Approaching Near Zero Energy In Historic Buildings

Deliverable No: WPT1.2.1

Deliverable Title: Report on barriers and opportunities for energy related renovation of historic buildings

Delivery: 2022

Deliverable Coordinator: Umeå University (UmU)

Lead Authors: Leo Verde, Gireesh Nair, Thomas Olofsson

Deliverable Type: R
R = Document, report
DEM = Demonstrator, pilot, prototype, plan designs
DEC = Websites, patent filing, press & media actions, videos, etc.

Dissemination Level: PU
PU = Public
CO = Confidential, only for members of the consortium, including the Commission Services

Refer the below publication for an updated version of this document:
Nair, G., Verde, L., Olofsson, T. 2022. A review on energy efficient retrofitting in heritage buildings. Energies 15 (20), 7472.

This project has received funding from the European Union's Northern Periphery and Arctic Programme (2016-2020) under Grant Offer Letter 304_1175_20194.

1 Introduction

The word historic is defined by the Merriam-Webster dictionary as something which is "famous or important in history" and "having great and lasting importance" [1]. For a building to be classified as historic it has to hold a particular significance, integrity and be of a certain age [2, 3]. The significance can be a result of e.g. the association with certain historical events or individuals, certain characteristics of an architectural style or a particular method of construction. The integrity is closely linked to the building characteristics (e.g. elaborate ornamentation), how well the building is preserved or be clearly linked to a certain cultural group. The age criterion is more straight forward and is usually set to be around 50 years [3]. The aforementioned attributes are quite general, the exact requirements and the level of protection are dependent on the specific building in question [3,4,5]. Furthermore, historic buildings are often constructed using vernacular and traditional building techniques, adding to their significance and the complexity of implementing retrofits. Due to all this it is recommended that retrofits in historic buildings are assessed on a case to case basis, there is no "one fits all" solution [6, 7, 8]. This is especially true when looking at religious buildings and public monuments which might contain sensitive artwork or artifacts requiring a certain climate [3].

The primary difference between a building built using traditional techniques and one using modern techniques is how it deals with moisture. Most modern buildings in northern Europe rely on impermeable vapour barriers, such as plastic films or paints, to control the movement of moisture through the building fabric. Traditional buildings take up moisture from their surroundings, both internal and external, and release it back according to the changing environmental conditions[1] [6]. This process is further aided in traditional stone buildings which has a high thermal inertia thus reducing rapid fluctuations in temperature and humidity [6]. In contrast to modern buildings, which rely on mechanical ventilation, the movement of air is normally not actively controlled in traditional ones. If a building has too little ventilation, or if the fabric is unable to release moisture, mould and rot can occur. An upper Relative Humidity (RH) level of 80% at normal room temperature is suggested to avoid bio-deterioration through mould, insects or the crystallisation of salts [9]. This process of moisture transport, commonly called hygrothermal behaviour, is a complicated and delicate balancing act which is paramount to the health of a traditional building and must be treated with great care during all renovation or retrofit work. According to a Swedish study 29% of the buildings had mould growth in the building fabric, highlighting the importance of understanding these mechanisms in existing buildings [10].

2 Challenges of retrofitting

The delicate hygrothermal behavior of a traditional buildings and the building specific legislative requirements can make retrofitting historic buildings rather challenging. In order determine proper retrofitting actions it is advised to perform a complete assessment of the building before anything is done [11, 12]. A good starting point is to follow a general energy audit procedure (or the EN 16883:2017 standard [13]) which may consist of: i) Preliminary energy data analysis, ii) In-situ investigation,

[1] As a matter of fact, this is a defining feature of regulations in the United Kingdom (UK) stating "Buildings of traditional construction with permeable fabric that both absorbs and readily allows the evaporation of moisture" [11].

iii) Energy consumption data correction, iv) Development of energy consumption calculation model, v) Model validation against measured data, vi) Renovation or retrofit package development [12, 14]. The importance of in-situ measurements of e.g. U-values, step ii), are discussed in several articles, stating that the energy performance of historic buildings can be better than calculated or simulated values [11, 15, 16, 17]. This is in part because standard methods for U-value calculation are generally not capable of taking the dynamic effects of moisture flow and the impact this can have on the thermal properties of other materials into consideration [11]. Another reason for faulty U-values can be the lack of knowledge concerning the exact building technique, materials used or of unknown previous building alterations [18, 19]. In-situ measurements, even though preferred, can be problematic since they have to be done over a long period of time and are impacted by the operative conditions[2] [11, 20].

The problem of data accuracy reflects on the development of traditional simulation models which often have to be built using assumptions, or disregarding the aforementioned moisture effects altogether, thus potentially giving results which may cause damage to the building [10, 17. 18]. There is however an emerging alternative to traditional simulation models in the form of hygrothermal ones. These have proven to be versatile tools giving accurate predictions of energy consumption, moisture transport and indoor climate in a variety of applications [3, 18, 21, 22, 23]. Unfortunately, hygrothermal models of historic buildings are subject to the same problems as traditional models where a lack of information about e.g. the specific building materials, techniques, ventilation rates and occupancy schedules can make development difficult and time intensive [18].

