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Renewable Energies and Architectural Heritage: Advanced Solutions and Future Perspectives

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Abstract: The current legislative framework and the recent energy crisis ask for massive applications of renewable energy sources (RES) in the built environment to reduce energy demand, environmental emissions, and energy costs. The uncritical application of these policies, especially on architectural heritage, could generate serious conservation issues, compromising their heritage values, biodiversity, traditional appearance, and materiality. Thus, there is an urgent call to balance architectural heritage preservation with energy production using clear rules, policies, criteria, and heritage-compatible technologies. The present study aims at defining an updated overview of the application of solar, wind, geothermal energy, and bioenergy on architectural heritage. A deep literature review of the studies published in the years 2020–2023 has been performed, identifying main topics, challenges, advanced solutions, and future perspectives. Acceptability, design criteria, and cutting-edge technologies are also illustrated through case studies to better understand practical approaches.

Keywords: heritage; renewable energies; solar energy; photovoltaic; wind energy; geothermal energy; bioenergy

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1. Introduction

The United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage Convention defines "*cultural heritage*" as any "*monument*" (e.g., paintings, sculptures, architecture, inscriptions, cave dwellings), "*group of buildings*" (e.g., buildings with similar architectural value thanks to the presence of a continuous historical process of modification and transformation), and "*site*" (e.g., historic town, archeological site) "(...) *with an outstanding universal value that express history, art, or science of a specific culture*" [1]. Inside them, "*architectural heritage*" refers to buildings, ruins, or groups of them characterized by physical, intangible, historical, or emotional values that increase over the years, according to the International Council of Monuments and Sites (ICOMOS) [2]. These cultural values reflect and express human knowledge, beliefs, craftsmanship, and traditions [3]. "*Architectural heritage*" can be both a physical "*artifact*" or a "*cultural meaning*" that expresses constructive cultures or events that occurred during the life of the building [1]. Each object has a specific "*heritage significance*", defined as the combination of the heritage values assigned to a building and its setting [4]. Architectural objects are classified into a protected (also called listed or historic) and not protected (also called not listed, traditional, or historical) group according to the presence of an "*architectural interest*"). The criteria for identifying and assessing the presence of an "*architectural interest*" are [3]: (i) age connected with the architectural history (e.g., pre-industrial, industrial, modernism, and post-war periods); (ii) aesthetic merits related to the visual appearance and materiality, as well as to significant technological innovation, engineering, or socio-economic distinction; (iii) selectivity or rarity connected with the unique architectural quality; and (iv) national interest that emphasizes distinctive regional elements, and vernacular features.

The preservation of architectural objects is faced with risks related to physical damage, environmental pollution, tourism pressure, climatic changes, and a lack of financial funding [5,6]. The conservation of "*architectural heritage*" requires any operation that aims at preserving its physical matters, visual appearances, and heritage values for a long time [7]. This trans-disciplinary work is based on the interaction among different competencies, not only a dull summation of specialist skills. It concerns a deep knowledge of its historical–critical foundations through the study of original documents, the survey of physical structures, the analysis of historical marks, and the critical interpretation of actual works [7]. More recently, architectural conservation has shifted its paradigm from purely physical preservation to making buildings functionally relevant for the age through constant redevelopment and repurposing. Any intervention involves a dialogue between "*old*" and "*new*" parts with a complex activity that includes changes and extensions that reveal the hidden meanings of the architectural monument [8]. Different approaches are highlighted at the international level [9]:

- "*Critical-conservation*" aims at transferring the architectural heritage to the future in the best possible conditions, studying and conserving its original matters and values while also interpreting and facilitating "*its reading*" through reversible interventions [10].
- "*Pure conservation*" aims at the meticulous conservation of the architectural heritage in its environment, adding only new necessary elements as well as preserving layers and marks of time transformations, not subtracting original matters [11].
- "*Repair and maintenance*" [12] aim at designing, "*by analogy*", forms and materials similar to the past through their reconstructions [11].

Carbonara [9] clarified that the operations affecting and transforming the "*architectural heritage*" with "*renovation*" or "*full redesign*" are not included in architectural conservation because they do not respect original matters and values (e.g., rehabilitation, functional repair, reinvention, or remaking of the entire building or an element). Moreover, "*building reuse*" and its ramifications (e.g., rejuvenation, improvement, recycling, recovery, regeneration, adaptive reuse) can be placed "*next to restoration*" as they preserve the existing property, giving new practical and economic functions [13], but preservation is not the main purpose of the intervention [9].

All these approaches emphasize the sustainability and circularity of cultural heritage [13]. The convergence between the 'culture of sustainability' and the 'culture of heritage protection' is revealed by their common primary intentions. The planet's resources, such as the natural environment and architectural heritage, are finite. Hence, they should be carefully protected and wisely used [14]. In the context of sustainable transitions, defined as "[. . .] *long-term, multidimensional, and fundamental transformation processed through which established socio-technical systems shift to more sustainable alternatives*" [15], any intervention on the "*architectural heritage*" requires a balance within the values and the constraints imposed by the historical matters and the criteria of environmental sustainability and affordability [14]. Thus, sustainable design options for cultural heritage must follow the same purposes, considering functional, structural, environmental, and energy adaptations as tools for conserving and transmitting the object to the future rather than a redevelopment process in opposition to conservation requirements [14,16]. Each design solution should follow the operative criteria suggested by the "*Restoration Charters*" [17], such as compatibility, minimum intervention, reversibility, distinguishability, expressive authenticity, durability, and respect for original materials [14,18]. Inside these new challenges, the attention to the issues of environmental sustainability and energy efficiency has progressively increased in recent years [19]. The COVID-19 pandemic and the current energy crisis have completely changed the worldwide energy situation, generating huge impacts on the "*architectural heritage*" [20]. On the one hand, pandemic lifestyles (e.g., smart working, home-schooling, online shopping) has improved energy consumption and costs, with a higher impact on old buildings [17,20]. On the other hand, the energy crisis and climate changes require cleaner energy production based on the use of renewable sources, adaptation, and mitigation activities for favoring energy autarky [21]. This opens the opportunity for the energy retrofit of buildings, integrating passive and active systems respecting their original materiality, meanings, and appearance [18]. This idea boosts the traditional concept of land and building reuse, embodied energy, and usage of raw materials. In parallel, the European legislative frameworks (and recently the worldwide legislations) ask for massive applications of renewable energy sources (RES) in the built environment to reduce the energy demand, the environmental emissions, and the costs for electricity, domestic hot water, heating, and cooling in the building sector [19,20]. Otherwise, RES targets in "*architectural heritage*" are hidden by the historic* constraints for preserving original and traditional values [16,17,20]. Additionally, the uncritical application of these policies could generate serious conservation issues, especially for heritage contexts (e.g., historic* buildings and towns, protected landscapes), compromising their heritage values, biodiversity, traditional visual appearance, and materiality. Thus, there is an urgent call to balance architectural heritage preservation with energy production using clear rules, policies, criteria, and heritage-compatible technologies [21].

Cabeza et al. reviewed the integration of RES into historical building envelopes, focusing on solar and geothermal energy [22]. This study showed several architectural applications at the material, system, and building levels, also discussing their energy potentiality and human wellbeing. The analyzed period is 2006–2017. Thus, the examples use mainly traditional technologies, such as conventional photovoltaic (PV) systems, thin films, and applied PV systems. On the contrary, the technological development of RES is very fast. Over the last 5 years, the renewable energy sector has undergone crucial expansions and evolutions, boosting the applicability of these systems also on the " *architectural heritage*" thanks to the customization of colors and textures, the geometric flexibility as well as the presence of compact shapes, mimetic design, low-rate reflection, and high-resolution printed images. Thus, the study aims at updating the knowledge of the state of the art of RES integration on "*architectural heritage*" to understand new possibilities, innovative developments, and future perspectives. After having defined the methodological approach (Section 2), a detailed discussion on the integration of active solar systems (Section 3), wind technologies (Section 4), geothermal energy (Section 5), and bioenergy (Section 7) in "*architectural heritage*" is presented. Here, main topics, challenges, advanced solutions, impacts, and future perspectives are delineated. In addition, integration criteria and cutting-edge technologies are illustrated through case studies to better understand cultural, climatic, environmental, and design specificities. In the end, conclusions on innovative developments and future perspectives are summarized (Section 7).

2. Materials and Methods

RESs are derived from natural sources that have a higher replenished rate than consumed. The United Nations (UN) classified RES into the following categories: (i) solar energy; (ii) wind energy; (iii) geothermal energy; (iv) bioenergy; (v) hydropower; and (vi) ocean energy [23]. As mentioned before, this study aims at updating the knowledge of RES application on the "*architectural heritage*", analyzing scientific studies and applications for the years 2020–2023. To this purpose, only RES with a direct application to "*architectural heritage*" are analyzed, such as solar, wind, and geothermal energy as well as bioenergy. Otherwise, hydropower and ocean energy are not studied because they are applied at the territorial level, not at an architectural level. The study is structured in two phases:

- Phase 1: A literature review on renewable energy and "*architectural heritage*".
- Phase 2: Definition and discussion of main topics, advanced solutions, and future perspectives.

First, the literature review was performed to identify and count the existing scientific studies published in the Scopus bibliometric database (Phase 1). The Scopus database was selected because it guarantees a more complete overview of the studies, thanks to its spectrum of publications that has 20% more coverage than Web of Science [24,25]. Additionally, Google Scholar and Researchgate were excluded for the low accuracy of the analysis that considers several overlapped manuscripts [24]. This bibliometric analysis allowed the determination of (i) the number of publications; (ii) their evolution during time; (iii) the provenience and geographic distribution of the publications; and (v) indexed and authors' keywords. To have the highest overview of the topic, the queries concern "titles, abstracts, and keywords" (TITLE-ABS-KEY). On the contrary, queries that consider only "keywords" (KEY) cut several important papers. Cultural heritage and technical keywords on solar energy, wind technologies, geothermal energy, and bioenergy have been analyzed through integrated queries to have the widest range possible of publications. The keywords used in the Scopus Database are shown below (Table 1).

Table 1. Keywords used in the Scopus database.

