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# Risk-Benefit Assessment Scheme for Renewable Solar Solutions in Traditional and Historic Buildings

**Cristina S. Polo López [1,*], Elena Lucchi [2,*], Eleonora Leonardi [2], Antonello Durante [2], Anne Schmidt [3] and Roger Curtis [3]**

[1] Department for Environment Construction and Design (DACD), Institute for Applied Sustainability to the Built Environment (ISAAC), University of Applied Sciences and Arts of Southern Switzerland (SUPSI), Via Francesco Catenazzi 23, CH-6850 Mendrisio, Switzerland
[2] Eurac Research, Institute for Renewable Energy, 39100 Bolzano, Italy; eleonora.leonardi@eurac.edu (E.L.); antonello.durante@eurac.edu (A.D.)
[3] Historic Environment Scotland, Longmore House, Salisbury Place, Edinburgh EH9 1SH, UK; anne.schmidt@hes.scot (A.S.); roger.curtis@hes.scot (R.C.)
* Correspondence: cristina.polo@supsi.ch (C.S.P.L.); elena.lucchi@eurac.edu (E.L.)

**Abstract:** Within the framework of IEA-SHC Task 59, a multidisciplinary team of experts from around the world has come together to investigate current approaches for energy retrofit of the built heritage with energy efficiency conservation-compatible measures, in accordance with cultural and heritage values, and to check and adapt the new standard EN-16883:2017 for historic buildings. This paper introduces activities within IEA-SHC Task 59 (Subtask C) focused on retrofit solutions with high impact on sustainability, energy efficiency, and the integration of renewables, which is the main goal of the solar group, focused on the integrated solar systems for historic buildings. Relying on an extensive, detailed, and accurate collection of case studies of application of solar photovoltaic and thermal systems in historic buildings, the assessment criteria of the standard have been reviewed and tailored for better solar implementation evaluation in a heritage context. All this is studied based on technical compatibility, the heritage significance of the building and its settings, the economic viability, the energy performances and indoor environmental quality and use, as well as the impact on the outdoor environment of solar renewables.

**Keywords:** heritage buildings; heritage; renewable energy sources; solar systems; historic buildings; photovoltaic systems PV; building-integrated photovoltaic BIPV; building applied photovoltaic BAPV; solar thermal systems ST; building-integrated solar thermal BIST

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## 1. Introduction

It is a proven fact that half of the energy consumed in Europe is invested in the operation of buildings, which accounts for 40% of total energy consumption, and that around 75% of them are energy inefficient [1]. The emissions have a lasting and negative impact on the environment. Unfortunately, the low renovation rate registered in recent years of about 1% of buildings each year suggests that it will take a long time to upgrade the building stock to modern standards of near-zero energy [1]. Next to this, it is worthwhile to note that a large volume of non-recoverable fossil fuels, which future generations will lack, is wasted in the heating and air conditioning of existing and historical buildings without achieving the desired levels of energy efficiency and comfort. Heating of space and water consequently represents 78.9% of the final energy consumed by households [2].

While buildings are usually regularly maintained or upgraded, works to improve energy efficiency have so far suffered from underinvestment and numerous obstacles. Especially for historic buildings, investors and individual owners will face a competition for scarce capital, lack of reliable information, lack of skilled workers, or doubts about possible benefits. The amendment of the Energy Performance of Buildings Directive together with the provisions of the Renovation Wave strategy within the EU Green Deal [3–5] will accelerate building renovation rates by reinforcing provisions on long-term building renovation strategies. The motion of the new cultural interdisciplinary movement New European Bauhaus, "beautiful, sustainable, together" [6], wants to include a holistic approach, which makes the European Union the leader of the circular economy [7,8]. The rehabilitation and renovation of buildings must be not only an environmental or economic project but also part of a cultural project, a mixture of mainstream, trends, and opportunities to be exploited in the coming years by all stakeholders. The architectural intervention necessary in heritage buildings to reduce energy and resource costs of the building process, which are especially high in this sector, should encourage reflection on the sustainability of contemporary living.

Improved quality of life, health, and well-being for residents are currently the aim of EU initiatives associated the NextGenerationEU program [9]. A public debate around the subject of building health and durability resulting from changes in construction has been generated [10]. However, there is little evidence that the industry, policy makers, or the public are well informed on such matters. Certainly, there is a need to address this issue, especially within the context of remedial works undertaken to improve energy efficiency, new forms of construction, furnishing, etc. To reach a safe and healthy built environment, appropriate information on the relationship between energy efficiency and indoor air quality in traditional and new build homes is vital [10]. Embodied energy—the energy costs associated with our choices of materials used in upgrade work—should also be considered in this process. However, we cannot assure that the new materials used will be as durable and long lasting as the element replaced [11]. Similarly, the impact of material choice on the internal environment in traditional buildings should be further investigated [12]. Many of the construction materials currently used in refurbishment projects act as a barrier to moisture flow. If damp accumulates, it can cause health problems and can further result in a deterioration of building fabrics. In addition, construction materials now contain more potentially dangerous chemicals, and overheating spaces could concentrate unhealthy pollutants [12]. For this reason, Historic Environment Scotland has been studying indoor environmental quality in refurbishment for years [10–12]. However, what will be the proper balance with factors such as ventilation and health in the future? Reduced air exchange rates and increased time spent indoors in buildings poses a threat to health, especially nowadays after Covid-19 spread all over the world. This is an aspect that is already being taken into account for new housing models [13]. The ventilation rates specified in current codes and standards will need to be revised in the future. It is clear that a balance needs to be found between reducing carbon emissions and measures related to building renovation and occupant health.

Moreover, real conditions of habitability, comfort, and health must be the verified directly from users' statements. As some authors stated, it is essential to deepen our knowledge of the physiology of human beings, as the end user of the architectural fact, recipients of the creative and constructive effort of the environment in which man's life unfolds: the habitat in its broadest sense [14]. It was proven that in traditional houses, sometimes it is better to consider adaptive comfort solutions that consider the psychological and physiological predisposition of the occupants, as comfort is influenced by cognitive and behavioural processes [11,15]. Passive conditioning strategies with optimum bioclimatic design will make more energy-efficient and comfortable living spaces possible. Thermal environment and air quality could be covered with a minimum energy supply. Although this cannot reduce energy consumption to the levels expected of newly built houses with modern standards of insulation and energy labels, adaptive measures and passive strategies can be used together with other technical energy upgrade measures but a minor final environmental impact [11,13].

Efficient lighting and appliances, domestic hot water management, and occupant guidance on using the building are effective ways to improve energy efficiency in traditional and historic buildings. However, a sustainable future includes a progressive change towards renewable energies with a view to decarbonising the building stock by mid-century based on a fusion between energy efficient architecture and renewable infrastructures.

Historic buildings are the unique evidence of a precious cultural past that in many cases needs urgent measures to achieve current standards of energy efficiency and comfort. Witnesses of time, historical monuments with their materials and their appearance make history visible in everyday life and are a cultural asset that creates identity in our cities or in small villages. In fact, most of the historic buildings are sustainable because the long duration of use over the centuries has safeguarded the resources and continues to do so today. By continuing to last into the future, they are saving more resources compared to new construction projects. They are an important resource to be revalued in order to avoid abandonment, but will only survive if adapted to today's standard of living conditions. Even for historic monuments, redevelopment can result in significant improvements in energy efficiency. However, as these are always unique cases, it is essential to consider them in detail and to adopt specific measures on the basis of a holistic concept. Hence, the intrinsic advantage of recognizing the value of the existing building substance, adapting it to the new use and redeveloping it in terms of energy.

However, this redevelopment is unlikely to be enough to reach net zero energy use. This means, that in order to save this heritage for future generations, we need to find conservation compatible energy retrofit approaches and solutions, which allow the preservation of the historic and aesthetic values while increasing comfort, lowering energy bills, and minimizing environmental impact. This principle has guided the development of the "Guidelines for the improvement of the energy performance of historic buildings" (EN-16883:2007) [16] but it is still a long process of implementation and adaptation that experts from all over the world are working on in the joint work of the International Energy Agency IEA-SHC Task 59/IEA-EBC Annex 76 [17].

Furthermore, their reuse or revitalization must be done to preserve them for future generations in the best way possible to facilitate their conservation [18,19]. The main goal of energy retrofit interventions is to decrease the long-term deterioration of a building's fabric by reducing higher energy efficiency targets. This in turn supports the significance of the building, but to achieve this it is necessary to have enough information to understand the impact of the proposed renovation strategies, especially for solar renewable energy integration. Choosing the appropriate intervention for a historic building or protected landscape is critical. Different solar solutions could be appropriate when deciding on the distinct approaches to the treatment of historic properties—preservation, rehabilitation, restoration, and reconstruction—depending also on the historical character and protection level [20,21]. On the other hand, the compatibility with the heritage value should be assessed on a case-by-case basis, which was certainly considered for the collection and appraisal of solutions in a step-by-step process. It would be necessary to carefully ponder the risks and benefits of possible technical energy improvement solutions (single solution or a combination of retrofit scenarios) with a compromise between the costs and benefits, as well as the impacts on the heritage significance of the building.

Renewable Energy Sources (RES) implementation in existing and historic buildings can contribute significantly to the reduction of energy requirements for thermal conditioning and electrical needs [22]. The use of renewable solar energy systems in existing buildings is strongly supported now by the legislative European (EU) framework, which introduced specific targets to increase the share of RES, to cut carbon dioxide emissions ($CO_2$ emissions), and to enhance the energy performances of existing buildings [23]. RES contributions play an important role for achieving these goals in energy renovations of existing buildings, as the legislation requires covering 50% of energy produced for domestic hot water, heating, and cooling by RES [23]. Their implementation in historic buildings, referring both to listed and unlisted buildings with significant elements worthy of preservation and symbol of exceptional cultural significance, has several constrains, mainly related to the aesthetic impact [24–26]. In recent or past years, it has been a topic of controversy and interest [1,27–30]. This could be an optimal solution if combined with a high-efficiency heat pump for heat production system with intelligent building management based on building management (BMS) system to best contribute in achieving the RES quota required by EU directives [23,31]. In parallel, the application of RES in architecturally sensitive areas and buildings is studied by several international and national research projects [29,30,32–44], demonstrating their technical and economic advantages as well as the compatibility with heritage shapes, features, and values [24]. Several studies demonstrate the feasibility of RES and solar systems integration in historic buildings, documenting their integration in real case studies [25,45,46], which represent an opportunity to gain an overall understanding of solar technologies and heritage preservation procedures and priorities and point out the opportunities and constrains [24–26,47].

Other studies stressed the need for adequate criteria for better implementation in the historic city centres, where on-site investigation and the study of compatible and suitable technologies are the basis of a larger-scale process of energy efficiency and on-site power generation provided by renewable solar energies [32,48]. A comprehensive analysis that encompasses history (e.g., architectural, historic, and aesthetics values), heritage constraints and urban policies, with the assessment of solar potentials based on available technological solutions, enables the verification of the feasibility and convenience of photovoltaic (PV) and solar thermal (ST) systems in historic contexts [49]. The work showed that the integration of PV systems in historic centres is feasible, requiring a multidisciplinary process that ensures the compatibility, the reversibility, and the integration of the intervention. The concept of historic buildings considered in the EN-16883:2007 standard [16] under review refers to traditional architecture of heritage buildings and ensembles beyond the level of protection. Nevertheless, addressing the statement of Venice Chart (article 7) [50], a monument is inseparable from the history to which it bears witness and from the setting in which it occurs as part of its cultural significance (Burra Charter 1979 and subsequent revisions) [51]. Cultural significance intended as the values worthy to be preserved by means of aesthetic, scientific, historic, social, or spiritual value for past, present, or future generations and embodied in the place itself [51]. The aim is to safeguard them as historical evidence, and their preservation and conservation are always helped by them having a socially useful purpose. Several studies reflect on the concepts "conservation, restoration, renovation, replacement, adaptation or reuse" [52–54]. It must be emphasized that these measures are interconnected, and based on the circumstances, they may be carried out one after the other or simultaneously [50]. In the case of historic buildings, previous extensive alterations may justify the renovation work and compatibility with the residual fabric is the only point that must be heeded. Replacements of missing parts must integrate harmoniously with the whole, but at the same time must be distinguishable from the original and in some cases, modifications demanded by a change of function and use should be envisaged and may be permitted (Venice Chart, article 12) [50]. Next to this, reversibility is a concept linked to the changes of the cultural significance of a monument [51]. However, decisions for reversible or irreversible measures naturally presuppose thorough preliminary investigations, as well as building research on materials and technologies and subsequently monitoring of results [51,55]. Following the principles of the Charter of Krakow 2000 [55], there is a great diversity in heritage concepts as entailed by a plural society and representing different moments in history and social-cultural contexts. Therefore, the tools and methods developed for appropriate preservation should be adapted to the evolving situations, which are subject to a process of continual change. Conservation of cultural heritage should be an integral part of the planning and management processes of a community, as it can contribute to the sustainable, qualitative, economic, and social developments of that society. On the other hand, the development of a highly dynamic landscape involves social, cultural, and aesthetic values. The sustainable development of regions and localities and the natural environment require establishment of links with the built and urban environment, as landscapes are historically related to urban territories and influences, and characterized by local architecture [55,56]. Because of this, it is important to consider the transformability when planning solar systems and PV integration in minor centres or historical contexts, as well as the visual and aesthetic that could modify the distinguishing character of the historic features and cultural landscapes mentioned previously [25,26,33,57]. Despite the heritage constrains, a large portion of the potential for PV integration in historical buildings remains unused due to the presence of several factors, such as economic reasons, lack of knowledge among decision makers and architects, general reluctance to "new" technologies, and architectural/aesthetic aspects. Furthermore, boundary conditions include architectural, typological, and construction characteristics, both at urban and building level, along with the economic and legislative framework [58].

Defining clear criteria to weight up advantages of energy retrofitting using solar systems or other combined strategies in terms of energy savings, comfort improvement, environmental benefits are mandatory in order to check the final energy balance "*post-operam*" and benefits obtained, compared to the initial situation [59]. That is only possible when considering the impact on the heritage building (i.e., compatibility with and respect for historical features, reversibility and the management, maintenance and conservation aspects of the historical asset) at the same time [59]. The building integration must involve a strict relationship between old and innovative solutions, referring to the theories of aesthetic or architectural restoration and integration of the lacunae [25,26]. The reduction of energy consumption by lowering energy loads lead to a minor need for highly efficient systems, which would allow the use of, for example, less efficient solar solutions for the best aesthetical architectural integration. Using new, multifunctional building integrated solar solutions, coloured, textured, or with specific patterns, could determine favourable conditions to moderate and soften the opposition of cultural heritage preservation bodies. Aesthetical and technical aspects are equally weighted, but a positive perception of building integrated photovoltaic (BIPV) or building integrated solar thermal (BIST) elements is essential for the acceptance of the external appearance of a building [60–62]. Current developments of the solar manufacturing industry focus on lower visual impact of solar modules, which would allow a better integration and enhancement of the historical building stock. The experimental characterization of coloured BIPV technologies in architecturally sensitive areas demonstrated that their application requires a specific design for modules and mounting systems [49].

