ReFoMo

Reduced Footprints of Monumental structures, landscapes and buildings

Review on techniques, tools and best practices for energy efficient retrofitting of heritage buildings.

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Climate-KIC

Climate KIC pathfinder project

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Published in June 2015 by Copernicus Institute of Sustainable Development, Utrecht University.

ACKNWOLEDGMENTS

The Copernicus Institute for Sustainable Development would like to give a very special acknowledgement to Paul Brouns (ARCADIS). His insight and knowledge regarding heating and ventilation systems was instrumental to the integrity of this report.

Finally, the Copernicus Institute for Sustainable Development would like to thank Sara Lúcia Gonçalves de Almeida for the permission to use part of her Master thesis “Retrofitting and refurbishment process of heritage buildings: application to three case studies” as a basis for writing this report.

Contents

1 INTRODUCTION

1.1 Research background

The cultural heritage sector is among the most important European attractors and economic drivers. It generates millions of jobs and is essential to the three economic sectors which contribute most to EU GDP; the Cultural and Creative industries, the Real Estate activities and the Tourism industry (Nypan, 2009). Heritage buildings reflect both the unique character and identity of European cities but include essential infrastructure for housing or public buildings. These buildings were constructed without much energy efficiency interests and show high energy consumption levels. For example the heating energy demand of a building built after 1990 is around 40 kWh/m^2 while buildings built before 1930 demand 170 kWh/m^2 (Balaras, 2004). Hence, improving energy efficiency in cultural heritage buildings will contribute to a growing economy. However, their energy performance and conservation must be studied with the thought of keeping their material and immaterial values. According to the Energy Efficiency Directive (EED, 2012/27/EU) adopted in October 2012, member States shall establish a long term strategy for mobilising investment in the renovation of national stock of residential and commercial buildings, both public and private. Furthermore the Directive includes a requirement to develop long term renovation strategies for national building stocks such as to renovate 3% of total floor area per year.

1.2 Problem definition

ReFoMo is a European project which believes that sustainable energy renovation of buildings can have economical, societal and environmental benefits. ReFoMo was carried out during 2014. The outcomes of the project are in the form of three reports: i) Review on techniques for energy efficient retrofitting of heritage buildings, ii) Energy efficient retrofitting in practice. Challenges and opportunities of 3 heritage buildings in Europe, and iii) A bright future for heritage buildings. How to promote energy efficient retrofitting measures?. The present report (the first one), presents an up to date review concerning the techniques and tools available in order to face the challenge of energy efficient retrofitting of a heritage building. The document is organized as follows. Section 1 briefly introduces the context of the ReFoMo project. Section 2, presents an overview of the main theoretical concepts needed to understand the energy efficient retrofitting of heritage buildings. Finally, section 3 discusses the main findings. The document is accompanied by appendices for the reader that desires to have an in depth theoretical knowledge. It also suggests further readings.

Heritage buildings present a low energy efficiency. Therefore their consequent retrofitting has a large potential. Although it is acknowledged that each heritage building is unique and therefore it needs customized energy solutions, this research aimed at finding which standards and tools can be considered universal. Hence, this report gives answer to the following research question:

How to improve the energy performance of heritage buildings?

To answer the main research question, the following sub-questions were formulated:

- Which diagnostic and monitoring tools are available to evaluate the energy performance of heritage buildings?
- What energy efficient retrofitting techniques are available for heritage buildings?

2 HERITAGE BUILDINGS

It is vital to understand that historic buildings are a finite resource and that in their existence there is not only embodied energy[1] and carbon but the spirit and identity of a country. Likewise in the drive towards sustainable design it should be ensured that local distinctiveness and character is retained. Care must be taken to achieve a balance between work to bring an old building up to modern performance standards and sustainability requirements (Godwin, 2011). A building of historic interest generally shows examples of design, building techniques or materials that inform contemporary and prospect developments. One of the most important thought in terms of building conservation is to retain the original fabric, when it still exists, and character of historic buildings. Optimising the existing historic building energy performance of heritage buildings may assist in achieving energy efficiencies and broader sustainability objectives. Nineteenth and some early twentieth century masonry buildings, for example, have very different functional characteristics than more modern buildings with their contemporary moisture barriers, damp-proof courses, membranes, cavity walls and insulation (Heritage Council of Victoria, 2009).

One of the most different functional characteristics between heritage and modern buildings is their ability to breath[2]. Modern buildings often require mechanical ventilation. On the other hand, heritage buildings of masonry construction or buildings with timber floors were designed to allow natural ventilation to reduce dampness. These features make them more porous and naturally ventilated, so they breathe more. They generally include soft and permeable materials that respond to air and moisture very differently to many of the hard impermeable materials used in modern buildings. The ventilation of historic buildings makes them less predisposed to condensation and its associated effects (Change Works, 2008).

Figure 1 shows moisture, air movement and thermal performance of a historic building (a) and of a modern building (b). Historic buildings present more sources of heat transfer through porous and permeable walls, ventilation through open flue and open fire and also from below floor. There are heat losses due to fabric characteristics and limited solar gain caused by small openings and massive walls. Modern buildings show a sealed envelope which reduces air infiltration and moisture from ground, creates vapour barriers and limits heat loss. Additionally solar gain increases within well-insulated fabric. Over-sealing historic buildings can cause considerable problems in terms of condensation and other associated problems. In addition, in rooms where there is a gas or solid fuel burning appliance, it is crucial to have adequate ventilation as a safety requirement (Change Works, 2008). Following the need to breathe that historic buildings have, they can often be draughty and leak heat. Larger window sizes and predominance of sash and case windows provide a greater area of low-efficiency glazing and more potential for draughts (Change Works, 2008).

[1] Embodied energy is the energy consumed by all of the processes associated with the production of a building. This includes the mining and manufacturing of materials and equipment, transportation of materials and administrative functions (Heritage Council of Victoria, 2009).

[2] Breathing refers to the ability of historic buildings to control moisture within the building fabric to evaporate freely away and potential long-term decay problems. It also enables provision of high quality indoor environments and uses less energy (English Heritage, 2012).

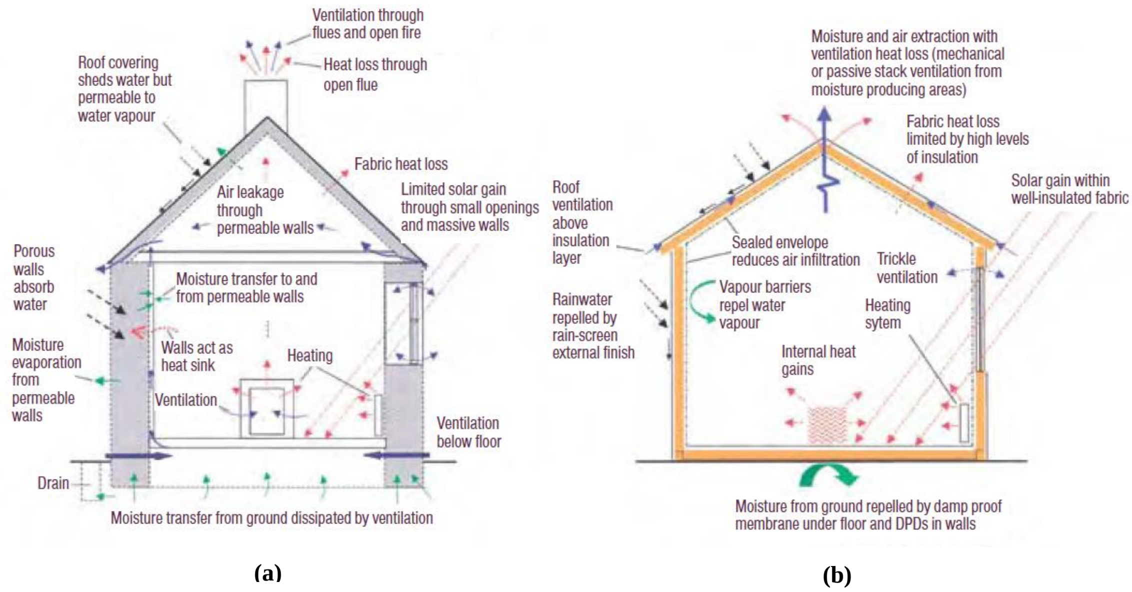

Figure 1 - Historic (a) and modern (b) buildings functioning (source: Change Works, 2008)

Historic buildings often have larger rooms with higher ceilings, which need more energy to keep them warm. Without proper insulation, internal heat gains are easier to leak. Many older building components have lower levels of thermal efficiency and heating systems tend to use more energy generating less heat when compared to modern materials and systems (Change Works, 2008). These buildings also perform differently from a thermal point of view in comparison with modern buildings. Heritage buildings traditionally built of masonry and stone are described as being thermally heavy or having high thermal mass due to massive and thick walls. In other words, these buildings present the ability to absorb heat in high temperatures and release it when temperatures fall (Godwin, 2011). These values allow for relatively easy identification of areas most prone to heat loss. Traditional buildings in the UK and Europe, due to their heavy thermal mass can stay cooler due to their construction and being thermally heavy. This effect might be useful for night ventilation in regions with hot summer climate. On the other hand, in case of temporary use of the building during the heating season, high thermal inertia is counterproductive for fast heating of the rooms. Internal insulation decouples the thermal capacity of the wall from the room air, which is good in terms of temporary use, but counterproductive in terms of night ventilation cooling (Rainer & Baldracchi, 2011).