For occupants and owners, one of the main drivers for energy retrofitting is to achieve a more comfortable indoor climate[3] and reducing the heating cost [15, 25]. An increased energy performance can enhance the resale value of a property, thereby providing additional incentive to carry out retrofits or renovation. The retrofitting process itself can however become costlier than initially anticipated due to unforeseen problems, such as moisture damage, within the building [13, 15]. Furthermore, certain projects may involve several different actors such as conservation officers, 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, 24, 25]. To reduce this an early dialogue at a local level should be held prior to the project to develop a suitable strategy and evaluate if any special skills are needed throughout the process [15, 25].

Increased education and cooperation for all aforementioned professionals and the owners about how historic 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 was found amongst conservation professionals at both an institutional level and at the point of implementation [30]. The same study recommends that a framework for decision making should be put in to place, like the Italian AiCARR

[2] Uncertainties in U-value of 8-50% are reported in an Italian study [26].
[3] This is subjective, inhabitants sometimes adapt to the often colder temperatures in historic buildings [27].

guidelines "Energy Efficiency in historic buildings" [31], to objectively decide the level of energy efficiency which can be obtained for the building in question [30].

The inconsistency of perceived historic values is a challenge all renovation or retrofits are subject to. It may be on a professional basis, as discussed above, or on a residential or public basis. A study from Gothenburg, Sweden, showed that the residents in older buildings were more likely to value the conservation of their building than people in newer ones [32]. Furthermore, when asked about which parts of the building the residents considered being important to its historic value it differed widely between respondents and their respective buildings. The variance is congruent with similar studies and indicate that it may be difficult to discern between "beautiful" and "historic" elements for people which are not trained in the field, thus making the perceived historic value hard to predict [32, 33]. The perception of historic, and sentimental, value is important on a social level since it can give a feeling of connection with the past, other people and society as a whole [32, 34]. Due to this, the history and beauty of a building can by some be considered more important than an improvement in comfort or economical savings[4] [32, 33].

3 Energy efficiency retrofits

Due to the delicate nature and often heavy protective restrictions of historic buildings the best, and often most cost effective, energy efficiency measures are the least intrusive ones [6, 7, 35]. Making sure to use minimal intervention, repair rather than replace and use natural (replace like-with-like) materials is widely considered best practice for conservation purposes [11, 35]. Potential retrofits and their impact should be evaluated pre-implementation on: reversibility (i.e. the ability to restore the fabric to its original state), compatibility with the building (i.e. making sure that the retrofit will not affect the fabric negatively) and authenticity (i.e. if the retrofit is authentic to the historic nature of the building) [3]. With these broad principles in mind, it is possible to restore and sometimes even drastically improve the energy performance (up to 65-90% in some cases [36, 37, 38]) of historic buildings without decreasing their significance [7].

As previously discussed there is no universal way to energy efficient retrofitting of historic buildings, which is apparent in the literature where case studies are the most prevalent. The following subsections aim to highlight various methods and their potential in preserving and protecting historic buildings, preventing them from becoming an energy liability now and in the future.

3.1 Draught-proofing

In many historic and traditional buildings heat loss often occurs as a result of unwanted ventilation, more commonly called draughts. The percentage of heat loss due to drafts varies widely, but values up to 40% have been recorded [39]. 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

[4] One respondent in the Swedish study even expressed an urge to move if the original windows were replaced with modern ones [32].

[40]. Previous building alterations (e.g. the removal or installation of services) 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 [41]. This can be done by a fan pressurization test, a very effective way to quantify the infiltration rate. During one of these tests it is advisable to temporarily tape around windows and doors to see how much they actually leak [41]. A study made on 35 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 [42]. 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 to these varying rates was found [42].

Applicable draught proofing measures are heavily dependent on the location and extent of the draught. Simple silicone or wool compression seals are good 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 [29]. Draught proofing a single-glazed window can have the same effect as installing an additional sheet of glass, reducing the heat loss by up to 90% [11]. 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 prior to sealing. During readjustments, sealing using natural materials such as hemp or flax should be performed between the frame and surrounding wall [35]. The installation of heavy curtains over windows and doors are another highly effective way of both insulating and reducing draughts, though these are normally only used at night [11].

Doors and windows in rooms without alternative means of ventilation should never be fully draught-proofed due to the risk of moisture build-up and poor air quality [43]. A simple way to circumvent over-sealing windows and doors can be to leave the top of the frames unsealed [35]. Furthermore, special care is needed in kitchens and modern bathrooms where a large amount of heat and vapour is produced.