The high level of customization constitutes a strength for their acceptability as well as a limit for cost reduction, test standardization, and performance documentations. Testbeds are also important to show the aesthetic appearance and the technical possibilities of BIPV systems in heritage contexts to the stakeholders [24]. Furthermore, to support the process for better implementation, short guidelines and guidance material encompass and discuss the use of renewables in the historic environment and highlight questions and considerations when the installations of such systems are being contemplated [63–66]. Planning procedures and a series of practical solutions for improving energy efficiency with solar renewable systems in traditional and historic buildings, with a collection of measures and tips, and addressed to architects, technicians, and engineers, are available in almost every country. Specific documents (brochures, user manuals) can be produced at a regional level, to guide municipalities and local authorities for a wider diffusion of solar systems [67,68]. These documents also provide useful information to owners, trade associations, and other interest groups regarding RES solar systems' implementation. For solar energy production, these documents usually define and specify the possibilities and strategies, to be weighted case by case, for the need to safeguard natural resources and protect monumental heritage. Although in many cases, the commissions for historic monuments and offices responsible for the conservation of cultural monuments and natural landscape consider identifying possible nearby places without affecting their historical aspect (e.g., on secondary buildings, retaining walls, slopes, industrial or craft buildings nearby) preferable, political strategies and measures are increasingly pushing for a major implementation of renewables in historic buildings.

## 2. Materials and Methods

This paper was written within the framework of the IEA-SHC Task 59/IEA-EBC Annex 76 activities, which has the ambitious target of renovating historic buildings towards zero energy [17]. Subtask C aims to find retrofit solutions on windows, walls, building services, solar systems, and general strategies compatible with the historic structures and this is, up to a point, independent of the particularities of the individual case [69–71]. IEA-SHC Task 59 is a collaborative research project that benefits from a large international network of researchers and practitioners working in the field of sustainability, energy, and heritage. Experts investigate to what extent the standard EN-16883:2017 [16] can be improved in order to better meet the needs of the stakeholders during the planning process of energy retrofitting of historic buildings (not necessarily protected). The standard EN 16883:2017 aims to facilitate the sustainable management of these buildings by integrating measures for energy performance improvements and reduction of greenhouse gas emissions with the adequate conservation of the buildings. It provides a flowchart of a suggested decision process, and brief information about how the different steps can be carried out. However, there is still a long process of implementation and adaptation. This research introduces the activities of the Working Group on "Solar Energies" focused on the integration of renewable solar systems into historic buildings. The paper aims to define a scheme for assessing risks and benefits related to the installation of solar energy systems in historic buildings and conservation areas, starting from the standard EN-16883:2017 [16]. The research is structured in the following parts: (i) definition of the risk–benefit assessment scheme for the integration of solar energy solutions in historic buildings (Section 3); (ii) quick assessment scheme of nineteen selected EU case studies (Section 4); (iii) detailed assessment scheme of three case studies (Section 5); (iv) discussion and conclusion about the weaknesses and the strengths of the procedure (Section 6).

As previously introduced, the assessment criteria of the standard EN-16883:2017 [16] have been reviewed and tailored to better suit solar implementation evaluation in heritage contexts by experts in technical and conservation fields. Experts in heritage, solar PV, and environmental technologies from Heritage Environmental Scotland, the Swiss BIPV Competence Centre and EURAC Research were involved. Relying on an accurate collection of case studies with solar PV and ST systems in historic buildings, the assessment scheme has been checked and validated to verify their correspondence to the adapted new criteria proposed. In the case studies investigated (all historic buildings listed, not protected, or placed in conservation areas or city centres), different solar renewable solutions (e.g., PV, ST, and solar hybrid photovoltaic-thermal) were implemented. According to the standard [16], to verify the applicability of the criteria, two different levels of assessment have been defined. First, nineteen solutions for solar systems applied or applicable to historic buildings are analysed by the quick assessment. The solutions include systems attached to the roof or façade, as well as integrated in the roof or façade. Furthermore, free-standing systems and systems integrated into the landscape are assessed, as well as models of local sharing or sharing via a network. This analysis highlights the main trends, strengths, and weaknesses of the solar solutions effectively implemented in historic buildings. In a second step, a more accurate detailed assessment of a selection of three case studies has been completed. These case studies have been selected from technological and conservation points of view to include a wide range of different geographical areas, heritage constrains, legislations, architectonic styles, building functions, solar technologies, intervention on roofs or façades, and so on. This analysis allows an in-depth evaluation of the aspects that were highlighted in the quick assessment as critical points, to show the weaknesses and the strengths of the application of the standard procedure [16]. It also permits the verification of the ease of interpretation, the future exploitability, the usefulness, and the convenience of use of the new tailored criteria to solar technologies. Finally, a discussion about these aspects has been introduced.

## 3. Risk-Benefit Assessment Scheme for Solar Energy Solutions

The European standard EN-16883:2017 [16] is a guideline for improving the energy efficiency of historic buildings, to find a sustainable balance between conservation, energy performance, and human comfort considerations. The standard provides a systematic procedure to facilitate the best decision in each individual case. The general intention is to achieve the best possible energy performance while retaining the heritage significance of the building. This procedure is based on a tabular risk–benefit scheme that does not prescribe specific measures or solutions but permits the identification of the needs for energy performance improvements for a historic building. A list of criteria serves to assess and to select the most suitable measures to facilitate the sustainable management of historic buildings. The standard describes the methodological approach, based on the assessment of specific aspects, such as: (1) technical compatibility; (2) heritage significance of the building and its settings; (3) economic viability; (4) energy performances; (5) indoor environmental quality; (6) impact on the outdoor environment, and (7) aspect of use. This scheme can be applied both to the evaluation of a building element or to the whole building. Specific risks or benefits for each assessment criteria are not proposed as the standards refer to general energy efficiency measures, and not to specific solutions. A five-level assessment scale is proposed to allow an overall evaluation of the measure, dividing in high and low risks, neutral, high, and low benefits (Figure 1). The assessment scale should be defined by the interdisciplinary dialogue between the experts involved in the planning process to allow a transparent assessment and to identify the most appropriate interventions for the building.

| | | | | |
|---|---|---|---|---|
| High risk | Low risk | Neutral | Low Benefit | High Benefit |

**Figure 1.** Five-levels assessment scale proposed by the standard EN-16883:2017 [16].

The assessment criteria of the standard have been tailored in the present research, to evaluate the implementation of solar energy solutions in historic buildings. The same assessment categories proposed by the standard [16], as generic procedure, have been considered. The assessment criteria has been adapted specifically with regard to the solar systems integration in historic buildings, defining a specific list of risks and benefits to be evaluated for each criterion. The new risk–benefit scheme is reported below (Table 1).

**Table 1.** Risk–benefit assessment scheme for solar solution in historic building: assessment categories and criteria proposed by the standard EN-16883:2017 [16] and its adaptation for solar energy solutions, work done within IEA-SHC Task59 [17].

| Assessment Category | Assessment Criteria Proposed by the Standard [16] | Assessment Criteria Developed in the Task 59 [17] for the Application of [16] to Solar Energy Implementation | |
|---|---|---|---|
| | | Assessment Criteria | Specific Risk–Benefits to Be Evaluated |
| Technical compatibility | Hygrothermal risk | Hygrothermal risk | Moisture accumulation on the backside of the panels |
| | Structural risk | Structural risk | Structural requirements of the lead support structure<br>Mechanical resistance<br>Resistance to climatic loads of panels, fixing and support systems<br>Structural risks connected to moisture accumulation in vulnerable elements |
| | Reversibility | Reversibility | Reversibility of hard materials for bonding<br>Reversibility of mechanical fixings |
| | Corrosion risks | | Not applicable |
| | Salt reaction risks | | Not applicable |
| | Biological risks | | Not applicable |
| | - | Waterproof | Rain and hail protection function of the panels |
| | - | Reduction efficiency risk | Influence of the external environment on energy generation efficiency)<br>Mismatch effects in solar panels and arrays<br>Influence of installation on energy generation efficiency |
| | - | Fire safety | Fire protection level of the system<br>Extinguishing procedure used |
| | - | Design and installation | Robustness of the system<br>Buildability of the system<br>Ease of installation and time of assembly<br>Extensibility of installation<br>Need for maintenance of connections |
| | - | Thermal bridges | Presence of thermal bridges between solar system and building element |
| Heritage significance of the building and its settings | Risk of material impact | Risk of material impact | Physical changes in the original material |
| | Risks of visual impact | Risks of visual impact | Visual change of the historic surface |
| | Risk of spatial impact | Risk of spatial impact | Change of geometrical relationships between the building and the surroundings |
| Economic viability | Capital costs | Capital costs | Cost of the intervention |
| | Operating costs | Operating costs | Operation/maintenance costs |
| | Economical return | Economical return | Economical return of the intervention |
| | Economic savings | Economic savings | Economic savings in the operational phase |
| Energy | Energy performance and operational energy demand in terms of primary energy rating | Energy performance and operational energy demand in terms of primary energy rating | Annual yield in relation to annual energy consumption |
| | Life cycle energy (LCE) demand in terms of use of | LCE demand in terms of use of renewable and non-renewable primary energy | LCA analysis' result |

| | | | |
|---|---|---|---|
| | renewable and non-renewable primary energy | | |
| Indoor environmental (IE) quality | IE conditions suitable for achieving good occupant comfort levels | IE conditions suitable for achieving good occupant comfort levels | Ability to contribute to the improvement of internal heat and light conditions |
| | IE conditions suitable for achieving content preservation | | Not applicable |
| | IE conditions suitable for achieving fabric preservation | | Not applicable |
| | Emissions of other harmful substances | | Not applicable |
| Impact on the outdoor environment | Greenhouse gas emissions from measures implemented and operation | Life cycle energy demand in terms of greenhouse gas emission | LCA analysis' result |
| | Emission of harmful substances | | Not applicable |
| | Natural resources | Natural resources | Demand of raw metals and minerals |
| Aspects of use | Influence on the use and the users of the building | Influence on the use and the users of the building | Effects of RES on the user |
| | Consequences of change of use | Consequences of change of use | Impact of these changes on the building |
| | Ability of building users to manage and operate control systems | Ability of building users to manage and operate control systems | Information for users on RES production |
| | Consequence of adding new technical room | | Not applicable |

Source: Elaboration of the authors from [1].

The evaluation scheme considers the same assessment categories of [16]:

1. Technical compatibility;
2. Heritage significance of the building and its settings;
3. Economic viability;
4. Energy;
5. Indoor environmental quality;
6. Impact on the outdoor environment;
7. Aspects of use.

### *3.1. Technical Compatibility*

The category "technical compatibility" assesses the risks connected to the material and physical impact of a new solution on heritage significance or building stability [16]. The standard assessment criteria are divided into: hygrothermal risk, structural risk, reversibility, corrosion risks, salt reaction risks, and biological risks [16]. These criteria need to be adapted to the solar systems: only the first three are taken from the standard, while others are not applicable for solar thermal or photovoltaic implementation. The hygrothermal risk is meant as the likelihood of moisture accumulation on the backside of solar panels, considering both indoor and outdoor sources of moisture (e.g., rain, snow, and vapour). The importance of this aspect is also connected to the impact on structural risks of building elements vulnerable to moisture a (e.g., timber, metals).

The structural risk refers to the structural requirements for the lead support structure and to the mechanical resistance of the roof. Additionally, the structural and mechanical resistance of panels and fixing systems to climatic loads (e.g., wind, snow, etc.) and the maximum distance between the support points of the RES panels should be considered. For custom-made solar modules is also necessary to perform specific testing procedures before the installation for the structural and mechanical characterization of panels and fixing systems to prevent excessive deflections [72].

Finally, the reversibility of the system should be evaluated, defined as an intervention that «(…) *can be undone without damage to the building*» [16]. The specific risk–benefit for the reversibility of solar system take into consideration the recommendations of the guidelines on solar integration in historic buildings that suggest installing solar panels facilitating their removing and the replacement of the original structure [73]. For this reason, the reversibility of both materials for bonding and mechanical fixings must be evaluated. The additional criteria inserted into the evaluation scheme consider: (i) waterproof of the solar system; (ii) reduction efficiency risk; (iii) fire safety; (iv) design and installation; and (v) connections.

The influence on reduction of energy generation efficiency of external environment (e.g., dust, snow, shadows, high temperature levels during operation and depending on mounting system, mismatch effects in solar modules and PV arrays when solar cells or modules do not have identical properties, etc.) must be considered. The installation of the system itself (e.g., inclination, temperature rise, reduced air-cooling effect, and natural decrease of efficiency over time) is another aspect to take into account.

Electrical connection needs to be optimized and easily accessible to prevent hot spots in the electronics (e.g., a faulty connection, reducing the possibility of electrical arcs, and to prevent fire risks). It would be important to verify the accuracy of the PV installation at each stage, verifying the wiring connections, checking for the presence of debris accumulation under the panels and the ignition risks of the mounting structure [74]. Furthermore, the combustibility of the cabling and the panel's materials, short circuit risks and hot spots of PV systems, or stagnation risks by the solar thermal systems are potential risks that may cause damage to the health and properties. Thus, the potential risks that can compromise the fire safety and the extinguishing procedure of the solar systems must be evaluated [75,76]. Fire prevention regulations must also be taken into account at the design level and during construction [77]. Moreover, the ability of a system to deal with uncertainty and variability of weather conditions, to protect against the risks of falling, installation mistakes, thermal bridges, and other imperfections will be evaluated. The solar RES system must comply with current standards and certifications. As a building product, it is necessary to observe the Construction Products Regulation CPR 305/2011 [78], and accordingly all building products should carry the CE-mark to indicate conformity with essential health and safety requirements set out in the applicable electro-technical requirements as stated in the Low Voltage Directive 2006/95/EC/or CENELEC standards. Thus, the robustness and buildability of the system must be evaluated, considering the current standards and certifications [75,79–82]. For this reason, system connections and the possible thermal bridges must be studied.

### *3.2. Heritage Significance of the Building and Its Settings*

The heritage significance is defined as the «(…) *combination of all the heritage values assigned to a building and its setting*» [16]. These aspects refer to locations, materials, forms, spatial configurations, uses, and cultural meanings that express the heritage significance of a historic building [16]. The standard EN-16883:2017 [16] includes three assessment criteria for the category "heritage significance", related to the risks of material, visual, and spatial impacts, respectively. According to this, the evaluation of solar technologies considers the same assessment criteria, tailoring the specific risks-benefits to be evaluated. First, the material impact concerns the respect of the historic setting, minimizing material loss, structural modifications, and damage to the original substrate and character [63,64,83–85]. The visual impact concerns the changes to the aesthetic or architectural aspect of the whole building or of a building element. For solar technologies, it implies the transformation of the building geometry, appearance of materials, colours, and textures of the building surface [24–26,32,46,47,49,63,64,66,86]. The former is particularly relevant when historic or original roof tiles, wall finishes, building façades, window shutters are still present and are covered by the application of new PV or ST layers with different visual properties and shapes. Next to this, the visual impact is connected to the changes in the geometric relationships of a building applying solar systems as shading elements (e.g., roof overhangs, window shutters, balcony railing). Finally, the risk of spatial impact of solar installations is intended as the change of the geometrical relationships with the building, as well as of its surroundings (e.g., streets, places).