With appropriate modification, properly managed traditional built structures will last and play an important part in the conservation of energy and control over carbon emissions both now and in the future. So by keeping existing structures and buildings a contribution and a reduction in energy use is already achieved. Accordingly to Godwin (2011), by retaining and re-using original materials wherever these are available and making use of the embodied energy of those materials rather than wasting it is a substantial contribution to the goal of achieving sustainable development. The growing perception that old historic buildings are often cheaper to convert to new uses than to demolish and rebuild is one of the reasons for the interest in adaptation and furthermore their retrofitting (Bullen, 2007). Giving a new use to historic buildings will minimise the consumption of greenhouse gases and energy used in demolition.

Additionally heritage buildings - when retrofitted - will provide more comfort, a reduction of primary energy demand and therefore an improvement of energy efficiency.

2.1 Retrofitting of Heritage Buildings

Heritage buildings are under a significant pressure to reduce carbon emissions. This revolves around energy conservation and efficiency of buildings. These buildings require retrofitting processes and the challenge is how to achieve it without damaging the intrinsic architectural or historic character and significance of a building and structure. Therefore a balance between making alterations to improve efficiency and safeguarding the special architectural and historic interest of a building needs to be taking into account (Godwin, 2011). Otherwise lasting damage could be inflicted and its significance diminished. Because of its many constraints and limitations, energy efficient retrofitting of heritage buildings (henceforth: EERHB) is an interdisciplinary process where several actors need to be involved. The goal of the project and its targets together with the financial budget define the scope of the retrofit project which is then influenced by the building specific characteristics (e.g. location and orientation. These factors altogether influence the type and extension of the project to implement, making of each retrofitting project a unique and complex optimization problem. Figure 2 depicts the different phases of an EERHB project.

EERHB is similar to a new construction process since it also involves: project definition, design, construction, commissioning and occupancy. The main difference consists in the project definition phase which requires a complete and comprehensive documentation of the existing building conditions. Once the scope of the retrofit project is defined and the extension and type of the retrofit project are determined. Energy auditing is required to set an energy profile (and a baseline) for the specific building to be retrofitted. According to the current state of the building and taking into account that it is also limited by the goals, targets and financial budget, there is a range of suitable technologies that could be employed. Here, the decision making takes place. The aim of this phase is to identify the definitive retrofit options to implement. This phase includes the use of energy models, economic analysis tools and risk assessment methods in order to assess the performance of the retrofit options in the building to retrofit. The quantitative assessment of money and energy savings enables to choose the suitable and cost-effective options. This phase recquires an honest and fluent commuinciation among all the actors involved in the retrofitting process.

After the retrofit measures are selected, the next phase is to implement the retrofit project. The implementation of the measures should be complemented with test and commissioning to ensure the building and its services systems operate in an optimal manner. The last phase consists in verifying the energy savings achieved using measurement and verification methods. A post occupancy survey is also important to ensure the satisfaction of the occupants of the building with the retrofit project (Ma et al., 2012). Building energy management and control system (EMCS) may also be implemented in order to allow the monitoring and controlling of the operation of the building services systems and ensure that thermal comfort and energy efficiency is maintained.

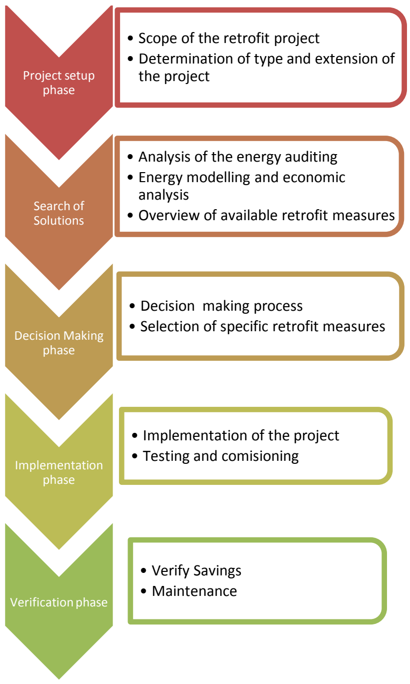

Figure 2 - Key phases of a retrofit project. (Source: Adapted from Mestre, 2014).

2.2 Energy performance evaluations of heritage buildings

In order to improve the energy performance of a building, any retrofit intervention should address some fundamental aspects concerning energy use in the operation of a building. To understand the energy improvements due to retrofitting, this research uses the approach of the *Trias Energica,* developed by Lysen (1996). Applied to the buildings sector, this approach involves achieving energy efficiency, the use of renewable energy sources and the clean use of fossil fuels. Thus, the strategy proposed in this research to reduce the energy use in building operation is to focus the retrofit actions first on reducing the energy demand and carbon emissions and second on transforming the energy supply side in an efficient and low or zero carbon energy supply. The energy demand side includes all the energy that the building requires to operate. This reflects the energy needed for heating and cooling, the energy required for lighting and for equipment and appliances. The energy supply side refers to the energy delivered to the building. It reflects the energy delivered through the grid in different forms (electricity, gas and/or heat).

2.2.1 Energy auditing in heritage buildings

An energy audit is fundamental to: i) assess the current building energy performance, ii) understand the energy use of the building and iii) identify the areas with the largest potential for energy savings. We build on the work of Butala & Novak (1998), to suggest three key elements where energy efficient retrofitting can be implemented in heritage buildings. These are building envelope, electrical appliances and heating and ventilation systems, and organisational measures.

- The first key element is building envelope. Building envelope is defined as the parts of a building that form the primary thermal barrier between interior and exterior, also known as the building shell, fabric or enclosure. The energy performance of building envelope components including external walls, floors, roofs, windows and doors, is critical in determining levels of comfort, natural lighting and ventilations, and how much energy is required to heat and cool a building (IEA, 2013). The building envelope has strict rules about what can be altered. As an example, in Hungary, external insulation is unauthorized in buildings listed as heritage by the National Office for Cultural Heritage (Alexa et al., 2014). This is the particularity and challenge of working with heritage buildings: energy performance must be improved and, at the same time, the inheritance and culture must be preserved.
- Electrical appliances, heating and ventilation and lighting systems refer to what consumes energy inside the building. Energy saving lighting and low consumption electrical appliances will improve energy efficiency of a building. Heating systems without or with deficient automatic regulation and not zoned are a cause for high energy consumption levels. Additionally, boilers that are old, systems that are often unbalanced and heaters without thermostatic valves promote low energy efficiency.
- The third key element refers to organisational measures. Improving energy efficiency and reducing carbon emissions from buildings is not only about heating and insulation of the building fabric. This concept deals with behavioural/systemic aspects. It also refers to energy use management and maintenance of heritage buildings. In this report, we refer exclusively to maintenance aspects of heritage buildings. Rosales Carreón (2015a) addresses the relevant systemic barriers that played a role in impeding EERHB within ReFoMo. Behavioural aspects usually refer to possible interventions while using the building. ReFoMo focuses mainly in technological aspects but we acknowledge that behavioural aspects play a key role in order to diminish the impact due to energy consumption in buildings.

There are common steps to energy auditing in any type of building. These are: i) Data analysis; ii) On-site survey; iii) Evaluation of energy conservation opportunities; and iv) Recommendations. We suggest that at each step the three key elements to improve energy performance in heritage buildings are audited. In the first phase energy bills should be analysed along with the occupation/function of the building and building structure, but also an inventory of electrical appliances and heating systems. The topic of organisational measures may not be applicable depending on the case as buildings may not present any conservation plan at the time of the audit. At the end of phase 1, the auditor will be ready to schedule an on-site survey. During phase 2 an *in situ* examination should be done. The fact of being on site allows the auditor to witness the status of the building looking at every element of the building envelope and energy systems. In phase 3, the aim of this layout is to clearly divide where to look for energy conservation opportunities through techniques that evaluate the energy performance. Therefore, opportunities will be found to improve the energy efficiency through building envelope, electrical appliances and heating systems and organisational measures. Once this line of the table is complete, the auditor already knows which recommendations to put forward.

2.2.2 Diagnostic and monitoring tools to evaluate energy performance of heritage buildings

Energy auditing assumes a simple energy balance within a building: what comes in equals what goes out (CIPEC, 2011). Figure 3 illustrates this mathematical expression. Energy can leave through a certain area, resulting in energy losses for the building (heat loss, exhaustion, ventilation). As a consequence, energy balances can only be prepared for restricted areas with boundaries defined. The envelope of a building is what defines the boundaries.

