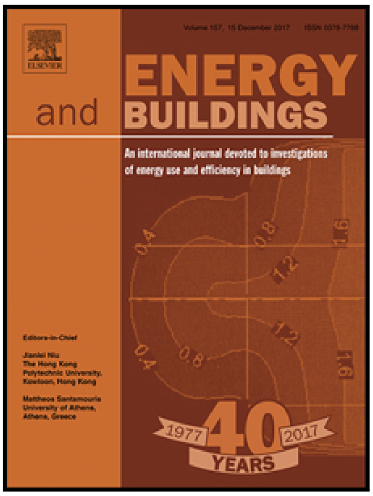

Integration of renewable technologies in historical and heritage buildings: a review

Luisa F. Cabeza , Alvaro de Gracia , Anna Laura Pisello

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Highlights

- Historical buildings need to preserve their key testimonial knowledge
- Tailored retrofit strategies have been investigated and implemented
- Examples in historical buildings are classified
- The use of energy efficiency and the integration of renewable energies are included
- HVAC, and renewable energies such as solar and geothermal are used

Integration of renewable technologies in historical and heritage buildings: a review

Luisa F. Cabeza[1,*], Alvaro de Gracia[1,2], Anna Laura Pisello[2,3]

[1]GREiA Research Group, INSPIRES Research Centre, Universitat de Lleida, Pere de Cabrera s/n, 25001-Lleida, Spain

[2]CIRIAF – Interuniversity Research Centre on Pollution and Environment "Mauro Felli", Via Duranti 63, 06125-Perugia, Italy

[3]Department of Engineering – University of Perugia, Via Duranti 93, 06125-Perugia, Italy

*Corresponding author: lcabeza@diei.udl.cat

Abstract

The need to achieve energy efficiency standards in new and existing buildings has triggered both research and design practice aimed at reducing their carbon footprint and improving their indoor comfort and functionality conditions. In this view, a dedicated scientific effort has to be spent while dealing with historical architectures needing to preserve their key testimonial knowledge into the society. Therefore, tailored retrofit strategies have been investigated and implemented without compromising their architectural value, especially when new uses are foreseen in those buildings. This review classifies different examples of the use of energy efficiency approaches and the integration of renewable energies in historical buildings, including solar and geothermal energy, and the use of heat pumps and other high-efficiency Heating Ventilation and Air Conditioning systems.

Keywords

Historical buildings; heritage buildings; energy efficiency; renewable energies; solar energy; geothermal energy; heat pumps.

1. Introduction

Buildings account for almost a third of final energy consumption globally and are an equally important source of CO_2 emissions [1]. Currently, both space heating and cooling as well as hot water production are estimated to account for roughly half of global energy consumption in buildings. These end-uses represent significant opportunities to reduce energy consumption, improve energy security, and reduce CO_2 emissions due to the fact that space and water-heating provision is dominated by fossil fuels while cooling demand is growing rapidly in countries with very carbon-intensive electricity systems. Building heating and cooling systems are used to maintain comfortable indoor temperatures through the generation and/or transfer of heat. There are four main technical approaches to reduce the heating or cooling load of a building:

1. Reducing the temperature difference between indoors and outdoors by adopting Adaptive Thermal Comfort principles - an indoor temperature that is closer to the outdoor temperature (as far as possible).
2. Improving the building envelope.
3. Increasing the efficiency of heating and cooling equipment.
4. Replacing the building with a new construction.

Related to this third point, low/zero-carbon and energy-efficient heating and cooling technologies for buildings have the potential to reduce CO_2 emissions by up to 2 Gt and save 710 Mtoe of energy by 2050. Most of these technologies – which include solar thermal, combined heat and power (CHP), heat pumps, and thermal energy storage – are commercially available today. The potential of these technologies presents, nevertheless, several barriers in order to increase the roll-out in the market [1], such as higher initial cost, market risks for new technologies, imperfect information, and uncertainty (technical, regulatory, policy, etc.).

On the other hand, historical buildings (defined as those built before 1945), which are usually low-performance buildings by definition (as shown for the Netherlands by van Krugten et al. [2]), represent almost 30-40% of the whole building stock in European countries [3]. Historical buildings often contribute to townscape character. They create the urban spaces that are enjoyed by residents and attract tourist visitors. They may be protected by law from alteration not only limited to their visual appearance preservation, but also concerning materials and construction techniques to be integrated into original architectures. According to Fabbri and Pretelli [4], a heritage building is a historical building which, for their immense value, is subject to legal preservation. In Italy, for instance, heritage buildings built before 1919 are around 19% of the total, and buildings built between 1919 and 1945 are about 12% of the total [5]. In UK, it has been estimated that approximately 1% of the existing buildings can be considered heritage ones [6]. According to Fabbri [7], historical buildings can be classified into three categories as monuments and buildings of special architectural interest, buildings built before an established historical date (i.e., historical threshold), and buildings that show unique constructive and technological systems. In the EU27, the 14% of buildings were erected before the 1919 and the 26% has been built before the 1945.

The complex definition of cultural heritage itself has influenced their architectural restoration, energy retrofit, and re-functioning all around the world, with a variety of approaches, starting from the very conservative ones, more popular in the Mediterranean areas, to the most radical ones, typically implemented in Northern European countries. Before dealing with energy retrofit design and integration issues, the definition of cultural heritage in buildings and architecture in general should be investigated and several interpretations should be taken into account for an exhaustive analysis of this complex multidisciplinary world. In this view, the Venice Charter, which is still operative as International Charter for the Conservation and Restoration of Monuments and Sites, expressed its position as follows: “Imbued with a message from the past, the historic monuments of generations of people remain to the present day as living witnesses of their age- old traditions. People are becoming more and more conscious of the unity of human values and regard ancient monuments as a common heritage. The common responsibility to safeguard them for future generations is recognized. It is our duty to hand them on in the full richness of their authenticity” [8]. The key messages to be addressed consist of the necessity to preserve cultural common heritage message of responsibility to be safeguarded for future generations. In a general perspective, preservation and valorisation of cultural heritage buildings and monument represents a social, together with technical, responsibility included under the large framework of sustainable development [9], which guides the preservation of our eco-system and natural resources for the future generations. The same future generations should be able to enjoy not only the original form and structure of natural resources and anthropogenic heritage sites, but also their functionalities, their intrinsic value, and also subsequent modifications and additions occurred over the course of the time, recognizing a deep stratification value of cultural development and historic identity of a society [10].

In recent years, redundant heritage buildings have been converted to other functions either for private or public use [11]. For example, in Italy many churches, former factories, and other heritage buildings in the historical centre of cities are being converted into museums, shops or showrooms [12]. Although buildings of cultural heritage significance are quantitatively a small proportion of the building stock, they are, nevertheless, significant in terms of their contribution to reduce greenhouse gas emissions through measures to improve their energy efficiency and the broader aims of achieving sustainable development [11]. To improve the energy performance of historical buildings, there are several studies that analysed the feasibility of different actions that follow regulatory restrictions [13]. According to these authors, most studies agree that the most significant actions are improvement of the building envelope insulation and the HVAC (Heating Ventilation and Air Conditioning) and DHW (Domestic Hot

Water) systems (heating cooling and air conditioning, and domestic hot water systems), while renewable energy sources and thermal energy storage are difficult to integrate.

Several methodologies have been proposed for the performance assessment and optimization of existing buildings [14,15,16,17,18]. The main steps usually pursued for a successful retrofit of historic buildings consist of energy auditing, building performance assessment, quantification of energy benefits, economic analysis, risk assessment, and measurement of energy savings [19]. Additionally, the implementation of effective retrofit scenarios for historic buildings usually starts from a preliminary diagnosis of the building conditions including the evaluation of the state of the building components, indoor environmental quality, obsolescence, and current energy use [20]. In 2014, Pisello et al. [21] described a complete methodology for the energy assessment of a historical building and the decision of the best energy approach. The methodology consisted in the following steps:

(i) Elaboration of the energy model of the building (i.e. with Energy Plus), considering the current status of the structure, both in terms of architectural and technical elements.
(ii) Simulation of the year-round energy performance of the building in terms of heating and cooling primary energy requirements, before the energy retrofit.
(iii) Proposal of a new integrated configuration of the energy systems, by taking into account all the architectural and technical constraints due to the historical value of the pilot case study building.

Another methodology was presented by Buratti et al. [22]. In this study the energy performance of buildings in Umbria was collected from energy certificates, and inserted in a database, in order to provide the necessary input data for further statistical analysis. In particular, the mean energy consumption and the CO_2 emissions were calculated and then compared to the ones reported in the Italian and European official sources. In order to compare these indicators, a climate normalization was necessary, to take the different climate conditions into account. Both the energy and CO_2 indicators estimated that simulated data are very close to the ones reported in European official reports and they allow to highlight an effective energy saving and CO_2 emissions reduction in the residential sector, which is one of the major energy consumers.