Questions to solve for the final decision would be: Which roof and wall surfaces are changed and to what extent? How much it is possible to imitate the original surface, is it more aesthetically pleasing to cover continuous surfaces completely or partially? Where does the geometry change by applying additional layers or components? What influence does this have on the perception of the historical value of the building (overhangs, shadowing elements, freestanding systems)? Is it possible to customize the solar elements to preserve the historic significance of the building, paying particular attention to the geometrical and visual aspects, and considering existing constrains? In conclusion, the evaluation, therefore, should be carried out as an impact assessment of the renovation measures on existing attributes in collaboration with the monument protection office, if applicable and when possible.

### *3.3. Economic Viability*

The standard assessment criteria for "economic viability" are evaluated in a logic of life cycle economy that includes direct costs, operation/maintenance costs, economical return, and economic savings of the intervention [16]. The evaluation for solar energy solution considers the same assessment categories. Location, size, and orientation of the solar system, the technology applied, and the possibility of energy storage influence the annual yield and the economic aspects. The capital costs refer to the cost of the intervention. If the installation of solar systems is done in combination with other energy efficiency measures, only the additional costs caused by installation of solar energy must be included. Operation costs refer to the maintenance costs of the system. Furthermore, maintenance costs consider the cleaning of the solar panels. In fact, soil and dust accumulation on solar plants can provoke malfunction, hot spots, and energy losses that in the long run could affect durability and the energy performance. In many cases, rain can be sufficient to wash away dirt, but in the case of heavy soiling or in areas with little precipitation, additional cleaning of the roof/façade elements is necessary. The economic savings can be estimated comparing the energy costs before and after the retrofitting and converting this value in money considering a scenario of increase in the energy purchase price year after year. Sometimes, it is also possible to consider the increase of the value of the retrofitted building.

### *3.4. Energy*

The standard assessment criteria for "energy" considers the energy performance and operational energy demand in terms of primary energy rating as well as the life cycle energy demand in terms of use of renewable and non-renewable primary energy [16]. The evaluation for energy solutions considers the same assessment criteria. In the first case, the annual yield in relation to annual energy consumption must be evaluated. In the second case, the LCA analysis in all the stages of the life of the product in terms of raw material extraction, material manufacture, disposal, and recycling must be assessed. Here, both the life cycle inventory datasets of solar panels and mounting systems must be considered. Specific data for PV technologies are reported by the IEA Photovoltaic Power Systems Program (IEA PVPS) Task 12 on "PV Sustainability" [87,88].

### *3.5. Indoor Environmental Quality*

The standard assessment criteria for "indoor environmental quality" refers to suitable indoor conditions for preventive conservation of cultural heritage buildings and objects as well as for human comfort levels [16]. Only the aspects linked to the indoor conditions for achieving good occupant comfort levels must be evaluated implementing solar system solutions, as they do not have an impact on indoor building fabric or heritage objects (e.g., paintings, frescoes, sculptures). Thus, the ability to contribute to the improvement of internal heat and light conditions of solar systems is evaluated.

### *3.6. Impact on the Outdoor Environment*

The standard assessment criteria for the "impact on the outdoor environment" is evaluating the greenhouse gas emissions from measures implemented, the emission of harmful substances, and the natural resources [16]. The application of solar technologies considers only two conditions: the life cycle energy demand in terms of greenhouse gas emission and the use of natural resources. In the first case, the LCA analysis can be an important instrument to estimate the real advantages of the solar system, considering also the energy used to produce it. In the second case, the demand of raw metals and minerals (e.g., cobalt, lithium) to manufacture the solar technologies must be assessed.

Technologies that handle these raw materials economically (an example for PV are the thinner films and advanced light trapping technologies) and technologies with better recyclability will be preferred. However, LCA calculation (if available) should consider all the stages of life of the product: from the raw material extraction, through the material manufacture, to the disposal or recycling. Relevant information for LCA is how much fewer emissions will be released due to energy generated by the RES with respect to the region's energy mix. The LCA should focus on the ecological impact of the material's life, with the focus on greenhouse emissions and emission of harmful substances. It is important to note that nowadays, many of the core components of solar panels can be recycled. Metal, glass, and wiring can all be recycled and reused. Although silicon cells and silicon wafers are not as recyclable as glass and plastic, some specialty recycling companies are able to reuse silicon cells by melting them down and reclaiming the silicon and various metals. For example, the non-profit PV Cycle Association [89] all over the world collect and recycle solar PV modules and offers national waste management services for electrical and electronic equipment, batteries, etc.

### *3.7. Aspects of Use*

Changes or additions of new functions should respect and be compatible with the heritage building, respond to community needs, and be sustainable [90]. The standard assessment criteria for the "aspect of use" considers the influence on the use and the users of the building, the consequences of change of use, the ability of building users to manage and operate control systems, and the consequence of adding new technical room [16]. The evaluation of solar energy systems considers the first three assessment criteria. In the first case, positive and negative effects on the user must be listed, such as change in habits, use, HVAC control, operating costs, or system maintenance procedures. Next to this, the ability to adapt the energy consumption to the current energy generation and the indications given to the users about the production of solar energy (e.g., monitoring with home-display, monitoring data accessible via mobile phones) are also evaluated.

### *3.8. Assessment Scale and Summary of the Section*

Building upon what the standard [1] suggests, the assessment consists of an evaluation of a RES solar system according to the criteria and sub-criteria previously identified (Section 3), through a five-points Likert scale (Figure 1). To accelerate the rating process, make comparisons easier, and visually emphasize results, the same color-coding of the standard was applied to the Likert scale. In order to allow for an overall assessment, the results are summarized in a table based on the categories and criteria shown in Table 1. This method, following the standard, should not be seen as a mechanical tool that provides an answer; rather it is meant to allow for a transparent assessment and the interdisciplinary dialogue that is needed to identify the interventions that best meet the requirements of the building in question. An overview of the scale with colours, definitions, and examples for a few meaningful assessment categories and criteria are provided in Table 2 for clarity. A similar approach can be applied to the other assessment categories and criteria. Thanks to this assessment procedure, by analysing the ratings of each category and for each individual sub-criterion, a comparison between different types of buildings (e.g., listed and protected buildings) or different type of solar integration (e.g., façade or roof integration) can be readily made.

In this section, a risk–benefit assessment scheme tailored to solar solutions has been described. A five-level assessment scale from *High Risk* to *High Benefit* has been proposed. Technical compatibility, Heritage significance of the building and its settings, Economic viability, Energy, Indoor environmental quality, Impact on the outdoor environment, and Aspects of use criteria have been described in detail. The assessment scale proposed offers an alternative way to evaluate RES systems. The color-coding allows for rapid comparison between the solutions. The results of this assessment are intended as a means for discussion between the members of the multidisciplinary team assessing RES solutions, in order to take into consideration aspects from different perspectives and similar aims.

**Table 2.** Assessment scale: definitions for each step of the scale and examples for some meaningful assessment categories and criteria [1]. Source: elaboration of the authors of the authors.

| Scale Grade and Colours | Rationale | Example 1 [1] | Example 2 [1] | Example 3 [1] |
|---|---|---|---|---|
| | | **Assessment Category: Technical Compatibility** | **Assessment Category: Heritage Significance of the Building and Its Settings** | **Assessment Category: Economic Viability** |
| | | **Assessment Criteria: Reversibility** | **Assessment Criteria: Risk of Visual Impact** | **Assessment Criteria: Capital Cost** |
| High benefit (deep green) | The installation results highly successful/provides high benefits/cost-benefit approach/effective | The installation is fully reversible as all fixing and cabling can be removed. | High positive impact | The solution capital cost is 50% below the average, i.e., [91] |
| Low benefit (light green) | The installation results sufficiently successful/provides medium-low benefits/average cost-benefit approach | The installation is fully reversible, fixing and cabling can be removed even if some alteration to the ancient fabric remains | Low positive impact | The installation capital cost is 25% below the average |
| Neutral (white) | The installation results neither a success nor a failure or it do not directly impact the historic building | No direct installation of PV system on the historic building is made | No impact | The installation capital cost is on average |
| Low risk (yellow) | The installation results almost not successful/of medium risk impact | The installation is partly reversible, only some components can be removed without altering the historic building | Low negative impact | The installation capital cost is 50% above the average |
| High risk (red) | The installation results not successful/of high risk impact/expensive/ineffective | The installation is not reversible, components can not be removed without damaging the historic building and its appearance | High negative impact | The installation capital cost is 100% above the average |

[1] Only an example related to a category and an evaluation criterion of those previously indicated in table 1 is presented here. Examples are not supposed to be conclusive; a similar approach is intended to be applied to the remaining criteria listed above.

## 4. Quick Assessment

As previously mentioned in Section 2, a panel of experts on heritage, energy, and sustainability [69] has participated in the collaborative project within IEA-SHC Task 59/IEA-EBC Annex 76 activities in order to review the standard EN-16883:2017 [16]; in this case to evaluate solar solutions, but also other compatible retrofit solutions such as walls or HVAC [70,71]. The first step of the selection of the possible compatible solutions for energy retrofitting is to eliminate any measures from the long list that are inappropriate, based on assessment criteria fixed by the standard and subsequently adapted by the experts of the working group, as has been explained in detail in Sections 2 and 3.

Based on the long list proposed by the standard, a quick assessment—as specified in Section 10.4 of the standard EN-16883:2017—is then carried out, undertaken by the expert team. This quick assessment, as the standard highlights, has been based on the above criteria (Section 3 and Table 1) using experience rather than thorough analysis. The different criteria should be seen as a checklist to consider all-important aspects in connection with the renovation of historic buildings.

With the aim of validating the adapted criteria of the standard, a quick assessment of nineteen solutions of solar systems implemented in traditional and historic buildings has been done. The solutions analysed represent different countries, building ages, refurbishment ages, types of building, use, protection levels, types of solar technology, and solar application in roofs or facades (Table 3). Heritage and traditional buildings analysed were grouped by typology, mainly dividing them based on their usage pattern (continuous/discontinuous) and on their occupancy (residential/non-residential), as well as on their relationship with the surrounding environment (e.g., urban or rural buildings, mainly residential buildings, single family houses (SFH) and multi-family houses (MFH)). The buildings' relationships with the surroundings and landscapes can have an impact on the aesthetic, visual, and material dimensions of the intervention. It also implies a direct relationship with aspects of the evaluation related to heritage significance of the buildings and their settings and technical compatibility. The different levels of occupancy (e.g., public buildings, museums, schools, etc.) represent different using-loads, electricity needs, or HVAC and ventilation requirements, as factors that affect the solar plant size. This aspect is directly related to the economic viability, energy, indoor environmental quality and aspect of use criteria. Another important aspect highlighted in this research is related to the type of solar system used (i.e., mostly roof solutions whilst façade solutions or accessory elements were found to a lesser extent). Likewise, the level of protection of the building (i.e., listed buildings with a higher level of protection or not protected) can also determine significant differences in the evaluated criteria. In this way, a rational analysis of the results has been possible thanks to a comparison between the risks and benefits of each intervention.

The tabular risk–benefit assessment scheme (Section 3) developed in the present research (Table 2) that follows the standard EN-16883:2017 qualitative approach (Figure 1) has been applied to the case studies, to validate the adapted criteria of the standard and to identify strengths and weaknesses of solar solutions. The results of the assessment of the single solutions were averaged, dividing solutions into listed and unlisted buildings; roof attached and roof integrated systems (Tables 4 and 5).

In the overall evaluation, all examples have been taken into consideration (roof attached, roof integrated solutions, and façade integrated or attached solar systems) evidencing the differences between protected and listed buildings or unprotected or unlisted buildings studied (Table 4). Since the number of analysed examples of facade solutions is a minority (5% of the total), only the roof solutions were averaged in Table 5 (solar integrated 63% and attached 11%).

**Table 3.** Solar solutions analysed in the quick assessment.

| Name | State | Building Age | Intervention Age | Protection Level | Building Type | Building Use | Solar Integration | Solar Technology |
|---|---|---|---|---|---|---|---|---|
| Kindergarten, Chur | CH | 1914 | 2015 | listed | school | nursery school | roof integrated | BIPV-BIST |
| Kindergarten, Chur | CH | 1914 | 2015 | listed | school | nursery school | local sharing | BIPV-BIST |
| Monument School, Innsbruck | AT | 1929 | 2014 | listed | school | school | roof attached | BAPV |
| Crichton Castle, Scotland | UK | 1500 | 2019 | listed | castle | monument | free standing | PV |
| Fondazione Museo Pino Pascali, Puglia | IT | 1800 | 2016 | not listed | public industrial | museum | roof integrated | BIPV |
| St. Franziskus Church, Ebmatingen | CH | 1989 | 2018 | not listed | church | church | roof integrated | BIPV |
| Kohlesilo Solar Silo, Basel | CH | 1844 | 2015 | not listed | public industrial | multiple uses | roof integrated | BIPV |
| Kohlesilo Solar Silo, Basel | CH | 1844 | 2015 | not listed | public industrial | multiple uses | facade integrated | BIPV |
| Parco Urbano Isola della Certosa, Venezia | IT | 1900 | 2020 | not listed | industrial | multiple uses | roof integrated | BIPV |
| Giardino Pensile Hotel Luna, Capri | IT | - | 2020 | not listed | third sector | hotel | landscape integrated | free-stand PV |
| Wine shed Milvignes | CH | 2018 | 2018 | listed | rural | wine shed | roof integrated | BIPV |
| Rural farm Galley, Ecuvillens | CH | 1859 | 2018 | listed | rural | farmhouse | roof integrated | BIPV |
| Doragno Castle, Rovio | CH | before 1600 | 2017 | not listed | castle | residential SFH | roof integrated | BIPV |
| La Capanna, Capannori, Lucca | IT | 1700 | 2017 | not listed | rural | residential MFH | annex building | BIPV |
| Glaserhaus, Affoltern im Emmental | CH | 1765 | 2015 | listed | residential | residential SFH | roof integrated | BIPV |
| Lauriston Housing Cooperation, Edinburgh | UK | 1840 | 2009 | listed | urban city | residential MFH | roof attached | BAST |
| Villa Castelli, Como | IT | 1850-1900 | 2013 | not listed | villa | residential SFH | roof integrated | BIPV |
| Feldbergstraße, Basel | CH | 1986 | 2009 | listed | urban city | residential MFH | roof integrated | BIPV |
| Chalet La Pedevilla, South Tyrol | IT | 2013 | - | not listed | mountain | residential SFH | roof integrated | BIPV |

Note: BIPV (Building-integrated photovoltaic); BAPV (Building applied photovoltaic); BIST (Building-integrated solar thermal).