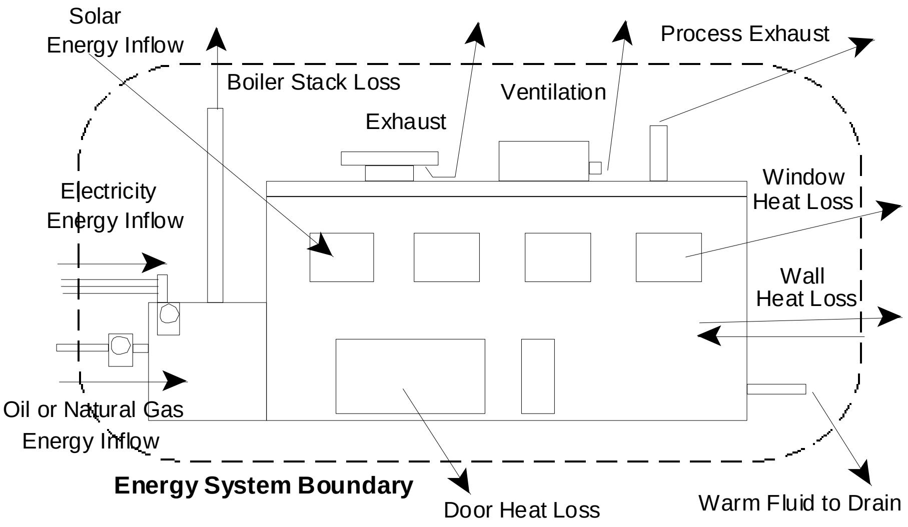

Figure 3 - Energy transfer in a system (source: CIPEC, 2011)

Measuring energy flows into and out of a building involves collecting energy flow data from various sources using different tools and techniques. These techniques and tools can be suitable in any kind of building. Air leakage test helps finding the source of draughts and infrared thermography enables to see where energy is leaking out of the building. Other testing and analysis includes heat flux measurement which compares the in-situ “U” value results to the “U” values calculated from published data and co-heating test which measures the energy efficiency of a building. Table 1 shows a summary on these techniques and tools, giving also a description of each one.

The technique that seems to be the best choice to evaluate energy performance in heritage buildings is a thermography. This might be because the only tool needed is an IR camera while other techniques require more than one tool to be performed. Given the specific needs of heritage buildings such as to diminish energy use values and improving comfort; performing a thermography comes as the most suitable technique. A thermography can be performed without moving objects or changing the building conditions. Additionally, through a thermography it is also possible to determine the air tightness of a building. In contrast, other techniques only focus on one aspect. Hence others techniques additionally have other demands such as unoccupied areas and minimal access during the tests in order to maintain steady conditions. Once the energy audit is done and analysed, the next step is to look for solutions. Appendices A and B discuss in depth the different techniques and tools to evaluate the energy performance of a heritage building. The retrofitting techniques available in the market for heritage buildings are presented in the next section.

Table 1- Summary table on techniques and tools to evaluate energy performance of heritage buildings

Technique	Description	Tool	PROs	CONs	Reference
Air tightness	Air permeability and location of air leakage paths	Blower door	When done in conjunction with a thermography t it can provide accurate information on the presence and location of air infiltrations and thermal bridges.	Depending on the flow rate, it may require more than one blower door.	(Pfluger & Baldracchi, 2011; Pfluger et al., 2013)
Thermography	Assessment of insulation continuity and measurement of thermal irregularities	IR camera	Measures the losses of energy through the façades and distribution system.	The results of a thermography should be analysed in conjunction with accurate evaluation of thermal parameters, building materials and effects of the boundary conditions.	(Spodek & Rosina, 2014)
Heat flux	Derivation of an *in situ* "U" value for the building element	Heat flux sensors Temperature sensors	The calculated values do not account for the effect of mortar, voids, etc., which are included in the *in situ* measurements.	*In situ* "U" values are lower than expected (from standard values of the thermal conductivity of stone).	(Baker, 2008)
Co-heating	Heat losses measurement resulting from both infiltration and thermal transmission through the building fabric	Electrical heaters and thermostatic controller Temperature and relative humidity sensors kWh meter	Elimination of human behaviour variables.	Restricted access during the test and usually carried out during winter months.	(Wingfield et al., 2010)

2.2.3 Energy Efficient Retrofitting for the building Envelope of heritage buildings

After performing an energy audit in a heritage building, it is possible to draw an energy profile of the building under study and reflect on where to make changes to enhance energy performance. For historic buildings an appropriate balance needs to be achieved between building conservation and measures to improve energy efficiency if lasting damage is to be avoided both to the character and significance of the building and its fabric (English Heritage, 2013a). For example, Roberts (2008) states that it would be neither sustainable nor cost effective to replace a 200-year-old window in a heritage building that is capable of repair and upgrading with a new doubled-glazed alternative, and even less so if the new window were to have an anticipated life of only 20-30 years. Insulation to roof and external walls are the most effective building interventions.

Table 2 presents a summary of the techniques that offer the least possible damage to architectural design regarding the different elements within the building envelope (i.e. windows, draught-proofing, floors, walls and roofs). It also shows the solutions that have been applied to heritage buildings and an innovative solution if that is applicable. An innovative solution is something that has recently been developed and is not yet much in use. They are solutions that prospect greater effectiveness in reducing energy consumption when compared to the solutions mostly adapted to heritage buildings. This table presents the best practices available in order to refurbish and/or retrofit a heritage building. However, when buildings have a list of constraints not allowing changes in the building envelope or the use of certain equipment, the retrofitting approach may ask for different solutions. In the same way as with the energy audit, overcoming these constraints will require the participation of a multidisciplinary team created for the specific project on EERHB. An in depth explanation of the retrofitting techniques regarding the envelope of heritage buildings is found in Appendix C.

Table 2 - Summary table for the retrofitting techniques regarding the building envelope of a heritage building

Element	Type	Most adopted solutions	Innovative solution	Additional information
Windows		Secondary glazing - a second window installed internally next to the original window reducing both radiated heat loss and air leakage. This option is generally acceptable from a building conservation viewpoint if the retrofitting is not damaging the building (Change Works, 2008).	"Smartwin historic" is based on a compound window basis: a box window basis and both with two layers. The outer layer is the part respecting the requirements for the historical aspect. The inner layer is the main energy efficient element with triple glazing, insulation, gaskets and fittings able to support the weight of the glazing (Rambelli et al., 2013).	The first prototype was installed in the Waaghau in Bolazano, Italy, in February 2012 (Engelhardt, 2012).
Draught proofing		Gunned mastic material in gaps between the floorboards or skirting. For draught-proofing doors and windows, the same principles apply: heavy-duty materials are particularly advisable for doors due to wear and tear from frequent opening and closing the doors (Change Works, 2008).		
Floors	Suspended floors	From below the floor: with wood-fibre, compressed hemp, wool of sheep (English Heritage, 2008c). From above the floor: with semi-rigid batts, boards or loose fill cellulose (English Heritage, 2008c).		
	Solid floors	Replacing carpets with wooden floors or tiles (Roberts, 2008).		The energy saving resulting from insulating solid ground floors can in many cases be

				very diminished mainly because the ground beneath maintains a stable temperature of around 10ºC (English Heritage, 2012d).
Walls	Internal insulation	Internal insulation is usually applied directly to the inner face of the external wall and then a finish is installed to the room side. Non-rigid insulating material will often be installed between timber studs or battens erected internally to the wall, with the new internal finish applied to the timber structure to control vapour and careful isolate from sources of dampness (English Heritage, 2012a).	Vacuum insulation panels consist in micro-porous core structure enclosed in a thin gas-tight envelope, to which a vacuum is applied VIPs have a thermal performance five to ten times better than conventional insulation (Johansson, 2012; Roberts, 2008).	Historic Austrian walls (clay bricks) built during 19th century with VIP sandwich panels (Buxbaum et al., 2010).
	External insulation	External insulation systems comprise insulation layer fixed to the existing wall and a protective render or covering installed on top to protect the insulation from weather and mechanical damage. Useful materials include hemp-lime composites, wool of sheep and mineral wool (English Heritage, 2012a).	Multi-foil insulation is made up of multi-layered reflective films only a few micrometres thick. These layers, which are separated by wadding such as foam or wool of sheep, are sewn together to form a thin insulating blanket. The total thickness of a multi-foil is about 30 mm (Roberts, 2008).	
Roofs	Pitched	Insulation is installed directly from above the top floor ceiling between the ceiling joists and it is generally referred to as loft insulation. Considering ventilation and moisture control a variety of materials can be used from mineral fibre to natural materials such as wool of sheep	Green roofs Green roofs can reduce the amount of heat penetration through roofs and in this regard play a similar role to roof insulation. They reduce the roof temperature by absorbing heat into their thermal mass and because of evaporation of	

		(Change Works, 2008).	moisture (Castleton et al., 2010).	
	Flat	The majority of insulation materials appropriate are vapour permeable. The lowest densities and highest insulation values are gained from soft fibre rolls or unformed loose-fill materials (English Heritage 2012e).		
Shading devices	Single glass type window	In southern regions the single glass type window is very typical (Pfluger & Baldracchi, 2011).		Historic buildings with single glazing, shutters and full length curtains could be as effective as double glazing, when preventing heat from leaving the room (Uspenskiy, 2013)
	Casement type windows	In northern regions casement windows are usual. For this solution spaces between glasses for shading integration (Pfluger & Baldracchi, 2011).		

2.2.4 Best practices on electrical appliances, heating and ventilation, lighting and integration of renewable energy systems for heritage buildings

Household appliances and equipment share a significant fraction of electricity consumption in domestic buildings. When compared to the total energy consumption they are a marginal share. Nevertheless is desirable for all the appliances to be "A" rated by the EU energy label for equipment and appliances. Lighting energy use can be reduced by a large extent through the combination of day lighting, energy efficient lighting and control (Hinnells, 2008). Efficient use of day lighting by passive methods, both in building design and fabrics, reduce the need for electrical lighting and increases visual comfort for the occupants. Day lighting use together with the replacement of inefficient lights (e.g. incandescent lights) by low energy lighting (e.g. Light-emitting diode [LED]) efficiently displaced in the space, and lighting control (e.g. sensors) represent the most cost-effective retrofitting solution for lighting. The electrical system may also need to be retrofitted in order to enhance the efficient display of lighting in the building. Energy management tools, such as sensors and energy meters connected to computer systems, are useful in monitoring and controlling the efficiency of the building services during the operation of the building. Smart meters, for instance, allow the monitoring in real time of how much electricity is being used, how much it costs, and of the temperature in the house. These tools encourage changes in the behaviour of the occupants and are able to detect whenever the optimal operating conditions are changed. Thus, they are important on the verification phase in order to monitor the energy performance of the retrofitted building, verify and measure the energy savings achieved, and ensure an efficient and effective operation (Ma et al., 2012; Hinnells, 2008).