Although the agreement on the difficulty of achieving acceptable energy performance and technical functionality of historical buildings is given in all the literature, there is not a study that shows all the actions that have been taken so far, to be able to learn from one another and replicate winning procedures in similar contexts. Therefore, this review aims at presenting all the published case studies and to organised them for better comparison.

2. Energy efficiency approaches

The implementation of internal envelope insulation [23], cool coatings, and window retrofit represents the best solution in order to improve the energy efficiency of building envelopes [24]. Additionally, upgraded control systems, lighting, ventilation, thermal storage, and heat recovery are listed as major retrofit technologies to reduce the energy demand of heritage buildings within temperate-Mediterranean climate conditions [25,26]. Historical brick buildings located in the Baltic Sea Region have similar requirements and often have been restored without preserving their identity [27].

A deep review of the possible retrofit actions suitable for existing European buildings is provided in [28], in terms of both architectural refurbishment and replacement of traditional energy systems with innovative energy plants. These retrofit actions include improvement of envelope thermal insulation in building envelopes, use of high-efficiency windows (both glass and frame systems), design of smart and high efficiency lighting components, renovation of HVAC and its integration in natural building volumes and vacuum spaces available in historic buildings, and implementation of renewable energy sources such as wind or solar by minimizing their impact on the architectural value of such buildings. And a good evaluation of the potential barriers to use such approaches in historical buildings is given in [6]. The main barrier, apart from the classic technical ones, is the reservation of stakeholders in the heritage industry about compatibility of energy efficiency and the conservation of building historical value.

As example, *Palazzo Ex-INPS* (Benevento, Italy), today used as administrative and didactic building of the Department of Engineering of University of Sannio, was studied [29]. The building was built in 1927, contextually to the redesign of the historic centre of Beneveto, Italy (Figure 1). Direct surveys permitted the census of all major uses of energy, as, for instance, lighting systems, computers, and office equipment. By using appropriate energy models (validated with measured data), energy and environmental indicators, and economic analysis tools, the performances of a set of retrofit actions, singularly analysed and then coupled if suitable, were evaluated. The study concluded, according to the dynamic energy simulation, that an adequate management regime, aimed at maintaining the desired levels of service and comfort, allowed a reduction by about 24% of the annual electricity request. Further studied actions were the reduction of infiltration, replacement of windows, increment of thermal insulation of the building envelope (i.e., vertical wall and roof slab), and addition of thermal inertia through the installation of phase change wallboards; in all these options, the integration in a building with historical value was considered. The most suitable combination (i.e., package) of energy efficiency measures is resulted as the replacement of windows with low-emissive ones, the application of thermal insulation plaster, and the new thermal insulation of the roof slab.

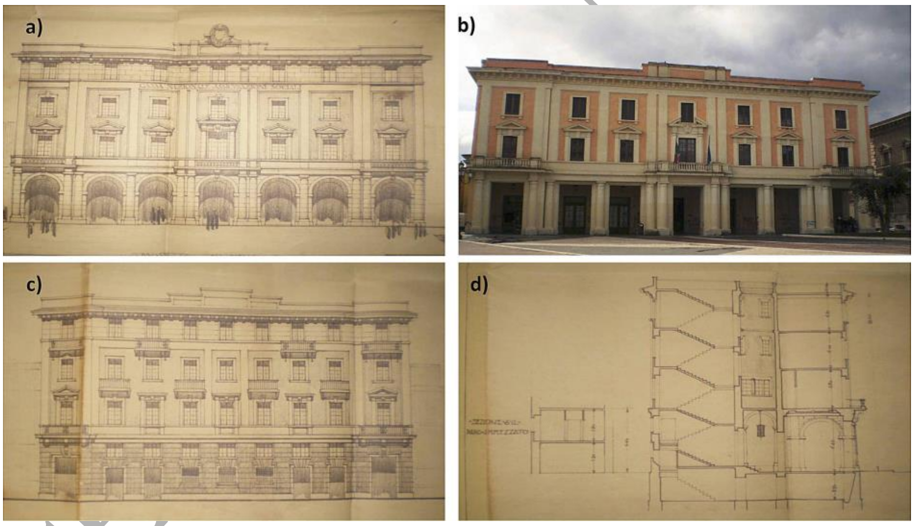


Figure 1. ***Palazzo Ex-INPS*** **(s. XX), Benevento, Italy [29]: (a) frontal view of the ancient project, (b) frontal view of present design, (c) back view of the ancient project, (d) cross section of the ancient.**

Another example is the *Albergo dei Poveri* in the Cargonara valley (Genoa, Italy), from the early decades of the 17th Century [16]. The monumental complex occupies about 60000 m^2 and has a plant and volume that have change over time (Figure 2). To increase the energy performance of the building envelope, possible interventions considered were insulation of the floor on the ground, combined with interventions to eliminate rising damp, insulation of roofing systems, and enhancement of the energy performance of external windows. In this case, more than purely estimating energy efficiency gains as the result of a complete substitution of historical windows, it was necessary to evaluate, even in terms of historical value, the possibility to restore them, keeping a single glass (as dimensions and technical features of these windows do not allow the insert of a double glass).

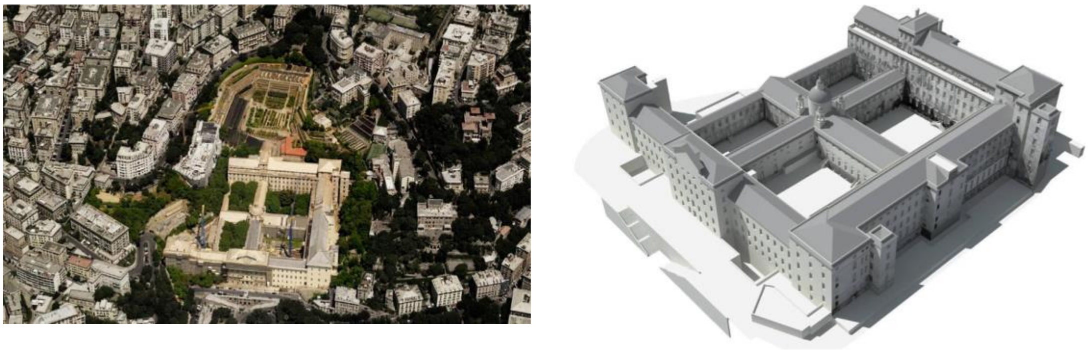


Figure 2. ***Albergo dei Poveri*** **(s. XVII), Genoa, Italy [16].**

One step forward was carried out at *Ca'S. Orsola* (Treviso, Italy), where its transformation into a prestigious residential building by a major renovation, mainly aimed at seismic and energy upgrading, took it to a nearly zero energy building (NZEB) [30]. The building was the old seat of Polish Institute (Figure 3). Originally it was a convent and it was inhabited for 40 years until 2000 and during this time it kept intact the original structure and architectural distribution. The major benefit given by renovation measures is the energy saving of 329.64 kWh/m^2·year, including heating, DHW, and ventilation systems. Moreover, after the retrofit intervention it was possible to underline also non-energy benefits, rather factors that can be brought back to social and economic aspects in the long term, such us recovering an historical building for high-standard uses, improving structural conditions for seismic consolidation, and providing aesthetical improvement, all of them increasing the market value of the property.

Figure 3. ***Ca'S. Orsola*** **(S. XX), Treviso, Italy [30].**

The refurbishment of the windows of the *Palace of the Hungarian Academy of Sciences* (*Magyar Tudományos Akadémica*), located in Budapest (Hungary) took place in 2014 [31]. The building is of Neo-Renaissance style of contemporary German palaces and was built between 1862 and 1865. The building has more than 200 windows of 23 different sizes, shapes, and opening types in rooms of also different sizes and uses, and the appearance of the windows had to be preserved. The simulation study of those windows showed that relying only on the U-value of window options is not an appropriate way to find optimized solution in all cases. The use of interpane shading devices and simple auto-mated control systems, a non-intrusive refurbishment measure, was shown to have a very beneficial effect on the energy balance of traditional windows in both cooling and heating seasons.

An example of an energy efficiency approach is the reconstruction of courtyard spaces into atriums (Figure 4). This has been carried out in historical buildings in Saint-Petersburg, Russia [32]. In the period from 1800 to 1860, Saint-Petersburg was built mostly with brick buildings along the perimeter of allotments with founding one or several courtyards.

Figure 4. The Zinger House in Saint-Petersburg (s. XX) [17]. Contemporary state, internal courtyard.

An example of energy retrofitting of a “modern” historical building was carried out in the *Urbino University Colleges* [33]. The *Collegi* were built between 1962 and 1983, they had a new usable area of 32396 m^2 and a gross heated volume of 127059 m^3. Any proposal of retrofitting the envelope had to cope with the historical and architectural value of the *Collegi*. Insulating by external coating was thus considered unacceptable in a conservation perspective, even if it would contribute to solve many energy issues. Also filling the wall with insulating materials was not an option, since there is no cavity to fill. In this case, the only option for the outer walls was thus internal insulation.