Keywords				
Cultural Heritage	**Solar Energy**	**Wind Energy**	**Geothermal Energy**	**Bioenergy**
Heritage	Solar energy *	Wind energy *	Geothermal energy *	Biomass *
Architectural heritage	Solar system *	Wind system *	Geothermal	Bioenergy *
Heritage building *	Solar technology *	Wind technology *	Heating, Ventilation, Air Conditioning (HVAC)	Wood energy *
Historic * building *	Photovoltaic * (PV)	Wind turbine *		Dung energy *
Built environment	Solar Thermal (ST)	Wind farm *		Charcoal energy *
	PVT		Heat pump *	

Note: * = plural and singular.

More specific heritage keywords (e.g., protected building*, listed building*, vernacular building*/architecture, traditional building*) did not produce any significant result. Conversely, the combination between heritage OR technical keywords was not focused on RES integration in architectural heritage but on energy retrofit of historic* buildings using internal insulation, windows, mechanical ventilation, etc. In the first step, the analyzed period was 1994–2023 to have wide results. Then, this period was reduced to the years 2020–2023 to update the knowledge and to understand future research perspectives. Scientific data have been cleansed after reading titles and abstracts to improve data relevance, eliminating duplications, etc. After this process, data were extracted and charted using database and filter services. First, a chronological view of the different periods was produced to show the evolution of the studies. Moreover, scientific studies were mapped and classified according to provenience, number, and indexed keywords. Authors and indexed keywords have been mapped with VOSviewer 1.6.18, the most widely open-source software for science mapping [26], to visualize data patterns and bibliometric networks. Associated keywords are clustered using the same colors. The popularity of a keyword is indicated by its size, while its proximity is interpreted as an indication of its similarity. In the second step, a detailed and critical discussion of the most relevant studies was carried out on the selected papers (Phase 2), focusing on the following questions: "*What are the main aspects considered?*", "*What is the approach for RES integration on architectural heritage?*"; "*Is it possible to balance heritage preservation and energy production?*"; "*In which way?*"; "*What are the differences for integrating different RES?*". Starting from these questions, a detailed discussion of main topics, advanced solutions, and future perspectives has been realized and presented.

3. Solar Energy

The integration of solar energy into architectural heritage refers to the use of photovoltaic (PV) and solar thermal (ST) systems. Fifty scientific documents have been found for the period 1994–2023, combining cultural heritage and solar energy keywords (Table 1). Between them, 23 papers have been published in the period 2020–2023. Thus, 46% of publications are from the last 3 years (Figure 1).

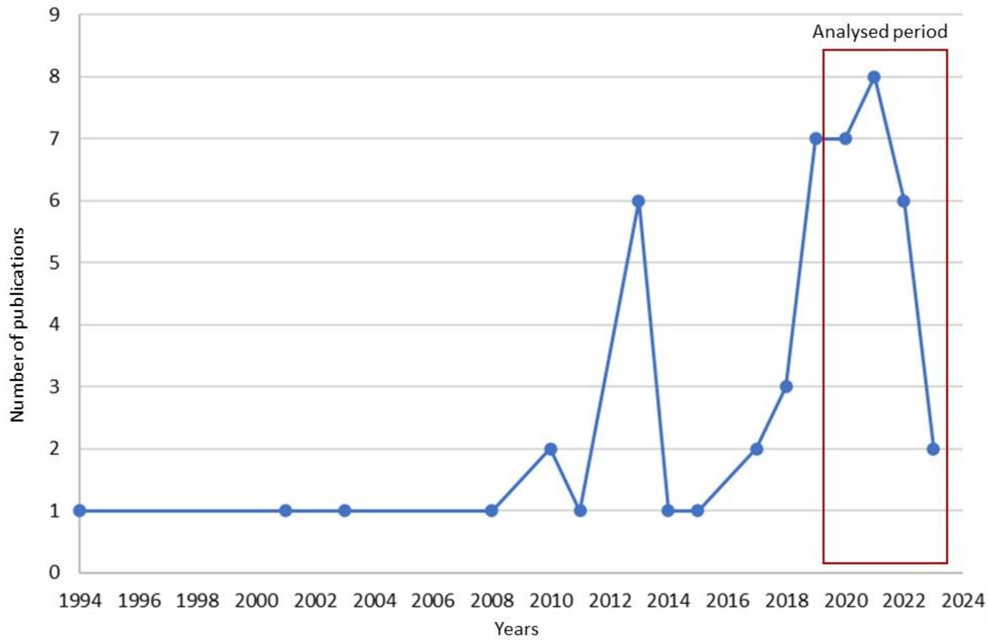

Figure 1. Chronological view of the studies on solar energies and cultural heritage: 50 scientific manuscripts have been realized from 1994 to 2023, 23 of them in the years 2020–2023 (Source: Author's elaboration using Scopus data).

The most active Countries in the analyzed period are Italy (9 papers), Switzerland (7 papers), and the United Kingdom (2 papers). Moreover, one paper on this topic was published in several Mediterranean Countries (e.g., Spain, Portugal, France, and Greece), Central Europe (e.g., Germany, Belgium, Poland), and Scandinavia (Sweden). Outside Europe, the active Countries are Peru, Iraq, Indonesia, and Egypt (Figure 2).

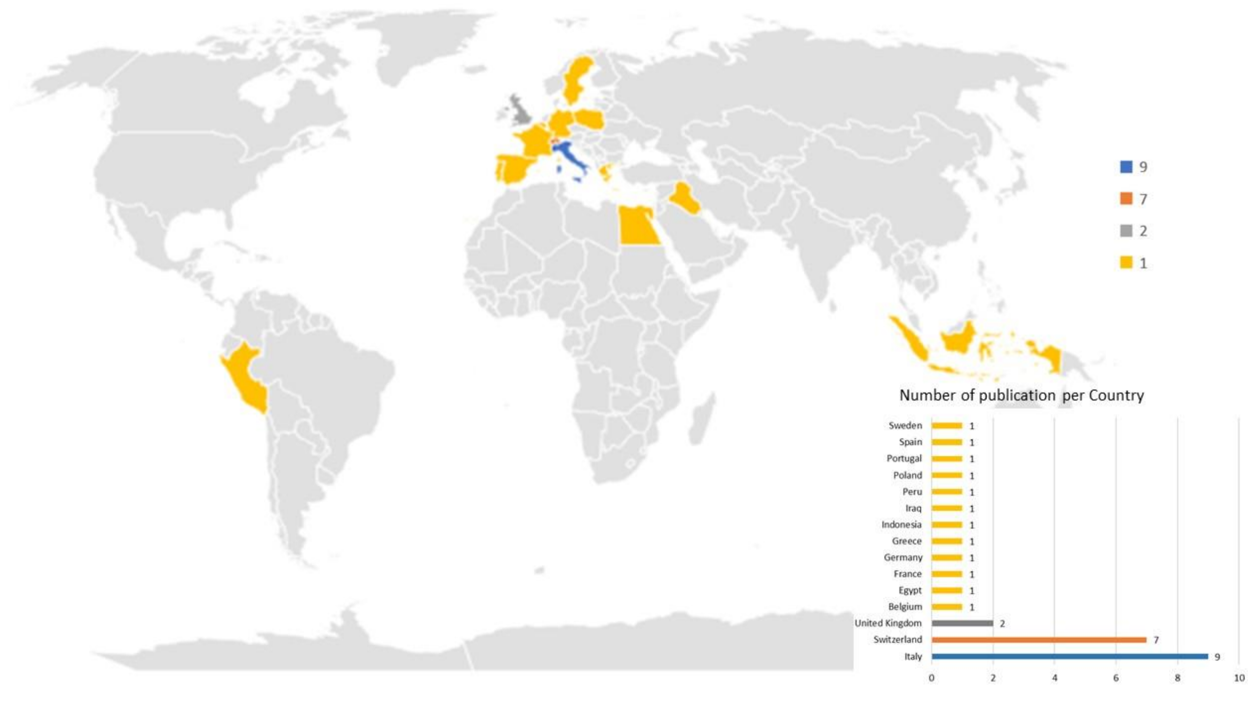

Figure 2. Map of scientific studies on solar energies and architectural heritage according to their provenience (Source: Author's elaboration using Scopus data).

The keywords of these studies have been analyzed. Authors' and indexed keywords produced a heterogenous cloud, difficult to be clustered for the overlapping of several keywords and concepts. Nine clusters are produced (Figure 3a): (i) solar energy retrofit; (ii) PV and building integrated PV (BIPV); (iii) sustainability; (iv) architectural conservation; (v) decision making; (vi) energy policies; (vii) energy production; (viii) climatic change; and (viii) award. On the contrary, indexed keywords can be divided into three clusters (Figure 3b): (i) solar energy production; (ii) energy efficiency and climate change; (iii) architectural conservation. This structure represents the three aims of the solar application on the architectural heritage that respond to energy, sustainability, and conservation purposes.

