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Review

A Review on Technical Challenges and Possibilities on Energy Efficient Retrofit Measures in Heritage Buildings

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Abstract: For heritage buildings, energy-efficient retrofitting cannot be applied with the same range of possibilities as with existing buildings. Applying such improvements to heritage buildings can be challenging due to their historic and/or cultural significance and non-standard construction methods. This paper reviews the technical challenges and potential of applying energy efficient retrofit elements in heritage buildings. The retrofitting measures reviewed are draught-proofing, windows, insulation, ventilation, heating, solar photovoltaics and phase change materials. It is possible to significantly reduce energy use in heritage buildings with such retrofits. However, there is no universal way to apply energy-efficient retrofitting in heritage buildings, which is apparent in the literature, where case studies are prevalent.

Keywords: energy efficiency; barriers; historic buildings; decision; adoption; implementation

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1. Introduction

The buildings in the European Union (EU) are responsible for approximately 40% of overall energy consumption and 36% of the greenhouse gas (GHG) emissions [1]. Retrofitting existing buildings is considered as an important approach to reducing the energy use and GHG emissions from the building sector [2]. By renovating existing buildings in member countries, it is estimated that the total energy consumption and carbon dioxide emissions can be reduced by 5–6% and 5%, respectively [3]. Improving energy performance of the existing building stock through renovation normally consists of the implementation of so-called "retrofits", i.e., changes made to the building after it has been built. One of the main drivers for energy retrofitting of buildings is to achieve a better indoor climate [4] and/or reduce the energy cost [5]. Improved energy performance can enhance the resale value of a property, thereby providing additional incentive to implement retrofit measures. However, there is a sub-sector of buildings that cannot, or may not, be subjected to the same retrofits as conventional buildings [6]. These types of buildings, which are categorized as heritage buildings, consist of residential (e.g., single or multi-home dwellings), non-residential (e.g., offices and stores), public monuments (e.g., museums) as well as religious buildings. Heritage buildings are those having artistic, historical, archeological, and ethno-anthropological interests [7]. Heritage buildings are often constructed using traditional building techniques, adding to their significance and the complexity of implementing retrofits. Due to all this, it is recommended that retrofits in heritage buildings are assessed on a case-to-case basis [8–10]. Heritage buildings, to protect their uniqueness, are often exempt from regulations and/or other strategies for energy efficiency improvement [11]. Further, due to their often cultural significance, special attention is required to preserve these buildings [12] and it also present certain challenges concerning energy efficiency. For example, due to the heritage value of the buildings, adding external insulation would not be permitted if it affects the appearance of the facade [13]. The delicate hygrothermal behavior of heritage buildings and building specific legislative regulations can make retrofitting of such buildings rather challenging.

The importance of in-situ measurements (for example, U-values), is discussed in several articles, stating that the actual energy performance of heritage buildings may differ as compared to the calculated or simulated values [14–17]. A study by Ficco et al. [18], on seven building components in different measuring conditions reported uncertainties in U-value of 8–50%. The incorrect U-values used in simulations for heritage buildings may be attributed to reasons such as lack of knowledge on building composition [17] and unknown previous building alterations. Walker and Pavía [19] in their study found that in-situ measurement of insulations' U-values generally underperformed as compared to the thermal conductivity values provided by the manufactures. They attributed the variation in thermal properties of insulation materials to the local environment as against the ideal laboratory testing conditions [19]. In-situ measurements, even though preferred, can be problematic since they must be done over a long period and are impacted by the operative conditions [12,14].

The problem of data accuracy reflects on the development of traditional simulation models which often built using assumptions or disregarding the moisture effects on thermal properties, thus potentially giving incorrect results for heritage buildings [17,20,21]. There is an emerging alternative to traditional simulation models in the form of hygrothermal ones. These tools provide predictions of energy use, moisture transport, and indoor climate in a variety of applications [21–25]. Nevertheless, hygrothermal models of heritage buildings are subject to the same problems as traditional models where a lack of information, such as the specific building materials, techniques, ventilation rates, and occupancy schedules can make model development difficult, and time-intensive [21].

Furthermore, certain retrofit projects may involve several different actors, such as conservation personnel, building inspectors, and building professionals to oversee and carry out the retrofits. Poor communication between these actors, and a potential clash of interests, may lead to problems where energy efficiency is preferred over conservation values or vice versa, thus potentially harming the building or reducing the energy-saving potential [15,26,27]. To reduce this, an early dialogue at a local level should be held before the project to develop a suitable strategy and evaluate if any special skills are needed throughout the process [15,27].

Increased education and cooperation for all aforementioned professionals and owners about how heritage buildings can be technically improved is required to reach a balance between conservation and energy efficiency [15,28,29]. The importance of this is highlighted in a study from the UK where an inconsistency of approach to energy efficiency improvements in heritage buildings was found amongst conservation professionals [30]. The same study recommends that a framework for decision-making should be put in place, such as the Italian AiCARR guidelines "Energy Efficiency in historic buildings" [31], to objectively decide the level of energy efficiency which can be obtained for the building [30].

The inconsistency of perceived historic values can be a challenge for retrofitting. A study from Gothenburg, Sweden, showed that the residents in older buildings were more likely to value the conservation of their buildings than people in newer buildings [32]. Furthermore, when asked about which parts of the building the residents considered as being important to its historic value, the responses varied widely between respondents [32]. The variance is congruent with similar studies and indicates that it may be difficult to discern between "beautiful" and "historic" elements for people who are not trained in the field, thus making the perceived historic value hard to predict [32,33]. Perceptions of historic and sentimental value are important on a social level since they can give a feeling of connection with the past, other people, and society as a whole [33,34]. Due to this, the history and aesthetics of a building can be considered as more important by some than an improvement in comfort or economical savings [32,33]. Further, the capital cost required for energy efficient retrofitting of heritage building is often higher than retrofitting of a conventional building [22]. Nevertheless, energy efficiency improvement in heritage buildings can contribute to reducing the GHG emissions of the building sector.

Recently, several review articles related to energy efficiency in heritage buildings have been published: Martínez-Molina et al. [11], Webb [22], Lidelöw, et al. [35], Berg et al. [36], Cabeza et al. [37], Buda et al. [38] and Hao et al. [39]. The review by Lidelöw et al. is on operational energy use along with other aspects such as life cycle analysis, behavior, and cultural heritage value of buildings. Martínez-Molina et al. [11], on the other hand, focus on energy efficiency studies in historical buildings based on building typologies. Webb [22] reviewed the criteria, analysis methods, and decision process for assessing energy retrofits in heritage buildings. Cabeza et al. [37] present various examples of energy efficiency approaches and integration of renewable energy measures in historical buildings. The review by Berg et al. [36] was focused on the users' role in energy use of heritage buildings. Buda et al. [38] are aimed to present a supporting tool for decision-makers in selecting a few retrofit solutions, while they also provide a brief overview of various barriers and drivers, such as legislative, technical, and economic aspects in the implementation of retrofit solutions in the heritage buildings. Hao et al. [39] review was on retrofitting of historical buildings within the context of climate change. The drivers and barriers on technical aspects of energy-efficient retrofitting of heritage buildings are not the focus of these reviews.

The heritage buildings offer technological challenges due to reasons such as materials used, design, requirement for protection to otherwise "conventional" retrofit measures. It may not be always possible to integrate the best available technology in heritage buildings due to issues such as non-compatibility with the architectural character of the building [40]. We contribute to the existing reviews on heritage buildings by focusing specifically on energy efficiency retrofit measures, their technical challenges, and possibilities with an aim to provide an overview on aspects one should be aware of before implementing such measures in heritage buildings.

2. Energy Efficiency Retrofit Measures in Heritage Buildings

Due to the delicate nature and restrictions on heritage buildings, cost-effective energy efficiency measures are often the least intrusive ones [9,41]. Potential retrofits and their impact should be evaluated on reversibility (i.e., the ability to restore the fabric to its original state), compatibility with the building (i.e., ensuring that the retrofit will not affect the fabric negatively), and authenticity (i.e., if the retrofit is authentic to the heritage nature of the building) [22]. With these broad principles in mind, it is possible to restore and sometimes even significantly improve the energy performance of heritage buildings [42–44].

The following section presents the literature review of seven energy efficiency retrofits applicable to heritage buildings: draught-proofing; windows, insulation; ventilation; heating; solar photovoltaics and phase change materials. The installation of energy efficient lighting systems may significantly reduce electricity use in heritage buildings [45]. The energy efficiency enhancement of heritage buildings through lighting interventions is relatively less invasive [46] and this review does not include lighting retrofit.

2.1. Draught-Proofing

In many heritage buildings, heat loss often occurs as a result of unwanted or uncontrolled ventilation due to leakages, more commonly called draughts. The percentage of heat loss due to drafts varies widely, and heat loss up to 40% due to air infiltration have been reported [47]. Over time, and due to seasonal changes, buildings settle, and building elements such as wood and plaster crack or shrink, creating gaps in the fabric where there were none before. This usually happens around windows, doors, and around the infill panels of timber-framed buildings [48]. Previous building alterations such as the removal or installation of components and localized decay may also introduce gaps in the building fabric, thus increasing the levels of draughts. However, a certain amount of ventilation through infiltration is normal and even required to maintain a suitable indoor climate. It is therefore important to identify both the extent and location of draughts before draught-proofing a building to maintain adequate ventilation [49]. This can be done by a fan pressurization test, a very effective way to quantify the infiltration rate. A study made on 68 historic houses in the Baltic region concluded that air leakage was mainly present between the window frames and wall structure as well as at the junctions of the walls, floor, and ceiling [50]. The air leakage rates varied widely from 3.9 to 35.2 $m^3/(h.m^2)$ for the different buildings and no unifiable explanation for these varying rates was found [50].

