requirements (e.g. dimensional flexibility, easy mounting, safety and reliability, thermal stability and comfort, fire security, climate protection, maintenance and durability over time, etc.) [11]. These solutions appear appropriate also for heritage contexts due to the technological advances, ensuring low-rate reflection, compact shapes, and mimetic appearance. Despite this, authorization requirement remains valid for historical centres, areas of landscape protection, vernacular and cultural heritage buildings [5; 6]. Their construction involve a high level of commitment of the experts appointed to execute the work, under the careful direction of the institutions responsible for protecting the buildings [5; 6; 12; 13; 14; 15; 16; 17]. Uncontrolled, although minor, alterations to the envelope, windows, facings, or installations may undermine the drive for conservation [12; 13; 15; 16]. However, a careful assessment of the benefits and feasibility of each case, together with the exploitation of the technological innovations currently available on the market, may lead to a number of potential solutions for RES integration in historical contexts [12; 13; 16; 17].

2. Aims and methodology

This paper discusses the integration of RES in heritage sites and buildings, aiming at the establishment of a conceptual framework on the application of RES systems for the retrofit of heritage buildings and sites, preserving their historic, aesthetic and natural values as well as lowering energy bills, increasing comfort, architectural and technical quality, economic and environmental sustainability. The conceptual background has been developed analysing international research projects, academic studies (i.e. scientific papers, conference proceedings, and books), and “grey literature” (i.e. guidelines, technical reports, awards, and internet sites from government, Heritage Authorities and PV and ST companies) focused on the application of solar systems in heritage contexts in Europe and the United States of America. This allows to consider both practical and scientific approaches. The legislative and normative framework has not been considered because, apart from the EU framework, it is strongly connected to local laws, regulations, and policies. Thus, it requires a deep analysis focused only on the comparison among different legislative approaches. The selection of the studies is based on technical keywords (“RES”, “Solar Energy”, “Solar Architecture”, “Building Integrated Photovoltaic”, “BIPV”, “Building Integrated Solar Thermal”, “BIST”) combined with heritage keywords (“Historical building”, “Historic Building”, “Heritage”, “Protected building”, “Landscape”, “Heritage site”, “Sensible context”, and “Energy retrofit”). Common searching engineering (i.e. google) have been used to identify research

projects, awards, guidelines, and “grey literature”. Then, academic studies have been selected in academic databases (i.e. Scopus, Sciencedirect, google scholar) and conference proceedings. Finally, the references of the scientific literature have been considered.

3. Framework on RES application in heritage contexts

The study presents the most important research projects, awards and prizes which reward historical buildings RES. Furthermore, the analysis gives a brief outlook of the main guidelines which advise on heritage renovation, preservation and sustainability. The main contribution constitutes in a conceptual framework which offers a comprehensive view on the development of the integration of the solar energy systems in historic buildings and sites. The selection of these three tools (research projects; awards and prizes; guidelines and policies) is based on the most prominent aspect related to RES integration emerged from the literature review.

3.1. Research projects

RES integration in heritage contexts is deeply examined within international, EU and local research projects (Table 1). The most popular strategy in cultural heritage is the integration of BIPV systems into building components, despite the above-mentioned architectural barriers [14; 17]. Initially, researches focused on the acceptability of PV and BIPV technologies in heritage context [9]. Few years later, a solid knowledge base was developed on BIPV and BIST solutions in building renovation, especially to demonstrate their advantages, e.g. technical competitiveness, economic savings, and building protection [14; 15; 18], or to achieve high-quality standards of solar architecture [20; 21; 24]. In several cases, an *ad hoc* design of BIPV and BIST systems was encouraged to preserve original shapes, features, and values [9; 13; 16; 18; 29; 21; 27]. The introduction of active collaboration with local and heritage administrations was a fundamental step for researchers to find unexplored solutions based on local legislations and policies (i.e. localisation on alternative structures close to heritage sites) [9; 12; 22; 27; 30]. Geographical Information Systems (hereinafter, GIS) has been used to calculate the solar potential, to interpret spatial data patterns, and to combine several spatial datasets [13; 30]. Several studies focus only on the RES integration in historic buildings [21; 22; 27; 29], towns [26; 29; 30], and landscapes [29; 30; 31]. Lately, the projects pay attention to the reduction of their impact on the electricity grid [28; 30]. Finally, outdoor test-beds and living labs have been created to investigate the application of innovative products in buildings and landscapes [28; 31].