To achieve heating and cooling production technologies with significantly lower carbon that could contribute to achieve a carbon neutral building , a shift is needed from conventional heat-only gas or direct-electric heating and electric chillers towards systems that make use of passive sources, renewable energy sources or waste heat from power generation, in that order of priority (Hinnells, 2008). According to that, desirable heating technologies include heat pumps, micro-CHP (combined heat and power) and district heating. Heat pumps recover heat from different sources (air, soil or water) for use in space heating and/or cooling. Since most heat pumps are reversible they can be used for cooling as well as for heating. Despite their high initial system cost, these technologies have high efficiencies and can represent, in some cases, a good alternative to retrofit building heating technologies (Friedman, 2012). Micro-CHP can run on natural gas and its advantage is to produce simultaneously heat and electricity in the same power plant, which increases the overall efficiency of a CHP process when compared to conventional thermal power plants (Friedman, 2012). The cases in which there are other technologies in use (e.g. boilers), these should be retrofitted in order to increase their efficiency. However, in most cases, the selection of heating systems to retrofit is not straightforward. As Friedman (2012) suggests, when selecting a mechanical heating system, one should consider factors such as cost, efficiency and effectiveness. Table 3 presents practices regarding electrical appliances. Appendix D discusses these aspects in depth.

Table 3 - Summary table for the best retrofitting practices regarding electrical appliances, HVAC and lighting systems

Element	Most adopted solutions	Innovative solution	Additional information
Electrical appliances	Energy labelling on appliances is a strategy to inform users about savings in energy consumption. The rate A +++ is considered the most efficient and economic (EDP, 2012).		
Heating systems	Wet systems differ from dry systems on having hot water circulating around in radiators which radiate the heat from the water into the rooms or through under-floor coils. These systems maximise effectiveness (Change Works, 2008).	Active overflow prototype: works as a mixing ventilation approach using corridors and staircases as distribution zones. This is an advantage compared to decentralised systems with two openings per room (in and outflow) to the outside, impacting on the building structure (Rambelli et al., 2013).	In Innsbruck, Austria, where the prototype was installed, the supply air from the heat recovery system at the attic flows via the staircase and the corridors to the class rooms. The extract air is ducted from the toilets and wardrobes back to the counter flow heat exchanger to preheat the ambient air (Pfluger, 2014).
Boiler	A condensing boiler has similar components of a gas boiler but it also makes use of the heat produced during the operation which otherwise would be lost increasing its efficiency with heat recovery (Change Works, 2008).		Dwellings built in 1810 with different boiler types: non condensing of 65% efficiency and condensing of 89% efficiency (Moran, 2013).
Lighting	LED technology is possible considering the needs of conservation of spaces, efficiency and energy savings (Rambelli et al., 2013).	Luminaire “wallwasher” provides on one hand optimized visual scenery and on the other hand it should slow down the deterioration process that any material undergoes in its natural (or artificial) environment (Rambelli et al., 2013).	
Passive heating and cooling	Passive heating of buildings is possible through direct heat gain and/or thermal		

	storage methods, that is, using transparent surfaces to gain heat and wall to storage it, making it available for the night (Givoni, 1991). Passive cooling is made mainly by increasing building thermal storage that allows reducing building load up to 60% (Pfluger & Baldracchi, 2011).		
RES integration	It is intolerable to carry out tasks where the roof orientation or inclination changes, with respect to the plans of the building, and actions on facade are virtually impossible, being reduced to the integration of solar roofs (Pfluger & Baldracchi, 2011).		Buildings built in the 19th century, working nowadays as house guesting in the UK present flat roofs which allow a collector to be hidden from ground level (English Heritage, 2008).

2.2.5 Organisational measures within the retrofitting of heritage buildings

Maintenance is one of the primary principles for conservation of heritage buildings in order to preserve the existing fabric of the buildings. Also, maintenance will upgrade the status and value of the heritage buildings. Maintenance is defined as a continuous caring performed to prevent the structure, fabric and positioning of the building which differs from the concept of repair works which is defined as the restoration or reconstruction that requires comprehensive planning (ICOMOS, 1999).

After the retrofitting of a heritage building, a maintenance program should be implemented.

- Inspection by the responsible authorities focusing in the building fabric and structural elements should be scheduled or periodic.
- A set-up for maintenance unit to carry out this specific work should be included by the responsible organisations and entities of heritage buildings.
- Financial incentives given to the entities responsible to carry out maintenance works in heritage buildings should be more attractive and extensive.

There are practices to take into account when it comes to the implementation of retrofitting solutions. They can be considered as rules of thumb when a retrofitting and/or retrofitting process is planned and are as follow:

- It is key to know the importance of the buildings and its inside treasuries (fixtures, fittings or features) previous to start planning an intervention.
- A variety of options (from the most applied solutions to an innovative one) should be considered before defining the one for improving performance and environmental sustainability.
- Minimise the physical and visual impact of any work or new equipment refers to the need of keeping the architectural design as little as possible changed. As an example, after being retrofitted, the original image of Bernardas' Convent in Lisbon both inside and outside still stands (Martins & Carlos, 2013).
- At the same time, the smaller details into historical fabric such as frames, windows or adornments on the walls should also be intervened as little as possible to prevent their damage. It is also desirable that short-term (daily) variations in RH are no greater than 5% because high humidity can compromise the life of the building envelope and artefacts (Saïd et al., 1997).
- The use of modern materials, if essential, needs to be based upon an informed analysis where the implications of their inclusion and the risk of problems are fully understood (English Heritage, 2012d).
- As heritage buildings need to breathe, the use of vapour barriers and many materials commonly found in modern buildings must be avoided when making improvements to energy efficiency, as these materials can trap and hold moisture and create problems for the building (English Heritage, 2012a).

- Micro-generation equipment can be beneficial for the energy performance of historic buildings. However, if they cause impact on the character and appearance of buildings their installation is intolerable. Nevertheless, it is possible to introduce micro-generation equipment in a heritage building without affecting its historical value (English Heritage, 2008).
- By the end of planning a retrofitting intervention, it is crucial to consider how the changes can be reversed without damaging the existing fabric. If something does not go according to the plan, if the heritage value is at risk, there must be a reversed solution. Pfluger (2014) states that the reversibility of planed interventions could be divided in two groups: a) the technical measures like ventilation or lighting system that can be dismounted and wall perforation could be blinded and b) the internal insulation that can be dismounted as well but the interior surfaces would need a complete reconstruction.

3 CONCLUSIONS

The concept of energy efficient retrofitting and its fundamental phases were discussed in this chapter. An energy efficient retrofitting focuses on reducing the energy use of a building in order to extend its life cycle and reduce its impact on the environment on the long-term future. To attain those goals, retrofit measures to achieve energy efficiency, the use of renewable energy sources and the clean use of fossil fuels were discussed. The fundamental phases of a retrofit project were discussed with particular emphasis on the project setup phase. During this phase several factors have an important influence on the scope, type and extension of the project: i) goals and targets of the project, ii) financial budget, iii) energy audit, iv) building specific characteristics and v) available retrofit technologies. In order to take into consideration all the constraints and limitations of the project, these factors require to be evaluated together, making of each project suitable for a multidisciplinary approach

ReFoMo recognizes that it is the fundamental the safeguard of the individual character of historic buildings and the local distinctiveness. However, energy efficiency objectives can be achieved without compromising the buildings still standing (Godwin, 2011). Sections 2.2.3, 2.2.4 and 2.2.5 clearly showed energy efficient solutions that have been applied to retrofit specific heritage buildings. This study has set the foundations of the different aspects involved in EERHB. Next, it is the turn to examine if the practices already described are widespread –or even used- in other setting. Therefore, ReFoMo is also interested in how EERHB was carried out in different European locations (Rosales Carreón, 2015b).

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APPENDICES

Appendix A Techniques to evaluate energy performance of heritage buildings

Energy efficiency measures are required to reduce energy demand. As an example, by adding internal cladding on external walls and roofs, the thermal performance of the building envelope is enhanced (Santoli et al., 2013). According to Taylor et al. (2013) in terms of detailed design and execution on site, the insulation layer needs to be continuous to avoid thermal bridges and the airtightness layer needs to be continuous to reduce infiltration (uncontrolled air movement through gaps and cracks in the building fabric). Furthermore it is suggested that a combination of testing techniques should be used to both measure and diagnose the energy performance[3] of a building. Various testing techniques may be used to investigate building performance. These are used in buildings in general and consequently can also be applied to evaluate the energy performance of heritage buildings. The techniques are as follow:

- Air leakage/tightness test

The amount of air leakage through the building envelope or air permeability can be measured using a fan pressurisation method such as the blower door test (BSI, 2001). Also smoke generators can be used to identify areas of leakage in the building or portable smoke pencil to identify leakage in specific locations. The maximum allowable infiltration or air permeability of a building is defined in various standards. Performing this technique will provide data relatively to the process of exhaustion and ventilation that Figure shows.