If the draughts are a result of cracks in the plaster, or gaps between logs, these areas should be repaired if possible[5]. In log buildings the reapplication of sealant or chinking between logs can help reduce drafts through the walls. For timber framed and stone buildings cracks or gaps in the plaster should be repaired with natural materials; silicone, cement or other modern sealants should *never* be used for this [8]. Draughts through the floor can be reduced by simply placing down heavy, non-plastic, carpets or rugs. There is of course also the possibility of lifting the floor boards to replace the insulation and install permeable membranes. However, the removal of floorboards can cause irreversible damage to the boards itself, the structural integrity of the building or the moisture balance and is generally not encouraged [11].

[5] The inclusion of artwork on the plaster, which is often the case in religious stone buildings, may limit the extent of such repairs.

3.2 Windows

Traditional 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. This will significantly alter the appearance of the building and is only justified if the current windows are well beyond repair [7]. Traditional windows were made with high quality wood, in contrast to modern windows which often use composite materials or poor quality soft wood, and are therefore often repairable even if they look bad [7, 35, 44]. The glass used in traditional windows is of special interest in itself due to the irregular surface, tint and light reflection properties they hold [11]. Furthermore, new high performance windows are often expensive, meaning that repairs and smaller retrofits on existing windows offers a better return of investment in cold climates [45].

Suitable retrofits depend on the overall construction of the window and the protection/historic value of the building in question. If there are interior single pane windows, these should be properly reinstalled and refurbished if needed. The inclusion of such extra windows can lower the U-value of the windows with 50-65% or more [30, 45]. Due to this it could serve as a good, non-disruptive, retrofit for buildings in general if the internal sills can accommodate it [11, 35, 37]. 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 [30, 46]. 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 [35].

The inclusion of extra window panes on the exterior is possible and can yield similar improvements to interior ones [45]. Although this is generally advised against for strictly energy efficient reasons due to the changes to fabric needed to do it [11, 35]. There is however a special case where exterior panes can be used to serve a 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[6] showed promise in both preserving the windows and improving the climate within the churches [47].

Finally, various surface films can be applied on the windows to e.g. reduce the emissivity or increase the transmissivity. Even though these films can reduce the U-value by 20-30% they often have a visible tint which in turn reduce the transmittance of visible light [45]. This visual alteration of the glass may render such films unsuitable for use in historic buildings [45]. There are films which, according to manufacturers, do not affect the transmissivity of visual light and could therefore possibly be used in historic buildings, if the window glass and frames allow for it [48].

3.3 Insulation

Adding, upgrading or replacing insulation in the building fabric (i.e. walls, roof and floor) is a cost effective retrofit which can contribute to the overall energy performance of a building as well as the perceived indoor comfort [11, 36, 49]. There is a plethora of

[6] External window panes, either with or without ventilation between the panes, which protect the original window from pollutants, moisture and rapid temperature fluctuations.

different breathable materials suitable for use in historic buildings such as: cellulose fiber, recycled paper, hemp, hemp-lime mixture, flax, cork and sheep wool just to name a few [11, 21, 50]. There are also some modern "super-insulation" materials which, according to some studies, are promising candidates being thin, light and with good insulation performance if implemented correctly. These modern materials include: aerogel, vacuum insulated panels (VIP) and porous silica [37, 51]. In the case of VIP's they have a limited use case flexibility since they cannot be adapted on the construction site and are non-permeable (in contrast to e.g. hemp-lime, cellulose-fibre boards and aerogel) [37, 52]. There are also concerns over moisture build up within the fabric when using modern non-permeable products, as reported in [37], although some case studies have rebutted this [51, 52, 53]. The aforementioned modern insulation materials are however largely untested, especially in regards to their long-term performance, and significantly more expensive than traditional or natural ones [51].

Where the additional insulation is installed (e.g. roof, attic, floor, internally or externally on the walls) is highly dependent on the historic building in question. The attic is usually the easiest to insulate since it is out of sight, often insulated beforehand and can give an immediate return [7]. Depending on the floor and foundation structure it may be possible to add extra insulation. There is a higher risk of moisture build up within the floor (due to e.g. 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 have been employed [7, 54].

It is generally advised to place extra wall insulation on the exterior, if the conservation of the fabric allows for it, to reduce the risk of moisture build up [11, 55, 56]. 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 [35, 57]. There are however studies where a multitude of different insulation materials have been placed on the interior of walls, with little negative impact on the hygrothermal performance of the building [37, 53, 58, 59]. The aforementioned studies highlight the importance of breathable materials and measurements of moisture content within the wall and insulation preand 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 behaviour [58]. By applying extra insulation to the walls their thickness will be increased which can have a negative impact on the architectural design, primarily by deepening the window recesses and reducing the overhang of the roof (if applied externally) [35, 57]. 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 [35, 57].

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 [60]. If insulation is added to one element of the building fabric while an adjacent element is unaltered new thermal bridges can occur [11]. These new thermal bridges can lead to cold spots, thus increasing the risk for localised moisture build up within the structure and potentially lead to mould, rot or cracks [11, 56]. Furthermore, building elements with less insulation will attract relatively more moisture compared to before 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 [55, 56].

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 [11, 55].

