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Sustainable refurbishment of exterior walls and building facades

Final report, Part B – General refurbishment concepts

VTT TECHNOLOGY 33

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Abstract

This report is the second part of the final report of Sustainable refurbishment of building facades and exterior walls (SUSREF).

SUSREF project was a collaborative (small/medium size) research project within the 7th Framework Programme of the Commission and it was financed under the theme Environment (including climate change) (Grant agreement no. 226858).

The project started in October 1st 2009 and ended in April 30th 2012.
The project included 11 partners from five countries. The coordinator of the project was Tarja Häkkinen, VTT.

SUSREF developed sustainable concepts and technologies for the refurbishment of building facades and external walls. This report together with SUSREF Final report Part B and SUSREF Final Report Part C introduce the main results of the project. Part A focuses on methodological issues. The descriptions of the concepts and the assessment results of the developed concepts are presented in SUSREF Final report part B (generic concepts) and SUSREF Final report Part C (SME concepts).

The following list shows the sustainability assessment criteria defined by the SUSREF project:

1) Durability
2) Impact on energy demand for heating
3) Impact on energy demand for cooling
4) Impact on renewable energy use potential
5) Impact on daylight
6) Environmental impact of manufacture and maintenance
7) Indoor air quality and acoustics
8) Structural stability
9) Fire safety
10) Aesthetic quality
11) Effect on cultural heritage
12) Life cycle costs
13) Need for care and maintenance
14) Disturbance to the tenants and to the site
15) Buildability.

This report presents sustainability assessment results of general refurbishment concepts and gives recommendations on the basis of the results.

The report covers the following refurbishment cases:

- External insulation
- Internal insulation
- Cavity wall insulation
- Replacement Insulation during renovation.

Keywords Sustainable refurbishment, exterior wall, façade, sustainability assessment

Preface

This report is the final report of Sustainable refurbishment of building facades and exterior walls (SUSREF).

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VTT Technical Research Centre of Finland	VTT	Finland
Stiftelsen SINTEF	SINTEF	Norway
Vahanen Oy	Vahanen	Finland
Cardiff University (CU)	CU	UK
Building Research Establishment	BRE	UK
TECNALIA	TECNALIA	Spain
Repair Estructuras S.L.	Repair	Spain
Oneka Architectura S.L.	ONEKA	Spain
Sustainable Gwynedd Gynaladwy Cyf	SGG	UK
Ehituskonstrueerimise ja Katsetuste OU	EKK	Estonia
Trondheim og omegn boligbyggelag	TOBB	Norway

The coordinator of the project was Tarja Häkkinen, VTT.

SUSREF developed sustainable concepts and technologies for the refurbishment of building facades and external walls. This report together with SUSREF Final report Part B and SUSREF Final Report Part C introduce the main results of the project. Part A focuses on methodological issues. The descriptions and assessment results of the developed concepts are presented in SUSREF Final report part B (generic concepts) and SUSREF Final report Part C (SME concepts).

The main objectives of the SUSREF project were:

- to identify and understand the quantitative needs to refurbish building envelops in the EU and neighbouring areas; to understand the meaning of these needs, in the first place, in terms of environmental impacts and secondly in terms of financial impact and business potential;
- to develop a systemized theory and different technologies for refurbishment of building facades and external walls in order to ensure the functional excellence of solutions; to analyse technologies from the view point of building physics and energy efficiency; to consider the various challenges in different parts of Europe in terms of present climate, technological differences, and cultural-historic differences; and finally to deliver sets of relevant performance specifications for sustainable refurbishment;
- to develop systemized methods for consideration of environmental performance of external walls; to assess and ensure the sustainability of the developed technologies in terms of environmental impacts, life cycle costs, social and cultural impacts;
- to develop sustainable concepts for carrying out refurbishments projects;
- to disseminate the results for a) building industry, b) standardisation bodies, and c) policy-makers and authorities in terms of technological knowledge, guidelines and recommendations.

All deliverables are available on SUSREF web site http://cic.vtt.fi/susref/

In addition to the authors of the Final report Part B the following experts are acknowledged

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- Kari Hemmilä, VTT for valuable contribution
- Jonathan Williams, Jelena Kiselova and Nicholas Beddoe, BRE for text editing.

Contents

Appendix A: Aesthetic quality and cultural heritage

1 Introduction

The report describes the most prevalent existing exterior wall refurbishment technologies, and describes the refurbishment concepts, presenting the assessment results of the concepts against the criteria set out by the project partners. In addition, the report also presents an overview of refurbishment technologies based on a literature review.

The main aim of this report is to evaluate and describe the concepts for sustainable refurbishment of external walls; and to create results for those assessments undertaken.

The main questions to deal with are:

- How far is it economically and ecologically reasonable to push the standards to improve the insulation capacity of the building envelope, when refurbishing existing buildings? In particular the Life Cycle issue arises when making calculations of estimated life-span that can be achieved with different technologies. In each case we need to be able to optimise the total energy consumption during the life-span, taking into account the embodied energy in the installation phase and the energy consumption during the life-span. At this moment in time there is limited reliable data to be able to make a reliable evaluation.
- Improving the insulation capacity and the air-tightness of the building envelope has an affect on the indoor air quality. What is that influence and how should we balance and optimize it, by introducing mechanical systems (heating, air-conditioning, ventilation…) to achieve the optimal indoor-air quality whilst balancing this against setting an optimal ecological impact?
- How to maximize the use of external energy sources by using intelligent envelope structures in refurbishment projects: how to optimize the energy absorption to the building envelope. The present U-value calculation methodology does not take into account the external energy sources which results in a reduction in the need for heating. How can we reduce the heat absorption during the warm season contained in the building envelope, thus reducing the need for air-conditioning? Would it be better in some cases to maximize the heat absorption and store it in the buildings with high levels of thermal mass? Would it be possible to use the absorbed energy as an energy source for heating during the cold seasons and for air-conditioning during the warm seasons?

- All of the mentioned criteria need to be studied in various climate conditions, which represent the EU climatic zones.

The product concept development uses the systemized approach developed by the project and presented in part A of the final report and incorporates the recommended and developed models of assessment.

2 Objectives

2.1 Introduction

The purpose of the report is to describe the reference concepts of SUSREF and summarise the assessment results.

This study is focused on additional thermal insulation of external walls; all other fabric elements of components and systems have been excluded. The main goal of this study is to give a comprehensive view of the different technologies available for the refurbishment of external walls.

Although the work undertaken in the SUSREF project is focused on residential buildings, it is reasonable to assume that the results and technologies presented here may also be applied to other building types of a similar construction.

The report describes generic concepts for refurbishment of external walls, does not represent any particular product and subsequently presents the assessment results of those concepts.

<u>The concepts are assessed from the view point of</u>

1. Durability (focus on moisture),
2. Need for care and maintenance
3. Indoor air quality, acoustics + thermal comfort
4. Impact on energy demand for heating
5. Impact on energy demand for cooling
6. Impact on renewable energy use potential (use of solar panels etc.)
7. Environmental impact of manufacture and maintenance
8. Life cycle costs
9. Aesthetic quality
10. Effect on cultural heritage
11. Structural stability
12. Fire safety
13. Buildability
14. Disturbance to the tenants and to the site
15. Impact on daylight.

Parameters considered for the ecological and economical assessment

1. Target u-values
2. Thermal conductivity of the chosen materials
3. Heating degree days
4. Cooling degree days
5. Investment costs
6. Construction costs
7. Heating costs
8. Environmental loads for materials used
9. Retrofit material quantities
10. Typical heating energy type
11. Environmental loads for energy types.

The report covers the following refurbishment cases

1. External insulation
2. Internal insulation
3. Cavity wall insulation
4. Replacement Insulation during renovation.

The following buildings types are covered in the development and assessment of the generic concepts

A. Small houses
B. Terraced houses
C. Multi-storey Apartments/Flats.

In the assessment of the refurbishment concepts the following climatic zones are considered

1) Cfb
2) Cfbw
3) Csa
4) Dfb
5) Dfc.

However, in some cases a lesser number of climatic conditions are considered, depending on the region where the methods are most commonly used.

The original wall types considered in the assessment of the generic refurbishment concepts are as follows:

Table 1. The original wall types considered in the assessment of the generic refurbishment concepts.

Wall type	Relevant in climatic zones	Relevant in building types?
Solid wall (brick, natural stone)	1, 2	A
Sandwich element (concrete panel + concrete panel)	2, 3	C
Load bearing wood structure (wooden frame)	2, 3	A, B, C
Load bearing cavity without insulation (brick + concrete block)	2	A, B, C
Insulated load bearing cavity (concrete block + concrete block)	2	A, B, C
Non-load bearing cavity (hollow brick + perforated brick)	1	A, C
Non-load bearing concrete block without insulation (hollow brick + concrete block)	1	A, C

The generic concepts are assessed analytically and when relevant, using a parametric approach. This parametric approach means that each performance aspect of the generic concepts will be assessed by dealing with relevant issues as parameters.

Relevant issues are very much determined by specific performance aspects, and these could be different in many issues. Relevant issues may be for example be

- Quality and performance properties of materials
- Thickness of insulation and other layers
- Existence of air cavity
- Fixing mechanisms
- Quality of surface material
- Condition of the existing structure
- Rainfalls and temperatures.

2.2 Classification of refurbishment technologies

This study combines different refurbishment technologies into four main groups. The technologies differ from each other mainly by the manner in how placement of new insulation layers would be normally undertaken. SUSREF D2.1 presents a brief explanation of each of these technologies and this study will discuss them in more detail.

The primary technologies for refurbishing external wall, as in SUSREF 2.1 are:

- Technologies for replacing existing walls (R)
- Technologies for applying external (insulation) layers (E)
- Technologies for inserting (insulation) materials in cavities in existing walls (C)
- Technologies for applying internal insulation (I).

This classification has been assessed earlier in (SUSREF WP 2.1) in terms of the significance of the insulation when considering the moisture and temperature balance of a wall structure. Each of the technologies has some advantages and disadvantages, which are listed in Table 4.

Table 2. Different placements for thermal insulation. Modified from IEA (2010).

Insulation mode	Advantages	Desadvantages
Insulation by outside	Eliminating risks of local thermal bridges Protecting the wall from freezing and fissuring Protecting the wall from penetration by driving rain Improving the external appearance in the case of a degraded external surfacing Conserving thermal inertia Conserving inside volumes and finishing	Changing the outside appearance (town planning permit application – difficulties with listed buildings and heritage sites) Costly solution, because it involves a new facing Possible encroachment on public ground
Insulation by inside	The external appearance is conserved (no town planning permit application) The cost is generally lower than for insulating on the outside	Thermal bridges sometimes not eliminated Possible degradation of the outer wall due to its cooling and increased dampness Risk of fissuring due to the temperature variations in the outer wall New interior finishes and smaller interior volumes (according to the insulation's thickness) Loss of thermal inertia Continuity of the vapour barrier difficult to achieve Modification of water network – placing the pipes so that they are protected from freezing
Insulation in the hollow (double wall)	Conserving thermal inertia Simple and less costly technique than insulating from the outside The external appearance is conserved (no town planning permit application)	Risk of thermal bridges at the breaks in the cavity Cooling of the facing wall Prior examination of the cavity is indispensable Ability to dry out the external surface of the wall is lessened

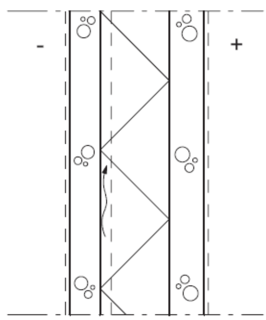
There is a number of different insulation materials exist that can be used with each of the technologies. The selection of the material depends on various factors and the optimal solution is often dependent on the project type and the individual characteristics of a refurbishment project, such as economic constraints, client wishes, and other external factors.

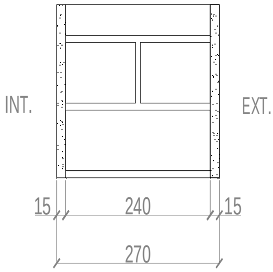
3 Background

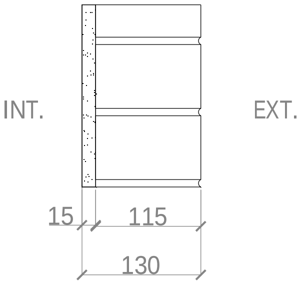
3.1 External thermal insulation

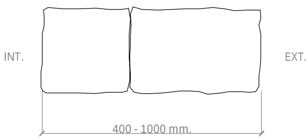
The external insulation concept is described in the following.

Table 3. External insulation concept.

NAME OF THE CONCEPT **External thermal insulation system** Two alternatives: • Repairing to match the original • Cladding the old material with a new material (new façade type)				
APPLICATION				
EXISTING WALL TYPES			REFURBISHED WALL	
	Building types	Climatic zones	Insulation type and thickness	Façade type
Sandwich element				
 For example existing type: 80 mm 90 mm 30 mm	Multi storey	Alternatives according to the SUSREF climate zones: For example: Dfb, Dfc,Cfb, Cfa	Alternative types and thicknesses For example Rockwool, Glasswool, Polyurethane Polystyrene, Other types	Alternative façade types For example: concrete with ceramic plate, different boards like concrete, natural stone, polymer, rendering or panels like wooden panel or PV panel installation etc.…
Solid wall (brick, natural stone)				

<table>
<tr>
<td>

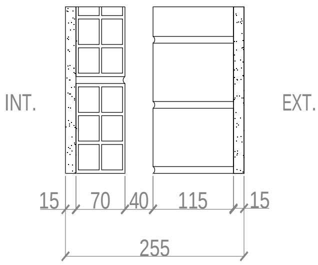
For example 270 mm


For example:130 mm


For example: 400 – 1000 mm</td>
<td>Small houses</td>
<td>For example: Cfb, Cfa, Cfbw</td>
<td>Alternative types and thicknesses

For example Rockwool, Glass wool, Polyurethane Polystyrene, Other types</td>
<td>Alternative façade types: concrete, natural stone, polymer, rendering, etc…façade types</td>
</tr>
<tr>
<td colspan="3">Insulated load bearing cavity (brick, cavity, concrete block façade)</td>
<td colspan="2">REFURBISHED WALL</td>
</tr>
<tr>
<td></td>
<td>Small houses
Terraced houses
Multi storey</td>
<td>For example: Cfb, Cfa, Cfbw</td>
<td>Alternative insulation types and thicknesses

For example: Rockwool, Glass wool, Polyurethane Polystyrene…etc</td>
<td>Alternative facade types like concrete, natural stone, polymer, rendering
PV panel (?)
wooden panel …etc</td>
</tr>
<tr>
<td colspan="3">Non-load bearing cavity (hollow brick + perforated brick or hollow brick + concrete block)</td>
<td colspan="2">REFURBISHED WALL</td>
</tr>
</table>

 Etc.	Small houses Multi storey	Cfb, Cfa, Cfbw	Alternative insulation types and thicknesses Rockwool, Glass wool, Polyurethane Polystyrene..etc	Different facade types like concrete, natural stone, polymer rendering PV panel (?) wooden panel...etc

External insulation is usually the preferred method for adding insulation to existing buildings for a number of reasons, its main advantage is that it does not reduce the amount of available interior space and it is usually possible to install the insulation while the building is in use, thus reducing the disturbance to the occupier and the additional cost of decanting the occupants. It also makes it possible to deal with heat and moisture transfer problems in a more comprehensive way. (SUSREF D2.1)

Additional external insulation can have a significant impact on mitigating the thermal losses of a wall, diminishing the effects of existing thermal bridges and improving the air tightness of a wall. (Groleau et al. 2007)

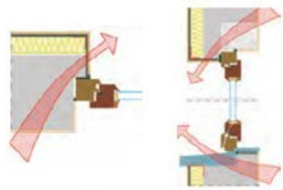
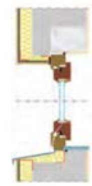
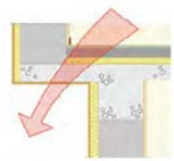
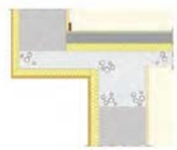
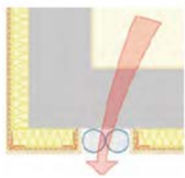
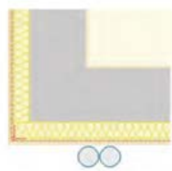
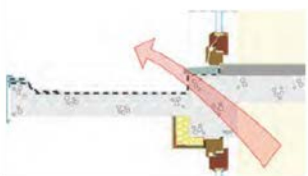
The additional insulation and new cladding are usually fixed straight to the load-bearing element of the existing walls, but some degree of removal of sub standard external construction, e.g. external siding, loose render etc may also be needed. (SUSREF D2.1)

However, in some cases, the external thermal insulation might be hard to implement, as it will normally alter the visual appearance of the building. This might be the case especially on the “street side” -facades of buildings in urban areas (IEA 2010) or in historical buildings. External thermal insulation causes also challenges when considering reduction of thermal bridging, since eaves, verges and details around windows often need to be altered (EST 2005).

Thermal bridges in external thermal insulation

It is easier when using external thermal insulation to guarantee the continuity of the insulation and reduce the number and impact of thermal bridges in the external wall (IEA 2010). However, eliminating all the thermal bridges during a renovation can be a complicated task, and they can rarely be removed or designed out completely. The following figure shows some typical thermal bridge problems for external thermal insulation and possible corrective measures for each of the problems which should be considered.

Table 4. Thremal bridge problems for external thermal insualtion and their possible solutions (IEA 2010).

	Problems	Possible solutions
Window frames		
Overhangs		
Gutter		
Terace		It doesn't exist simple solution for this type of construction detail. *Two typical solutions are:* *- vacuum insulation on top (if heated space underneath)* *- cut balcony and rebuild with a new independent construction, thermally separated*

Air tightness in external thermal insulation

Poor air tightness of external wall can cause unwanted air infiltration through the walls, which increases energy losses and can create a risk of condensation inside the wall, known widely as interstitial condensation.

One typical source for air leakage is the connection area between the external wall and windows, doors, and other service penetrations. These connections can be re-sealed when installing external insulation relatively easily. Other sources of unwanted air-leakage are cracks and fissures in the enclosing surfaces and porous materials used in walls. (IEA 2010)

Porous materials, such as bricks, concrete, or mineral wool, which are permeable to air are often used in wall structures, if these materials are not protected with an airtight layer, such as coated plasterboard, parge coat of render or paint, then the air can flow through the structures causing thermal losses. (IEA 2010)

Different concepts for applying external thermal insulation layers

External thermal insulation means the introduction of a thermal insulation layer, which is installed on the outer surface of an external wall. These systems can be implemented in most cases directly on top of the existing structure, however, in some cases it might be necessary to remove the cladding and existing thermal insulation before applying or undertaking some preparatory repairs.

This study divides the external thermal insulation into four different categories, which are

- External thermal insulation composite systems (ETICS)
- Ventilated façades
- External thermal insulation panel systems
- Insulating plasters.

Each of these concepts will be discussed, and examples of different concepts will be provided, in the following chapters.

External thermal insulation composite systems (ETICS)

External thermal insulation composite systems consist of insulating material, reinforcement layer and a finishing layer. The insulation layer is attached to the wall either by an adhesive or by both adhesive and mechanical fixings. The top layers with rendering, reinforcement and surface treatment are applied directly on the insulation layer without any air cavities in between the layers.

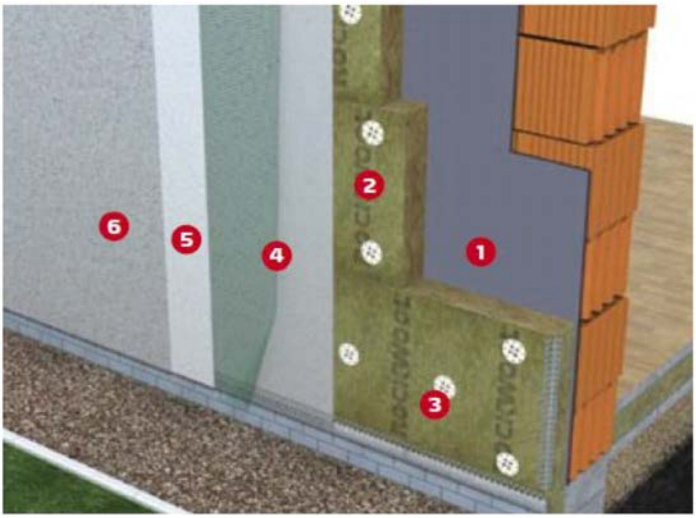
In various parts of Europe, these systems are called ‘external thermal insulation composite systems’ (ETICS). Also other names exist, since in Ireland and United Kingdom term ‘external wall insulation systems’ and in the United States and Canada ‘exterior insulation and finish systems’ (EIFS) are used. It should be noted that the abbreviation EIFS also translates to ‘external insulation of façades’ or ‘Externally Insulated Façade System’ in Central Europe, both of which mean the same type of system. (Künzel et al 2006)

External thermal insulation composite systems (ETICS) are the most commonly used method of improving the thermal protection of external wall structures in Europe. It is the most popular thermal insulation system in countries such as Germany, Poland, Italy, Netherlands and Portugal (Wetzel and Vogdt 2007, Plewako et al. 2007, Brunoro 2007, Ravesloot 2007, Bragança et al. 2007)

The insulating material of ETICS is typically polystyrene or mineral wool, which is attached to the existing structure either by bonding, mechanical fixings or a combination of these two. Also rail mounted systems can be used as they are applicable if the surface is unfavourable for the other options. (Wetzel and Vogdt 2007)

Image below Figure 1 shows an example of an ETICS and Figure 2 shows the composition of the system.

Figure 1. Façade before and after installing external thermal insulation (Rockwool).



1. Primary fixing layer
2. Insulation
3. Mechanical fixing
4. Basecoat
5. Reinforcement mesh
6. Finish Coat

Figure 2. Example of a bonded and doveled mineral fibre system. (Rockwool)

<u>Ventilated façades</u>

External thermal insulation panel systems consist of an insulating material inside a façade panel. The panels are usually made of metal (i.e. aluminium or steel) and filled with a thermal insulation, such as EPS or mineral wool. Panel systems are used, for example, in France in approximately 10% of all façade renovations. (Groleau 2007)

The panel systems can be attached to a new, lightweight supporting frame that is fixed to the existing wall. Or if preferred the panels can be fitted to an existing structural frame where the original panel system needs to be replaced. (TATA)

One of the benefits of panel insulation is that the panels can be relatively large (up to 12 m long), which speeds up the installation process.

Figure 3 shows an example of a ventilated façade and Figure 4 shows the composition of the system.

Figure 3. Example of a ventilated facade system. (Vetisol ATLAS)

Figure 4. Structure of a ventilated façade. (Vetisol ATLAS)

External thermal insulation panel systems

External thermal insulation panel systems consist of insulating material inside a façade panel. The panels are made of metal (i.e. aluminium or steel) and filled with a thermal insulation, such as EPS or mineral wool. Panel systems are used, for example, in France in approximately 10% of façade renovations. (Groleau 2007)

The panel systems can be attached to a new, lightweight supporting frame that is fixed to the existing wall. On the other hand, the panels can also be fitted to an existing structural frame where original panel system needs to be replaced. (TATA)

One of the benefits of panel insulation is that the panels can be relatively large (up to 12 m long), which speeds up the installation.

Figure 5 shows an example of a ventilated façade and Figure 6 shows the composition of the system.

Figure 5. Example of a panel insulation system. (Vetisol CLIN).

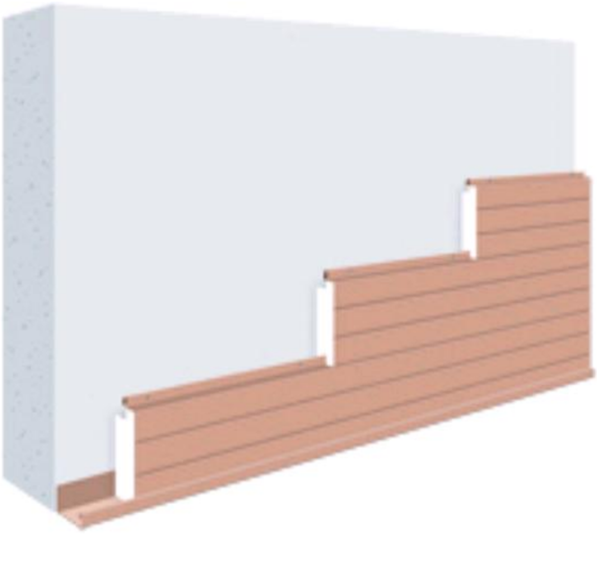


Figure 6. Structure of a panel insulation system. (Vetisol CLIN).

Insulating plasters

Insulating plasters are a form of insulation, where the insulating material is sprayed directly onto the existing wall structure.

The benefits of these systems is that they can help fix irregularities and defects in the existing wall and can be easily applied to irregular or complicated facades. They do not need additional adhesive for fixing. (Protherm 2011)

In one example system the insulation material is a lightweight insulation plaster, which is made of polystyrene (PS) beads mixed with plaster. The plaster is prepared on site with a plastering machine and sprayed on the wall in multiple layers. The surface layer is leveled and a coating layer is applied on top of it. The coating layer is then finished with paint.

Figure 7 shows an example of a ventilated façade and Figure 8 shows the application of the system.

Figure 7. Insulating plaster finished with paint (Protherm 2011).

Figure 8. Applying insulating plaster (Protherm 2011).

3.2 Internal thermal insulation

The internal insulation concept is described in the following.

Table 5. Internal insulation concept.

NAME OF THE CONCEPT **Internal thermal insulation system**				
APPLICATION				
EXISTING WALL TYPES			REFURBISHED WALL	
	Building types	Climatic zones	Insulation type	Internal layer type
All existing wall types are possible		All climatic zones	Alternative insulation types and thicknesses Rockwool, Glass wool…etc	Alternative types for example gypsum board with paint, Wall paper…etc

DESCRIPTION
Internal insulation on top of existing inner wall structure:

- new insulation is fixed on old inner surface
- new wall covering layer installed.

Other alternatives

- Type of existing structure
- Quality and performance properties of materials
- Thickness of insulation and other layers
- Existence of tight layers such as plaster etc.
- Quality of surface material.

The main factor affecting the efficiency of internal insulation is the available space for insulation, this is because the insulation thickness of a material relates closely to its performance, the thicker the material the better it performs.

Internal insulation has a lot to gain from high-performance insulation materials, since the insulation thickness is often limited. Materials like polyurethane (PU) and phenolic foam (PF) can give higher U-values than mineral fibre or cellulose insulation with same insulation thicknesses. (Energy Saving Trust 2005)

The internal thermal insulation lacks the weather cover that protects the existing structures on external insulation systems. It can also add stress to the outer surface of the wall by lowering the temperature of the external walls. When the influence of the indoor climate is diminished, freezing temperatures are more likely to occur on the external façade. (IEA 2010)

Risk of condensation

Additional internal insulation creates a barrier between the existing wall and the indoor climate when installed, preventing the external wall from warming up. Due to this the structures' dew point (the temperature in which the water vapour condensates) shifts towards the inside of the wall. In order to prevent water vapour from condensing between existing wall and the insulation, the least permeable materials should be placed on the warm side of the insulation and a water vapour barrier should be placed between the insulation and the interior finishing. (IEA 2010)

Thermal bridges and air tightness in internal thermal insulation

When installing internal insulation the joints between insulation and vapour barrier should be seamless to avoid the risk of condensation. This is important especially at the junctures i.e. between walls and between walls and ceilings. However, this might prove difficult and require detailed studies and design of the junction points. (IEA 2010)

The following figure shows some problematic details considering thermal bridges and vapour barrier with their possible solutions. (IEA 2010)

Different concepts for applying internal thermal insulation

Internal thermal insulation concepts can be divided into two main types, based on the fixing method of the insulation. The insulation can be fixed either to the existing structure or to a freestanding studwork.

Insulation systems which are discussed here in detail are:

- plasterboard laminates fixed to the existing wall
- insulation boards fixed to the wall with timber battens and covered with plasterboard
- insulation boards fixed to the wall and plastered directly
- insulation fixed to a freestanding studwork.

Plasterboard laminates

Plasterboard laminates are widely used and easy to install. The available products' insulation thicknesses might cause a problem, if very high improvements in thermal insulation are targeted. (EST 2005)

As an example, one manufacturers' plasterboard laminate product range includes thicknesses from 30 to 90 mm. With a plasterboard thickness of 10 mm, this gives insulation thicknesses from 20 to 80 mm.

Figure 9. Plasterboard laminated insulation. White layer is plasterboard, brown layer is insulation. (Gyproc 2010).

<u>Insulation boards covered with plasterboard</u>

The difference between this system and the plasterboard laminates is that the system components are installed separately. The installation is not as fast, but the benefits are lower cost and that the insulation thickness can be chosen freely.

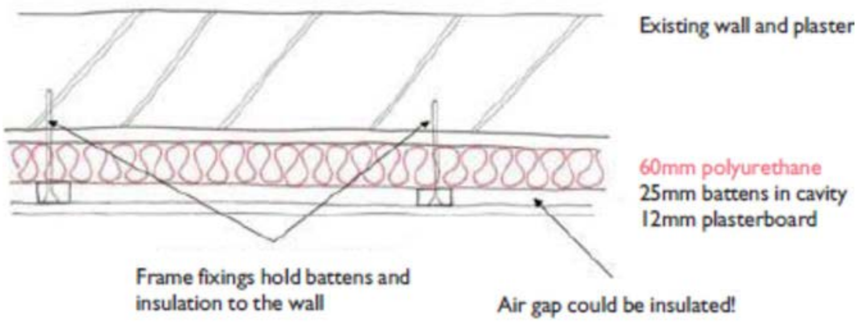


Figure 10. Insulation board fixed to the wall with timber battens. (EST2005)

<u>Insulation boards fixed to wall and plastered directly</u>

Insulating wall internally with directly plastered insulation boards is quite similar to the ETICS-system. However, this system is lighter, as there is no need for anchoring of the boards. Compared to the previous two systems, chamfered corners are easier to make with this system.

The insulation work starts with rendering the wall with cement or lime slurry and then rubbing the insulation boards into place to avoid air pockets. The top coat consists of two coats of base coat plaster. (EST 2005)

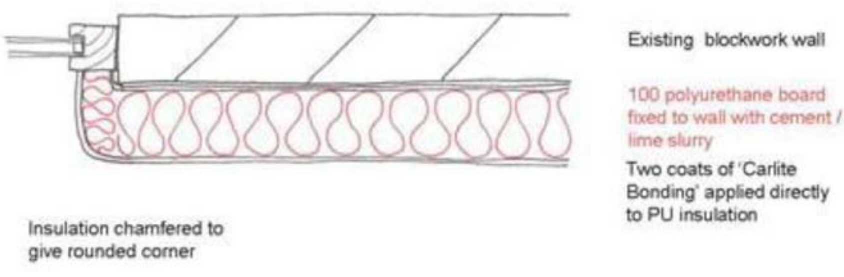


Figure 11. Insulation boards fixed to wall and plastered directly. (EST 2005)

Insulation fixed to a freestanding studwork

Freestanding studwork gives the possibility to leave an empty air cavity behind the additional thermal insulation layer. This cavity might be needed for ventilation, if it is suspected that moisture can penetrate the outer wall structure. The disadvantage of this kind of ventilated structure is that it takes even more of the limited space that is available for installing the internal insulation than the other solutions.

Freestanding studwork can be made from steel or wood. The benefit of steel studwork is the faster installation speed. However, due to higher thermal conductivity of steel, the steel studwork can cause significant thermal bridges. (EST 2005)

According to EST (2005) a 100 mm steel studwork wall can achieve U-value of less than 0.31 W/m^{2}K if thermal bridges are not concerned, giving it a better U-value than that of a similar wood studwork wall (0.39 W/m^{2}K). However, when the thermal bridges are taken into account, the U-value for a steel studwork wall rises to 0.54 W/m^{2}K. (EST 2005)

Figure 12. Installation of freestanding steel studwork internal insulation with an air cavity. (EST2005)

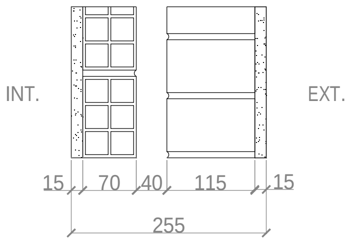
Figure 13. Installation of freestanding wood studwork internal insulation with an air cavity. (EST2005)

3.3 Cavity insulation

The concept for cavity insulation is described in the following.

Table 6. Cavity insulation concept.

NAME OF THE CONCEPT **Cavity insulation – Case C**				
APPLICATION				
EXISTING WALL TYPES			REFURBISHED WALL	
	Building types	Climatic zones	Insulation type	
All existing cavity wall types				
	Small houses, Terraced houses	Cfb, Cfa, Cfbw	Possible insulation types and thicknesses Rockwool, Glass wool…etc	

<table>
<tr>
<td>

Cavity width 40–120 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td colspan="5">DESCRIPTION
Prior walls must be in good state and without frost damage. Mortar joints should not have more than hairline cracking
• A series of holes is drilled to the outer leaf of the cavity wall, diameter about 1.4 cm.
• The insulating beads or other insulating materials are injected/ blown into the cavity. The insulation thickness depends on the width of the cavity. Cavity will normally have a width of 40 mm–120 mm (?).
• The outer structure is also made good and all necessary air vents are checked to ensure they are still working as designed.
Other alternatives
• Type of existing structure.
• Quality and performance properties of insulation materials.
• Thickness of insulation and other layers.</td>
</tr>
</table>

Cavity insulation is a simple way of insulating cavity walls during renovation. It is a popular method of additional insulation in countries, where cavity walls are common. It is widely used i.e. in the Netherlands, where cavity insulation is the most popular insulation system after ETICS. (Ravesloot 2007)

The most common way of installing the material is by bulk material insulation, where the cavity is filled by blowing a bulk of insulating material into the wall cavity. Also foam injection techniques exist, but they are not as commonly used due to the more advanced installation process. (IEA 2010)

The occupants can remain in the building while the cavity insulation is installed. This way it will cause minimal disturbance.

Figure 14. Installation of cavity insulation (EST 2007).

Thermal bridges and humidity

Cavity insulation may not be effective in all the cases, due to the thermal bridges between the two wall wythes. This might be the case with old cavity walls where the wythes may be linked together with many connecting bricks that additional internal insulation becomes profitless. Therefore, the size and type of thermal bridges needs to be inspected when planning renovation by filling the cavity. (IEA 2010)

When the cavity is filled with insulating material, the transportation of humidity out of the masonry must be ensured (Ravesloot 2007). The insulation material itself must not be capillary or hydrophilic and it must also be permeable to water vapour (IEA 2010).

The following images show typical thermal bridge problems with cavity insulation and possible solutions for them.

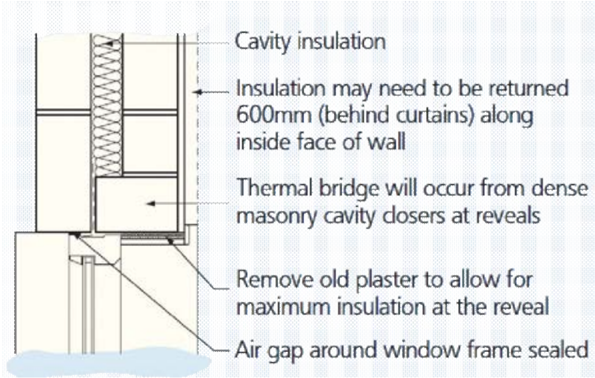


Figure 15. Thermal bridges at reveal (EST 2007).

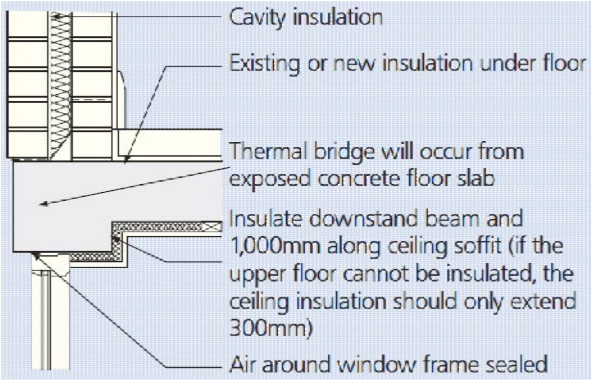


Figure 16. Thermal bridge at floor slab (EST 2007).