Table 1. Research projects on RES integration in historical buildings and sites (non-exhaustive list).

Acronym	Program	Years	RES aims	Type	Focus
PV Accept [9]	FP5	2001-2004	To develop marketable modules with an innovative design for historical buildings and sites; To study the PV acceptability	PV BIPV	Historical buildings and sites
IEA-SHC T37 [14]	IEA	2006-2010	To develop a solid knowledge base on the advanced housing renovation with RES, comfort and conservation	BIPV BIST	Examples of historic Buildings
New4Old [15]	IEE	2007-2010	To promote the integration of RES & RUE measures in historical buildings	BIPV BIST	Historical buildings
Sechurba [18]	IEE	2008-2011	To demonstrate the advantages of technical competitiveness, economic savings and protection through the application of integrated RES and energy distribution systems	BIPV BIST	Historic buildings and sites

IEA-SHC T41 [20]	IEA	2009-2012	To achieve high quality architecture for RES integration in buildings	BIPV BIST	Buildings Products
3encult [12]	FP7	2010-2014	To install less visually intrusive commercial products, with the commitment of heritage authorities	PV BIPV	Roofs
Enbau [21]	Local (CH)	2010-2012	To promote energy retrofitting of historic buildings with RES systems	BIPV	Historic buildings
SuRHiB [22]	Local (CH)	2011	To develop technical and architectural guidelines for RES integration	BIPV	Historical buildings
UrbanSol+ [23]	IEE	2011-2014	To apply ST in major renovations and protected urban areas	ST	Buildings Towns
IEA-SHC T47 [24]	IEA	2011-2014	To develop a solid knowledge base on renovation of non-residential buildings towards the NZEB standards	BIPV BIST	Examples of historic buildings
Effesus [13]	FP7	2012-2016	To assess the solar potential in historic towns, preserving their values	BIPV	Roofs
IEA-SHC T51 [25]	IEA	2013-2017	To support urban planners, authorities and architects to achieve architectural integration of RES in urban areas	BIPV	Towns Landscapes
CarSOL [26]	Local (CH)	2016-2019	To promote solar technologies at urban level in a pilot project for municipalities to produce RES and preserve heritage sites	BIPV BIST	Historic buildings and sites
IEA-PVPS T15 [10]	IEA	2016-2022	To enable a framework for the acceleration of BIPV	BIPV	Buildings Products
Rehib [27]	Tecnio spring plus	2017-2019	To improve the application of RES in historical buildings	BIPV BIST	Building
Solarise [28]	Interreg 2 Seas Mers Zeeén	2018-2021	To adopt RES in historical and public buildings, with a focus on low-income families; To develop living labs; To reduce RES impact on the electricity grid	BIPV BIST	Roofs Façades Balconies Sunshades
IEA-SHC T59 [16]	IEA	2017-2021	To identify and to assess several RES compatible with historic buildings	BIPV BIST	Historic buildings
BIPV meets history [29]	Interreg IT-CH	2019-2021	To create a value chain for BIPV in historical buildings and landscapes; To develop a platform with building examples, products, guidelines	BIPV	Buildings Towns Landscapes

Pearls [30]	H2020 MCSA (RISE)	2018- 2022	To enhance skills related to RES spatial planning, analysis and decision-making methods in landscapes; To understand the legal frameworks and practice in the implementation of RES in landscapes	BIPV BIST	Towns Landscapes
BIPV UPpeal [31]	Local (IT)	2019- 2020	To set up an outdoor test-beds to verify the application of BIPV in landscapes	BIPV	Roofs Landscapes

3.2. Awards and prizes

Several prizes on RES integration in heritage contexts have been established in the last decade. They reward historical buildings or settlements to effectively meet the challenge for innovation using solar systems, considering architectural and planning rules. Prizes include innovative and creative solutions for BIPV and BIST that must combine aesthetic aspects and energy performances (Table 2).

Table 2. Awards and prizes on RES integration in historical buildings and sites.