3.4 Ventilation

Proper ventilation of a building is important both in regards to indoor air quality and to facilitate the transport of moisture from the building fabric. In many traditional and historic buildings this 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 [3, 35]. 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 [42]. 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 [7]. If the building already has designated vents or ducts these should be located, their function verified and 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 [41, 61]. By doing this in conjunction with reducing drafts, the original amount of ventilation can be restored and the energy consumption reduced.

Excessive draught proofing measures, even though beneficial from an energy efficiency point of view, can lead to too low ventilation rates [43]. Furthermore, the use of a 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[7]. 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 by control schemes [11, 61]. If the fireplace is not used at all, or out of order, the flue can either be capped off or be repurposed into a ventilation duct [11, 62, 63, 64]. Ducts from e.g. extractor fans located in kitchens and bathrooms or extra vents can be installed in the flue to provide ventilation for rooms without any other means of ventilation [62, 64]. 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 [35, 42, 64]. It may therefore be tempting to use a more modern and efficient approach to ventilation, something which can improve the energy performance of a historic building [37, 42, 63, 65].

Modern mechanical ventilation and/or heat recovery systems can closely regulate the temperature, air quality and moisture content within the building. In order to do this the systems require the building to be well sealed and have a well-insulated building fabric [37, 64, 66]. Even if a historic building is well sealed and show 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 [41, 43]. The difficulty stems from the fact that most traditional residential 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

[7] During summer time when buildings are not heated the windows and/or door openings s are used to increase ventilation rates [61].

the appearance of the interior can be challenging [37, 63]. Furthermore, ventilation systems can generate unwanted levels of noise if placed within the building and also be costly investments [37, 67].

Mechanical ventilation can be relatively more easily implemented in larger historic buildings such as churches, museums or palaces since there is more available space [63, 64, 68]. This extra space can make it easier to place, and hide, ventilation systems and ducting within the structure. These buildings are often unoccupied for most of the year and ventilation systems can therefore be focused more on conservation and reduction in humidity than on human comfort [68]. Conservation ventilation and heating is already well documented in the literature and will not be discussed in this review (see e.g. [68-73] for examples).

3.5 Heating

Most traditional buildings, dependent on age and location, originally used fire 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 [40]. This means that most existing heating system, plumbing and electrical installations are not original fixtures and there may therefore have some flexibility in upgrading them [40]. Many existing buildings have a waterborne heating system with some sort of boiler. By replacing the existing boiler with a higher efficiency one and insulating the pipes can result in energy savings in the range of 20-30% depending on the original boiler, can be achieved [7, 35, 74]. The replacement can also reduce GHG-emissions if a fossil fuel based boiler is changed to one using biofuels. However particulate emissions can be up to 30 times higher while using wood over oil [74, 75]. 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 room and the old flue for the boiler can be used for ventilation purposes [35]. 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 [35].

The main constraints of a GTHP is the potential lack of space (which should not be an issue if there is already a boiler present) and the achievable supply temperatures [76]. Older waterborne heating systems generally require a supply temperature of about 80˚C to operate as designed [35, 76]. In contrasts, most GTHP’s 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 [7, 76]. In order to maintain a high COP it may be required to replace the entire heating system, something which is costly and my alter the historical significance of the building [76, 77]. Instead of a replacement, there is the possibility to retrofit fans behind the existing radiators, dependent on the specific system in question, thus increasing the convective heat transfer and converting the entire system into a low temperature one [76].

If the building is without any waterborne system air-to-air heat pumps may be an alternative to reduce energy [14, 77]. Since these pumps rely on the exterior air temperature their COP is variable and a back-up heating system may be required on cold days [77]. 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 [14, 77].

As mentioned earlier, most traditional buildings 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, very inefficient at around 15-20% efficiency [7, 77]. There are a multitude of more efficient wood stoves, 70-80% efficiency in some cases, which produce significantly less emissions due to higher burn temperatures or catalysts [78]. 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 [79]. 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 [35].

A potential way of decreasing the GHG-emissions from a historic building is the use of renewable energy sources such as solar collectors, for heating water, or photovoltaic (PV) solar panels which generate electricity [24, 80]. Solar thermal panels have the potential of delivering up to 70% of domestic water needs in a Northern European climate [8] and reducing emissions with up to 75% in some cases [7, 81, 82, 83]. Furthermore, these systems can be coupled with waterborne heating systems to supplement boilers or heat pumps thus contributing to reduce GHG-emissions [7, 35]. The installation of solar collector and PV-panels in historic buildings is however usually very difficult [14, 77]. Reasons for this include a potential lack of space, the need to route new pipes or cables (thus potentially harming the fabric) and the negative visual impact such installations can have on the building itself [14, 35, 43, 77]. 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 ground work and may disturb the area around the building (which might also be protected) [14, 35, 66]. There are however 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 coloured PV-panels (to better blend in with e.g. the facade) and PV-windows (integrated PV-cells within the window pane) [14, 24, 35, 66, 77]. Such installations can further reduce the negative visual impact PV-technology can have on historic buildings giving more flexibility to energy efficiency measures [24].