A similar study was reported for a building located in Rome (Nomentano district), built during the urban expansion of the zone in the early 1900s [34]. The building is a block composed of 5 floors over earth, the gross area of each floor is about 370 m^2 and the net area is about 240 m^2. This study highlighted the need to carry out a measurement campaign to discover hidden control inefficiencies and energy wastes. The study of the energy refurbishment of residential historical buildings in Kiev gave the same results [35]. In this case, a residential building built in 1909 on the Malaya Zhitomirskaya street, 12-A, Kiev was taken as an example for the assessment (historical and architectural monument of local importance).

Another approach is the use of the passive thermal performance of the building to reduce energy demand. This approach has been successfully studied in Asia. For example, Penang shop houses (Malaysia) can remain cooler than modern buildings, regulating the indoor air temperature and reducing the peak temperature (Figure 5) [36]. Although the use of mechanical ventilation was not seen as essential, the aid of electric fans may improve the indoor air conditions. Similarly, in China Nanjing Tulou buildings, built of rammed earth and in a wooden framework, were evaluated [37]. These large-scale residential buildings can be found across southeast China (Figure 6). The study of the energy performance of these buildings showed that the total annual primary energy consumption per household was lower than normal rural buildings of the same area, and the residents experienced better thermal comfort.

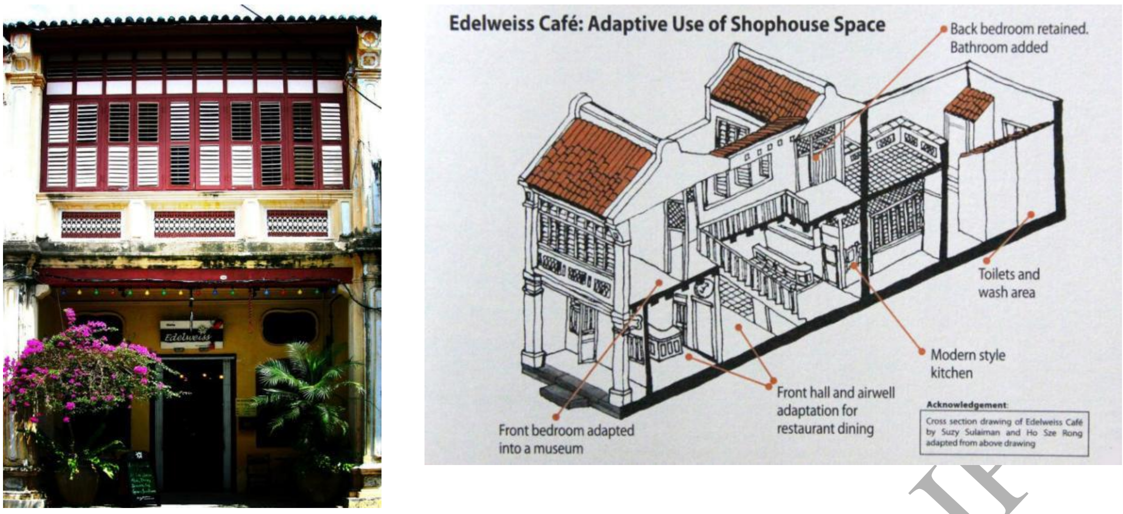


Figure 5. Penang shop house (Malaysia) [36].

Figure 6. Hekeng Tulou cluster (China) [37].

Energy efficiency approach implementations in historical buildings still lack of a proper regulation and detailed protocols, which can be followed to drive the integrated design process. The very first one consists of the Green Building Council (GBC) Historic Building protocol, developed by the Italian GBC according to LEED standards and ready to me implemented in Italy and for further translation into other languages. This protocol, according to the LEED guidelines, supports the innovation in design and material selection, but it also valorises the heritage preservation capability of designers and construction companies. Therefore, the real integrated procedure is put in place thanks to this standard. A new category was elaborated, corresponding to the Italian translation of “Historical value”, and therefore a new relative distribution of credit numbers was proposed, always according to carbon emission proportion, according to the LEED approach [38]. At the moment, several case studies in Italy are under development and the very first certification was released in central Italy. This Gold certification concerns the ancient stable of a Middle Age Rocca in central Italy, where offices and laboratories take place [39]. The interesting ideas of that historical building retrofit may be summarized as follows:

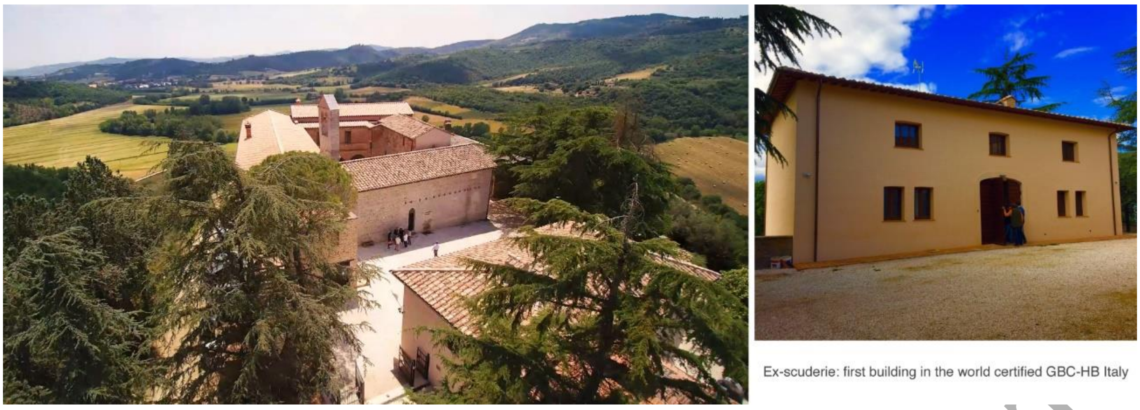


Figure 7. First building to be certified by means of the GBC Historic Building protocol in Perugia, Italy

- Local materials for both structural and energy restoration, to reduce the whole carbon footprint: cork thermal insulation coming from local recycled market are selected.
- New cool tiles for historical building applications are designed and launched into the market, as first example of cool roof for historical buildings, already approved by the Cultural heritage preservation authorities [40].
- New outdoor pavements using cool cement [41] and stone-aggregate materials for urban heat island mitigation coming from local quarries [42,43].
- A complete circular economy design, reaching energy self-sufficiency and waste recovery of local agricultural biomass feeding a trigeneration system and a biogas plant [44].

The building tried to propose a sort of repeatable scheme of structural and energy retrofit the large scale potential implementation in all these off-shore architectures where local energy systems may not be easily and sustainably accessible, to reach energy self-sufficiency with low carbon footprint by taking advantage from local waste.

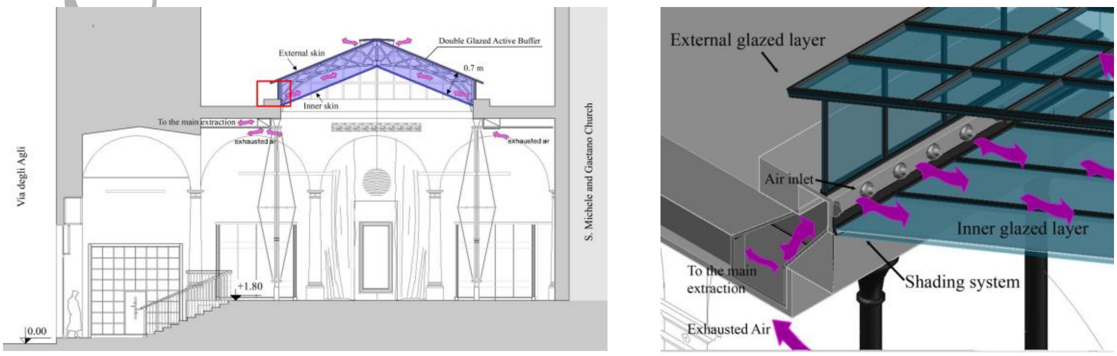
3. Use of heat pumps and other HVAC systems

Becchio et al. [**Error! Reference source not found.**45] discussed that the inclusion of an air conditioning system in a historical building is a complex operation. Usually, in historical downtowns, the background noise is very low (especially if there is no car traffic) and the buildings are very close to each other. The noise of all HVAC equipment must be addressed, especially if the generators usually work also during the night. The main difficulty to use HVAC equipment is to find the locations for the generators, especially for heat pumps and chillers, for which it is often necessary to find open spaces. Heat pumps and chillers are not pleasant to see, especially in the context of a building characterized by important architectural value and historic significance. Consequently, they must be hidden or masked. The best solution is to place them in the upper parts of the building on existing terraces or creating suitable space acting on the profile of the roof. Moreover, in some cases, there could be the problem of the equipment weight. In fact, probably, the original design of the historical building did not include weights so big and, for this reason, the structure of the building must be carefully verified. Furthermore, in historical buildings, the use of boilers is never easy, because often there is not a gas flue chimney or, when it is present, it still remains the problem of the structure fire protection. In these conditions, a heat pump should be used, in place of traditional chillers and boilers for cooling and heating, respectively.