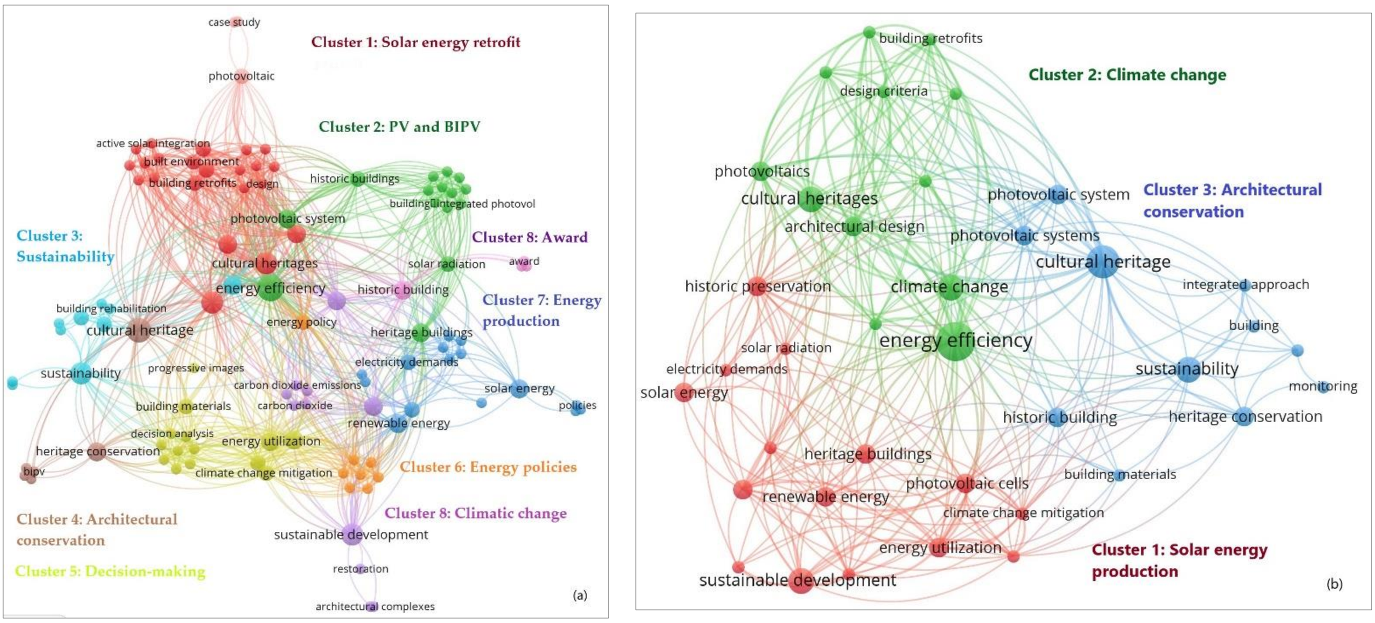

Figure 3. Scientific landscape of architectural heritage and solar energy and architectural heritage keywords: (**a**) 276 total keywords; (**b**) 186 indexed keywords (source: Author's elaboration using VOSviewer, based on Scopus data).

Solar energy and heritage keywords have been extracted from indexed keywords through detailed data mining to verify the main topics of these works. One hundred three indexed keywords have been selected, and four main topics can be defined (Figure 4): (i) solar acceptance; (ii) solar potential evaluation; (ii) visibility mapping; and (iv) solar integration criteria.

PV applications on architectural heritage are extensively investigated for their significant contribution to the reduction of energy requirements for electrical needs and thermal conditioning [19], as well as for their aesthetic appeal and multifunctionality [18]. Only one study investigates ST systems, while PVT is not studied. Initially, the studies focused on the acceptability of PV systems in the built environment [27]. Then, their technical advantages [28,29], energy performances [29,30], and economic benefits are demonstrated [29], also focusing on aesthetic design [27,28] and energy potentials for solar architecture [29,30]. Specific studies refer to historic buildings, with a section dedicated to RES integration in old [31,32], heritage [33,34], historical [35], and existing buildings [36], as well as in historical towns [37,38]. Here, the focus is on the criteria for ensuring the heritage compatibility of conventional technologies. Recently, attention has been focused mostly on innovative PV technologies [39,40], assessing their energy performance, risks, solutions, and design criteria. Lately, energy landscapes have been introduced [39–42]. Next, each cluster is deeply discussed.

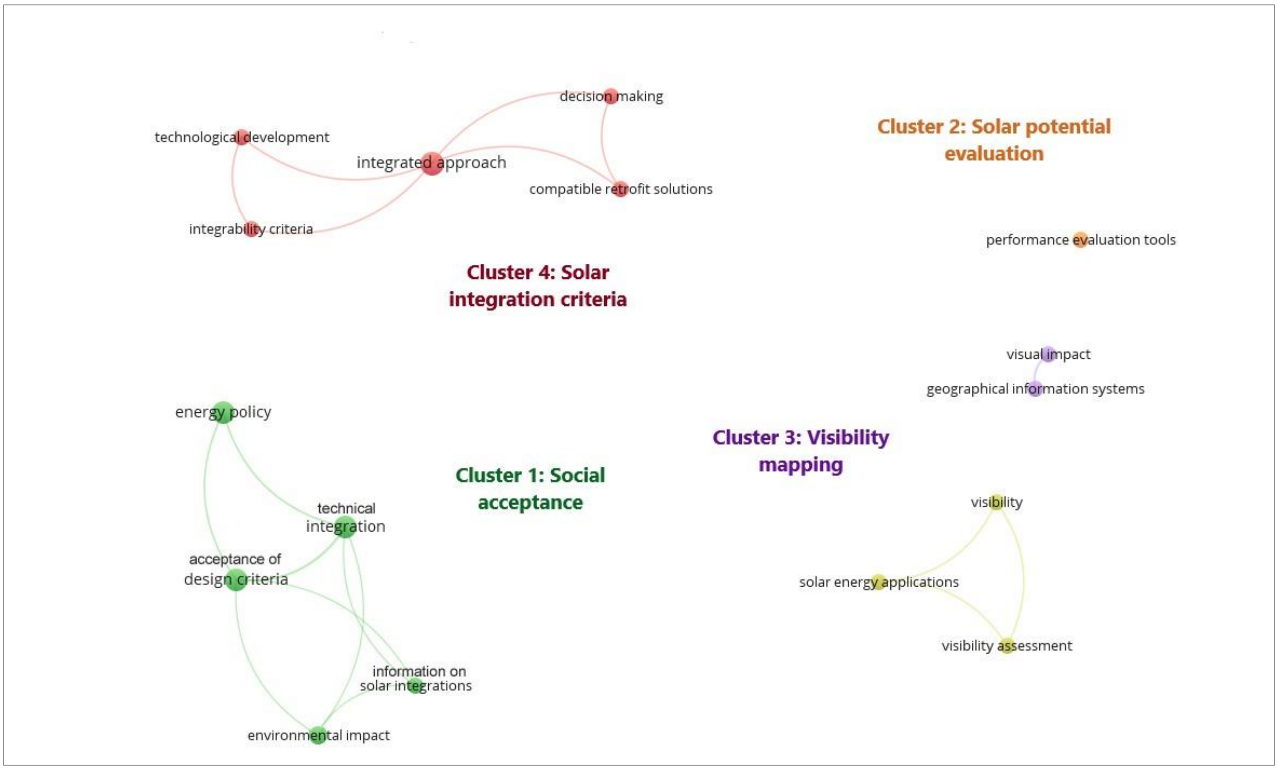

Figure 4. Main clusters of the studies based on co-occurrence network of the selected indexed keywords on solar energies and architectural heritage (source: Author's elaboration using VOSviewer, based on Scopus data).

3.1. Social Acceptance

Social acceptance and acceptability of active solar systems is a commonly debated topic, both on new and existing buildings [43,44]. Social acceptability is a mental representation (or a priori phenomenon) related to the use of a specific technology. On the contrary, social acceptance is a posteriori pragmatic evaluation of technology after knowing it. Active solar applications in architectural heritage are hindered by numerous barriers linked to the presence of outstanding values, traditional features, and materials [20,21]. Color ranges, high reflection, modularity, and geometric pattern of PV and ST systems have an impact on vernacular and historic buildings [45]. Thus, their application is not always compatible [45]. The literature mainly highlights the following barriers:

- Technical aspects.
- Costs.
- Policy.
- Information and knowledge.

In the past, the aesthetic aspect [27,28], technical knowledge [28], and economic issues [27,28] were underlined as key problems for the visual appearance of conventional technologies [27] and the economic crisis of the solar market [28]. More recently, these barriers have been less perceived thanks to the technological innovation of the solar sector, especially for the visual appearance and customization of innovative PV panels (e.g., thin films, hidden colored PV) [14,20,21]. Technical doubts affect the energy efficiency and the environmental impact linked to the production of innovative systems [46], especially for PV and PVT [21,47] (e.g., colored solar cells, thin films, solar concentrators). Technical doubts are strictly related to the economic barriers, which pertain mainly to large initial investments [43,46], long payback periods [46], and the absence of financial incentives [43]. In addition, the complexity and fragmentation of legislative frameworks and authorization processes are perceived as important elements for blocking the application of solar energies on cultural heritage [45]. The restrictions of local Heritage Authorities [43] and the absence of shared regulations [14,21] expand this problem [45]. Finally, information barriers concern the lack of information and confidence in innovative systems related to human expertise both for energy and heritage [20,45] as well as to training [18,43] and capacity building [43,46]. Recently, economic barriers have been decreasing progressively due to the increasing costs of fossil fuels [46]. Thus, economic aspects are perceived as the main benefits of solar energy applications. Positive aspects of PV integration in heritage buildings are connected to the enhancement of economic values [19], functionality [20], and human comfort [46]. Moreover, the creation of soft tourism and the multiplier economic effects are suggested as positive benefits related to heritage towns and buildings [27]. PV benefits are identified in scalability, reliability, versatility, low maintenance costs, on-site production, self-consumption coverage, and energy peak shaving [20,21,46]. A synthesis of barriers and benefits of active solar energies applied to architectural heritage is reported below (Table 2).

Table 2. Barriers and benefits for the social acceptance of active solar energy applications on architectural heritage (Source: Author's elaboration).

Aspect	Barrier	Benefit
Technical	Energy performance of innovative systems 🟩 Environmental impact of production 🟩	Innovative aesthetic appearance and versatility 🟩 Reliability and on-site production 🟩 Multifunctionality and scalability 🟩
Economic	Large initial investments 🟩 High costs 🟥 Long payback period 🟥 Lack of incentives 🟩	High energy costs 🟩 Appeal for soft tourism 🟥 Multiplier economic effects 🟥 Low maintenance costs 🟩
Policy	Complex legislation 🟥 Long authorization process 🟥	New local policies for solar applications 🟥
Information	Lack of knowledge of innovation 🟩 Lack of examples 🟥 Lack of training 🟥	New awareness after energy crisis and COVID-19 pandemic 🟩

Note: 🟩 = Common for the integration of active solar in buildings and architectural heritage; 🟥 = Specific for the integration of active solar systems in architectural heritage.

In general, people engagement and co-creating design are considered the correct approaches for improving the social acceptance of active solar technologies [14]. The development of tailored materials and solutions for building integration is always suggested as a possible measure for overcoming technical and information barriers [46].

3.2. Solar Potential Evaluation

The solar potential evaluation of heritage buildings is the starting point for decision-making purposes in urban planning. In the past, heritage buildings and towns were mainly excluded by these calculations for the presence of high urban and architectural constraints [46–48]. Recently, only a few studies investigated the impact of vernacular urban shapes, such as narrow streets, porches, and mutual shadows, on buildings. In all these cases, two deterministic approaches are used (Table 3):

- Bottom-up models.
- Solar cadasters.