The draught-proofing measures are heavily dependent on the location and extent of the draught. Simple silicone or wool compression seals are great for sealing small gaps, up to around 6 mm, around moving parts such as windows or doors. Since they are usually mounted inside the frame of doors or windows, they are well hidden, largely unaffected by seasonal warping, and easily removed [49]. Draught-proofing of windows can reduce the air leakages from windows by 33–50% [51]. If the gaps are too large to be effectively sealed by these strips, readjusting the frame or renovating the window or door might be required before sealing. During readjustments, sealing using natural materials such as hemp or flax should be performed between the frame and surrounding wall [41]. Compression seals and wiper seals are the two main types of draught-proofing seals and are used based on the types of windows and applications (see [51] for further reading on window seals).

Doors and windows in rooms without alternative means of ventilation should not be fully draught-proofed due to the risk of moisture build-up and poor air quality [52]. A simple way to circumvent over-sealing windows and doors can be to leave the top of the frames unsealed [41]. Furthermore, special care is needed in kitchens and modern bathrooms where a large amount of heat and vapor is produced.

If the draughts are a result of cracks in the plaster, or gaps between logs, these areas should be repaired, if possible. The inclusion of artwork on the plaster may limit the extent of such repairs. For timber-framed buildings, cracks or gaps in the plaster should be repaired with natural materials such as lime-putty mortars, while cement and other impermeable sealants should be avoided [10]. There is also the possibility of lifting the floorboards to replace the insulation and install permeable membranes. However, the removal of floorboards may cause irreversible damage to the boards or to the structural integrity of the building or the moisture balance.

2.2. Windows

Windows are often one of the first building elements to be targeted when energy efficiency measures are to be carried out. A common approach is to replace them with modern energy-efficient windows. However, new high-performance windows are often expensive, and therefore repairs and smaller retrofits on existing windows offer a better return on investment in cold climates [53]. Furthermore, traditional windows often give the distinct identity to the heritage buildings. Replacing windows could significantly alter the appearance of the traditional building and is only justified if the current windows are well beyond repair [9]. Traditional windows were made with high-quality wood, in contrast to modern windows which often use composite materials or poor-quality softwood and are therefore often repairable even if they appear in bad condition [41,54]. While carrying out wooden window replacements, it is recommended to pre-treat the timber to ensure that it is free from sapwood, as sapwood, due to its sugar and starch content, is susceptible to decay [51]. Thermal roller blinds were reported to reduce the heat loss by 57% in a trial [51]. The incorporation of wooden shutters to single glazing windows in heritage buildings in Scotland showed a reduction of U-value from 5.2 W/m^2 K to 1.1 W/m^2 K, which is a reduction of 79% [55].

The glass used in traditional windows is of special interest due to its distinctive appearance [51]. Suitable retrofits depend on the overall construction of the window and the protection of historic value of the building. If there are interior single-pane windows, then they should be properly reinstalled and refurbished, if needed. The inclusion of such extra windows can significantly lower the U-value of the windows. Due to this, it could serve as a good, non-disruptive, retrofit for buildings in general if the internal sills can accommodate it [13,41,43]. Replacing single panes with modern slim double glazing can be an alternative if there is no room for extra window frames. By doing this, the heat loss can be reduced by 35–73%, and the U-value by around 60%, depending on the window type [56]. This may, however, lead to some minor alterations to the window frames, the loss of historic glass, and reduce the amount of light entering the building [41].

The inclusion of extra windowpanes on the exterior is possible and can yield similar improvements to interior ones [53], although this is generally advised against for strictly energy efficient reasons due to the changes required in the fabric to implement it [41]. There is, however, a special case where exterior panes can be used to serve the double purpose of conservation and energy improvement in conjunction with stained glass in e.g., churches. In a study of churches in Germany and France, the installation of different protective glazing showed promise in both preserving the windows and improving the climate within the churches [57].

Various surface films can be applied on the windows to reduce the emissivity or increase the transmissivity. The recommended positioning of such films on windows are influenced by the climate [58]. A study in a heritage building in Sweden indicated a heat loss reduction of approximately 35% through glazing when low-emissivity films (low-E) are applied on the outward-facing surface of the inner pane of the double-glazed windows [58]. However, the payback period for the investment was not attractive in that case, which is partly attributed to the high cost of the low-E films and low district heating prices. Further, such films may have a visible tint which in turn reduces the transmittance of visible light [53]. This visual alteration of the glass may render such films unsuitable for use in heritage buildings [53]. There are films which, according to manufacturers, do not affect the transmissivity of visual light and could therefore possibly be used in heritage buildings if the window glass and frames allow for it [59].

2.3. Insulation

Adding, upgrading, or replacing insulation in the building envelope such as walls, and roof can often significantly improve the overall energy performance of a building as well as the perceived indoor comfort [13,42,60]. There is a plethora of different breathable materials suitable for use in heritage buildings, such as cellulose fiber, recycled paper, hemp, hemp-lime mixture, flax, cork, and sheep wool just to name a few [13,23,61]. There are also some modern insulation materials which are thin, light, and provide good insulation performance, if implemented correctly. These modern materials include aerogel, vacuum insulated panels (VIP) and porous silica [43,62], and capillary active and diffuse open material without a vapor barrier [63]. A study by Lucchi et al. [64] suggested that the use of a newly developed aerogel "Spacefill", which was blown into the air gap behind the plaster-lath finish, could reduce the U-value by up to 70%. VIPs have a limited flexibility for use as they cannot be adapted on the construction site and are non-permeable [44,65]. A simulation study on a historical fort building suggests that silica aerogel used as thermal insulation material can reduce a building's heating demand by 40% [66]. There are also concerns over moisture build-up within the fabric when using modern non-permeable products [43], although a few case studies have rebutted this [62,67]. The aforementioned modern insulation materials are however largely untested, especially in regard to their long-term performance, and significantly more expensive than traditional or natural ones [62]. It is also advised to be cautious before deciding on cavity insulation. For example, a retrofitting project study in a church building in Cork with cavities in the majority of its walls, initially considered pumping insulation to the cavity walls [68]. However, the conservation architects advised against it as the cavity was important for retaining air circulation, and a full cavity insulation could affect the breathability of the wall fabric, which in turn can cause condensation issues [68]. While retrofitting heritage buildings, one needs to be considerate of the "reversibility" aspects, which suggests that the future removal of interventions should not damage or cause as little damage as possible to the historical significance of the building [64]. Accordingly, it is not recommended to use polystyrene and PU-foams in heritage buildings as it is not possible to fully remove them [64]. There could be constraints in using innovative products in heritage buildings. For example, in

Ireland, before a new material can be used in a heritage building, it must be proven to work in the country, ideally for 25 years [52]. Advice from professionals specializing in heritage building conservation will be required before one can use innovative products in heritage buildings in Ireland [52].

Where the additional insulation can be installed (e.g., roof, attic, floor, internally or externally on the walls) is highly dependent on the specific heritage building. The attic is usually the easiest to insulate since it is out of sight, often insulated beforehand, and can give an immediate return [9]. It is possible to successfully insulate above the ceilings of heritage buildings by taking into consideration the specific situations, especially on the condensation risk [69]. Depending on the floor and foundation structure it may be possible to add extra insulation. A trial in a heritage building in Scotland, with an addition of 80 mm fiberboard, resulted in reduction of U-value of the floor from 2.4 W/m^2 K to 0.7 W/m^2 K [70]. There is a higher risk of moisture build-up within the floor (due to aspects such as capillary rise from the ground), it can be expensive or damaging to the building and should therefore only be an option during larger refurbishment once all other measures are implemented [9,71].

In heritage buildings, it is often not possible to use external insulation due to the architectural and historic significance of the exterior facades [19]. If the conservation of fabrics allows, then it is advised to place extra wall insulation on the exterior to reduce the risk of moisture build-up [72,73]. Insulation on the interior of walls can cause the wall structure to become colder which in turn can lead to condensation and an increase of thermal bridges [41,74] and mold growth behind wooden beam construction [63]. There are however studies where a multitude of different insulation materials have been placed on the interior of walls, with a little negative impact on the hygrothermal performance of the building [43,75,76]. The aforementioned studies highlight the importance of breathable materials and measurements of moisture content within the wall and insulation pre- and post-installation. Furthermore, the exact material and placement may be different depending on the building type, with solid stone walls being rather challenging to insulate while maintaining historic values and adequate hygrothermal behavior [75]. A study in a Danish heritage building, wherein internal insulation was stopped 20 cm above the floor, showed an annual energy use reduction of 39% [13]. This approach reduces the possible heat savings, as compared to if it was fully insulated through the walls, by approximately 15% and may maintain the moisture to safe levels due to the creation of a thermal bridge around the wooden beams and the subsequent increase in temperature [13]. Addition of extra insulation to the external walls increases wall thickness, which can harm the architectural design, primarily by deepening the window recesses and reducing the overhang of the roof [41,74]. These alterations would impact the way light shines through the windows and may lead to an increase in driving rain hitting the facade if the roof is not altered as well [41,74]. Further, internal insulation can result in issues such as replacing historic linings, disturbing internal features, and incompatibility with traditional construction [19]. EU project RIBuild provides guidelines for deciding whether a heritage building is suitable for internal insulation and also for the selection of an internal insulation system [77].

When insulation is added, it is important to make sure that the subjected building element is dry, or as dry as possible, to reduce the risk of moisture build-up [78]. If insulation is added to one element of the building fabric while an adjacent element is unaltered, new thermal bridges can occur [73]. These new thermal bridges can lead to cold spots, thus increasing the risk for localized moisture build-up within the structure, and potentially lead to mold, rot, or cracks [73]. Thermal bridging could be a cause of concern in insulation retrofitting as the continuity of the insulation would be difficult in places such as connections with other building components [79,80]. Furthermore, building elements with less insulation will attract relatively more moisture compared to before when adding insulation to other elements. This is in part due to them potentially being colder, but also since other better-insulated elements no longer share the moisture load [72]. This means that in some cases, even if it is possible, it may be better to not add any insulation to certain elements to preserve the fabric [73].

A study that tested different insulation materials in a heritage building from 1805 in Dublin showed that the internal insulation resulted in a reduction of U-value of the walls between 34–61%, and Polyisocyanurate (PIR) boards provided the largest reduction in U-value [19]. The energy-saving potential due to insulation improvement depends on the in-situ U-value of the existing walls. As per Rye and Scott [81], simulation programs usually overestimate the U-value of traditional walls, which is often due to the non-availability of thermal conductivity of traditional building materials [81,82].