A case study was developed in the *Castle of Zena*, Italy [**Error! Reference source not found.**]. It is a squared building with an internal courtyard, a missing side, and it is surrounded by a wall corresponding to the old moat. The original building was probably built in the 13th Century, but it was afterwards modified and transformed until the last restoration carried out in the decade of 1970s (**Error! Reference source not found.**Figure 8). The castle has a residential function, but it also hosts events. In this case study, due to the historical constraints and the installation effort needed, it was decided to exclude the HVAC technologies belonging to the category of all-air systems, and water systems were selected instead. In particular, two pipe fan-coils were chosen as emissions systems, characterised by easy integration despite the good emission efficiency. Given the environmental and landscape constraints, wind, photovoltaic, and solar thermal technologies were excluded. Therefore, heat pumps were chosen as generation system using renewable energy. Two different types of heat pump systems were compared via simulation. The first one was the widely used electric heat pump based on a compression cycle electrically powered, and the second one was a gas driven absorption heat pump. Moreover, two types of both heat pump technologies were analysed. The first one was an air source heat pump, while the second one was a water source heat pump connected to the existing well. The results of the study, which considered environmental aspects and economic feasibility, concluded that the last one, the electrical heat pump connected to the already existing well, was the best choice as presents a payback period of 7 years. Moreover, significant reduction of greenhouse gas emissions could be obtained by using a gas driven absorption heat pump instead of the electric heat pump.

Figure 8. ***Castle of Zena*** **(s. XIII), Italy [46**Error! Reference source not found.**].**

A second example is the cloister of the ancient Baroque monastery connected to the church of *SS. Michele e Gaetano* in Florence (Italy) [12]. This cloister is used as showroom and had a glazed pitched roof with a single glazed surface. This roof was redesigned as an active double glazed covering (**Error! Reference source not found.**Figure 9) used as thermal buffer and integrated with a Variable Air Volume (VAV) plant and the heating/cooling floor panels. The proposed active double glazed covering is based on the thermal buffer concept: this system allows the reduction of the high heat load exchange and control of the incident solar radiation. The new plant system (VAV combined with radiant panels) and the integrated active double glazed covering with a mechanical ventilation system, had a very low impact on the architectural structure of the existing building. The solution was perfectly integrated in the given historical constraints, but also ensured high internal comfort conditions.



(a) (b)

Figure 9. Showroom at the cloister of *SS. Michele e Gaetano* in Florence (Italy) [12]. (a) Double glazed active buffer system concept, and (b) technical details.

Similarly, the *church of St. Francis* in San Giovanni in Persiceto, Italy has been converted into an auditorium, concert hall, and/or exhibition hall [**Error! Reference source not found.**]. This church is placed inside a convent complex and was founded in the 13th Century by the Franciscan order. Over the centuries it has undergone transformations such as the 15th Century expansion, damage during wartimes, decay due to improper use after Napoleonic disposals, and final radical change in the 18th Century. The new building is in Baroque style from the Bologna area and it is enriched with elegant decorations consisting of stucco and paintings on the lateral walls of the church (**Error! Reference source not found.**Figure 10). The overall length of the building is about 44 m, with an internal height between 18 m and 21 m at the dome, and a total volume of about 10400 m^3. Radiant floors were not of the historical and archaeological interest of different layers which make up the flooring, therefore gas emitters at high temperature were selected. The relative humidity was controlled with a mechanical ventilation system. Air ducts can be inserted inside vertical and empty spaces, near the recesses, avoiding further destructive actions on the walls and minimizing the visual impact. The proposed solutions were simulated, and results show that a good microclimate control and well-being of the visitors is achieved without detriment of architectural and artistic perception of space and its decorations, nor disregarding the principles of restoration of minimum intervention, reversibility and distinctness.

Figure 10. *San Francesco church* (s. XIII, changed in s. XVIII), San Giovanni in Persiceto (Italy) [Error! Reference source not found.**].**

The *Crucifiers complex* in Venice, Italy, was refurbished to become a university campus of the University Iuav (**Error! Reference source not found.**Figure 11) [**Error! Reference source not found.**]. The area covers about 10000 m^2. From its foundation in 1150 to present days the convent was subject to different uses, from devotional confraternity to pilgrims shelter, to school, to barracks, and today to university campus. The HVAC terminal units consist of fan coils and air diffusers, which ensure the required ventilation. The air handling units (AHU) are distributed in various areas of the complex and each of them is installed in the garret of the building served. The main piping is embedded in the furnishings installed along the perimeter walls together with the largest number of fan coils serving the apartments (Fig. 5). Secondary piping for internal rooms was inserted in the new structures like walls of internal partitions or floors of mezzanines. The selected HVAC system is a surface water heat pump. Also, trigeneration system was installed, consisting of a turbine with an electric capacity of 100 kW fuelled by natural gas. Everything was controlled by an intelligent BMS system with continuous monitoring of the performances.

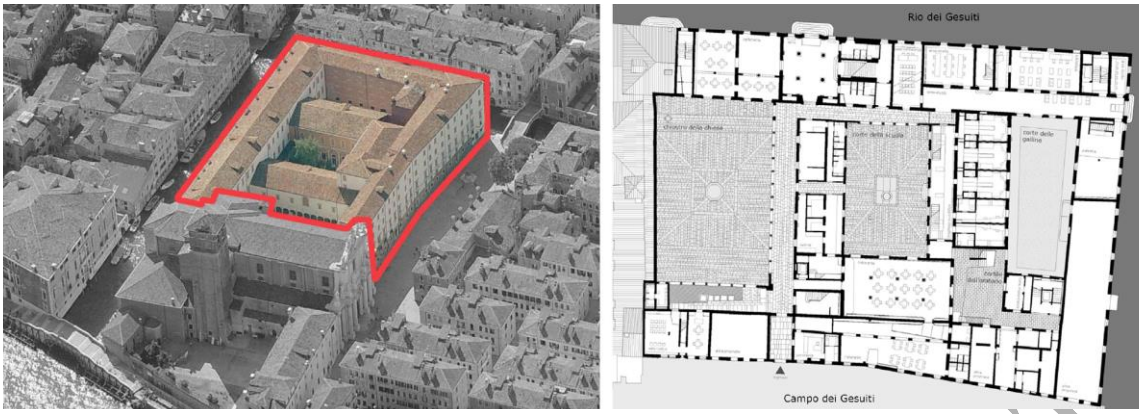


Figure 11. ***Crucifers complex*** **(s. XII), Venice (Italy) [**Error! Reference source not found.**].**

Another challenge of historical buildings is when the occupancy is sporadic, such as in churches, cathedrals, synagogues, mosques, and other places of worship [**Error! Reference source not found.**]. Moreover, sometimes those buildings are located in remote areas where fuels, such as natural gas, are not available. Different HVAC systems can be used in those cases. A comparison of different such systems was done in different Spanish churches, in particular *Santo Domingo de Silos* (Pinto, Madrid), *San Juan Bautista* (Talamanca de Jarama, Madrid), and *Nuestra Señora de la Asunción* (Algete, Madrid). *Santo Domingo de Silos* is a 14th Century Romanesque building transitioning to Gothic at the roof. Its heating system has eight butane-propane category 13+ (28–30/37 mbar) furnaces. *San Juan Bautista* is a 12th-13th Century Romanesque building, with a nave from the 16th Century in Renaissance style, side aisles in Mudéjar style, and a 17th-18th Century tower in Baroque style. The heating system is an OS-125 LIESCOTHERM fuel oil-powered hot air generator, fitted with mechanical atomisation and automatic burner, and was installed in 1972. And *Nuestra Señora de la Asunción* is an early 16th Century church. In this case, a high-performance YGNIS LRP G-5 thermal set heats water in a natural gas-fuelled hot water heater, that is later distributed across steel pipes buried in ditches. The study shows that although thermal comfort is achieved, the cost of the three systems was quite different, both at commissioning and operation phases.

In museums, the direct link between indoor and outdoor environments, which represents a significant risk for exhibited items, is not easily avoidable even when adopting HVAC equipment [**Error! Reference source not found.**,**Error! Reference source not found.**]. This is mainly due to the difficulty of designing and installing air conditioning systems which preserve the special value of the building's architecture, which, in many cases, is a work of art in itself. The study of the best HVAC system for the preservation of artworks is not the aim of this review, but an example of historical buildings hosting a museum and going through energy retrofitting is the *Palazzo Abatellis*, Palermo (Italy) [**Error! Reference source not found.**]. The building is recognized as one of the most interesting examples of Gothic-Catalan architecture in Sicily, built in the 15th Century. The palace was later converted into a convent and, subsequently, has been modified several times. After the serious damage caused by the bombing during the Second World War, it was refurbished as a museum by Carlo Scarpa (**Error! Reference source not found.**Figure 12) and later nominated as the Regional Gallery in 1953. This study corroborates the need to take into account the artworks inside the museum when selecting the HVAC system for energy requirements, considering thermal-hygrometric conditions, and air quality.