- Thermography

Thermography is the technique used to measure contactless temperature of an object or area. This is used to determine the cause of cold and drafts tracking. The 2D thermography images are surface temperatures shown in different colours. Through this technique it is be possible to analyse where the heat losses occur. The heat losses normally occur through windows, doors and walls. Applications of thermography include: identifying delamination of external wall finishes; assessing the effectiveness of external wall insulation (Taylor et al., 2013). Additionally there is a 3D thermal modelling that harnesses the advantages of 2D thermal imaging but with a much higher potential for complete models that can be easily compared over temporal separations. However, this technique is expensive and time consuming. It requires specialist equipment in combination with 2D cameras and it is more difficult to process the data. The 3D model can be visualized in real time by the operator so that they can monitor their degree of coverage as the sensors are used to capture data. This technique can identify and measure thermal irregularities such as thermal bridges[4], insulation leaks, moisture build-up and HVAC faults (Vidas & Moghadam, 2013).

- Heat flux measurement

[3] Energy performance of a building examines the energy flow through all the elements of the building shell. It analyses the ways energy is expended to maintain desirable conditions inside buildings. (Cairns & Grimsrud, 1987)

[4] Thermal bridges are discontinuities in thermal barriers and occur when there is a gap between materials and structural surfaces (Totten et al., 2008).

Heat transfer is measured by heat flux sensors. Monitoring the heat flows for an extended period of time (typically between 7 and 14 days) makes it possible to derive an *in situ* "U" value for the building element (Doran, 2000).

- Co-heating test

This technique is described as for the thermal calibration of houses (Taylor et al., 2013). It aims to measure heat losses resulting from both infiltration and thermal transmission through the building fabric. "Co-heating" refers to the energy balance for the building during the test: under steady state conditions, the transmission and ventilation heat losses are balanced by heat gains from both electrical and solar heating. The heat loss co-efficient can then be calculated for the building by plotting the daily heat input against the daily average difference in temperature between the inside and outside of the building.

Appendix B Tools to evaluate the energy performance of heritage buildings

This section presents the tools used to evaluate the energy performance of buildings. These tools are used – in buildings in general – to perform the tests discussed in section 2.2.2.

- **Blower door to perform air leakage/tightness test**

Blower Doors is a tool used to measure the tightness of the air which is the major building factor in determining infiltration and air leakage. These can lead to heat loss, unpleasant drafts, and problems with moisture, mildew and ice dams. By quantifying the air loss, it is possible to determine the potential savings by actions like home weatherization and air sealing. Blower doors are capable of pressurizing and depressurizing a building and measuring the resultant airflow and pressure. This technology can be used in a variety of ways with different purposes such as energy, air quality, comfort and safety. A blower door test locates air infiltration by exaggerating the defects in the building shell (US Department of Energy, 2012). However, this type of test only measures air infiltration at the time of the test. Changes in atmospheric pressure, weather, wind velocity, or any activities of the occupants that may affect air infiltration are unaccounted.

Blower doors are still used to find and fix the leaks but the values generated by the measurements are more often used to estimate infiltration for both indoor air quality and energy consumption estimations. These estimations are used for comparison to standards or to provide program or policy decisions (Kreith & West, 1997). The construction quality of the building envelope plays an important part having to assure that the envelope is tight enough so leakage does not affect energy, comfort or airflow. Hence, the construction quality of the building envelope plays an important part having to assure that the envelope is tight enough so leakage does not affect energy, comfort or airflow. Blower Door data estimates airflows at a variety of pressures and mostly at a 50 Pa pressure difference (Sfakianaki et al., 2007). In case of buildings with many leaks and particularly large buildings, the airtightness measurement should be performed at 25 Pa instead of 50 Pa (Pfluger & Baldracchi, 2011). The advantage of this method is that their results are less affected by climatic conditions. During the measurements a fan is used to supply or exhaust air from dwellings at rates required to maintain a specified pressure difference across the building envelope, as shown in Figure 4.

Figure 4 - Set-up equipment of a blower door for the measurement of air tightness (source: Chen et al., 2012)

The air flow and the pressure difference are measured once and again; after the test conditions are stabilized, the measurements are recorded (Chen et al., 2012).

- **Infrared camera to perform thermography**

An infrared (IR) camera is used to assess temperature distribution in the interior or exterior surfaces of a building envelope. It can detect uninsulated wall sections, air leaks and moisture. This technique is referred to as thermal imaging or thermography. Localised reductions in the thermal conductivity of the building envelope (caused by flaws in the insulation layer or thermal bridges) will result in surface temperature variations if a stable difference of temperature is established between the inside and outside of a building (Taylor et al., 2013). Under suitable environmental conditions, these surface temperature variations can be detected using an IR camera. Wind pressures can also provide a driving force for infiltration through cracks or gaps in the building structure. Therefore, inspecting areas of the building that are exposed to strong winds with an IR camera enable identification of air leakage. Although dependent on the weather, this approach dispenses mechanical fans (Siddall, 2009).

In addition to identifying insulation defects and thermal bridges, thermography is also used to locate air leakage paths in the building envelope. Air leakage can be observed internally when the building is depressurised (e.g. during an air leakage test) provided there is a difference between internal and external air temperatures. 5 shows the appearance of some typical insulation and air leakage defects.

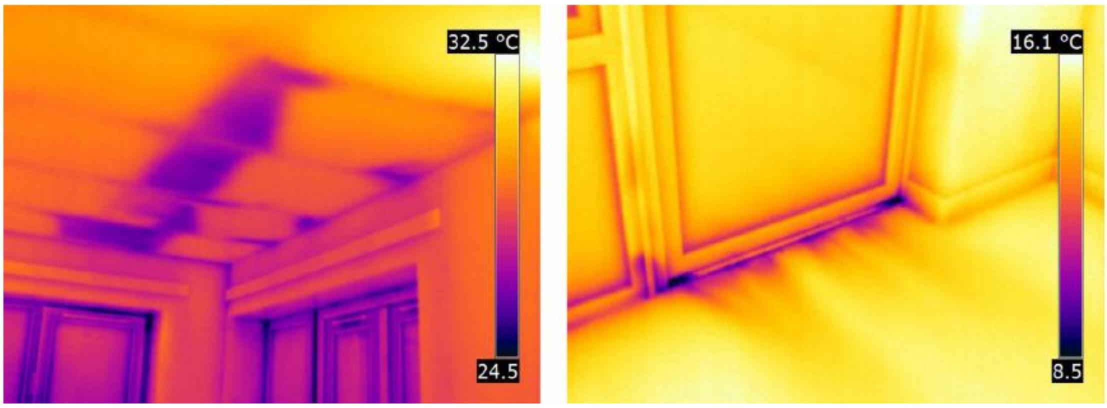

Figure 5 – Construction flaws identified using thermography: on the left) an area of ceiling where insulation above was installed incorrectly; on the right) air leakage below a door cools the surface of the surrounding floor. (source: Taylor et al., 2013)

Modern infrared cameras have simplicity of operation and decreasing costs that means the technology is more accessible to non-specialists even if the correct interpretation of results requires a working knowledge of the building and the underlying physics involved. Without contradicting the benefits of formal training in thermography, some problems are relatively easily to locate with an IR camera (e.g. insulation defects).

- **Heat flux sensors to perform heat flux measurement**

Heat exchange is measured with heat flux transducers. Heat flux transducers are used to determine thermal properties of buildings and materials. This tool contains two thermopiles separated by a matrix with a fixed thermal resistance. When heat flows through a heat flux transducer the matrix causes a temperature gradient to develop between the two thermopiles. By the Seebeck effect[5], each thermopile generates a voltage proportional to its absolute temperature. The differential voltage between the two thermopiles is proportional to the temperature gradient and therefore, since the thermal resistance of the matrix is fixed, to the heat flow through the heat flux transducer (Perl et al., 2004). With heat flux transducers it is possible to measure heat gain or heat loss by radiation, convection and conduction. The evaporative heat loss cannot be measured with heat flux transducers, because the water vapour is not able to pass through the heat flux transducer.

- **Temperature sensors to perform heat flux measurement**

Thermocouples are the most commonly used temperature sensors because they are relatively economical yet accurate sensors that can operate over a wide range of temperatures. Their functioning is also based on the Seebeck effect. A thermocouple consists of two wire legs made from different metals. The wire legs are welded together at one end, creating a junction where the temperature is measured. When the junction experiences a change in temperature, a voltage is created (National Instruments, 2012). The voltage can then be interpreted using thermocouple reference tables to calculate the temperature.

- **Electrical heaters and thermostatic controller to perform co-heating test**

The co-heating test involves heating the inside of the building with electrical heaters controlled by a thermostat to achieve a static internal temperature of approximately 25ºC (Johnston et al., 2012). During months that typically require heating (i.e. when the inside of the building reaches approximately 25ºC) the internal air starts to cool and the electrical heaters start working again. Since the energy that goes in equals the energy that goes out of a system and knowing the efficiency of the electrical heaters, the energy consumed is acknowledged. Consequently, the losses can be calculated.

- **Temperature and relative humidity sensors to perform co-heating test**

There is a great variety of temperature and relative humidity sensors in the market. What is expected from these kinds of sensors is an accurate relative humidity sensing, with fast response time and durability. The sensor outputs a precise temperature and relative humidity measurement to the HVAC control module to optimize the efficiency of a building.