2.4. Ventilation

Appropriate ventilation of a building is important both in regard to indoor air quality and to facilitate the transport of moisture from the building fabric. If a building has too little ventilation, or if the fabric is unable to release moisture, it could lead to mold and decay. Relative humidity (RH) is one of the most critical parameters from a building conservation perspective, and needs to be maintained as stable as possible within a defined level [83]. An upper RH level of 80% at normal room temperature is suggested to avoid bio-deterioration through mold, insects, or the crystallization of salts [84]. Additionally, a too low RH can cause cracks in some materials [83]. In many heritage buildings, ventilation is achieved by natural ventilation through openings in the fabric (both intentional ones like ducts or vents and unintentional ones) as well as the fireplace and flue [22,41]. Sufficient ventilation in all parts of the building can be ensured by a variety of different means, depending on the particular building and the need for ventilation [50]. In buildings with poor ventilation, it may be possible to install designated vents in the fabric e.g., over windows or in the walls to increase ventilation in certain rooms [9]. If the building already has designated vents or ducts, these should be located, their function verified, and be cleaned or repaired if required. If there are dampers installed in the flue, vents, or ducts it should be made sure that these are working and in the correct position, which might be different depending on the time of year or closed when the room is not occupied [49,85]. By doing this in conjunction with reducing drafts, the original amount of ventilation can be restored, and the energy use reduced.

Excessive draught-proofing measures, even though beneficial from an energy efficiency point of view, can lead to too low ventilation rates [51]. Furthermore, the use of fire as a primary mode of heating is less common today which leads to lower ventilation rates through the flue during the cold parts of the year. In these cases, the ventilation rates can be increased by e.g., installing a metal cowl on top of the flue, heating elements, or small electric fans in the flue (or in the ventilation ducts if there are any) and by opening windows either manually or with control schemes [14,85]. If the fireplace is not used at all, or out of order, the flue can either be capped off or be redirected into a ventilation duct [14,86–88]. The use of natural ventilation is a balancing act and not very energy efficient since there is little control of where or at what rates the air enters and exits the building [50,88]. It may therefore be tempting to use a more modern and efficient approach to ventilation, something which can greatly improve the energy performance of a historic building [43,50,87,89].

Modern mechanical ventilation and/or heat recovery systems can closely regulate the temperature, air quality, and moisture content within the building. This requires the building to be well sealed and have a well-insulated building fabric [43,88,90]. Even if a heritage building is well sealed and shows no signs of moisture build-up during simulations or in-situ investigations, retrofitting mechanical ventilation systems can be very difficult, or even damaging to the fabric [49,52]. The difficulty stems from the fact that most heritage buildings are not designed to accommodate mechanical ventilation systems. Therefore, finding a place where the unit can be installed and routing the ducting in a non-damaging way without altering the appearance of the interior can be challenging [43,87]. Furthermore, ventilation systems can generate unwanted levels of noise if placed within the building, and also be costly investments [43,91].

Mechanical ventilation can be relatively easy to implement in larger heritage buildings such as churches, museums, or palaces due to the availability of larger space [87,88,92]. This extra space can make it easier to place, and hide, ventilation systems and ducting within the structure. These buildings are often unoccupied and/or partially occupied for most of the year and ventilation systems can therefore be focused more on conservation and reduction in humidity than on human comfort [92].

Airtightness and improved insulation may result in overheating of buildings which might exacerbate in the future due to climate change [93]. A study in historical buildings in South Tyrol, Italy suggests that due to the combined impact of climate change in future (2021–2050) and energy retrofit, overheating in retrofitted buildings can reach up to 33% (1881 h) [93]. Hao et al. [93] suggest that overheating can be reduced to a large extent by using wooden window shutters and a ventilation strategy wherein ventilation is active when indoor and outdoor temperature is higher than 24 °C and 18 °C, respectively. Incorporating wooden shutters in historical buildings is not an issue in their study region as the authors report that several historical buildings used to have hinged shutters [93].

2.5. Heating

Monumental buildings such as churches originally did not have heating, and, due to their construction, that includes massive walls and large indoor air volume, have a relatively stable indoor environment as compared to the outdoor climate [94]. Further, the heritage buildings had initially used firewood as their main source of heating. Over time open fires have been supplemented or replaced with other means of heating to provide a better indoor climate [48]. This means that most existing heating systems, plumbing, and electrical installations are not original fixtures and therefore there may be some flexibility in upgrading them [48]. Many existing buildings have a waterborne heating system with some sort of boiler. Replacing old boiler in a heritage building with an efficient boiler can result in significant energy savings [95]. A boiler replacement can also reduce GHG emissions if a fossil fuel-based boiler is replaced by one using biomass, however, particulate emissions can be very high in a wood chip boiler over oil fired boiler [96].

Convector heating, warm air heating, radiant floor heating and pew heating are a few types of heating systems used in heritage buildings in a cold climate. Convector heaters could provide sufficient heating; however, the associated relative humidity may increase the risks for damages to historical artefacts in the buildings [97].

Pew heating is a localized heating strategy directed to people who are sitting in the church. Pew heating does not heat the whole building and also causes fewer temperature and RH fluctuations [98]. Pew heating could be typically through radiant heaters kept on pews or through warm air from the floors or footboards. As per a detailed study in a church by Camuffo et al. [99], a balance of thermal comfort and preservation of artefacts can be achieved by using low- temperature radiant emitters fitted in pews. The proper functioning of pew heating will depend on the positioning of radiant surfaces and view factors, and installation of such systems requires detailed assessment including specific local comfort analysis [98]. Camuffo et al., [99] carried out an experiment in a church building wherein each pew with three emitters (i) under the seat (55 °C), (ii) under -kneeler (65 °C), and (iii) hand warmer (60 °C). According to their study, the proposed heating strategy was "friendly" to the occupants, preservation of the buildings and also energy efficient. One possible concern with pew heating is that the emitters, due to associated temperature cycles, could damage the pews and this would be critical if the pews have heritage value [99]. Camuffo et al. [99] in their experiment did not find this to be an issue, as they noted that the emitters in three different locations in pews caused a rise in temperature much lower than those generated by the people sitting in the pews.

Floor heating become popular during the 1970s [94]. As floor heating is "invisible", it is aesthetically better and has a high thermal contact temperature [94]. It is challenging to install underfloor heating in heritage buildings as it may disturb the floors. Such heating systems may be considered if the building's floors need to be replaced for some other purposes [100]. Under-floor heating is not recommended for the intermittent heating of buildings due to the high thermal inertia of such systems [83]. A recent study in a Swedish church that used floor heating showed that cyclic-temperature settings may result in energy savings, and in such setting, a small thermal inertia of heating systems should be preferred to reduce the recovering time for the indoor temperature [101]. A disadvantage of floor heating, due to convection, is that it could lead to the deposition of air-borne particles in frescos in walls and ceilings [102]. As per [102], this problem may be avoided if the floor heating is kept at a lower setting as compared to the radiators, which are kept below windows, as this would prevent convective motions below the radiators.

District Heating (DH) is another heating alternative if the building is located within a DH grid and fitted with a waterborne heating system. A DH substation does not take up much space and the old flue for the boiler can be used for ventilation purposes [41]. If the building is outside of any DH-grid, and it is time for a boiler replacement, an air-to-air or geothermal heat pump (GTHP) can be an alternative [41]. A simulation study in a university building in Italy, indicated that the replacement of an existing energy system by a ground source heat pump coupled with water storage tanks in the underground can reduce the primary energy use for heating and cooling by 64% and 69%, respectively [103]. The main constraints of a GTHP are the potential lack of space (which should not be an issue if there is already a boiler present) and the achievable supply temperatures [104]. Older waterborne heating systems generally require a supply temperature of about 80 °C to operate as designed [41,104]. In contrast, most GTHPs normally supply a temperature of 50–60 °C. If the temperature is higher it may lead to a reduction of the COP-value of the pump, thus undermining its energy efficiency potential [9]. To maintain a high COP, it may be required to replace the entire heating system, something which is costly and may alter the historical significance of the building [104,105]. Instead of a replacement, dependent on the specific system, there is the possibility to retrofit fans behind the existing radiators thereby increasing the convective heat transfer and converting the entire system into a low-temperature one [104].

If the building is without any waterborne system air-to-air heat pumps may be an alternative to reduce energy use [38,105]. Since these pumps rely on the exterior air temperature their COP is variable, and a backup heating system may be required on cold days [105]. If the building lacks a central heating system, it can be difficult to fit a heat pump without damaging the fabric or the exterior aesthetics of the building [38,105].

As mentioned earlier, most traditional buildings in cold climate were heated with firewood which means that there is likely a fireplace or a tiled stove still left in the structure. Traditional open fireplaces are, however, inefficient at around 15–20% efficiency [9,105]. Modern wood stoves have significantly higher efficiency and produce much lower carbon dioxide emissions as compared to an open fireplace [106]. Furthermore, a multitude of stoves with water jackets exists which can supplement heat pumps, water heaters, or be coupled into a waterborne heating system to further increase energy efficiency [107]. Using wood stoves in existing flues will also help to maintain adequate ventilation and reduce the risk of moisture problems in the basement and chimneys by keeping them at a higher temperature [41].

Building integrated solar thermal panels have the potential of delivering up to 70% of domestic water needs [108] and may reduce emissions by up to 75% in some heritage buildings [109]. Solar panels can be used in conjunction with other type of heating systems to meet the heating demand [9,41]. However, energy savings from solar thermal panels are highly site specific. For example, a simulation study on solar thermal panels in residential buildings in a Portuguese world heritage site suggests an energy savings of only up to 8%, which was not an economically viable solution [110].