Figure 12. ***Palazzo Abatellis*** **(s. XV), Palermo (Italy) [**Error! Reference source not found.**].**

A very similar case is that of the *Prosforio tower*, located at the port of Ouranoupolis, Chalkidiki (Greece) [**Error! Reference source not found.**]. The building was completed before 1344 and it is considered to be one of the most characteristic buildings of defence and monastery architecture (**Error! Reference source not found.**Figure 13). It is a Byzantine tower, typical for its era and the region, used as a fortress by the Byzantine army until the mid-15th Century and then by the Osman army. After had several uses, even residential one, until it was completely restored in 1996 and later it was decided to convert it to a museum. The Prosforio tower is located in the town centre, directly by the sea and it has 22 m height and a useful plan area of 330 m^2. The building physics properties of the tower, combined with the climatic conditions and the requirements set by its function as a museum are in that sense not easily compatible. The only way of compensating for the buildings deficiencies and of establishing acceptable indoor thermal and acoustic comfort conditions is by using a high quality, flexible, and well dimensioned central HVAC system, installed in the most discrete possible way. The resulting energy consumption values would be, at best, moderate, but it was still accepted.

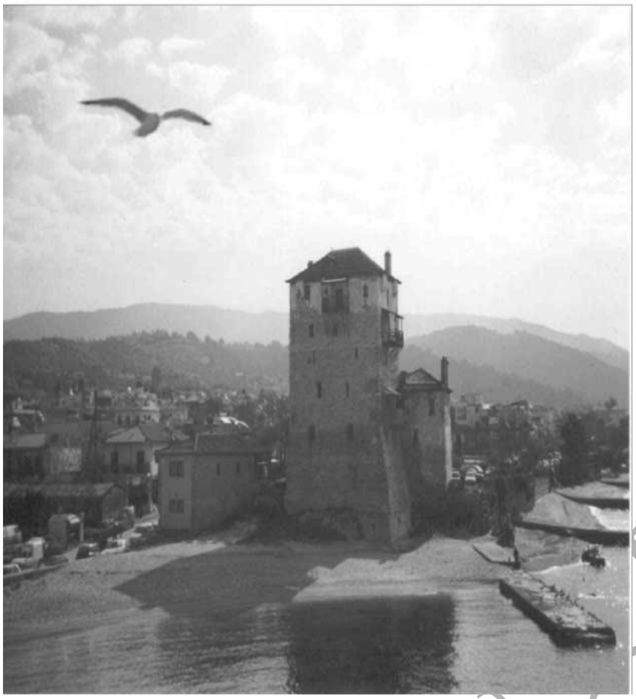


Figure 13. ***Prosforio tower*** **(s. XIV), Ouranoupolis (Greece) [**Error! Reference source not found.**].**

4. Integration of renewable energies

4.1. Integration of multiple renewable energies

Several investigations at material, system, and building level have been carried out in the last decades with the purpose to effectively integrate renewables into envelopes of historical buildings [10]. Most of these attempts are focused on PV integration into building roof systems, typically made by natural red clay components.

An example of the possibility to incorporate energy efficiency measures and renewable resources in existing buildings was shown in the refurbishment of the 140 years-old *Renewable Energy House*, in Brussels (Belgium) [6]. It was refurbished to minimise energy consumption and to explore different methods for integrating renewable energy technologies, making it a 100% renewable energy building. Figure 14 shows the facades before and after refurbishment. The concept was designed to reduce the annual energy consumption for HVAC by 50% compared to a reference building, and to cover all the needs for heating and cooling by 100% renewable energy sources. The building was equipped with energy efficiency technologies (such as insulation of the facades and roof, highly efficient double glazing, high-efficiency lamps, and ventilation with heat recovery), and 100% of the building heating and cooling demand were provided by renewable energy sources (biomass wood pellets, geothermal heating, solar thermal heating, and absorption cooling). Moreover, the latest PV technologies (modules, thin-film, semi-transparent) for the production of electricity were included. It was observed that all implemented measures contributed to reduce the energy consumption of the building in addition to the benefit of increasing the comfort for its tenants.

Figure 14. Renewable Energy House, Brussels (Belgium). Front and back facade (a) before refurbishment, and (b) after refurbishment [6].

The *headquarter of the University of Teramo*, Italy needed structural restoration after different seismic events, therefore the possibility of including renewable energy sources and rain water recovery was investigated [53]. The building was built in 1929 as a hospital and at the end of the 20th Century it became part of the academic campus, in which the administrative offices are located. The study evaluates the possibility of including PV in the parking area as a roof, a biomass plant, and a rainwater recovery plant, obtaining a payback period of 9 years and the reduction of 80 tons of CO_2 per year.

A very similar study was carried out for the research centre *Instituto Eduardo Torroja – CSIC*, located in Madrid, Spain [54]. The building was finished in 1953 and after 80 years it is found not to comply with the European energy standards. The study proposes the substitution of the windows, the insulation of walls, the substitution of all lighting and the use of biomass.

The study of different retrofit strategies for the achievement of NZEB target always includes the increase of insulation of the building and the inclusion of different renewable energies. One example is the *headquarters of the Province of Agrigento*, Italy [55]. The building was built in 1860, in the type of a palace of the pre-unitary era with an internal courtyard (Figure 15). In this paper, the simulations and cost analysis shows that only using energy produced on-site from renewable sources, the budget can ensure the achievement of the NZEB target. In this case PV and a geothermal heat pump were considered.

Figure 15. Headquarters of the Province of Agrigento (s. XIX), Agrigento (Italy) [55].

4.2. Integration of solar energy

Integration of solar energy in historical buildings is usually difficult [56,57]. One reason is the lack of useful space [**Error! Reference source not found.**]. Another one of more concern is the need to protect the architecture of the building.

As discussed before, attempts to integrate solar energy systems into building components probably represent the most popular strategy in cultural heritage, despite the above-mentioned architectural barriers. The European funded project 3EnCult showed a variety of possible integration solutions in roofs and facades (Figure 16). Additionally, the project pointed out how a pro-active collaboration with the local administration is a key step to explore other effective options, such as the localization of renewables in alternative structures located in close proximity of the heritage site, but which are not openly visible from public places and view-points, such as the building complex backyard.

The integration effort may be also focused on specific technologies. In this view, new photovoltaic tiles may be relatively less visually intrusive than other retrofit systems and contribute to reduce the carbon emissions associated to building operations [10].

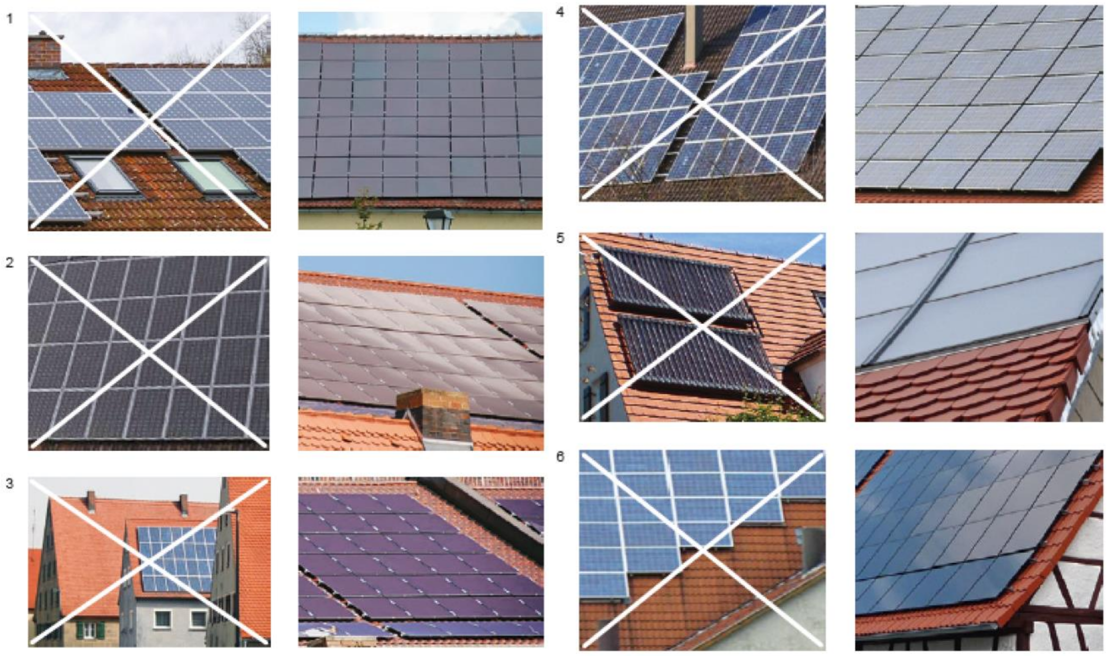


Figure 16. Comparison between acceptable and not-acceptable integration of PV systems over traditional clay based roof systems [10].