- **kWh meter to perform co-heating test**

[5] Seebeck effect was discovered in 1821 by the physicist Thomas Seebeck. The effect consists of the conversion of temperature differences into voltage (Pollock, 1985).

An energy meter is the device that measures the amount of electrical energy supplied to or produced by a residence, business or machine. The device records other variables including the time when the electricity was used. Modern electricity meters operate by continuously measuring the instantaneous voltage and current and finding the product of these to give instantaneous electrical power (watts) which is then integrated against time to give energy used (joules, kilowatt-hours, etc). The most common type is a kilowatt hour (kWh) meter. When to evaluate energy performance of a building, the co-heating test requires the daily heat input to maintain the internal temperature and it is determined from measuring electrical energy consumed by a kWh meter.

Appendix C Retrofitting the building envelope

- Windows

The design of the windows is a significant factor in shaping the overall character of the building. There are two main considerations regarding window appearance: the frame and the glazing. Some manufactures can fit double glazed panes into existing timber window frames, to obey to older framing styles. Being a heritage building restricts the replacement options and there are local authorities that do not permit double glazing. Consequently secondary glazing is often considered to have less of an impact to the appearance of the window than double or triple glazing. Secondary glazing consists of a second window installed internally next to the original window reducing both radiated heat loss and air leakage (Change Works, 2008). This option is generally acceptable from a building conservation perspective if the retrofitting is not damaging the building but brings some disadvantages with it. Intrusion into the room, loss of usable window ledge space, loss of use of internal shutters, the need to reposition curtains and blinds and a double reflection visible from outside are some of the disadvantages (Change Works, 2008). However, separating the thermal insulation layer from the external glazing of the window seems to be the best solution that will help maintain the external original appearance while the internal insulation layer enhance comfort, hygiene and air tightness.

A "smartwin historic" is a solution suggested by Rambelli et al. (2013) that gives the possibility to both keep the historical habitus of the window and achieving comfort of a modern window. This window system is based on a compound window basis, a box window basis and both with two layers. The outer layer is the part respecting the requirements for the historical aspect. The inner layer is the main energy efficient element with triple glazing, insulation, gaskets and fittings able to support the weight of the glazing.

- Draught-proofing

According to Change Works (2008), sealing draughty gaps in a heritage building, is unlikely to cause problems associated with over-sealing, as the historic building materials are porous. If sealing redundant flues, careful is needed to prevent moisture becoming trapped in the space and causing deterioration. At floor level the easiest way of sealing gaps is by using a gunned mastic material in gaps between the floorboards or skirting. For draught-proofing doors and windows, the same principles apply: heavy-duty materials are particularly advisable for doors due to wear and tear from frequent opening and closing the doors. As a rule of thumb, historic buildings need to be ventilated at a rate of 0.8 to 1.0 air changes per hour – a modern building requires two times that value. Since infiltration rates in many historic buildings exceed this value, draught-proofing is beneficial (English Heritage, 2008).

- Floors

It is possible to install insulation to reduce the heat loss from floors whether there are solid floors built directly on the surface of the ground or suspended timber floors (floorboards laid across timber joists). There are two ways to install floor insulation: from below or from above. The choice of insulation type and method will depend on the original floor type. Suspended timber floors in historic buildings commonly have a layer of deafening material below the floorboards, laid between the joists. This can be an effective fire retardant and so should not be removed. However, it is possible to make space more limited so thinner solid insulation panels or insulating foam may be more appropriate than insulating quilt (Change Works, 2008).

According to Change Works (2008) the installation of insulation in heritage buildings from below suspended timber floors is relatively simple as long as there is sufficient space to access this area (900mm crawl space is the minimum recommended). Insulation is then fitted between the joists and held in place with netting. A variety of insulation materials can be used in this situation. Ideally these should be vapour permeable such as wood-fibre, compressed hemp, wool of sheep (English Heritage, 2012c). Installation of insulation from above suspended floors is the situation most frequently found in historic buildings, particularly where the boards can be lifted without unacceptable levels of damage (English Heritage, 2012c). If boards are to be lifted for any other reason it would normally be appropriate to take the opportunity to install insulation at the same time. Once the floorboards have been removed, the installation process is the same as described to insulation from below. However, the mesh netting is fixed in place between the joists before the insulation is laid. Afterwards, the floorboards are re-laid. Suitable materials are semi-rigid batts, boards or loose fill cellulose (English Heritage, 2012c). When insulating solid floors in heritage buildings the most common method is to install a floating floor with integral insulation. In historic buildings this can be an issue due to the fact of covering the historical floor – it is unlikely to be accepted. Retrofit options for ground floor rooms with solid floors include replacing carpets with wooden floors or tiles to expose the cooling effect of the ground (Roberts, 2008).

- Walls

Historic paintings and frescos present on the walls and ceilings are the reason why in historic buildings interventions and additions in walls and ceiling structures are doubtful, (Pfluger and Baldracchi, 2011; European Renewable Energy Council, 2009). Solid walled buildings, particularly those with thicker walls have comparatively high thermal capacities, which means they can absorb heat over time and release it relatively slowly as the surroundings cool down (Aste et al., 2009). External insulation means little of this heat will be lost to the exterior. This allows a building to maintain a level of warmth over day-night heating and cooling cycles, improving human comfort and potentially reducing overall energy use (English Heritage, 2012a).

English Heritage (2012a) states that external insulation systems comprise insulation layer fixed to the existing wall and a protective render or covering installed on top to protect the insulation from weather and mechanical damage. However, this type of insulation requires adaptation to the roof and wall junctions, around window and door openings and the repositioning of rainwater down-pipes what can modify the appearance of a building. External insulation should normally be considered as a two-component system. Useful materials for the external insulation itself include hemp-lime composites, wool of sheep and mineral wool (English Heritage, 2012a). Moisture-permeable finishes protecting the insulation materials from weather and mechanical damage include: lime renders and rain-screen cladding (English Heritage, 2012a). Cellulose fibre is too susceptible to damp to be used externally. Internal insulation is usually applied directly to the inner face of the external wall and then a finish is installed to the room side. A non-rigid insulating material will often be installed between timber studs or battens erected internally to the wall, with the new internal finish applied to the timber structure (English Heritage, 2012a). Occasionally there may be a cavity between the insulating layer and the original wall. An example of this is the kind of insulation retrofitting performed by Harold Janssen in the Netherlands which outside walls were untouchable and the solution a secondary glass wall inside at a distance of 1 meter (Janssen, 2013). In listed buildings, consent will be required for any internal alterations that affect the appearance and character, including any materials, details and finishes of historic or architectural interest. In many cases this may simply make the installation of insulation unacceptable. Almost any insulation material available can be used internally, subject to proper control of vapour and careful isolation from sources of dampness (English Heritage, 2010). The conceivable internal finishes can be applied either to replicate the original or to introduce a new design.

Vacuum insulation panels (VIPs) are a novel thermal insulation component used in refrigerators and cold shipping containers which during the last decade, also have been introduced in the building industry (Johansson, 2012). Johansson (2012) describes this solution as a micro-porous core structure enclosed in a thin gas-tight envelope, to which a vacuum is applied. Furthermore the author affirms that VIPs have a thermal performance five to ten times better than conventional insulation and it can be placed on the interior or exterior of the existing structure. However, it is recognised that VIPs are fragile compared with conventional construction materials and edge effects are significant, requiring careful design and fabrication. Another technology is multi-foil insulation, which is made up of multi-layered reflective films only a few micrometres thick. These layers, which are separated by wadding such as foam or wool of sheep, are sewn together to form a thin insulating blanket. The total thickness of a multi-foil is about 30 mm (Roberts, 2008). In summer multi-foil insulation reflect radiant heat; in winter it retains the heat and prevents cold air from penetrating the building (ACTIS, 2010). In case of inside wall insulation, Pfluger and Baldracchi (2011) suggest capillary active thermal insulation materials or vapour retarder dependent on the relative humidity in combination with airtight construction of embedded wooden beam ends.

- Roofs

As warm rises the roof is an important place to insulate and it is also one of the easiest places to add insulation in most buildings (English Heritage, 2012). Regardless of the location, insulation should be installed avoiding potential fabric and structural damage (timber rot due to condensation on the roof timbers) or cold bridging and condensation within the home (i.e. the habitable rooms below roof). It is possible to install insulation to reduce the heat losses whether the roofs are pitched or flat (European Renewable Energy Council, 2009).

In a traditional pitched roof, insulation is installed directly from above the top floor ceiling between the ceiling joists. The main conservation considerations surrounding insulation of roofs relate to ventilation and moisture control. The warm air rising to the roof space carries moisture which will condense on the underside of the roof and the timbers causing rot. Insulating the loft reduces this flow of warm air, but moisture will still enter. So it is important that the roof space is well ventilated to allow any moisture to disperse. Loft insulation can be made from a variety of materials, ranging from mineral fibre to natural materials such as wool of sheep (Change Works, 2008). Flat roofs typically have a structure with waterproof covering laid over timber decking on timber joists (English Heritage, 2012e). The majority of insulation materials appropriate for use in historic buildings are vapour permeable. The lowest densities and highest insulation values are gained from soft fibre rolls or unformed loose fill materials (English Heritage 2012e). These materials are incapable to support their own weight or of any other materials and should be placed loose with nothing covering them.