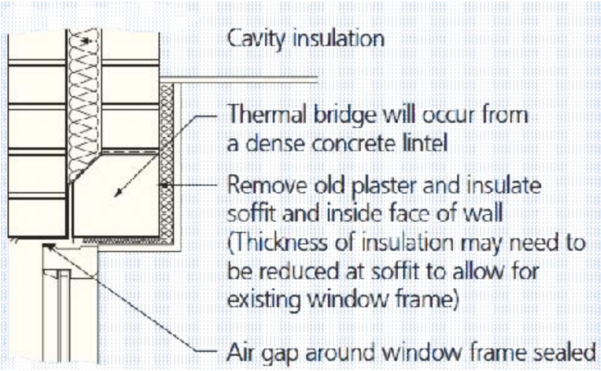


Figure 17. Thermal bridge at lintel (EST 2007).

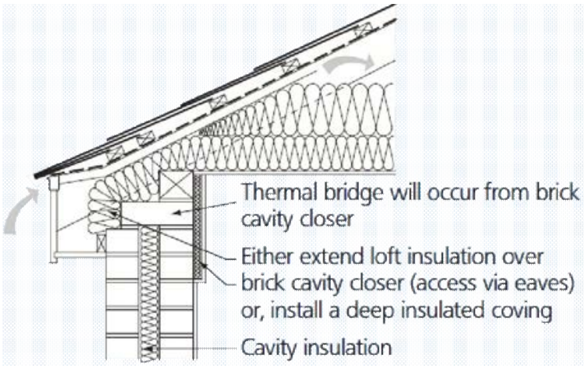


Figure 18. Thermal bridge at eaves (EST 2007).

<u>Insulating with bulk material</u>

The following image visualises the installation of one specific cavity insulation material, EcoBead. The beads are injected into the cavity together with adhesive, which bonds the components into a solid mass. Each of the beads has single point of contact with the surrounding beads, which allows the cavity to breathe and the penetrating moisture to drain away. (Springvale 2011)

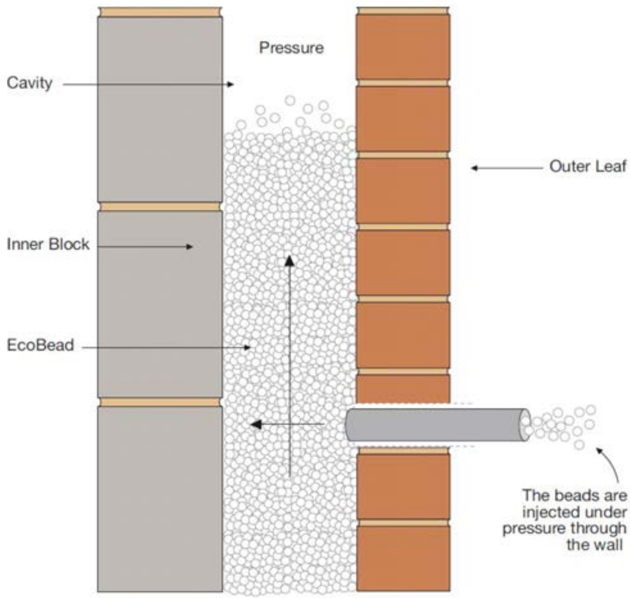


Figure 19. Filling the cavity with insulating beads. Source: Springvale.

Insulating with foam

Foam injection techniques are not as commonly used today as bulk material insulation, since they require precise measuring of the filling and foam's expansion to avoid the facing to be pushed out of shape by too much pressure. (IEA 2010)

This is mostly due to the installation process, which requires more advanced methods than the bulk insulation technique. While insulating the cavity, the filling of the cavity and the foam's expansion needs to be measured in order to avoid deformations on the façade due to excessive pressure.

3.4 Combined wall insulations

In some cases, a combination of different refurbishment technologies may be justified. However, in most of the cases, the use of a single system is usually a better solution. Some possible combinations of external, internal and cavity insulation are discussed in the following. In some cases a combination of different refurbishment technologies may be justified. However in most of the cases, the use of a single system is usually a better solution. Some possible combinations of external.

Internal insulation + External insulation

In general, combining internal and external insulation technologies does not bring much benefits compared to the scenario, where either the internal or external wall can be insulated. If, for example, external insulation can be applied, it is more reasonable to add insulation thickness to the external insulation layer than add another insulation layer on the internal side of the wall.

However, in some cases both internal and external insulation may be used in different parts of a building. This might be the case in urban environments, when the front façade needs to be insulated internally (to avoid changes in the appearance of the façade) and the back façade can be insulated externally. (IEA 2010)

To ensure the functioning of mixed insulation, thermal bridges need to be minimised. The places where wall insulated from outside meets a wall insulated from the inside should also have overlapping insulation (both internal and external insulation). (IEA 2010)

Internal insulation + Cavity insulation

In some cases, when the façade of a building may not be altered, but a highly efficient additional thermal insulation is needed, combining cavity insulation with internal insulation might be a viable option. By insulating the cavity, the insulation thickness of the inner insulation layer can be reduced. However, this method is not commonly used. (EST2005)

<u>External insulation + Cavity insulation</u>

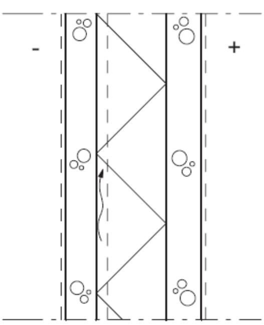
Combining external insulation with cavity insulation may be used in some cases. When a cavity is insulated and thermal insulation is applied also externally, the thickness of external insulation layer can be reduced to gain the same U-value. (EST 2005)

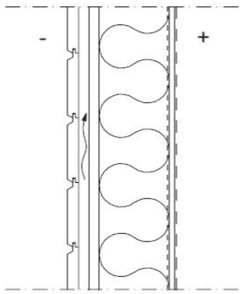
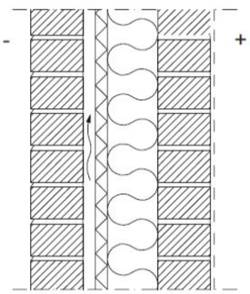
On the other hand, a thin external insulation layer can be added to enhance the insulating capability of cavity insulation, and to protect the outer wall from rain penetration problems. (EST 2005)

3.5 Technologies for replacing existing walls

The concept for replacing refurbishment concept is described in the following.

Table 7. Replacement insulation concept.

<table>
<tr><td colspan="5">NAME OF THE CONCEPT
Example for: Replacing renovation (replacing façade or façade with an old insulation layer) (R)
Two alternatives:
• Repairing to match the original
• Repairing with a new façade type.</td></tr>
<tr><td colspan="5">APPLICATION</td></tr>
<tr><td colspan="3">EXISTING WALL TYPES</td><td colspan="2">REFURBISHED WALL</td></tr>
<tr><td></td><td>Building types</td><td>Climatic zones</td><td>Insulation type and thickness</td><td>Façade type</td></tr>
<tr><td colspan="3">Sandwich element</td><td colspan="2"></td></tr>
<tr><td>
For example existing type: 80 mm 90 mm 30 mm</td><td>Multi storey</td><td>Alternatives according to the SUSREF climate zones:
For example: Dfb, Dfc,Cfb, Cfa</td><td>Alternative types and thicknesses
For example Rockwool,
Glasswool,
Polyurethane
Polystyrene,
Other types</td><td>Alternative façade types
For example:
concrete with ceramic plate, different boards like concrete, natural stone, polymer, brick, rendering or panels like wooden panel or PV panel installation etc.…</td></tr>
<tr><td colspan="3">Load bearing wood structure (wooden frame)</td><td colspan="2"></td></tr>
</table>

	Small houses	For example: Dfb, Dfc	Alternative types and thicknesses For example Rockwool, Glass wool, Cellulose wool, Other types	Alternative façade types: Wood, rendering, etc…
			REFURBISHED WALL	
	Small houses	Dfb, Dfc Cfb, Cfa, Cfbw	Alternative insulation types and thicknesses Rockwool, Glass wool, Polyurethane Polystyrene..etc	Different new facade types like: Brick, concrete, natural stone, polymer rendering wooden panel...etc

DESCRIPTION

Replacing façade and insulation + new insulation and facade

- old outer layer removed
- old insulation material possible removed
- retrofit insulation is fixed on old insulation or on inner layer
- new outer layer (mortar, board, brick or concrete, etc) installed.

Other alternatives

- Fixing mechanisms
- Existence of air cavity
- Quality and performance properties of materials
- Quality of insulation material
- Thickness of insulation and other layers
- Existence of tight layers
- Quality of surface material
- Rainfalls, temperatures.

Technologies for replacing existing walls or parts of them are large-scale renovations. If the walls to be replaced are non-load-bearing, they may be completely replaced in some cases. Especially curtain walls of high-rise buildings or parts of walls in residential blocks of flats may be suitable for complete replacement. (SUSREF 2.1)

In the case of load-bearing walls, only the existing façade and insulation layer are usually removed and the inner load-bearing layer is left in place.

Replacing refurbishment technologies may be the only means of refurbishment if insulation layer has excessive microbe growth or the façade or its anchoring has massive structural damage. Replacing technologies may also be used if an especially long service life is wanted or if the wall would become too thick with additional external thermal insulation. Replacement also enables hidden damages to be fixed. (Haukijärvi 2006)

Replacing refurbishment technologies give a lot of freedom in selection of the new wall structure. If non-load-bearing walls of a building are completely removed, the new wall structure can be chosen freely. In case of load-bearing walls, all the methods presented in the section “technologies for applying external thermal insulation layers” can be used for new external layer, once the existing façade and insulation are removed.

4 Description and assessment method of parametres

This section of the report describes generic concepts for the refurbishment of external walls and presents the assessment results of the concepts using the parameters set by the project team.

Concepts and assessment criteria are covered in the assessment of the refurbishment concepts:

Aspects	1. Durability (focus on moisture) 2. Need for care and maintenance 3. Indoor air quality, acoustics + thermal comfort 4. Impact on energy demand for heating 5. Impact on energy demand for cooling 6. Impact on renewable energy use potential (use of solar panels etc.) 7. Environmental impact of manufacture and maintenance 8. Life cycle costs 9. Aesthetic quality 10. Effect on cultural heritage 11. Structural stability 12. Fire safety 13. Buildability 14. Disturbance to the tenants and to the site 15. Impact on daylight.
Refurbishment types	Concept external insulation (E) – New outer service with retrofit insulation o Case E1 – insulation fixed without air gap o Case E2 – insulation fixed with air gap and wind protection. Concept internal insulation (I) - New inner insulation with new inner layer. Concept cavity wall insulation (C) – insulation into cavity. Concept replacing renovation (R) – Old outer layer removed and new layer with additional insulation installed.
Buildings types	A. Small houses B. Terraced houses C. Multi-storey.
Climatic zones	• Cfb – temperate without dry season, warm summer • Cfbw – temperate without dry season, warm summer and windy

<table>
<tr><td></td><td>(influence of wind-driven rain)
• Csa – temperate with dry, hot summer
• Dfb – cold, without dry season and warm summer
• Dfc – cold, without dry season and with cold summer.
However, in some cases a less number of climatic conditions are considered.</td></tr>
<tr><td><u>Wall types</u></td><td>
<table>
<tr><td>Wall type</td><td>Relevant in climatic zones</td><td>Relevant in building types</td></tr>
<tr><td>W1- Solid wall (brick, natural stone)</td><td>1, 2</td><td>A</td></tr>
<tr><td>W2-Sandwich element (concrete panel + concrete panel)</td><td>2, 3</td><td>C</td></tr>
<tr><td>W3- Load bearing wood structure (wooden frame)</td><td>2, 3</td><td>A, B, C</td></tr>
<tr><td>W4- Load bearing cavity without insulation (brick + concrete block)</td><td>2</td><td>A, B, C</td></tr>
<tr><td>W5- Insulated load bearing cavity (concrete block + concrete block)</td><td>2</td><td>A, B, C</td></tr>
<tr><td>W6- Non-load bearing cavity (hollow brick + perforated brick)</td><td>1</td><td>A, C</td></tr>
<tr><td>W7- Non-load bearing concrete block without insulation (hollow brick + concrete block)</td><td>1</td><td>A, C</td></tr>
</table>
</td></tr>
</table>

<u>Suitable solutions</u>

Wall type	Cfb	Cfbw	Cfa	Dfb	Dfc
Solid wall (brick, natural stone)	E,I	E,I	E,I	I	I
Sandwich element (concrete panel + concrete panel)	E,I,R	I	E,I,R	E,I,R	E,I,R
Load bearing wood structure (wooden frame)	I	I	I	I,R	I,R
Load bearing cavity without insulation (brick + concrete block)	E,I,C	E,I,C	E,I,C	I	I
Insulated load bearing cavity (concrete block + concrete block)	I,C	I,C	I,C	I	I
Non-load bearing cavity (hollow brick + perforated brick)	E,I,C	E,I,C	E,I,C	I	I
Non-load bearing concrete block without insulation (hollow brick + concrete block)	I	I	I	I	I

4.1 Durability assessment

The building elements and any subsequent joints in the building envelope must withstand different loads and stresses. The load carrying ability is typically the main task of external wall structures, but exterior walls also protect the internal room space from the outside climate, and as a weather barrier. The interactions of these factors are shown in Figuare 20. The effect of exposure to the weather results in different types of stress, which rarely result in catastrophic failure but a gradual deterioration in performance.

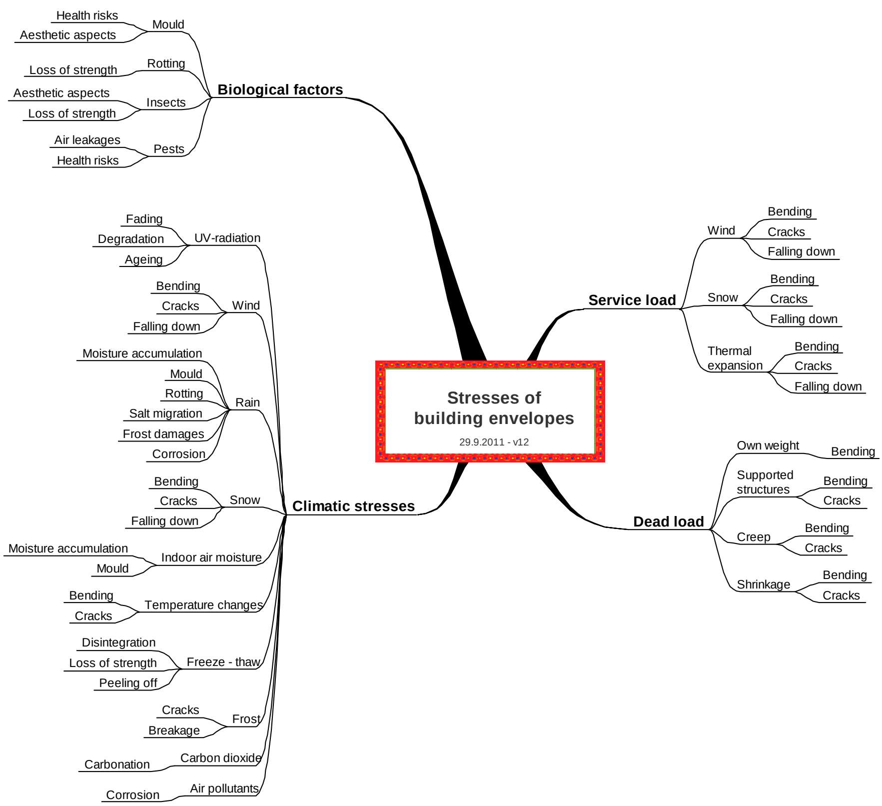


Figure 20. Loads and stresses of a building envelope and their affect to building materials.

Figure 21 indicates a range of typical factors that can result in building materials and components failing the load bearing strength are the easiest and most accurate to design and predict how they will perform. It is also possible to predict moisture flow through a wall, but not to the same level of accuracy or certainty.

Certain factors of reduction in performance are almost impossible to predict with an degree of certainty such as degradation of polymers, and, salt migration etc. These life shortening phenomena are best avoided or the risk of failure minimised by selecting suitable building materials and components.

Software models on how to calculate the durability of concrete in exterior climates do exist, but these specifically look at frost damage, carbonation and corrosion of any reinforcement used. .

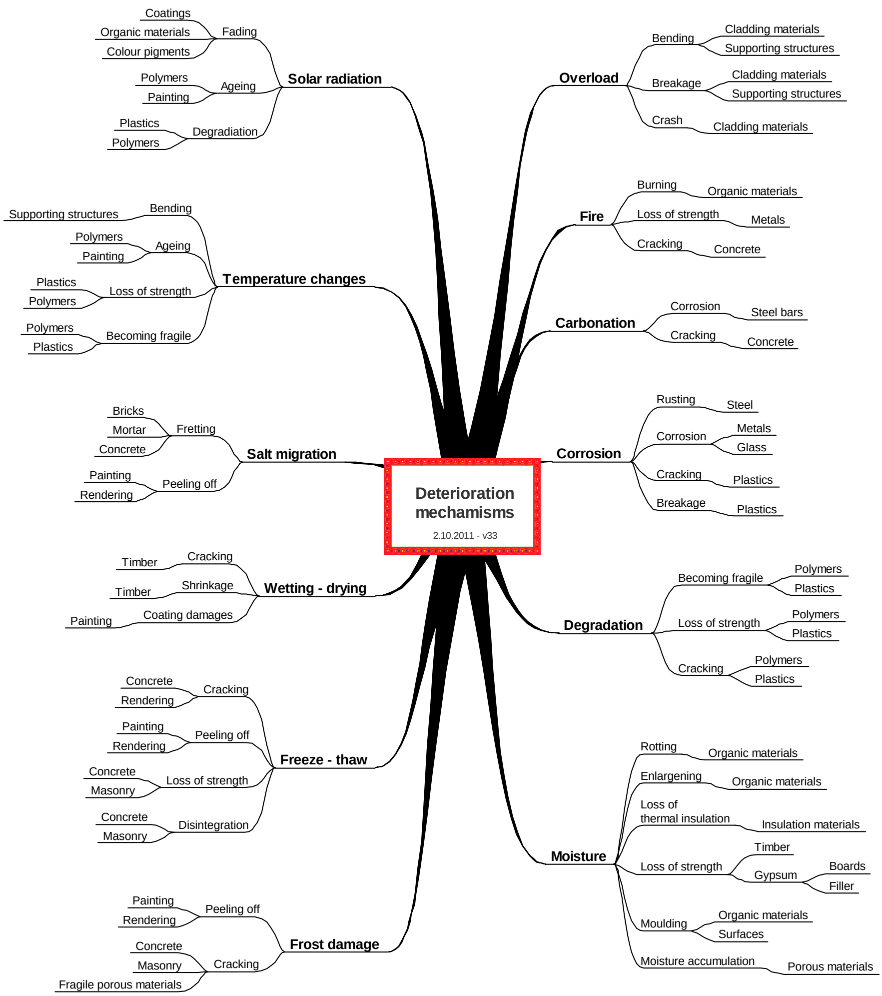
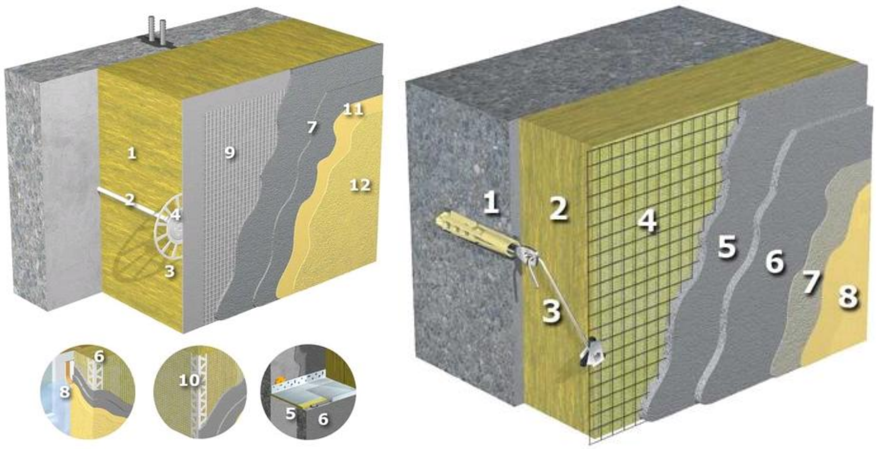


Figure 21. Causes of deterioration processes of a building envelope.

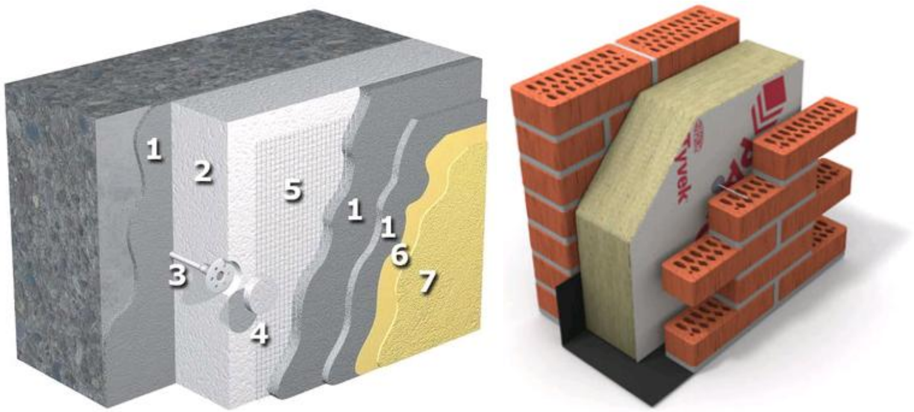
4.1.1 Mechanical strength and stability

The mechanical strength of a structure is relatively straight forward to calculate if the material properties of the construction are known. In many cases it is the metal reinforcement that is corroded, resulting in the concrete carbonating and cracking. With older existing properties it is unusual for the material properties to be known with any accuracy without expensive sample testing. Refurbished walls and windows have to carry not only the original loadings but also the additional imposed load of any added material layers. It is important that the correct Fixings and connections between a new outer surface layer and an original wall are sufficiently designed to prevent buckling and collapse of the layer. The loads of the new and the old fixings are mainly dead load so any new works should consider that building regulations are most likely to have been changed since the building was constructed, and therefore the fixings of the original wall must be inspected and checked for structural integrity. The following Figure 22 and Figure 23 show typical methods of fixing a new layer.



(source: Weber Saint Gobain) (source: Weber Saint Gobain)

Figure 22. Fixings of mineral wool and rendering with float and set.



(source: Weber Saint Gobain) (source: Paroc Oy)

Figure 23. Fixings of mineral wool insulated brick wall and polystyrene insulated wall covered by rendering with float and set.

The actual strength and stability design is based on national building codes. European standards will replace national building codes within a few years. These standards specify European wide design principles and they can be applied already alongside national building codes. The national demands based on climatic conditions etc. are shown on NA appendix pages in the Eurocodes. The Eurocodes are divided to ten main categories and these standards may consist of several parts. The main categories are:

- EN1990 Eurocode 0: Basis of structural design
- EN1991 Eurocode 1: Actions on structures
- EN1992 Eurocode 2: Design of concrete structures
- EN1993 Eurocode 3: Design of steel structures
- EN1994 Eurocode 4: Design of composite steel and concrete structures
- EN1995 Eurocode 5: Design of timber structures
- EN1996 Eurocode 6: Design of masonry structures
- EN1997 Eurocode 7: Geotechnical design
- EN1998 Eurocode 8: Design of structures for earthquake resistance
- EN1999 Eurocode 9: Design of aluminium structures.

4.1.2 Moisture behaviour

The major cause of building envelope failure is the effect of water in the form of wind driven rain or excessive moisture content of the building materials. Most building materials and components have a capability to absorb some water for a defined period of time without deteriorating, and subsequently dry out in the summer or drier months. The key issue is the critical moisture content of different materials. The level of moisture that can be absorbed is material specific, for example some highly porous materials (such as timber and aerated concrete) can absorb a lot of moisture without risking deterioration, but others such as mineral wool and plastic foam insulation materials are capable of absorbing little moisture. Extensive modelling of this phenomena has been undertaken in the Susref project, but is should be noted that these simulations are based on a one dimensional model and the structures are assumed to have no apparent defects, in reality there will always be some defects such as air infiltration. The direction of air flow and speed affect how well a wall structure is performing and do alter the risk of deterioration. It is difficult to accurately factor these parameters exactly when judging the moisture behaviour in a purely theoretical basis. What is apparent from the modelling and analysis undertaken is that the accuracy of the simulation is very much determined by the material properties and the climatic data used as input data.

The moisture behaviour of the different refurbishment methods were evaluated using WUFI 1D and were undertaken using climatic data from five European cities which represent European climate from cold Nordic to warm Mediterranean climate as decided in an earlier work package of the Susref report. The selected cities are shown in Table 8.

For a proper evaluation of the most critical factors of refurbishment methods on any given wall type, it is essential to know the wall orientation which is exposed to greatest range of weather variations including driven rain, wind and solar radiation. The maximum water content for a typical reference wall was calculated in each of the cities, and then remodelled using four basic orientations; the orientation which was exposed to the greatest range of weather exposure was then selected for use in further simulations (Table 8).

Table 8. The maximum water absorption from driven rain in a typical reference wall facing to different orientations in selected cities. The bold figures show the walls that have the greatest water content and risks.

	Frankfurt	**Jyväskylä**	**Krakow**	**Modena**	**Oostende**
Orientation	**Germany**	**Finland**	**Poland**	**Italy**	**Belgium**
South	**32.03**	**30.36**	18.72	19.32	**30.92**
East	13.81	23.01	25.06	**31.16**	28.99
North	16.43	21.49	23.12	25.90	29.43
West	31.79	24.76	**31.13**	30.86	30.78

The affect of exposure to wind driven rain directly corresponds to the height of buildings, the modelling shows that the wind driven rain effect may be three times as high with tall buildings as with low buildings, due to surrounding shelter possibilities in lower buildings. This effectively means that wall structures that are risk free in low rise buildings may be still at risk if in a tall building. The effect of wind driven rain can be seen in easily in Figure 24 below which is an output of Wufi 1D. The moisture levels of exterior walls in lower floors, shown on the left are much lower than the moisture levels in upper floors shown on the right and may lead to health and durability risks.

The refurbishment of exterior wall structures can be divided into three methods of improvement, insulation applied externally to an existing wall, insulation inserted into the cavity of a wall and retrofit insulation fitted to the internal face of the wall. The moisture modelling undertaken indicates that effect is a little different in each case. These cases are studied separately in following chapters.

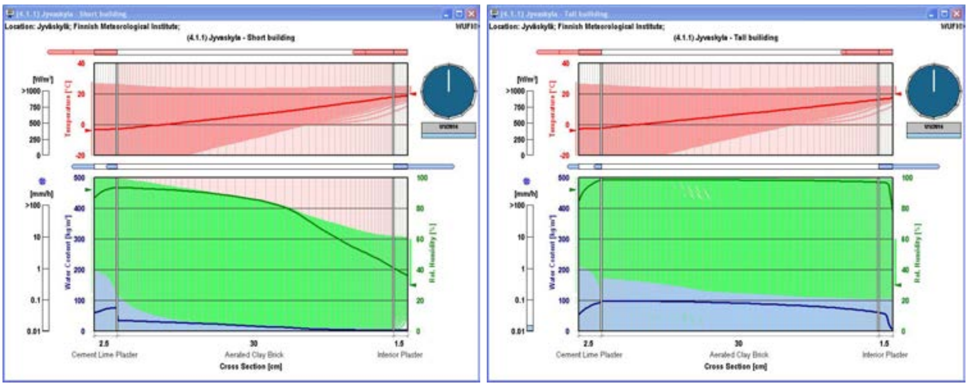


Figure 24. Humidity of an un-insulated wall in Jyvaskyla in a low rise building (left) and at the top floors of a high rise building (right).

Table 9. Studied cases using retrofit insulation on an external surface (E), in a cavity (C) and on an inner surface (I). The Retrofit insulation materials are mineral wool (MW), polyurethane foam (PUR) and expanded polystyrene (EPS).

Location	**Concrete sandwich panels**	**Cavity walls**	**Timber frames**	**Solid walls**
Oostende (south wall)	-	(C) 100 mm PUR (C) 100 mm EPS (C) 100 mm MW	-	BrickS (E1) 150 mm MW,PUR BrickS (E2) 150 mm MW,PUR BrickS (I) 50 mm EPS
Frankfurt (south wall)	(E1) 100 mm PUR (E2) 100 mm MW (R1) 150 mm PUR (R2) 150 mm MW (I) 50 mm EPS	-	(E1) 100 mm MW (I) 50 mm EPS	BrickH/Concr. (E1) 150 mm MW,PUR BrickH/Concr. (E2) 150 mm MW,PUR BrickH/Concr. (I) 50 mm EPS
Modena (east wall)	-	(C) PUR (C) EPS (C) MW	-	BrickS/BrickH (E1) 50 mm MW,PUR BrickS/BrickH (E2) 50 mm MW,PUR BrickS/BrickH (I) 50 mm EPS
Jyväskylä (south wall)	(E1) 150 mm PUR (E2) 150 mm MW	-	(E1) 150 mm MW (E2) 150 mm MW	Concrete (E1) 200 mm MW,PUR Concrete (E2) 200 mm MW,PUR

	(R1) 200 mm PUR (R2) 200 mm MW (I) 50 mm EPS		(I) 50 mm EPS	Concrete (I) 50 mm EPS
Krakow (west wall)	(E1) 100 mm PUR (E2) 100 mm MW (R1) 150 mm PUR (R2) 150 mm MW (I) 50 mm EPS	-	-	BrickH/Concr. (E1) 150 mm MW,PUR BrickH/Concr. (E2) 150 mm MW,PUR BrickH/Concr. (I) 50 mm EPS
Finishing	a) Thin rendering (E1, R1) b) Brick boards (E2, R2)	-	a) Thin rendering b) Timber c) Plywood (Jyväskylä, E2) d) Brick	a) Thin rendering b) Brick boards with air gap c) Brick d) Polymer concrete boards (Jyväskylä, E2)

4.1.3 Modelling of deterioration

Different refurbishment concepts of building facades and external walls were analysed for possible long-term degradation. The analyses were conducted using climate conditions of various European climates as stated previously and with various outer construction materials and various types of thermal insulation materials.

Computer simulation software that was developed at VTT in the 1990s was used to evaluate possible degradation in refurbished concrete facades (Vesikari 1999). Simulation in this context refers to theoretical emulation of temperature and moisture variations in a cross-section of a structure and application of temperature and moisture sensitive degradation models at critical points of the structure. Evaluation of possible mould growth (Viitanen et al. 2011) was also evaluated.

For the purposes of this modelling, the weather data of five different European sites were used in the calculations. The weather data used was the same as that applied in the thermal and moisture mechanical program WUFI for continuity of assumptions and effect. The weather data was transformed to be relevant and applicable to vertical walls.

The VTT software allows the use of different thermal insulation materials and coatings. although the software was originally designed for use on concrete wall construction, other stone materials, such as brick and rendering can also be applied if the heat and water transfer and durability parameters of are known. For concrete materials the maturity of concrete can also be considered when evaluating e.g. water content, temperature and the risk of frost attack. As for frost attack the majority of the risks seem to be related to the immaturity of concrete and possible use of coatings. The coatings modelled will no doubt deteriorate over time and subsequently become more permeable. Deteriorated coatings will probably accelerate the degradation process of concrete.

Although the calculations give seemingly exact degradation rates and service lives they should not be taken as exact information, but predicted performance. This is mainly due to variations in material make up and content, structural condition and weather exposure parameters. So, in reality the actual rate of degradation and the service life will vary from case to case. The results of the simulation seek to show the average values among a great dispersion of values which can be realised with the same material, structural and weather parameters used in the calculations.

Another reason for variation in the outputs could be attributed to simplification of the modelling parameters, as although parameter values used in the calculations are based on some measurements, there is insufficient reliable measurement data available to be certain on their accuracy.

However, the determined degradation rates and service life gives indicative data on the risk of degradation that may happen in refurbished façade walls. The calculated degradation data give also a basis for comparing the relative rate of degradation with different refurbishment concepts and in different parts (climates) of Europe.

Degradation models

Frost attack

In the VTT simulation software the occurrence and propagation of frost damage is evaluated based on the theory of the critical degree of saturation developed by (Fagerlund 1977). Frost damage is assumed to take place when the moisture content of concrete exceeds the critical water saturation characteristics and the temperature descends below freezing point at the same time.

When evaluating the critical degree of water saturation the amount of air porosity and the form of air pore distribution are considered. The air pores are assumed to be filled with water in the order of their size, from the smallest to the largest, and the critical amount of water in the air pores is determined based on the critical distance of air pores based to the Powers theory ($V_{air;\ cr}$). Any changes in the concrete mix design affects the critical amount of water filled air pores (and consequently the critical degree of water saturation).

Carbonation and corrosion

The model used to evaluate the rate of corrosion on the reinforcement includes an initiation period and a propagation period. Initiation of corrosion is assumed to take place when carbonation reaches the depth of any reinforcement present in the structure. Both the rate of carbonation and the rate of corrosion depend on the temperature and moisture content of the concrete.

Carbonation and corrosion of the reinforcement are evaluated taking into account the momentary temperature and moisture conditions in concrete. The rate of carbonation increases when the moisture content in concrete is lowered. Both the carbonation and corrosion rate increase with higher temperatures. The effect of frost attack on the rate of carbonation is also considered in the analysis.

Mould growth

Numerical simulation of mould growth can be used as one of the hygrothermal performance criteria for assessing the building structures. Mould is one of the first signs of excessive moisture content of materials and it may affect the indoor air quality and also result in the degradation of the appearance of the visible surfaces. Mould growth potential can be predicted by solving a numerical value, this is called the mould growth index, and by using the dynamic temperature and relative humidity histories of the subjected material surfaces.

The model was originally based on mould growth on wooden materials but has now been updated to include several other building materials. The model can be used in parallel with heat, air and moisture simulation models or as a post-processing tool.

Concrete parameters

The computer program is able to design the concrete mix based on some design parameters such as the nominal strength, air content and cement type. Many material parameters related to thermal and water transport and degradation depend on the mix design of concrete, with the main parameters governing the frost resistance of concrete is the water/cement ratio and air content.

The maturity time of concrete can be defined, with the water content, temperature (hydration of cement) and material parameters depending on the maturity time of the concrete.

Thermal insulation

The primary function of thermal insulation is to work as a heat loss barrier between indoor and outdoor climate. However, the moisture transferring properties of thermal insulation can differ greatly. For example the water vapour diffusion coefficient of mineral wool is approximately two orders of magnitude higher than that of polyurethane. This is one of the reasons why it is not only highly important to study the performance of different thermal insulations in a refurbishment concept from the moisture technical point of view, but also very interesting. Cumulated or capsulated moisture may be a reason for several degradation processes, such as corrosion and mould growth.

Coatings

Coatings act like a barrier or rain screen against penetration by moisture and aerial gases. They retard the flow of liquid moisture and gases through the surface of concrete in both directions. The capillary water uptake, the evaporation of water vapour from concrete and the diffusion of aerial gases, such as CO_2, depend greatly on any coating properties.

It is assumed that the permeability of coatings is not constant but change with time as a result of ageing and deterioration. Accordingly, the moisture conditions in concrete do not remain the same during the service life of the structure. A coating that deteriorates with time and not recoated in time may increase the risk of frost damage, as the deteriorated coating may let water penetrate the structure which cannot evaporate out, this is a good reason why it is important that any covering or coating should be adequately maintained throughout the building life.

The degradation of concrete facades is a complex function of weather conditions, compass point, indoor conditions, structural composition of the wall, insulation materials, initial moisture conditions and possible coatings. There are also several degradation processes going on at the same time which may have interaction and combined effect, for example frost damage may promote both the carbonation and corrosion of reinforcement. These very complicated processes can hardly be studied by direct exposure tests or laboratory tests. However, computer simulation does allow a possible method for such analyses to be considered.