**Table 4.** Results of the quick assessment averaged grouping solutions on listed and not listed buildings (Note: in brackets is the number of solutions averaged over).

| Assessment Category | Listed Building | | Not Listed Buildings | |
|---|---|---|---|---|
| | **Strengths** | **Weakness** | **Strengths** | **Weakness** |
| Technical compatibility | Hygrothermal risk (9)<br>Structural risk (9)<br>Waterproof (9)<br>Fire safety (9)<br>Design and installation (9)<br>Thermal bridges (9) | Reversibility (9)<br>Reduction efficiency risk (9) | Hygrothermal risk (10)<br>Structural risk (10)<br>Waterproof (10)<br>Reduction efficiency risk (10)<br>Fire safety (8)<br>Design and installation (10)<br>Thermal bridges (10) | Reversibility (10) |
| Heritage significance | Risks of visual impact (9)<br>Risk of spatial impact (9) | Risk of material impact (9) | Risks of visual impact (10)<br>Risk of spatial impact (10) | Risk of material impact (10) |
| Economic viability | Operating costs (2)<br>Economical return (2)<br>Economic savings (7) | Capital costs (8) | Operating costs (1)<br>Economic savings (3) | Capital costs (6)<br>Economical return (5) |
| Energy | Energy performance (9)<br>LCE demand (1) | | Energy performance (10) | Life cycle energy demand (2) |
| IE quality | IE conditions suitable (7) | | IE conditions suitable (10) | |
| Impact on the outdoor environment | Greenhouse gas emission (7) | Natural resources (5) | Greenhouse gas emission (1) | Natural resources (2) |
| Aspects of use | Effects of RES on users (7)<br>Effects of change of use (7) | Easy to manage and operate (3) | Effects of RES on users (10)<br>Effects of change of use (10)<br>Easy to manage and operate (4) | |

**Table 5.** Results of the quick assessment averaged grouping roof attached and roof integrated solar solutions (Note: in brackets is the number of solutions averaged over).

| Assessment Category | ROOF ATTACHED BAPV-BAST | | ROOF INTEGRATED BIPV-BIST | |
|---|---|---|---|---|
| | **Strengths** | **Weakness** | **Strengths** | **Weakness** |
| Technical compatibility | Hygrothermal risk (2)<br>Structural risk (2)<br>Reduction efficiency risk (2)<br>Fire safety (2)<br>Design and installation (2)<br>Connections (2)<br>Reversibility (2) | Water proof (2) | Hygrothermal risk (12)<br>Structural risk (12)<br>Waterproof (12)<br>Design and installation (12)<br>Connections (12) | Reduction efficiency risk (12)<br>Fire safety (12)<br>Reversibility (12) |
| Heritage significance | Risks of visual impact (2)<br>Risk of spatial impact (2) | Risk of material impact (2) | | Risks of visual impact (12)<br>Risk of spatial impact (12)<br>Risk of material impact (12) |
| Economic viability | Operating costs (1)<br>Economical return (1)<br>Capital costs (2)<br>Economic savings (2) | | Operating costs (2)<br>Economical return (5)<br>Economic savings (6) | Capital costs (9) |
| Energy | Energy performance (2)<br>Life cycle energy demand (1) | | Energy performance (12) | Life cycle energy demand (2) |
| IE quality | IE conditions suitable (2) | | IE conditions suitable (10) | |
| Impact on the outdoor environment | Greenhouse gas emission (1) | Natural resources (2) | Greenhouse gas emission (5) | Natural resources (3) |
| Aspects of use | Effects of RES on users (2)<br>Effects of change of use (2)<br>Easy to manage and operate (2) | | | Effects of RES on users (10)<br>Effects of change of use (10)<br>Easy to manage and operate (4) |

*Results and Summary of the Section*

The technical compatibility criteria of solar systems do not represent a critical aspect, whether it is protected or unprotected buildings. The risk of reduction of efficiency is higher for listed buildings (as the weighted value is lower). The analysed examples showed that PV or BIPV systems, for the selected case studies and in listed buildings, are used mainly on less visible surfaces (e.g., in an internal courtyard such as in the Feldbergstrasse building or using only the surfaces best exposed to solar radiation or as in the case of Villa Castelli, not visible by the lake). In some solutions, for example, it is preferable to use solar technologies with improved aesthetic integration, which minimize the impact of the system, even if this can compromise the efficiency of the solar system (e.g., Terracotta colour modules in the rural farm Galley or no visible solar cells in the Solar Silo building). In a BAPV system, waterproofness does not depend on the solar solution. Thermal bridges and poor connections are avoided in all cases analysed. As the greater number of cases analysed correspond to BIPV or BIST, the reversibility value turns out to be a critical point (lower value than others).

Heritage significance criteria are better in roof-attached than in roof-integrated systems. This is evidenced by the fact that lower risks (higher values) are found by the architectural, aesthetic, and visual also as well as the spatial impact criteria considered. It could be the result, as previously mentioned, of less visible and more reversible solutions implemented.

Economic viability criteria are a critical issue in most of the case studies analysed, especially capital costs, which is not usually publicly known and is difficult to obtain. Data on the operating and maintenance costs or economic return is missing in most cases, and for a quick evaluation there is no value that can really be taken into account. Energy criteria are good, considering the energy performance and operational energy demand in terms of coverage of the building's energy needs.

Few differences are shown between listed and unlisted buildings and the value is also better in the case of integrated systems compared to non-integrated ones. Data on life cycle analysis (LCA) was found in only three cases analysed and for this reason is not a factor that can be considered of weight in a quick study. This means LCA is not widely used yet, not even in the field of research. Indoor environmental quality criteria, indicating the conditions to achieve good comfort levels for occupants, were achieved mainly when the solar systems are complemented with other technical solutions for the energy retrofit of the building. In this case, the improvement of the overall energy performance compared to the previous situation is given in most of the cases studied and, therefore, generally the value found is good, with a lower value for roof-integrated solutions. Impact on the outdoor environment criteria considers two main aspects, firstly the carbon emissions and harmful substances emissions reduction, which is generally good or very good with an always-positive impact considering the use of solar renewable sources. On the other hand, it takes into account the factor of the natural resources used, which is evidenced by the experts as a critical aspect (neutral or bad although there are fewer examples with information in regards to the total number of cases analysed). Aspects of use criteria are based mostly on the ability of building users to manage information about the solar plant. It manifests itself as a positive factor when there is the possibility for users to be able to supervise and monitor the solar installation (e.g., having a display with data or a home automation control system to evaluate if the system is working properly), which is not usual or is not well understood. The analysed examples show that there is no influence on the use or on the users due to the change of use of the building after the intervention.

In conclusion, by means of the quick assessment of nineteen solar solutions, the adapted assessment criteria described in Section 4 are validated. This allowed the analysis of the strengths and weaknesses of the different solutions types. The most relevant difference in the evaluated criteria between listed and unlisted buildings is the risk of reduction of efficiency that is a weakness for the listed building, due to the position and type of plants. More differences can be found between roof-integrated and roof-attached systems. In general, roof-integrated systems have a lower assessment. Among others, these systems have no benefit for the heritage significance criteria, in contrast to the attached systems, probably due to their reversibility and hiddenness in the assessed solutions. The outcome of this step was to determine a short list of measures that are considered potentially suitable, which shall be assessed thoroughly with respect to risks and benefits in the next step.

At this point, in-depth assessment of the measures—as specified in Section 10.5 of the standard EN-16883:2017 —involving both quantitative and qualitative assessment will be made (Section 5, detailed assessment), which is intended to contribute to the decision-making process. The level and extent of the assessment shall be suited to the size and complexity of the project and in some cases an extended technical and economic evaluation may be needed.

## 5. Detailed Assessment

A more in-depth study of the risk–benefit scheme has been carried out in a detailed assessment of different case studies. Since it is necessary to carry out a more exhaustive analysis, three projects have been selected from the case studies analysed, for which there is enough information (technical, economic, and functional) to carry out a detailed and in-depth analysis. Furthermore, the selected buildings have different protection levels (a listed building and unlisted buildings in conservation areas), building typology (castle, industrial building, villa), function (museum, multipurpose, residential), solar technology type (BAPV, BIPV), and solar application (roof, façade). Different and opposite scenarios have been chosen to see possible differences and approaches of intervention. This was done consciously to show how solar technologies can be applied in different situations and what effect this might have on the chosen solar solution. These case studies have been selected, both from technological and conservation points of view, as representative projects that use renewable energy and in particular solar energy in combination with other energy retrofit measures to achieve a rational use of energy and low $CO_2$ emissions.

As best-practice examples of renovated buildings that achieve high levels of energy efficiency while respecting and protecting their heritage and historical significance, these selected case studies have been documented in the Historic Building Energy Retrofit Atlas (HiBERatlas database), a free access best-practice database of exemplary energy efficient interventions in historic buildings. The documentation gathered for these projects provides information on the building and its construction, location and environmental context, climate, architecture and heritage assessment, building material specifications, energy efficiency data, information on building services and comfort, as well as, on energy refurbishment solutions (e.g., building envelope, windows, HVAC and DHW, renewable energy), products, or financial aspects. In addition to this, technical solutions for improving the energy performance of the building envelope and of technical installations, documented in detail, have been the basis of the HiBERtool. HiBERtool is a web platform that aims to guide the user in selecting retrofit solutions that might be suitable for the renovation of historic buildings. All documentation for the specific solutions for windows, walls, ventilation, heating and solar, with information about the context and with additional information on technical compatibility, heritage conservation impact and energy savings can be found in both tools (Crichton Castle is only in the HiBERtool).

The detailed assessment of each building has been carried out by a multidisciplinary group of experts on the field on energy, sustainability, and heritage: (i) members of Historic Environment Scotland, the lead public body established to investigate, care for, and promote Scotland's historic environment; (ii) members of the Swiss BIPV competence centre of Switzerland within University of Applied Sciences and Arts of Southern Switzerland (SUPSI), as experts on the field of solar energy and energy efficiency in buildings; (iii) and members of EURAC Research, with researchers from a wide variety of scientific fields mainly in the areas of renewable energies, including sustainable energy sources. This paper summarises the main characteristics of the buildings under study necessary for the analysis relating to the criteria of the examined standard and which serve to justify the detailed evaluation carried out by the experts.

The selected buildings are:

- Crichton Castle, a listed castle in Scotland (United Kingdom);
- Solar Silo, an unlisted industrial building in a protected area of Basel (Switzerland);
- Villa Castelli, an unlisted villa in a protected landscape on Lake Como (Italy).

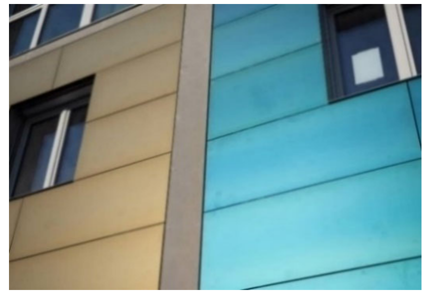
*Crichton Castle* is a ruin of a former aristocratic seat in southern Scotland (UK), near the village of Crichton in Midlothian, Scotland (coordinates: 55°50′28″ N–2°59′22″ W). The site consists of a stone building arranged around a courtyard with corner towers, on a slightly elevated grass hill, in a largely uninhabited area. The walls consist of solid sandstone in varying thickness. As a ruin, the structure has very few interior details and is mostly unroofed. Due to its isolated location, it is not connected to mains electricity. The small requirement for space heating during the open season (April to September) in the ticket office, as well as to supply a phone and fax line, was generated by a petrol generator in the past. In a bid to provide a low-carbon alternative, solar panels were installed in 2005, providing most of the electricity required. These were installed on a non-historic roof on one of the castle towers. Due to the nature of the site, the panels were located in such a way, that they are not visible from the ground. This was important since the ruin is a prominent feature in the wider landscape. Cables were run within the walls where possible, or otherwise fixed into the mortar joints. The solar panels installed had a maximum output of 1.0 kWp, enough power for most needs but not enough to run the space heater. The generator was still required during the early spring and late autumn when more heating was required. In 2019, it was decided to upgrade the panels to newer models with an output of 1.8 kWp but retaining the existing fixings and cable routings. New batteries also enabled the storage of the energy as needed. With these improvements, 100% of the energy requirements can now be met with renewable energy (Figure 2).

(**2a**)

(**2b**)

**Figure 2.** Crichton Castle and surrounding landscape (**2a**) and the view of the solar panels on one of the towers (**2b**). Sources: © Historic Environment Scotland. More information available online: https://blog.historicenvironment.scot/2019/04/here-comes-the-sun/ (assessed 18 February 2021).

The *Solar Silo* is the former building of the heating centre and the coal silo of Maschinenfabrik Sulzer and Burckhardt in Gundeldinger Feld (coordinates: 47°32′31″ N 7°35′36″ E), Basel, Switzerland. The building dating from the 1800s was modernized in 2014. It has been completely converted into a multipurpose building over the past fifteen years, creating a cultural district [92]. The interiors of the concrete structure that contained the four coal silos and the heating plant for the industrial area have been retained and the former use is still readable from the new facade. As the entire ensemble and old industrial area is under heritage protection, the retrofitted building was required to match the style and colour scheme of the site. As part of a research project, it investigates new approaches for BIPV integration as cladding innovative materials and new energy storage strategies [93]. Green, gold, orange, blue, and grey BIPV modules with monocrystalline solar cells and some standard PV black modules were used on the roof as well as on the south and north facades. The BIPV module technology is characterized by a colour coating on the outer surface of the module's glass, making them matte panels, and resulting in the PV cells being hardly recognizable. Next to the technologically specific features of the modules, the roof modules have standard dimensions and have been used as mosaic tiles, whereas the façade modules have been customized in order to keep the modularity of the existing surface with a smaller number of custom-sized panels. The BIPV system combines two functions in one layer. Firstly, it protects the building from the weather and environmental conditions; secondly, it serves as RES production. The solar modules installed in the Solar Silo building had a maximum output of 24 kWp covering 165 m$^2$ between roof and facades surfaces. The solar plant generates nearly half of the building's total energy consumption to fulfil the users' needs. However, it is also connected to a district heating supply. The project is part of the "2000-Watt society—pilot region Basel" (Figure 3).

(**3a**) (**3b**)

**Figure 3.** Solar Silo: roof-integrated and façade-integrated BIPV (**3a**) and façade BIPV system detail (**3b**). Source: 1a. BFE—SUPSI Photo: ©C. Martig; 1b. SUPSI©P. Bonomo. Detailed information available online: https://www.hiberatlas.com/en/solar-silo-in-gundeldinger-feld-basel--2-51.html (assessed 18 February 2021).