Name	Country	Year	Organizer	Main topic	RES
European Solar Prize	EU	From 1994	Eurosolar	Solar architecture and urban planning	BIPV BIST
Swiss Solar Prize	Switzerland	From 1990	Patronat des Bundesamte	Solar architecture	BIPV BIST
Norman Foster Solar Award	Switzerland	From 2010	s für Energie & Solar Agentur	PlusEnergy Buildings	BIPV BIST
Horizon Prize	EU	2016-2018	H2020	BIPV in EU protected historic urban districts	BIPV

3.3. Guidelines and policies

Several countries define national guidelines that include RES installation in sensitive buildings and landscapes (Table 3). The American NREL gathers best practices of solar guidelines and policies of different US municipalities, giving some clear and practical guidelines to ensure RES successful installation, balancing energy efficiency and preservation [33]. Scottish guidelines propose a comprehensive approach on micro-RES, considering PV, ST, wind, biomass, etc. [32; 34], while taking into account conservation, energy, costs, and maintenance aspects. The Italian guideline on energy efficiency in historic buildings [37] provides operative indications for evaluation and improvement of the energy performance in listed buildings, with reference to the national regulations. It mainly provides designers with a tool to assess the energy performance of historic buildings on the basis of the national regulations, and personnel working at the Ministry with a useful tool to communicate with technicians. This document also focuses on the need of common and agreed criteria to evaluate and authorize the energy improvement of historic buildings. Some general principles are currently commonly shared, such as the maximum conservative attitude and the integration of RES where historic matter and materials are irremediably damaged or lost. On the other side, difficult to assess is the architectural quality of an intervention that depends also on non-objective criteria, based on personal sensibility or the level of product innovation, as some projects shown several years ago [9]. Quality evaluation, at least in Italy, remains an open question. In Switzerland non-compulsory but indicative reference documents are active at national and federal scale [39] or local level (cantonal/regional) [40]. These documents are directed to specialists in the field of design, architecture, physics of construction and energy consulting as well as to the services of Public Authorities involved in the preservation of monuments, energy issues and release of building permits. The handbook of SolarKultur [41] illustrates how municipalities can

reconcile the use of RES with heritage culture, highlighting the importance of planning larger territorial units to achieve good solutions. The document is based on the global solar planning of the city of Carouge [26], a Swiss ISOS site of national heritage significance in the Canton of Geneva, which aims at reconciling the protection of the building stock with the RES installation (mainly PV and ST). In addition to that, several Swiss Cantons published guidelines to evaluate the RES installation (i.e. in Ticino RES installation on roof is possible when are coplanar, protrude < 0.2m, compact and rectangular, have appropriate colour and no visible connections or pipes) [40]. Overall, these guidelines suggest to insert the solar panels on: sites of a historic resource, new constructions, non-historic buildings, additions, areas that minimise their visibility from a public thoroughfare or a natural site [32; 33; 34; 35; 37]. The solar panels installation must not create permanent loss of heritage features, obstruct views of significant architectural or decorative characters, permanently transform the historic fabric, or create disjointed and multi-roof solutions [33; 34; 35; 36; 37; 39; 40; 41]. Furthermore, to reduce their appearance is necessary: (i) to have solutions and low aesthetical profiles [33; 34; 37; 40; 41]; (ii) to preserve the distinctive materials, features, finishes, construction techniques, or examples of original craftsmanship [33; 34; 37; 39; 40; 41]; (iii) to ensure the integrity of the historic property and its environment [33; 34; 37; 40]; and (iv) to guarantee the chemical or the physical compatibility with old fabrics [33]. Finally, historic features with severe deterioration can be replaced with new features that match the old in design, colour, texture, and materials while missing features can be substantiated by documentary and physical evidence [33; 37; 39; 40; 41].

Table 3. Guidelines on RES integration in historical buildings and sites.

Name	Country	Year	Recommendations	RES
Changeworks [32]	Scotland	2009	Guide to facilitate the reduction of fossil fuel in historical/historic homes with RES	PV/ST
NREL [33]	USA	2011	Criteria that balance historic preservation and energy production	BIPV BIST
BDA [34]	Austria	2011	Definition of a scale of compatibility of different RES technologies	PV/ST
HES [35]	Scotland	2013	Discussion on the use of micro-RES, with examples and considerations	BIPV BIST
Solarenergie [36]	Switzerland	2014	Production of handbooks with technical solutions to reduce energy consumption, even in historic buildings	BIPV BIST
MiBACT [37]	Italy	2015	Definition of best practices on PV integration in historic buildings	PV BIPV
DFI [39]	Switzerland	2016	RES installation should be clarify with competent authorities	BIPV BIST
Cantonal guideline [40]	Switzerland	2018	Definition of specific rules for the aesthetical and technical integration of RES	PV/ST BIPV BIST
FOC [41]	Switzerland	2019	Illustrations for reconciling PV and quality of constructions	BIPV