Climatic variables

For the purposes of the modelling and analysis the outer surface of the wall was assumed to be exposed to all climatic stresses, such as variation in temperature, and the relative humidity of air, solar radiation, wind and (driving) rain. The data of the weather used was hourly temperature, relative humidity, radiation, and rain throughout a year. The climate data sets were the same as those used in the software WUFI to ensure comparisons between results to be assessed.

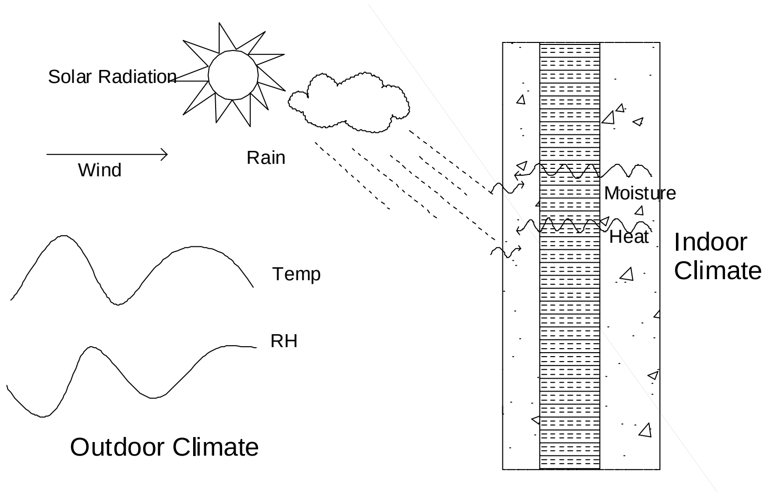


Figure 25. Climate strains of the façade.

Optional geographical sites (defining the weather) were:

- Jyväskylä (Finland)
- Frankfurt (Germany)
- Oostende (Belgium)
- Modena (Italy)
- Krakow (Poland).

The WUFI weather data defines the weather variations of a typical year when delivered on a vertical wall using the worst compass point (south or south-east) as far as exposure rating is concerned. In the VTT software the weather of the year is repeated over and over again until a simulated 150 year period has occurred, covering the whole service life of the structure.

4.2 Environmental impact assessement

4.2.1 Introduction

Environmental impact assessment focuses on the impact of non-renewable energy (energy transmission through the wall and energy consumption of refurbishment materials), non-renewable raw materials (from energy production and refurbishment materials) and especially released greenhouse gases and thus carbon footprint.

Carbon footprint is assessed according to IPCC’s greenhouse gas potentials (2007):

CF = CO_2 + 25*CH_4 + 298 * N_2O

Environmental assessment and GHG's for the building materials, used in refurbishment cases, based mainly on VTT's database. The assessment of these follows the guidelines of relevant ISO standards and ILCD handbook. The material assessment covers life cycle stages from "cradle to factory gate" including information from raw material supply, transportations, manufacturing of products and all upstream processes. Additionally to those also material transportation to the building site is included as the impact from typical transportation distances.

Main parameters which werre used for the assessment of environmental impact and for different wall renovation concepts were:

- Material type (insulation, façade) and properties (specific weight, consumption, thermal conductivity, environmental impact)
- Existing wall type, deterioration rate and corresponding U-value
- Renovation concept and target U-value
- Building location and heating degree days
- Heating type and environmental impact from heating
- Material service lives and need for maintenance.

Energy renovation target level is dependent on building location and need for heating and cooling. Here the generic renovation concepts assessed according to the European climate regions: Nordic, Central- and Southern Europe and heating dealt as heat loss calculation through the wall.

4.2.2 Insulation materials and there properties

For the energy renovation different insulation materials are available. These materials have different thermal properties, different specific weights, thickness and amount needed to ensure same thermal resistance (R-value). Also the environmental impacts from production processes differ; materials which origin is renewable resource or waste are "burden free" materials whereas materials from fossil bases have high burdens. Some materials have less environmental burdens per kg bases, but when thermal performance is taken into account these could cause more burdens per m^2 than others because the material amount and thickness are smaller to achieve the same level of performance. Figure 26 shows the relation between U-value and insulation thickness for the materials which having different thermal conductivity. According to that it could be seen that 100 mm insulation thickness could cause quite a big variation for annual energy consumption (8–50 $kWh/m^2/a$, energy consumption calculated as heat loss through the wall and according to the Helsinki weather data).

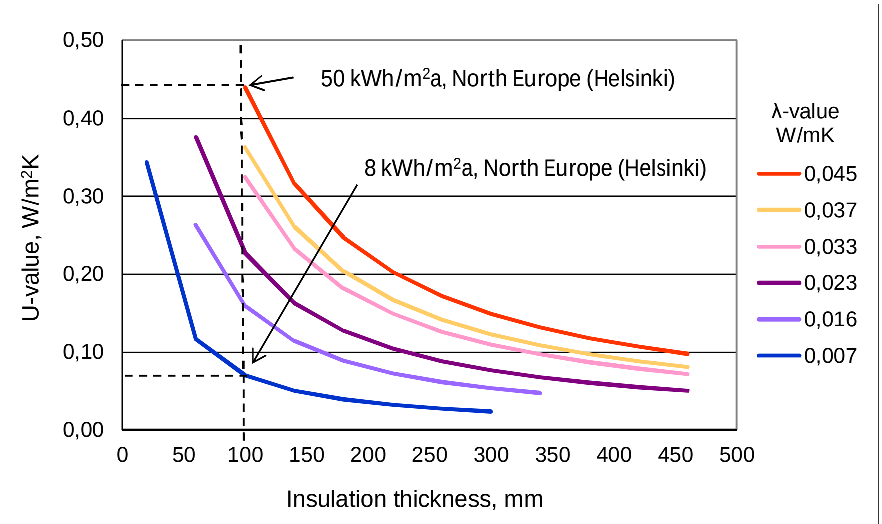


Figure 26. Correlation between U-value and insulation thicknesses for the materials which have different thermal conductivities (λ d).

Table 10 shows some technical parameters for insulation materials.

Table 10. Insulation materials and their properties.

Insulation materials	Thickness mm	Density kg/m^3	Amount kg/m^2	Lambda design W/mK	Resistance m^2K/W
Soft rock wool	100	30	3.0	0.035	2.9
Hard rock wool	100	60	6.0	0.036	2.8
Hard rock wool	100	80	8.0	0.036	2.8
EPS	100	30	3.0	0.036	2.8
Carbon EPS	100	30	3.0	0.031	3.2
PUR	100	35	3.5	0.023	2.8
Sheep wool	100	23	2.3	0.039	2.9

4.2.3 Environmental impact for heating

Major environmental impact comes over the long lasting building lifetimes from energy use (heating, cooling, and electricity). The impacts from building materials have been traditionally small but as the buildings became more efficient in terms of energy use the impact from used materials relatively increases and impact from heating decreases.

Heating systems are moving towards decentralized and smaller solutions and the use of renewable energy sources (for example making use of wind, ground soil, water and solar energy) is growing. As the need for heating energy decreases, large energy production companies face the need for remarkable development programmes regarding the reduction of carbon footprint and changes in pricing methods. This survey doesn't deal with changes in electricity and heat production methods in the near future.

In this calculations space heating is assumed to be mainly gas because this is the heating type which is widely used in different countries and the production method and released emissions is well known. In Nordic countries the energy source in built areas is mainly district heat where also local energy resources are widely utilised. District heat enables flexible energy mix and the carbon emissions varied according to the amount of renewable resources used. Heat plant, which using mostly bio based fuels, CO_2 emissions remains low, and these are for example 20 kg/MWh, whereas plants which using mainly fossil based fuels it could be also as high as 500 kg/MWh.

Table 11 shows the heating modes and their non-renewable raw-material consumption, fossil energy consumption and carbon footprint. The heating modes and their environmental profiles presented in this calculations taking into account pre- and stationary combustion of the fuels, where pre-combustion includes extraction, processing and transportation of the fuels. Environmental profiles for the pre-combustion of gas and heat mix bases on ELCD database and fuel combustion values bases on IPCC Guidelines for Stationary combustion emission values (IPCC 2006)[1]. Electricity Nordel is given as an example of the electricity mix where fossil fuel consumption is small.

Table 11. Carbon footprint, non-renewable raw-material and fossil energy consumption for the heating modes.

Heating mode	Fossil energy, MJ/kWh	Non-renewable raw-material, kg/kWh	Carbon footprint (CO_2 eq), kg/kWh
Gas heating	4.0	0.088	0.271
Average district heat produced in Finland 2008	3.1	0.103	0.210
Electricity (Nordel)	Not measured	Not measured	0.167

1 Guidelines for National Greenhouse Gas Inventories. Vol. 2. Energy. 2006. Chapter 2. Stationary combustion.

4.2.4 Insulation thickness

Environmental impact from different insulation thicknesses are estimated according to the energy and raw material consumption and carbon footprint. Existing building with concrete façade and U-value with 0.44 W/m^{2}K was chosen as an example for renovation. Renovation concept was external insulation with cement lime rendering façade (E1). Three options for rock wool insulation capacity were chosen: additional insulation layer was 100 mm, 200 mm or 300 mm. The efficiency in all environmental parameters varies according to the geographical region.

According to the Helsinki result the fossil energy saving for renovated concrete sandwich element with 100 mm rock wool and rendering façade was 1,952 MJ /wall-m^2/20-year. Additional 100 mm wool layer gave extra heat savings 550 MJ/wall-m^2/20-year and next 100 mm insulation gives heat savings subsequently only 286 MJ/wall-m^2/20-year. In the warmer climate regions (Berlin and Barcelona) energy savings remain much smaller (Figure 27).

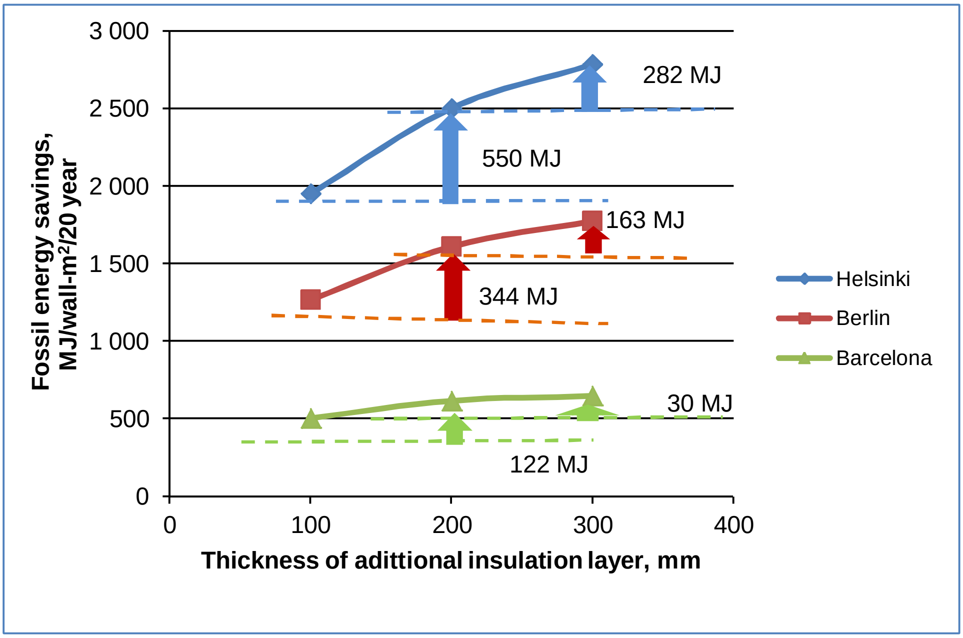


Figure 27. Fossil energy savings in the renovation of concrete element (renovation type: external 3-layer cement-lime render, galvanized steel mesh and additional rock wool insulation). Fossil energy contains gas heating energy consumption and embodied energy from materials used in renovation.

Carbon footprint result depends from saved energy type, but in the same time it depends also from the renovation materials and their production processes.

Energy consumed and emissions released during material production and these have also impact to the value of carbon footprint. Figure 28 shows the result for carbon footprint savings for external renovation concept calculated for the operation time period 20 year and the heating type is gas. According to that it can be seen that carbon footprint savings are very small for Southern countries and in 200 mm and 300 mm rock wool insulation cases. The optimum thickness for Central Europe is 200 mm or less and for Southern Europe is 100 mm or less. In Nordic countries renovations with insulation thickness of 300 mm still saves the reasonable amount of energy and carbon emissions.

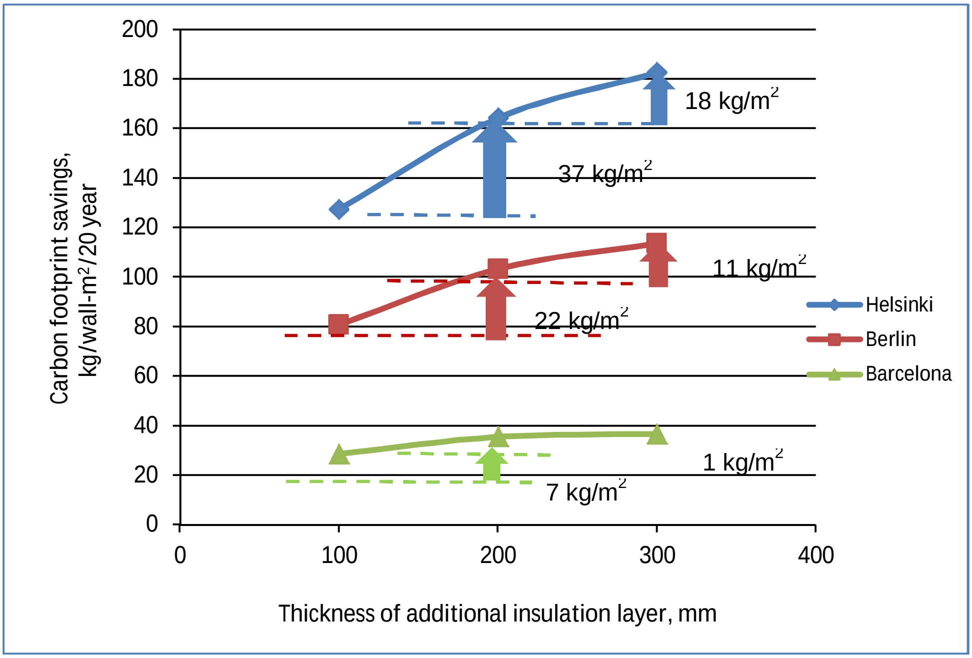


Figure 28. Carbon footprint savings in the renovation of concrete element (renovation type: external 3-layer cement-lime render, galvanized steel mesh and additional rock wool insulation).

<u>Heating type</u>

It is claimed that building materials affect the energy use and emissions roughly so that their share is 5…15% but according to the external renovation concept (Image 30) the material share from the total carbon footprint for the wall renovation can be higher. Material types used in renovation may have a significant meaning and may cause almost half (41%) of the total carbon footprint when the reference period is 20 year (case electricity Nordel and for the case where heat transfer through the wall was small, U-value = 0.10 W/m^{2}K).

According to the result the material share from carbon footprint is very much dependent on the heat production mix and amount of renewables used. Electricity Nordel which gave the highest share to the used materials has the lowest carbon footprint from the heating types studied. Material share can grow almost to 100% for the cases were the heating utilizes renewable energy sources.

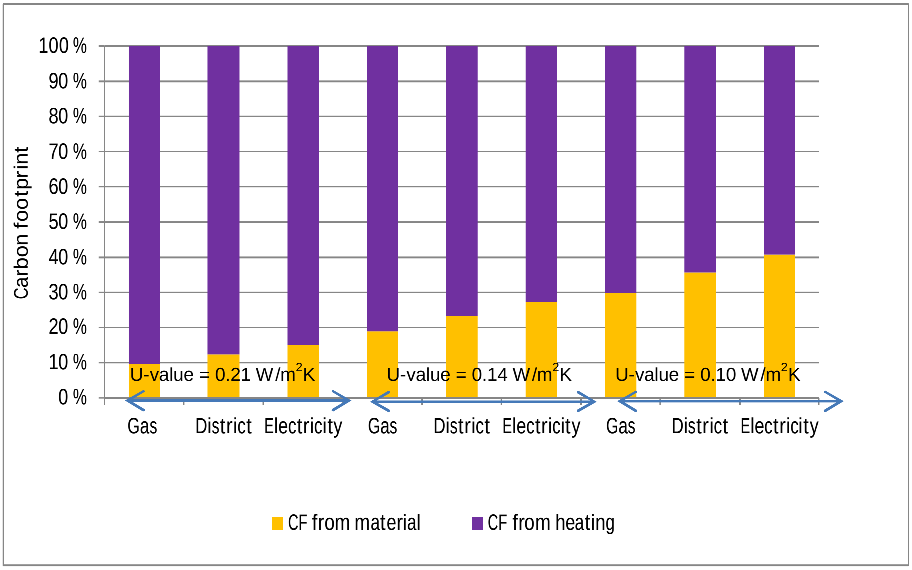


Figure 29. Material share from the total carbon footprint (carbon footprint from renovation materials and heating, time period 20 year and location Northern Europe). Renovation concept is external insulation and renovation case is rock wool with rendering façade).

4.2.5 Raw material consumption

Depending on the building conditions the material consumptions in renovations can be substantial or not. In any case, all renovation processes need new raw-materials and the impact which comes from the material use is depending on material origin: natural raw material, waste material, material from renewable sources etc. Materials are used not only for renovation but also building operation need materials for heating. Figurae 30 shows the non-renewable raw material share for the concept of external renovation (E1) with rock wool and 3-layer rendering.

Inspection time 20 year is such a short time that raw- material consumption in renovations is often much bigger than raw-materials needed for heating. According to the result non-renewable raw material amount from renovation is 60–90% when raw-materials used for heating is 40–10% (Figure 30).

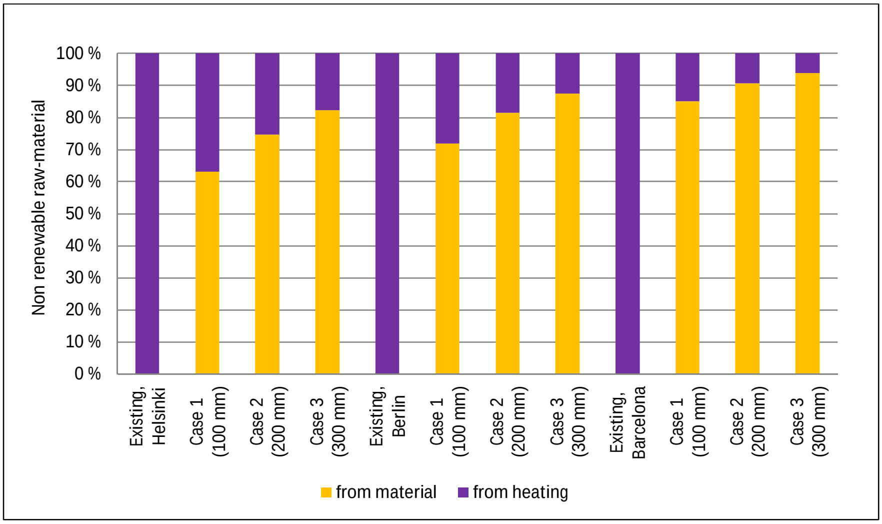


Figure 30. Non-renewable raw-material consumption for the external renovation with the rock wool and 3-layer rendering. Existing Helsinki, Berlin and Barcelona is the cases were U-value is 0.44 W/m^{2}K, renovated 100 mm is the case where U-value is 0.21 W/m^{2}K, renovated 200 mm is the case where U-value is 0.14 W/m^{2}K and renovated 300 mm is the case where U-value is 0.10 W/m^{2}K.

4.2.6 Façade type

The external renovation concept, where façade material installed with the presence of air gap (E2), makes possible to use various façade boards, plates and material types. The carbon footprint is different for different façade materials and can vary from 1 kg/m^2 to almost 40 kg/m^2.

The total result illustrated with the help of solid lightweight concrete case typically used in the countries of Eastern Europe and in former USSR where the need for energy renovation is high. This renovation concept results in extensive energy and carbon footprint savings, because the starting point was so weak in the terms of insulating capacity.

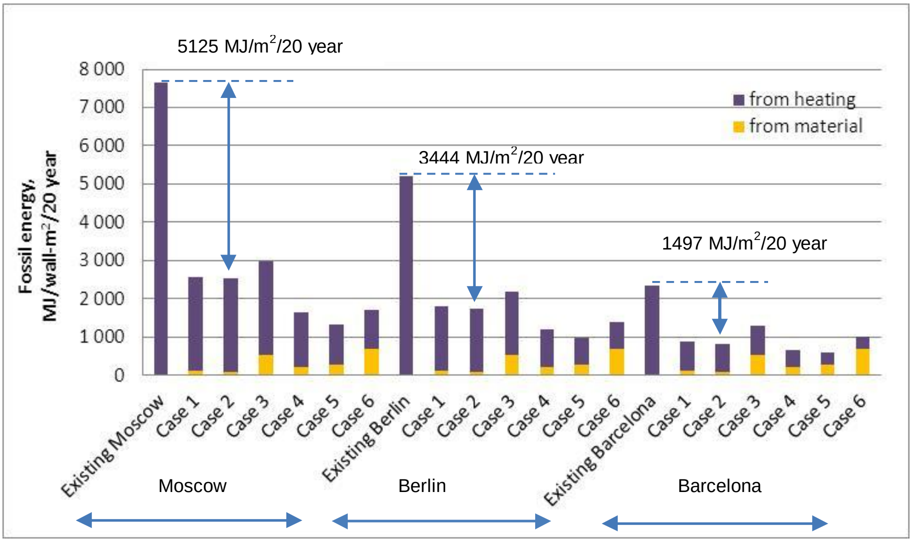


Figure 31. Fossil energy consumption for lightweight concrete element renovation. Heating type is gas, insulation type is rock wool, insulation thickness for Case 1, Case 2 and Case 3 is 100 mm (U-value = 0.28 W/m^{2}K), for Case 4 is 200 mm (U-value = 0.16 W/m^{2}K), for Case 5 and 6 is 300 mm (U-value = 0.12 W/m^{2}K). Façade type for Case 1, Case 4 and Case 5 is concrete board (30 mm), for Case 2 wooden façade, for Case 3 and 6 is clay brick (85 mm).

The maximum energy saving is achieved for wooden façade and for all target U-value studied. In the case of Moscow and U-value 0.28 W/m^{2}K the saving is 5125 MJ/m^2/20 year, for Berlin is 3444 MJ/m^2/20 year and for Barcelona is 1497 MJ/m^2/20 year (Figure 31).

The carbon footprint result for Eastern, Central and Southern Europe (Moscow, Berlin and Barcelona) and for different U-value is given in the Figure 32, Figure 33, Figure 34.

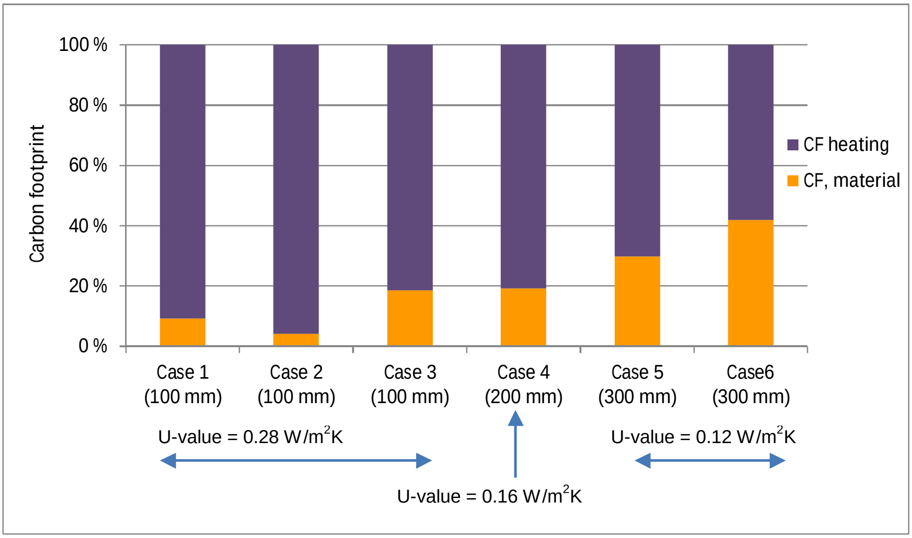


Figure 32. Carbon footprint for lightweight concrete element renovation. Case Eastern Europe (Moscow). Heating type is gas, insulation type is rock wool with different thickness. Façade type for the Case 1, Case 4 and Case 5 is concrete board (30 mm), for Case 2 wooden façade, for the Case 3 and 6 is clay brick (85 mm).

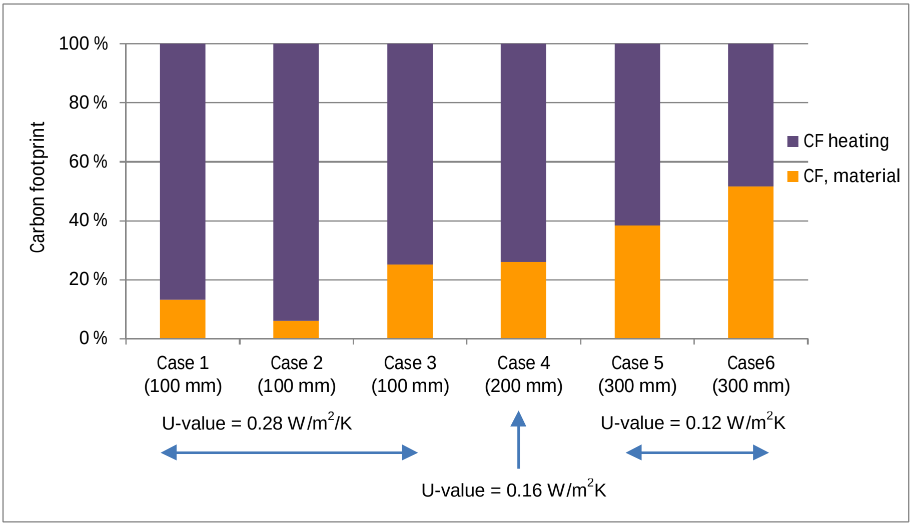


Figure 33. Carbon footprint for lightweight concrete element renovation. Case Central Europe (Berlin). Heating type is gas; insulation type is rock wool with different thickness; façade type for Case 1, Case 4 and Case 5 is concrete board (30 mm), for Case 2 wooden façade, for Case 3 and 6 is clay brick (85 mm).

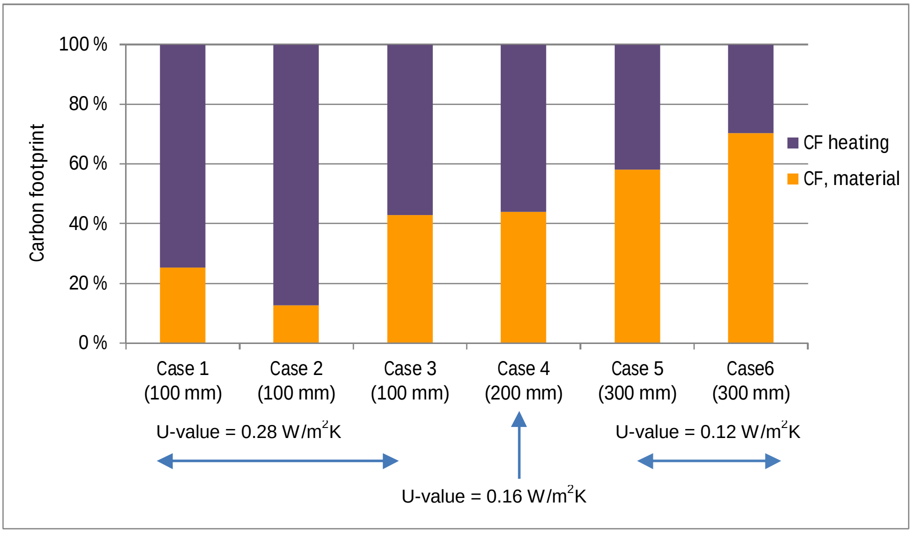


Figure 34. Carbon footprint for lightweight concrete element renovation. Case Southern Europe (Barcelona). Heating type is gas, insulation type is rock wool with different thickness; façade type for Case 1, Case 4 and Case 5 is concrete board (30 mm), for Case 2 wooden façade, for Case 3 and 6 is clay brick (85 mm).

When U-value decreases from 0.86 W/m^{2}K to 0.28 W/m^{2}K the carbon footprint decrease was more than 300 kg/m^2 for the case Moscow and time period 20 year. When U-value decreases to the value 0.12 W/m^{2}K the carbon footprint decrease was more than 400 kg/m^2/20 year (Case Moscow and Figure 31). In Central and Southern Europe the carbon footprint decrease was smaller.

Relative material share from the total carbon footprint is 4–20% for the region of Eastern Europe, Moscow (Figure 32) when the U-value was 0.28 W/m^{2}K and the time period 20 year. For better insulation capacity, U-value = 0.12 W/m^{2}K, material share in wall renovation is 30–40%.

Relative material share from the total carbon footprint is 6–25% for the region of Central Europe, Berlin (Figure 33) when the U-value was 0.28 W/m^{2}K and the time period 20 year. For better insulation capacity, U-value = 0.12 W/m^{2}K, material share in wall renovation is 38–52%.

Relative material share from the total carbon footprint is 13–43% for the region Southern Europe, Barcelona (Figure 34) when the U-value was 0.28 W/m^{2}K and the time period 20 year. For better insulation capacity, U-value = 0.12 W/m^{2}K, material share in wall renovation is 58–70%.

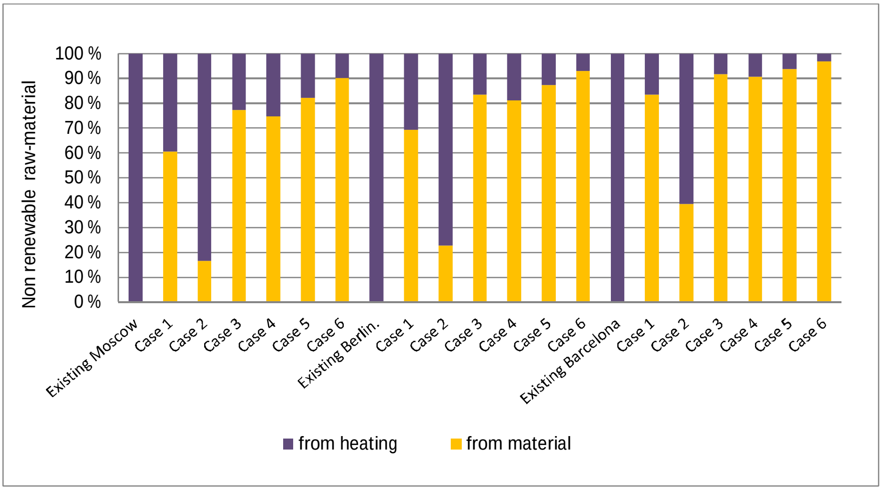


Figure 35. Non-renewable raw-material share: materials used for renovation and energy raw-materials used for heating. External renovation concept for lightweight concrete. Heating type is gas, insulation type is rock wool, insulation thickness for Case 1, Case 2 and Case 3 is 100 mm, for Case 4 is 200 mm, for Case 5 and 6 is 300 mm. Façade type for Case 1, Case 4 and Case 5 is concrete board (30 mm), for Case 2 wooden façade, for Case 3 and 6 is clay brick (85 mm).

According to the non-renewable raw material consumption (Figure 34 and Figure 35) the best option is also wooden façade.

4.2.7 Insulation type

The total impact from insulation type is assessed on the bases of solid wall and internal insulation with rock wool, EPS, PUR or lamb wool (Concept I). Target U-value for all the studied cases was the same (0.17 W/m^{2}K) but material amount varied according to the thermal conductivity and specific weight (Table 10). In the case of mineral and lamb wool the wool installed with gypsum board and timber battens whereas EPS and PUR insulation installed with gypsum board and adhesive.

Carbon footprint for insulation materials depend on their origin and thickness. But normally insulation materials which are used in building renovations save more energy and avoid emissions than was used and released during their production processes. On the other hand when the target is low energy buildings embodied energy and released emissions became as important as or even more important than heating. The energy saving result is very much dependent on thermal conductivity because the same insulation thickness with different thermal conductivity can cause quite a big variation for annual energy consumption (Figure 26).

According to the result for a 20 year time period, the total carbon footprint for the renovation case based in Moscow is 107–125 kg/m^2/20 year, for the case in Berlin 74–92 kg/m^2/year and for the case in Barcelona 36–54 kg/m^2/year which mean that difference between studied insulation types is 18 kg/m^2/20 year (Figure 36).

According to the result for 20 year time period total fossil energy for renovation case Moscow is 1,571–2,056 MJ/m^2/20 year, for case Berlin 1,084–1,569 MJ/m^2/20 year and for case Barcelona 520–1,005 MJ/m^2/20 year which mean that difference between studied insulation types is 485 MJ/m^2/20 year (Figure 37).

According to the result for 20 year time period total non-renewable raw material consumption for renovation case Moscow is 44–59 kg/m^2/20 year, for case Berlin 33–48 kg/m^2/20 year and for case Barcelona 21–36 kg/m^2/20 year which mean that difference between studied insulation types is 15 kg/m^2/20 year (Figure 38).

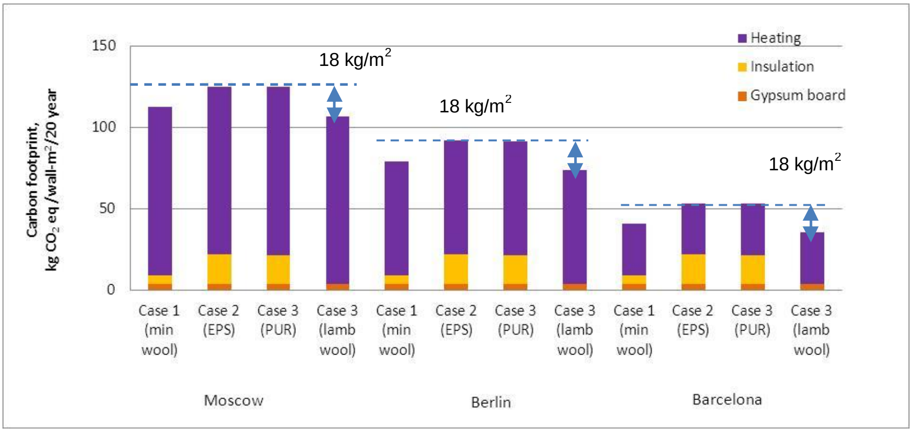


Figure 36. Carbon footprint for internal renovation with different insulation materials and gypsum board finishing. Wall U-value for Moscow, Berlin and Barcelona is 0.17 W/m^{2}K.

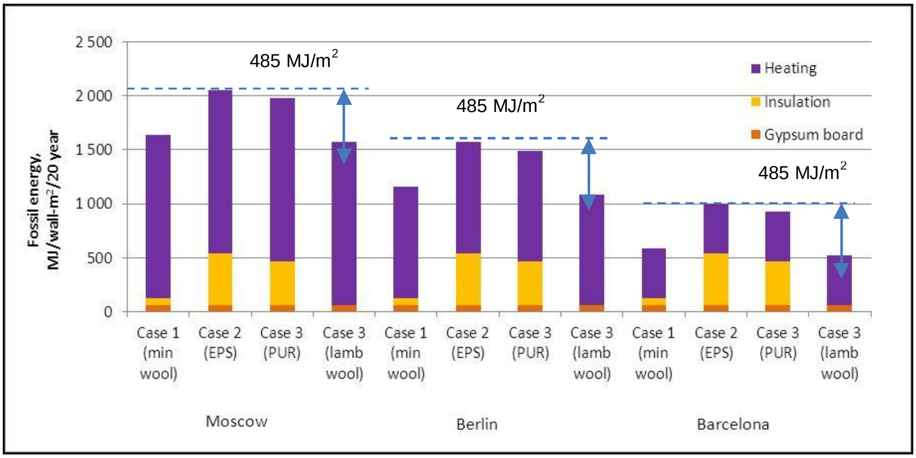


Figure 37. Fossil energy consumption for internal renovation with different insulation materials and gypsum board finishing. Wall U-value for Moscow, Berlin and Barcelona is 0.17 W/m^2K.