*Villa Castelli* is a historic mansion on the eastern side of Lake Como, Bellano, Italy (coordinates: 46°4′17″ N, 9°18′18″ E). The villa, built during the second half of the nineteenth century, has been mainly used as a holiday house over the years [94,95]. It was subjected to several expansions and renovations until 1925 when it acquired its current shape. Depending on the construction period, the building was built with different construction methods and materials. The oldest load-bearing walls of the building are made of local natural stone (thickness 42 cm and 62 cm); the first extension was built in solid brick walls, the following extension in perforated bricks and concrete. Over the course of the renovation, the originally "monk and nun" roof tiles were also replaced with an aluminium roof. The structure has valuable architectural elements: coloured frames, columned balustrades and façade decorations made using the graffiti plaster technique. In 2014, some important energy efficiency and conservative renovation interventions were put in place by a multidisciplinary team of experts composed of designers, researchers, and contractors. The interventions solved structural problems, limited the decay process and insulated foundations, walls, and roof. New heating and ventilation systems were installed as well as a BIPV roof. This PV system used custom-made flexible and ultra-thin panels that blend in with the roof pitches. This technology is based on an innovative monocrystalline cells lamination process, which uses special and selected techno-polymers as encapsulants. The BIPV system installed has a nominal power of 10 kWp and the total area of the panes is about 90 $m^2$. The panels are tilted by 27.5° and varied in orientation and dimensions. The system provides part of the energy necessary to fulfil the users' needs. Thanks to the interventions made, there is an 88% reduction in consumption. Additionally, the environmental impact is reduced considerably. Finally, the villa was a pilot building for the validation of the calculations and certification procedures with the CasaclimaR© protocol. The project also won the "CasaClima Award 2016" (Figure 4).


(**4a**) (**4b**)

**Figure 4.** Villa Castelli: roof-mounted BIPV (**4a**) and system detail (**4b**). Sources: ©Valentina Carì, Progetto Serr@. Detailed information available online: https://www.hiberatlas.com/it/villa-castelli--2-23.html (assessed 18 February 2021).

The main findings of the detailed assessment are described below, divided into the assessment categories defined by the standard [1].

*5.1. Technical Compatibility*

In the solar solution implemented in *Crichton Castle*, the technical compatibility has no particular risks, thanks to the installation and fixing system as well as the siting of the panels. The solar panels were installed by being bolted into a non-historic concrete roof using the manufacturer's guidelines and current standards. As there is space surrounding the panels and the adjacent materials are not prone to moisture or fire, there was no hygrothermal, structural, or fire risk. The installation is fully reversible as all fixing and cabling can be removed and have been placed into modern materials or sacrificial mortar joints.

*Solar Silo* BIPV system is made by innovative cutting edge coloured PV modules realized by using monocrystalline solar cells, glass/glass (4 + 4mm) laminated safety glass (VSG), both framed-standard size integrated in the roof and custom-sized frameless glass/glass modules installed on the façades. A special glass cover was developed to make the solar cells invisible and to reduce efficiency losses [96]. The externally clad façades consist of a layer of BIPV and fibre cement panels, a ventilating air space (s = 00.8 m), and a thermal insulation (s = 0.2 m) held by a wooden and aluminium substructure. The building envelope is thermally insulated without thermal bridges and made airtight according to the SIA 180-C1 standard [97], which requires a careful execution of the connections between the construction elements. The solar system is easily removable similar to other ventilated roofs or façades. The BIPV modules are ventilated and serve as the water resistant element. Moisture accumulation on the backside of the PV module is not probable in this case. The ventilation gap allows for the heat that is generated behind the modules to dissipate, which has a positive effect on their efficiency and output, and also allow effective ventilation of the roof and façade solution. Next to this, the external insulation placed over the original concrete surface of the building allows increased water repellence, identified as low capillary water absorption and diffusivity, which means low resistance to the diffusion of water vapour. The structural risks due to the risk of humidity in this case are not present, since the PV system has been applied on the roof or in the ventilated wall with structural elements that are not vulnerable to humidity. BIPV modules are subject to tests for the qualification of the design according to current standards [78–80].

In *Villa Castelli,* ultra-thin panels of less than 0.02 m are used. They are encapsulated in eight layers of different polymers and coatings. They are flexible, were designed for sailing boats and then adapted for special installations on buildings. PV panels are glued to the aluminium surface of the roof using a structural double-sided glue with a thermal expansion coefficient comparable to that of the roofing material. Cells are encapsulated in plastic, so there is no risk of condensation, waterproofing, limited fire risk, and thermal bridges reduction. Panels are thin and walkable, which facilitates buildability, installation, and maintenance of both the panels and the roof, and there are no problems of possible theft. Due to its technical characteristics, this PV system could be easily dismounted or substituted, without any significant detrimental effect on the historic building.

A synthetically overview of the assessment is reported in Table 6.

**Table 6.** Risk–benefit scheme for assessing the technical compatibility of solar solution in historic buildings and sites: detailed evaluation of the selected buildings.

| Assessment Category | Assessment Criteria | Crichton Castle | Solar Silo | Villa Castelli |
|---|---|---|---|---|
| Technical compatibility | Hygrothermal risk | Absence of condensation risk due to ventilation around the panels | Absence of condensation risks for the use of structural elements not vulnerable to humidity | Absence of condensation risks for the PV cells encapsulation in plastic |
| | Structural risk | The installation and fixing system of the panels on a modern flat roof presents no particular risk | The installation and fixing system as well as the siting of the panels has not particular risk | Absence of risk as PV panels are lightweight and glued to the roof |
| | Reversibility | Reversibility of fixing and cabling that are also placed into modern materials or sacrificial mortar joints | The installation is fully reversible as all fixing and cabling can be removed. | Reversibility thanks to the of the glue-based installation |
| | Waterproof | Not applicable, as the panels are in what is effectively an external area | BIPV modules are ventilated and serve as the water-bearing stratum The external insulation placed over the original concrete surface allows increased water repellence. | Waterproof thanks to the PV cells encapsulation in plastic |
| | Reduction efficiency risk | No risk of reduction efficiency due to location and installation. | Ventilation allows for the heat that is generated behind the modules to dissipate, which has a positive effect on their efficiency and output | Moderate risk for reduction efficiency due to the higher decay of the polymer used |
| | Fire safety | No fire risk due to non-combustible materials throughout | Fire prevention regulations have been taken into account at the design level and during construction. BIPV tested according to IEC standards | Limited fire resistance thanks to the PV cells encapsulation in plastic |
| | Design and installation | Solar panels tested according to manufactures guidelines and current standards | BIPV modules robustness tested according to IEC standards | Robustness and lightweight; easiness of maintenance due to modules walkability |
| | Thermal bridges | Not applicable (the building is unheated) | Absence of thermal bridges due to design of thermal insulation and airtightness of the building envelope (not tested) | Absence of thermal bridges due to the encapsulation of PV cells in plastic (airtightness tested with blower door test) |

Source: Elaboration of the authors.

### *5.2. Heritage Significance of the Building and Its Settings*

*Crichton Castle* is a scheduled monument within a largely uninhabited landscape. The vistas to the castle on all sides are an important feature of the building. This means that this installation had to minimize the visual impact on the historic fabric, as well as the overall aesthetics of the surroundings. To minimize the visual and aesthetic impact, the solar panels were installed behind the historic parapet of one of the towers and are not visible from the ground level. The panels were attached to a modern roof, and any services and cables were attached to mortar joints where necessary. Additionally, the replacement of an oil generator with solar systems generates a significant reduction pin noise on the tranquil and picturesque site. All of this means that the architectural, aesthetic, and visual impact of the installation has been kept to an absolute minimum and the overall setting has been improved.

On the contrary, *Solar Silo* is not a listed building and a visual change in the exterior finish has occurred with respect to the original status. However, as "Gundeldinger Feld" ex-industrial ensemble is under heritage protection, the remodelled building was required to match the style and colour scheme of the site and all the old industrial area, which has been converted into a new model energy district. The original structure of the building is still legible after the intervention, as the shape and architectural design have been maintained and the solar system matched and adapted the vertical uprights of the facade completely in line with the other construction elements. The customized PV modules are used to create a particular visual design, but the configuration of the original construction and structure of the building remains intact. Even though there is no protection on the building, the cooperation with the department for building conservation was crucial and positive. The changes do not influence any conservation aspects. The handling of the existing building fabric, the design quality of renewables embedded into the energy concept in an entire area has resulted in a high energy efficiency in operation.

The PV architectural integration in *Villa Castelli* followed a long design process to guarantee a low visual impact on the building and its surroundings. Three prototypes were developed: a classic polycrystalline photovoltaic cell with transparent support made combining two glass sheets; a panel made by greyish and greenish small cells of a size similar to stone-made local roof tiles; a dark-grey thin-film BIPV modules applied on a metal cover. The first solution was poorly integrated while the second, although aesthetically integrated, was not walkable and required complex maintenance. For these reasons, the third solution was chosen. Given the architectural constraints, panels could not be arranged for optimal orientation. Therefore, the modules do not have the same orientation, or the same dimensions. This causes a moderate risk of visual impact related to the absence of a total coverage of the roof with the PV cells and the reflectance value slightly different from the aluminium finishes of the roof. Otherwise, the aesthetic integration is based on the coplanarity, compliance with the rooflines, consistency with the roof pitch shape and dimensions, grouping of panels, and matching in colours and reflectivity. The ultra-thin-film panels allowed for coplanarity between them and the new roof. They were installed according to the original roof symmetry lines and designed to conceal the triangular or trapezoidal shape of the pitches, as something close to a homogeneous coating surface could be perceived from the surroundings. The PV panels have the same dark-greyish colour of the metallic roof cover and similar to the traditional stone roofs of the area. For these reasons, the solar panels are not visible from the lake and barely visible from a short distance. Thanks to these features, the aesthetic impact of the BIPV system is limited, and, therefore, the historical value of the villa is not affected.

An overview of the assessment is reported in Table 7.

**Table 7.** Risk–benefit scheme for assessing the heritage significance of solar solution in in historic buildings and sites: detailed evaluation of the selected buildings.

| Assessment Category | Assessment Criteria | Crichton Castle | Solar Silo | Villa Castelli |
|---|---|---|---|---|
| **Heritage significance of the building and its settings** | Risk of material impact | There was no impact on the historic part of the building | The original structure of the building after the intervention is still legible as the shape and architectural design have been maintained | Null or extremely limited risk thanks to the ultra-thin-film and lightweight panels |
| | Risk of visual impact | Null impact thanks to the solar panels not being visible from ground level | Improvement of the visual design, matching local styles and colours and creating an energy district | Visual compatibility based on coplanarity, grouping of panels, symmetry, colour matching, reduction of reflectivity |
| | Risk of spatial impact | No impact on surroundings of the building | No risk. The handling of the existing building fabric, the design quality of BIPV and the energy concept in an entire area have supposed a high energy efficiency in operation | No changes in the geometrical relationships between the building and the surroundings |

Source: Elaboration of the authors.

### *5.3. Economic Viability*

The investment for *Crichton Castle* comes from within the organization, with a view to creating a greener and more sustainable estate. The total cost of the 2019 installation £8580 (10,000€) for the new batteries, new panels, their installation as well as the charge controllers. The cables, battery housings, fixings, and inverter were retained from the 2005 installation. The old panels were retained and are currently in holding for future installation, as there is still a significant portion of the 25-year lifespan left. The reason for the replacement was the desire to obtain 100% of the energy required from the panels and to only keep the oil generator as a backup. Since the site and maintenance is managed on an ad-hoc basis and by in-house staff, this is done in conjunction with other tasks around the monument related to the conservation of the historic fabric. As such, there are no additional maintenance costs associated with this.

The *Solar Silo* refurbishment project is being funded as a pilot project (the 2000-Watt Society Pilot Project) by the University of Applied Sciences Northwestern Switzerland (FHNW), for the coloured BIPV, BES, and monitoring. It is a successful partnership connecting scientists with planners and administrators from the Canton of Basel-Stadt. The consortium of institutional partners and research aims to use the City of Basel, and this former industrial area in Switzerland, as an experimentation arena for sustainability and advancing technologies in transport, buildings, urban development, and energy [98]. Canton Basel has financed the BIPV system with CHF 150,000. The BIPV system costs about CHF 125,000, which is a relatively high price for similar construction systems considering current prices (ventilated BIPV facades/roof or conventional ventilated façade systems) [92]. It is true that the building dates from 2014 when the price was higher and that BIPV prices today have fallen. Moreover, it should be considered that it is an experimental and highly innovative BIPV prototype. There is no information available about economical return cost or running and operating cost. However, the innovative nature of the solar system used and the substantial renovation of the neighbourhood justify the major investment cost and the necessity of public subsidies.

The BIPV system for *Villa Castelli* cost approximately 43,500€. Due to their ultra-light weight, the modules were more manageable than traditional walkable modules: this overall reduced installation time and costs. The maintenance of the system used is similar to that of a system with ordinary walkable panels. The plastic film used as an encapsulant for the silicon cells, even with a long lifetime as guaranteed by the manufacturers, could deteriorate more quickly than traditional systems using glass supports. This might affect operating costs when considering an extended life cycle of the system or would limit the reuse of the panels in other contexts if that foreseen.

A brief overview of the assessment is reported in Table 8.

**Table 8.** Risk–benefit scheme for assessing the economic viability of solar solution in historic buildings and sites: detailed evaluation of the selected buildings.

| Assessment Category | Assessment Criteria | Crichton Castle | Solar Silo | Villa Castelli |
|---|---|---|---|---|
| **Economic viability** | Capital costs | 215 €/m² (installed in 2019) | 786 CHF/m² (≅720€/m²) (installed in 2014) | 490 €/m² (installed in 2014) |
| | Operating costs | Data not available | Data not available | Data not available |
| | Economical return | Data not available | Data not available | Data not available |
| | Economic savings | Data not available | The building was previously a not used industrial silo and had no use or energy consumption | Data not available (the building was rarely used before refurbishment) |

Source: Elaboration of the authors.

*5.4. Energy*

At *Crichton Castle,* while old panels generate a maximum of 1,0 kWp (2005) by comparison, the new panels generate a maximum of 1,8 kWp of peak production (2019). It has a maximum power point tracking (MPPT) built into the system. The energy is stored in six deep cycle batteries. While the exact amount of energy used per year is highly variable and not available at this point, 100% of the energy during normal operation is produced by the solar panels. The energy used is metered at the batteries. Any surplus energy collected but not stored and any energy leaking out from the batteries is not measured and is wasted. While LCA is not available, the product is Cradle to Cradle CertifiedTM Silver, a certification awarded if the materials and methods are safe and enable a circular economy.

The solar plant of *Solar Silo* generates 16,400 kWh of solar power annually that covers around 37% of the building's total energy requirement of 44,400 kWh/y. The effectiveness of using energy storage is being assessed. To optimize the self-consumption of electricity in the area, a "second-life battery storage" made of used lithium-ion batteries from electro-mobility were installed [99]. Monitoring records the performance data of each BIPV module. The measurements serve to optimize the 24 kWp total PV system installed and to investigate the effects of the different colours on the PV performance. A total of 77 m² of solar panels were installed in the northern and southern facade with a nominal power of 11.2 kW, while 88 m² were installed with 12.8 kW, respectively. Thanks to the interventions made, a high-energy performance rate was achieved (66 kWh/m²yr) and received the "Swiss Solar Prize 2015" for design quality of solar PV.