Relatively minor-impact interventions are feasible even in high-value historical buildings such as a church in Carlow, Germany (Figure 17). The medieval building roof was integrated with PV panels which were designed to be effectively mitigated within the building roof layer colour and shape, during the course of its retrofit. More in details, a tailored polycrystalline module was industrialized in order to properly match the configuration visual appearance of the existing roof substrate, which was replaced by the same PV module, by also keeping the same roof plane for better visual integration [10], as recommended by the local monument protection authority.

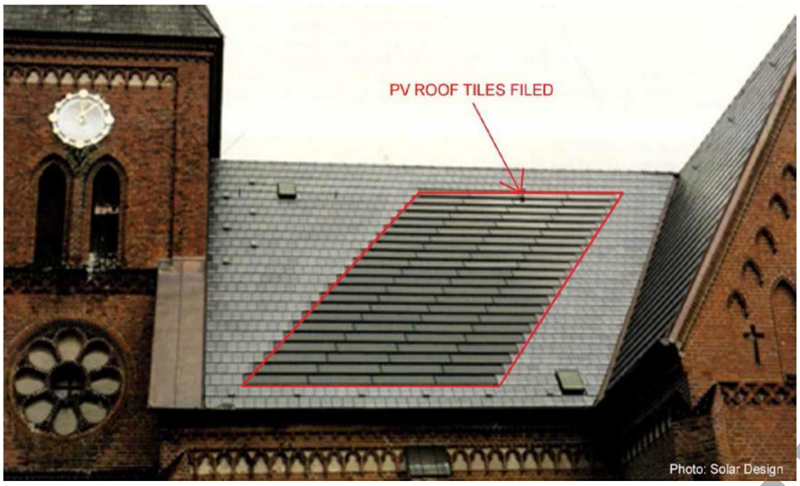


Figure 17. Roof integration of PV system in a heritage religious building in Germany [10].

The possibility of integrating solar energy in a historic building in downtown Catania has been also studied [58]. The selected traditional building shows a main facade facing up to public street and a secondary one to private space. The first one is enriched by a formal composition representative of 19th Century architecture, the second one does not have got any particular architectural value. The proposal given was to use PV tiles in the roof using thin films of amorphous silicon.

Three case studies were examined in Switzerland to improve the energy features of the buildings and the level of comfort inside by integrating solar energy [17]. The three case studies were the Manetti House in Bironico, Monte Ceneri, 1600, the Hôtel de La Sage, in Avolène, Vallese, 1890, and the Anatta House in Monte Verità Ascona, 1904 (Figure 18). The buildings had different features and problems, and, in particular, with varying levels of freedom in terms of permissible solutions. The Manetti House is and has always been a residential building continuously used; its historical value is low in most of it. The Hôtel de La Sage was continuously used and the building was changed during time; its historical value is also low in most of it. Finally, the Anatta House was not continuously used and today is a museum; its historical value is high. After assessing the improvement of the insulation in the buildings and the condition of the windows, the inclusion of solar energy (PV and thermal) was studied. In the Anatta House a solar glass facade was considered adequate; in the Hôtel de La Sage a PV shutter was recommended; and in the Manetti House the PV cells were integrated in the roof tiles.

Figure 18. From left to right: Manetti House, Bironico, Monte Ceneri (s. XVII), Hôtel de La Sage, Avolène, Vallese (s. XIX), and Anatta House in Monte Verità Ascona (s. XX) (Switzerland) [17].

The design of a PV roofing at the top level of a part of the *Real Albergo de Poveri* in Napoli has been evaluated [59]. This is a unique monument for its architecture, dimensions, and volumetric organization that was built in the second half of the 18th Century. The building is only one half of the original project (Figure 19). It was transformed, modified, partly demolished, and occupied unlawfully, until 1980 when a strong earthquake caused collapses and severe damages. The rehabilitation project had the aim to reach high energy performance levels and to follow sustainability criteria, and maximum use of daylight was a priority. The results of the modelling showed that an opaque PV roof results to be more convenient than a semi-transparent PV roof, for aesthetic, energy production, and thermal comfort aims. This is true also for daylight entrance: the half-transparent roof causes a very low increase of daylight in the corridor of the level below, while it has a very significant impact only on the footbridge at the top level. There, however, it could cause dazzling and overheating during the summer season.

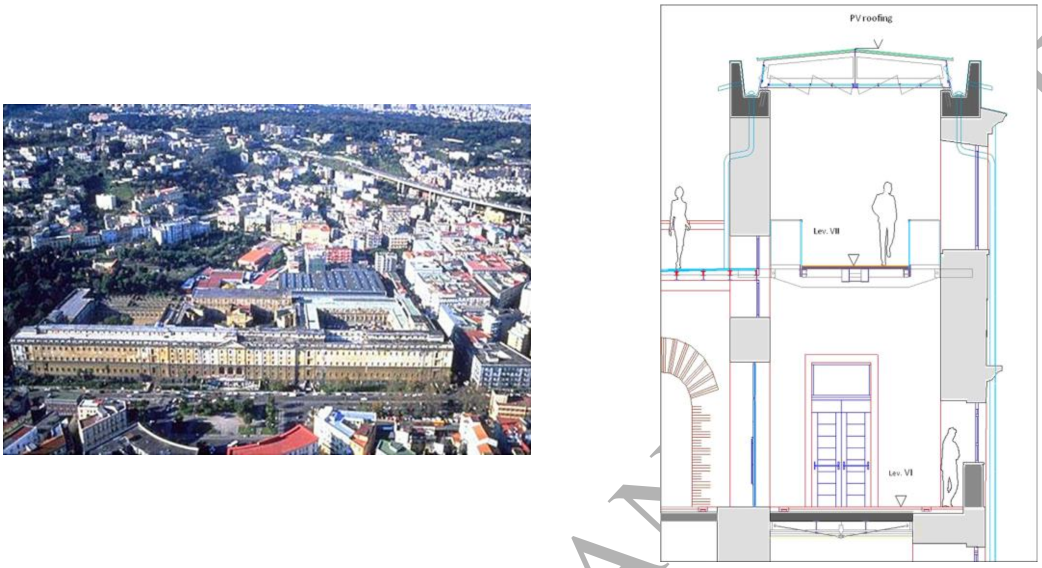


Figure 19. The *Real Albergo dei Poveri* (s. xVIII), Naples (Italy) and its PV integration project [59].

The importance of daylighting control in cultural historic buildings and museums was studied and applied in the *cloister of Santa Maria El Paular*, Rascafría (Madrid, Spain) [60]. The cloister was renewed between 2007 and 2011 to relocate a permanent exhibition. The natural light was controlled using filters installed on the windows to limit the incident radiation over the paintings. The authors developed spatiotemporal damage maps by measuring the spectral distribution in the building to give a tool for a better distribution of the artwork.

The use of solar powered lighting was developed for traditional hammams in North Africa [61]. The developed prototype combined three functions: day-lighting, solar powered LED lighting, and natural ventilation. In hammam buildings of North Africa heritage cities natural light and ventilation of most spaces is only possible through the round piercings of their roof which consists of a composition of domes and vaults (Figure 20). The light quality provided by the roof piercing is just sufficient for visual comfort but does not result in a bright atmosphere. Moreover, hammams are open at night, needing electrical lighting. A hammam lighting prototype which combines the vernacular glass bulbs and a solar powered LED lighting system was developed and tested in the *hammam Seffarine* (Fez, Morocco). Glass bulb prototypes were produced to specifically cover the openings on the roof. The glass bulb shape is formed as a hemisphere with a flange to aid fixing. A neoprene seal acts as a watertight barrier and absorbs any movement through thermal expansion. The solar panel connected produces 18 V at 10 W and is used to charge a 12 V battery pack. Control logic turns the LED light on at a predetermined lighting level and a DC-DC converter maintains the voltage from the batteries to the LED bulb at 12 Volt even as the batteries discharge. The light is turned off when the batteries reach a certain level of exhaustion. The developed prototype was very well received by hammams managers and users.

Figure 20. ***Hammam Seffarine*** **in Fez (Morocco) and the solar lighting system installed [61].**

EFFESUS FP7 Project dealt with investigation of possible effective ways to integrate PV systems in architectures located in the historical city centre of Santiago de Compostela (Spain). To this aim, the building stock located in the case study area was clusterized in order to define specific classes of constraint boundaries, corresponding to the possibility to implement different retrofit interventions [62].

4.3. Integration of geothermal energy

Efforts have been made in order to establish installation standards and to develop design methods for high-efficient geothermal systems such as ground source heat pumps [63], which have the potential to reduce cooling energy by 30-50% and heating energy by 20-40%, and are able to reduce the amount of greenhouse gases emissions to the atmosphere.