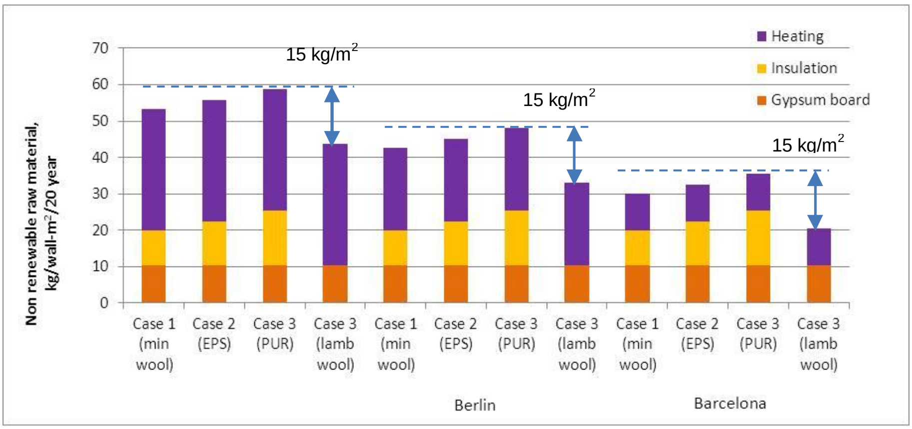


Figure 38. Non-renewable raw-material consumption for internal renovation with different insulation materials and gypsum board finishing. Wall U-value for Moscow, Berlin and Barcelona is 0.17 W/m^2K.

4.2.8 Summary

This study assessed the environmental impacts of the general wall renovation concepts as previously set out in this report. Carbon footprint (CF), raw material consumption, and energy consumption were assessed with the help of life cycle inventories, managed or known by the Project Partners. The magnitude of the environmental impact in connection with building renovations and refurbishments depends on the existing building type, building condition and renovation concept used. In a typical building design, where the shape of the buildings are square and rectangular, the exterior walls form 1.2–1.5 wall-m^2/one floor-m^2. Wall structures can be divided into light, medium and high when considering their thermal mass and when the amount of material used is high, normally the environmental impact are also higher compared to lightweight cases. The same principle is applicable also to renovation concepts; the lighter the structure is, typically the smaller are the environmental impacts of the concept, but this can be dependent on the type of material used. At the same time, exterior walls are responsible for the heat transmission and thus have an effect on the total energy performance of the building. Because of that, the impact from renovation materials should be studied alongside the heat transmission and heating type.

Depending on the existing building types, the additional insulation can be placed on the existing wall either externally, internally or into the wall cavity, as discussed previously. This study focused mainly on the external and internal renovation cases because the material consumption remains small in the case of cavity walls and doesn't cause a significant effect in terms of energy saving and environmental impact. However, cavity walls are included when the renovation is performed internally or externally. The examples are given for chosen building types to illustrate the ability of energy saving building renovation and the subsequent environmental impact.

The main findings in this study are related to the insulation thickness, insulation type, façade type and energy type used.

- Energy efficiency from specific insulation types depends on their thermal conductance. Insulation materials have a large range of variation in thermal conductance (varying at least between 0.07–0.44 W/m2K) and in the case of 100 mm insulation this can cause an annual heat transmission of 8–50 kWh/m^2/a in Northern Europe (Figure 26). Correspondingly, insulation materials also have different specific weights which mean that the volume needed in wall renovation to achieve the same efficiency is different. It must be noted that insulation materials are developed for certain conditions and with certain properties which makes the selection of the right material very important. Insulation material selection has a significant impact not only on the energy and physical performance but also on the environmental impact of the works undertaken.
- Expanded polystyrene (EPS), polyurethane (PUR), rock wool and lamb wool were studied. According to the results, PUR and EPS, which are based on fossil materials, caused highest environmental impact whereas lowest impact were achieved for the solution which makes use of waste materials. In this study lambs wool was considered as waste material and no production impacts were allocated for it. Lambs wool can be dealt with as waste because some wool types have properties which are not suitable for textile industry and these lambs are bred only for the meat industry.

- The optimal consumption of insulation materials depends on building condition and the region it is located in. In Northern Europe, 300 mm of rock wool still save a reasonable amount of energy and reduce carbon emissions but in Southern Europe the optimal amount is less than 100 mm (Figure 27, Figure 28) when both material and heating related impacts are considered.
- In the case of external renovation, where the façade is installed with the presence of air gap, different new façade materials can be used. Façade types studied in this survey were concrete, wood and clay brick façades.
    - The best façade material in terms of environmental impacts (carbon footprint, non-renewable raw material and - energy consumption), was a wooden façade. This renovation concept is a light weight option, wood is a renewable raw material and timber production utilizes by-product energy which also renewable.
    - In the case of U-value 0.28 W/m^2K, the materials' share form CF in Nordic regions was 4–20%, but in the case of better insulation (U-value 0.12 W/m^2K) it was 30–40% (Figure 32). In Central Europe, the materials' share from CF varied between 38–52% (Figure 33) and in Southern Europe between 58–70% (Figure 34).
- Replacing renovation concept often causes a significant consumption of materials. In the case of concrete element renovation with outer concrete layer replacement, the amount of new concrete is high. This causes a higher carbon footprint compared to the case of a 3 layer rendering façade, where the material used is less.
- Replacing renovation concept with a massive concrete structure and insulation had a carbon footprint value 50 kg/wall m^2 which is twice as high as lighter weight renovation options, where rock wool with 3 layer rendering façade is used.
- Materials' share from the total carbon footprint depends on heating energy consumption and heating type.
    - In the regions where the heating period is long (Northern Europe), the materials used in wall renovation can cause up to 41% of total carbon footprint (when considering renovation materials and heating energy for 20 year operation) (Figure 29). This result refers to a case where mineral wool with 3-layer rendering façade was used and heating energy was produced with the Nordel electricity mix (where renewable energy share is high).
    - For the U-value 0.21 W/m2K, the materials' share from total CF is roughly 10–15% but it varies depending on heating types. In the case of U-value 0.1 it is varies between roughly 30–40% (Figure 29). The material share can be higher, when high share of heating energy is produced from renewable resources.
    - The material share is much higher in southern Europe where the heating energy demand is much smaller as would be expected.

Present study shows that exterior wall renovation can achieve a big reduction in energy saving measures and the environmental impact. Which renovation option is suitable and best in particular cases should be determined considering the overall building condition, historical background and building neighbourhood and region. Walls form only one part of the buildings and impacts should therefore be assessed also on building level.

4.3 Life cycle costs assessment

4.3.1 Introduction

The Life Cycle costing covers only extra costs and energy cost caused by sustainable refurbishment compared with necessary refurbishment of facades. The analysis basis includes price of money (+ 2%/y). Economic assessment is based on the calculation of life cycle cost according to ISO 15686-5 Life Cycle Costing (LCC)[2]. LCC is a technique for estimating the cost of whole buildings, systems and/or building components and materials, and used for monitoring the occurred throughout the lifecycle.

The results are presented in terms of net present values. This is calculated by summing up the activated costs in different years for present with present unit costs (without discount rate). The energy costs were calculated considering the realistic increase of costs.

Table 12. Life Cycle Cost factors.

Type of life-cycle cost	Description
Investment cost	Cost including all material, labour and sub costs caused by construction of facility, product or material. The comparable economy of energy saving concepts has been calculated based on extra investment cost compared to necessary refurbishment.
Energy cost	Continual heating cost caused by the use of building by real +2%/y rise of energy prices.

The present value methodology means summing up of the activated costs in different years for present either with present unit costs or taking the foreseen realized costs (usually energy cost) into account.

2 ISO 15686-5 Life Cycle Costing.

Table 13. Extra costs caused by heat plastering compared to basic renovation (Case Finland).

Insulation materials	**Extra Renovationcos t**
	€/m^2
Soft rock wool 100 mm	15
Soft rock wool 200 mm	21
Soft rock wool 300 mm	26
Hard rock wool 100 mm	21
Hard rock wool 150 mm	26
Hard rock wool 200 mm	30
EPS (100S) 50 mm	27
EPS (100S) 100 mm	43
EPS (100S) 150 mm	57
EPS (100S) 200 mm	71
EPS (100S) 250 mm	83
Carbon EPS 50 mm	48
Carbon EPS 100 mm	78
Carbon EPS 180 mm	113
Carbon EPS 250 mm	158
PUR foam with Al surface 120 mm	53
PUR foam with Al surface 150 mm	58
PUR foam with Al surface 170 mm	63
	Extra cost €/m2
100 mm	20
200 mm	35
300 mm	60

Table 14. Heating costs present value (year 2011).

Heating mode	**Heating cost, present value inc. taxes**
	€/kWh
District heating	0.055
Electricity	0.08…0,09
Oil	0.105
Gas (North and Middle Europe)	0.05
Gas (South)	0.08
Electric mix	0.11

Table 15. Labour cost and material cost indexes indexes in average.

	Labour index	Material index
Belgium	105	100
Eastern non-EU countries	40	90
Germany	100	100
Estonia	40	90
Greece	60	90
Spain	75	90
Finland	100	100
France	120	100
Italy	90	95
Lithuania and Latvia	40	90
Netherlands	110	100
Norway	150	110
Sweden	130	110
United Kingdom	140	110

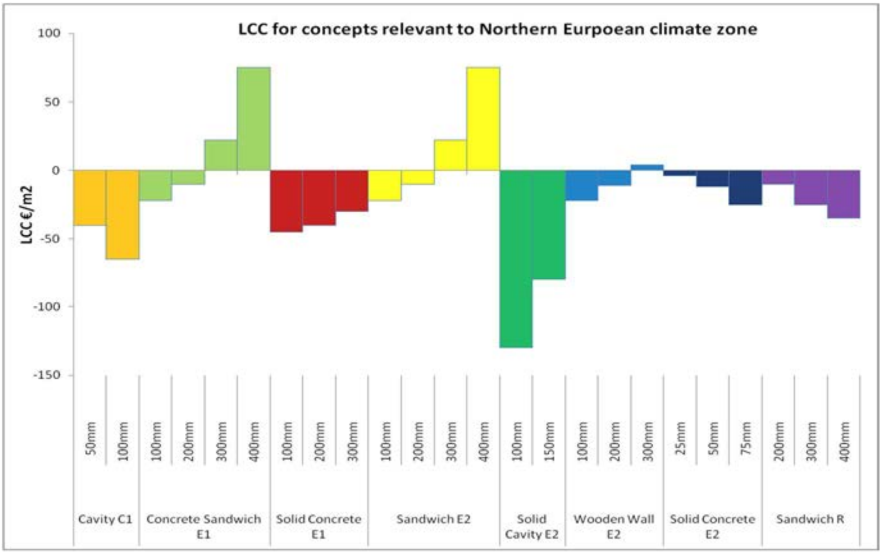


Figure 39. LCC for concepts relevant to Northern European climate zone.

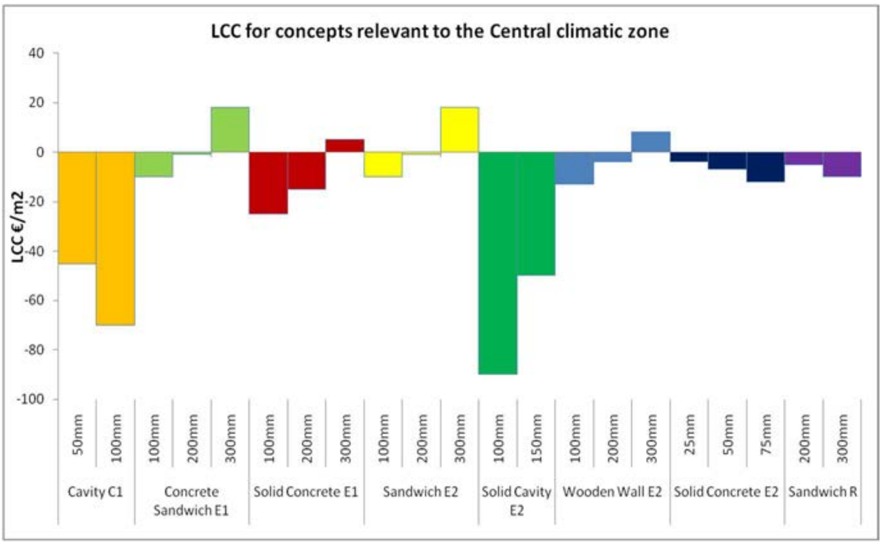


Figure 40. LCC for concepts relevant to Central European climate zone.

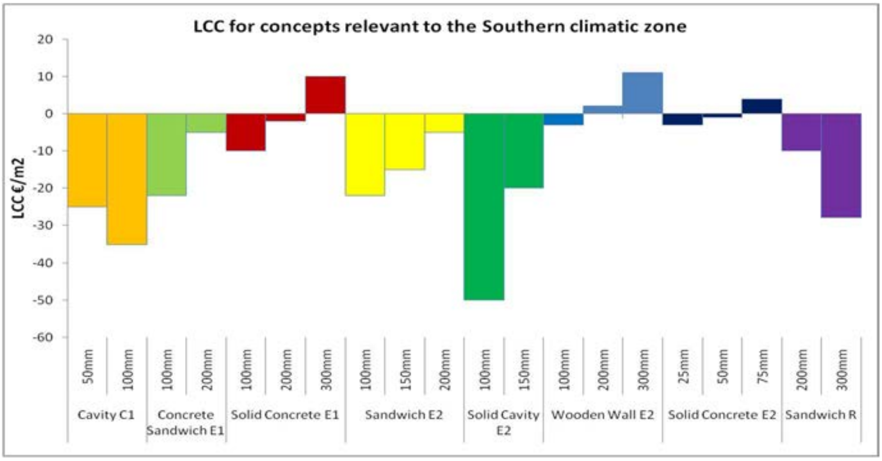


Figure 41. LCC for concepts relevant to Southern European climate zone.

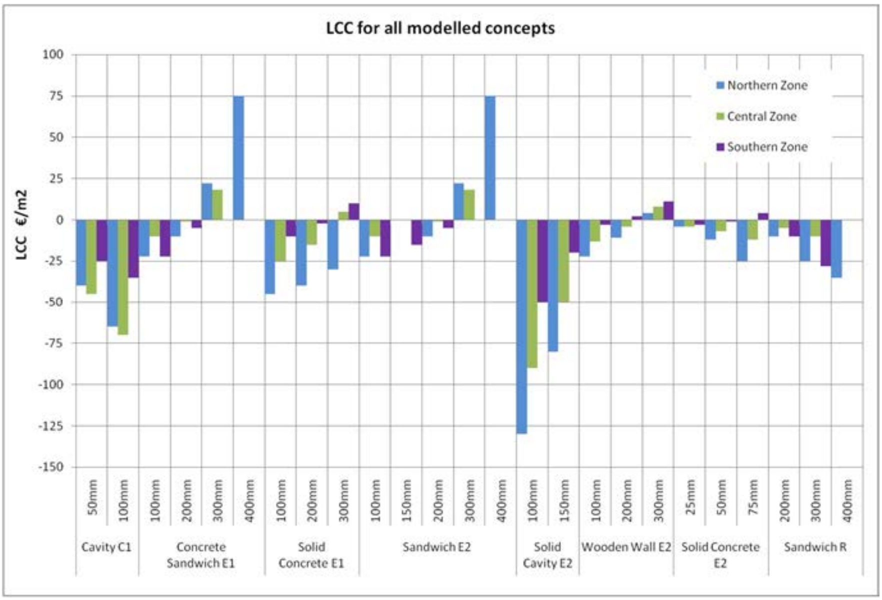


Figure 42. LCC for all modelled concepts within the 3 relevant climate zones.

4.3.2 Summary and conclusions

These refurbishment concepts have been compared to a basic case in order to understand more clearly the different effect of material and structure selections. The results show that it is not profitable to improve the thermal insulation of an external wall if the outer layer of the wall doesn't need repair. If the energy price assumed increase rate is high, the refurbishment may become profitable.

When comparing different options, the effect of the decrease of housing area (5% in average) when using internal insulation, has to be taken into account additionally. The costs of refurbishment vary considerably across Europe. Especially the cost of any additional insulation is often non economical. However, the energy saving potential may be very high with a short payback time at least in the cases where an adequate investment support is available.

The export businesses of companies as well as the free mobilisation of experts and labour are increasing.

The economical impacts of the SusRef Concepts can be summarised as follows:

- remarkable reduction of energy consumptions and carbon footprint
- reasonable increase of investment cost
- relevant savings in life cycle cost
- increase of resale value.

The most remarkable risks concern:

- management of changes in energy production
- adequacy and management of movements of labour connected to timing, quality and cost demands
- management of damage mechanisms of façade structures
- possible cost and health effects of individual unsuccessful refurbishments.

Most remarkable possibilities concern:

- acceleration of refurbishment innovations
- adequate training programmes of companies and labour
- new kind of financing and supporting mechanisms
- creating concepts where thorough renovations are carried out in the context of big areal refurbishment projects.

However, the more durable increase of economic value (market value) can be achieved with the help of refurbishment especially when the building or the block of buildings is located in a relatively valuable neighbourhood and when the whole neighbourhood is refurbished at the same time. In these cases the costs of refurbishment can be compensated with help of the increase of market value. This can also be realised with the help of increasing the density of the area, the increased use of sustainable building classification methods, such as enhanced display energy certificates may also increase the valuation of refurbished areas.

4.4 Impact on energy demand for heating and cooling assessment

4.4.1 Impact on energy demand for heating

4.4.1.1 Introduction

The Susref project considers different refurbishment techniques for additional insulation of facades. The extra insulation can be installed on the exterior surface or on the inside surface or in some cases in the cavity of the external and internal walls, as discussed.

The placement of the insulation has a different influence on the heating energy use even if the thermal conductance (U-value) of the walls were the same. This results from the fact that the extra insulation changes the active thermal capacity of the wall. The thermal capacity of the wall determines the capability of the wall to store heat. In general, internal insulation decreases the active thermal capacity in regard to varying internal heat loads like heat from home equipment, heat from people (metabolic gains) and solar heat load that comes to the room through windows. This decreased heat storage capacity reduces the utilization of internal heat loads in heating especially during spring and autumn when the heat loads are large compared to the heat demand. Whereas cavity and external insulation increases internal active heat storage capacity of the wall thus enabling the utilization of the internal heat loads and reducing the heating energy use. The effect of the placement of the insulation on the heating demand can only be studied with dynamic simulation but it is possible to estimate roughly the effect of the insulation on the heating demand with simple stationary calculation techniques like has been done here using the heating degree day method (HDD).

The heating degree day method gives in most cases rather reliable and easy way to estimate theoretically the effect of extra insulation on the heating demand. And because the HDD method can’t make a difference in heating demand between the placement of the insulation in regard to the changes in thermal capacity, the refurbishment cases (external, cavity and internal) are treated as one and the same case. The influence of the possible thermal bridges can be included in the HDD method by taking them into account in the U-value and differences between insulated areas can be treated as well by their surface area.

Parameters of extra insulation that effect on the heating energy demand of a building are:

- Insulation thickness and heat conductivity of the insulation material
- Placement of the insulation
  - internal
  - external
  - cavity
- Cold bridges

- Mountability
- Effect on air tightness and air infiltration of the envelope
- Effect on heat gains (solar heat, internal loads).

4.4.1.2 Heating degree day analysis on the heating energy demand

A simple way to estimate the impacts of any extra insulation of the walls on the heating energy demand is to use the heating degree day calculation method. Heating degree day reflects the heating energy demand for heating a building. The heating requirements for a given structure at a specific location are considered to be directly proportional to the number of heating degree days at that location. The heating degree day is defined as the number of degrees that a day's average temperature is below chosen base temperature. The base temperature is a certain outdoor air temperature below which the building needs to be heated. The base temperature is actually specific for each building depending on the heat losses (walls, roof, floor, windows, air change) and the heat loads (solar, people, devices). Heating degree days are often available with base temperature of 18 °C which is also used in this presentation. The HDD data source for different locations is the Energy Plus weather data files (http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data2.cfm/).

Heating degree day calculations do not take into account the effect of the extra insulation on the utilization of internal heat loads in the heating. There are two physical phenomena that are ignored; namely the change in the relation of heat losses versus internal heat loads and the change in the thermal inertia of the renovated structures. For these reasons it is recommended that careful analysis should be used when calculating the effect and the use of calculation methods or software that can handle these physical aspects.

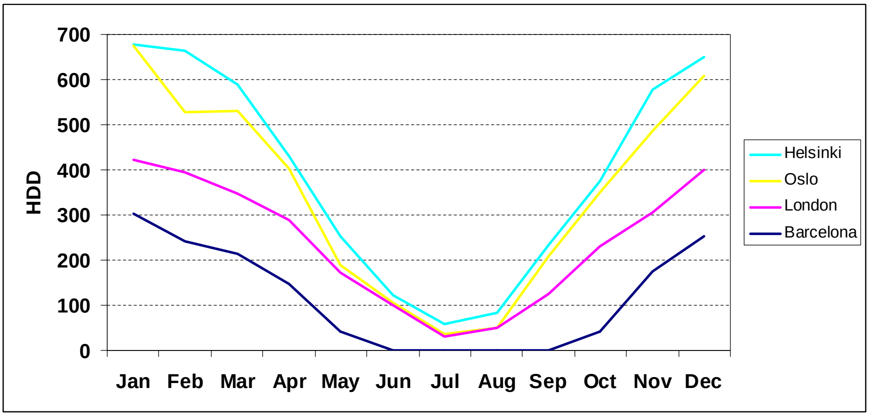


Figure 43. Monthly heating degree days (HDD) of different locations. Heating degree days are calculated using the base temperature of 18 °C.

The bigger the HDD is, the higher the heat loss for the same structure. In Oslo and Helsinki the HDD is three times higher than in Barcelona and for London two times higher.

Specific heat losses (Q/A, kWh/wall-m^2) for analyzed locations are presented in Figure 44.

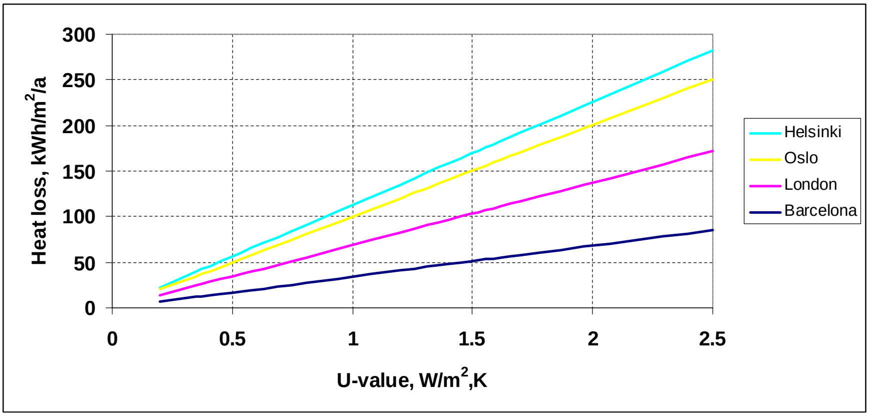


Figure 44. Specific heat loss of the wall as function of the U-value of the wall.

In general the extra insulation of wall decreases the heat demand and the effect on heating energy saving can be roughly estimated by heating degree day calculation.

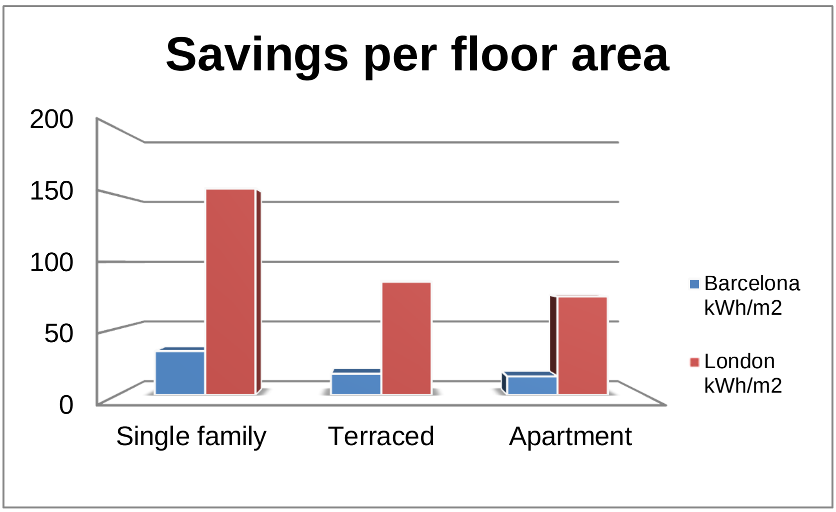


Figure 45. Estimated heating energy savings of facade refurbishments in Barcelona and London based on HDD method.

Heating energy savings are calculated for the same kind of wall structure and same renovation measure to show the differences between building types. The results reveal that the biggest saving potential is in single family houses which arise from the fact that in the single family house the wall area compared to the floor area is at a higher ratio than in the other building types. The heating energy saving potential is substantially bigger in England than in Spain due to the differences in climate as would be expected in all the example cases the heating energy saving potential is substantial.

4.4.1.3 Discussion

It should be reminded that heating degree day analysis usually gives the maximum saving potential that can be achieved with conventional extra insulation refurbishment. In practise the savings are in most cases lower because the extra insulation affects the utilization of internal heat loads (sun, appliances and people) that cannot be taken into account with HDD method. Dynamic simulations show that usually external insulation gives somewhat higher savings than internal insulation and cavity insulation is somewhere between when the change of the conductance (UA-value) is the same.

There are also practical details that define the success of the extra insulation. Only with external insulation it is possible to cover the whole shell of the building with a continuous layer. In wall cavities there are usually bonds between the external and internal walls, such as wall ties, that form thermal bridges in cavity insulation thus weakening the heat resistance of the wall. Moreover the insulation work of the cavities is technically difficult to carry out so that all the cavities are rarely insulated according to the specifications. Internal insulation is practically impossible to install without breaks in the insulation because of the internal walls and ceilings which decreases the effect of the thermal insulation. The internal and cavity insulation are also sensitive to errors in design and in installation in regard to condensation problems. Moisture in insulation not only has a detrimental effect on the thermal behaviour of the insulation but also increases the potential for indoor quality issues.

4.4.2 Impact on energy demand for cooling

4.4.2.1 Applied criteria

Cooling energy demands in residential buildings, such as those in the scope of the SUSREF project, are specific to Southern-European climates, roughly Greece and the southern half of Portugal, Spain and Italy.

Cooling loads in other European locations are uncommon, and mainly created by improper building design, excessive solar gains without shading and insufficient ventilation rates.

Cooling loads are highly dependent on the thermal performance of buildings and façade constructions, this dependency is even greater than of that of the heating performance of buildings. Being so, cooling thermal loads should be calculated specifically for every single building refurbishment.

A proper calculation should be made on building-specific level, and for this project a simplified approach is proposed. This evaluation will provide annual envelope heat gain reductions during cooling periods, considering to some extent the thermal inertia of the façades.

The heat gain calculation will be done based on the degree-period method for cooling and the thermal transmittance of the wall, U-value.

The heating degree-period method for cooling will be calculated in a time basis according to the inertia of the building type:

- 4 h for light-weight buildings (such as timber frame)
- 8 h for heavy-weight buildings (such as brick walls, concrete slabs)
- 24 h for heavy-weight buildings (stone buildings).

This degree-period will be then transposed to degree-days. Calculation of Cooling Degree Periods.

6 European climates have been selected in the present study. These climates have been selected among those previously used in WP3 and WP4 of this project. As the impact of the refurbishments on cooling loads is mainly produced in southern-European Countries, the selection has focused on those cases. In addition some extreme climates have been added to evaluate the impact for the southern edges of the European mainland and the Mediterranean Sea.

The finally selected climates are the following:

1. Paris
2. Lyon
3. Bilbao
4. Barcelona
5. Almeria
6. Catania.

4.4.2.2 Impact on cooling demand

According to the typical buildings in southern-European countries and there thermal mass properties, the most appropriate Cooling degree day time base selection is 8 h. For the purposes of this calculation the selected building façade is a brick façade, thus a construction heavy mass, which is usually placed in concrete structured buildings, with massive concrete slabs on them.

Results show that the refurbishment techniques provide a yearly thermal gain reduction of 2 kWh in Almeria and 3 kWh in Catania, per square metre of opaque façade.

Nevertheless, these results are conditioned by the thermal dynamic response of the whole building to external conditions. The provided results could be applied in the case of external refurbishment methods being considered. Internal refurbishment reduces the capacity of the building to absorb peak loads, and thus increases the cooling demand during the central hours of the day. This effect cannot be considered at façade level, and has not been considered, as it can lead to an improper result for this kind of insulation placement.

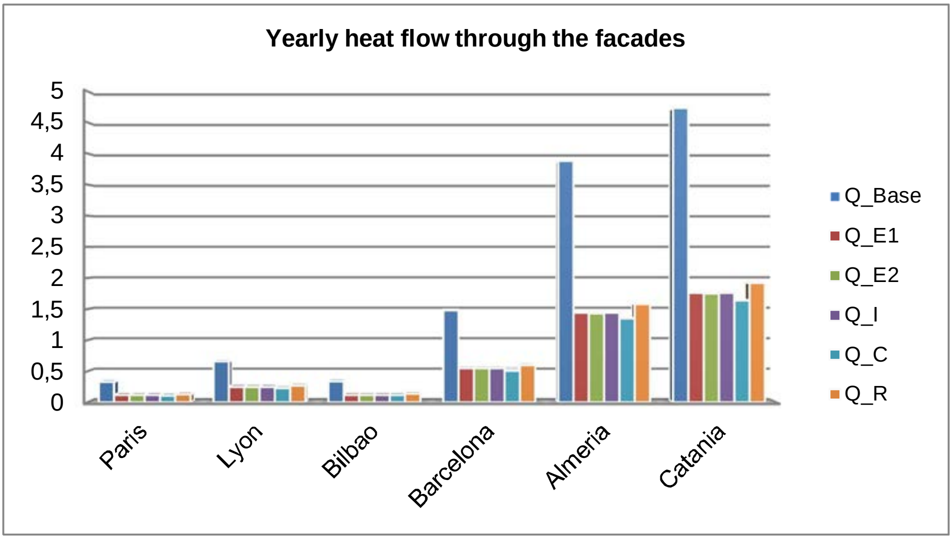


Figure 46. As results state, cooling is only relevant in Almeria and Catania while the other 4 climates would not require of cooling systems due to their envelope.

Residential buildings in Bilbao, Barcelona, Paris and Lyon would not require specific cooling equipment should they be properly operated. Proper ventilation and blocking of solar gains through windows should be enough to avoid cooling, as residential buildings do not usually have high internal loads.

4.4.2.3 Conclusions

The selected calculation method shows that façade insulation reduces the heat gain during cooling periods, by up to 75%. For hot Mediterranean climates such reductions can be directly converted into cooling load reductions.

Nevertheless, this method does not take into account that walls also increase the thermal capacity of the building, and thus, internal insulation can lead to a reduction of the effective thermal capacity of the building.

Care should be taken in this case, as this can result in higher peak cooling loads in Mediterranean climates. These cases can only be properly addressed by direct dynamic modelling and simulation of the whole building.

4.5 Daylight Assessment

4.5.1 Introduction

Illumination, and more specifically daylight, plays an important role in the delivery of comfort and quality of life in buildings for the occupiers. Correct daylight design can also deliver significant potential for reduction of energy consumption in buildings.

Building façade refurbishment can significantly alter daylight quality in the interior spaces of the refurbished buildings, even when windows are not replaced, if the geometry of the aperture in which the window is inserted changes, such as reduction in the width of the aperture by insulating the reveals and heads (see Figure 47).

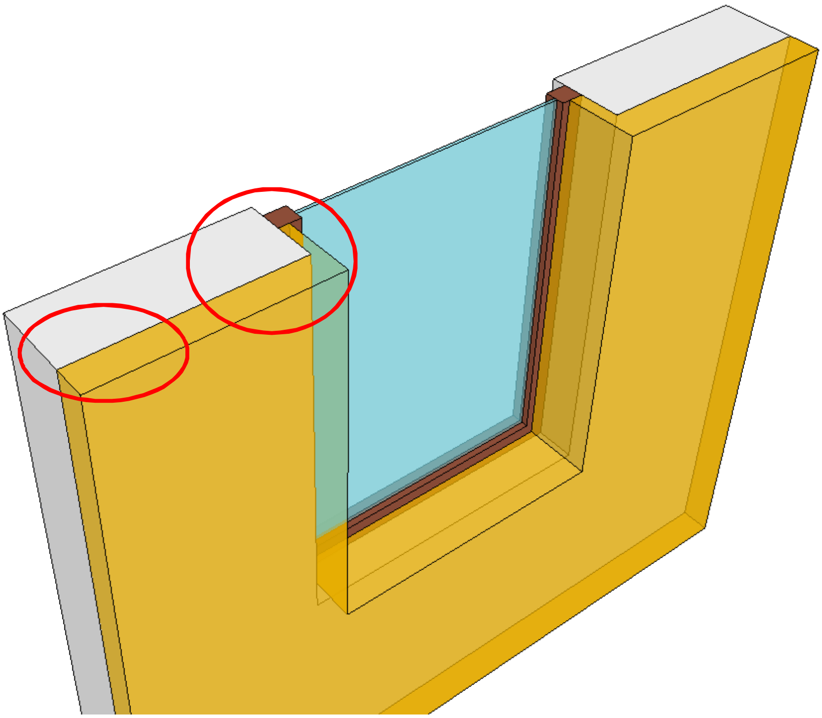


Figure 47. Example aperture geometry change after facade refurbishment.

Geometry variations (more evident in the case of external insulation can include an increase in wall thickness as well as occasional slight variations in aperture dimensions as a result of the insulation of window reveals, as discussed.

In order to assess the impact of façade refurbishment in daylight quality in interior spaces, simulation-based analysis is proposed, using validated, ray tracing based software such as radiance. The selected locations are Helsinki, Oslo, Berlin, Paris, and Bilbao. The final results of this assessment are presented in the graphics below.

4.5.2 Results

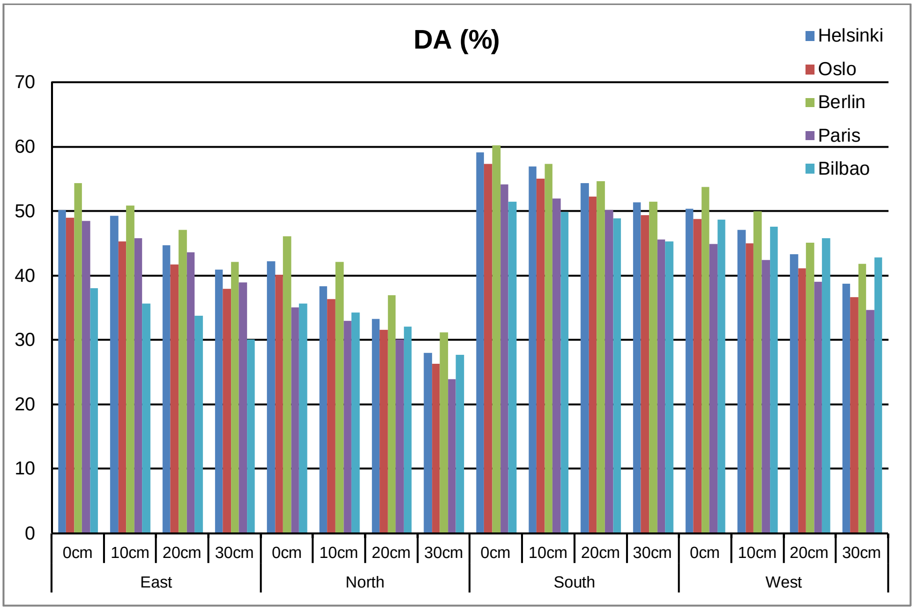


Figure 48. DA – Daylight Autonomy.