Since the lifespan of a 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 [77]. Ultimately it will come down to a judgement call on a case-by-case basis weighing the historic aspects of the building against sustainability values [84].

3.6 Behavioural aspects

Technical and physical improvements are, as discussed above, the usual way to achieve higher levels of energy efficiency in buildings. There can however be significant differences between actual energy consumption and theoretical/simulated

[8] The exact number is variable and depends on a multitude of different factors such as water usage, size of installation and location [82].

[49]. This is often attributed to differences in occupant behaviour and can swing both ways, a Norwegian study found that energy use was almost 50% less than modelled [85]. In order to improve the accuracy of simulations, and to find the most effective physical retrofits, there is a need for more empirical data specifically for occupant behaviour in historic buildings [86]. General occupant-based energy saving measures in historic buildings are the same in almost all buildings, but the degree to which these are done may differ [86]. Simple measures such as using less hot water, opening windows less frequently, adjusting thermostats during the course of the day or leaving certain areas colder can all contribute to lower the energy consumption of a building [49, 86]. Leaving certain areas of the building cooler than others is often referred to as "zoneheating" and can be easily achieved by actively closing doors or using thick curtains in doorways between rooms with different temperature settings [7, 35, 86].

User behaviour can also change after an energy efficiency retrofit (often referred to as a rebound behavioural effect), leading to an increase in energy consumption rather than a decrease [49]. It is therefore very important to properly inform occupants how any new systems should be utilised and what savings they can expect [7, 86]. A procedural approach on how this can be achieved in conjunction with the EN 16883:2017 standard is provided in [86]. The project "Low-Energy Apartment Futures (LEAF) from the EEC further highlights the importance of user participation via surveys before, during and after projects [87]. Their findings suggest that these surveys improved both the retrofitting decision making process as well as being able to identify the user profiles in the buildings, thus allowing for more accurate theoretical savings via simulation.

Acknowledgment

This work has been carried out as part of the “Energy pathfinder” project supported by Northern Periphery and Arctic program (NPAP) and the authors gratefully acknowledge the financial support from NPAP.

References

[1] Merriam-Webster, *historic*, Available: https://www.merriam-webster.com/dictionary/historic. [Accessed: 7 July 2020]

[2] L. Mazzarella, *Energy retrofit of historic and existing buildings. The legislative and regulatory point of view*, Energy and Buildings no.95 pp 23-31, 2015.

[3] A.L. Webb, *Energy retrofits in historic and traditional buildings: A review of problems and methods*, Renewable and Sustainable Energy Reviews no.77 pp 748-756, 2017.

[4] UK Department for Digital, Culture, Media & Sport, November 2018, *Principles of Selection for Listed Buildings*.

[5] Swedish National Heritage Board, *Historic Environment Act (1988:950)*, Available:https://www.raa.se/in-english/cultural-heritage/ historic-environment-laws/historic-environment-act-1988950/.

[6] I. McCaig, R. Pender, D. Pickles, *Energy Efficiency and Historic Buildings: How to Improve Energy Efficiency*, Historic England, 2018.

[7] Irish Georgian Society, 2013. *Energy Efficiency in Historic Houses, Proceedings produced from ten regional seminars held during 2009 & 2010.*