The BIPV system of *Villa Castelli* has a nominal power of 10 kW and it is connected to an electrical supply with a committed power of 16.5 kW. Modules of three different sizes have been installed with surfaces of 0.6, 0.54, and 0.6 m² with a power of 80, 72, and 45 W, respectively. In total, there are 144 items divided into six strings. The total surface of the installed modules is 89 m² and the modules' efficiency is about 13.3%. To avoid consequent mismatching losses, specific plant solutions have been implemented. The PV installations with different orientations were connected to separate inverters. Further considerations about the reliability (and consequently the energy production) of the entire BIPV system led to the choice to decentralise DC/AC conversion based on three inverters rather than one. This way, any possible converter failure will not affect the whole plant production but only that of the corresponding subfield. Furthermore, to reduce energy losses on the PV generator and, thus, maximize energy production, the following design choices have been made: (i) the electrical characteristics of the modules (short-circuit current and current at maximum power) and of the strings (no-load voltage and voltage at maximum power) that are part of the same string are similar to each other to limit the power losses due to current mismatching; (ii) the sizing of the electrical conduits has been made in such a way as to limit voltage drops to a maximum of 2% of the rated voltage of the circuit, but also to ensure a lifespan of the conduits at least equal to that of the plant (30 years) taking into account their particular installation conditions; and (iii) the voltage of the PV generator was dimensioned in such a way as to reduce the currents involved and, therefore, the power losses due to the Joule effect. Considering the location of the villa, the shading due to trees in the garden, the orientation of the modules and their characteristics, the net of useful losses is 19.83%. For these reasons, the energy produced by the plant on an annual basis (Ep, a) is 10,543.99 kWh. The PV system manages to cover more than half of the energy needs of the building.

An overview of the assessment is reported in Table 9.

**Table 9.** Risk–benefit scheme for assessing the energy performances of solar solution in historic buildings and sites: detailed evaluation of the selected buildings.

| Assessment Category | Assessment Criteria | Crichton Castle | Solar Silo | Villa Castelli |
|---|---|---|---|---|
| **Energy** | Energy performance and operational energy demand in terms of primary energy rating | Nominal power: 1.8 kWp (new intervention 2019) No data on energy production 100% of the energy consumption | Nominal power: 24 kWp Energy produced by the plant on an annual basis Ep,y = 16,400.00 kWh y 37% of the energy consumptions | Nominal power: 10 kWp Energy produced by the plant on an annual basis Ep,y = 10,543.99 kWh y 55% of the energy consumptions |
| | LCE demand in terms of use of renewable and non-renewable primary energy | Data not available | Data not available | Data not available |

Source: Elaboration of the authors.

*5.5. Indoor Environmental Quality and Impact on the Outdoor Environment*

In all cases, there is no change to the indoor environment as a result of the PV installation. In *Crichton Castle* the solar panels are replacing an oil generator and are now producing 100% of the energy used during the time the monument is open to visitors. As such, there is a great reduction in the total use of oil and emission of greenhouse gases during the normal operation of the panels.

All retrofitting measures implemented on the *Solar Silo* building due the change in use of the building contribute to increase the users' comfort of living by increasing thermal and sound protection, and to guarantee better natural illumination and ventilation. Furthermore, a ventilated and well-insulated BIPV solar roof and façade contribute to avoiding overheating the indoor spaces and to increase energy efficiency of the building [93]. In the Solar Silo, many of the core components of solar panels can be recycled on their own, such as metal, glass, plastic, and wiring. Silicon cells and silicon wafers are not recyclable, but dedicated recycling companies are able to reuse them by melting down and reclaiming the silicon and various metals.

Similarly, the BIPV roof of *Villa Castelli* has an indirect benefit on indoor environmental quality because the energy produced by the BIPV system is used to power specific active systems for temperature regulation and mechanical ventilation, which provides, together with other passive systems, a satisfactory comfort level for the occupants. The data on the impact of the outdoor environment are not available for all the case studies. According to the producer, parts of PV panel components installed in Villa Castelli are produced locally. That reduces the environmental impact of their production.

An overview of the assessment is reported in Table 10.

**Table 10.** Risk–benefit scheme for assessing the indoor and the outdoor environmental quality of solar solution in historic buildings and sites: detailed evaluation of the selected buildings.

| Assessment Category | Assessment Criteria | Crichton Castle | Solar Silo | Villa Castelli |
|---|---|---|---|---|
| **Indoor environmental (IE) quality** | IE conditions suitable for achieving good occupant comfort levels | No changes | Ventilated and well insulated BIPV solar roof and façade avoid overheating of indoor spaces | No changes |
| **Impact on the outdoor environment** | Greenhouse gas emissions from measures | Data not available | Data not available | Data not available |
| | Natural resources | Data not available | Data not available | Data not available |

Source: Elaboration of the authors.

*5.6. Aspects of Use*

Due to the installation of the solar panels at *Crichton Castle*, there is a reduced risk of the users to be exposed to the fuel during delivery (staff only) as well as the fumes produced by the generator (staff and visitors). The considerable reduction in noise can also be considered a positive effect on the users. In addition, the connection of the generator to produce electricity required staff to climb a ladder and run a cable through a small window. As such, not running the generator avoids the inconvenience and potential risk associated with this task. There is no direct user control and monitoring of the solar panels. The electricity meter measuring the electricity used from the batteries is checked periodically and no remote access to this data is available.

The *Solar Silo* building, which belongs to an industrial cultural heritage area, came back to life after the energy retrofit interventions and is being used as scientific test site. As previously explained, as part of a "P+D" (pilot and demonstration) program of Swiss confederation, Solar Silo is a cutting-edge pilot building demonstrating various innovations in energy efficiency and progress engineering technologies [98]. The pilot demo site focused mainly on the trial of two emerging technologies: (i) coloured BIPV modules on buildings measuring their technical performances, and (ii) to assess the techno-economic potential of second-life batteries using EV lithium-ion batteries to store excess onsite RES in buildings [96,98,99]. To verify changes in solar modules performances due to different colours, a monitoring system collecting data (fifteen-minute intervals) is used to analyse results. Besides, data is collected to evaluate battery behaviour. The tenants do not have access to the data, which are only gathered for scientific purposes. The different motivations of the university and city planners led to contrasting relevance aspects and time horizon results. This resulted in the monitoring and evaluation of the building energy performance being neglected in some cases. An active engagement of citizens into the project design and implementation seems to be important and the role of this pilot building as an example for sustainable industry innovation linked to the valuable scientific results will ensure the expected large-scale implementation in other urban regeneration and renovation projects of historic buildings [99].

In *Villa Castelli,* there is no influence on the use and the users of the building as well as no significant changes of use. To favour the management and the control of BIPV systems by building user, a system for production and consumption monitoring and measuring was also installed along with a series of radio sockets that allow for direct management of the plant's privileged loads. The monitoring system receives the PV production data and the data from the grid continuously. A forecast of output can be determined through the available meteorological data. Based on the latter, the automatic activation of controlled loads is set. By analysing both production and consumption data, self-consumption can be increased dynamically, especially when energy is produced in excess.

A brief overview of the assessment is reported in Table 11.

**Table 11.** Risk–benefit scheme for assessing the aspects of use of solar solution in historic buildings and sites: detailed evaluation of the selected buildings.

| Assessment Category | Assessment Criteria | Crichton Castle | Solar Silo | Villa Castelli |
|---|---|---|---|---|
| Aspects of use | Influence on the use and the users of the building | Reduced hazard risk to staff and visitors | No influences | No influences |
| | Consequences of change of use | No change | As part of an industrial heritage, the building came back to life after the energy retrofit interventions and is being used as pilot and demonstration test site | No changes |
| | Ability of building users to manage and operate control systems | No user controls | Data not available | Automated control system |

Source: Elaboration of the authors.

### *5.7. Summary of Findings*

In conclusion, the use of three different case studies, selected based on different protection levels, approaches to retrofit intervention and solar implementation, has allowed in-depth assessment of real implementations of solar systems in historic buildings. This activity has involved both quantitative and qualitative assessment, which has been possible with detailed information about the projects studied. Thanks to this analysis, the experts have been able to verify point by point the suitability of the proposed evaluation criteria, confirming that the selected criteria for solar systems suited the evaluated project.

Through the analysis of the proposed Likert value scale, aspects of greater benefit or greater risk have been evidenced, as well as factors that have no influence on the criteria analysed based on technical compatibility, function, or energy efficiency and the heritage significance of the building and its settings. Due to the in-depth analysis of these examples, other aspects, such as the economic viability, indoor environmental (IE) quality, the impact on the outdoor environment, or aspect of use have also been verified.

Results of the comparison evidence that there is a lack of data relating especially to the economic viability (operating costs, economical return or economic savings) in addition to data related to LCE demand in terms of use of renewable and non-renewable primary energy. Furthermore, there is no information found about the impact on the outdoor environment as it refers to greenhouse gas emissions or the use of natural resources in the solar systems used, based on an LCA analysis available.

Other data, like capital cost of the solar plant or the risk of reduction efficiency due to the solar PV and the mounting system used, seems to be a potential risk only in certain case. For example, in the Solar Silo project, the cost has been higher than usual because the solar BIPV implemented in highly innovative and it is a pilot project; in the case of Villa Castelli there is a moderate risk for reduction efficiency due to the higher decay of the polymer used in the solar panels.

## 6. Discussion and Conclusions

Solar energy, next to other renewable energies, is most suitable for use in buildings. Additionally, other possible sustainable sources of energy should also be considered for their direct application in the built heritage, such as geothermal or biomass, whose impact on the built environment and the landscape is much less than that of solar panels [8,47]. However, in many cases, a well-implemented local district heating network needs to be envisaged [100]. For the improvement of energy performance of historic buildings and for the conservation of cultural heritage, the standard EN 16883:2017 [16] proposes a working procedure that takes into account the cultural value of the building. Based on an investigation, analysis, and documentation of the building, a selection of compatible measures to improve energy performance are assessed using assessment criteria that consider heritage significance and conservation opportunities and constraints. However, there is still a long process of implementation and adaptation. For this reason, a step-by-step process involving an interdisciplinary team is necessary to review the procedure and to adapt the criteria to the retrofitting measures. Experts from all over the world in the fields of sustainability, energy, and heritage are working on reviewing the standard in the collaborative research project by the International Energy Agency IEA-SHC Task 59/IEA-EBC Annex 76 [17]. This paper analysed and discussed an assessment procedure for the integration of renewable solar systems in historic buildings and conservation areas, according to the (tabular) risk–benefit scheme developed by the standard EN-16883:2017 [16]. The standard scheme was tailored for solar RES systems by discarding inappropriate criteria and introducing other criteria internationally considered for these systems. To verify and validate its applicability to heritage contexts, quick and detailed assessment approaches were used. A multidisciplinary team of the Working Group on “Solar Energies” of the IEA-SHC Task 59 [17] composed of experts in the fields of energy, sustainability, and heritage has been involved in the application of both approaches. Experts in other fields (e.g., HVAC and walls) within IEA-SHC Task 59 activities have already tested a similar methodological procedure introduced in this research [70,71], proving the validity of the method.

The first step of the selection of possible compatible solutions for energy retrofitting is to eliminate any measures that are inappropriate, based on assessment criteria fixed by the standard and subsequently adapted by the experts of the working group, as has been explained in detail in Section 2. Based on the assessment criteria list, a quick assessment is then undertaken by the expert team using experience rather than thorough analysis. The quick assessment dealt with nineteen case studies from four different nations of different building typologies, functions, protection levels, and types of the solar system installed [101]. A variety of different buildings have been intentionally selected to verify that the method is applicable to all types of buildings and modes of intervention for the energy retrofitting of historic buildings, applying in this case solar technologies. The analysed case studies fall into two roughly equal groups of type of use (continuous or discontinuous). Trends regarding BIPV or BAPV systems, listed or unlisted buildings, roof-mounted or façade-mounted systems were identified, as follows:

- A multidisciplinary approach is necessary to have a coherent and consistent evaluation of RES systems integrated in a heritage context, as their design, installation, assessment, and utilization requires different backgrounds and approaches;

- For technical compatibility, the criteria that received a low rating were risk reduction, which was lower for listed buildings;
- Information is not homogeneous for all the assessment categories;
- Economic aspects are critical for all case studies, mostly because of a general lack of information and benchmarks;
- Environmental sustainability on RES technologies in a heritage context is a critical point;
- Few data on LCA were found for real cases. Available information is still available from research and manufacturers' only, while product certification in this sense is vital;
- Evaluating the environmental impact of these RES solutions in these contexts requires specific data and applied cases. This should be a topic for further research;
- RES solutions generally do not have an impact on the indoor environmental quality of the building;
- RES solutions do not have a specific influence on the use or the user of the building;
- Home-automated controls for the RES system are only rarely installed.

The second step, as the standard proposes, involves both quantitative and qualitative assessment. At this point, experts must verify if the selected criteria are suited to the size and complexity of the project, and an extended technical and economic assessment may be needed to make a final conclusion. The detailed assessment, as explained in Section 5, dealt with three case studies from different countries, typologies, protection levels, functions, solar technology types, and solar applications. Due to the differences between the case studies selected for the detailed assessment, no direct comparison is intended. Each specific case study has been chosen in relation to its information availability to the authors. Detailed technical indications, specific solutions, and the suitability of the procedure to different context were the main results of the analysis. Detailed assessment allows for in-depth analysis of aspects that were highlighted in the quick assessment as critical points, as for example, cost or the use of natural resources. In the examples discussed in this paper, the standard has helped to showcase how different scenarios influence the choice of solar technology. For example, the protection standard of the building had a great influence on the position of the system. Similarly, the use of the building meant that the system was able to supply a higher percentage of the energy used in Crichton Castle compared to the others. Additional points related to the different assessment criteria can be highlighted:

- Technical compatibility and heritage significance aspects can be assessed through a better understanding of the technical details of the project and the specific documents related to the heritage protection of the building. For example, in the listed Crichton Castle, the panels were positioned to not be visible from ground level in order not to disturb the aesthetics of the site;
- Technical compatibility concerns the assessment of the system's design, which implies the absence of structural, hygrothermal, and fire risks and attention to reversibility as a common element in the design of PV systems in prestigious contexts;
- Heritage significance assessment of the building and its settings is difficult, even after an in-depth examination. A proper and consistent assessment occurs only through a multidisciplinary team. For example, in Villa Castelli, a team of experts made up of the designer, the local heritage authority, a roof manufacturer, and a PV manufacturer from the sailing sector designed the custom BIPV components using thin dark flexible panels generally used for boating that were positioned on the similarly coloured roof. This allowed for a lower aesthetic impact of the panels;

- The risk of material impact is lower in roof-attached than in roof-integrated, because it is a highly reversible solution. In some cases, this reversibility is secondary to other concerns, as in the Solar Silo. Therefore, this procedure can highlight situations when one method is more suitable;
- BAPV solutions could be considered as an excellent form of PV system integration if conservative aspects are considered along with technological aspects;
- Information about economic or environmental aspects is not always available and rarely considered also in a detailed evaluation of PV systems. Creating a benchmark on costs can be difficult. In addition, actual benchmarks relate mostly to new buildings, so proper databases that collect historic buildings or buildings in conservation areas would be beneficial;
- Energy data is always present, but not homogeneous. This is also due to the varied use of the analysed buildings, meaning that the energy consumption is vastly different;
- No particular information on the indoor environment was found because solar RES solutions do not have a direct impact on this. Therefore, this part of the standard is less applicable for solar solutions;
- Impact on the outdoor environment, environmental sustainability, and LCA remains a weak point also in the detailed assessment due to lack of information about this topic;
- The most popular tool for RES system management installed in most of the cases was a display where the production of the system could be evaluated, or the correct function of the system could be confirmed.