DA – Daylight Autonomy, defined as "the percentage of the occupied hours of the year when a minimum illuminance threshold is met by daylight alone" (Reinhart & Walkenhorst 2001). Variation of this percentage before and after refurbishment will give a clear indication of impact of façade refurbishment in daylight availability.

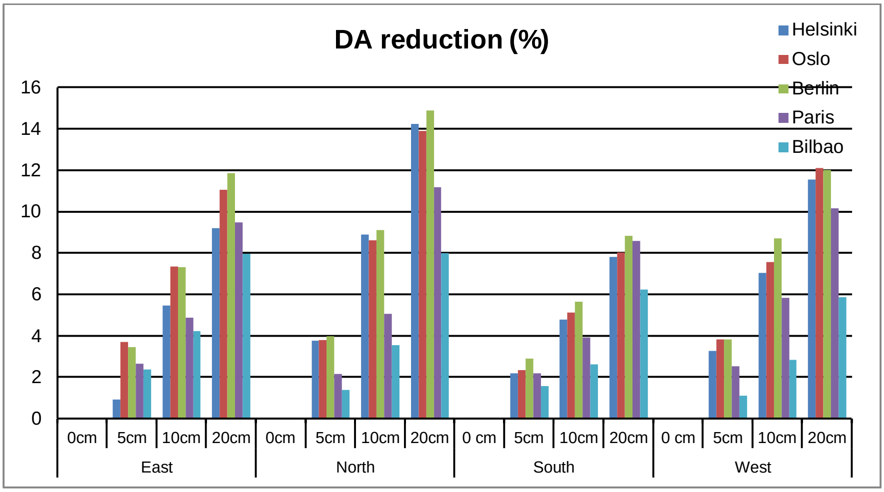


Figure 49. DA reduction (%).

From this data, the following considerations can be extracted.

- Reductions in Daylight Autonomy are consistently higher in north oriented facades and lower in south oriented facades. Larger latitude angles increase reductions, although local climate conditions can have an effect as well.
- Large increases in façade thickness can affect substantially the available daylight, with reductions up to 15% of day lit time for 30 cm of added insulation, and 8%–9% for 20 cm.
- Reductions in Useful Daylight Illuminance indicate lower increases in values for time with no useful daylight, (4% to 6% for 30 cm), as well as reductions in potential glare situations (especially in west and south orientations).

4.6 Structural stability assessment

The term structural stability is the condition of the existing wall regarding:

– structural performance of the building
– effects, such as decay and mould growth, due to connections between existing and additional wall construction layers.

Assessment of structural stability is restricted in this project to a qualitative assessment of how the following properties will be affected by the refurbishment:

- Structural performance of the wall and the building (load bearing capacity).
- Mounting of fastening points in the existing wall.

- Changes in water drainage, changes in humidity and danger of frost heave.
- Sensitivity for seismic loads.

Normally the structural performance of the wall and the building will remain unchanged. Often, the insulation materials weights little and the additional load is low for the systems that have been evaluated here (E1, E2, I, C and R). The assessment of the load bearing capacity of the existing walls must also include verification to ensure that it can withstand mounting of fastening points, this would be assessed using "pull tests" to ensure integral strength.

The wind load will not increase due to refurbishment. Changes in water drainage, changes in humidity and danger of frost heave etc. may affect the structural stability in a long term.

Construction types/walls built with heavy materials, such as natural stone or concrete, are more susceptible to seismic loads. Light construction timber frame wall have features making this type of construction more flexible. Any kind of heavy material wall must be fitted with settlement and movement joints.

Connection technology is necessary for expanding joints.

4.7 Buildability assessment

Assessment of buildability is here restricted to a qualitative assessment of how the following properties will be affected by the refurbishment:

- Current condition of the existing wall
- Constructional feasibility
- Access to the building site
- Domestic factors
- Climate zones.

Current condition of the existing wall

The quality of the existing wall must be assessed. Assessment of current conditions of an existing wall will highlight the need for repairs and suitability for improvement prior to refurbishment. Necessary repairs that could be encountered might be the removal of existing cladding or render, improving joints or drainage. Furthermore it is imperative to assess the load bearing capacity on the existing wall. Rot damage to a load bearing wood structure or ripped/torn concrete might be impossible to improve to the extent where it can support an additional refurbishment system, and it is therefore important that this is assessed correctly from the outset. A visible assessment of a cladded wall will not necessarily reveal moisture damage beneath, and therefore some destructive investigation may be required.

If the surface of the existing wall is very rough or uneven, air gaps might occur between the insulation and the wall, this may affect the performance of the external insulation, actions and in these cases this gap must be closed, (weathers trip, dubbed out or rendered etc.).

Moisture emission throughout walls is minimally altered through most refurbishment methods. The moisture is transported in the shape of air leakages via other channels (windows, airvent etc.). Very little moisture transports through walls in the shape of diffusion, so if no improvement or change is made to the windows, the influence of the refurbishment of the walls is marginal. The windows and ventilation rates make the difference when considering moisture movement.

Any kind of lead-in wires or penetrations must be planned carefully and can only be implemented where no cold drafts can occur, and in all cases Holes in vapour/wind barrier must be avoided.

Constructional feasibility

Quality, straight forward design, manufacturing, and detailing are important keywords. Straight forward building methods can be easily undertaken by craftsmen with traditional building skills, and therefore not requiring highly qualified craftsmen with special skills. If the solution chosen requires a at this stage that there is the need for specialized craftsmen. If considering using vacuum insulated panels, prefab is the only solution, as they can only be manufactured under controlled conditions. Prefabrication is quick and easy to mount/assemble and seldom demands special tools or proficiency, more an understanding of how the system fits together, whilst in-situ solutions are adaptable but requires tools and skills to i.e. miter panels. Prefabrication has an advantage when the wall consists of large areas of smooth surface, with no lead-in wires or significant penetrations.

In some cases the only when assessing the options for improvement there is no alternative but to remove the outer cladding (only REF R will be useable), since one needs to access the load bearing system. In the case of an uninsulated wall using refurbishment type C (cavity insulation) alternatively type E (external insulation).

The following insulation materials are in common use:

- Cellplastic foam
- Glass wool
- Rock wool
- EPS/XPS
- Vacuum Insulated panels.

The heat transport properties vary, but in the context of constructional feasibility we are more concerned about the practical use in the building process when it comes to cutting and adaption in a wall. Cellplastic, glass wool and rock wool can easily been cut, eps/xps are cut able, while vacuum panel cannot be cut at the building site, and may require the manufacture of special sizes of panel.

Access to the building site

When considering this element of assessment there are a number of key issues to consider, Is there enough room around the building to refurbish using the chosen concepts? Is it possible to erect scaffolding around the building? Insulation type I (internal insulation) and C (cavity insulation) might be the only possibility in cases where there is restricted space around the building and therefore no possibility for erecting scaffolding. Any kind of exterior refurbishing requires scaffolding, even for small houses. Some refurbishment systems are more sensitive to rainfall; hence a tarpaulin or weather barrier is needed to protect the structure during the works.

Domestic factors

To ensure the method is chosen, it is imperative to take into account any existing domestic or local building cultures, it will be necessary to rely on indigenous expertise and experience. These are matters crucial for the project achieving the right combination of wall type and refurbishment methods, this will help to optimize the outcome.

There might be cultural and or conservation measures that can constrict the possibilities and options for refurbishment. This can result in a distinction between interior and exterior insulation. Furthermore, the stance can differ within European countries, restricting the refurbishment alternatives or the thickness, and therefore local knowledge and understanding is imperative.

Climate zones

Dependency of weather conditions and climate zones must be assessed when considering the options for refurbishment or renovation, it is imperative to pay special attention to climate zones where the temperature fluctuates frequently down to the zero point due to the increased risk of condensation issues. This is especially important when using refurbishment method”I” (internal). There might be a specific need for developing the climate distinctions further, in the northern countries where there is hard, driving rain, creating problems both during the construction period and through life span of the building. A wall in the coastal regions of Norway for instance will be down around the zero point in temperature, thus creating elevated condensation risks.

Some systems when being applied are more sensitive to rainfall and require tarpaulin during the whole of the construction period, for protection. A dry, external insulation system with air gap can endure rain, and with any wall type insulation type I and C are indifferent to rain, as they within the confines of the structure. Exterior refurbishment that is going to be painted requires weather protection to ensure adhesion. Hence, the climate zone can have a significant influence on the Buildability of any particular system. It should be noted that brick systems with cladding are more vulnerable than other systems, and, vacuum insulated panels act as a vapour barrier and may cause condensation problems when placed in too thick a layer.

When refurbishing an exterior wall, no matter what kind of refurbishment method, the temperature drops outside of the insulation layer. Special considerations must be made in climate zones. Dfc with frequent fluctuations around the zero point in temperature due to the occurrence of condensation,this means all materials located on the outside of the insulation layer must be tolerant to moisture and frequent changes in temperature, which will help with resistance to frost damage.

<u>Rating scale for sensitivity of solutions</u>

Table 16 shows the rating scale for the sensitivity of solutions regarding structural stability and buildability.

Table 16. Rating scale for sensitivity of solutions regarding structural stability and buildability

Score	General effect of refurbishment	Effect of solution regarding static load, wind, seismic load, frost heave on structural stability
-2	Significant aggravation or highly vulnerable	Structural stability significantly worse after refurbishment or highly vulnerable solution. The buildability is highly vulnerable and highly depending of the defined criteria.
-1	Minor aggravation or vulnerable	Structural stability worse after refurbishment or vulnerable solution. The buildability is vulnerable and depending of the defined criteria.
0	No change or acceptable	No change in stability or acceptable solution. The buildability is acceptable and is only in some degree depending of the defined criteria.
1	Minor improvement or good	Structural stability better after refurbishment or good solution. The buildability is good and is in little degree depending of the defined criteria.
2	Significant improvement or very good	Structural stability significantly better after refurbishment or very good solution. The buildability is very good and is not depending of the defined criteria.

4.8 Need for care and maintenance

<u>Maintenance and vulnerability to damage</u>

Refurbishment of external walls can affect the future need for care and maintenance in several ways. First the refurbishment process may involve replacing existing materials with new materials with a longer or shorter expected service life. Also, temperature and moisture conditions in the wall may change, affecting the maintenance need and expected service life of the existing structure as well as any new materials. Where new external surfaces are introduced, surface treatment methods may change completely. Finally, a refurbished wall may be more or less susceptible to mechanical damage or vandalism than the existing structure. Thus these parameters should preferably be known both for the original and refurbished wall, which will allow a considered assessment on the effects to be made.

- Requirement for maintenance: work and material required for necessary maintenance operations, interval between operations and factors affecting this. When labor and materials costs are known, the results forms part of the LCC analysis.
- Ease of maintenance (existing technology, dangerous substances, etc.).
- Existence of maintenance plan.
- Maintenance culture at the local level. Quality demand varies, e.g. reaction to molds, fading and other disfigurement.
- Vulnerability to damage: Vandalism (graffiti), sun radiation, rain, pollution, accidental damage etc.
- Removability of new solution – potential to exchange/remove (reversibility).

Several data sources exist for the maintenance intervals and costs for the original constructions, see SUSREF D 5.2.for the ones considered in this element of the project These cover to some extent the most commonly used refurbishment concepts in the EU. However, large discrepancies between predicted and actual maintenance cost and intervals is to be expected due to local variations in microclimate, user acceptance, accessibility to vandalism etc.

<u>Report scope</u>

The report describes the maintenance procedures and vulnerability to damage of the original wall types as well as the refurbished solutions. The description of the original walls is limited to a set of common wall types found in Europe; see Holøs et al. 2010:

- Solid walls made with brick or natural stone
- Sandwich elements made with concrete
- Timber framed walls with wooden cladding
- Cavity walls with or without insulation in the cavity.

In this context damage includes unacceptable disfigurement.

The description of the refurbished solutions is limited to some common systems for retrofitting insulation:

- External thermal insulation composite system
- Frames, insulation and cladding added to the outside wall
- External insulation with brick veneer
- Internal insulation
- Insulation injected into cavity walls.

In this report the following maintenance related topics are discussed:

- Needs for maintenance – includes inspection, cleaning, repairs to minor and major damages and replacements
- Vulnerability to damage – includes graffiti, air pollution (sulfur compounds, nitrous compounds, organic compounds and ozone) and microbial growth (fungi, algae and bacteria)
- The effect of retrofitting insulation on the maintenance needs and on any increased vulnerability to damage.

<u>Grading system</u>

The maintenance needs are graded in the following categories:

- Light maintenance – procedures that, relatively, require little time and few resources. Typically inspection (primarily visual) of the facade, cleaning and minor repairs fall into this category.
- Moderate maintenance – procedures that require more time and more resources. A typical example is painting the facade.
- Heavy maintenance – procedures that are very disruptive, time consuming and costly. A typical example is exchange of the entire cladding on a wooden house.

The vulnerability to damage is graded in the following categories:

- Low vulnerability. The system can be damaged, but it takes a long time for damage to occur under normal circumstances, or damage occurs only in extreme cases.
- Medium vulnerability. The system can be damaged, but not easily.
- Heavy vulnerability. The system is easily damaged.

The effect of retrofitting insulation on the maintenance needs and vulnerability to damage is evaluated on a scale from -2 through 2:

Table 17. Evaluation of the effect of retrofitting insulation evaluation.

-2	Significant aggravation. The need for maintenance/vulnerability of the new facade is significantly higher than for the old facade
-1	The need for maintenance/vulnerability of the new facade is somewhat higher than for the old facade
0	The need for maintenance/vulnerability of the new facade is the same or almost the same compared to the old facade
1	The need for maintenance/vulnerability of the new facade is a bit lower than for the old facade
2	The need for maintenance/vulnerability of the new facade is significantly lower than for the old facade

4.9 Indoor thermal climate and air quality assessment

4.9.1 Indoor climate

Indoor environment is a broad term that includes all factors affecting a person's perception of a room. *Indoor climate* is normally defined as the physically measurable intrinsic factors affecting people inside buildings. It is often divided into thermal, chemical, actinic, acoustic and mechanical climate, excluding the psycho-social and aesthetical factors of the indoor environment. In this section assessment is restricted to indoor thermal climate, indoor air quality and acoustics.

<u>Thermal climate</u>

The main building related factors affecting the thermal comfort are air temperature (including temperature gradient), air movement, radiant temperature and asymmetry as well as air humidity. Elaborate methods for predicting thermal satisfaction was developed by Fanger, and are implemented in EN 7730. Application of these methods requires more detailed knowledge of the person's clothing and activity, HVAC-systems and other building parts, than is available in the assessment of the refurbishment concepts. Furthermore indoor air temperature is a parameter for assessment when assessing the need for heating and cooling energy (see sections 2.4 and 2.5), and periods when thermal comfort criteria cannot be met are treated in those sections.

Assessment of thermal climate is thus here restricted to a qualitative assessment of how the following properties will be affected by the refurbishment:

1. Air leakage through envelop
2. Temperature asymmetry
3. Surface temperature
4. Internal air humidity.

These properties will be affected not only by the U-values of the refurbished solutions, but by the individual solution's ability to improve airtightness and any uncontrolled air infiltration, remediate thermal bridges, buffer moisture and store heat. The above mentioned properties are quantifiable physical entities that generally are more dependent on other factors than on external wall refurbishment solution. The effect of the refurbishment on the individual property is assigned to a qualitative scale according to criteria in Table 18 and Table 19.

Table 18. Qualitative scale for refurbishment effect on air tightness and temperature asymmetry.

Score	General effect of refurbishment	Effect of refurbishment on Air tightness	Effect on temperature asymmetry
-2	Significant aggravation	n_{50} increased > 0.5 OR new annoying air leaks** likely	Radiant asymmetry increased > 7 °C (cold wall) or > 12 °C (hot wall) (Not likely to be relevant)
-1	Minor aggravation	n_{50} increased < 0.5 OR new annoying air leaks possible	Radiant asymmetry increased < 7 °C (cold wall) or < 12 °C (hot wall) (< 2% PPD)
0	No change	No effect on infiltration or	No effect
1	Minor improvement	n_{50} reduced < 0.5 OR removal of annoying air leaks possible	Radiant asymmetry decreased < 7 °C (cold wall) or < 12 °C (hot wall)
2	Significant improvement	n_{50} reduced > 0.5 OR removal of annoying air leaks likely	Radiant asymmetry decreased > 7 °C (cold wall) or > 12 °C (hot wall)

*) n_{50} is the calculated number of air leaks per hour at 50 Pa pressure difference between indoor and outdoor air, see EN 13829. Not to be confused by infiltration rate.

**) Air leaks are generally perceived as annoying when air speed exceeds 0.15 m/s, but the effect is temperature-dependant

Table 19. Qualitative scale for refurbishment effect on indoor air humidity and surface temperature.

Score	General effect of refurbishment	Effect on indoor air humidity*	Effect on interior surface temperature
-2	Significant aggravation	Moisture buffering capacity significantly reduced in cases where RH is critical for more than 50 h/year	Extreme value for |T (indoor air) – T (surface)| increased > 5 °C
-1	Minor aggravation	Moisture buffering capacity slightly reduced in cases where RH is critical for more than 50 h/year	Extreme value for |T (indoor air) – T (surface)| increased < 5 °C
0	No change	No change in moisture buffering capacity, or RH not critical more than 50 h/year	No change in indoor surface temperature
1	Minor improvement	Moisture buffering capacity slightly increased in cases where RH is critical for more than 50 h/year	Extreme value* for |T (indoor air) – T (surface)| decreased < 5 °C
2	Significant improvement	Moisture buffering capacity significantly increased in cases where RH is critical for more than 50 h/year	Extreme value for |T (indoor air) – T (surface)| decreased > 5 °C
*) In the cases where influx of water through walls is significant, refurbishment will reduce this. The indirect effect on relative humidity by changing temperatures of indoor surfaces and indoor air is not treated under this criterion.			

In some wall types, moisture influx from outside is a problem. Wall refurbishments may reduce this by introducing watertight or ventilated and drained layers in the new construction layers. Where relevant this is scored from 0 through 2 using the general criteria (column 1–2 in above table).

4.9.2 Indoor air quality assessment

Indoor air quality is in this context regarded as the freedom from pollutants in indoor air. Sources of pollution to indoor air are innumerable, including outdoor air, the building itself, its interior, inhabitants and technical equipment. In general, the indoor air quality is seen as being mainly determined by the likelihood of a pollution source and ventilation efficiency. In the context of this deliverable it is reasonable to reduce the assessment of indoor air quality to assessing to what extent the refurbishment option can:

1. Reduces existing pollution sources?
2. Introduces new pollution sources?
3. Changes ventilation efficiency?
4. Changes air pressures over the construction?

It is noted that new pollution sources (# 2 above) may stem from the materials or from the refurbishment process. Changed ventilation efficiency is predominantly related to reduced air leakage, which generally can be abated by increasing supply air by balanced ventilation or the introduction of vents. The criteria used are given in Table 20. Factor # 4 above is particularly of interest in the context of radon from the ground polluting the indoor air, and is likewise closely connected to reduced air leakage. The assessment of # 3 & 4 above is combined in Table 21.

Table 20. Qualitative assessment of effect on pollution sources.

Score	General effect of refurbishment	Effect of existing pollution sources	Introduction of new pollution sources
-2	Significant aggravation	Not relevant	New pollution sources introduces (not fulfilling RTS M0 or M1 criteria)
-1	Minor aggravation	Existing pollution sources more exposed to indoor air due to removal of barriers in wall	New minor pollution sources (Corresponding to RTS M0 or M1) introduced
0	No change	No change	No pollution sources introduced
1	Minor improvement	Minor pollution sources removed or covered	Not relevant
2	Significant improvement	Major pollution sources removed or covered	Not relevant

Table 21. Qualitative assessment of effect on ventilation efficiency and air pressure differences.

Score	**General effect of refurbishment**	**Effect of refurbishment on ventilation efficiency and air pressure differences**
-2	Significant aggravation	Infiltration rates likely to be reduced by > 0.1 h^{-1} OR Vents covered by refurbishment (where ventilation rates < class 2 in EN 15259) OR i pressure difference (ground – indoor air) increased > 50 Pa
-1	Minor aggravation	Infiltration rates likely to be reduced by < 0.1 h^{-1} OR Vents having reduced efficiency by refurbishment (where ventilation rates <class 2 in EN 15259) OR increased pressure difference (ground – indoor air) increased 5–50 Pa
0	No change	Ventilation rates not changed. Pressure difference against ground
1	Minor improvement	Ventilation rates increased by < 0.1 h^{-1} OR pressure difference against ground decreased 5–50 Pa
2	Significant improvement	Ventilation rates increased by < 0.1 h^{-1} OR pressure difference against ground decreased > 50 Pa

4.9.3 Acoustics Assessment

This is another complex topic that in the present context can be reduced to assessing whether the refurbishment option

1. Changes the transmission of sound from exterior to interior
2. Changes the sound transmission between apartments
3. Changes the absorption / reflection of sound from internal surfaces.

Criteria used are specified in Table 22. Criterion 1 is the one where the refurbishment of a building’s envelops is most likely to make significant difference to the inhabitants.

In some cases, external wall refurbishment may reduce internal sound transmission in the building, e.g. when internal insulation decreases air leaks through dividing floors or walls, known as air bourne transmission. Such reductions may be highly appreciated by inhabitants, and can be viewed as an added benefit of the refurbishment chosen. However, in some cases the solution of wall refurbishment when located in the inside side of the building may increase the internal sound transmission in the building. Assessments have to be made at building level to fully understand the impacts of any given option.

Table 22. Qualitative scale for assessment of effect on building acoustics.

Score	General effect of refurbishment	Effect on sound transmission from exterior	Effect on sound transmission between apartments	Effect on Internal acoustics
-2	Significant aggravation	$R_w + C_{tr}$* of construction decreased > 5 dB	Rarely relevant (external wall of relatively minor importance for majority of buildings)	Not relevant (external wall of relatively minor importance for majority of buildings)
-1	Minor aggravation	$R_w + C_{tr}$ of construction decreased < 5 dB	Decreased sound insulation R_w decreased < 5 dB	Increased sound reflection from interior surface
0	No change	$R_w + C_{tr}$ +/- 1 dB	No change	No change to internal surface
1	Minor improvement	$R_w + C_{tr}$ of construction increased < 5 dB	Increased sound insulation $R_{w\ i}$nrreased < 5 dB	Decreased sound reflection from interior surface
2	Significant improvement	$R_w + C_{tr}$ of construction increased > 5 dB	Rarely relevant (external wall of relatively minor importance for majority of buildings)	Not relevant (external wall of relatively minor importance for majority of buildings)
*) $R_w + C_{tr}$ Sound reduction number and spectrum adaptation term (EN-ISO 717-1)				

4.10 Disturbance to tenants and to the site

Refurbishment processes needs space for the actual work processes to be undertaken as discussed earlier in the Buildability section of this report, for storage of tools and materials, as well as for scaffolding and securing the site. The process may involve replacement of elements of the structure, and the process may generate noise, dust and emissions.

As a consequence of these demands and effects both the inhabitants of the building under refurbishment as well as neighbours and passers-by may experience more or less grave disturbance. The actual consequences may vary according to the local conditions. For example, extensive scaffolding may be unproblematic for a free-standing building in a sub-urban setting, but very problematic in a historic city centre.

Examples of effects and qualitative evaluation is given in Table 23.

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Table 23. Qualitative scale for assessment of effects for inhabitants and the site.

Score	General effect of refurbishment	Effect on inhabitability	Effect on neighbours and site
-2	Grave effect	Premises needs to be evacuated for extended periods	
-1	Significant effect	Premises generally not usable > 48 h OR major noise, dust or emission problems OR Possibilities for airing or access to daylight seriously affected for longer periods	Major noise or dust problems for extended periods OR use of surrounding space seriously restricted for extended periods
0	Minor effect	Use restricted for shorter periods OR minor noise, dust or emission problems.	Minor noise or dust problems for neighbours. Restricted availability of surrounding space.
1	No effect	No noticeable effect for inhabitants	No noticeable effect for neighbours or surrounding space

4.11 Aesthetic quality and cultural heritage assessment

4.11.1 Aesthetic quality

Many buildings and groups of buildings are valued as much for their aesthetics as for their functional characteristics. Aesthetics distinguish one building from another, often controversially, and establish the character of buildings, towns and cities. Unlike many of the criteria discussed elsewhere in this report, aesthetic quality is notoriously difficult to measure or reach a consensus view on, which often means these qualities are neglected and absent from legislation and guidance. Aesthetic quality is more of a judgement and a perception rather than a scientific calculation.

In most conversations about architecture, the term “aesthetics” is reserved for matters relating to the visual appearance of a building. However, it refers to more than this; it means the appreciation of beauty or the pleasure given from beauty. This is a much wider definition than is normally adopted. The beauty in older buildings is often obvious in their appearance, but for some beauty can be perceived in the acoustics, the thermal conditions, tactile experience of elements and components, the construction materials and how they are assembled, and even the smell of a building. Assessing refurbishment options for their aesthetic qualities, therefore, is a complex affair. The issue is further discussed in Appendix A.

4.11.2 Effect on cultural heritage

The built environment represents an important part of human culture. It reflects the artistic, technological and spiritual achievements and values of cultures that persist and evolve politically, socially and economically. Buildings also reflect the effects of climate and locality in the materials that have been used and how they have weathered over time. In many cases (and places), they are recognised as embodiments of our core values and meanings and as such are essential to defining who we are. Not surprisingly, proposals that seek to change the character of the built environment often meet resistance from citizens who have a keen interest in the character of their environments. This is most vigorous when there are plans to demolish, replace or extend existing buildings, but can be equally vocal against plans to alter existing buildings even in seemingly minor ways. The purpose of this section is to consider how refurbishment proposals for external walls might be assessed for the possible impact on built cultural heritage. The issue is further discussed in Appendix A.

4.12 Impact on renewable energy use potential

The purpose of this chapter is to give an expert assessment about the use potential of renewable energy technologies in the context of alternative refurbishment concepts of exterior wall.

Renewable energy sources are: solar thermal, photovoltaic systems, wind power, geothermal energy or bio energy. In this presentation we concentrate on solar energy exploitation which is relevant in façade refurbishments. In this perspective we analyze the electricity generation potential photovoltaic systems and solar thermal systems that are wall integrated.

4.12.1 Photovoltaic systems

Photovoltaics (PV) is a method of generating electrical power by converting solar radiation into electricity using semiconductors that exhibit the photovoltaic effect. Photovoltaic power generation employs solar panels composed of a number of solar cells containing a photovoltaic material. Materials presently used for photovoltaics include monocrystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride, and copper indium gallium selenide/sulfide (Jacobson).

Photovoltaic arrays are often associated with buildings: either integrated into them, mounted on them or mounted nearby on the ground.

Figure 50. Ruukki's fully-integrated solar panel façade (http://www.ruukki.com).

Arrays are most often retrofitted into existing buildings, usually mounted on top of the existing roof structure or on the existing walls. Alternatively, an array can be located separately from the building but connected by cable to supply power for the building. Building-integrated photovoltaic systems (BIPV) are increasingly incorporated into new domestic and industrial buildings. Facades can be installed on existing buildings, giving old buildings a whole new look. These modules are mounted on the facade of the building, over the existing structure, which can increase the appeal of the building and its resale value. Transparent modules can be used to replace a number of architectural elements commonly made with glass or similar materials, such as windows and skylights. Transparent solar panels use a tin oxide coating on the inner surface of the glass panes to conduct current out of the cell. The cell contains titanium oxide that is coated with a photoelectric dye (Tiwari).

Most conventional solar cells use visible and infrared light to generate electricity. In contrast, the innovative new solar cell also uses ultraviolet radiation. Used to replace conventional window glass, or placed over the glass, the installation surface area could be large, leading to potential uses that take advantage of the combined functions of power generation, lighting and temperature control.

Electricity generation potential

Electricity production of a photovoltaic (PV) system is calculated by

$$E = P_{pk} \cdot E_{sol} \cdot f_{perf} \qquad (1)$$

where

P_{pk} is the peak power represents the electrical power of a photovoltaic system with a given surface and for a solar irradiance of 1 kW/m^2 on this surface (at 25 °C), kW

E_{sol} is the monthly or yearly average of daily global irradiation on the horizontal or inclined surface, kWh/month or kWh/year

f_{perf} is the system performance factor.

The power output of photovoltaic systems for installation in buildings is usually described in kilowatt-peak units (kWp). This is the power that the manufacturer declares that the PV array can produce under standard test conditions, which are a constant 1000 W of solar irradiation per square meter in the plane of the array, at an array temperature of 25 °C. The peak power can be calculated as

$$P_{pk} = A \cdot K_{pk} \qquad (2)$$

where

A is the surface area of the PV-panel, m^2

K_{pk} is the peak power coefficient (efficiency) depending on the type of the PV-panel (see table 5), kW/m^2.

Typically the peak power coefficients for crystalline silicon panels are between 0.1–0.14. Thus the area needed for 1 kWp varies between 10–7 m^2 and the specific power of the PV-panel between 100–140 W/m^2. Information on solar panel products and producers can be found for example on POSHARP website: http://www.posharp.com.

Table 24. Typical values for peak power coefficients of different types of PV-materials (EN 15316-4-6:2007).

Type of PV-module	K_{pk}, kW/m²
Mono crystalline silicon	0.12–0.18
Multi crystalline silicon a	0.10–0.16
Thin film amorphous silicon	0.04–0.08
Other thin film layers	0.035
Thin film Copper-Indium-Galium-diselenide	0.105
Thin film Cadmium-Telloride	0.095

System losses that are taken into account in system performance factor are all the losses in the system, which cause the power actually delivered to the electricity grid to be lower than the power produced by the PV modules. There are several reasons for this loss, such as losses in cables, power inverters, dirt (sometimes snow) on the modules. Default value of 0.25 is often used for the system losses.

If the PV modules are to be built into an existing wall, the inclination (the angle of the PV modules from the horizontal plane) and orientation angles (angle of the PV modules relative to the direction due South) will already be known. However, if you have the possibility to choose the inclination and/or orientation, the electricity production is increased dramatically. This is visualized with figures 4 and 5. An optimal inclination that is the inclination which gives the highest electricity production, are presented in Table 25.

Table 25. Optimal inclinations of PV modules at different locations and for different orientations.

Location		Barcelona	London	Oslo	Helsinki
Optimal inclination	South	33°	36°	39°	40°
	West	4°	0°	0°	0°
	North	0°	0°	0°	0°
	East	0°	0°	0°	0°

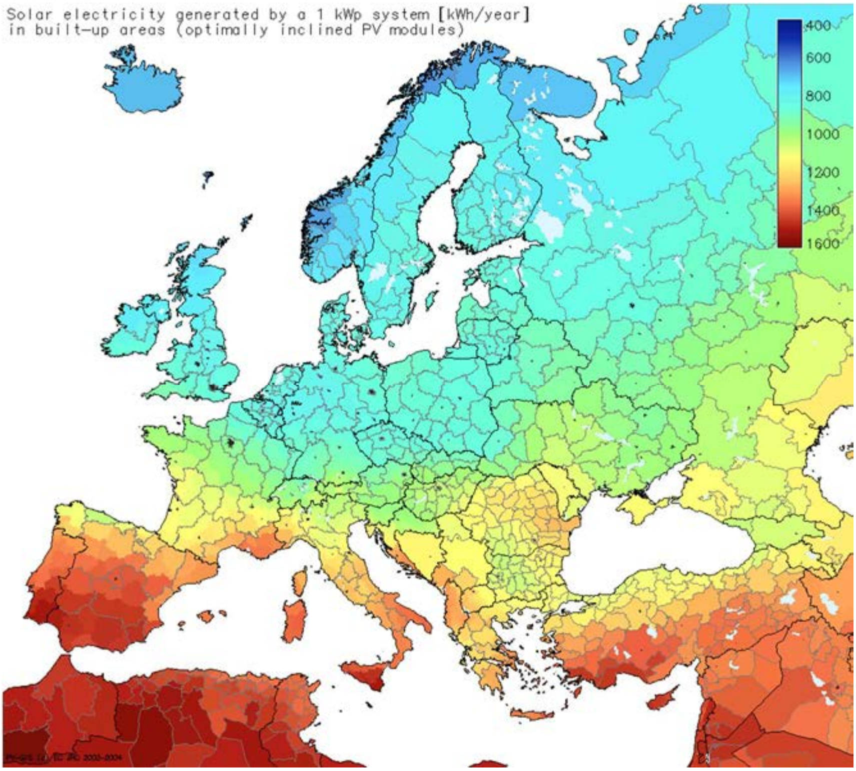


Figure 51. Solar electricity generated by a 1 kWp optimally inclined, south facing PV-panels in Europe. (Source: PVGIS (c) European Communities, 2001–2010, http://re.jrc.ec.europa.eu/pvgis/)

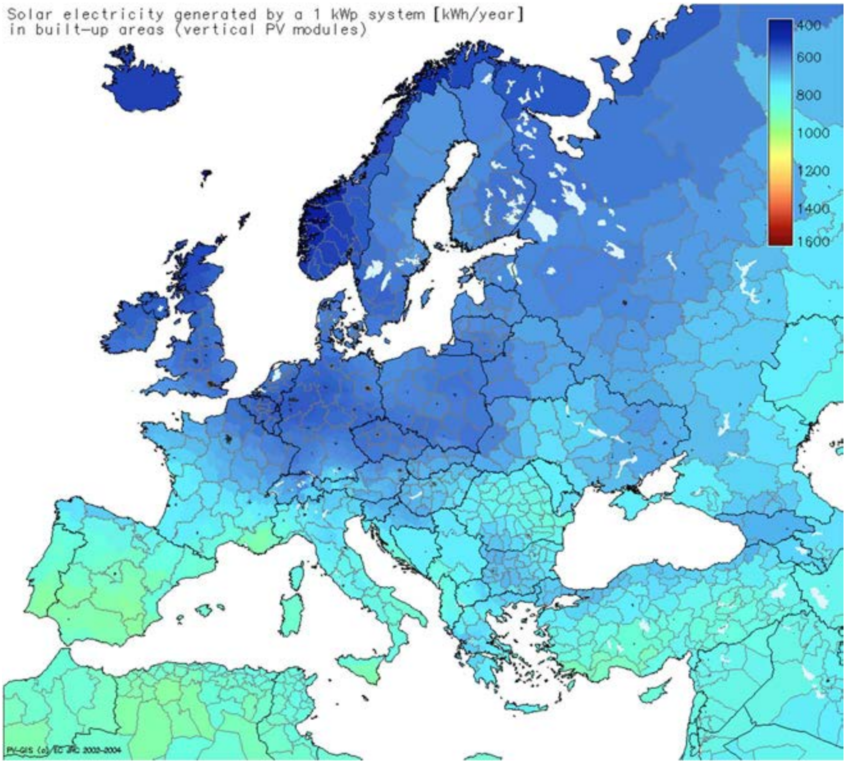


Figure 52. Solar electricity generated by a 1 kWp vertically mounted, south facing PV-panels in Europe. (Source: PVGIS (c) European Communities, 2001–2010, http://re.jrc.ec.europa.eu/pvgis/)

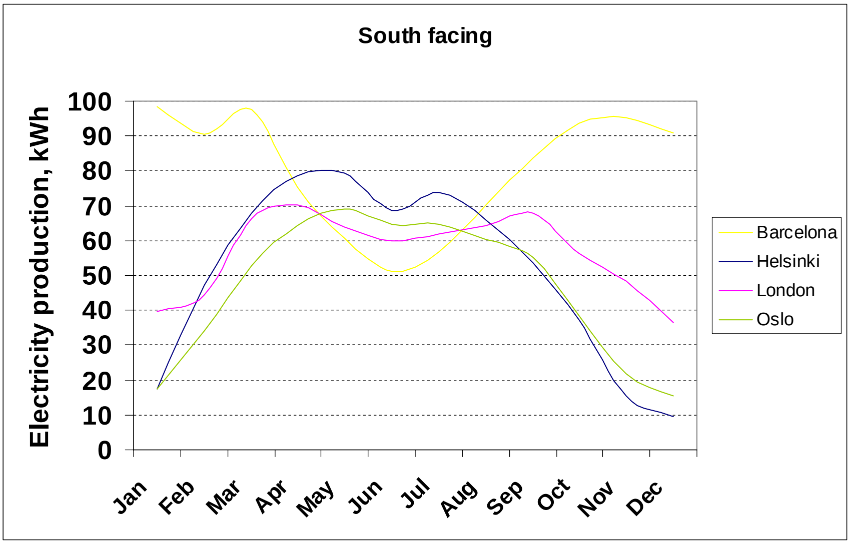


Figure 53. Monthly solar electricity production by a 1 kWp vertically mounted, wall integrated, grid-connected and south facing PV-panels (crystalline silicon) in studied cities. No shading of surrounding is involved.