[8] English Heritage, February 2010, *Energy Efficiency in Historic Buildings-Insulating timber-framed walls*, Journal of Cultural Heritage no.14 pp.527-536, 2013.
[9] T. Broström, G. Lejonhufvud, 2008, *Heat pumps for conservation heating*, Available:https://www.researchgate.net/publication/237732716_Heat_pumps_for_ conservation_heating.
[10] P. Johansson, P. Wahlgren, *Renovation of buildings from before 1945: status assessment and energy efficiency measures*, Energy Procedia 132, pp.951-956, 2017.
[11] English Heritage, *Energy efficiency and historic buildings – application of part L of the building regulations to historic and traditionally constructed buildings*, London, English Heritage, November 2010.
[12] K. Kass, A. Blumberga, D. Blumberga, G. Zogla, A. Kamenders, E. Kamendere, *Pre-assessment method for historic building stock renovation evaluation*, Energy Procedia, no.113, pp. 346-353, 2017.
[13] European standard 16883:2017, *Conservation of cultural heritage. Guidelines for improving the energy performance of historic buildings*.
[14] L.F. Cabeza, A. de Gracia, A.L. Pisello, *Integration of renewable technologies in historical and heritage buildings: A review*, Energy & Buildings no. 177,pp. 96–111, 2018.
[15] M. Rispoli, S. Organ, *The drivers and challenges of improving the energy efficiency performance of listed pre-1919 housing*, International Journal of Building Pathology and Adaptation, 37(3), pp. 288-305, 2019.
[16] H. Norrström, M. Edén, *Energy Efficiency and Preservation in our Cultural Heritage in Halland, Sweden*, Heritage 2010: Heritage and Sustainable Development, Vol. 1–2. 2nd International Conference on Heritage and Sustainable Development, Evora, Portugal, 22–26 June, pp. 589–99.
[17] J. Zagorskas et.al., *Thermal insulation alternatives of historic brick buildings in Baltic Sea Region*, Energy & Buildings no.78, pp.35-42, 2014.
[18] G.B.A. Coelho, H.E. Silva, F.M.A. Henriques, *Calibrated hygrothermal simulation models for historical buildings*, Building and Environment no.142, pp.439–450, 2018.
[19] R. Walker, S. Pavía, *Thermal performance of a selection of insulation materials suitable for historic buildings*, Building and Environment 94, pp. 155-165, 2015.
[20] Ü. Alev et. al, *Renovation alternatives to improve energy performance of historic rural houses in the Baltic Sea region*, Energy and Buildings no.77 pp 58-66, 2014.
[21] C.J. Whitman, O. Prizeman, J. Gwilliam, A. Shea, P. Walker, *Energy Retrofit Infill Panels for Historic Timber-Framed Buildings in the UK: Physical test panel monitoring versus hygrothermal simulation*, Architectural Science Review, 2020.
[22] E. Arumägi, *Renovation of Historic Wooden Apartment Buildings*, Doctoral thesis, Tallinn University of Technology, 2015.
[23] S. Dubois, M. de Bouw, Y. Vanhellemont, D. Stiernon and S. Trachte, *Combining multi-view photogrammetry and wireless sensor networks when modelling the hygrothermal behaviour of heritage buildings*, Conference Report: The 3rd International Conference on Energy Efficiency in Historic Buildings, September, 2018.
[24] C.S. Polo López, F. Frontini, *Energy efficiency and renewable solar energy integration in heritage historic buildings*, Energy Procedia, no.48, pp. 1493–1502, 2014.

[25] K. Fouseki, M. Cassar, *Editorial: Energy Efficiency in Heritage Buildings — Future Challenges and Research Needs*, The Historic Environment, Vol. 5 No. 2, pp. 95–100 2014.
[26] G.Ficco et.al, *U-value in situ measurement for energy diagnosis of existing buildings*, Energy and Buildings 104,pp. 108–121, 2015.
[27] Ü. Alev et. al, *Indoor hygrothermal condition and user satisfaction in naturally ventilated historic houses in temperate humid continental climate around the Baltic Sea*, Architectural Science Review, 2015.
[28] P. Delhaye, *The approach of the Walloon Heritage Agency on the energy upgrade of listed buildings*, Conference Report: The 3rd International Conference on Energy Efficiency in Historic Buildings, September, 2018.
[29] F. Haas, D. Herrera, W. Hüttler, D. Exner, A. Troi, *Historic Building Atlas-Sharing best practices to close the gap between research & practice*, Conference Report: The 3rd International Conference on Energy Efficiency in Historic Buildings, September, 2018.
[30] N. Ginks, B. Painter, *Energy retrofit interventions in historic buildings: Exploring guidance and attitudes of conservation professionals to slim double glazing in the UK*, Energy and Buildings no. 149, pp. 391–399, 2017.
[31] AiCARR, 2014, *Energy Efficiency in Historic Buildings*, Available: http: //www.aicarr.org/Pages/EN/Resources%20and%20Publications/Energy%20efficiency%20in%20historic%20buildings%20guide3.aspx.
[32] P. Femenías, P. Eriksson, L. Thuvander, K. Mörk, P. Wahlgren, P. Johansson, *Value creation by re-renovation - Focus on the user perspective*, Conference Report: The 3rd International Conference on Energy Efficiency in Historic Buildings, September, 2018.
[33] M. Sunikka-Blank, R. Galvin, *Irrational homeowners? How aesthetics and heritage values influence thermal retrofit decisions in the United Kingdom*, Energy Research & Social Science no. 11, pp. 97–108, 2016.
[34] Riksantikvarieämbetet (eng. Swedish Heritage Board), *Räkna med kulturarvet: Kulturarvets bidrag till en hållbar samhällsutveckling. (eng. Count on the cultural heritage: the contribution of the cultural heritage to a sustainable development of sociecty.)*, Karlskrona, Sweden, 2017.
[35] F. Ståhl, M. Lundh, P. Ylmén, *Hållbar och varsam renovering och energieffektivisering av kulturhistoriskt värdefulla byggnader (eng. Sustainable and Careful Renovation and Energy Effeciency improvements of historic buildings*, SP Sveriges Tekniska Forskningsinstitut (eng. RISE), Borås, 2011.
[36] E. Arumägi,T. Kalamees, *Analysis of energy economic renovation for historic wooden apartment buildings in cold climates*, Applied Energy no.115, pp.540-548, 2014.
[37] M. Morelli, et.al, *Energy retrofitting of a typical old Danish multi-family building to a "nearly-zero" energy building based on experiences from a test apartment*, Energy and Buildings no.54, pp.395-406, 2012.
[38] E.J. de Place Hansen, K.B. Wittchen, *Energy savings due to internal façade insulation in historic buildings*, Conference Report: The 3rd International Conference on Energy Efficiency in Historic Buildings, September, 2018.
[39] E. Héberlé, J. Burgholzer, *Guidance for finding a sustainable balance between energy efficiency, comfort, moisture damage and cultural heritage value in historic buildings*, Energy Efficiency and Comfort of Historic Buildings, 2nd International Conference Proceedings, Brussels, October 2016.