2.6. Solar Photovoltaics

Solar photovoltaics in buildings can be broadly categorized into Building Applied Photo Voltaic (BAPV) and Building Integrated Photo Voltaic (BIPV). In BPAV, modules are mounted to buildings using additional structures and PVs do not have a direct effect on the building structure [111]. Solar PV is one of the retrofit measures which is widely implemented among nZEBs in Europe [112]. A simulation study in a Turkish heritage building suggested an "energy consumption reduction" of approximately 14% by installation of PVs [113]. In BIPV the PV modules are integrated into the building and/or solar modules are used to replace some of the conventional construction elements. Integration of BIPV and BIST in heritage buildings is currently a research topic of interest, as shown by a list of 20 research projects (the list is non-comprehensive) on RES integration in heritage buildings and sites during the last two decades [114].

Installation of solar energy systems in heritage buildings could be often challenging due to reasons such as potential lack of space, the need to route new pipes or cables and the negative visual impact such installations can have on the building itself [37,52,105,115,116]. The visual impact and potential harm to the fabric can be reduced by placing the solar collector or PV-panels away from the protected building or out of sight away from public eyes, although this may require extra groundwork and may disturb the area around the building (which might also be protected) [37,90]. In heritage buildings, as compared to integrating to façade, roof integration of PVs is more common, which can be done by replacing roof tiles with PV elements [115]. Further, if the PV installation is planned on the buildings' roofs, then the structure of the buildings must be verified to ensure that it will support the additional load of PV solar systems [117]. A study on a heritage building (castle) in southern Sweden showed that BIPV was not a suitable solution as the building has too little roof area with good solar potential [118]. However, their study suggests that it is possible for heritage buildings to become net zero energy buildings with a landscape integrated PV solution along with deep renovation [118].

A survey of 19 historical buildings showed that PV or BIPV systems are installed mainly in less visible places such as in an internal courtyard [119]. Similarly, Buda et al. [38] mention case studies that demonstrate the possibility of harmonization between conservation and solar technologies in heritage buildings. There are several examples of successful and clever PV installations in historic buildings, mainly in southern Europe, using PV-tiles (roof tiles either completely or partially made from PV-cells), differently colored PV-panels (to better blend in with e.g., the facade), and PV windows (integrated PV-cells within the windowpane) [26,37,41,90,105]. Such installations can further reduce the negative visual impact PV technology can have on historic buildings giving greater flexibility to energy efficiency measures [26].

The visual impact of the BIPV in historical buildings is determined by the color of PV cells that affect its overall insertion in the heritage buildings [116]. Accordingly, the visibility issue of solar panels could be reduced if its color matches with the premise where it is installed, and the reflectivity is minimized [120]. Reducing the visual impact of solar modules could facilitate better integration of such systems in heritage buildings [118]. Thin-film cells with no visual impact which can blend into buildings' skin are being developed and tested [121]. Another possibility is to provide overlapping layers wherein the top layer is given a finishing similar to heritage building material while the photovoltaic element is hidden beneath [122]. The integration of emerging transparent solar cells (TSC) could overcome the visibility issue in heritage buildings; however, the power conversion efficiency of such solar cells is currently lower than the established products in the market [123]. Further, there are other challenges with TSC such as the selection of material and its fabrication and as per Husain et al. [124], the solutions are currently in the pre-commercialization stage.

The new emerging solar products offer customization possibilities and thereby could provide better possibilities for the integration of solar products in heritage buildings without compromising the aesthetical and heritage value of such buildings [125]. Since the lifespan of solar collectors and PV systems is considerably shorter than that of a building, the removal or replacement of the systems must be taken into consideration during planning and installation [105]. The installation of such technologies will ultimately come down to a judgment call on a case-by-case basis weighing the historic aspects of the building against sustainability values [126].

2.7. Phase Change Materials

Phase change materials (PCM) used as a thermal storage system can reduce the heating and cooling demand of the buildings and can also enhance the indoor thermal comfort [127]. PCM, with its high energy storage density, is considered useful in designing nearly zero energy buildings [128] and for the renovation of heritage buildings [129]. The incorporation of PCMs in buildings needs to be cautiously carried out as the daily charge-discharge cycles require careful planning [129]. The challenges identified in using PCMs in heritage buildings includes architectural integration and economic aspects [127]. It may not be possible to incorporate PCMs directly into the construction materials of heritage buildings as it may alter the aesthetics and may cause changes in porosity or permeability of the materials and thereby affecting its hygrometric behavior. The most feasible integration of PCMs in heritage buildings is to place boards of materials incorporating PCMs in contact with the roofs/walls only if they are not painted, nor decorated or has heritage elements [127]. Bernardi et al. [127] recommends avoiding direct contact of materials incorporating PCMs with heritage objects as there could be a risk of thermal stresses at the front and back surfaces of the objects, which could lead to mechanical damage. There are simulation and modeling studies on the application of PCMs in heritage buildings [130,131]. However, to the best of knowledge of the authors, there are no published study on actual implementation of PCMs in heritage buildings.

3. Discussion and Conclusions

Energy efficiency improvement in heritage buildings is a topic that garnered a lot of research attention since 2000s, especially in Europe. This is evident from the plethora of projects and publications, including a few review articles on the topic. This paper contributes to the existing body of knowledge by focusing on technical challenges and possibilities of energy efficient retrofitting in heritage buildings. The literature review suggests the possibility of significant energy savings in heritage buildings using energy efficient retrofit measures. A few of the studies reviewed provide energy saving potentials from the retrofitting (Table 1). The wide range of energy savings from retrofit measures shows that the potential should be understood as case specific and cannot be generalized. The difficulty in generalization of retrofitting measures in heritage buildings is highlighted in a review by [132] wherein, they stated that there is no consensus in literature on how and what materials to be used for wall insulation of heritage buildings.

Table 1. Energy savings potentials from retrofits in heritage buildings reported in literature.

Energy Efficiency Retrofit Measures	Energy Savings (%)	Comments
Draught-proofing		
[110]	Up to 1.39%	
[60]	5.86%	Infiltration rate reduced from 0.25 ach to 0.05 ach
Windows		
[13]	47%	Replacement of windows (4.2 W/m^2 K) with windows of U-value 0.89 W/m^2 K
[131]	33%	Annual primary energy saving due to a combination of windows (1.5 W/m^2 K) and insulation of the roof slab
[42]	12%	Replacement of new windows of U-value 0.8 W/m^2 K

Table 1. *Cont.*

Energy Efficiency Retrofit Measures	**Energy Savings (%)**	**Comments**
[12]	Up to 9%	U-value of 0.8 W/m^2 K
[133]	15%	Replacement of windows (5.8 W/m^2 K) with windows of U-value 1.46 W/m^2 K
[101]	Up to 27%	Replacing windows of a church in Sweden with windows of U-value of 0.6 W/m^2 K
[41]	Approximately 16%	A net saving of 48 KWh/m^2.year by replacing a window with a U-Value of 1 W/m^2 K
[60]	6.24%	Replacement of windows (5.7 W/m^2 K) with windows of U-value 2.7 W/m^2 K
[134]	41%	Refurbishing and restoring window frames
[135]	20%	Controlled window shading device
Insulation improvement		
[110]	Up to 9.6%	Roof and wall insulation
[134]	64%	The external mortar and screed were replaced with insulating material of thermal conductivity 0.045 W/m K and 0.06 W/m K, respectively
[42]	17%	External wall + 220 mm insulation
[60]	9%	Wall insulation improved from a U-value of 1.7 W/m^2 K to 0.5 W/m^2 K
[12]	Up to 47%	Additional external thermal insulation and 20 mm sheathing
[12]	Up to 15%	Additional thermal insulation for attic floor: 400 mm insulation + 20 mm sheathing
[113]	2.7%	Internal insulation of 3 cm thick in the outer wall
[136]	Up to 20%	Vacuum insulation panels on the exterior facade
Ventilation		
[12]	Up to 14%	Supply-exhaust ventilation with heat recovery 80%
[42]	Up to 19%	Balanced ventilation with heat recovery of 80%
Heating		
[98]	Up to 95%	Primary energy reduction in a church building in Italy by having an innovative hydronic pew-based heating system as against an all-air heating
[103]	Up to 64%	Primary energy reduction achieved through ground source heat pump system with water storage
[95]	Up to 14.1%	Improved heating control
[12]	Up to 77%	Ground source heat pump (primary energy reduction up to 42%)
[110]	Average 7.9%	Solar thermal panels
[137]	20–30%	Replacing existing boilers with new energy efficient boilers
Solar Photovoltaic *		
[138]	27%	Primary energy use reduction during the heating season
[12]	Up to 6%	Primary energy use reduction (KWh/(m^2 a)
[113]	14.45%	PV panels on roof
[119]	37%	The solar plant generates 37% of the building's total energy need of 44,400 KWh/year

* electricity generated by solar PVs.

Table 2. Literature references suggesting challenges to be aware of for the reviewed renovation strategies to reduce energy use in heritage buildings.

Energy Efficiency Retrofit Measures	Moisture/Mold	Construction/Component Damage/Constraint	Aesthetics	Interior and Artefacts	Light Level in the Building
Draught-proofing	[52]	[10,73]			
Windows		[41,51,73]	[9]		[41,53,73]
Insulation	[41,43,64,74,78–80]	[9,19,64,71,73]	[9,19,41,74]		[41,74]
Ventilation	[84]	[43,49,52,87]			
Heating		[94,99]	[9]	[97,102]	
Solar photovoltaic		[35,37,105,116]	[9,35,37,52, 105,119]		
Phase changing material		[127]			

Energy efficient renovation of heritage buildings is often more resource and energy intensive than the renovation of conventional buildings. There are various technical challenges to implementing retrofit measures. However, the reviewed articles suggest that solutions exist to overcome most of the challenges. The major concerns that could arise due to the implementation of retrofit measures are mold formation, construction damage, aesthetical issues, potential damages to building interiors and to artefacts and lighting levels in buildings (Table 2).

Majority of the articles reviewed here deal with energy efficient retrofitting that are case specific. This review study reiterates that there is no "one size fit all" solution for energy efficient retrofitting of heritage buildings. As Buda et al. [38] states, solutions to improve the energy efficiency of heritage buildings are available, it is required to be tailored to specific cases. An inappropriate approach to energy efficient renovation could have negative consequences on buildings' structure and also on the health of its occupants [139]. It calls for being cautious in selecting and applying energy efficient retrofit measures in heritage buildings. Polo López and Frontini [26] recommend close cooperation among stakeholders for the successful integration of energy retrofitting measures in heritage buildings.