4. Discussion and conclusions

This study shows that solar technologies have high barriers from the conservative point of view, but there are significant market innovations and long-term benefits. The BIPV products are very mature to allow a good integration with heritage buildings and landscapes. As previously shown in Table 1, several research projects have been approaching this topic since a long time. At national, regional and local level, authorities and legal framework already contemplates the delicate issue related to the integration of RES systems in heritage sites and buildings. Nonetheless, a small number of examples are well-known and only few of them are shown as exemplary case studies, recognised mainly at international

level (IEA tasks). Solar prizes, instead, intend to reward historical buildings or towns using RES technologies and considering architectural, planning, and technical constraints. These prizes aim to recognise private and public investment and to encourage them to replicate similar solutions. The EU Horizon prize dedicated only to the integration of new PV systems in protected historic urban districts, also generating and supplying electricity for the district consumption is of a particular interest. It aspires also to foster the development of the best suitable architectural and aesthetic design in combination with optimal technical solutions, low visible impact, and minimal intrusion into the buildings structure. Unfortunately, only five applications have been submitted but, nevertheless, none was found to be eligible according to the “rules of contest”. However, national and local guidelines define clear criteria and rules for RES integration, trying to balance preservation and energy efficiency requirements. These guidelines suggest three different criteria [6]: (i) “localising criteria”, related to project siting and location; (ii) “qualitative criteria”, mainly referring to the minimal intervention on materials, features, spaces, and spatial relationships and to the mitigation of the visual impact, with the correct selection of colours, texture, anchoring, arrangement and alignment; and (iii) “quantitative criteria”, driven by system performance (dependent on weather, type of technology, site characteristics, impact of shade, and orientation, tilt angle, surface extension) and economics (related to initial, operating and maintenance costs, availability of incentives, discount and fuel escalation rate). These criteria show different approaches to maintain the balance of preservation, usage of energy sources, and economic and energy cost in different levels. Although national and local guidelines clearly define criteria and rules for RES integration, it looks like that there are not enough examples of perfect BIPV systems in historic urban areas.

To conclude, energy transition needs clear policies and systems regulations, updated guidelines, simple rules, professional trainings and widespread dissemination. Dissemination of pilot projects and interventions, in which the concept of integration is not a simple juxtaposition of solar panels on an existing surface, is fundamental. On the building level, it is necessary to work on projects where the word ‘integration’ involves a more deeply relationship between old and new solutions at the level of detail, recalling the Brandi’s idea on pictorial restoration and integration of the so called ‘lacunae’ (the lacking part of frescos decoration on walls or vaults: how do we “restore” missing parts? Should we paint what we think the original drawing or could we interpret in a more contemporary way?). By demonstrating that a technological element can become an integral part of a conservative project (unless it is the cause of an unnecessary demolition), it will be possible to eliminate some taboos or, at least, to open some paths in that direction. On the territorial level, several EU countries (e.g. Switzerland, Sweden, Germany, Austria, and Denmark) developed a new approach to solar planning which show that it is possible to achieve optimal use of solar energy, preserving the heritage and architectural quality of a site. Conversely, in Italy, a lively debate took place after that some medium-sized installations in prestigious territories were implemented, favoured by the State economic incentives. This led to consider this technology as one of the least appropriate for architectural and landscape protection. The ability to insert new technological devices in such a way that respect both the aesthetical appearance and the physical matter of the historic building, will contribute to opening up the world of architectural restoration to research and innovation. In the near future, synthetic organic photovoltaic films on large glazed surfaces as well as graphene sheets and materials of new generation will be able to create smart cities, capable also of preserving the inheritance from past generations. Clearly, this topic is still under discussion, but the first steps in the right direction have been taken and hopefully this challenge will be met in next years, thanks to innovative, excellent and high-quality products under development in the solar industry market. This study provides an inspiring view on the need for environmental, economic and cultural sustainability in the field of heritage renovation and preservation, and addresses the importance of being aware of eco-friendly techniques and policies in heritage preservation.

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