Limitations of the two assessment approaches were also identified: generally, the experts see the quick assessment as an excellent way to evaluate a solution. The detailed assessment requires a thorough knowledge of the building, its history, design, and construction technology involving several professionals (i.e., architects, engineers, public bodies related to building protection). This process takes considerable time and effort. On the contrary, a quick evaluation is based on the most easily accessible data and results in a less time-consuming and labour intensive approach. However, at the same time, it is more difficult to ensure and show the objectivity of the evaluation. Therefore, it is recommended to use the detailed assessment when an in-depth evaluation is needed and see the quick assessment more as a checklist that can help in a building retrofit decision process. Overall, both quick and detailed assessments were useful because they offered a cross-disciplinary overview of the adopted PV solution. International guidelines and standards put emphasis mainly on conservative aspects rather than technological and aesthetic aspects. Similarly, Heritage Authorities (HA) and, consequently, Public Administrations (PA) focus on conservation primarily during the authorization procedures. Nevertheless, it is of fundamental importance that energy production-related aspects, technical compatibility aspects like system durability, and environmental aspects like environmental liability are considered. Usually, clients consider economic and performance aspects the most, even if that affects aesthetic integration, which requires attention to targeted historical references and conservative aspects. Focusing only on economic and performances aspects might affect HA authorization. It could also lead to conservation areas degeneration, especially prestigious areas that are not under any form of protection yet. These assessments are also considered useful for designers who will deal with all the HA and clients' requests together, so the assessment can be used as reference guide or checklist.

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## References

1. European Commission. *Impact Assessment for the Amendment of the Energy Performance of Buildings Directive*; European Commission: Brussels, Belgium, 2016.
2. Publications Office of the European Union. *Energy, Transport and Environment Statistics 2019 Edition*; Theme: Environment and Energy; Collection: Statistical Books 2019; Imprimeries Bietlot Frères: Charleroi, Belgium, 2019; ISBN 978-92-76-10971-6, doi:10.2785/660147.
3. European Union. EU Directive 2018/844 of the European Parliament and of the Council of 30 May 2018 Amending Directive 2010/31/EU on the Energy Performance of Buildings and Directive 2012/27/EU on Energy Efficiency. *Off. J. Eur. Union* **2018**, *L156/75*. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2018.156.01.0075.01.ENG (accessed on 15 April 2021).
4. European Commission. *EC 2020 Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. A Renovation Wave for Europe–Greening Our Buildings, Creating Jobs, Improving Lives*; European Commission: Brussels, Belgium, 2020.
5. European Commission. *EC 2019 Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal*; European Commission: Brussels, Belgium, 2019.
6. New European Bauhaus Initiative. Available online: https://europa.eu/new-european-bauhaus/about/about-initiative_en (accessed on 15 April 2021).
7. Borrallo-Jiménez, M.; LopezdeAsiain, M.; Herrera-Limones, R.; Lumbreras Arcos, M. Towards a circular economy for the city of Seville: The method for developing a guide for a more sustainable architecture and urbanism (GAUS). *Sustainability* **2020**, *12*, 7421, doi:10.3390/su12187421.
8. Viola, S.; De Medici, S.; Riganti, P. The circular economy and built environment. Maintenance, rehabilitation and adaptive reuse: Challenging strategies for closing loops. In *An Introduction to the Circular Economy*; Nova Science Publishers: Hauppauge, NY, USA, 2021.
9. European Commission, Directorate-General for Communication. The Next Generation EU Recovery Plan. Available online: https://ec.europa.eu/info/strategy/recovery-plan-europe_en (accessed on 15 April 2021).

10. Halliday, S. *Technical Paper 6: Indoor Air Quality and Energy Efficiency in Traditional Buildings*; Historic Scotland: Edinburgh, UK, 2009. Available online: https://www.historicenvironment.scot/archives-and-research/publications/publication/?publicationId=e079f85f-4aa6-4218-b3c9-a59400e211fc (accessed on 15 April 2021).
11. Humphreys, M.; Nicol, F.; Roaf, S. *Technical Paper 14: Keeping Warm in Cooler House: Creating Thermal Comfort with Background Heating and Local Supplementary Warmth*; Historic Scotland: Edinburgh, UK, 2011. Available online: https://www.historicenvironment.scot/archives-and-research/publications/publication/?publicationId=f2f2ebfd-ff37-4417-be92-a59400bb2665 (accessed on 15 April 2021).
12. Hobday, R. *Technical Paper 12: Indoor Environmental Quality in Refurbishment*; Historic Scotland: Edinburgh, UK, 2011. Available online: https://www.historicenvironment.scot/archives-and-research/publications/publication/?publicationId=a753afcc-c9a9-4059-afd9-a59400b55838 (accessed on 15 April 2021).
13. López-Escamilla, Á.; Herrera-Limones, R.; León-Rodríguez, Á.L.; Torres-García, M. Environmental comfort as a sustainable strategy for housing integration: The AURA 1.0 prototype for social housing. *Appl. Sci*. **2020**, *10*, 7734.
14. Herrera-Limones, R.; Millán-Jiménez, A.; López-Escamilla, Á.; Torres-García, M. Health and habitability in the solar decathlon university competitions: Statistical quantification and real influence on comfort conditions. *Int. J. Environ. Res. Public Health* **2020**, *17*, 5926, doi:10.3390/ijerph17165926.
15. Ortiz, M.A.; Kurvers, S.R.; Bluyssen, P.M. A review of comfort, health, and energy use: Understanding daily energy use and wellbeing for the development of a new approach to study comfort. *Energy Build*. **2017**, *152*, 323–335, doi:10.1016/j.enbuild.2017.07.060.
16. Standard EN 16883:2017. *Conservation of Cultural Heritage. Guidelines for Improving the Energy Performance of Historic Buildings*; Comitè Européen de Normalization (CEN): Bruxelles, Belgium, 2017.
17. IEA-SHC Task 59: Deep Renovation of Historic Buildings towards Lowest Possible Energy Demand and $CO_2$ Emission (nZEB). Available online: http://task59.iea-shc.org (accessed on 24 April 2021).
18. *Integrated Conservation Chart*; Council of Europe: Amsterdam, The Netherlands, 1975.
19. Moschella, A.; Salemi, A., Lo Faro, A.; Sanfilippo, G.; Detommaso, M.; Privitera, A. Historic buildings in Mediterranean area and solar thermal technologies: Architectural integration vs. preservation criteria. *Energy Procedia* **2013**, *42*, 416–425.
20. Franco, G.; Magrini, A.; Cartesegna, M.; Guerrini, M. Towards a systematic approach for energy refurbishment of historical buildings. The case study of Albergo dei Poveri in Genoa, Italy. *Energy Build*. **2015**, *95*, 153–159, ISSN 0378-7788.
21. Schibuola, L.; Scarpa, M.; Tambani, C. Innovative technologies for energy retrofit of historic buildings: An experimental validation. *J. Cult. Herit.* **2018**, *30*, 147–154.
22. Cabeza, L.F.; de Gracia, A.; Pisello, A.L. Integration of renewable technologies in historical and heritage buildings: A review. *Energy Build.* **2018**, *177*, 96–111, doi:10.1016/j.enbuild.2018.07.058.
23. European Union. EU Directive 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources; European Union: Luxembourg, 2018.
24. Lucchi, E.; Polo López, C.S.; Franco, G. A conceptual framework on the integration of solar systems in heritage sites and buildings. *Mater. Sci. Eng.* **2020**, *949*, 012113.
25. Polo López, C.S.; Lucchi, E.; Franco, G. Acceptance of building integrate photovoltaic (BIPV) in heritage buildings and landscapes: Potentials, barriers and assessments criteria. In Proceedings of the 8th Euro-American Congress on Construction Pathology, Rehabilitation Technology and Heritage Management, REHABEND 2020, Granada, Spain, 24–27 May 2020.
26. De Medici, S. Italian architectural heritage and photovoltaic systems. Matching style with sustainability. *Sustainability* **2021**, *13*, 2108, doi:10.3390/su13042108.
27. ATLAS. Advanced Tools for Low-Carbon, High-Value Development of Historic Architecture in the Alpine Space. Available online: https://www.alpine-space.eu/projects/atlas/en/home (accessed on 29 April 2021).
28. SECHURBA. Sustainable Energy Communities in Historic Urban Areas. Available online: http://www.itabc.cnr.it/progetti/sustainable-energy-communities-in-historic-urban-a (accessed on 29 September 2020).
29. 3ENCULT. Efficient Energy for EU Cultural Heritage. Available online: http://www.3encult.eu (accessed on 07 October 2020).
30. BIPV Meets History. Value-Chain Creation for the Building Integrated Photovoltaics in the Energy Retrofit of Transnational Historic Buildings. Available online: http://www.bipvmeetshistory.eu (accessed on 7 October 2020).
31. European Union. European Parliament directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending directive 2012/27/EU on energy efficiency. *Off. J. Eur. Union*. **2018**. Available online at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0210.01.ENG (accessed on 26 February 2021).
32. Lucchi, E.; Garegnani, G.; Maturi, L.; Moser, D. Architectural integration of photovoltaic systems in historic districts. The case study of Santiago de Compostela. In *Proceedings of the International Conference on Energy Efficiency and Historic Buildings, Proceedings of the International Conference on Energy Efficiency and Historic Buildings, Madrid, Spain 29–30 September 2014;* Fundación de Casas Historicas y Singulares and Fundación Ars Civilis: Madrid, Spain, 2014; ISBN 978-84-617-3440-5.
33. PV Accept. Available online: http://www.pvaccept.de (accessed on 7 October 2020).
34. IEA-PVPS T15. Enabling Framework for the Acceleration of BIPV. Available online: http://www.iea-pvps.org (accessed on 7 October 2020).
35. EFFESUS. Energy Efficiency for EU Historic Districts' Sustainability. Available online: http://www.effesus.eu (accessed on 7 October 2020).
36. IEA-SHC T20. Solar Energy in Building Renovation. Available online: https://task20.iea-shc.org/ (accessed on 6 May 2021).

37. IEA-SHC T37. Advanced Housing Renovation with Solar & Conservation. Available online: http://task37.iea-shc.org/ (accessed on 7 October 2020).
38. IEA-SHC T41. Solar Energy and Architecture. Available online: http://task41.iea-shc.org/ (accessed on 7 October 2020).
39. Polo López, C.; Frontini, F.; Ferrazzo, M.; Jean, G.; Kaehr, P.; Generelli, M.; Gambato, C.; Zanetti, I. *Optimization of Energy Interventions in Building of Historical-Architectonical Value*; SUPSI: Manno, Switzerland, 2014.
40. SuRIHB. Sustainable Renovation of Historical Buildings. Available online: http://www.ccem.ch/MediaBoard/SuRHiB_webupdate.pdf (accessed on 23 April 2021).
41. UrbanSol+. Solar Thermal in Major Renovations and Protected Urban Areas. Available online: https://www.rhc-platform.org/project/solar-thermal-in-major-renovations-and-protected-urban-areas/ (accessed on 6 May 2021).
42. IEA-SHC T51. Solar Energy in Urban Planning. Available online: http://task51.iea-shc.org/ (accessed on 28 April 2021).
43. REHIB. *Renewable Energies in Historical Buildings*; SOC: Hartford, CT, USA, 2021.
44. BIPV UPpeal. *Boosting the Outdoor PV Integration Lab by Acquiring and Testing Innovative BIPV Products*; BIPV: Grass Valley, CA, USA, 2021.
45. Bellia, L.; d'Ambrosio Alfano, F.R.; Giordano, J.; Ianniello, E.; Riccio, G. Energy requalification of a historical building: A case study. *Energy Build.* **2015**, *95*, 184–189, doi:10.1016/j.enbuild.2014.10.060.
46. Franco, G.; Magrini, A. *Historical Buildings and Energy*; Springer International Publishing: Cham, Switzerland, 2017; ISBN 978-3-319-52613-3.
47. Rosa, F. Building-Integrated Photovoltaics (BIPV) in historical buildings: Opportunities and constraints. *Energies* **2020**, *13*, 3628.
48. Bonomo, P.; De Berardinis, P. PV Integration in minor historical centers: Proposal of guide criteria in post-earthquake reconstruction planning. *Energy Procedia* **2014**, *48*, 1549–1558.
49. Pelle, M.; Lucchi, E.; Maturi, L., Astigarraga, A., Causone, F. Coloured BIPV technologies: Methodological and experimental assessment for architecturally sensitive areas. *Energies* **2020**, *13*, 4506.
50. ICOMOS EU. *International Charters for Conservation and Restoration*; ICOMOS: Paris, France, 2014; Volume 1, p. 179, ISBN 3-87490-676-0. Available online: https://openarchive.icomos.org/id/eprint/431 (accessed on 28 April 2021).
51. ICOMOS EU. *The Burra Charter: The Australia ICOMOS Charter for Places of Cultural Significance*; ICOMOS: Burwood, Australia, 2013. Available online: https://openarchive.icomos.org/id/eprint/2145 (accessed on 28 April 2021).
52. Jafar, R. Development of the theories of cultural heritage conservation in Europe: A survey of 19th and 20th century theories. In Proceedings of the 4th International Congress on Civil Engineering, Architecture & Urban Development, Tehran, Iran, 27–29 December 2016.
53. Webb, A.L. Energy Retrofits in historic and traditional buildings: A review of problems and methods. *Renew. Sustain. Energy Rev*. **2017**, *77*, 748–759, doi:10.1016/j.rser.2017.01.145.
54. Ascione, F.; Cheche, N.; De Masi, RF.; Minichiello, F.; Vanoli GP, Design the refurbishment of historic buildings with the cost-optimal methodology: The case study of a XV century Italian building. *Energy Build*. **2015**, *99*, 162–176, doi:10.1016/j.enbuild.2015.04.027.
55. The Charter of Krakow 2000. Principles for Conservation and Restoration of Built Heritage. Available online: http://smartheritage.com/wp-content/uploads/2015/03/KRAKOV-CHARTER-2000.pdf (accessed on 16 April 2021).
56. Della Torre, S. A coevolutionary approach to the reuse of built cultural heritage. In *Il Patrimonio Culturale in Mutamento. Le Sfide Dell'uso;* Biscontin, G., Driussi, G., Eds.; Arcadia Ricerche: Venezia, Italy, 2019; pp. 25–34.
57. De Berardinis, P.; Bonomo, P. BiPV in the refurbishment of minor historical centres. The project of integrability between standard and customized technology. *J. Archit. Civ. Eng*. **2013**, *9*, 1073–1079.
58. Corti, P.; Bonomo, P.; Zanetti, I.; Polo, C.S.; Frontini, F. Overcoming barriers for the BIPV diffusion at urban and building scale, 2018, In Proceedings of the 20 Status-Seminar «Forschen für den Bau im Kontext von Energie und Umwelt», Zürich, Switzerland, 6–7 September 2018.
59. Polo López, C.S.; Frontini, F. Energy Efficiency and Renewable Solar Energy Integration in Heritage Historic Buildings. *Energy Procedia* **2014**, *48*, 1493–1502, doi:10.1016/j.egypro.2014.02.169.
60. Zanetti, I.; Bonomo, P.; Frontini, F.; Saretta, E.; van den Donker, M.; Vossen, F.; Folkerts, W. Building Integrated Photovoltaics: Product Overview for Solar Building Skins. Status Report 2017 SUPSI-SEAC, 2017. Available online: http://www.bipv.ch/images/Report%202017_SUPSI_SEAC_BIPV.pdf (accessed on 23 December 2020).
61. Saretta, E.; Bonomo, P.; Frontini, F. Active BIPV glass facades: Current trends of innovation. In *Conference Proceedings. #GPD2017. All Eyes on Glass, Proceedings of the GPD Glass Performance Days 2017, Tampere, Finland, 28–30 June 2017*; Glass Performance Days: Tampere, Finland 2017; pp. 2–7. Available online: http://www.gpd.fi/GPD2017_proceedings_book/GPD2017_conference_book.pdf (accessed on 28 April 2021).
62. Eder, G.; Peharz, G.; Trattnig, R.; Bonomo, P.; Saretta, E.; Frontini, F.; Polo Lopez, C.S.; Rose Wilson, H.; Eisenlohr, J.; Martín Chivelet, N.; et al. *Coloured BIPV. Market, Research and Development*; International Energy Agency: Paris, France, 2019. Available online: https://iea-pvps.org/wp-content/uploads/2020/01/IEA-PVPS_15_R07_Coloured_BIPV_report.pdf (accessed on 29 September 2020).
63. Historic England (HE). *Energy Efficiency and Historic Buildings: Solar Electric (Photovoltaics)*; Historic England: Swindon, UK, 2018.
64. Kandt, A.; Hotchkiss, E.; Walker, A.; Buddenborg, J.; Lindberg, J. *Implementing Solar PV Projects on Historic Buildings and in HistoricDistricts*; Technical Report NREL/TP-7A40-51297: Golden, CO, USA, September 2011