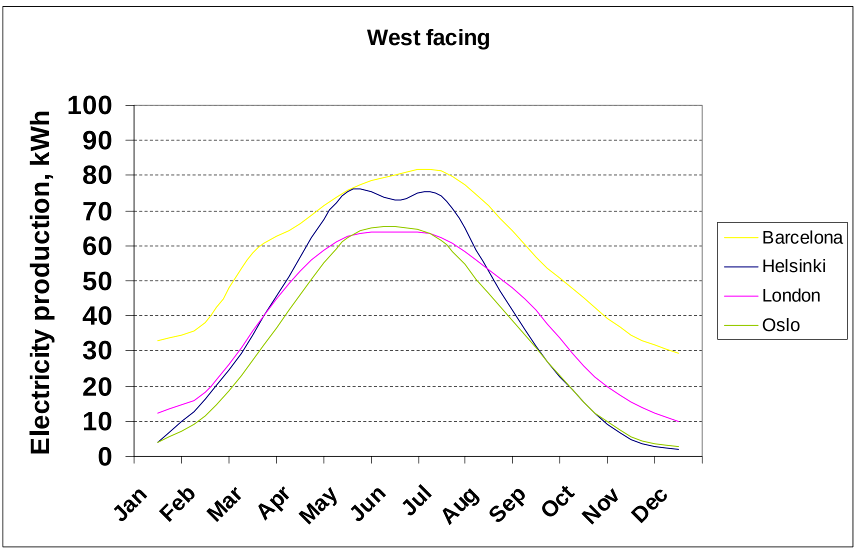


Figure 54. Monthly solar electricity production by a 1 kWp vertically mounted, wall integrated, grid-connected and west/east facing PV-panels (crystalline silicon) in studied cities.

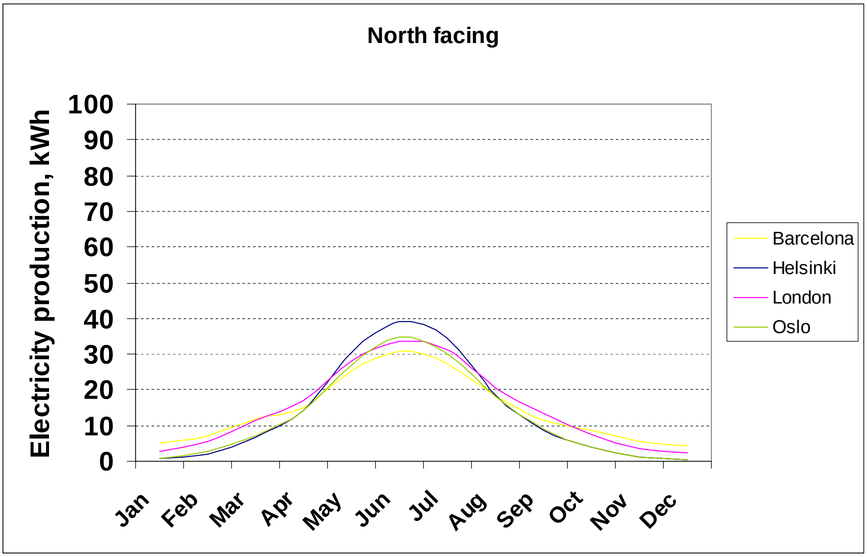


Figure 55. Monthly solar electricity production by a 1 kWp vertically mounted, wall integrated, grid-connected and north facing PV-panels (crystalline silicon) in studied cities. No shading of surrounding is involved.

Summation of the yearly electricity production for the calculated cases are presented in Table.

Table 26. Yearly cumulative electricity production of a 1 kWp vertically mounted, grid-connected and wall integrated PV-panels (crystalline silicon). No shading of surrounding is involved.

Location\Orientation	South kWh/a	West kWh/a	North kWh/a	East kWh/a	Total kWh/a
Helsinki	615	441	160	444	1660
Oslo	558	380	149	384	1471
London	680	454	177	459	1770
Barcelona	964	670	171	683	2488

Obviously the heat generation of studied PV-panels is highest in Barcelona, > 50% higher than in other locations. Generation of the north façade does not depend on the location but the generation is very modest compared to other orientations, less than 10% of the total production.

Case study, single family house

The following study demonstrates the maximum electricity production of PV-panels, if all the available wall area was covered with panels in ideal conditions, defined as nothing overshadows the walls. The electricity production depends on the efficiency of the panels and here it has been assumed that the peak power coefficient is K_{pk} = 0.14, which means that for nominal power of 1 kWp, panel area of 7.14 m^2 is needed. The other limiting factor is the free wall area of the building which is the total area of the walls minus windows and doors. The dimensions of the detached single family house are 10 m x 9 m x 6 m (width x length x height). The free wall area and the corresponding electrical power (kWp) for each point of compass for glazing ratio of 25% (proportion of floor area) are given in Table 8.

Table 27. PV-panel area and corresponding electrical power (kWp) for detached single family house (outside dimensions 10 m x 9 m x 6 m) with glazing proportion of 25%. The values has been calculated for a case where the long wall (10 m) is facing south. The assumed peak power coefficient of the PV-panels is 0.14.

Orientation	South	West	North	East	Total
Panel area (= free wall area), m^2	47 m^2	42 m^2	47 m^2	42 m^2	178 m^2
P_{pk} of PV-panels, kWp	6.6 kWp	5.9 kWp	6.6 kWp	5.9 kWp	25 kWp

The electricity production rates for four different locations in Europe of the studied single family house in ideal case are presented in Figure 56, Figure 57, Figure 58. and Figure 59. The calculation basis for electricity use is given in table Table 28.

Table 28. Household electricity consumption per floor area of the single family house.

Hours per day	Lights, W/m^2	Appliances, W/m^2	Consumption per year, kWh/m^2
8	0.44	0.44	2.57
11	1.32	1.32	10.60
4	4.40	4.40	12.85
Total			26.02

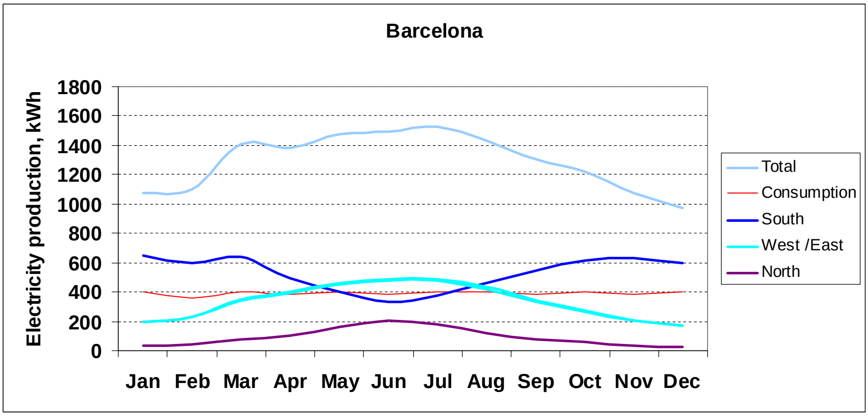


Figure 56. Electricity production of the single family house in ideal case in Barcelona. The electricity production has been calculated for a case where the walls (excluding windows and doors) are all covered with PV-panels and the panels are unshaded (no trees or neighbouring buildings etc.).

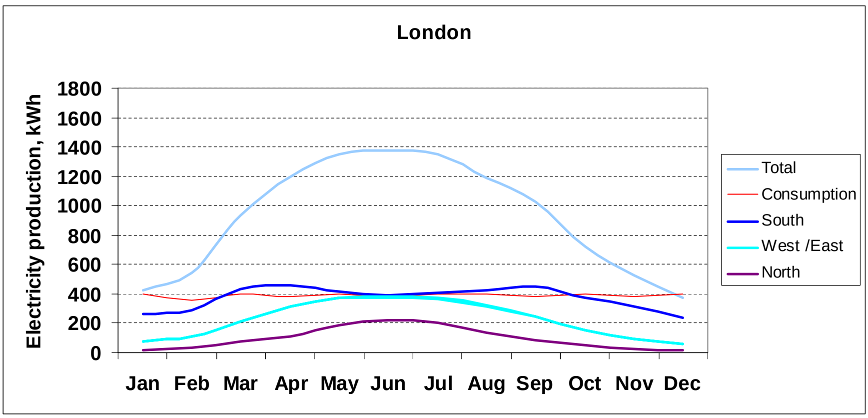


Figure 57. Electricity production of the single family house in ideal case in London. The electricity production has been calculated for a case where the walls (excluding windows and doors) are all covered with PV-panels and the panels are unshaded (no trees nor neighbouring buildings etc.).

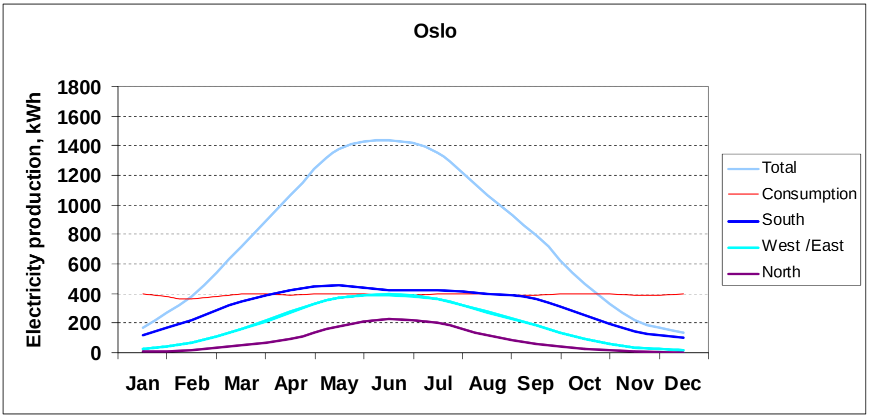


Figure 58. Electricity production of the single family house in ideal case in Oslo. The electricity production has been calculated for a case where the walls (excluding windows and doors) are all covered with PV-panels and the panels are unshaded (no trees or neighbouring buildings etc.).

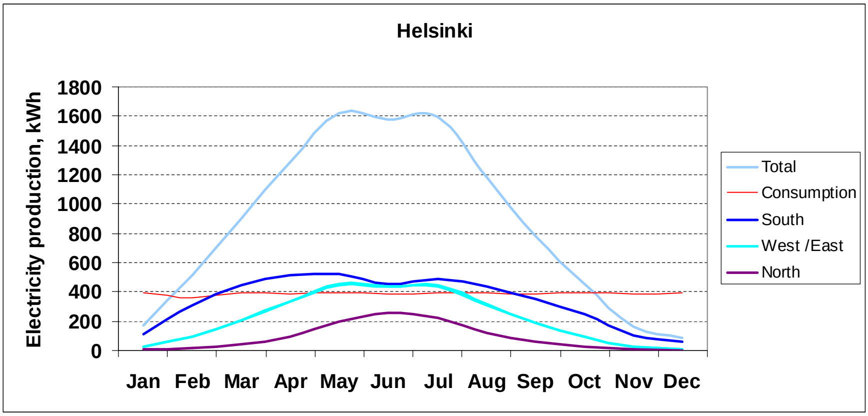


Figure 59. Electricity production of the single family house in ideal case in Helsinki. The electricity production has been calculated for a case where the walls (excluding windows and doors) are all covered with PV-panels and the panels are unshaded (no trees or neighbouring buildings etc.).

The yearly electricity production for each studied location and orientation is presented in Table 29.

Table 29. Yearly electricity production of PV-panels of the studied single family case with ideal hypothesis.

Location	Yearly electriity production, kWh				
	South	West	East	North	Total
Barcelona	6343	3966	4040	1124	15472
London	4469	2686	2713	1164	11032
Oslo	3673	2248	2272	981	9174
Helsinki	4044	2609	2630	1055	10337

When the household energy consumption of the single family house is 4683 kWh/a, it can be seen (Table 29) that this could be covered on yearly basis in Barcelona by covering only the south façade with PV-panels. On a monthly basis the production of the south façade and the consumption don't match in June in Barcelona (Table 29). In all studied locations the household electricity consumption could be covered on yearly basis and even produce surplus electricity to the grid, but may not always meet the month by month demand. On a monthly basis the household electricity usage is higher during the winter months (November, December and January) than the total electricity production of the PV-panels in northern Europe (Oslo and Helsinki).

Most of the electricity, about 40%, is produced by the south façade, east and west facades produce each about 25% and north faced 10%.

Discussion

For fixed systems the way the modules are mounted will have an influence on the temperature of the module, which in turn affects the efficiency. Experiments have shown that if the movement of air behind the modules is restricted, the modules can get considerably hotter (up to 15 °C at 1000 W/m^2 of sunlight) (Sharma). In the application there are two possibilities: free-standing, meaning that the modules are mounted on a rack with air flowing freely behind the modules; and building-integrated, in which case the modules are completely built into the structure of the wall of a building, with no air movement behind the modules. Solar panels, provided there is an open gap in which air can circulate between them and the wall, provide a passive cooling effect on buildings during the cooling season. On the other hand solar panels affect the solar heat gain through the walls during the heating season. Usually these effects are insignificant when the walls are insulated. Heated air can also be innovatively utilized as a heat source of an air source heat pump.

4.12.2 Thermal solar systems

System description

Typically thermal solar systems are used to produce domestic hot water or for space heating or both hot water and space heating (so called combi systems).

In order to heat water using solar energy, a collector, is often fastened to a roof or a wall facing the sun, this subsequently heats a working fluid that is either pumped (active system) or driven by natural convection (passive system) through it. The collector could be made of a simple glass topped insulated box with a flat solar absorber made of sheet metal attached to copper pipes and painted black, or a set of metal tubes surrounded by an evacuated (near vacuum) glass cylinder. In industrial cases a parabolic mirror can concentrate sunlight on the tube, the Heat generated is then stored in a hot water storage tank. The volume of this tank needs to be larger with solar heating systems than with conventional systems in order to allow for bad weather, and increase the efficiency of the system. The heat transfer fluid (HTF) for the absorber may be the hot water from the tank, but more commonly (at least in northern Europe) is a separate loop of fluid containing anti-freeze and a corrosion inhibitor which delivers heat to the tank through a heat exchanger (commonly a coil of copper tubing within the tank). Another lower-maintenance concept is the 'drain-back' in which case no anti-freeze fluid is required; instead all the piping is angled to cause water to drain back to the tank. The tank is not pressurized and is open to atmospheric pressure. As soon as the pump shuts off, flow reverses and the pipes are empty before freezing could occur.

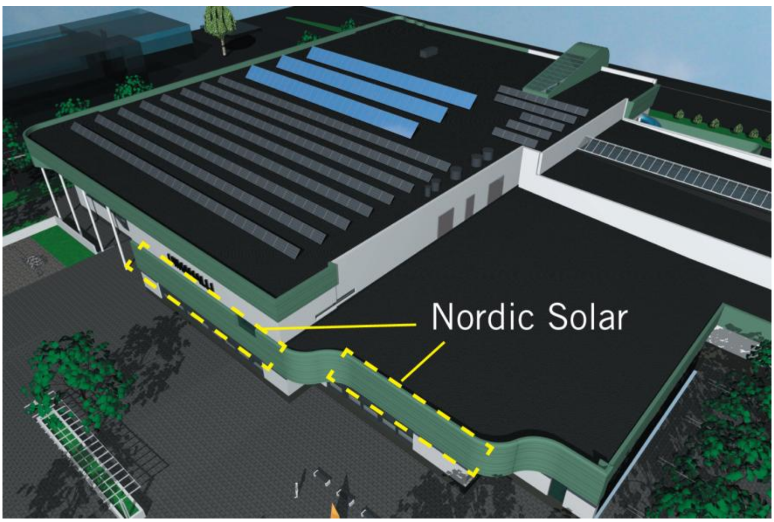


Figure 60. Luvata's fully-integrated non-glazed solar thermal collectors façade (http://www.luvata.com).

Residential solar thermal installations typically include an auxiliary energy source (electric heating element or connection to a district heat, gas or fuel oil central heating system) that is activated when the water in the tank falls below a minimum temperature setting such as 55 °C so that hot water of the correct temperature is always available. The combination of solar water heating and using the back-up heat from a wood stove chimney to heat water can enable a hot water system to work all year round in cooler climates, without the supplemental heat requirement of a solar water heating system being met with fossil fuels or electricity.

When a solar water heating and hot-water central heating system are used in conjunction, solar heat will either be concentrated in a pre-heating tank that feeds into the tank heated by the central heating, or the solar heat exchanger will replace the lower heating element and the upper element will remain in place to provide for any heating that solar cannot provide. However, the primary need for central heating is at night and in winter when solar gain is lower.

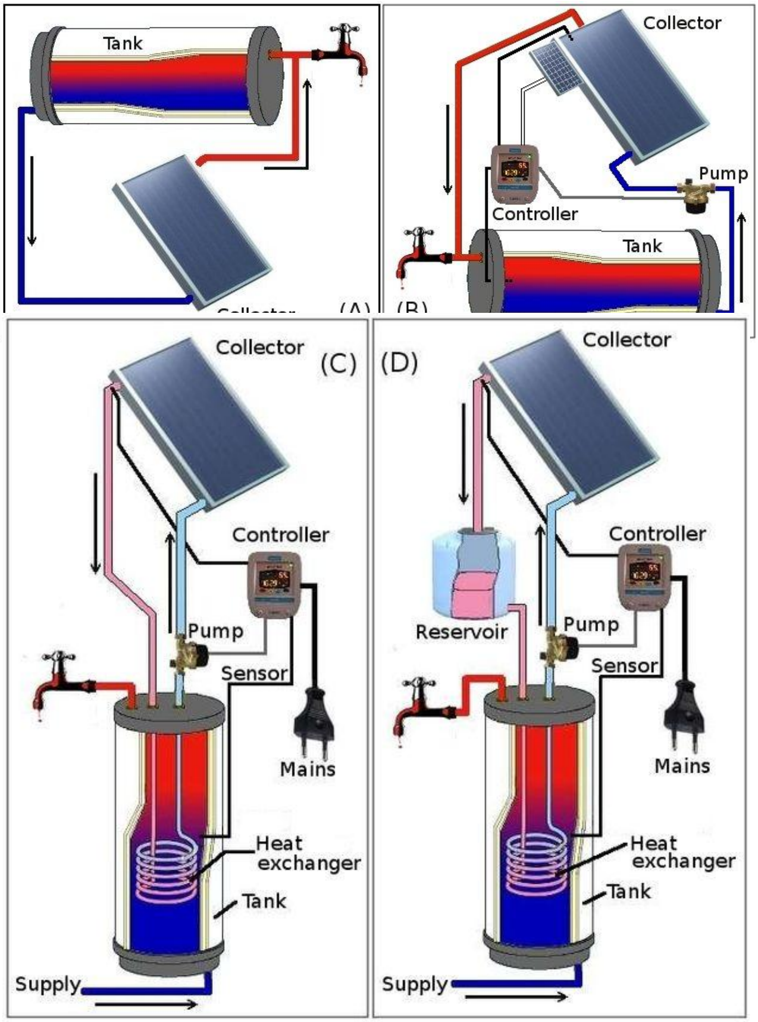


Figure 61. Solar thermal heating systems a) buancy driven direct system without circulation pump, b) pump driven direct system c) pump driven indirect system, d) pump driven indirect system with drainback (Source: http://en.wikipedia.org/wiki/Solar_water_heating).

Heating potential studies

The performance of a thermal solar system depends on the thermal use applied to the system. The thermal use applied to the thermal solar system is the heat demand of the building; domestic hot water and space heating. In general, the higher the total thermal use applied to the thermal solar system is, the higher is the output of the thermal solar system. Therefore it is necessary to know the energy use applied to the thermal solar system before the determination of the solar system output.

The performance of the thermal solar system is determined by the following parameters (EN 15316-4-3:2007):

- product characteristics according to product standards
- collector parameters (collector aperture area, zero loss efficiency, heat loss coefficients etc.)
- size of the storage tank
- collector loop thermal losses and thermal losses of the distribution between storage tank and back-up heater (length, insulation, efficiency etc.)
- control of the system (temperature difference, temperature set points etc.)
- climate conditions (solar irradiation, outdoor air temperature etc.)
- auxiliary energy of the solar collector pump and control units
- heat use of the space heating distribution system
- heat use of the domestic hot water distribution system.

In many climates, a solar hot water system can provide from 50% up to 85% or even 100% in hot climates of domestic hot water heating demand. In northern European countries, combined hot water and space heating systems (solar combisystems) can provide 10 to 25% of the space heating energy.

<u>Case studies on single family house</u>

The production is calculated with typical values according to standard EN 15316-4-3:2007, which takes into account the heat losses of the system. The calculations are made for hot water demand of 200 litres per day which equals to the demand of roughly four persons.

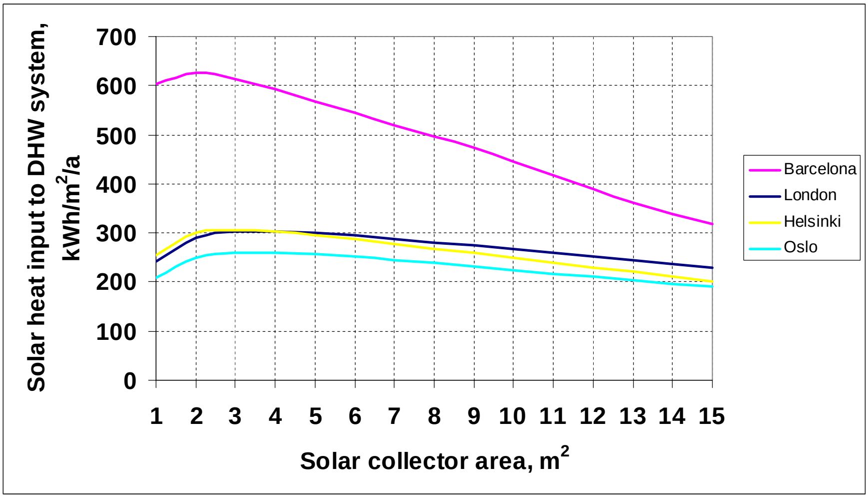


Figure 62. Typical heat gain of south facing wall integrated (inclination 90°) solar collector DHW system in detached houses in different climates. No shading of surrounding is involved. The size of the needed hot water storage is optimum for each collector size V = 75 * area (litres).

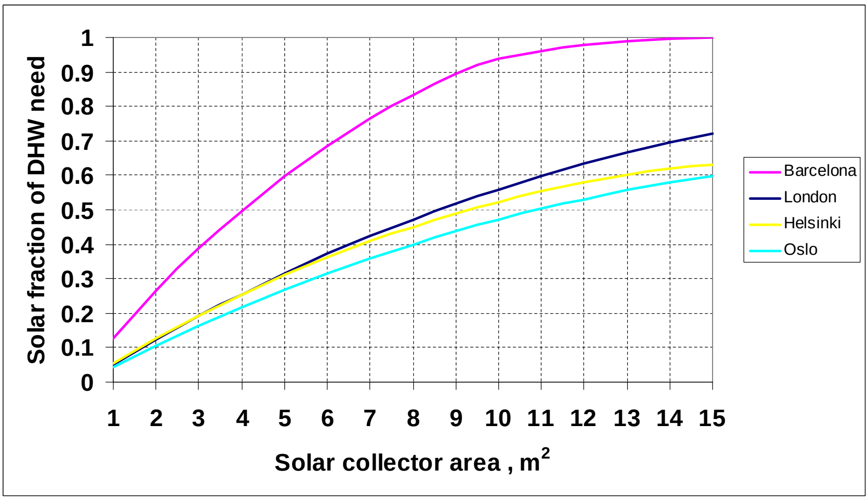


Figure 63. Typical solar fraction of hot water demand that the south facing and wall integrated (inclination 90°) solar collector system can cover in detached houses in different climates. No shading of surrounding is involved. The size of the needed hot water storage is optimum for each collector size V = 75 * area (litres).

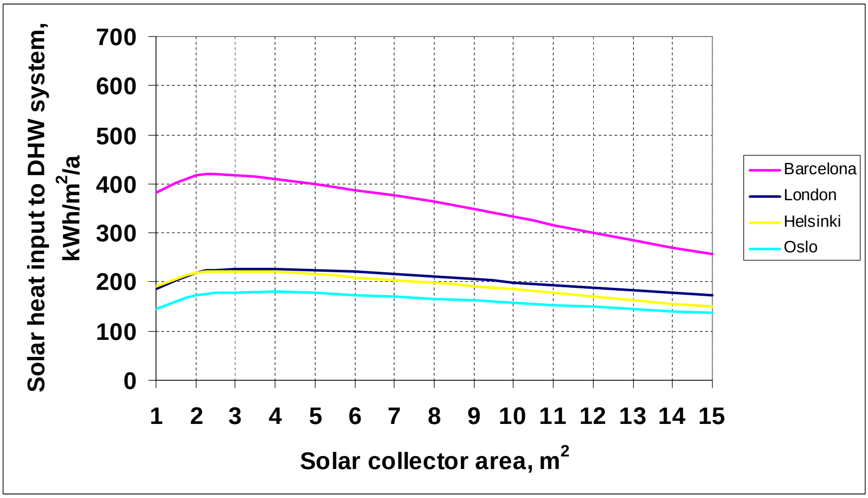


Figure 64. Typical heat gain of south facing wall integrated (inclination 90°) solar collector DHW system in detached houses in different climates. No shading of surrounding is involved. The size of the needed hot water storage is optimum for each collector size V = 75 * area (litres).

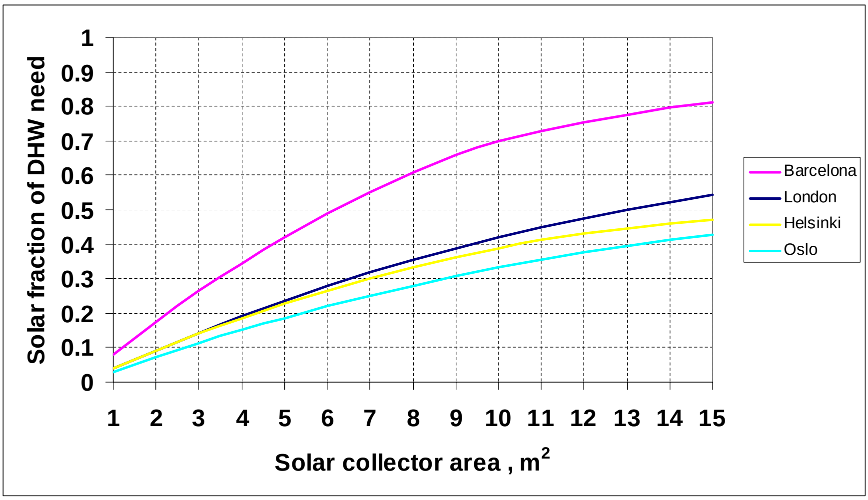


Figure 65. Typical solar fraction of hot water demand that the west or east facing and wall integrated (inclination 90°) solar collector system can cover in detached houses in different climates. No shading of surrounding is involved. The size of the needed hot water storage is optimum for each collector size V = 75 * area (litres).

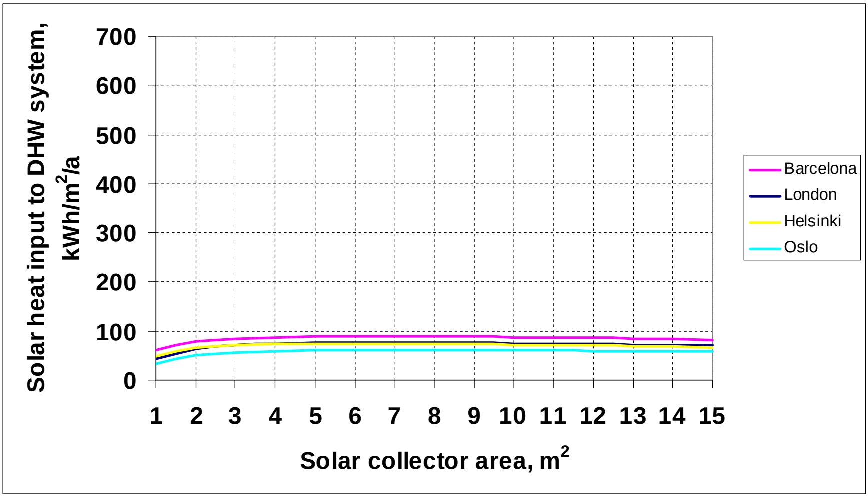


Figure 66. Typical heat gain of south facing wall integrated (inclination 90°) solar collector DHW system in detached houses in different climates. No shading of surrounding is involved. The size of the needed hot water storage is optimum for each collector size V = 75 * area (litres).

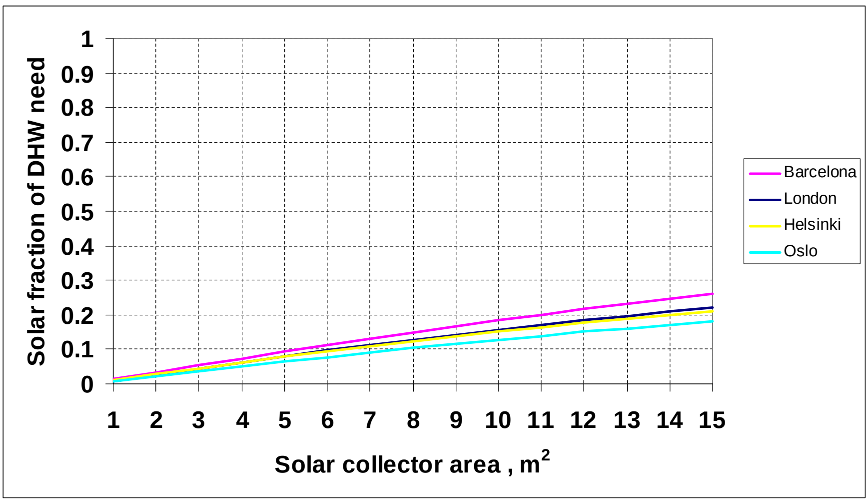


Figure 67. Typical solar fraction of hot water demand that the north facing and wall integrated (inclination 90°) solar collector system can cover in detached houses in different climates. No shading of surrounding is involved. The size of the needed hot water storage is optimum for each collector size V = 75 * area (litres).

It is clear that the solar output from the solar thermal system is much higher in Barcelona than in northern locations (London, Oslo, Helsinki) for south and east or west facades but for north façade the output is more or less equal. The highest output for each location is reached for south façade and lowest naturally for north facade the maximum output of the analyzed solar system is reached with collector aperture area of 2–4 m^2. In Barcelona it is possible to cover over 90% of the hot water heating demand with south facing system, whereas 40–60% is reasonable in the northern locations. East and west facing systems can cover 70% of DHW and 30–40% in northern areas. North facing system is inefficient, capable to produce 10–20% of the DHW need.

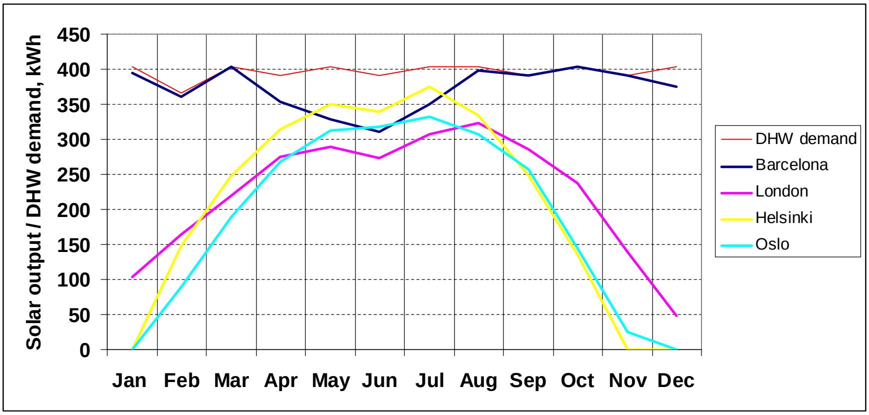


Figure 68. Example of the monthly output of the solar heat system and respective domestic hot water demand. The system produces only domestic hot water (DHW), the collector is integrated into the south façade, the collector area is 10 m^2 and storage tank volume is 750 litres.

An example monthly basis calculation of the solar heat system producing hot water is presented in Figure 19. The results illustrate that in Barcelona the solar system can cover nearly all of the DHW need except during the summer months. In northern Europe the DHW demand is nearly covered during summer months where as during the winter months the output is practically zero.

<u>Discussion</u>

In southern climates the solar thermal system has great potential in decreasing heating energy consumption of both domestic hot water and space heating. In northern climates the potential is first of all in hot water production and less in heating energy consumption.

4.12.3 PVT Photovoltaic and thermal

PVT is defined as a device using PV as a thermal absorber. By using the heat generated in the PV, a PVT device generates not only electrical, but also thermal energy.

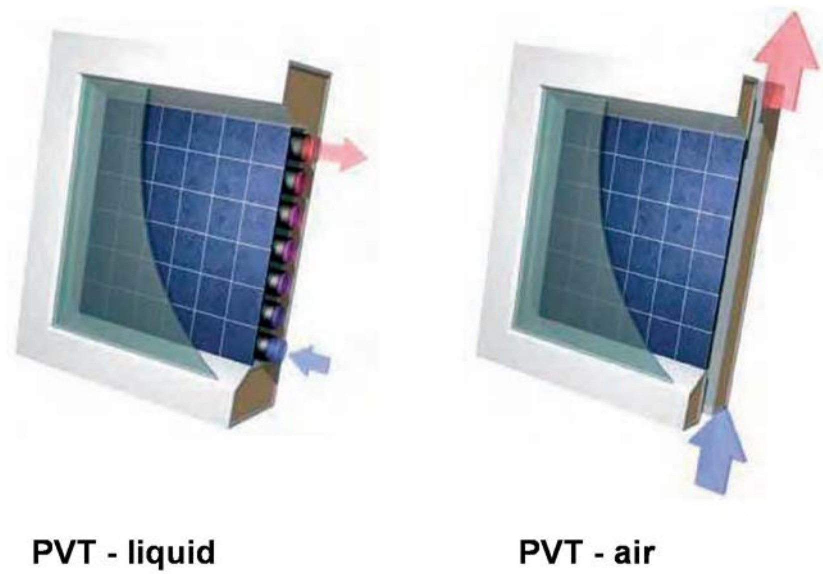


Figure 69. PVT consepts (Source: Affolter, P., et al. PVT ROADMAP – A European guide for the development and market introduction of PV-Thermal technology. ECN Petten. 2008.)

Building integrated PV or PVT facades, apart from providing electricity and heat, have additional benefits:

- PV-facade may limit the thermal losses from the building to the ambient (especially those related to infiltration).
- In addition, the PV facade shields the building from the solar irradiance, thereby reducing the cooling load. This makes such facades especially useful for retrofitting badly insulated existing offices.
- Air collectors and PV-facades can use their buoyancy induced pressure difference to assist the ventilation, if there is no demand for the generated heat.
- Facade integration of PV has the cost incentive of substituting expensive facade cladding materials.

Apartement building Lundebjerg
(Cenergia, Photo Peder Vejsig Pedersen)

Public library, Mataro (TFM)

Figure 70. Examples of building integrated PVT systems. Apartment building Lundebjerg use PVT for preheating ventilation air whereas Mataro uses PVT system to preheat air for solar cooling system. (Source: P. Affolter, et al. PVT ROADMAP – A European guide for the development and market introduction of PV-Thermal technology. ECN Petten. 2008.)