Table 3. Approaches used for the solar potential evaluation of architectural heritage (Source: Author's elaboration).

Characteristics	Bottom-Up Models	Solar Cadaster
Object	Representative building typologies	Entire building stock
Time	Short	Long
Cost	Low	High
Heritage constraints	✓	✓
Urban constraints	✘	✓
Impact of surroundings	✘	✓
Impact of mutual shadows	✘	✓
Impact of urban geometric irregularities	✘	✓
Difficulties	Selection of representative buildings Cluster analysis of building differences	Detailed approach with high costs and long times

Note: ✘= Neglected ✓= Considered.

First, bottom-up models are mapping tools that cluster statistical and technological information for defining "*representative buildings*" characterized by similar dimensions, geometries, typologies, features, materials, and orientations for roofs and façades [48]. This approach is not appropriate for historic* features because the calculation of the solar potential of single representative buildings neglects heritage specificities, such as architectural constraints [49,50], urban geometric irregularities [51], surrounding structures, short-wave solar radiations [52], and mutual shadows from aggregated buildings [50–54]. Only a few studies investigate the impact of heritage features [49,50] and urban shapes [49–53] with the support of digital mapping. In the first case, only detailed investigations of urban, architectural, and historical values and constraints of roofs and façades permit the correct selection of building typologies and solar interventions [49]. The cluster analysis particularly demonstrates the difficulties of grouping heritage inhomogeneous building stocks due to the differences in constructive features, heritage values, utilization levels, and urban and building constraints [50]. In the second case, a study demonstrates that urban shadows are very important in historic towns, as the Urban Shading Ration (USR) can reach 60% of building façades and 25% of roofs [54]. The energy potential is significantly reduced by this aspect. Thus, the influence of mutual shadow on the energy potential is investigated, especially on building façades [51,52], ground [51], and roofs [51–53], also focusing on the influence of reflections [52], urban shadows [53,54], and complex geometries [55].

Second, solar cadasters are web-based mapping tools supported by mathematical models for determining the production capacity of active solar systems through two-dimensional (2D) maps or orthophotos [51]. Thus, the calculation is realized on the entire building stock. Examples of solar cadaster for heritage towns refer to the Swiss towns of Geneva (2018) [56] and Carouge (2018) [57] using 3D and 3D light detection and ranging (LiDAR) data, heritage and urban constraints, and building data. In the solar cadaster of Carouge, each building is analyzed in a detailed way, suggesting specific design criteria and installation procedures for PV and ST technologies.

In both cases, Geographic Information System (GIS) tools are matched with simulation software for data management, cluster analysis, and query interactions. The main models used for assessing the solar potential are divided according to the dimension of the urban areas [52]. In general, the higher the area, the lower the optical precision of reflection [52], and thus the calculation of USR, especially on building façades. A synthesis of these models is reported below (Table 4).

Table 4. Models used for assessing the solar potential at urban level (Source: Author's elaboration).

Aspect	Tool	Logo
Large scale analysis	CitySim [58]	
	Archelios Map [59]	
District level	Grasshopper (Honeybee, Daysim, Ladybug, and DIVA) [60]	
	Climate Studio [61]	

3.3. Visibility Mapping

Visibility mapping is strictly connected with the solar potential evaluation. The visibility of a solar installation can be assessed by [62]:

- Spatial modeling.
- Experts' inquiries.
- Simplified graphical methods.

In all cases, the visual impact is evaluated mainly from public spaces or significant views [21,60]. Thus, active solar systems can be located on hidden roofs, interior façades, behind parapets, outbuildings, or new additions [21,61].

LESO-QSV (Quality–Sensitivity–Visibility) is a cross-mapping tool for assessing the criticality of solar installations in heritage territories [63]. The "criticity" level of an installation combines the visibility of the solar system and the sensibility of the urban area. Heritage buildings are high-sensible in context, and thus, they require low-visibility technologies to reduce their impact. The evaluation of their visibility is based on the coherency of their geometry, materiality, and pattern (Figure 5).

This approach is combined with spatial modeling for assessing solar visibility in historic* towns. The cross-mapping between visual criticality and solar radiation maps of a specific surface evaluates the possibility/difficulty of solar installation [62,64]. This method advises decision-making on urban planning at different levels [62] (Table 5).

Table 5. Visual criticality and solar radiation maps to be used on heritage contexts (Source: Author's elaboration from [62]).

Planning Level	Visual Criticality Map	Solar Radiation Map
Strategic planning (1:100,000–1:30,000)	Photo shooting locations Relevant historical sightseeing	Aggregated solar radiation data over terrain models
Development planning (1:10,000–1:5000)	Roof visibility ratio Visual amplitude per surface	Calculated solar radiations on a roof surface
Detailed planning (1:2000–1:500)	Roof visibility ratio Façade visibility ratio	Calculated solar radiations on roof and façade surfaces

To this purpose, two new parameters have been defined: (i) "*roof visibility ratio*" and (ii) "*façade visibility ratio*", respectively equal to the relationship between visible roof/façade areas and total roof/façade areas [62]. The combination of these maps and the potential energy consumption permits an understanding of the energy matching between production and consumption in historical areas [64].

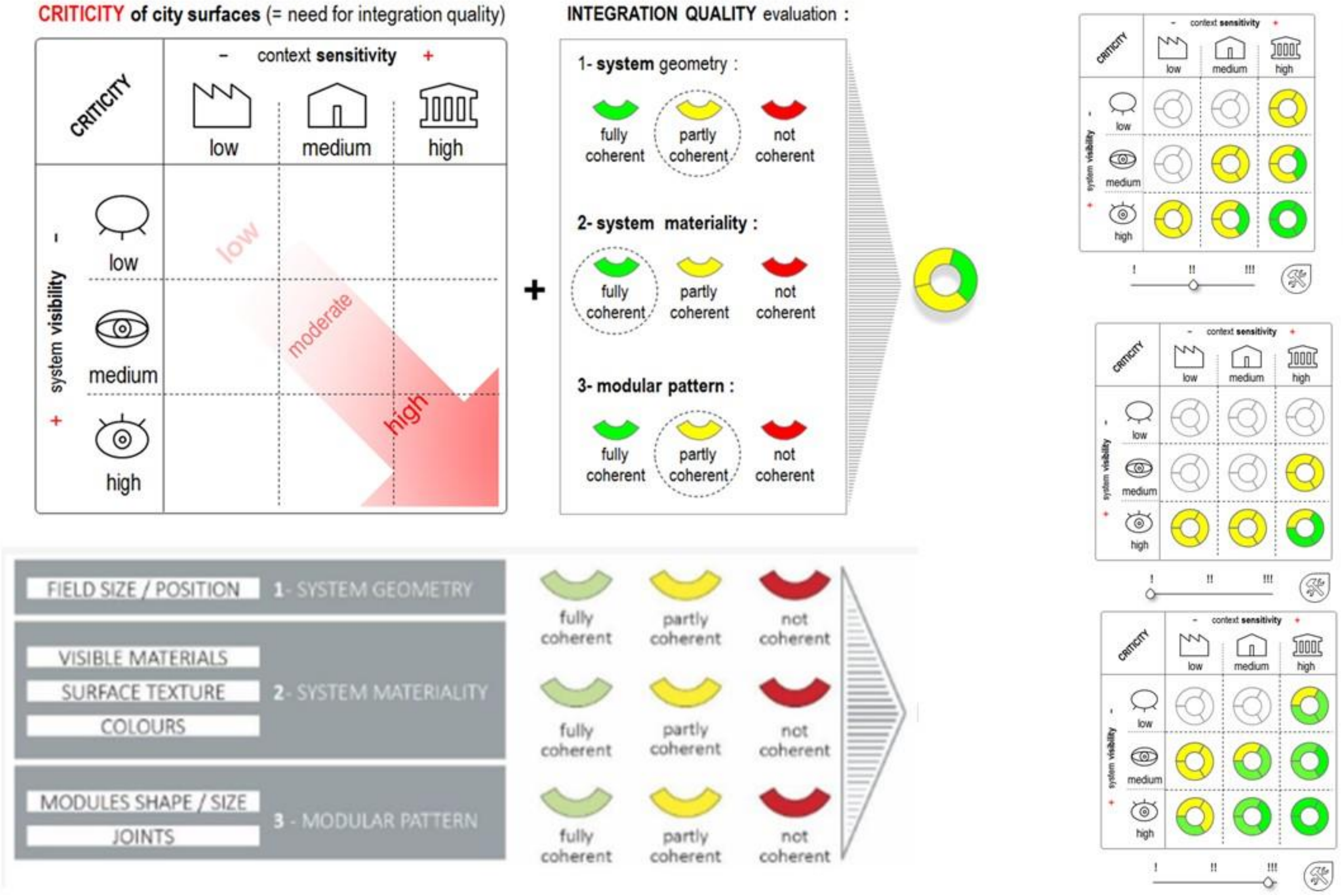

Figure 5. "Criticity map" considering visibility and sensitivity (Source: Authors' elaboration from LESO-QSV—Architectural integration tool, https://www.epfl.ch/labs/leso/research/domains/renewables_integration/leso-qsv, accessed on 14 February 2023).

Experts' inquiries involve experts, Heritage Authorities, and local and regional planning bodies for the evaluation process [21]. The assessment generally refers to specific buildings, considering their history, location, protection level, conservation states, and modifications during the years. This method is applied both to singular buildings and historical towns. First, at the building level, an approach [65,66] classified the architectural heritage in building elements according to the "*combinatory grouping approach*" proposed by the standard UNI 8290-1 [67]. Possible PV interventions and technologies are defined for each building element, evaluating their compatibility with the local Heritage Authority [65,66]. At the urban level, the "*target-based method*" evaluates "*target elements*" (e.g., the historic* building, the building envelope) rather than a set of significant points [68]. Thus, the visibility assessment is realized only for buildings that are of interest (e.g., listed, protected, or traditional buildings). Here, solar exposure (e.g., absence of shading, high irradiance) and heritage values (e.g., conservation state of the roof, absence of heritage constraints) are evaluated. A comparison between the cross-mapping and the target-based methods applied to the same historical center of Geneve in Switzerland shows a significant difference in the roof percentage that can be used for solar installations. Respectively, 50% and 64% of roofs can be used for solar installations using the two methods [68]. Thus, the target-based method respects heritage compatibility but also increases the energy potential of historic city centers.