Life cycle assessments (LCA), carried out over a 60-year span, in a Norwegian building from 1936 (with an uninsulated timber-frame structure, outside vertical wooden cladding and full concrete basement) showed that it can be favorable to refurbish heritage buildings over constructing new low-energy buildings [140]. However, only a few studies highlight the life cycle carbon emission implications of retrofitting heritage buildings, the authors of this article could find only five publications [140–144] that studied retrofitting of heritage buildings from a life cycle perspective. Information on the material used may not be available for many heritage buildings, which provides challenges for a proper LCA study. Buda and Lavagna [145] stated that [141] and [144] tried to gather information on historic building materials by communicating with the architecture historians and by examining the historiography. More life cycle research studies on heritage buildings are needed for making decisions that could reduce the climate impact from operation of such buildings.

In situations that require contextual assessment, supporting tools such as multicriteria analysis [146] and web toolkits [147] could be used to support the decisions. Ensuring the availability of documents, such as those developed by Historic England and Historic Environment Scotland, that provides guidance on heritage building retrofits, could be helpful for the practitioners and other relevant actors. Similarly, the webinars (recorded) organized by various expert organizations such as Historic England on technical aspects for retrofitting and maintenance of heritage buildings is a good resource for practitioners.

The energy efficiency studies on heritage buildings often focus on one specific energy efficient retrofit measure. The complexity of the historic buildings requires retrofitting solutions which have a whole-building approach [148]. The European standard EN 16883 provides guidelines to improve the energy performance of buildings in a sustainable manner [149]. However, there are limited research publications on heritage buildings that analyze the impact of various retrofit measures on the building as a system by taking into consideration the interlinkage between building process, technologies, and human interactions.

The publications in peer reviewed journals on heritage buildings are often based on simulations. It has been reported that simulations overestimate the energy use in heritage buildings and the models may be recalibrated to reflect the actual energy use [21,150]. Ex-post evaluation publications on retrofits in heritage buildings are limited, which reduces the documentation of specific impacts of such retrofits on the building as a system. The review is predominantly based on publications in English. Relevant sources in other languages are not included, which is a limitation of this review.

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References

1. European Commission. Energy Performance of Buildings Directive. 2018. Available online: https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en#facts-and-figures (accessed on 12 January 2022).
2. Ma, Z.; Cooper, P.; Daly, D.; Ledo, L. Existing building retrofits: Methodology and state-of-the-art. *Energy Build.* **2012**, *55*, 889–902. [CrossRef]
3. European Commission. In Focus: Energy Efficiency in Buildings. 2020. Available online: https://ec.europa.eu/info/news/focus-energy-efficiency-buildings-2020-feb-17_en (accessed on 10 May 2022).
4. Azizi, S.; Nair, G.; Olofsson, T. Analysing the house-owners' perceptions on benefits and barriers of energy renovation in Swedish single-family houses. *Energy Build.* **2019**, *198*, 187–196. [CrossRef]
5. Nair, G. Implementation of Energy Efficiency Measures in Swedish Single-Family Houses. Ph.D. Thesis, Mid Sweden University, Sundsvall, Sweden, 2012.
6. Mazzarella, L. Energy retrofit of historic and existing buildings. The legislative and regulatory point of view. *Energy Build.* **2015**, *95*, 23–31. [CrossRef]
7. Filippi, M. Remarks on the green retrofitting of historic buildings in Italy. *Energy Build.* **2015**, *95*, 15–22. [CrossRef]
8. McCaig, I.; Pender, R.; Pickles, D. *Energy Efficiency and Historic Buildings: How to Improve Energy Efficiency*; Historic England: London, UK, 2018.
9. Irish Georgian Society. Energy Efficiency in Historic Houses. In *Proceedings Produced from Ten Regional Seminars Held during 2009 & 2010*; Irish Georgian Society: Dublin, Ireland, 2013.
10. Historic England. Energy Efficiency in Historic Buildings-Insulating Timber-Framed Walls. 2016. Available online: https://historicengland.org.uk/images-books/publications/eehb-insulating-timber-framed-walls/heag071-insultating-timber-framed-walls/ (accessed on 10 February 2022).
11. Martínez-Molina, A.; Tort-Ausina, I.; Cho, S.; Vivancos, J.-L. Energy efficiency and thermal comfort in historic buildings: A review. *Renew. Sustain. Energy Rev.* **2016**, *61*, 70–85. [CrossRef]

12. Alev, Ü.; Eskola, L.; Arumägi, E.; Jokisalo, J.; Donarelli, A.; Siren, K.; Broström, T.; Kalamees, T. Renovation alternatives to improve energy performance of historic rural houses in the Baltic Sea region. *Energy Build.* **2014**, *77*, 58–66. [CrossRef]
13. Harrestrup, M.; Svendsen, S. Full-scale test of an old heritage multi-storey building undergoing energy retrofitting with focus on internal insulation and moisture. *Build. Environ.* **2015**, *85*, 123–133. [CrossRef]
14. Baker, P. *U-Values and Traditional Buildings: In Situ Measurements and Their Comparisons To Calculated Values*; Technical Paper, Historic Scotland Technical paper 10; Historic Scotland: Edinburgh, UK, 2011.
15. Rispoli, M.; Organ, S. The drivers and challenges of improving the energy efficiency performance of listed pre-1919 housing. *Int. J. Build. Pathol. Adapt.* **2019**, *37*, 288–305. [CrossRef]
16. Norrström, H.; Edén, M. Energy Efficiency and Preservation in our Cultural Heritage in Halland, Sweden, Heritage 2010: Heritage and Sustainable Development. In Proceedings of the 2nd International Conference on Heritage and Sustainable Development, Evora, Portugal, 22–26 June 2010; Volumes 1–2, pp. 589–599.
17. Zagorskas, J.; Zavadskas, E.K.; Turskis, Z.; Burinskiene, M.; Blumberga, A.; Blumberga, D. Thermal insulation alternatives of historic brick buildings in Baltic Sea Region. *Energy Build.* **2014**, *78*, 35–42. [CrossRef]
18. Ficco, G.; Iannetta, F.; Ianniello, E.; Alfano, F.R.A.; Dell'Isola, M. U-value in situ measurement for energy diagnosis of existing buildings. *Energy Build.* **2015**, *104*, 108–121. [CrossRef]
19. Walker, R.; Pavía, S. Thermal performance of a selection of insulation materials suitable for historic buildings. *Build. Environ.* **2015**, *94*, 155–165. [CrossRef]
20. Roberti, F.; Oberegger, U.F.; Gasparella, A. Calibrating historic building energy models to hourly indoor air and surface temperatures: Methodology and case study. *Energy Build* **2015**, *108*, 236–243. [CrossRef]
21. Coelho, G.B.A.; Silva, H.E.; Henriques, F.M.A. Calibrated hygrothermal simulation models for historical buildings. *Build. Environ.* **2018**, *142*, 439–450. [CrossRef]
22. Webb, A.L. Energy retrofits in historic and traditional buildings: A review of problems and methods. *Renew. Sustain. Energy Rev.* **2017**, *77*, 748–756. [CrossRef]
23. Whitman, C.J.; Prizeman, O.; Gwilliam, J.; Shea, A.; Walker, P. Energy Retrofit Infill Panels for Historic Timber-Framed Buildings in the UK: Physical test panel monitoring versus hygrothermal simulation. *Archit. Sci. Rev.* **2020**, *64*, 5–16. [CrossRef]
24. Dubois, S.; de Bouw, M.; Vanhellemont, Y.; Stiernon, D.; Trachte, S. Combining multi-view photogrammetry and wireless sensor networks when modelling the hygrothermal behaviour of heritage buildings. In Proceedings of the 3rd International Conference on Energy Efficiency in Historic Buildings, Visby, Sweden, 26–27 September 2018; Uppsala University: Uppsala, Sweden, 2018.
25. Arumägi, E. Renovation of Historic Wooden Apartment Buildings. Ph.D. Thesis, Tallinn University of Technology, Tallinn, Estonia, 2015.
26. Polo López, C.S.; Frontini, F. Energy efficiency and renewable solar energy integration in heritage historic buildings. *Energy Procedia* **2014**, *48*, 1493–1502. [CrossRef]
27. Fouseki, K.; Cassar, M. Editorial: Energy Efficiency in Heritage Buildings—Future Challenges and Research Needs. *Hist. Environ.* **2014**, *5*, 95–100. [CrossRef]
28. Delhaye, P. The approach of the Walloon Heritage Agency on the energy upgrade of listed buildings. In Proceedings of the 3rd International Conference on Energy Efficiency in Historic Buildings, Visby, Sweden, 26–27 September 2018; Uppsala University: Uppsala, Sweden, 2018.
29. Haas, F.; Herrera, D.; Hüttler, W.; Exner, D.; Troi, A. Historic Building Atlas-Sharing best practices to close the gap between research and practice. In Proceedings of the 3rd International Conference on Energy Efficiency in Historic Buildings, Visby, Sweden, 26–27 September 2018; Uppsala University: Uppsala, Sweden, 2018.
30. Ginks, N.; Painter, B. Energy retrofit interventions in historic buildings: Exploring guidance and attitudes of conservation professionals to slim double glazing in the UK. *Energy Build.* **2017**, *149*, 391–399. [CrossRef]
31. AiCARR. *Energy Efficiency in Historic Buildings*; AiCARR Publication: Milan, Italy, 2014.
32. Femenías, P.; Eriksson, P.; Thuvander, L.; Mörk, K.; Wahlgren, P.; Johansson, P. Value creation by re-renovation—Focus on the user perspective. In Proceedings of the 3rd International Conference on Energy Efficiency in Historic Buildings, Visby, Sweden, 26–27 September 2018; Uppsala University: Uppsala, Sweden, 2018.
33. Sunikka-Blank, M.; Galvin, R. Irrational homeowners? How aesthetics and heritage values influence thermal retrofit decisions in the United Kingdom. *Energy Res. Soc. Sci.* **2016**, *11*, 97–108. [CrossRef]
34. Riksantikvarieämbetet. *Räkna Med Kulturarvet: Kulturarvets Bidrag till en Hållbar Samhällsutveckling (Count on the Cultural Heritage: The Contribution of the Cultural Heritage to a Sustainable Development of Society)*; Riksantikvarieämbetet: Karlskrona, Sweden, 2017.
35. Lidelöw, S.; Örn, T.; Luciani, A.; Rizzo, A. Energy-efficiency measures for heritage buildings: A literature review. *Sustain. Cities Soc.* **2019**, *45*, 231–242. [CrossRef]
36. Berg, F.; Flyen, A.-C.; Godbolt, Å.L.; Broström, T. User-driven energy efficiency in historic buildings: A review. *J. Cult. Herit.* **2017**, *28*, 188–195. [CrossRef]
37. Cabeza, L.F.; de Gracia, A.; Pisello, A.L. Integration of renewable technologies in historical and heritage buildings: A review. *Energy Build.* **2018**, *177*, 96–111. [CrossRef]
38. Buda, A.; de Place Hansen, E.J.; Rieser, A.; Giancola, E.; Pracchi, V.N.; Mauri, S.; Marincioni, V.; Gori, V.; Fouseki, K.; Polo López, C.S.; et al. Conservation-Compatible Retrofit Solutions in Historic Buildings: An Integrated Approach. *Sustainability* **2021**, *13*, 2927. [CrossRef]