[40] J. Donnelly, *Energy Efficiency in Traditional Buildings Recent Developments in Ireland*
[41] Historic England, *Energy Efficiency and Historic Buildings-Draught-proofing Windows and Doors*, Historic England, April 2016.
[42] Û. Alev et.al., *Air tightness, Air Exchange and Energy Performance in Historic Residential Buildings with Different Structures*, International Journal of Ventilation, ISSN 1473-331,5 Vol.14 No.1, 2015.
[43] The Department of the Environment, Heritage and Local Government, *Energy Efficiency in Traditional Buildings*, Stationery Office of Ireland, 2010.
[44] Allt om Torp (eng. Everything about homesteads), *Om Gamla Fönster (eng. About old windows)*, Available: http://alltomtorp.se/ta-hand-om-ditt-hus/fonster/ om-gamla-fonster/. [Accessed: 9 July 2020]
[45] National Trust for Historic Preservation, *Saving Window, Saving Money:Evaluating the Energy Performance of Window Retrofit and Replacement.*, Preservation Green Lab, 2012.
[46] N. Heath, P. Baker, Dr. G. Menzies, *Historic Scotland Technical Paper 9*, Historic Scotland, September 2010.
[47] A. Bernardi et.al., *Conservation of stained glass windows with protective glazing: Main results from the European VIDRIO research programme*, Journal of Cultural Heritage no.14 pp.527-536, 2013.
[48] Réflective, *Clear solar protection*, Available: https://www.reflectiv.com/ product/heat-resistant/. [Accessed: 28 July 2020].
[49] H. Ben, K. Steemers, *Energy retrofit and occupant behaviour in protected housing: A casestudy of the Brunswick Centre in London*, Energy and Buildings no.80, pp.120–130, 2014.
[50] P. Strandberg-de Bruijn, A. Donnarelli, K. Balksten, *Full-scale Studies of Improving Energy Performance by Renovating Historic Swedish Timber Buildings with Hemplime*, Applied Sciences, 18 June 2019.
[51] P. Johansson, B. Adi-Zarrabi, *Super insulation materials in the building sector: Field studies and future challenges*, 7th International Building Physics Conference, IBPC 2018 At: Syracuse, NY, USA, September 2018.
[52] P. Johansson, A. Donarelli and P. Strandberg, *Performance of insulation materials for historic buildings-Case studies comparing a super insulation material and hemplime*, Conference Report: The 3rd International Conference on Energy Efficiency in Historic Buildings, September, 2018.
[53] M. Krus, R. Kilian, B. Pfundstein, *Comparison of different systems for internal wall insulation with reversible application for historic buildings*, Energy Efficiency and Comfort of Historic Buildings, 2nd International Conference Proceedings, Brussels, October 2016
[54] English Heritage, 2010, *Energy Efficiency in Historic Buildings-Insulation of suspended timber floors*.
[55] English Heritage, 2010, *Energy Efficiency in Historic Buildings-Insulating Solid Walls*.
[56] English Heritage, 2010, *Energy Efficiency in Historic Buildings-Insulating timber framed walls*
[57] T. Örn, *Energy Efficiency in Heritage Buildings- Conservation Approaches and Their Impact on Energy Efficiency Measures*, Licentiate thesis, Luleå University of Technology, 2018.
[58] R. Curtis, *Energy efficiency in traditional and historic buildings: keeping it simple*, Energy Efficiency and Comfort of Historic Buildings, 2nd International Conference Proceedings, Brussels, October 2016.