Finally, simplified graphical methods check the visual impact of the solar installations considering the variation of the distance between the observer and significant views, the slope of the roof, and the building height [69]. Several examples have been produced.

3.4. Solar Integration Criteria

Design and evaluation criteria for the integration of active solar technologies into the historic* built environment are deeply investigated. Several countries developed national or local guidelines for balancing heritage preservation and energy production. These criteria refer to the architectural restoration theories that consider both physical and semantic issues, respectively linked to the preservation of original materiality and latent meanings [20,21]. There are no differences between the integration of PV and ST technologies [70], although PV systems are supported by a huge amount of the literature. Solar design criteria are "*universally recognized*" although their implementation has declined according to local climate, orography, morphologies, land features, resources as well as traditional features, building typologies, techniques, and materials. These criteria also differ according to the type of cultural heritage (building element, buildings, towns, landscape, site of historic resource) and the protection level (e.g., heritage protected or traditional features) [21]. Furthermore, the conservation level influences the heritage-compatibility: active solar installations are allowed in heritage contexts with lower conservation levels but avoided with high conservation levels for conserving original materials [71]. A taxonomy of international recommendations has been published, identifying recurring and transferable criteria, design suggestions, and a glossary for helping designers and Public Authorities in the selection and evaluation of appropriate design alternatives and products [21,70,72]. Additionally, new design solutions, shared criteria, positive local applications, and knowledge gaps on PV product innovation are identified through several focus groups with the Heritage Authorities [21]. The criteria are classified as aesthetic, technological, and energy integration [21,70]. Aesthetic criteria imply a compatible visual interaction with traditional characters, materials, and values [20,70]. Technological criteria are based on durability, reversibility, and detailed design [20,21]; energy integration entails an efficient coverage of the overall energy consumption [21,65,70]. The solar integration criteria can be summarized as follows:

- "*Visual compatibility*" maintains the original aesthetic appearance [21,65].
- "*Material compatibility*": preserving original materials, construction techniques, and heritage significances as evidence of the "*material culture*" of a specific period and territory [20,21,68,70].
- "*Minimum intervention*": thanks to the reduction of physical changes and material losses as well as to the preservation of the original visual appearance maintaining its geometries, proportions, shapes, sizes, colors, patterns, textures, and reflectance (Figure 6) [21,70].
- "*Reversibility*" of the solar interventions without damaging the original building (Figure 7) [20,21,70].
- "*Durability*" of the transformation preventing structural, electrical, hygrothermal, energy-efficiency risks, negative effects, or degradation process due to new solar installation [20,70].
- "*Balance between preservation and energy production*" dimensioning the active solar systems according to the real energy needs [21,46,70].
- "*Interdisciplinarity*" of different skills and competencies in architectural restoration, energy design, technology development, urban planning, and landscape design [18,71,73].

Figure 6. Positive example of the "*minimum intervention*" criteria on the PV roof of the La Certosa Island in Venice (Italy) with respect to the geometries, shapes, proportions, colors, and reflectance of traditional clay roofs [74] (Source: Elena Lucchi).

Figure 7. Positive example of the "*reversibility*" criteria on the solar intervention of Palazzo Leonori in Rome (Italy), where the transparent BIPV roof is detached from the original XIX Century Palace by metallic columns [75] (Source: Elena Lucchi).

Otherwise, the traditional restoration criteria of "*recognizability*" or "*distinguishability*" of the new intervention are contradictory and not accepted by all the recommendations. In some cases, the recognizability of the transformation is boosted to ensure a clear differentiation between new and existing elements, respecting original features and values [20,70]. This idea is correct, especially for modern buildings or industrial archaeology as well as for building extensions [21] (Figures 8 and 9).

Figure 8. Positive example of the "*recognizability*" criteria on the solar roof of the Winery Alois Lageder in Magrè (Italy) thanks to the presence of traditional PV panels oriented to the maximum solar exposure (Source: Elena Lucchi).

Figure 9. Negative examples of the "*recognizability*" criteria of the solar intervention in a XX Century School in Milan (Italy) and in traditional alpine buildings in Val Sarentino (Italy) where PV and ST panels are visible from public spaces for their irregular shapes, blue colors, and high reflectance (Source: Elena Lucchi).

In traditional or historic buildings, the "*concealment*" of the solar systems from public view or prominent visual assets is often suggested to reduce any potential visual impact of the new installation [20,21,70] (Figure 10). Hidden colored, thin films, semi-transparent, and textured PV systems resulted in promising visibility minimization [21,65]. Thus, the visibility of the solar system requires a deep analysis through a detailed mapping of architectural and environmental characteristics (Section 3.3).

Figure 10. Positive example of the "*concealment*" of the solar intervention in the Podere Case Lovara in Levanto (Italy) thanks to the presence of traditional PV and ST panels hidden behind a parapet and not visible from the protected landscape of the Cinque Terre Natural Park (Source: Fondo per l'Ambiente Italiano).

Tailored active solar design solutions can be supported by Building Information Modeling (BIM), which provides spatial and functional representations of architectural heritage elements using parametric objects. It permits early-stage visualization, data management, error correction, data sharing, and calculation. The studies focus mainly on PV optimization on rooftops without fulfilling specific integration criteria [76,77]. The main purposes of these studies are energy performance evaluation, shape and orientation investigation, layout and color preview, and cost reduction. Only one study highlights the theoretical benefits of Heritage BIM (HBIM) for PV installations on architectural heritage [46].

4. Wind Energy

The integration of wind energy into the "*architectural heritage*" refers mainly to the use of large wind turbines located on land (onshore) or water (offshore). Applications at the building level are neglected, probably for the strict heritage constraints that normally do not allow these applications on a historic building. Thus, the literature refers mainly to heritage sites. Nineteen scientific documents have been found for the period 1994–2023, combining cultural heritage AND wind energy keywords (Table 1). Between them, seven papers have been published in the period 2020–2023. Thus, 36% of publications are from the last 3 years (Figure 11).

Active Countries for the analyzed period are the UK, Australia, the US, Turkey, Portugal, Brazil, and Denmark, with one paper each (Figure 12).

The keywords of these studies have been analyzed. Authors' and indexed keywords produced a heterogenous cloud with five clusters (Figure 13a): (i) biodiversity; (ii) wind farms; (iii) risk assessment; (iv) decision-making; and (v) climatic change. Indexed keywords produced four more rational clusters (Figure 13b): (i) biodiversity; (ii) risk assessment; (iii) decision-making; and (iv) climate change. This classification represents the most important topics of the decision-making process on wind energy on heritage landscapes that require a detailed risk assessment for balancing the influence on biodiversity and climate change.

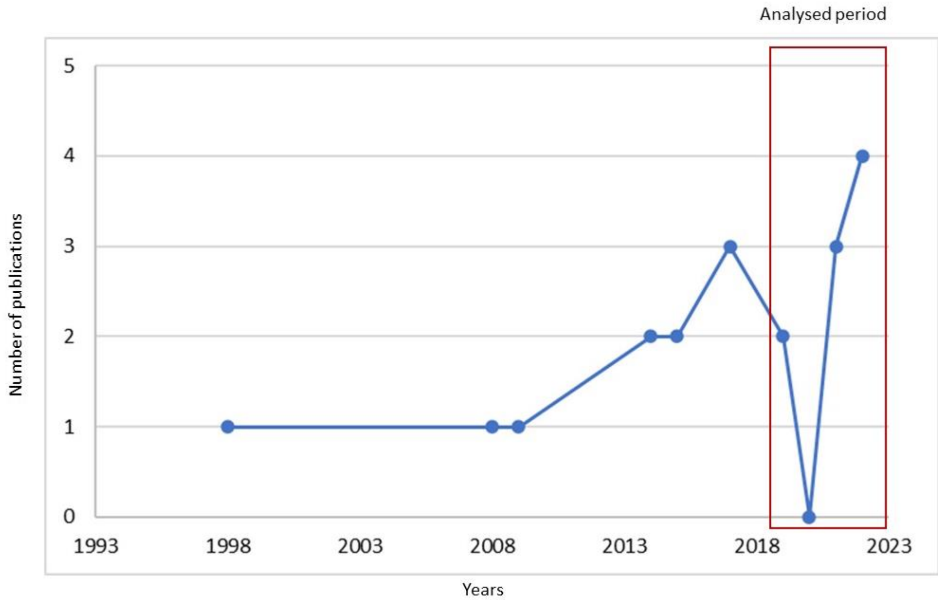

Figure 11. Chronological view of the studies on wind energy and architectural heritage: 19 scientific documents have been realized from 1998 to 2023, 7 of them in the years 2020–2023 (Source: Author's elaboration using Scopus data).