39. Hao, L.; Herrera-Avellanosa, D.; Pero, C.D.; Troi, A. What Are the Implications of Climate Change for Retrofitted Historic Buildings? A Literature Review. *Sustainability* **2020**, *12*, 7557. [CrossRef]
40. Milone, D.; Peri, G.; Pitruzzella, S.; Rizzo, G. Are the Best Available Technologies the only viable for energy interventions in historical buildings? *Energy Build.* **2015**, *95*, 39–46. [CrossRef]
41. Ståhl, F.; Lundh, M.; Ylmén, P. *Hållbar och Varsam Renovering och Energieffektivisering av Kulturhistoriskt Värdefulla Byggnader (Sustainable and Careful Renovation and Energy Efficiency Improvements of Historic Buildings)*; SP Sveriges Tekniska Forskningsinstitut: Borås, Sweden, 2011.
42. Arumägi, E.; Kalamees, T. Analysis of energy economic renovation for historic wooden apartment buildings in cold climates. *Appl. Energy* **2014**, *115*, 540–548. [CrossRef]
43. Morelli, M.; Rønby, L.; Mikkelsen, S.E.; Minzari, M.G.; Kildemoes, T.; Tommerup, H.M. Energy retrofitting of a typical old Danish multi-family building to a "nearly-zero" energy building based on experiences from a test apartment. *Energy Build.* **2012**, *54*, 395–406. [CrossRef]
44. de Place Hansen, E.J.; Wittchen, K.B. Energy savings due to internal façade insulation in historic buildings. In Proceedings of the 3rd International Conference on Energy Efficiency in Historic Buildings, Visby, Sweden, 26–27 September 2018; Uppsala University: Uppsala, Sweden, 2018.
45. Scorpio, M.; Ciampi, G.; Gentile, N.; Siblio, S. Effectiveness of low-cost non-invasive solutions for daylight and electric lighting integration to improve energy efficiency in historical buildings. *Energy Build.* **2022**, *270*, 112281. [CrossRef]
46. Salvadori, G.; Fantozzi, F.; Rocca, M.; Leccese, F. The Energy Audit Activity Focused on the Lighting Systems in Historical Buildings. *Energies* **2016**, *9*, 998. [CrossRef]
47. Héberlé, E.; Burgholzer, J. Guidance for finding a sustainable balance between energy efficiency, comfort, moisture damage and cultural heritage value in historic buildings. In Proceedings of the 2nd International Conference on Energy Efficiency and Comfort of Historic Buildings, Brussels, Belgium, 19–21 October 2016.
48. Donnelly, J. *Energy Efficiency in Traditional Buildings, Advice Series*; Government of Ireland: Dublin, Ireland, 2010; ISBN 978-1-4064-2444-7.
49. Historic England. *Energy Efficiency and Historic Buildings-Draught-proofing Windows and Doors*; Historic England: London, UK, 2016.
50. Eskola, L.; Alev, Û.; Arumägi, E.; Jokisalo, J.; Donarelli, A.; Sirén, K.; Kalamees, T. Air tightness, Air Exchange and Energy Performance in Historic Residential Buildings with Different Structures. *Int. J. Vent.* **2015**, *14*, 11–26.
51. Historic England. *Traditional Windows Their Care, Repair and Upgrading*; Historic England: London, UK, 2017.
52. The Department of the Environment. *Heritage and Local Government, Energy Efficiency in Traditional Buildings*; Stationery Office of Ireland: Dublin, Ireland, 2010; ISBN 978-1-4064-2444-7.
53. National Trust for Historic Preservation. *Saving Window, Saving Money: Evaluating the Energy Performance of Window Retrofit and Replacement. Preservation Green Lab2*; National Trust for Historic Preservation: Washington, DC, USA, 2012.
54. Allt om Torp (Everything about Homesteads), Om Gamla Fönster (About Old Windows). 2017. Available online: http://alltomtorp.se/ta-hand-om-ditt-hus/fonster/om-gamla-fonster/ (accessed on 15 February 2022).
55. Currie, J.; Williamson, J.B.; Stinson, J.; Jonnard, M. *Thermal Assessment of Internal Shutters and Window Film Applied to Traditional Single Glazed Sash and Case Windows*; Historic Scotland Technical Paper 23; Historic Scotland: Edinburgh, UK, 2014; ISBN 978-1-84917-174-8.
56. Menzies, G.F. Slim-Profile Double Glazing; Thermal Performance and Embodied Energy. Historic Scotland Technical Paper 9. 2010. Available online: https://pure.hw.ac.uk/ws/portalfiles/portal/645950/slim_profile_double_glazing_2010.pdf (accessed on 10 March 2022).
57. Bernardi, A.; Becherini, F.; Verità, M.; Ausset, P.; Bellio, M.; Brinkmann, U.; Cachier, H.; Chabas, A.; Deutsch, F.; Etchevery, M.-P.; et al. Conservation of stained glass windows with protective glazing: Main results from the European VIDRIO research programme. *J. Cult. Herit.* **2013**, *14*, 527–536. [CrossRef]
58. Moghaddam, S.A.; Mattsson, M.; Ameen, A.; Akander, J.; Da Silva, M.G.; Simões, N. Low-Emissivity Window Films as an Energy Retrofit Option for a Historical Stone Building in Cold Climate. *Energies* **2021**, *14*, 7584. [CrossRef]
59. Réflective. Clear Solar Protection. 2020. Available online: https://www.reflectiv.com/product/heat-resistant/ (accessed on 11 November 2021).
60. Ben, H.; Steemers, K. Energy retrofit and occupant behaviour in protected housing: A case study of the Brunswick Centre in London. *Energy Build.* **2014**, *80*, 20–130. [CrossRef]
61. Strandberg-de Bruijn, P.; Donnarelli, A.; Balksten, K. Full-scale Studies of Improving Energy Performance by Renovating Historic Swedish Timber Buildings with Hemp-lime. *Appl. Sci.* **2019**, *9*, 2484. [CrossRef]
62. Johansson, P.; Adi-Zarrabi, B. Super insulation materials in the building sector: Field studies and future challenges. In Proceedings of the 7th International Building Physics Conference (IBPC 2018), Syracuse, NY, USA, 24 September 2018.
63. Harrestrup, M.; Svendsen, S. Internal insulation applied in heritage multi-storey buildings with wooden beams embedded in solid masonry brick façades. *Build. Environ.* **2016**, *99*, 59–72. [CrossRef]
64. Lucchi, E.; Becherini, F.; Di Tuccio, M.C.; Troi, A.; Frick, J.; Roberti, F.; Hermann, C.; Fairnington, I.; Mezzasalma, G.; Pockele, L.; et al. Thermal performance evaluation and comfort assessment of advanced aerogel as blown-in insulation for historic buildings. *Build. Environ.* **2017**, *122*, 258–268. [CrossRef]