[59] N.R.M. Sakiyama, J. Frick, H. Garrecht, *Cultural heritage compatible insulation plaster- Analysis and assessment by hygrothermal simulations*, Conference Report: The 3rd International Conference on Energy Efficiency in Historic Buildings, September, 2018.
[60] T. Kalamees, E. Arumägi, Ü. Alev, *Performance of interiorly insulated log wall - Experiences from Estonian cold climate conditions*, Conference Report: The 3rd International Conference on Energy Efficiency in Historic Buildings, September, 2018.
[61] National Property Board Sweden, Stockholm, 2009, *Ventilation in historic buildings*.
[62] English Heritage, 2010, *Energy Efficiency in Historic Buildings-Open fires, chimneys and flues*.
[63] A.A. Hamid, D. Johansson, H. Bagge, *Ventilation measures for heritage office buildings in temperate climate for improvement of energy performance and IEQ*, Energy & Buildings vol.211, 109822, 2020.
[64] P.K. Larsen, T. Broström, 2015, *Climate Control in Historic Buildings*.
[65] S.P. Bjarløv, P. Vladykova, *The potential and need for energy saving in standard family detached and semi-detached wooden houses in arctic Greenland*, Building and Environment no. 46, pp. 1525-1536, 2011.
[66] O.K. Akande, D. Odeleye, A. Coday, *Energy Efficiency for Sustainable Reuse of Public Heritage Buildings: The Case for Research*, International Journal of Sustainable Development and Planning, Vol. 9, No. 2 ,pp. 237–250, 2014.
[67] J. Zemetis, A. Borodinecs, T. Kalamees, 2019, *Analysis of Various Ventilation Solutions for Residential and Non-residential Buildings in Latvia and Estonia: Sustainable Buildings in Cold Climates*.
[68] M. Wessberg, *Design and analysis of energy efficient indoor climate control methods for historic buildings* Doctoral thesis, Czech Technical University in Prague, 2018.
[69] A. Hayati, J. Akander, M. Mattsson, *Simulation of Ventilation Rates and Heat Losses during Airing in Large Single Zone Buildings in Cold Climates*, Cold Climate HVAC 2018, The 9th International Cold Climate Conference, Sustainable new and renovated buildings in cold climates, Kiruna, Sweden, 12-15 March 2018.
[70] *Developments in Climate Control of Historic Buildings*, Proceedings from the international conference "Climatization of Historic Buildings, State of the Art", December, 2010.
[71] M. Legnér, A. Luciani, *The historical indoor climate: A long-term approach to conservation environments within heritage buildings.*, M. Boriani, R. Gabaglio and D. Gulotta (ed.), Online Proceedings of the Conference: Built Heritage 2013, Monitoring Conservation and Management; Milan, Italy (pp. 1321-1328), 2013.
[72] G. Leijonhufvud, A. Henning, *Rethinking indoor climate control in historic buildings: The importance of negotiated priorities and discursive hegemony at a Swedish museum*, Energy Research & Social Science, no. 4, pp. 117–123, 2014.
[73] T. Broström, G. Leijonhufvud, *Heat pumps for conservation heating*, Proceedings of the 8th symposium on building physics in the Nordic countries: Copenhagen, Technical university of Denmark, pp. 1143-1150, 2008.
[74] J. Ritson, *Benign changes and building maintenance as a sustainable strategy for refurbishment of historic (Pre-1919) English dwellings*, Conference Report: The 3rd International Conference on Energy Efficiency in Historic Buildings, September, 2018.

[75] L. Rectora, P. J. Millera, S. Snook, M. Ahmadia, *Comparative emissions characterization of a small-scale wood chip-fired boiler and an oil-fired boiler in a school setting*, Biomass and Bioenergy vol.107, pp.254–260, 2017.
[76] GEO4CIVHIC, 2018, *D1.1 Report on different kind of barriers for shallow geothermal in deep renovation*.
[77] Changeworks, 2009, *Renewable Heritage - A guide to microgeneration in traditional and historic homes*.
[78] DRU, *What is the efficiency and capacity of a wood burning fire or stove?*, Available: https://www.drufire. com/en-gb/essential-info/wood-burning-stoves-and-fires/ efficiency-and-capacity-wood-burning-fire. [Accessed: 23 July 2020]
[79] V. Lenza, D. Büchnera, K. Wurdingera, *Evaluation of combining an air-to-water heat pump with a wood stove with water jacket for residential heating*, 12th IEA Heat Pump Conference, 2017.
[80] F. Moran, T. Blight, S. Natarajan, A. Shea, *The use of Passive House Planning Package to reduce energy use and CO2 emissions in historic dwellings*, Energy and Buildings 75, pp. 216–227, 2014.
[81] N.S. Brito, *Mismatch, exclusion and inclusion: threats / opportunities for historic buildings in the current energy efficiency paradigm*, Energy Efficiency and Comfort of Historic Buildings, 2nd International Conference Proceedings, Brussels, October 2016.
[82] G. Faninger, *The Potential of Solar Thermal Technologies in a Sustainable Energy Future*, IEA solar heating & cooling programme, 2010.
[83] AEE - Institute for Sustainable Technologies, Vienna University of Technology, *Potential of Solar Thermal in Europe*.
[84] T. Broström, K. Svahnström, *Solar energy and cultural-heritage values*, World Renewable Energy Congress, 2011.
[85] F. Berg, M. Fuglseth, *Life cycle assessment and historic buildings: energy-efficiency refurbishment versus new construction in Norway*, Journal of Architectural Conservation, vol.24, no.2, pp. 152-167, 2018.
[86] F. Berga, A. Flyen, Å. Lund Godbolt, T. Broström, *User-driven energy efficiency in historic buildings: A review*, Journal of Cultural Heritage 28, pp. 188–195, 2017.
[87] Changeworks, 2016, *Improving the energy efficiency of apartment blocks- Low Energy Apartment Futures (LEAF)-Final Report*.