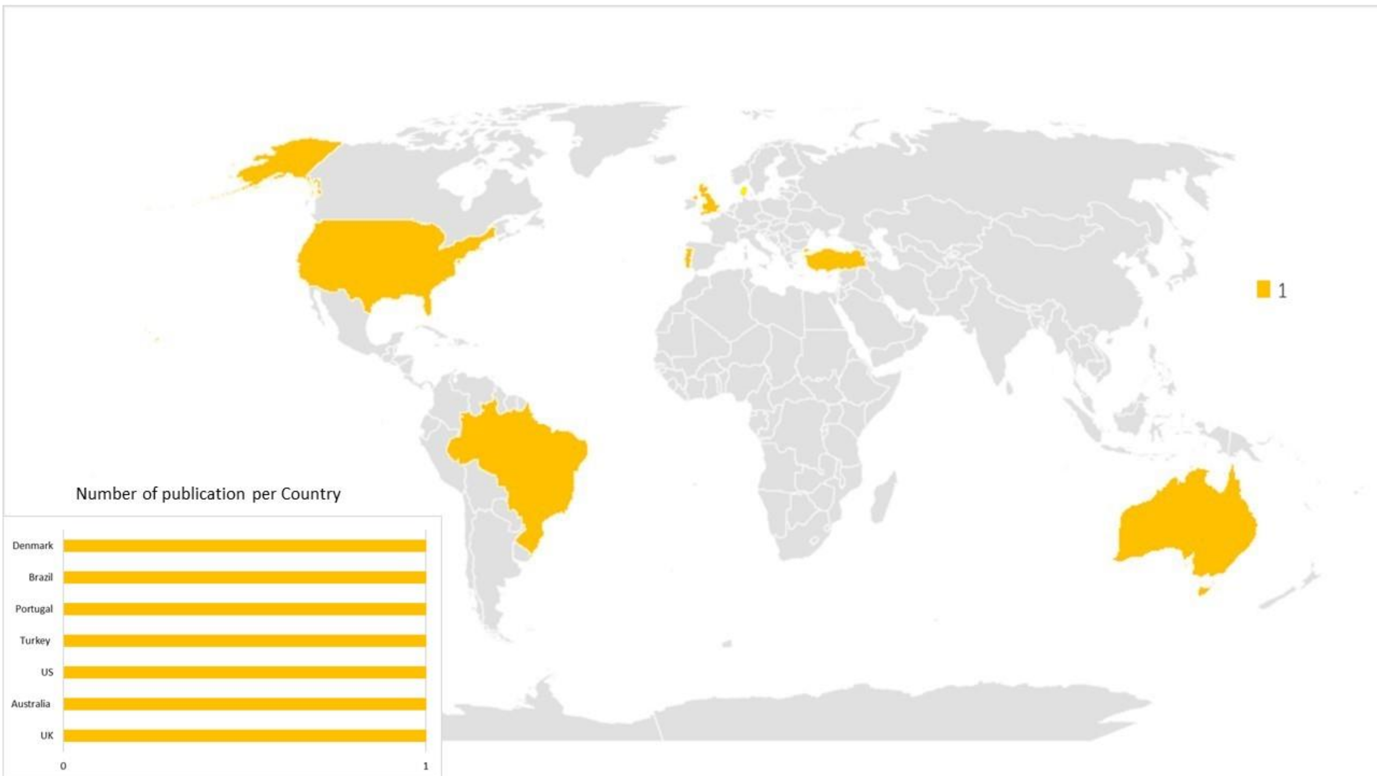

Figure 12. Map of scientific studies on wind energy and architectural heritage according to their provenience (Source: Author's elaboration using Scopus data).

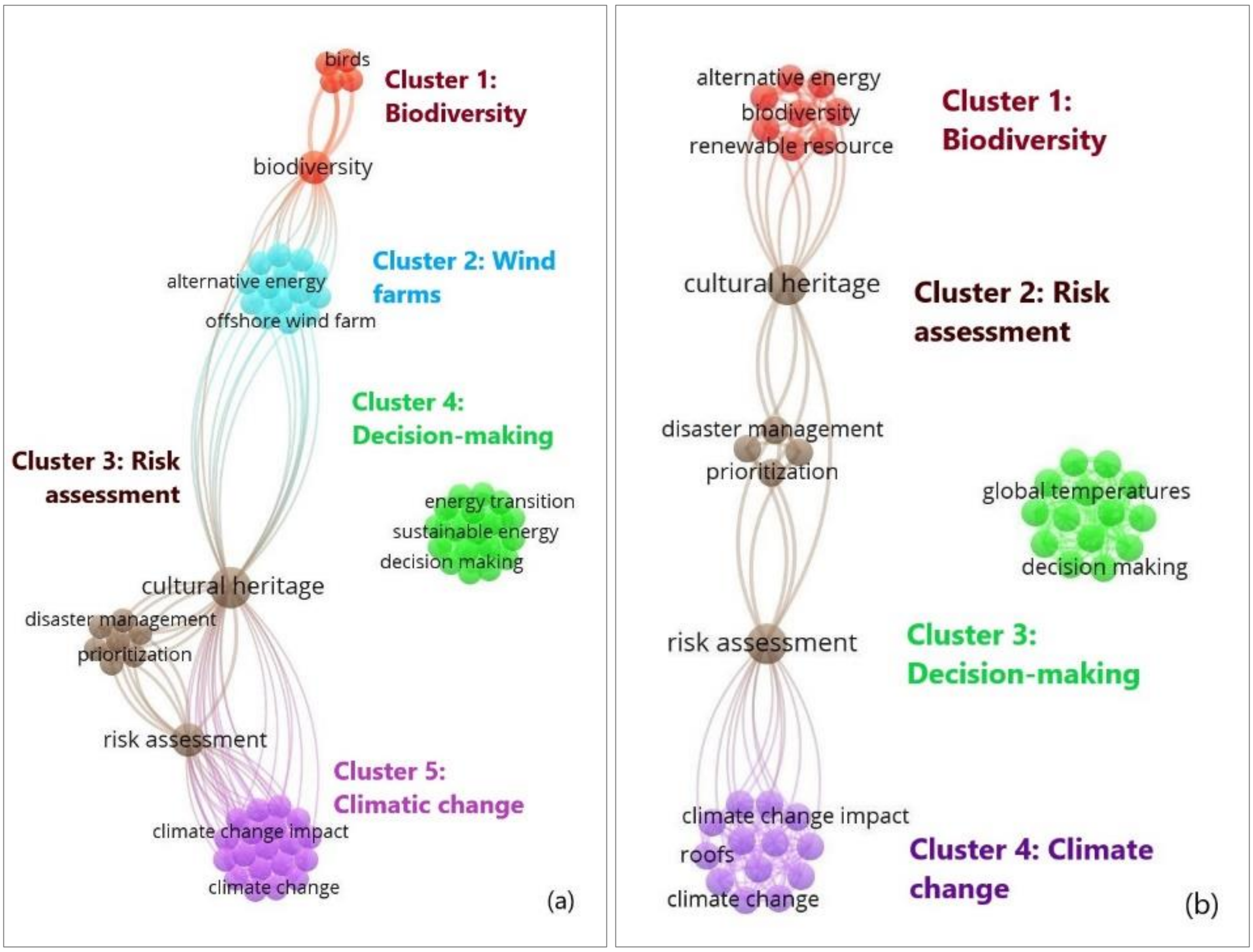

Figure 13. Scientific landscape of of wind energy and architectural heritage keywords: (**a**) 71 keywords; (**b**) 57 indexed keywords (source: Author's elaboration using VOSviewer, based on Scopus data).

Finally, wind and heritage keywords have been extracted from indexed keywords through detailed data mining to verify the main topics of these works. Twenty-eight indexed keywords have been recognized, and four main topics can be defined (Figure 14): (i) wind farm red; (ii) wind potential evaluation; (iii) social acceptance and visibility mapping; and (iv) wind integration criteria. Each topic is discussed deeply.

4.1. Wind Farms

The literature refers only to offshore wind farms. Restrictions for their implementation concern the protection of natural areas (e.g., archaeological monuments, shipwrecks, environmentally protected areas for biodiversity, refuges for wildlife) as well as the presence of technical constraints (e.g., marine pilot zones, underwater lines, pipelines), maritime uses (e.g., exploration or extraction of hydrocarbons and minerals), environmental risks (e.g., aquaculture and fishing banks), and military operations [78]. Moreover, maritime zones with mean wind velocity smaller than 4 m/s [78] and earthquake fault lines [79] are excluded, respectively, for their low energy potential and risks. The main impacts of floating wind farms concern the destruction or the disturbance of foraging or breeding habitats, the collision of marine species and seabirds [80], as well as the generation of negative social perceptions in local communities [80].

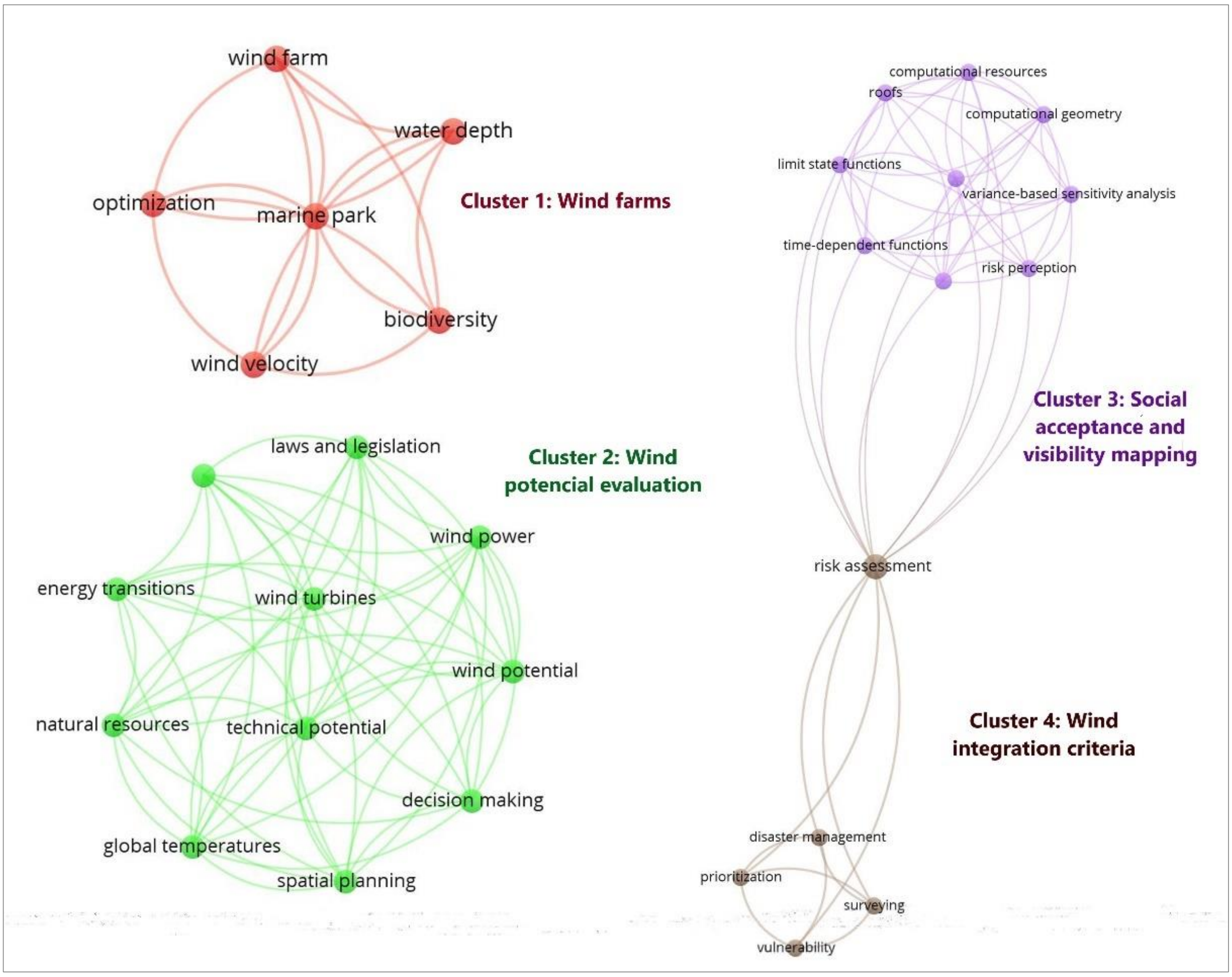

Figure 14. Main clusters of the studies on wind energy and architectural heritage based on co-occurrence network of the selected indexed keywords (source: Author's elaboration using VOSviewer, based on Scopus data).