65. Johansson, P.; Donarelli, A.; Strandberg, P. Performance of insulation materials for historic buildings-Case studies comparing a super insulation material and hemp-lime. In Proceedings of the 3rd International Conference on Energy Efficiency in Historic Buildings, Visby, Sweden, 26–27 September 2018; Uppsala University: Uppsala, Sweden, 2018.
66. Saio, C.; Nocentini, K.; Tagliafico, L.A.; Biwole, P.H.; Achard, P. Application of advanced insulating materials in historical buildings. *Int. J. Heat Technol.* **2017**, *35*, S345–S352. [CrossRef]
67. Krus, M.; Kilian, R.; Pfundstein, B. Comparison of different systems for internal wall insulation with reversible application for historic buildings. In Proceedings of the 2nd International Conference on Energy Efficiency and Comfort of Historic Buildings, Brussels, Belgium, 19–21 October 2016.
68. NCA. *Insulation. JCA Report from Cork, Ireland*; JCA Architects: Cork, Ireland, 2020.
69. English Heritage. Energy Conservation in Traditional Buildings. 2008. Available online: https://michaelhornsby.co.uk/assets/Uploads/documents/EH-energyConservation.pdf (accessed on 16 March 2022).
70. Historic Scotland. *Short Guide: Fabric Improvements for Energy Efficiency in Traditional Buildings*; Historic Scotland: Edinburgh, UK, 2013.
71. English Heritage. *Energy Efficiency in Historic Buildings-Insulation of Suspended Timber Floors*; English Heritage: Battle, UK, 2010.
72. English Heritage. *Energy Efficiency in Historic Buildings-Insulating Solid Walls*; English Heritage: Battle, UK, 2010.
73. English Heritage. *Energy Efficiency and Historic Buildings—Application of Part L of the Building Regulations to Historic and Traditionally Constructed Buildings, London*; English Heritage: Battle, UK, 2010.
74. Örn, T. Energy Efficiency in Heritage Buildings—Conservation Approaches and Their Impact on Energy Efficiency Measures. Ph.D. Thesis, Luleå University of Technology, Luleå, Sweden, 2018.
75. Curtis, R. Energy efficiency in traditional and historic buildings: Keeping it simple. In Proceedings of the 2nd International Conference on Energy Efficiency and Comfort of Historic Buildings, Brussels, Belgium, 19–21 October 2016.
76. Sakiyama, N.R.M.; Frick, J.; Garrecht, H. Cultural heritage compatible insulation plaster—Analysis and assessment by hygrothermal simulations, In Proceedings of the 3rd International Conference on Energy Efficiency in Historic Buildings, Visby, Sweden, 26–27 September 2018; Uppsala University: Uppsala, Sweden, 2018.
77. RIBuild. Robust Internal Thermal Insulation of Historic Buildings. Project Number 637268. 2020. Available online: https://static1.squarespace.com/static/5e8c2889b5462512e400d1e2/t/5f04215c5b6cfa0aa7baa5b1/1594106230146/Written+guidelines+for+decision+making+concerning+the+possible.pdf (accessed on 21 March 2022).
78. Kalamees, T.; Arumägi, E.; Alev, Ü. Performance of interiorly insulated log wall -Experiences from Estonian cold climate conditions. In Proceedings of the 3rd International Conference on Energy Efficiency in Historic Buildings, Visby, Sweden, 26–27 September 2018; Uppsala University: Uppsala, Sweden, 2018.
79. Theodosiou, T.; Papadopoulos, A. The impact of thermal bridges on the energy demand of buildings with double brick wall constructions. *Energy Build.* **2008**, *40*, 2083–2089. [CrossRef]
80. Ge, H.; McClung, V.R.; Zhang, S. Impact of balcony thermal bridges on the overall thermal performance of multi-unit residential buildings: A case study. *Energy Build.* **2013**, *60*, 163–173. [CrossRef]
81. Rye, C.; Scott, C. *The SPAB Research Report 1 e U-Value Report, Published 2010 and Revised*; SPAB: London, UK, 2012.
82. Browne, D. *The SPAB Hygrothermal Modelling: Interim Report. The SPAB Research Report 3*; SPAB: London, UK, 2012.
83. *BS EN 15759-1:2011*; Conservation of Cultural Property—Indoor Climate Part 1: Guidelines for Heating Churches, Chapels and Other Places of Worship. British Standards Institution (BSI): London, UK, 2011.
84. Broström, T.; Lejonhufvud, G. Heat Pumps for Conservation Heating. 2008. Available online: https://www.researchgate.net/publication/237732716_ (accessed on 22 June 2022).
85. National Property Board Sweden, Stockholm. *Ventilation in Historic Buildings*; National Property Board Sweden: Stockholm, Sweden, 2009.
86. English Heritage. *Energy Efficiency in Historic Buildings-Open Fires, Chimneys and Flues*; English Heritage: Battle, UK, 2010.
87. Hamid, A.A.; Johansson, D.; Bagge, H. Ventilation measures for heritage office buildings in temperate climate for improvement of energy performance and IEQ. *Energy Build.* **2020**, *211*, 109822. [CrossRef]
88. Larsen, P.K.; Broström, T. Climate Control in Historic Buildings. 2015. Available online: http://eprints.sparaochbevara.se/862/1/Climate_control_in_historic_buildings.pdf (accessed on 20 June 2022).
89. Bjarløv, S.P.; Vladykova, P. The potential and need for energy saving in standard family detached and semi-detached wooden houses in arctic Greenland. *Build. Environ.* **2011**, *46*, 1525–1536. [CrossRef]
90. Akande, O.K.; Odeleye, D.; Coday, A. Energy Efficiency for Sustainable Reuse of Public Heritage Buildings: The Case for Research. *Int. J. Sustain. Dev. Plan.* **2014**, *9*, 237–250. [CrossRef]
91. Zemetis, J.; Borodinecs, A.; Kalamees, T. Analysis of Various Ventilation Solutions for Residential and Non-residential Buildings in Latvia and Estonia: Sustainable Buildings in Cold Climates. In Proceedings of the 9th International Cold Climate Conference Sustainable New and Renovated Buildings in Cold Climates, Kiruna, Sweden, 12–15 March 2018; Springer: Berlin/Heidelberg, Germany, 2019.
92. Wessberg, M. Design and Analysis of Energy Efficient Indoor Climate Control Methods for Historic Buildings. Ph.D. Thesis, Czech Technical University in Prague, Prague, Czech Republic, 2018.
93. Hao, L.; Herrera-Avellanosa, D.; Pero, C.D.; Troi, A. Overheating Risks and Adaptation Strategies of Energy Retrofitted Historic Buildings under the Impact of Climate Change: Case Studies in Alpine Region. *Appl. Sci.* **2022**, *12*, 7162. [CrossRef]

94. Schellen, H.L. Heating Monumental Churches: Indoor Climate and Preservation of Cultural Heritage. Ph.D. Thesis, Technische Universiteit Eindhoven, Eindhoven, The Netherlands, 2002. [CrossRef]
95. Ritson, J. Benign changes and building maintenance as a sustainable strategy for refurbishment of historic (Pre-1919) English dwellings. In Proceedings of the 3rd International Conference on Energy Efficiency in Historic Buildings, Visby, Sweden, 26–27 September 2018; Uppsala University: Uppsala, Sweden, 2018.
96. Rectora, L.; Millera, P.J.; Snook, S.; Ahmadia, M. Comparative emissions characterization of a small-scale wood chip-fired boiler and an oil-fired boiler in a school setting. *Biomass Bioenergy* **2017**, *107*, 254–260. [CrossRef]
97. Uyttenhove, W.; De Paepe, M.; Janssens, A. CFD-Modelling of Temperature and Humidity Distribution in the St. Pieter's Church. IAE Annex 41, Subtask 1, Meeting 12–14 May 2004, Zürich. 2004. Available online: https://bwk.kuleuven.be/bwf/projects/annex41/protected/data/UG%20May%202004%20Paper%20A41-T1-B-04-5.pdf (accessed on 27 June 2022).
98. Aste, N.; Torre, S.D.; Adhikari, R.S.; Buzzetti, M.; Pero, C.D.; Leonforte, F.; Manfren, M. Sustainable church heating: The Basilica di Collemaggio case-study. *Energy Build.* **2016**, *116*, 218–223. [CrossRef]
99. Camuffo, D.; Pagan, E.; Rissanen, S.; Bratasz, L.; Kozłowski, R.; Camuffo, M.; Valle, A. An advanced church heating system favourable to artworks: A contribution to European standardization. *J. Cult. Herit.* **2010**, *11*, 205–219. [CrossRef]
100. Historic England. Heating Systems for Historic Buildings. 2021. Available online: https://historicengland.org.uk/advice/technical-advice/building-services-engineering/heating-historic-buildings/heating-systems-for-historic-buildings/ (accessed on 12 April 2022).
101. Zhang, Y.; Zhao, C.; Olofsson, T.; Nair, G.; Yang, B.; Li, A. Feld measurements and numerical analysis on operating modes of a radiant floor heating aided by a warm air system in a large single-zone church. *Energy Build.* **2022**, *255*, 111646. [CrossRef]
102. Camuffo, D.; Pagan, E.; Bernardi, A.; Becherini, F. The impact of heating, lighting and people in re-using historical buildings: A case study. *J. Cult. Herit.* **2004**, *5*, 409–416. [CrossRef]
103. Pisello, A.L.; Petrozzi, A.; Castaldo, V.L.; Cotana, F. On an innovative integrated technique for energy refurbishment of historical buildings: Thermal-energy, economic and environmental analysis of a case study. *Appl. Energy* **2016**, *162*, 1313–1322. [CrossRef]
104. GEO4CIVHIC, 2018, D1.1 Report on different kind of barriers for shallow geothermal in deep renovation.
105. Changeworks. *Renewable Heritage—A Guide to Microgeneration in Traditional and Historic Homes*; Changeworks: Edinburgh, UK, 2009.
106. DRU. What is the Efficiency and Capacity of a Wood Burning Fire or Stove? 2019. Available online: https://www.drufire.com/int/essential-info/wood-burning-stoves-and-fires-en/efficiency-and-capacity-wood-burning-fire (accessed on 22 April 2022).
107. Lenza, V.; Büchnera, D.; Wurdingera, K. Evaluation of combining an air-to-water heat pump with a wood stove with water jacket for residential heating. In Proceedings of the 12th IEA Heat Pump Conference, Rotterdam, The Netherlands, 15–18 May 2017.
108. Faninger, G. *The Potential of Solar Thermal Technologies in a Sustainable Energy Future: Results from 32 Years of International R&D Co-Operation. IEA Solar Heating & Cooling Programme*; International Energy Agency: Paris, France, 2010.
109. Brito, N.S. Mismatch, exclusion and inclusion: Threats/opportunities for historic buildings in the current energy efficiency paradigm. In Proceedings of the 2nd International Conference on Energy Efficiency and Comfort of Historic Buildings, Brussels, Belgium, 19–21 October 2016.
110. Flores, J. An investigation of the energy efficiency of traditional buildings in the Oporto World Heritage Site. In Proceedings of the 2nd International Conference on Energy Efficiency and Comfort of Historic Buildings, Brussels, Belgium, 19–21 October 2016.
111. Kumar, N.M.; Sudhakar, K.; Samykano, M. Performance comparison of BAPV and BIPV systems with c-Si, CIS and CdTe photovoltaic technologies under tropical weather conditions. *Case Stud. Therm. Eng.* **2019**, *13*, 1003744. [CrossRef]
112. D'Agostinom, D.; Tzeiranaki, S.T.; Zangheri, P.; Bertoldi, P. Assessing Nearly Zero Energy Buildings (NZEBs) development in Europe. *Energy Strategy Rev.* **2021**, *36*, 100680. [CrossRef]
113. Ozbalta, T.G.; Yildiz, Y.; Bayrama, I.; Yilmaz, O.C. Energy performance analysis of a historical building using cost-optimal assessment. *Energy Build.* **2021**, *250*, 111301. [CrossRef]
114. Lucchi, E.; Polo Lopez, C.S.; Franco, G. A conceptual framework on the integration of solar energy systems in heritage sites and buildings. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *949*, 012113. [CrossRef]
115. Durante, A.; Lucchi, E.; Maturi, L. Building integrated photovoltaic in heritage contexts award: An overview of best practices in Italy and Switzerland. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *863*, 012018. [CrossRef]
116. Rosa, F. Building-Integrated Photovoltaics (BIPV) in Historical Buildings: Opportunities and Constraints. *Energies* **2020**, *13*, 3628. [CrossRef]
117. Beechio, C.; Corgnati, S.P.; Vio, M.; Crespi, G.; Prendin, L.; Magagnini, M. HVAC solutions for energy retrofitted hotel in Mediterranean area. *Energy Procedia* **2017**, *133*, 145–157. [CrossRef]
118. Gremmelspacher, J.M.; Pizarro, R.C.; van Jaarsveld, M.; Davidsson, H.; Johansson, D. Historical building renovation and PV optimisation towards NetZEB in Sweden. *Sol. Energy* **2021**, *223*, 248–260. [CrossRef]
119. Polo López, C.S.; Lucchi, E.; Leonardi, E.; Durante, A.; Schmidt, A.; Curtis, R. Risk-Benefit Assessment Scheme for Renewable Solar Solutions in Traditional and Historic Buildings. *Sustainability* **2021**, *13*, 5246. [CrossRef]
120. Kandt, A.; Hotchkiss, E.; Walker, A.; Buddenborg, J.; Lindberg, J. *Implementing Solar PV Projects on Historic Buildings and in Historic Districts. National Renewable Energy Laboratory Technical Report NREL/TP-7A40-51297*; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2011.