As example, the *Palazzo Gallenga Stuart* (Perugia, Italy), a four story university building, was energetically retrofitted [21,64] (Figure 21a). It is one of the very few original ‘‘Rococò’’ style buildings in Italy. The structure is composed by two underground levels (professors offices, classrooms, cafeteria), and four floors above ground (reception hall, classrooms, laboratories, dean’s office, conference room), for a global area of about 7000 m^2 and total height of about 25 m above the street level. The opaque envelope is composed by bearing masonry, brickwork finishing and internal cement plasterboard. The retrofit strategy proposed for the building consisted of:

(i) The disposal of the outdoor condensing units (Figure 21b) and the maintenance of the existing radiators.

(ii) The substitution of the old methane boiler with a more performing and effective ground-source heat pump plant, with the consequent recovery of the pre-existing technical rooms.

(iii) The installation at the building’s second basement of a system for the heat storage. In particular, the system consists of 10 tank modules (12 m^3/each) for a total number of 36 vertical underground heat exchangers (34 m length/each) positioned in the vertexes and in the centre of the tank base surface. The total provided thermal power corresponds to 170 kWt, consistent with the predicted required power calculated. The heat pump, the boreholes length, and the tank volume were determined based on the peak heating consumption.

(iv) Simulation of the building energy performance after the energy retrofit, in order to evaluate the heat pump energy consumption over a year of operation. The calculated annual energy consumption was therefore compared to the consumption of the building before the energy retrofit. According to the results, the implementation of such active systems achieved energy savings higher than 60% in comparison to the non-retrofitted building.

(a)

(b)

Figure 21. ***Palazzo Gallenga Stuart*** **(XVII-XVIII cent.), Piazza Grimana, Perugia, Italy. (a) Front facade [21]; (b) Detail of the outdoor condensing units spoiling on the ancient façade [64]**

Ground source heat pumps have been used in several historical buildings. Emmi et al. [65] evaluated numerically the implementation of ground source heat pumps in two historical buildings. The first building is *Ca' Lupelli Wolf Ferrari*, in Venice (Italy). The building is located in the historical city centre, fronting the *Canal Grande* in a complex of buildings where the main building is *Ca' Rezzonico*, a museum block. *Ca' Lupelli Wolf Ferrari* is a smaller building occupied by the direction offices of the museum (Figure 22). The construction of the complex started in 1649, and it was closed in 1756. Afterwards it was decorated by some of the most famous painters of Venice, like Gianbattista Crosato, Pietro Visconti and Gianbattista Tiepolo, so the palace was completely finished in 1758. Until 1810 the building was property of the Rezzonico family. It was then sold and went through many hands. Finally, in 1935 it became property of Venice Municipality. It was immediately renovated and in 1936 it became a museum called *Museo del Settecento Veneziano* whose particularity was that all the works of art were disposed like they were part of the equipment of the buildings. And the second building was the *Opera Santa Croce*, a museum located in the city centre of Florence, on the south of the cathedral *Santa Maria del Fiore* and on the east of Ponte Vecchio. The museum is part of the *Basilica di Santa Croce* complex, and it is located in correspondence to the ex-refectory and cenacle. It became a museum in 1900 under the direction of Guido Carocci, and it was enlarged in 1959. In 1969 both the building and the works of art were damaged, because of the flood of Florence, therefore it was under renovation for a long period. It was opened again in 1975, but all the works of art were replaced only in 2009. Today the museum is formed by 5 rooms. There is the ancient *Cappella Cerchi*, which contains frescos, sinopites, reliefes, sculptures and ligneus equipment, and the cenacle. The last one is a large rectangular room with a trussed ceiling, and it is used as expositive room for conferences, display of works of art or sometimes as a concert room. Nowadays important works of famous artists are exposed, for example the *Crocifisso di Cimabue* and the Giorgio Vassari *Tavola dell'ultima cena*, that attract thousand visitors every year. In the past, the site complex was studied aiming at improving the sustainability and installations efficiency. Results showed that the used of ground source heat pumps with borehole heat exchangers is a good option for energy retrofitting of those buildings if compared to an air to air heat pump, or to a common gas boiler.

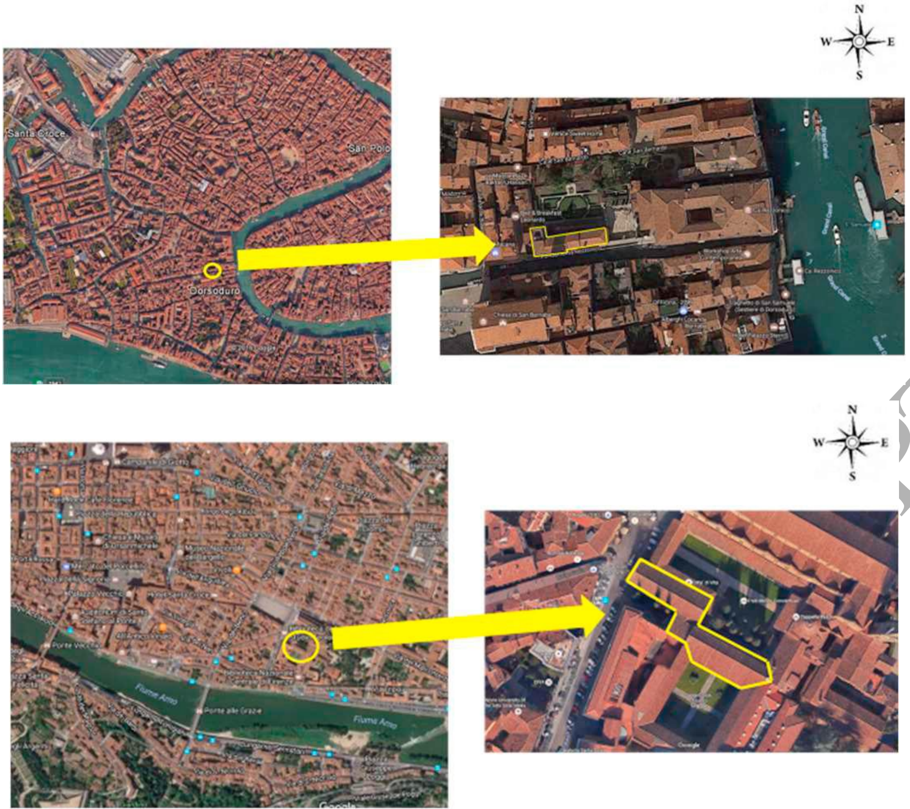


Figure 22. Overview of the city of Venice and of the building *Ca' Lupelli* (top) and of the city of Florence (Italy) and of the building *Opera Santa Croce* (bottom) [65]

A similar simulation study was done by Pacchiega et al. [66] for a rural single-family house dating from the 15th Century and subjected to various renovations over the years; the last one, dating from 1803, gave it the present architectural and artistic characteristics. For its historically and artistically important features in the province of Ferrara, the building is subject to monumental restrictions. The building is located near the city of Ferrara, in an agricultural area, and is surrounded by a large green area used as a garden. The climate zone is Cfa (Warm temperate, fully humid, hot summer), according to the Koppen Geiger classification [67]. After the renovation it will be used for residential purposes. The building is composed of two heated and cooled floors and an uninhabitable attic, and is approximately 12 m high. The plan has a rectangular shape for a total of net heated area of 874 m^2. The roof has four slopes. In their current state, the walls are made of bricks bonded with mortar; the slabs between floors consist of a double frame of wooden beams, with decorated reed false ceilings with gypsum plaster. Windows have wooden frames and are single-glazed. The paper compares different heat pump systems, where the geothermal heat pump gives the lower payback period.

5. Conclusions

Historical buildings are usually considered as low-performance buildings, even if their ancient passive systems are often able to guarantee indoor comfortable conditions all around the year thanks to high thermal inertia and air cavities throughout the opaque envelope systems [61]. At the same time they provide a fundamental testimonial role in the society, by often contributing to townscape character of the built environment and the relative community identity. The use of renewable energy technologies integration during building restoration represents a challenge that has been addressed in several case studies and examples around the world. This review shows the different approaches that can be found and highlights their key educational role for citizens and visitors [61], who have the chance to learn and experience the real effectiveness of best practices for energy efficiency, indoor wellbeing and functionality, and more in general, environmental sustainability. Such evidences are compared in Table 1.