<u>Construction constraints of renewable energy systems</u>

The product specific construction constraints depends largely on the product itself but some common requirements can be suggested:

1. The mounting system must stand the strains of wind and possible snow load
2. The mounting system must not be noisy (vibration proof caused by wind)
3. The mounting system must not cause heat bridges through the insulation
4. The mounting system must not cause water leakage problems through the façade
5. Safety must be ensured in cases when the glass coverings breaks
6. Heating of the back-side of PV-panels and collectors must be taken care of when designing the wall integration.

In most wall constructions the internal as well as cavity insulation of the walls does not effect on the use of photovoltaic or solar thermal systems. With external insulation particular attention must be paid to heat bridges through insulation.

4.13 Fire safety assessment

To achieve sufficient safety for people in or on the building, to reduce the damage on material properties, and to reduce the impact on the environment and society, buildings must be planned and built with sufficient fire safety. This can be accomplished by using materials and products without unacceptable contribution to the ignition and development of the fire, and by designing the building, building parts and installations to reduce the development and spread of fire. In addition to reducing spread of fire between the compartments in a building, the design shall also limit the risk of fire spread between buildings. The design must also facilitate quick and safe evacuation from the fire. And it must reduce the risk of premature structural collapse, which can obstruct safe evacuation and rescue of the people in the building and lower the possibility to restore the building after the fire.

When refurbishing a load bearing or non-load bearing façade the fire safety might be affected, and must therefore be evaluated. The fire safety of the refurbishment concepts is in this project assessed based on their *reaction to fire* and their *fire resistance*. The reaction to fire is the material's ignitability, rate of heat release, rate of spread of flame, rate of smoke production, toxic gases, flaming droplets/particles and/or a combination of these safety aspects. The fire resistance is the load bearing structure's or the fire separation wall's ability to maintain its load bearing, insulation or integrity properties when exposed to a fire.

The effect of the refurbishment on the reaction to fire and fire resistance is assigned to a qualitative scale according to the criteria in Table 30.

There are mainly two scenarios for a fire; the wall can be ignited from the internal side or the external side. A fire that starts inside the building can become very severe and the temperatures and pressure can result in the breakage of windows, or burn through of internal separating walls and ceilings. If the fire starts on the external side of the wall or spreads from the inside to the outside through windows, the flames can spread on the facade to other units of the building.

<u>Reaction to fire</u>

The reaction to fire performance will be influenced by the following factors:

- Contribution to fire of materials and products used
  - Non-combustible
  - Combustible: Ignitability, heat release, spread of fire, smoke production, burning droplets and particles, melting or charring products
  - Smouldering combustion
- Materials directly exposed to fire or protected
- Existence of air cavities
- Fire spread hazards are more important for higher building.

<u>Evaluation criteria</u>

- Contribution to fire: Reaction to fire classification of components and the whole system
- Combustible products protected – yes or no
- Cavities present – yes or no
- Combustible surfaces in cavities – yes or no
- Fire stops in cavities – yes or no
- Falling of particles (includes fire performance of fixing mechanisms)
- Number of stories (when combustible products used)
- Risk of arson (external).

Fire resistance

The fire resistance of the wall and its structural components will be influenced by the following factors:

- The use of combustible materials inside the wall cross-section
- The use of combustible load bearing structures
- The use of non-classified windows, doors and other
- Contribution to load bearing capacity and to fire separation function (when relevant; more important for higher buildings).

Evaluation criteria

- Load bearing structures: R (15, 30, 45, 60, etc. min)
- Fire separation walls: E (integrity) and I (insulation) (15, 30, 45, 60, etc. min).

Qualitative scale for assessment

The effect of the refurbishment on the reaction to fire performance and the fire resistance of the wall and façade is assigned to a qualitative scale according to the criteria in Table 30.

Table 30. Qualitative scale for assessment of refurbishment effect on reaction to fire and fire resistance.

Score	General effect of refurbishment	Effect of refurbishment on Fire safety
-2	Significant aggravation	Significantly increased risk of ignition and spread of fire, or significantly reduced fire resistance
-1	Minor aggravation	Slightly increased risk of ignition and spread of fire, or slightly reduced fire resistance
0	No change	No effect on ignition and spread of fire, or fire resistance
1	Minor improvement	Slightly reduced risk of ignition and spread of fire, or slightly improved fire resistance
2	Significant improvement	Significantly reduced risk of ignition and spread of fire, and significantly improved fire resistance

Sometimes an increased or reduced risk of ignition and spread of fire, or fire resistance due to the refurbishment is insignificant to the necessary total fire safety of the building. For example, for a small single family house the increased risk of spread of fire and reduction of fire resistance might be considered insignificant, because the habitants of the house can evacuate quickly, and there is no risk of the fire spreading to other units in the building. For a small house (single family) ignition is the main important factor, while for a multi-storey building with several units all three factors (ignition, fire spread and fire resistance) are all very important.

Assessment results of Cases E, I, C and R on fire safety

The assessments of the refurbishment concepts on the fire safety of the different wall types described in this chapter. The scores are based on the scale given in Table 30.

The refurbished external wall has been compared to the existing wall and the change in fire safety has been given a score based on Table 30. Refurbishing an external wall and façade can reduce the risk of ignition and spread of fire, or it can increase the risk, or the changes can reduce or improve the fire resistance of the wall. An improvement of these properties will result in a positive score, and a reduction of these properties will give a negative score. In cases where there is no improvement or reduction of the properties the score will be 0.

Several issues must be considered when refurbishing a wall and façade. For example, unprotected combustible material in the wall can ignite and contribute to spread of the fire. Combustible cladding might cause rapid spread of the fire to the next storey, and combustible insulation might cause fire to spread inside the wall to the next storey. Combustible insulation behind a thin non-combustible cladding can catch fire due to rapid heating, and the flames can spread to the next unit. An air gap might cause the fire to spread behind the façade cladding to the next unit. If the wall contains combustible material through the cross-section, the fire might burn through the wall quicker and the fire resistance of the wall is impaired.

Major fire development and spread can lead to loss of integrity (especially through windows). It is therefore important to pay attention to the fire classification and position of the window, and whether fire stops are required.

Applying combustible material on a non-combustible wall can increase the risk of ignition and spread of fire, and reduce the fire resistance. Applying non-combustible material on a combustible wall can reduce the risk of ignition and spread of fire, and improve the fire resistance. The spread of fire is more critical for buildings with multiple units, especially multi-storey buildings. For small single family houses the spread of fire is usually not critical. The fire resistance will not be affected by the number of storeys in the building.

It is very important that existing fire separating functions are not impaired or compromised by the refurbishment of the wall and façade.

5 Assessment results

5.1 Concept E1 – External insulation fixed without air gap

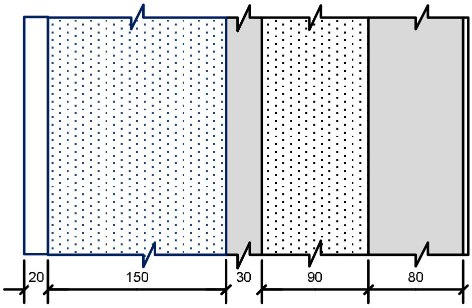
5.1.1 Durability

Durability – moisture behaviour

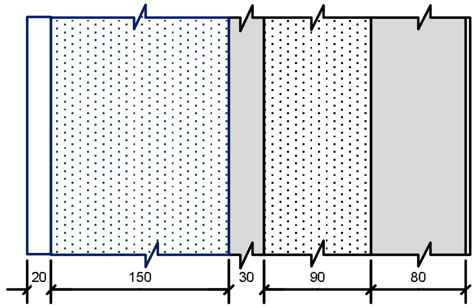
Two concepts of external insulation refurbishment were used. The first was to add PUR panels with a thick external render layer (E1), and secondly adding mineral wool and brick wall with a ventilated cavity between them (E2). The thickness of insulation chosen for the buildings in Frankfurt and Krakow was 100 mm and the buildings in Jyväskylä 150 mm.

The results of the modelling indicate that when adding a foam thermal insulation on the outer surface of an existing wall and applying a three layer rendering on the outer surface of the insulation it may cause moisture concentrations in two ways:

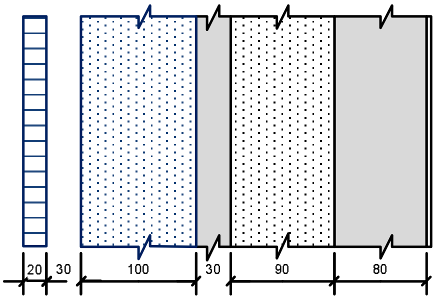
- The plastic foam thermal insulation is water vapour tight, so the water vapour that would naturally flow from indoor air to outdoor air through a wall may actually build up on the inner surface of the foam insulation and condensate to water.
- The second problem may occur if the render fails and cracks above the joints of the foam panels. It is then possible for water caused by wind driven rain to penetrate to the boundary of the old external surface and the retrofit insulation. The effects of these risks are studied in more detail in following examples.



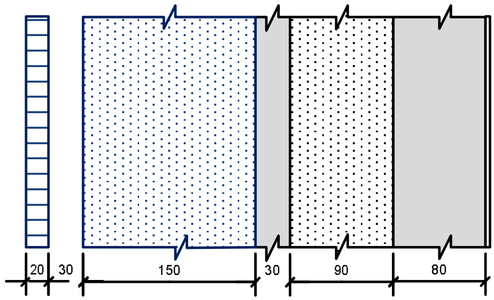
(E1) 100 mm PUR + 20 mm rendering in Frankfurt, Krakow



E1) 150 mm PUR + 20 mm rendering in Jyväskylä



(E2) 100 mm MW + brick boards in Frankfurt, Krakow



(E2) 150 mm MW + brick boards in Jyväskylä

Figure 71. Refurbishment methods of a concrete sandwich element wall.

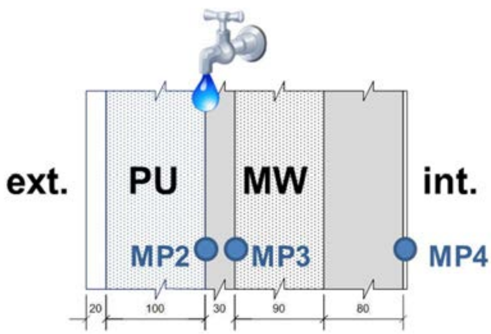


Figure 72. Monitor points of a refurbished wall.

For the detailed study, case was undertaken using Frankfurt climate data. The relative humidity and temperature during one year was calculated in five Monitor Points (MPs): outside air (MP1), boundary of retrofit insulation and original wall (MP2), the boundary of original outer layer and original thermal insulation (MP3), the boundary of in indoor concrete layer and plaster (MP4) and indoor air (MP5).

The indoor and outdoor conditions are not reported because they are set as default input data in the simulations.

ASHRAE standard 160-2009 “Criteria for Moisture-Control Design Analysis in Buildings” assumes that 1% of the wind driven rain infiltrates into a wall for comparison purposes the selected refurbished wall structure was studied with the same 1% penetration rate of driven rain behind the PUR panel shown in the diagrams as the orange line, and without the saturation point (green line). Both calculations were compared with the unrefurbished reference case (grey line). At the monitor point MP2 there is a significant increase in levels of relative humidity. The modelling indicates that arelative humidity of 100% was reached on the south and west walls. This is felt to be as a result of higher wind driven rain portion on those walls.

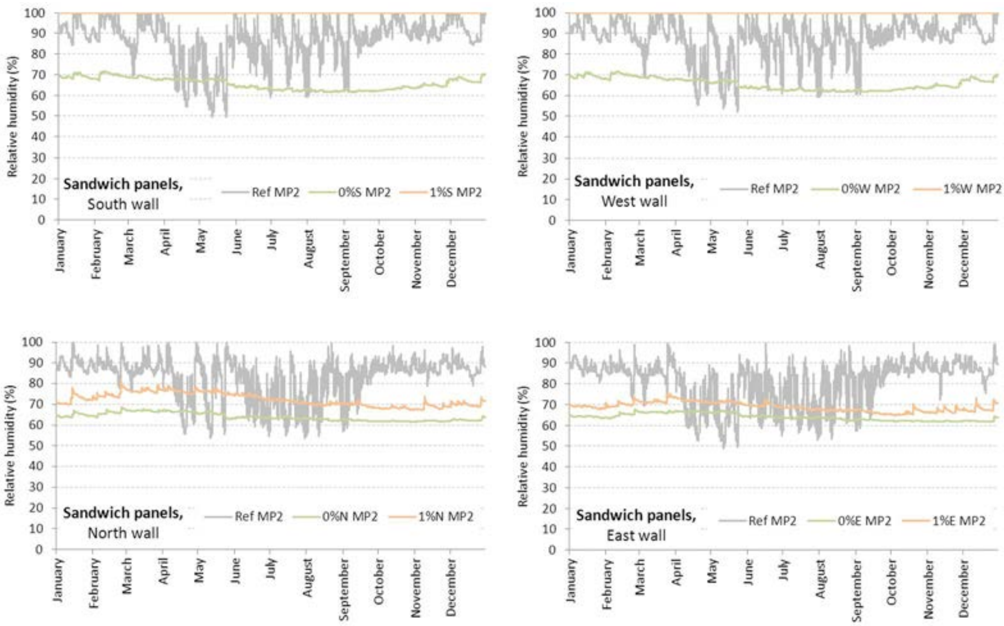


Figure 73. Relative humidity of monitor point 2. Calculations were made for a wall using different orientations using Frankfurt climatic data. The Green line is the structure with no water penetration, orange line is water penetration rate 1% and grey line is unfurbished original wall.

Similar comparisons were made for Monitor Point MP3, where the increase of relative humidity was also the most significant with walls that were orientated south and west wall.

The situation was considerably better in the inner concrete layer, showing only minimal increase of relative humidity compared to the refurbished case without any penetration and slight increase of relative humidity in the refurbished case with 1% penetration.

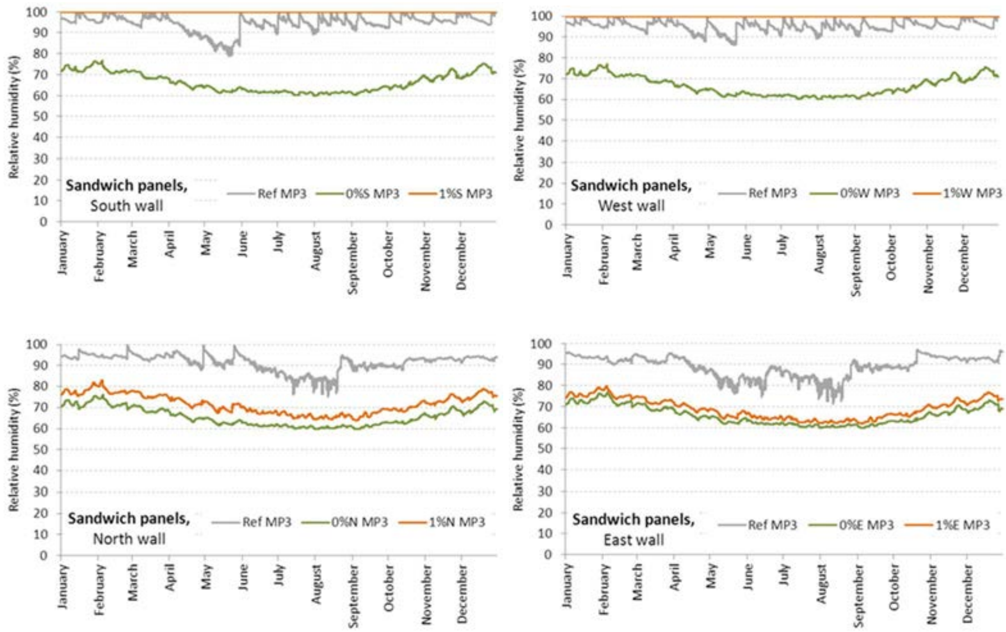


Figure 74. Relative humidity of monitor point 3. Calculations were made for wall with four different orientations using Frankfurt climatic data. Green line is the structure with no water penetration leakage, orange line is water penetration rate 1% and grey line is the unrefurbished original wall.

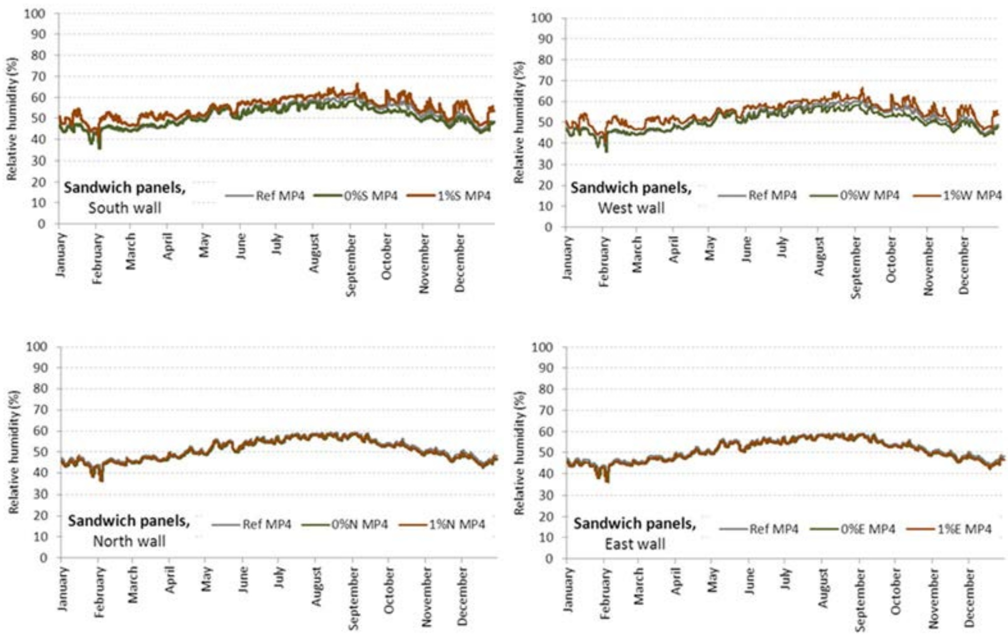


Figure 75. Relative humidity of monitor point 4. Calculations were made for a wall with four different orientations using Frankfurt climatic data. The Green line is the structure with no water penetration, the orange line is water penetration rate 1% and grey line is unrefurbished original wall.

When using water vapour tight thermal insulation panels on the external surface of an original concrete sandwich wall it is essential to ensure that the outer surface layer is as dry as possible and able to prevent rain water penetration to the boundary of the insulation and the old exterior surface of a wall. The excessive moisture in the concrete layers of an original wall dries mainly inwards. For this reason extra moisture inside a wall can cause several kinds of risks and defects.

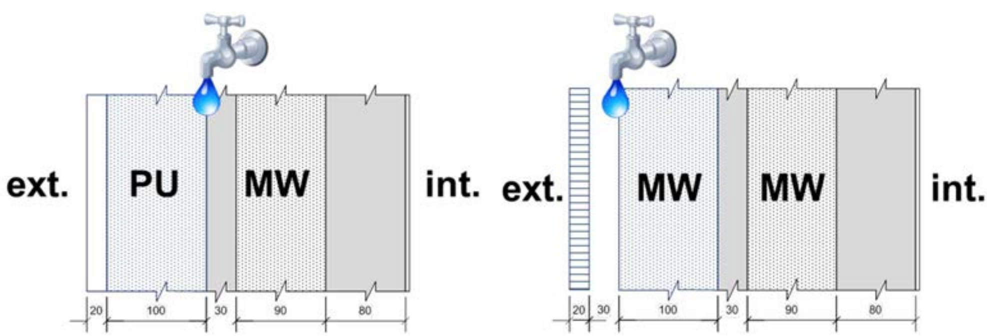


Figure 76. Water penetration points in different kind of refurbished walls.

If the insulation used is mineral wool, because of its material properties any water penetration will not flow horizontally towards the exterior surface of an old wall. The leaked water will run down because of the gravity. It doesn't matter if there is an air gap or not between a new exterior layer or not. The leaked water acts in the same way.

In order to evaluate the risks of water leakage in refurbished walls, the simulations were made so that the leaking rate was increased gradually until the water content of walls did not rise any more. If this maximum leakage rate is low and the leaked water amount causes problems, the refurbished wall structure is sensitive to construction failures. This should be taken into account in design and construction.

Table 31. The maximum possible water leakage rate of different walls.

				Water content (kg/m^3)				
Case	**Location**	**Ref.met.**	**Leaking**	**CMAX**	**INS1**	**INS2**	**Result**	**Note**
1.2.1	Frankfurt	Ext.PU	0.00% 1.29%	85.66 **179.70**	1.79 **27.05**	3.80 35.80	OK **Fail**	Internal mineral wool insulation
1.2.1	Krakow	Ext.PU	0.00% 1.43%	87.52 **179.02**	1.79 **20.43**	3.83 32.66	OK **Fail**	Internal mineral wool insulation
1.2.2	Jyväskylä	Ext.PU	0.00% 2.35%	86.23 **179.92**	1.79 **35.72**	3.32 32.30	OK **Fail**	Internal mineral wool insulation
1.2.3	Frankfurt	Ext.MW	0.00% 6.66%	75.99 76.65	1.79 1.79	5.02 **40.14**	OK **Fail**	External mineral wool insulation
1.2.3	Krakow	Ext.MW	0.00% 8.28%	76.64 76.84	1.79 1.79	5.35 **38.43**	OK **Fail**	External mineral wool insulation
1.2.4	Jyväskylä	Ext.MW	0.00% 10.23%	76.67 76.57	1.79 1.79	3.81 **31.11**	OK **Fail**	External mineral wool insulation

The maximum possible water leakage was varying from 1.29 to 10.2%. In the following table the maximum water content in the concrete walls (CMAX) original mineral wool insulation (INS1) and the new insulation (INS2 that was PUR in cases 1.2.1 and 1.2.2 and mineral wool in cases 1.2.3 and 1.2.4) was recorded. Because the leaking position was different in the PUR and mineral wool cases, also the increase of water content was observed in different locations. In the case of PUR panels, the failure was in the original insulation while in case of new external mineral wool with the air gap, the biggest increase of water content was observed in this new external insulation.

In case of PUR panels, the typical ranges of temperature, relative humidity and water content levels are indicated in the following images, the image on the left shows the case without any leaking and the image on the right indicates the maximum possible leaking.

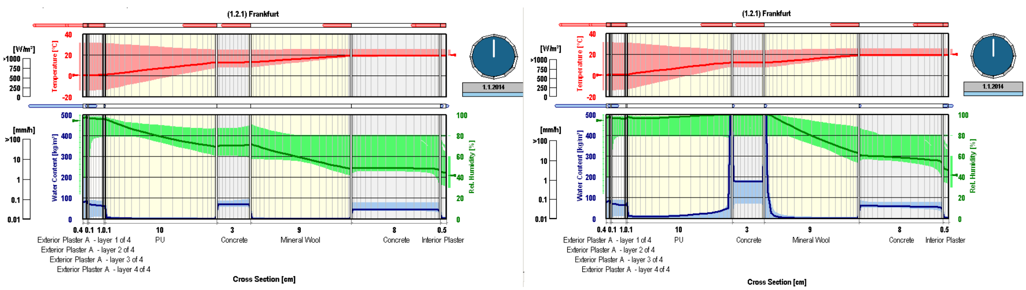


Table 32. Moisture and temperatures levels in PUR retrofitted wall structures. The left image is with no water leakage and the right image is with maximum water leakage rate.

In the case of using mineral wool insulation, the typical ranges of temperature, relative humidity and water content are indicated in the following images, the example without any leaking is on the left and the case with the maximum possible leaking is on the right.

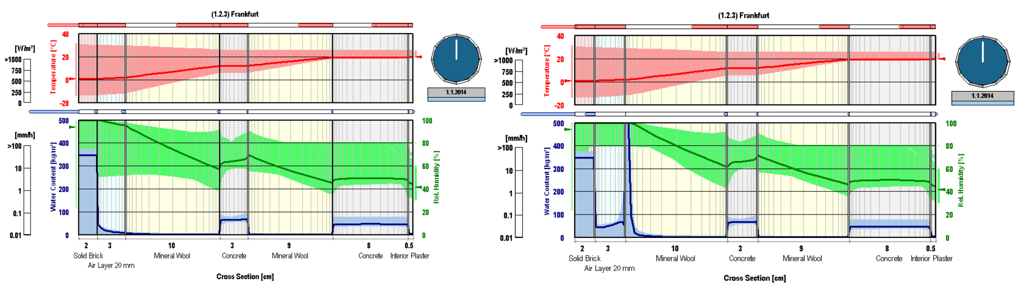


Table 33. Moisture and temperatures levels in mineral wool retrofitted wall structures. The left image is with no water leakage and the right image is with maximum water leakage rate.

The simulations showed that if the driven rain leakage rate is 0%, there will be no problem with the refurbished concrete sandwich element structure, and no reason why the thermal insulation cannot be located on the exterior surface. The same results were found if the outer surface layer and possibly the original thermal insulation were replaced with new ones.

When a new outer layer enables driven rain to penetrate, the r risk increases when the existing facade uses polyurethane foam as a retrofit insulation, than facades being insulated using mineral wool.

Durability – Modelling of deterioration of refurbished concrete facades

Case study: Refurbishment Concept E1 (Jyväskylä/Finland)

The original wall is assumed to be a typical sandwich wall. Both the inner and the outer cores of the sandwich are constructed of concrete. The thermal insulation between the layers is mineral wool.

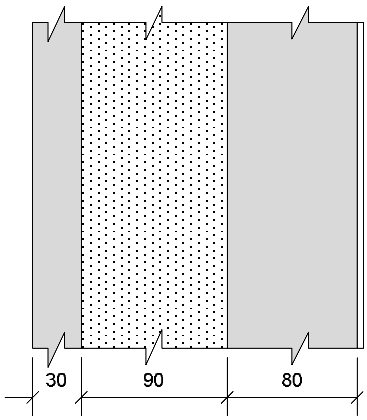


Figure 77. Original unrefurbished sandwich wall.

It is assumed that the thickness of the outer concrete layer of the original sandwich is 30 mm and it is centrally reinforced with a steel mesh. The diameter of the steel bars of the mesh is 5 mm and they are of normal corroding steel. The concrete cover is 10 mm on both sides of the core slab. The nominal strength of concrete is 25 MN/m^2 and the air content is 2%. There is no ventilation gap present between the thermal insulation and the outer layer slab.

The limit state of frost attack is assumed to be 66.7% from the original RDM which is 100%. The limit state of carbonation is the carbonation depth being equal to the thickness of concrete cover (modelled here as only 10 mm). The limit state of corrosion is the indication of the concrete cover cracking as a result of corrosion.

The critical moisture content in the figures shows the moisture content above which internal frost attack is possible.

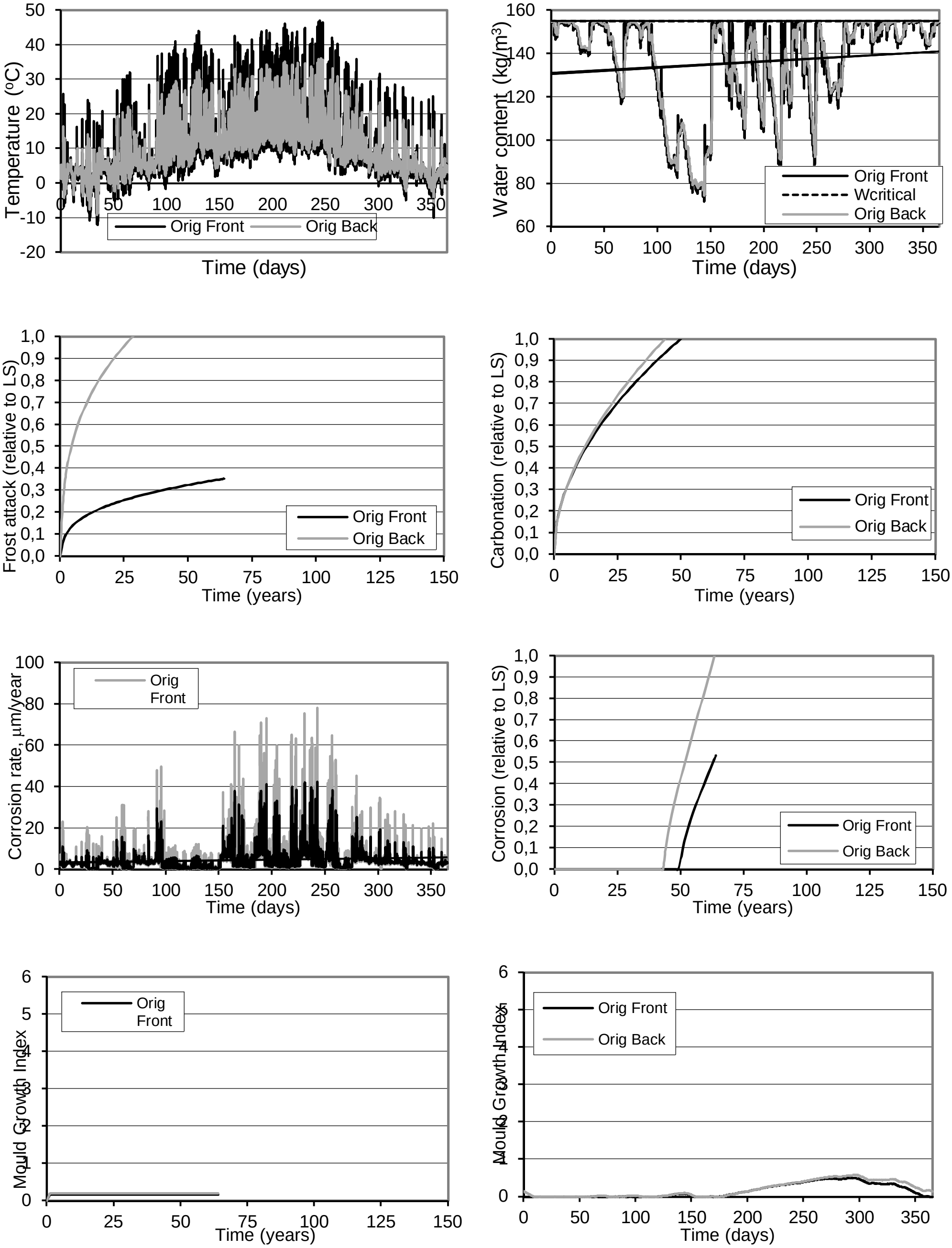


Figure 78. Results for the original unrefurbished outer concrete core faces of the sandwich wall in Jyväskylä – temperature, water content, frost attack, carbonation, corrosion rate, corrosion, mould growth.

The condition and the expected remaining service life of the old façade effect on the possibility and profitability to use various refurbishment concepts. That is why the unrefurbished exterior wall was also analysed. The lowest temperature of concrete was about -34 °C and the critical water content was constantly exceeded both in spring and in autumn. Severe frost attack occurred. However, the determining degradation mechanism for repair time was assumed to be carbonation + corrosion of reinforcement. The effect of frost attack had been taken into account on the rate of carbonation. The slow carbonation depth was the result of high moisture content of concrete. The calculation was stopped at the time of corrosion of reinforcement reached the serviceability limit state (65 years).

Refurbishment

The assumed type of refurbishment was the Concept E1:

The cross-section of the analysed refurbishment concept is presented in Figure. A mineral wool or a polyurethane insulation board is placed on the outer core of the original sandwich and a layer of rendering (mortar) on top of the insulation board. The reinforcing network of the rendering is assumed to be of zinc coated steel which is not assumed to be corroded in a carbonated rendering. So the corrosion of reinforcement in the rendering is not considered. However corrosion of reinforcement may occur in the original concrete outer core.

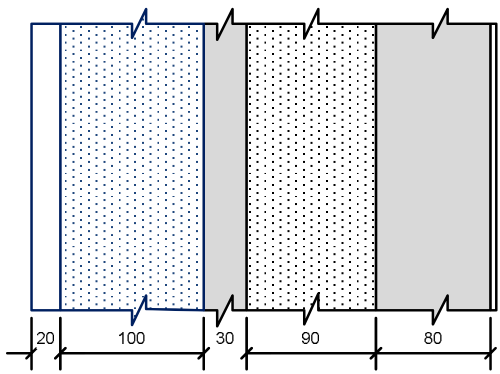


Figure 79. Refurbishment Concept E1.

Two things were specially monitored: corrosion of reinforcement in the original outer core and the mould growth index on both sides of the original outer core. The criterion for the corrosion reinforcement was changed however. Instead of using the serviceability limit state (cracking of the concrete cover as a result of corrosion) the ultimate limit state (1 mm depth of corrosion) was used. For mould growth the possible increase of the mould growth index and the length of maximal mould growth index time were monitored.

For the mineral wool thermal insulation the analysis results were the following.

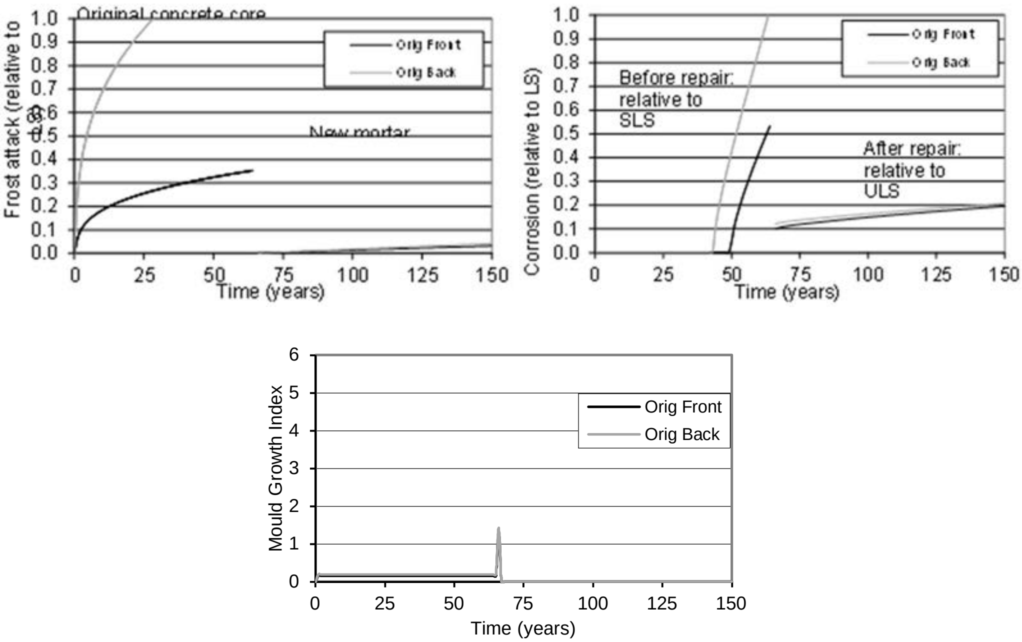


Figure 80. Results for the MW refurbished outer concrete core faces of the sandwich wall, – frost attack, corrosion and mould growth.

According to the analyses results the Concept E1 in Jyväskylä with mineral wool thermal insulation appears to be safe. The risk of frost attack is small and the risk of reaching the ultimate limit state of reinforcement corrosion after the repair in the original concrete core is small.

The mould growth index in the original concrete core rises up very rapidly after the refurbishment. However it also descends rapidly after 1–2 years. As the time of high mould index is short the risk of any problems as a result of mould is small.