121. Escarré, J.; Li, H.-Y.; Sansonnens, L.; Galliano, F.; Cattaneo, G.; Heinstein, P.; Nicolay, S.; Bailat, J.; Eberhard, S.; Ballif, C.; et al. When PV modules are becoming real building elements: White solar module, a revolution for BIPV. In Proceedings of the 2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC), New Orleans, LA, USA, 14–19 June 2015; pp. 1–2.
122. van Berkel, B.; Minderhoud, T.; Piber, A.; Gijzen, G. Design innovation from PV module to building envelope (EU PVSEC 2014). In Proceedings of the 29th European Photovoltaic Solar Energy Conference and Exhibition, Amsterdam, The Netherlands, 22–26 September; pp. 3606–3612.
123. Yang, C.; Liu, D.; Bates, M.; Barr, M.C.; Lunt, R.R. How to accurately report transparent solar cells. *Joule* **2019**, *3*, 1803–1809. [CrossRef]
124. Husain, A.A.F.; Hasan, W.Z.W.; Shafiea, S.; Hamidon, M.N.; Pandey, S.S. A review of transparent solar photovoltaic technologies. *Renew. Sustain. Energy Rev.* **2018**, *94*, 779–791. [CrossRef]
125. Polo López, C.S.; Lucchi, E.; Giovanna, F. Acceptance of building integrated photovoltaic (BIPV) in heritage buildings and landscapes: Potentials, barrier and assessment criteria. In Proceedings of the 2020 Construction Pathology, Rehabilitation Technology and Heritage Management Conference, Granada, Spain, 24–27 March 2020.
126. Broström, T.; Svahnström, K. Solar energy and cultural-heritage values. In Proceedings of the 2011 World Renewable Energy Congress, Linkoping, Sweden, 8–13 May 2011.
127. Bernardi, A.; Becherini, F.; Romero-Sanchez, M.D.; Lopez-Buendia, A.M.; Vivarelli, A.; Moretti, P.; Baldisseri, G.; Ghiretti, C.; Pockele, L. Adaptation of energy storage systems to cultural heritage: The application of Phase change materials technology to historical buildings and objects. In Proceedings of the 3rd European Workshop on Cultural Heritage Preservation (EWCHP 2013), Bolzano, Italy, 16–18 September 2013.
128. Bastani, A.; Haghighat, F.; Kozinski, J. Designing building envelope with PCM wallboards: Design tool development. *Renew. Sustain. Energy Rev.* **2014**, *31*, 554–562. [CrossRef]
129. Guarino, F.; Dermardiros, V.; Chen, Y.; Rao, J.; Athienitis, A.; Cellura, M.; Mistretta, M. PCM thermal energy storage in buildings: Experimental study and applications. *Energy Procedia* **2015**, *70*, 219–228. [CrossRef]
130. Lagou, A.; Kylili, A.; Šadauskiene, J.; Fokaides, P.A. Numerical investigation of phase change materials (PCM) optimal melting properties and position in building elements under diverse conditions. *Constr. Build. Mater.* **2019**, *225*, 452–464. [CrossRef]
131. Ascionea, F.; Biancoa, N.; De Masi, R.F.; de'Rossi, F.; Vanoli, G.P. Energy retrofit of an educational building in the ancient center of Benevento. Feasibility study of energy savings and respect of the historical value. *Energy Build.* **2015**, *95*, 172–183. [CrossRef]
132. Castele, D.S.; Webb, A.L. Insulating the Walls of Historic Buildings: A systematic review of existing guidance. *J. Preserv. Technol.* **2019**, *50*, 37–44.
133. Ascione, F.; Cheche, N.; De Masi, R.F.; Minichielloa, F.; Vanoli, G.P. Design the refurbishment of historic buildings with the cost-optimal methodology: The case study of a XV century Italian building. *Energy Build.* **2015**, *99*, 162–176. [CrossRef]
134. Cornaro, C.; Puggioni, V.D.; Strollo, R.M. Dynamic simulation and on-site measurements for energy retrofit of complex historic buildings: Villa Mondragone case study. *J. Build. Eng.* **2016**, *6*, 17–28. [CrossRef]
135. Bakonyi, D.; Dobszay, G. Simulation aided optimization of a historic window's refurbishment. *Energy Build.* **2016**, *126*, 51–69. [CrossRef]
136. Johansson, P.; Hagentoft, C.-E.; Kalagasidi, A.S. Retrofitting of a listed brick and wood building using vacuum insulation panels on the exterior of the facade: Measurements and simulations. *Energy Build.* **2014**, *73*, 92–104. [CrossRef]
137. Blennerhassett, E. *Building Services: Implications in Historic Houses. Energy Efficiency in Historic Houses*; Irish Georgian Society: Dublin, Ireland, 2013; ISBN 978-0-9545691-4-3.
138. Bellia, L.; Alfano, F.R.A.; Giordano, J.; Ianniello, E.; Riccio, G. Energy requalification of a historical building: A case study. *Energy Build.* **2015**, *95*, 184–189. [CrossRef]
139. Marincioni, V.; Gori, V.; de Place Hansen, E.J.; Herrera-Avellanosa, D.; Mauri, S.; Giancola, E.; Egusquiza, A.; Buda, A.; Leonardi, E.; Rieser, A. How Can Scientific Literature Support Decision-Making in the Renovation of Historic Buildings? An Evidence-Based Approach for Improving the Performance of Walls. *Sustainability* **2021**, *13*, 2266. [CrossRef]
140. Berg, F.; Fuglseth, M. Life cycle assessment and historic buildings: Energy-efficiency refurbishment versus new construction in Norway. *J. Archit. Conserv.* **2018**, *24*, 152–167. [CrossRef]
141. Iyer-Raniga, U.; Wong, J.P.C. Evaluation of whole life cycle assessment for heritage buildings in Australia. *Build. Environ.* **2012**, *47*, 138–149. [CrossRef]
142. Hu, M. Balance between energy conservation and environmental impact: Life-cycle energy analysis and life-cycle environmental impact analysis. *Energy Build.* **2017**, *140*, 131–139. [CrossRef]
143. Ruggieri, G.; Dotelli, G.; Melià, P.; Sabatini, S. Life Cycle assessment of refurbishment strategies for historic buildings. In *Retrofitting the Built Environment*; Swan, W., Brown, P., Brown, P., Eds.; John Wiley and Sons: Hoboken, NJ, USA, 2013; pp. 113–127.
144. Bin, G.; Parker, P. Measuring buildings for sustainability: Comparing the initial and retrofit ecological footprint of a century home—The REEP House. *Appl. Energy* **2012**, *93*, 24–32. [CrossRef]
145. Buda, A.; Lavagna, M. LCA methodology to compare alternative retrofit scenarios for historic buildings: A review. In *Life Cycle Thinking in Decision-Making for Sustainability: From Public Policies to Private Business, Proceedings of the 12th Italian LCA Network Conference, Messina, Italy, 11–12 June 2018*; ENEA: Stockholm, Sweden, 2018.
146. Roberti, F.; Oberegger, U.F.; Lucchi, E.; Troi, A. Energy retrofit and conservation of a historic building using multi-objective optimization and an analytic hierarchy process. *Energy Build.* **2017**, *138*, 1–10. [CrossRef]

147. Lee, S.H.; Hong, T.; Piette, M.A.; Taylor-Lange, S.C. Energy retrofit analysis toolkits for commercial buildings: A review. *Energy* **2015**, *89*, 1087–1100. [CrossRef]
148. Buda, A.; Gori, V.; de Place Hansen, E.J.; Polo López, C.S.; Marincioni, V.; Giancola, E.; Vernimme, N.; Egusquiza, A.; Haas, F.; Herrera-Avellanos, D. Existing tools enabling the implementation of EN 16883:2017 Standard to integrate conservation-compatible retrofit solutions in historic buildings. *J. Cult. Herit.* **2022**, *57*, 34–52. [CrossRef]
149. *BS EN 16883:2017*; Conservation of Cultural Heritage—Guidelines for Improving the Energy Performance of Historic Buildings. British Standards Institution (BSI): London, UK, 2017.
150. Moran, F.; Blight, T.; Natarajan, S.; Shea, A. The use of Passive House Planning Package to reduce energy use and CO_2 emissions in historic dwellings. *Energy Build.* **2014**, *75*, 216–227. [CrossRef]