Green roofs are an innovative solution that can reduce the amount of heat penetration through roofs and in this regard play a similar role to roof insulation. They reduce the roof temperature by absorbing heat into their thermal mass and because of evaporation of moisture (Castleton et al., 2010). Two examples can be given to show incompatibleness and compatibleness of green roofing in historic buildings. The first one in figure 6 showed to be incompatible because the green roof features were visible along the street where the building stands. Although the buildings have substantial parapets, the trees which can be seen from the street below, negatively impact the character of these late nineteenth century historic buildings. Figure 7 shows the second example which consists of planted terraces used by tenants of the penthouse offices that were also added as part of the rehabilitation of an early twentieth century building. The green roof increases the energy efficiency of the building and the green groundcover also acts as an acoustical damper for the rooftop offices. The tall parapets hide the green roof ensuring that the historical character of the building is retained while incorporating this energy efficient and environmentally-friendly feature (Petrella, 2009).

Figure 6 - Incompatible solution: the plantings were highly visible above the parapet wall (source: Petrella, 2009).

Figure 7 - Compatible solution: the tall parapet wall prevents the viewing of the green roof sections from the street below (source: Petrella, 2009).

- Integration of shading systems within window/ glazing system

Shading devices can be either fixed or movable. Since windows are most often untouchable on historic buildings and the only source of daylighting the possible positions for the integration of shading systems are limited.

According to Pfluger & Baldracchi (2011) in southern regions the single glass type window is very typical for historic buildings, whereas in northern regions casement windows are usual. In case of single pane windows only internal shading systems seem to be suitable. For casement type windows the spaces between the glasses could be used for shading system integrations.

Appendix D Retrofitting electrical appliances, heating and ventilation and lighting systems.

Electrical Appliances

Heritage buildings have today different purposes than the ones from the past. Their adaption into conference rooms, hotels and libraries justify the need of acquiring electrical appliances. Appliances have an energy labelling which is a tool to inform consumers about their energy efficiency. Energy label starts on A, being the one that provides greater savings in energy consumption. Figure 8 shows the new energy label, released in 2012, which added three efficiency classes (A +, A ++ and A +++) and eliminated the "E", "F" and "G" classes to the previous label. For the same capacity and characteristics, a device rated as A +++ is considered more efficient and economic (EDP, 2012). In other words and as an example, opting for refrigerators and freezers rated as A +, A ++ or A +++ provide savings of about 20%, 40% and 60%, respectively, compared to class A.

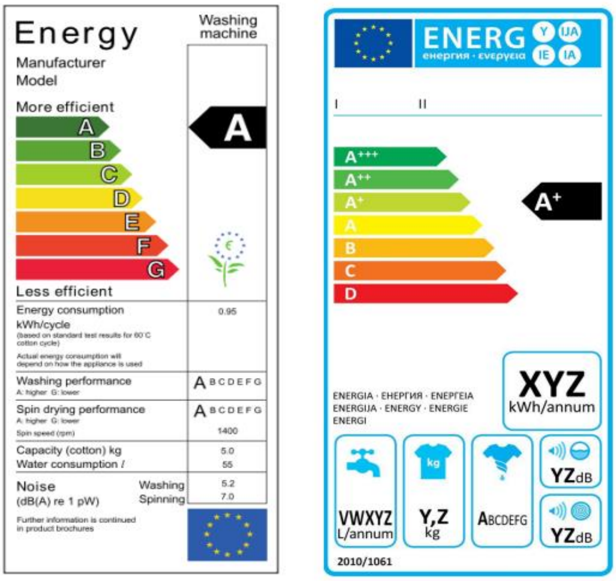

Figure 8 - Old and new energy label [since the recast of the Directive (2010/30/UE)], (source: ADEME, 2013)

The energy labelling system could make that those responsible for heritage buildings become aware of the ways energy and money can be saved. Smart monitors (sometimes called real time display units) show the amount and cost of electricity usage at any time, together with the greenhouse gas emission levels. The readings change as appliances are turned on and off, so the energy consumption of individual appliances can be calculated (Molina-Markham et al., 2010).

Heating systems

The heating systems can be observed at 3 levels: heat generation, distribution and heat exchange to the building.

Heat exchange to the building

Central heating system is one of the most effective ways of heating and it can be a dry system or a wet system. Dry system comprises storage heaters that retain the heat in internal thermal blocks and release the heat over time at a variable rate. However, with this system it can be difficult to control room temperatures and it requires a separate water heating system (Change Works, 2008). Wet system differs from a dry system on having hot water circulating around via radiators which radiate the heat from the water into the rooms or through underfloor coils. These systems maximise effectiveness but it is important to retain the appearance and character of the historic property. Although portable heaters and electrical oil-filled are alternative options to central heating systems, they are less efficient and more expensive. Besides application of modern technology, an energy efficient heating system is controlled by time or temperature. It may include: an electronic timer, a room thermostat, and thermostatic radiator valves (Change Works, 2008).

Pfluger & Baldracchi (2011) overviewed possibilities of integration of a heat exchanger in the building structure such as integration in walls and ceilings. In most cases the systems are not really integrated into the structure of the building. Nevertheless, an active overflow prototype (Figure 9) was constructed and tested in a heritage building working as a school. The idea is to vent fresh air into the corridor and staircase with fans actively pushing the air from the corridor into the classrooms. Typically, to optimize this approach the ventilation system is linked to a heat recovery and therefore ducts for air inlet and exhaust to and from the rooms. Silencers are also needed to prevent noise. The prototype aims at avoiding the need for ducts in the corridor or for the installation of a vertical shaft to provide fresh air. The heat recovery system is instead placed on the attic and the fresh air is distributed via the open staircase and corridors through vertical ducts. For protected buildings, this is an advantage compared to decentralised systems with two openings per room (in and outflow) to the outside (impacting on the building structure). Hence this solution should only be applied for heritage buildings (Rambelli et al., 2013).

Figure 9 - Prototype of active overflow system (source: Rambelli et al., 2013)

Heat distribution

Heat can be distributed between heat generator (mostly a boiler) and the rest of the building in different ways, for example by heated air or heated water. Distribution by heated water is more efficient than by air because of the larger heat capacity of water compared to that of air.

An example of distribution of heat by air is mechanical ventilation systems in with air is first heated and then transported throughout the building by air duct systems. A central heating system in which water is heated up in a boiler first, and transported to heat exchangers in the building's rooms by pipework throughout the building, is an example of distribution by heated water heated water for heat distribution. Driving forces of these systems can be fans, respectively pumps. Energy saving measures on fans will be discussed in the paragraph "Ventilation". This paragraph will focus on distribution systems containing water.

The energy performance of system types can be improved by minimising heat losses and unnecessary friction losses on driving forces.

Heating losses can be reduced by insulating ducts or pipes and components in these systems like valves, air handling units (if applied) or pumps.

Unnecessary friction losses can be accounted for by re-tuning the installation (e.g. tune-in valves).

Another improvement on energy performance is to apply high efficiency pumps. These high efficiency pumps mostly contain permanent magnets and use direct current power supply. Moreover in most cases their energy performance can be further improved by a installing a pump switch, and/or a speed controller in order to control operation, or optimizes its working load with respect to power demand from the system. If speed control is not possible or necessary because of constant required load, a check on overcapacity of pump is advised. Overcapacity of these parts results in excessive power consumption.

Besides applying efficient components and control system, efficiency can also be realised by changes in the system design, like applying more distribution systems/groups for different building areas with different heating demand e.g. due to different orientation, occupation times and desired operation temperatures.

Heat generation

Performance of heat generation can be improved by applying energy efficient central heating components like for example condensing boilers or heat pumps with efficient control systems. Efficiency improves at lower water supply temperatures. The minimum temperature depends on the capacities of the heat exchangers in the room at different temperature levels and flow capacity of the distribution system.

Like the distribution system, heat losses at the heating generation components can be reduced by applying insulation material. Existing central heating components with insulation should be checked with regard to the status of the insulation. Also good maintenance is important for the components to perform efficiently.

Boiler

Modern technology can offer distinct enhancements to the thermal performance of older buildings whatever their construction and age (English Heritage, 2012b). Gas boiler systems are the most common generation system in heritage buildings having efficiency between 80% and 95%. A condensing boiler has similar components of a gas boiler but it also makes use of the heat produced during the operation which otherwise would be lost increasing its efficiency (with heat recovery). For example, condensing boilers are highly efficient and with effective controls and programming can make heating systems work in ways which are relatively harmonious with the construction of heritage buildings (Change works, 2008).

Important regular maintenance measures on the boiler's burners are decarbonisation and optimization of air/fuel mixture.

Heat pump

A heat pump transfers heat from a source medium to another (secondary) medium with high efficiency, dependent on the temperature levels of the these media. The secondary medium mostly is water, while the source medium can be outdoor air, soil, aquifer or surface water. The efficiency of the heat pump's operation decreases at lower source temperatures and higher secondary medium temperatures (the maximum secondary temperature should not exceed about 50°C in order to maintain high efficiency).

Hot domestic water preparation

A building's energy consumption on preparation of hot water heavily depends on its function. Functions with relatively large hot water demands (like hospitals, restaurants, hotels and residential buildings) generally have other hot water preparation systems than functions like offices and schools. In the first place it would be best to reduce hot water usage by hot water saving (sanitary) equipment and lower mixed water temperatures if possible (like standard temperatures in showers).

In case of a hot water recirculation system, system losses can be reduced by lower hot water temperatures, optimal pipe and equipment insulations. Installing energy efficient pumps with pump switches and/or pump speed control will decrease energy consumption for water transportation. For single hot water tapping points at distant locations it is can be more efficient to provide an electric hot water preparation device at that location in order to reduce losses in the distribution system (and moreover in the recirculation).