Table 1. Summary of case studies presented

Approach	**Case study**	**Experimental implementation / Simulation**	**Action**	**Results**
Energy efficiency	*Palazzo Ex-INPS* (Benevento, Italy) [29]	Both	Adequate management regime. Reduction of infiltration, replacement of windows, increment of thermal inertia	Reduction of 24% annual electricity request
	Albergo dei Poveri in the Cargonara valley (Genoa, Italy) [16]	Simulation	Better insulation, restoration of windows, addition of micro cogeneration	Preliminary approach of the options available
	Ca'S. Orsola (Treviso, Italy) [30]	Real renovation	Energy upgrading	Energy savings of 329.64 kWh/m^2·year, including heating, DHW, and ventilation systems. Social co-benefits are also listed
	Palace of the Hungarian Academy of Sciences (*Magyar Tudományos Akadémica*), located in Budapest (Hungary) [31]	Simulation	Windows non-intrusive refurbishment: use of interpane shading devices and simple auto-mated control systems	Use of double glazing is not always the best option. Dynamic windows with higher U-value and higher solar transmittance with automatic interpane shading are a good option
	Historical buildings in Saint-Petersburg (Russia) [32]	Real renovation	Improvement of the quality of courtyards	Improve of daylight performance and of airing, reduction of power consumption, increase of commercial attractiveness and socialization
	Urbino University Colleges [33]	Monitoring of the building and simulation	Insulation and integration of controlled mechanical ventilation	Comprehensive conservation plan
	Building in Nomentano district, Rome [34]	Simulation	Building management, HVAC control, and envelope quality	Reliable simplified dynamic simulation of a historical building

	Residential historical buildings in Kiev [35]	Theoretical calculation	Insulation and replacement of transparent walling	Compensation of heat loss in 3.1 times
	Penang shop houses in Malaysia [36]	Pilot demonstration house	Replacement of the terracotta roof tiles, the granite flooring in the air well area, iron staircase, and wooden louvre window shutters	Reduction of the peak temperature
	China Nanjing Tulou buildings [37]	Experimental survey	None	Total primary energy consumption lower than the normal rural buildings of the area
	Middle Age *Rocca* in central Italy [39]	Real renovation	Local materials, new cool tiles, new outdoor pavements	A complete circular economy design is used. The LEED approach was used.
Heat pumps and other HVAC systems	*Castle of Zena* in Italy [46]	Simulation	Electric heat pump based on compression cycle and gas driven absorption heat pump were compared.	Electrical heat pump connected to the existing well provided lowest payback period. However, gas driven absorption heat pump led to higher gas emissions reduction.
	Church of *SS. Michele e Gaetano* in Italy [12]	Real renovation	Active double glazed covering in the roof	System allows the reduction of high heat loads and controls the incident solar radiation.
	Church of *St. Francis* in Italy [47]	Simulation	Relative humidity is controlled by means of a mechanical ventilation system	Good microclimate control was achieved
	Crucifiers complex in Italy [48]	Real renovation	Water heat pump with trigeneration system was installed	
	Palazzo Abatellis in Italy [50]	Real renovation	Use of heat pump for preservation of works of art.	
	Prosforio Tower in Greece [52]	Real renovation	Use of heat pump integrated in the building	Moderate but acceptable levels of energy consumption
Renewable energies	*Renewable Energy House* in Belgium [6]	Real renovation	Building was passively improved (insulation, double	50% energy savings compared to reference and 100% of heating and

			glazing). PV, biomass and geothermal heat pump were installed as well as ventilation with heat recovery	cooling produced by renewable energy sources.
	Headquarter of the University of Teramo in Italy [53]	Real renovation	Inclusion of PV and biomass plant	Payback period of 0 years and reduction of 80 of CO_2 per year.
	Headquarters of the Province of Agrigento in Italy [55]	Simulation	Installation of PV and geothermal heat pump was analyzed	Achievement of NZEB target.
Solar energy	Church in Carlow in Germany [10]	Real renovation	Integration of PV with a visual appearance similar to existing roof.	PV panels were accepted by the local monument protection authority.
	Manetti House in Bironico in Switzerland [17]	Real renovation	PV cells integrated in the roof tiles.	---
	The *Hôtel de La Sage* in Avolène in Switzerland [17]	Real renovation	PV shutter was installed.	---
	Anatta House in Monte Verità Ascona in Switzerland [17]	Real renovation	Building was passively improved in terms of insulation and windows. PV panels and solar thermal collectors were studied.	---
	Real Albergo de Poveri in Italy [59]	Simulation	Opaque and semi-transparent PV panels were analyzed.	Semi-transparent PV panels provide a very low increase of daylight and limits energy production.
	Hammam Seffarine in Morocco [61]	Experimental prototype	Vernacular glass bulbs and a solar powered LED lighting was tested.	---
Geothermal energy	*Palazzo Gallenga Stuart* in Italy [21,64]	Real renovation	Active geothermal system with cool tiles with appearance of traditional historic tiles	Innovative cool tiles lead to 14% cooling energy savings. Geothermal energy system lead to about 65% energy savings.

	Ca' Lupelli Wolf Ferrari and *Opera Santa Croce* in Italy [65]	Simulation	Inclusion of ground source heat pump (GSHP) system	GSHP is energetically better to an air-to-water heat pump or a condensing boiler but it is not always economically cheaper
	Rural single-family house from the 15th century in Italy [66]	Simulation	Different heat pump systems compared	Inverter-driven GCHP is energetically better to other analysed systems. Inverter-driven air-source HP is economically better

Energy efficiency with the implementation of internal envelope insulation, the use of cool coating, and window retrofitting is the first approach that can be considered. Examples can be found with the *Palazzo Ex-INPS* (Benevento, Italy), the *Albergo dei Poveri* in the Cargonara valley (Genoa, Italy), *Ca'S. Orsola* (Treviso, Italy), and the *Palace of the Hungarian Academy of Sciences* (*Magyar Tudományos Akadémica*, Budapest, Hungary). Another strategy is reconstruction of courtyard spaces into atriums (Saint-Petersburg, Russia). More aggressive strategies can be used in the energy retrofitting of the so-called "modern" historical buildings (those built in the XX century). Examples are the *Urbino University Colleges* (Urbino, Italy), the Nomentano district (Rome, Italy), or the residential historical buildings in Kiev. On the other hand, Asia has followed the approach of reducing the energy demand, with examples in the Penang shop houses (Malaysia) and the Nanjing Tulou buildings (China). Finally, recently the first historical building to be retrofitted following the Green Building Council Historic Buildings protocol (following LEED guidelines) was the *Sant'Apollinare Rocca* (Perugia, Italy), a Middle Age Rocca where a completely self-sufficient trigeneration plant is operating in an energy efficient building envelope already characterized by local bio-based insulation materials and cool roof clay tiles.

The integration of renewable energies into envelopes of historical buildings can be done at material, system, and building level. Examples can be found in the 140 years-old *Renewable Energy House*, in Brussels (Belgium), the *headquarter of the University of Teramo* (Italy), the *Instituto Eduardo Torroja – CSIC* (Madrid, Spain), and the *headquarters of the Province of Agrigento* (Italy).

Although the integration of solar energy in historical buildings is usually difficult due to the lack of space or the need to preserve the exterior architecture, successful examples can be found in the use of PV tiles or PV panels, placed in buildings such as a church in Carlow (Germany), downtown Catania (Italy), the Manetti House in Bironico (Monte Ceneri, Switzerland), the Hôtel de La Sage, in Avolène (Vallese, Switzerland), the Anatta House in Monte Verità (Ascona, Switzerland), the *Real Albergo de Poveri* in Napoli (Italy), and the historical city centre of Santiago de Compostela (Spain). The use of solar lighting has been thoughtfully studied for museums located in historical buildings, such as the *cloister of Santa Maria El Paular*, Rascafría (Madrid, Spain), or the solar powered lighting developed for traditional hammams in North Africa.

Heat pumps and other HVAC systems seem to be one of the most popular systems to improve energy efficiency in historical buildings without compromising its architecture. Examples can be found in the *Castle of Zena* (Italy), the cloister of the ancient Baroque monastery connected to the church of *SS. Michele e Gaetano* in Florence (Italy), the *church of St. Francis* in San Giovanni in Persiceto (Italy), and the *Crucifiers complex* in Venice (Italy). The challenge of sporadic occupancy was studied in churches such as *Santo Domingo de Silos* (Pinto, Madrid), *San Juan Bautista* (Talamanca de Jarama, Madrid), and *Nuestra Señora de la Asunción* (Algete, Madrid). The special case of museums was implemented in the *Palazzo Abatellis*, Palermo (Italy) and the *Prosforio tower*, at the port of Ouranoupolis (Chalkidiki, Greece).

Finally, geothermal energy use can be found in the investigation of *Palazzo Gallenga Stuart* (Perugia, Italy). This technology has been also studied for *Ca' Lupelli Wolf Ferrari,* in Venice (Italy), the *Opera Santa Croce,* in Florence (Italy), and a rural single-family house located in Ferrara (Italy).

The critical literature review finally showed promising potentiality in improving energy efficiency and indoor wellbeing in historical buildings by means of behavioural and operations control solutions, which may radically optimize their performance while minimising any invasive construction impact.

Conflict of interest

The authors confirm that the work described has not been published previously, that it is not under consideration for publication elsewhere, that its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out, and that, if accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder.

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