4.2. Wind Potential Evaluation

The determination of wind potential and of optimized sites for utility-scale wind systems requires the integration of multiple factors that affect the conservation of landscapes and wild environments, as well as the costs of electricity generation and use [81]. Normally, multicriteria evaluation techniques (MCE) are coupled with GIS to compare environmental, economic, legal, social, and technical aspects [81,82]. The most common techniques are simple additive weighting (SAW), the analytical hierarchy process (AHP), the ideal point methods (e.g., TOPSIS), the elimination and choice expressing (ELECTRE), and the outranking techniques (e.g., PROMETHEE) [78]. AHP is the most used technique for the high complexity of wind studies. AHP is a semi-quantitative method that involves quantitative and qualitative criteria defined through public inquiries or expert working tables for guiding informed decision processes in a conscious way [82]. The parameters considered try to balance geo-resources and geo-hazards detection with land-use suitability to evaluate both wind potential and risks [78]. The evaluation is characterized by well-known steps [79]. First, areas not suitable for locating a wind farm are identified using general criteria (Section 4.1). These criteria are grouped into decision and exclusion criteria based on public inquiries [79] or general rules. These criteria are evaluated through the AHP method and scored according to their importance. Finally, the most suitable area is determined and georeferenced.

4.3. Social Acceptance and Visibility Mapping

Wind energy involves historically unprecedented changes to the visual integrity of a landscape [83]. Thus, wind integration criteria are strictly related to the assessment of the risk of wind turbines on the natural environment [84]. Wind turbines have a total high of 180–200 m. They are visible up to 80 km in lowlands and up to 30 km in the mountains [83]. Thus, they have an impact also on heritage towns, groups of isolated buildings, and heritage sites. The assessment of their location is very important to reduce a potential negative impact [83]. In many cases, wind technologies are excluded from conservation areas, sites of interest (e.g., heritage, archaeological, and paleontological sites), and agricultural lands with high fertility for the visual impact on high-sensitive heritage values [82]. They are not compatible not only with "*heritage core zones*" (the area with the listed property) but also with "*heritage buffer zones*" (the outside area of about 100 m that protects historic features from external influences) [83]. Otherwise, some visibility methodologies are provided for identifying suitable zones for their location. The most common is the production of a baseline with high-quality and georeferenced photographs from selected viewpoints to evaluate the impact and the risk connected with the installation of wind turbines [84,85]. Viewpoints must be selected according to the presence of heritage significance and historic testimony [85] (Figure 15).

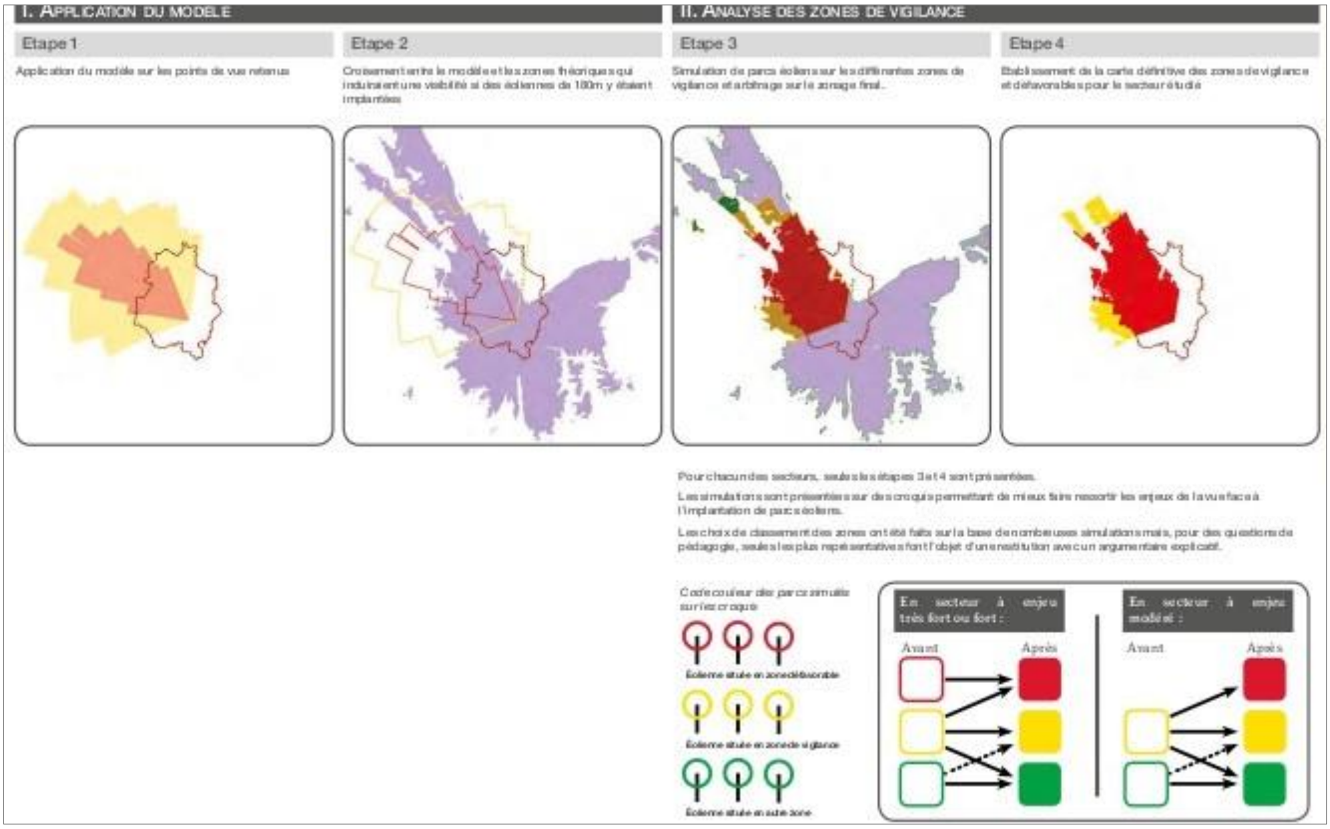

Figure 15. Zoning of wind turbines in the Vézelay landscape (France) based on angle of view and distance of the turbines: unfavorable (red), caution (yellow), and other zones (green) (Source: [84]).

The impact of these technologies may vary depending on their visibility, number, and distance from the property. Kloos et al. suggested the importance of maintaining the overall quality of the landscape by studying the interrelations between wind elements and surroundings [86]. The visibility of wind turbines should be assessed according to the following criteria: (i) technical dominance of the landscape image; (ii) visual dominance of the turbines; and (iii) distortion of the landscape scale. Noisy of wind turbines is not reported as a problem, probably because of the distance from inhabited areas.

4.4. Wind Integration Criteria

The main influencing factors for assessing the visual acceptability of wind turbines in a broader landscape perception are as follows:

- "*Distance*" from significant viewpoints and heritage property [76–84,87]. In general, a maximum distance of 10 km from conservation sites is required to reduce visibility while also considering changing weather and atmospheric conditions. Otherwise, suitable protection perimeters are within the range of 5–7 km from the property.
- "*Reduced visibility*" from important angles of view, maintaining an undisturbed horizon and defining correct color ranges and blade directions [85,86] (Figure 16).
- *Visual competition*" requires the conservation of an undisturbed visual setting, and quality of the landscape considering the interaction between wind turbines, a heritage property, and its surroundings [84,86].
- "*Environmental impacts*" on pre-existing elements express the need to reduce the disturbance on wildlife, seaside, biodiversity, and natural elements [78,82].
- "*Balance between preservation and wind potential*" consider the most suitable position also in terms of wind speed, wind direction, uniform directions, and absence of heritage values [76,81].