65. de Santoli, L. Guidelines on energy efficiency of cultural heritage, *Energy Build.* **2015**, *86*, 534–540, doi:10.1016/j.enbuild.2014.10.050.
66. Ministero per i Beni e le Attività Culturali (MiBACT). *Linee di Indirizzo per il Miglioramento Dell'efficienza Energetica del Patrimonio Culturale. Architettura, Centri e Nuclei Storici ed Urbani*; MiBACT: Roma, Italy, 2015.
67. Federal Office of Culture. *Cultura Solare–Conciliare Energia Solare e Cultura Della Costruzione*; Federal Office of Culture (OFC): Bern, Switzerland, 2019; p. 60. Available online: https://www.bak.admin.ch/culturasolare (accessed on 30 December 2020).
68. Camponovo, R.; Frei, A.; Desthieux, G.; Dubois, D.; Chognard, S.; Rinquet, L.; Frontini, F.; Polo López, C.S.; Delucchi, A.; Bourgeois, C.; et al. *La Planification Solaire Globale, une Démarche au Service de la Transition Énergétique et D'une Culture du Bâti de Qualité, Rapport D'étude;* Federal Office of Culture (OFC): Bern, Switzerland, 2018.
69. Buda, A.; de Place Hansen, E.J.; Rieser, A.; Giancola, E.; Pracchi, V.N.; Mauri, S.; Marincioni, V.; Gori, V.; Fouseki, K.; Polo López, C.S.; et al. Conservation-compatible retrofit solutions in historic buildings: An integrated approach. *Sustainability* **2021**, *13*, 2927, doi:10.3390/su13052927.
70. Marincioni, V.; Gori, V.; de Place Hansen, E.J.; Herrera-Avellanosa, D.; Mauri, S.; Giancola, E.; Egusquiza, A.; Buda, A.; Leonardi, E.; Rieser, A. How can scientific literature support decision-making in the renovation of historic buildings? An evidence-based approach for improving the performance of walls. *Sustainability* **2021**, *13*, 2266, doi:10.3390/su13042266.
71. Rieser, A.; Pfluger, R.; Troi, A.; Herrera-Avellanosa, D.; Thomsen, K.E.; Rose, J.; Arsan, Z.D.; Akkurt, G.G.; Kopeinig, G.; Guyot, G.; et al. Integration of energy-efficient ventilation systems in historic buildings—Review and proposal of a systematic intervention approach. *Sustainability* **2021**, *13*, 2325, doi:10.3390/su13042325.
72. Bonomo, P.; Parolini, F.; Frontini, F.; Caccivio, M.; Bellenda, G.; Vega de Seoane, J.; Valencia, D.; Boddaert, S. Report D5.1 Report on Standardization, Performance Risks and Identification of Related Gaps for Performance in BIPV. BIPVBOOST Deliverable: Bringing down Cost of Building-Integrated Photovoltaic (BIPV) Solutions and Processes Along the Value Chain, Enabling Widespread Near Zero Energy Buildings (NZEB) Implementation. Grant Agreement 817991. Published March 27, 2020. Available online: https://bipvboost.eu/public-reports/ (accessed on 29 March 2020).
73. Change Works. *Renewable Heritage: A Guide to Microgeneration in Traditional and Historic Homes*; Changeworks: Edinburgh, UK, 2009. Available online: https://www.changeworks.org.uk/sites/default/files/Renewable_Heritage.pdf (accessed on 29 April 2021).
74. UNI EN. *Standard UNI EN 13501-1:2019. Classificazione al Fuoco dei Prodotti e Degli Elementi da Costruzione. Parte 1: Classificazione in Base ai Risultati delle Prove di Reazione al Fuoco*; Ente Italiano di Normazione (UNI): Milano, Italy, 2019.
75. Parolini, F.; Bonomo, P.; Frontini, F.; Caccivio, M.; Manzini, G.; Traina, G.; Cancelliere, P. Fire performance assessment of BIPV façades equipped with active rapid shutdown. In *Photovoltaic Solar Energy Conference and Exhibition. European. 37th 2020. (EU PVSEC 2020), Proceedings of the 37th European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC 2020), Online, 7–11 September 2020*; WIP GmbH & Co Planungs-KG: München, Germany, 2020; ISBN 3-936338-73-6, doi:10.4229/EUPVSEC20202020-6CV.2.22.
76. Bonomo, P.; Saretta, E.; Frontini, F.; Caccivio, M.; Bellenda, G.; Manzini, G.; Cancelliere, P. Fire safety of PV modules and buildings: Overviews, bottlenecks and hints. In *Photovoltaic Solar Energy Conference and Exhibition, Proceedings of the 33rd European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC 2017), Amsterdam, The Netherlands, 25–29 September 2017*; WIP GmbH & Co Planungs-KG: München, Germany, 2017; ISBN 3-936338-47-7, doi:10.4229/EUPVSEC20202020-6CV.2.22.
77. International Energy Agency (IEA). *Photovoltaics and Firefighters' Operations: Best Practices in Selected Countries, Report of IEA PVPS Task 12, 2017*; IEA: Paris, France, 2017. Available online: https://www.nrel.gov/docs/fy19osti/68415.pdf (accessed on 23 February 2021).
78. European Union. EU Regulation No 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC. *Off. J. Eur. Union* **2011**. Available online: https://eur-lex.europa.eu/eli/reg/2011/305/2014-06-16 (accessed on 29 April 2021).
79. IEC. *IEC 61215-2:2016–Terrestrial Photovoltaic (PV) Modules–Design Qualification and Type Approval–Part 2: Test Procedures*; IEC: Geneva, Switzerland, 2016.
80. IEC. *IEC 61730-1:2016–Photovoltaic (PV) Module Safety Qualification–Part 1: Requirements for Construction and IEC 61730-2:2016–Photovoltaic (PV) Module Safety Qualification–Part 2: Requirements for Testing*; IEC: Geneva, Switzerland, 2016.
81. Bonomo, P.; Parolini, F.; Frontini, F.; Caccivio, M.; Bellenda, G.; Vega de Seoane, J., Valencia, D.; Boddaert, S. Performance assessment of BIPV systems: Research on BIPV characterization methods. In *Photovoltaic Solar Energy Conference and Exhibition. European. 37th 2020. (EU PVSEC 2020), Proceedings of the 37th European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC 2020), Online, 7–11 September 2020*; WIP GmbH & Co Planungs-KG: München, Germany, 2020; ISBN 3-936338-73-6, doi:10.4229/EUPVSEC20202020-6DO.12.2.
82. Bonomo, P.; Parolini, F.; Saretta, E.; Frontini, F.; Caccivio, M.; Bellenda, G.; Vega de Seoane; J., Valencia, D.; Machado, M.; Boddaert, S. Performance assessment of BIPV systems: From current normative framework to next developments. In *36th European Photovoltaic Solar Energy Conference and Exhibition, Proceedings of the 36th European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC 2019), Marseille, France, 9–13 September 2019*; WIP GmbH & Co Planungs-KG: München, Germany, 2019; ISBN 3-936338-60-4, doi:10.4229/EUPVSEC20192019-6BV.4.6.
83. Bertolin, C.; Loli, A. Sustainable Interventions in Historic Buildings: A Developing Decision Making Tool, *J. Cult. Herit.* **2018**, *34*, 291–302, doi:10.1016/j.culher.2018.08.010.
84. Bundesdenkmalamt (BDA). *Richtlinie. Energieeffizienz am Baudenkmal*; BDA: Wien, Austria, 2011.

85. Lucchi, E.; Dias Pereira, L.; Andreotti, M.; Malaguti, R.; Cennamo, D.; Calzolari, M.; Frighi, V. Development of a compatible, low cost and high accurate conservation remote sensing technology for the hygrothermal assessment of historic walls. *Electronics* **2019**, *8*, 1–20.
86. Serraino, M.; Lucchi, E. Energy efficiency, heritage conservation, and landscape integration: The case study of the San Martino Castle in Parella (Turin, Italy). *Energy Procedia* **2017**, *133*, 424–434.
87. Frischknecht, R.; Stolz, P.; Krebs, L.; de WildScholten, M.; Sinha, P. *Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems*; IEA: Paris, France, 2020. Available online: https://iea-pvps.org/wp-content/uploads/2020/12/IEA-PVPS-LCI-report-2020.pdf (accessed on 23 February 2021).
88. Komoto, K.; Lee, J.S. *End-of-Life Management of Photovoltaic Panels: Trends in PV Module Recycling Technologies*; IEA: Paris, France, 2016. Available online: https://iea-pvps.org/wp-content/uploads/2020/01/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf (accessed on 23 February 2021).
89. PV CYCLE. Available online: http://www.pvcycle.org/ (accessed 16 April 2021).
90. ICOMOS International Council on Monuments and Sites. *European Quality Principles for EU-funded Interventions with potential impact upon Cultural Heritage*; ICOMOS International Secretariat: Paris, France, 2020.
91. SUPSI-Becherel Institute. *Building Integrated Photovoltaics: A Practical Handbook for Solar Buildings' Stakeholders*; SUPSI: Manno, Switzerland, 2020. Available online: https://solarchitecture.ch/wp-content/uploads/2021/02/BIPV_Status_Report.pdf (accessed 29 April 2021).
92. Kantensprung, A.G. *Gundeldinger Feld—A Machine Factory in Transition;* Editions Denkstatt: Basel, Switzerland, 2020; ISBN 978-3-9524556-0-9. Available online: https://www.denkstatt-sarl.ch/app/download/10804542174/Buch_GundeldingerFeld_SCREEN.pdf?t=1586173367 (accessed 16 April 2021).
93. Müller, K. Transformation of a historical coal bunker into a solar power station using multi-colored BIPV. In *Adaptive Facade Systems–Review of Performance Requirements, Design Approaches, Use Cases and Market Needs*, *Proceedings of the 10th Conference on Advanced Building Skin, Bern, Switzerland, 3–4 November 2015;* EF Economic Forum Ed.: Munich, Germany; ISBN 978-3-98120538-1, pp. 175–182.
94. Carì, V.; Stuffer, O.; Lucchi, E. Risanamento conservativo sulle sponde del lago. In *Casa&Clima;* Quine Business Publisher: Milan, Italy, 2014; Volume 51, pp. 44–52.
95. Lucchi, E.; Tabak, M.; Carì, V.; Perna, M. BIPV and historic buildings: A possible integration? In Proceedings of the AiCARR Conference, 34° Convegno Nazionale Bologna—Soluzioni Impiantistiche per Edifici a Basso Consumo di Energia: Indirizzi Normativi, Tecnologie e Strategie di Gestione, Bologna, Italy, 20 October 2016; pp. 1–14.
96. Jolissaint, N.; Hanbali, R.; Hadorn, J.-C.; Schüler, A. Colored solar façades for buildings. *Energy Procedia* **2017**, *122*, 175–180, doi:10.1016/j.egypro.2017.07.340.
97. *SN 520180-C1: 2015, SIA (Swiss Association of Engineers and Architects) 180-C1: 2015 Construction, Thermal Insulation, Protection against Humidity and Internal Climate of Buildings–Errata C1 of the SIA 180: 2014, 2015*; Swiss Society of Engineers and Architects: Zurich, Switzerland, 2015.
98. Trencher, G.; Geissler, A.; Yamanaka, Y. 5-years and still living: The Basel pilot region laboratory and Switzerland's pursuit of a 2000-Watt Society. In *Urban Living Labs: Experimentation and Socio-Technical Transitions*; Marvin, S., Bulkeley, H., Mai, O., Mccormick, K., Voytenko Palgan, Y., Eds.; Routledge: London, UK, August 2017.
99. Menn, C.; Steinke, G.; Dorusch, F.; Geissler, A. Transformation of a coal silo into a solar power plant with colored PV modules and second-life storage. In Proceedings of the Status-Seminar Brenet, Zurich, Switzerland, 7–8 September 2016; doi:10.26041/fhnw-775.
100. Polo López, C.S.; Bettini, A.; Khoja, A.; Davis, A.M.; Hatt, T.; Braun, M.; Kristan, M.; Podgornik, J.; Haas, F. Strategies and tools for potential assessment of Renewables (RES) in Alpine Space areas valid for historic buildings and sites. In Proceedings of the SBE21 Sustainable Built Heritage, Online, 14–16 April 2021.
101. Durante, A.; Lucchi, E.; Maturi, L.; BIPV in heritage contexts award. An overview of best practices in Italy and Switzerland. In Proceedings of the SBE21 Sustainable Built Heritage, Online, 14–16 April 2021.