For both categories of hot water demand can be stated that efficiency of the hot water generator and distribution system (if present) should be as high as possible, especially for large systems with large pipe lengths and large hot water demands.

The following measures regarding hot water generator types should be taken into consideration:

- Use high efficient boilers
- Decrease hot water storage temperature set point (but never < 60°C!!)
- Heat pump on exhaust air;
- Use a thermos-hydraulic boiler;

- In case of PV-panels: use over-capacity of PV-panels for hot water preparation;
- Tie in to a local heat distribution network (e.g. block heating/waste heat)

With regard to user equipment savings can be realised by the purchase of for example a hot fill washing machine and hot fill dishwasher. Instead of electrically heating up cold water, this equipment takes in hot water that is prepared by a more efficiently hot water generator. Be aware that this also requires adjustment of the hot water piping system to the location where this equipment is placed.

Mechanical cooling systems

Like the heating systems cooling systems can be dived in: exchange system, distribution system and chillers. For these systems to perform efficiently, the same measures that are mentioned for the heating systems apply. The main differences can be found in temperature levels and cooling generation components. For cooling systems the losses on thermal energy (heating up) can be reduced by applying higher air or water temperatures if possible. As for the heating systems this depends on capacities of heat exchangers and the distribution system.

In addition to selecting high efficient chillers, free cooling enables further reduction of energy consumption. Free cooling is based on using low water (e.g. from an aquifer) or air (outdoor air in winter) temperatures if available and if low enough for cooling appliances. Energy consumption is limited to energy use for transportation of air or water through the cooling system. The cooling medium (water or air) itself is not cooled down mechanically. An example of applying free cooling is cooling of server rooms in winter by a chiller that is equipped with a heat exchanger that bypasses the chilling circuit of a compressor chiller.

Maintenance measures for reducing energy consumption of chillers incorporate cleaning of heat exchanging surfaces like condensers and evaporators. An alternative for mechanical chillers that are only applied for cooling in the air handling system is (indirect) adiabatic cooling. This technique can be applied by sprinkling water on to a special heat exchanger in the air handling unit for cooling down the fresh air (or exhaust air). Air will be cooled due to heat transfer to (non-chilled) water with relatively low temperature and also the evaporation of the water which extracts heat from the surrounding air.

Lighting

Interventions as additions in the wall and ceiling structures are limited in heritage buildings. Therefore, according to Pfluger & Baldracchi (2011) artificial lighting installation is defined to be a difficult requirement which can be fulfilled by stand-alone-solutions such as floor lamps. It is also recognised that currently there are not many luminaries available on the market aligned for the lighting of historic buildings. In general it can be said that the artificial lighting in historic buildings is much reduced. As solutions, consistent with the needs of conservation of spaces, efficiency and energy savings, LED technology is ideal for buildings in which invasive refurbishment is not an option. The use of LEDs allows the luminaire to reproduce the illumination given by incandescent lighting: 2700K (Weitlaner, 2013). An illumination concept was developed, that is able to fulfil the human and material requirements (Rambelli et al., 2013). Figure 10 shows the luminaire “wallwasher”, which can be installed in a non-invasive way. It provides on one hand optimized visual scenery and on the other hand it should slow down the deterioration process that any material undergoes in its natural (or artificial) environment.

Figure 10 - Prototype of luminaire (source : Rambelli et al., 2013)

For some areas / rooms energy consumption for lighting can be reduced by applying proper lighting controls like;

- Occupancy detection
- Light switch combined with absence detection
- Artificial lighting levels controlled on basis of daylight entrance level

Dividing the lighting systems in more separate switchable groups will make the lighting control mentioned above even more efficient. In situations in which mentioned lighting controls are not interesting due to for example continuous occupation or low daylight levels. Besides artificial lighting energy can also be saved by using day light systems.

Passive heating and cooling

In order to understand the potential performance of the passive solutions originally conceived during the building design and realisation, Pfluger & Baldracchi (2011) advocates that it is essential to know when the building was built, its original use and its evolution trough times in terms of renovations and changes of use. Therefore a whole geometric survey, the identification of the materials and of the heating/cooling strategy and systems are requested. Passive heating of buildings is possible through direct heat gain and/or thermal storage methods, that is, using transparent surfaces to gain heat and wall to storage it, making it available for the night. Direct heat gain method is simple and cheap, but it depends on climatic loads swings (Pfluger & Baldracchi, 2011). Especially in moderate or cool climates, the passive heating solutions should be studied together with the cooling ones in order to avoid overheating and glaring by daylight. Passive cooling is made mainly by increasing building thermal storage that allows reducing building load up to 60% (Pfluger & Baldracchi, 2011). Moreover, Pfluger & Baldracchi (2011) also state that some historic buildings are already provided with natural ventilation systems which increase both the comfort in the indoor environment and the overall energy performance of the building. Therefore, the reuse and reactivation of these natural ventilation techniques should be always investigated.

Ventilation

For a healthy indoor environment, sufficient ventilation is required. Nevertheless extensive ventilation results in unnecessary energy consumption for heating or cooling and –in case of mechanical ventilation- fan power. Applying natural ventilation has the advantage of lacking fans that consume energy. On the other hand, natural ventilation is less easy to control, not guaranteed at all weather conditions and has no possibility of regaining heating/cooling energy that escapes from the building with the exhaust of indoor air.

In case of mechanical balanced ventilation (mechanical air supply and return) the amount of ventilation should be reduced to the minimal required ventilation capacity. This needed capacity depends on the occupation level (e.g. CO2-level), function (minimal required ventilation by Building Decree), climate system (needed ventilation capacity for cooling and heating) and pollution (e.g. emission of copiers and printers) of the rooms and areas of the building.

Measures that can be taken in order to reduce necessary ventilation capacity are:

- Variable air flow system with CO2 control in rooms/areas with changing occupation
- Variable air flow system with temperature control in rooms/areas with changing heating and cooling demand
- Water-filled secondary heating and/or cooling equipment in rooms/areas instead of all-air climate installations
- Local air extraction near polluting equipment

Transportation of air to rooms/areas should be done as efficient as possible. This means that friction losses in ducts systems must be minimized. To check and to adjust this -if necessary – rebalancing of tuning valves can be advised. Also reducing pressure loss over filters by regularly changing filters may contribute to a more efficient transportation of air. In order to monitor the need of filter replacement a pressure loss alarm can be installed.

An additional measure is to apply high efficiency fans (for example directly driven or with Direct Current motors) with speed controllers in order to optimise the fans working load with respect to ventilation demand from the system.

In systems with air handling units following options can contribute to a reduction of energy demand:

- Heat recovery (e.g. by recovery wheel of plate exchanger)
- In case of air humidification: apply ultrasonic or infrasonic air moistening, or gas fired steam generator instead of an electric generator. Also apply moisture recovery from exhaust air.

Besides applying efficient components and control system, efficiency can also be realised by changes in the system design, like applying more distribution systems/groups for different building areas with different heating demand e.g. due to different orientation, occupation times and desired operation temperatures.

For buildings with operable windows and climate control on room level, integrate window contacts into the climate system's control system in order to switch off the climate system in the specific room when windows are opened. Also switching on basis of presence detection in rooms can be realised by key card switches, optional detection or a registration button on a room controller.

In case of cooling with the ventilation system, use night ventilation in order to use colder outdoor air at night to dispose heat that is stored in the building mass during daytime.

RES integration

Integration of Renewable Energy Sources (RES) in heritage buildings of high architectural and historical value is more restrictive than in the other buildings due to conservation demands. The most common tasks in that type of buildings are maintenance and restoration works, in which the original buildings have not formal variations. Available micro-generation equipment tends to either provide hot water or electricity, either through solar panels (hot water or photovoltaic) or from wind generators. However, these are generally useful and well-proven types of equipment and can make valuable contributions to overall energy use. Wherever the opportunity arises, small-scale hydro power can also be viable. Small-scale combined heat and power systems which have recently come to the market have great promise. Nevertheless, Pfluger & Baldracchi (2011) assume that it is intolerable to carry out tasks where the roof orientation or inclination changes, with respect to the plans of the building, and actions on façade are virtually impossible (unless whilst walls renovation), being reduced to the integration of solar roofs.

In the UK, there is a terraced house from the 19th century, which flat roof allows a collector to be hidden from ground level. Figure 11 shows the horizontally mounted collector having the least visual impact behind the parapet wall. If it is not acceptable to fix collectors to the roof, or it is not physically possible to accommodate them one alternative is to position them elsewhere – on another building, for example – with the pipes buried and routed back to the storage tank (English Heritage, 2008). Where land is abundant the collector may be mounted on the ground. An example of such a free-standing installation is in a vacancy cottage, also in the UK. The collector is mounted in the garden and surrounded by a fence, with hot water piped back to the cottage (English Heritage, 2008).

Figure 11 - Evacuated-tube solar collector on a flat roof of a 19th century house (source: English Heritage, 2008)

In most situations it may be hard to change the existing climate installations, especially the parts that are in sight in rooms and areas. An option to integrate RES without changing the existing heating exchange bodies and heat distribution system is to replace an existing boiler on fossil fuel by a boiler on biomass like for example wood blocks or wood pellets. As an alternative cogeneration of heat and electric power on biogas, bio oil or biomass may be interesting in situations where a continuous heating and electricity demand is present.