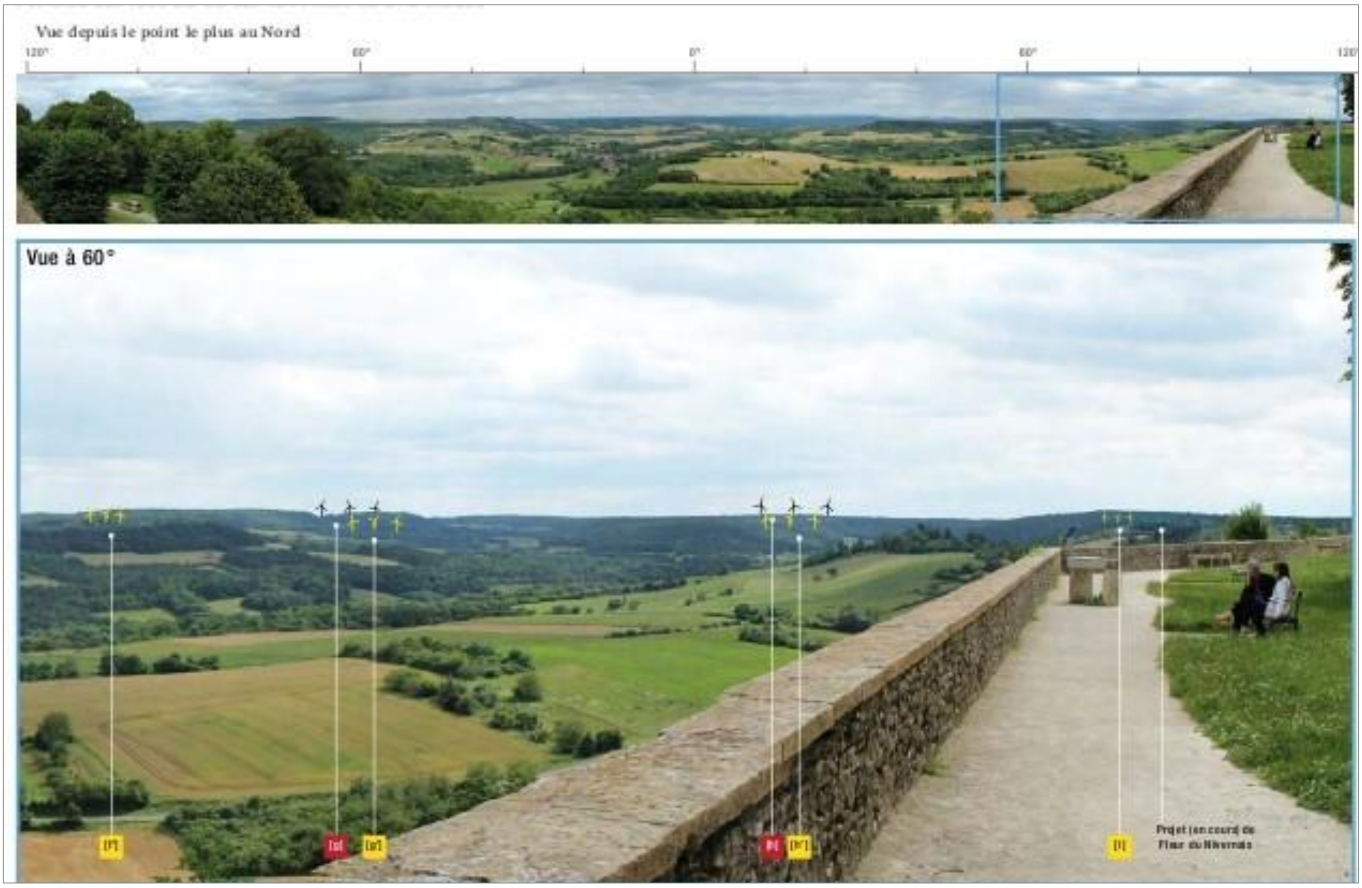

Figure 16. Positive example of the depiction of an outgoing view with panorama baseline on top and the view section with graphic accentuation, color code, and reference to evaluation scheme in Vézelay (France) (Source: [84]).

5. Geothermal Energy

The integration of geothermal energy refers mainly to ground source heat pumps in historic* buildings, and it is seldom investigated. Four scientific documents have been found for the period 2017–2023, combining cultural heritage and geothermal energy keywords (Table 1). Between them, one paper was published in the period 2020–2023. Thus, 25% of publications are from the last 3 years (Figure 17).

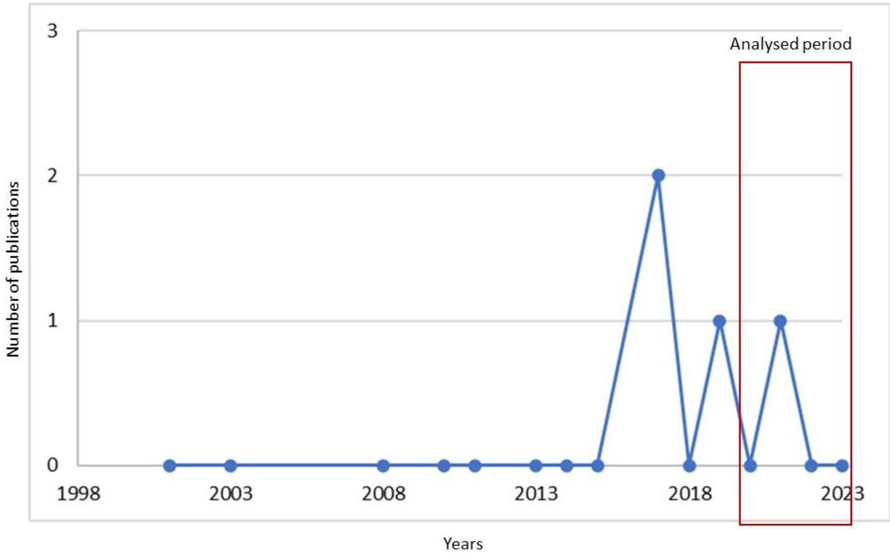

Figure 17. Chronological view of the studies on geothermal energy and architectural heritage: 4 scientific documents have been realized from 2017 to 2023, 1 of them in the years 2020–2023 (Source: Author's elaboration using Scopus data).

All documents described an Italian case study. The most recent publication presents the design and construction of a ground-coupled heat pump in a heritage building located in Naples (Italy) to demonstrate its feasibility in densely built historic towns [88]. The system is based on a low-enthalpy geothermal plant that uses groundwater temperature to produce both heating and cooling. The main problems for historic* towns concern the following difficulties:

- Access to mechanical devices for the construction of deep wells without altering the original architectural layout.
- Drilling and excavation due to the presence of narrow alleys.
- Interception of cavities that can reduce the effectiveness of the geothermal well.
- Long administrative and technical procedures.

In this case, the monitored coefficient of performance (COP) was better than the one certified by the manufacturer (5.65 instead of 4.32). Moreover, significant reductions in greenhouse gas emissions (CO_2) were found without causing alterations in the heritage values. Previous studies on historic buildings demonstrated the reduction of cooling and heating energy, respectively, of 30–50% and 20–40% [89,90]. Moreover, the construction of a geothermal heat pump showed lower payback periods compared with other heat pumps [90].

6. Bioenergy

Bioenergy is produced from several organic materials (also called biomass, e.g., wood, dung, charcoal) and agricultural crops for liquid biofuel. Only biomass can be integrated into the "*architectural heritage*", while biofuels are used mainly for agricultural purposes. Thus, the present study considered only biomass and cultural heritage keywords (Table 1). Unfortunately, no studies have been found on this topic.

7. Conclusions and Research Perspectives

The present study aims at defining an updated overview of the application of RES on "*architectural heritage*". RES analyzed are (i) solar energy (Section 3); (ii) wind energy (Section 4); (iii) geothermal energy (Section 5); and (iv) bioenergy (Section 6). A deep literature review of the studies published in the years 2020–2023 has been performed, identifying main topics, challenges, advanced solutions, impacts, and future perspectives. Acceptability, design criteria, and cutting-edge technologies are also illustrated through case studies to better understand practical approaches. Innovative aspects of the present study concern:

- Overcoming the knowledge fragmentation on RES integration in architectural heritage, updating the state of the art of this topic in the period 2020–2023.
- Bridging the traditional boundaries between architectural restoration, landscape design, urban planning, building physics, engineering, and social science.
- Description of current applications and future perspectives for the research sector on RES integration on architectural heritage.

In conclusion, some comments can be summarized considering current regulations, shortcomings, and challenges introduced by the updated state-of-the-art. The key findings are the following:

- The integration of active solar solutions into architectural heritage is more studied than wind technologies, geothermal energies, and bioenergy especially thanks to the presence of specific research projects.
- Among active solar solutions, photovoltaic systems are deeper studied thanks to the aesthetical and technical opportunities offered in the last years as well as to the publication of clear design criteria and recommendations.
- The integration of wind technologies is studied mainly at a territorial level for offshore and wind farms in natural areas, while the integration of wind technologies in historic* buildings is not considered due to the presence of strict regulation constraints.
- The integration of geothermal energy refers mainly to historic* buildings, delineating problems and opportunities for energy production.
- No publications have been found on bioenergy and "*architectural heritage*".
- Acceptability (and acceptance) of solar and wind energy in heritage contexts is low for the presence of technical, economical, informative, and legislative barriers. This topic is internationally discussed, delineating recurring problems in all countries.
- Geothermal energy in historic* buildings is quite acceptable, and it did not produce specific literature.
- Visual and material compatibility are important criteria for maintaining the original appearance and minimizing the intervention on buildings and towns for all renewable energy technologies.
- Visibility mapping is at the basis of solar and wind energy integration, thanks to the elaboration of spatial modeling, experts' inquiries, and simplified graphical methods.
- Energy potential estimation of active solar and wind technologies in heritage contexts is less studied. In many cases, historic* city centers are excluded from the solar cadasters for the presence of heritage constraints. Otherwise, wind potential estimation refers mainly to offshore wind farms.
- HBIM constitutes a strong tool for balancing energy production and heritage protection, especially for the design of active solar and geothermal energies.

The detailed study of the state of the art of literature also highlights future perspectives for the research on RES applied to "*architectural heritage*". These perspectives are different for active solar systems and other technologies because the state of the art of research on solar technologies is more advanced. In the first case, the following research perspective can be delineated:

- Practical applications and tests of energy, aesthetical, and sustainable performances (e.g., life cycle assessment) of innovative photovoltaic and solar thermal systems.
- Mapping of commercial products.
- Study on the real aesthetic and technological impact of these technologies on heritage and traditional buildings, supported by case study applications and interviews with the stakeholders.

- Economic analysis of direct and operational costs as well as of payback periods of innovative photovoltaic and solar thermal panels integrated into "*architectural heritage*".
- Implementation of building integrated photovoltaics and solar thermal system on BIM and HBIM systems for implementing the visual appearance and for calculating the energy production from the early design to the construction phase.
- Prototyping of new products through focus groups with producers and Heritage Authorities.
- Otherwise, the research perspective for wind, geothermal, and bioenergy are the following:
- Implementation of research design projects on their application to cultural heritage, especially considering historic* buildings.
- Definition of the state of the art of the legislation in different countries to understand real barriers and constraints.
- Definition of clear rules, design criteria, and recommendations for "*architectural heritage*" and landscape applications to boost their applicability.
- Collection and mapping of positive and negative examples (products and case studies) to learn from the practice.

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Nomenclature

UNESCO	United Nations Educational: Scientific and Cultural Organization
EU	European
RES	Renewable Energy Sources
PV	Photovoltaic
BIPV	Building Integrate Photovoltaic
ST	Solar Thermal
USR	Urban Shading Ration
GIS	Geographic Information System
BIM	Building Information Modeling
HBIM	Heritage Building Information Modeling
HVAC	Heating Ventilation Air Conditioning

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