In the case of polyurethane thermal insulation (Concept E1 in Jyväskylä) the analysis results were the following:

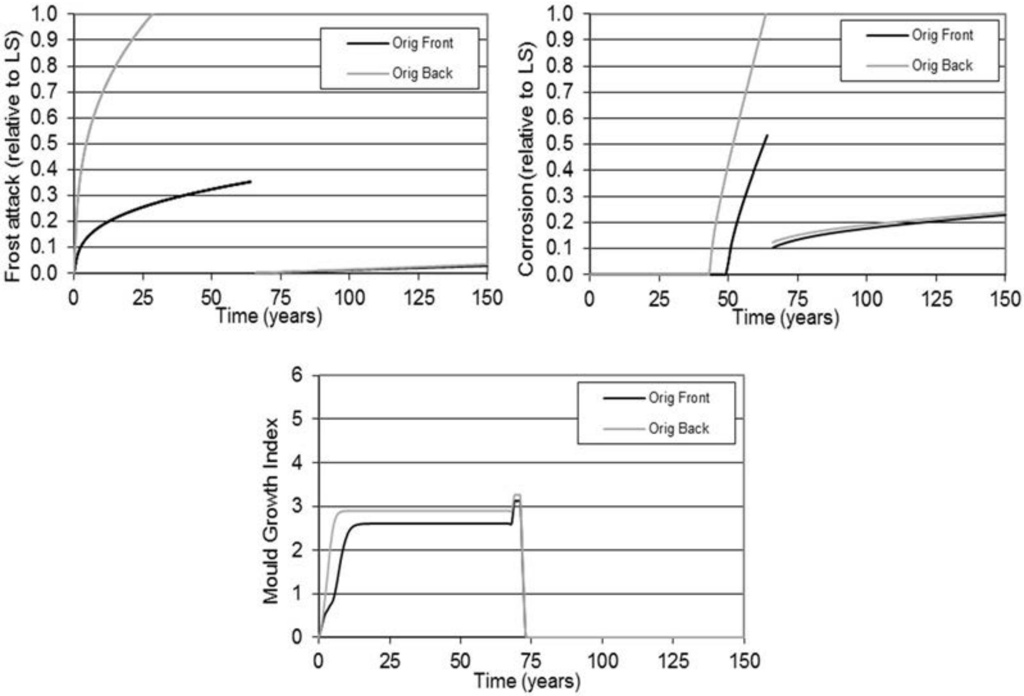


Figure 81. Results for the PUR refurbished outer concrete core faces of the sandwich wall – frost attack, corrosion and mould growth.

The risk of frost attack is small and the risk of reaching of the ultimate limit state of reinforcement corrosion after the repair in the original concrete core is small. However the analysis results of the Concept 1 with polyurethane thermal insulation indicate some mould risks. The mould growth index in the original concrete core rises up very rapidly after the refurbishment. It also stays high for about 10 years. After this period it reduces rapidly to 0 when the relative humidity reduces below 85%.

Case study 2: Refurbishment Concept E1 assuming that the thermal insulation of the original structure is of expanded polystyrene (ESP) (0ostende/Belgium)

Original structure

The original wall is a sandwich wall as in the previous cases but the thermal insulation between the concrete cores is of expanded polystyrene (ESP). The dimensions and other material properties are as in the previous cases.

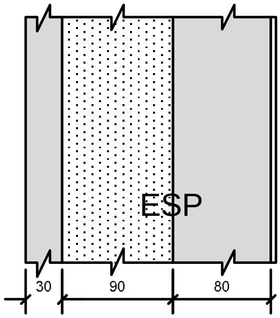


Figure 82. Original unrefurbished sandwich wall.

Because of the relatively high temperature no frost attack was observed in Oostende. The lowest temperature was about -5 °C but the moisture content rarely exceeded the critical content. The high moisture content of Oostende causes the carbonation rate to be low but the corrosion rate high as compared to some other European cities. The service life withregard to corrosion of reinforcement appeared to be 69 years.

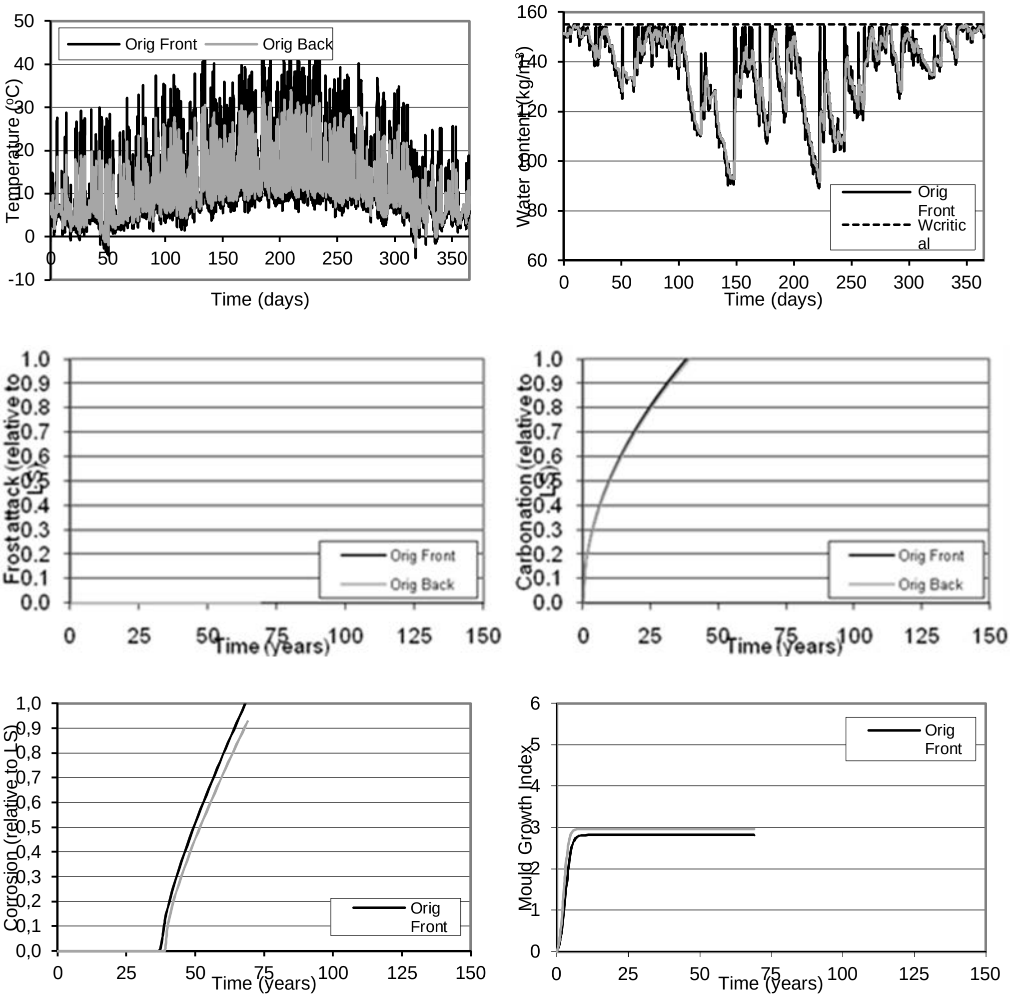


Figure 83. Results for the original unrefurbished outer concrete core faces of the sandwich wall in Oostende, – temperature, water content, frost attack, carbonation, corrosion, mould growth.

<u>Refurbishment</u>

Concept E1 was also used in Oostende (as in Jyväskylä). A mineral wool or a polyurethane insulation board is placed on the outer core of the original sandwich and a layer of rendering (mortar) on top of the insulation board.

For the mineral wool thermal insulation the analysis results were the following:

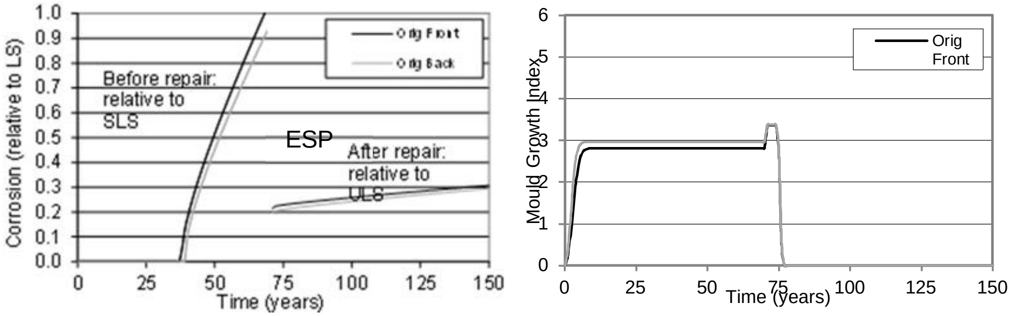


Figure 84. Results for the MW refurbished outer concrete core faces of the sandwich wall, corrosion and mould growth.

The risk of frost attack is small and the risk of reaching of the ultimate limit state of reinforcement corrosion after the repair in the original concrete core is small.

However, there is an elevated mould growth risk after the repair around the original concrete core. The risk period is about 6 years after which the mould index is reduced rapidly to 0.

For polyurethane insulation the results were as following.

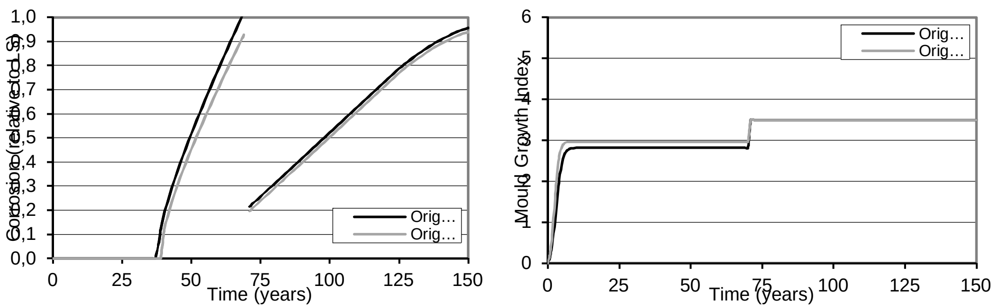


Figure 85. Results for the PUR refurbished outer concrete core faces of the sandwich wall, – corrosion and mould growth.

If the original thermal insulation is of expanded polystyrene (ESP) and the additional thermal insulation is of polyurethane (PUR) there is clear moisture problem between these insulations. This is because the water vapour diffusivity coefficient of both ESP and PUR is very small. As the moisture maintains long within these insulation boards there is mould risk on both sides of the original concrete core and also a continued corrosion risk in the reinforcement of the original concrete core.

Because of these risks the Concept E1 with PUR insulation cannot be accepted when the original insulation is of ESP or similar material.

5.1.2 Environmental Impact

The insulation and rendering concept is a one traditional way to renovate brick, stone and concrete buildings. The concept installed straight on top of existing wall structure with no need of wall renovation or removals, it is assumed that existing façade is in quite good condition. This concept can be implemented for almost all wall type. This is also one favourable renovation method also in the point of heat and moisture movement.

Façade material

There are thin and thick rendering method exists. Normally, in the cases of thin rendering the layer thickness is up to 10 mm and the strengthening material is glass fibre mesh, but in the case of two or three layer rendering the rendering thickness is 20–30 mm and galvanized steel mesh or stainless steel mesh is used. In the case of thin render (10 mm) the mortar amount which needed to render 1 m^2-wall is 15 kg whereas in the 3-layer render (30 mm) the mortar amount is 54 kg. In these two cases also the mortar type is differ, in thin render case polymer modified mortar is mainly used whereas in 3 layer rendering all three layers are cement lime based mortars.

In this assessment the 3-layer cement lime render mix is used. In this mix cement and lime are the binder materials whereas sand is used as an aggregate. The cement lime ratio in all three layers depends on the needed strength. Cement with the presence of water, strengthening rather quick whereas lime need for the strengthening carbon dioxide and the process itself is much slower. The adhesive rendering layer guarantees that the adhesion remains durable and it also balancing existing wall moister absorbing capacity. Filling layer, according to the name, filling and smoothing the façade and top layer is meant for finishing, which gives the pattern and character to the whole building facade.

Carbon footprint, energy and raw material consumptions for the production of thin render are calculated according to the dry mix. It is assumed that mix composition is 50/50/600, which means that cement lime binder ratio is 1:1and binder aggregate ratio is 1:6. The water consumption for the render is about 15–20%. It is assumed that all three layers have the same cement lime ratio and water content, total rendering thickness is 30 mm. For strengthening also galvanized steel mesh with the size of 10 x 10 mm and wire size Ø 1 mm is used.

Energy efficiency and insulation thickness

Environmental impact assessment is made for the refurbishment concept where U-value for the existing wall is 0.44 W/m^2K. This wall type is assumed to be sandwich element, but external insulation and rendering is a good option also for masonry structures, brick and solid stone walls. In not insulated masonry or stone wall cases the U-value for existing structures can be in a range of 1–1.5 W/m^2K

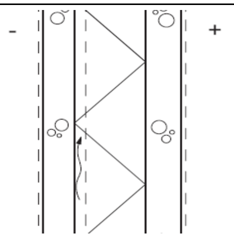
and in these cases the energy saving rate is relatively higher for any insulation thicknesses compared to the existing wall type.

Environmental impact assessment is made for the refurbishment concept where U-value for the existing wall is 0.44. This wall type is assumed to be sandwich element, but external insulation and rendering is a good options also for masonry structures, brick and solid stone walls. In not insulated masonry or stone wall cases the U-values for existing structures can be in range and in these cases the energy saving rate is relatively higher for any insulation thicknesses compared to the existing wall type.

Energy efficiency is studied through the heat loss of existing and refurbished wall with different insulation levels (100 mm, 200 mm or 300 mm rock wool). Heat loss was calculated for Northern, Central and Southern Europe by taking into account heating degree days (locations for Northern Europe was Helsinki, Central Europe was Berlin and Southern Europe was Barcelona).

- Case 1 – sandwich element renovation with additional 100 mm rock wool + render (Helsinki, Berlin, Barcelona)
- Case 2 – sandwich element renovation with additional 200 mm rock wool + render (Helsinki, Berlin, Barcelona)
- Case 3 – sandwich element renovation with additional 300 mm rock wool + render(Helsinki, Berlin, Barcelona).

Table 34. Energy consumption for external renovation concepts with rock wool and three layer rendering. Existing wall type is concrete sandwich element and location is Helsinki, Berlin and Barcelona.

Existing wall type (60 mm concrete + 80 mm rock wool + 120 mm concrete)	Studied cases	Insulation thickness, mm	U-value, W/m K	Energy, kWh/wall-m^2/year		
				Helsinki	Berlin	Barcelona
	Existing wall*	80**	0.44	50	33	15
	Case 1 (rock wool +render)	80* + 100	0.21	24	16	7
	Case 2 (rock wool+ render)	80* + 200	0.14	16	11	4.8
	Case 3 (rock wool + render)	80* + 300	0.10	11	8	3.4

* insulation thickness layer from an existing wall

** Note that results are relevant for walls, the original u-value of which is 0.44, independent on the structure of the existing wall type.

Table 35. Carbon footprint for concrete element renovation with external insulation and three layer rendering. Main heating energy type for Helsinki, Berlin and Barcelona is gas, for Helsinki also district heat and electricity result is given.

Carbon footprint				
	Façade, kg/wall-m^2/ 20 year	Insulation, kg/wall-m^2/ 20 year	Heating, gas/district/electricity, kg/wall-m^2/ 20 year	Total gas/district/electricity kg/wall-m^2/ 20 year
Existing sandwich element, Helsinki			270/209/166	270/209/166
Case 1 (rock wool 100 mm + render)	8	6	129/100/79	143/114/93
Case 2 (rock wool 200 mm + render)	8	12	86/66/53	106/86/73
Case 3 (rock wool 300 mm + render)	8	18	61/47/38	88/74/64
Existing, Berlin			181/-/-	181/-/-
Case 1 (rock wool 100 mm + render)	8	6	86/-/-	100/-/-
Case 2 (rock wool 200 mm + render)	8	12	58/-/-	78/-/-
Case 3 (rock wool 300 mm + render)	8	18	41/-/-	67/-/-
Existing, Barcelona			81/-/-	81/-/-
Case 1 (rock wool 100 mm+ render)	8	6	39/-/-	53/-/-
Case 2 (rock wool 200 mm + render)	8	12	26/-/-	46/-/-
Case 3 (rock wool 300 mm + render)	8	18	18/-/-	45/-/-

– Not calculated as not relevant for Central and Southern Europe

Table 36. Fossil energy consumption for concrete element renovation with external insulation and three layer rendering. Heating energy type for Helsinki, Berlin and Barcelona is gas.

Fossil energy consumption				
	Façade, kg/wall-m²/ 20 year	Insulation, kg/wall-m²/ 20 year	Heating, gas kg/wall-m²/ 20 year	Total, kg/wall-m²/ 20 year
Existing sandwich element, Helsinki			3,961	3,961
Case 1 (rock wool 100 mm + render)	40	78	1,890	2,009
Case 2 (rock wool 200 mm + render)	40	156	1,260	1,457
Case 3 (rock wool 300 mm + render)	40	234	900	1,175
Existing, Berlin			2,652	2,652
Case 1 (rock wool 100 mm + render)	40	78	1,266	1,384
Case 2 (rock wool 200 mm + render)	40	156	844	1,040
Case 3 (rock wool 300 mm + render)	40	234	603	877
Existing, Barcelona			1,193	1,193
Case 1 (rock wool 100 mm + render)	40	78	569	687
Case 2 (rock wool 200 mm + render)	40	156	380	576
Case 3 (rock wool 300 mm + render)	40	234	271	546

Table 37. Non-renewable raw material consumption for concrete element renovation with external insulation and three layer rendering. Heating energy type for Helsinki, Berlin and Barcelona is gas.

Non- renewable raw-material consumption				
	Façade, kg/wall-m^2/ 20 year	Insulation, kg/wall-m^2/ 20 year	Heating, gas kg/wall-m^2/ 20 year	Total, kg/wall-m^2/ 20 year
Existing sandwich element, Helsinki			88	88
Case 1 (rock wool 100 mm + render)	61	11	42	113
Case 2 (rock wool 200 mm + render)	61	21	28	110
Case 3 (rock wool 300 mm + render)	61	32	20	113
Existing, Berlin			59	59
Case 1 (rock wool 100 mm + render)	61	11	28	100
Case 2 (rock wool 200 mm + render)	61	21	19	101
Case 3 (rock wool 300 mm + render)	61	32	13	106
Existing, Barcelona			26	26
Case 1 (rock wool 100 mm + render)	61	11	13	84
Case 2 (rock wool 200 mm + render)	61	21	8	91
Case 3 (rock wool 300 mm + render)	61	32	6	99

5.1.3 Life cycle costs

It has been calculated life cycle cost of two structures in case of
E1 – Insulation fixed without air gap, existing façade in good condition:

- Concrete sandwich (figure)
- Solid concrete (figure).

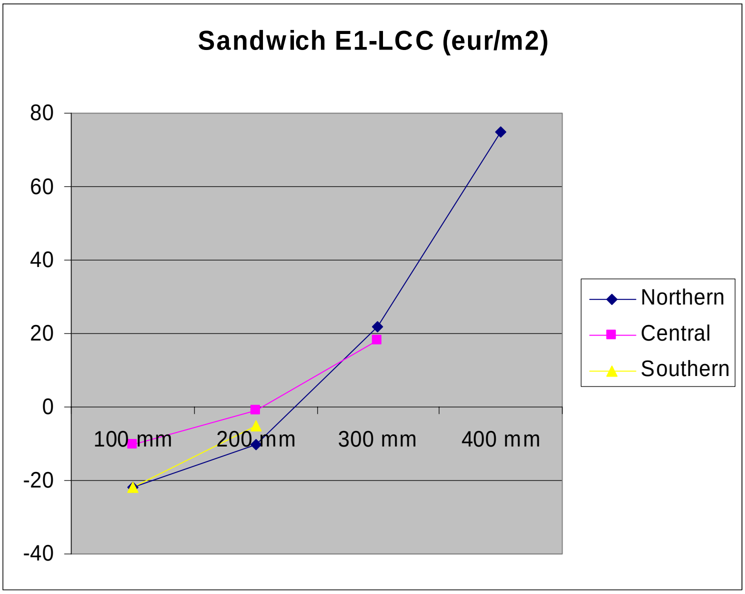


Figure 86. Life cycle Costs of concrete sandwich by weather zone and insulation thickness.

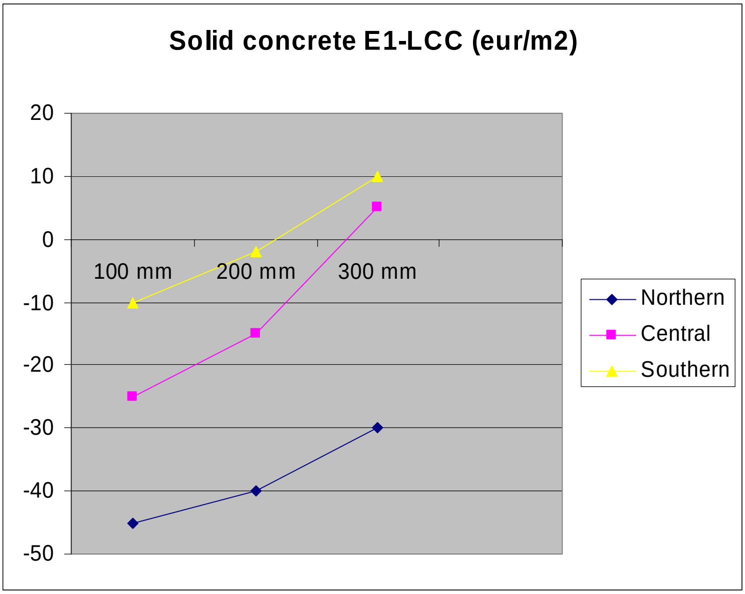


Figure 87. Life cycle Costs of solid concrete by weather zone and insulation thickness.

The results show that in all cases the thickness of 100 mm is the most economical, the thickness of 200 mm is life cycle economical too, but thickness of 300 mm is not economical in the case of a concrete sandwich. However the economy of insulation fixed without air gap is more economical in the case of solid concrete than in the case of concrete sandwich.

5.1.4 Energy demand for heating and cooling

The following Table shows an example of assessment results. All assessment results regarding Energy demand for cooling are presented in Appendix B. The assessment results regarding Energy demand for heating are presented in Appendix C.

Table 38. Calculated monthly and yearly heat flow through façade E1 on the selected climates.

Q_E1 [kWh/m^2]

Month	Paris	Lyon	Bilbao	Barcelona	Almeria	Catania
1.00	0.00	0.00	0.00	0.00	0.00	0.00
2.00	0.00	0.00	0.00	0.00	0.00	0.00
3.00	0.00	0.00	0.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00	0.00	0.00	0.00
5.00	0.00	0.00	0.00	0.00	0.01	0.00
6.00	0.00	0.03	0.00	0.04	0.08	0.14
7.00	0.06	0.12	0.05	0.27	0.47	0.73
8.00	0.06	0.10	0.04	0.20	0.62	0.72
9.00	0.00	0.00	0.03	0.04	0.25	0.15
10.00	0.00	0.00	0.00	0.00	0.01	0.00
11.00	0.00	0.00	0.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00	0.00	0.00	0.00
Whole year	0.12	0.25	0.12	0.55	1.44	1.76

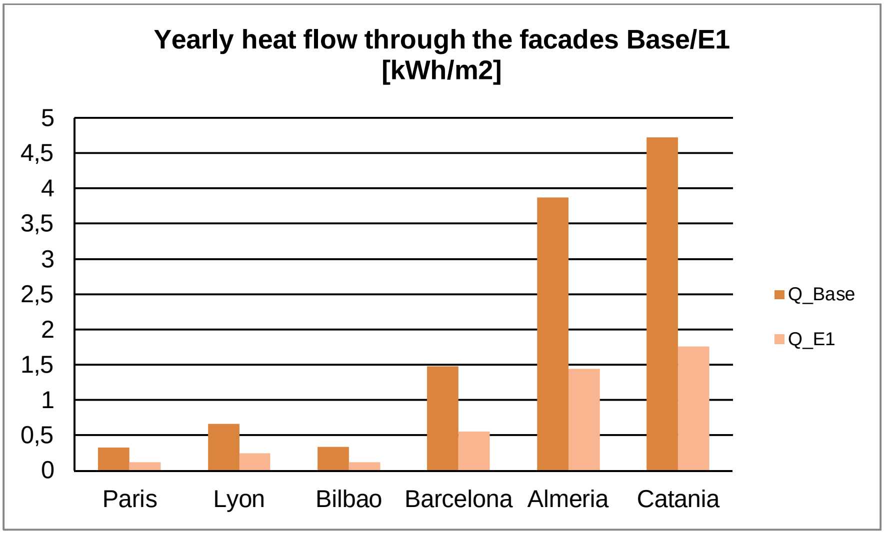


Figure 88. Yearly heat flow through the facades (E1).

5.1.5 Impact on daylight

Energy refurbishment solutions involving façade thickness increase can substantially affect daylight availability in interior spaces, with the associated additional energy consumption for lighting.

Large increases in façade thickness affect substantially the amount of daylight availability, with reductions up to 15% of day lit time for 30 cm. of added insulation, and 8%–9% for 20 cm.

Reductions in Useful Daylight Illuminance indicate lower increases in values for time with no useful daylight, (4% to 6% for 30 cm.), as well as a reductionin potential glare situations (especially in west and south orientations).

Additional measures should be taken into account in this type of façade retrofit actions. These could include:

- Window enlargement or improvement in terms of daylight performance.
- Bright colour window reveals/interiors.
- Additional energy efficiency measures in lighting systems (bulb replacement, dimmable lights, control measures…).

5.1.6 Structural stability

<u>Structural performance of the wall and the building (load bearing capacity)</u>

The structural performance of the different types of walls (W1–W6) will normally remain unchanged for this type of light-weight insulation system.

Mounting of fastening points in the existing wall

The possibilities for sufficient anchor strength to the wall must be assessed closely, by undertaking pull tests. The load bearing capacity of the brick wall W4 and W6 might need fastening in the more durable underlying wall (see also restriction under buildability).

Changes in water drainage, changes in humidity and danger of frost heave

Risks of negative effects that can reduce the quality of the wall must be assessed. External insulation will normally have no negative effect on changes in humidity and will give no danger of frost heave. The water drainage must be ensured and not compromised, but this will be a part of the refurbishment system itself. It is important to secure that the refurbishment system does not lead to new water leakages into the existing wall, and therefore must be suitably designed.

Sensitivity for seismic loads

The sensitivity for seismic loads must be assessed, especially the connection of the insulation system to the wall. External light weight insulation system are normally not sensitive for seismic loads, but the wall system itself may be more or less sensitive (see descriptions of the wall systems).

Table 39. Rating of E1 vs. wall type W1-W6 for structural stability.

Concept / Parameter	E1 + W1	E1 + W2	E1 + W3[2)]	E1 + W4[2)]	E1 + W5	E1 + W6[2)]	Note
Structural performance of the wall and the building (load bearing capacity)	0	0	0	0	0	0	The structural stability will normally remain unchanged
Mounting of fastening points in the existing wall	2	1	0	1	1	1	Sufficient anchor to the wall may be limited for wood structures (W3)
Changes in water drainage, changes in humidity and danger of frost heave	2	2	2	2	2	2	Normally no negative effects that can reduce the quality of the wall
Sensitivity for seismic loads	0	0	1	0	0	0	Normally of low importance. Wood structures are rated with lowest sensitivity.

5.1.7 Buildability

Current condition of the existing wall

For some types of insulation materials it may be necessary that the surface is even to avoid air gaps between the insulation and the wall or to close them with weather-strip, render, parge coat etc.

Constructional feasibility

External insulation system are conditionally buildable for W3, W4 and W6 due to unsuitable insulation system outside a ventilated cavity. W4 should also be defined as unsuitable as it is for E2. The condition that needs to be addressed is that the cavity must be removed or closed to avoid air infiltration.

The flexibility of EPS and XPS is lower than for mineral wool due to the feasibility of it being able to respond to the irregularities of the surface of the existing wall. The flexibility of vacuum panels are low since they cannot be cut to fit in any direction, and need a clean flat surface to be used.

Access to the building site

Any kind of external insulation system requires scaffolding. Some kind of outer surface/cladding, e.g. external insulation composite systems (ETICS) are more sensitive to rainfall; hence a tarpaulin for weather protection is needed. Exterior refurbishment that is to be painted requires a tarpaulin for weather protection.

Domestic factors

Factors that may restrict the refurbishment alternative must be assessed. Such factor may be cultural and conservation measures that causes a distinction between interior and exterior insulation.

Climate zones

Dependency of weather conditions and climate zones is important. The choose of cladding and drainage system is of great importance when you have wind driven rain.

Table 40. Rating of E1 vs. wall type W1-W6 for buildability.

Concept / Parameter	E1 + W1	E1 + W2	E1 + W3[3)]	E1 + W4[3)]	E1 + W5	E1 + W6[3)]	Note
Current condition of the existing wall	0	0 through -1	0 through -2	0 through -1	0 through -1	0 through -1	Depending of insulation materials. EPS and XPS need even surface or extra tightening (-1)
Constructional feasibility	1 through -2	1 through 0	1 through -2	1 through -2	1 through -2	1 through -2	Depending of insulation materials. Mineral wool (1), EPS/XPS (-1), Vacuum panels (-2)
Access to the building site	-1	-1	-1	-1	-1	-1	All external insulation need scaffolding, also small houses
Domestic factors	-2 through +2	-2 through +2	-2 through +2	-2 through +2	-2 through +2	-2 through +2	Domestic factors may restrict the refurbishment alternative strongly
Climate zones[2)] Cfb Cfbw Csa Dfb Dfc	 1 -2 2 0 -1	 1 -2 2 0 -1	 1 -2 2 0 -1	 1 -2 2 0 -1	 1 -2 2 0 -1	 1 -2 2 0 -1	Ratings for different climate zones vary. Wind driven rain has a low score due to lack of ventilation and draining.

5.1.8 Need for care and maintenance

An external thermal insulation composite system (ETICS) is typically attached to masonry or concrete facades (Blom et al. 2006), but can also be used on facades with sandwich panels (Correia, et al., 2006) or timber framed walls. The system consists of insulation slabs (mineral wool or expanded polystyrene) that is fastened to the substrate with an adhesive and plugs, see Figure 89. The insulation is covered with plaster that is reinforced with a fiber glass reinforcing net and a decorative finish, e.g. (pigmented) render or silicate paint.

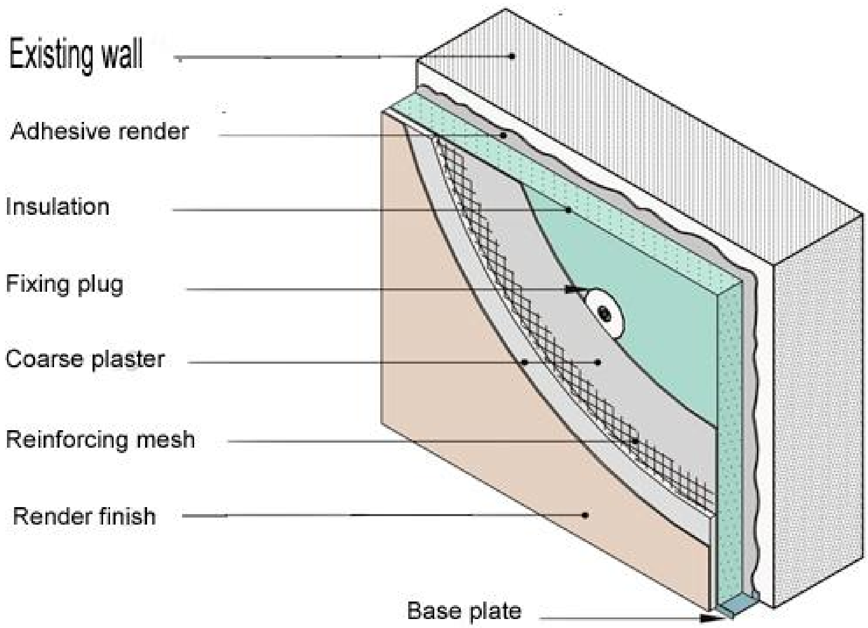


Figure 89. External thermal insulation composite system attached to a concrete surface (Blom 2010). The insulating layer is green.

Maintenance is performed because of the following damages (Blom, et al., 2006) (Künzel et al. 2006):

- Dirt and microbial growth.
- Minor cracks that do not lead to increased moisture ingress.
- Major cracks and delamination. Cracks are frequently along insulation board joints.
- Moisture ingress due to contact with the ground or improper finishing of the ETICS towards windows, balconies etc.

Damage to the render due to movements in the structural wall occur more seldom on ETICS facades than on conventional masonry due to the decoupling effect of the insulation layer (Künzel et al. 2006). Maintenance intervals and costs are similar to those of conventional masonry facades.

Moisture and temperature strains (built in moisture or moisture from driving rain combined with high temperatures) may cause damage to the mineral wool insulation in ETICS (Zirkelbach 2005).

The water vapor permeability of the render and coating layer should have a value not exceeding s_d = 0.6 m (equivalent air layer thickness) (Šadauskiene et al. 2009). Otherwise moisture may build up in the insulation. When a facade is repainted several times with an acrylic coating the water vapor resistance of the render-coating layer may become too high. This will not be a problem when inorganic coatings are used as these coatings have a much lower water vapor resistance than an acrylic coating.

Maintenance procedures and intervals are shown in table Table 41. The vulnerability to damage is assessed in Table 42.

The effect on maintenance and vulnerability to damage of refurbishing a wall with an external thermal insulation composite system is assessed in Table 43.

Table 41. Maintenance procedures and intervals for external thermal insulation composite systems.

Maintenance type	Level	Procedure	Interval (y)
Inspection	Light	Visual inspection – check for damages to render or coating.	1
Cleaning of facade	Light	Cleaning with water and washing agent or other suitable cleaning method.	Depends on rate of dirt deposits and microbial growth. The rate is highly climate and pollution dependent.
Repair damages to the render[1)]	Light-Moderate	Repair damages and apply new coating. The new coating may be applied to only part of the facade unless this leads to unacceptable visual changes (e.g. spots with differing color).	No data available.
New coating	Moderate	Repair cracks and other minor damages to the facade. Clean facade. Apply new coating.	5–20 (Künzel, et al., 2006) 4–18 (Larsen 2010)
Exchange ETICS	Heavy	Remove ETICS system and replace	60 (Künzel et al. 2006)

1) These areas are particularly prone to cracks or delamination: Connections around windows or doors, places on the facade close to the ground or gutter pipes (delamination due to water ingress).

Table 42. Vulnerability to damage – external thermal insulation composite systems.

Damage type	Vulnerability to damage	Comments
Graffiti (aerosol paint)	- Render and inorganic paint: High (Withford 1992) (Kvande 2002)	
Pollution	*Diluted sulfuric acid + nitric acid:* - Painted surface (organic paint): Low/medium (Norvaišienė et al., 2007)	Sulfur dioxide (SO_2) is oxidized to sulfuric acid (H_2SO_4). The main component in acid rain is sulfuric acid. In recent times the levels of sulfur dioxide as atmospheric pollutant have decreased. Soot and nitrogen compounds now form the main part of pollutants depositing on building surfaces (Grossi et al. 2007). The photo initiated reaction of atmospheric hydrocarbons with nitric oxide (NO) leads to the formation of ozone. Ozone reacts with nitric oxide and leads, in the end, to the formation of nitrogen dioxide (NO_2) and nitric acid (HNO_3) (Charola et al. 2002). The effect of nitrogen compounds on building materials is much less studied than the effect of sulfur dioxide/sulfuric acid.
Microbial growth	- Render: Medium - Painted surface: Low-medium (Guilitte et al. 1995) (Barberousse et al. 2007)	Render: algae and cyanobacteria Painted surfaces: algae, fungi and cyanobacteria (Gaylarde et al., 2005) The roughness and porosity of paint and render greatly influences the algae and bacterial growth. Use of low porosity, smooth surface materials reduces growth (Barberousse et al., 2007).
Mechanical damage	Low (Künzel et al. 2006)	

Table 43. The effect on maintenance parameters and vulnerability to damage of changing the facade to an external thermal insulation composite system.

Old wall	Parameter	Change due to refurbishment	Comments
Solid masonry wall – without surface treatments	Need of inspection	0	
	Need of cleaning	-1	
	Need of repointing	2	New wall does not need repointing
	Need of repairing damages to render	-1	
	Need of painting	-2	
	Vulnerability to graffiti	0	
	Vulnerability to pollution	0 through 2	Depends on type of natural stone in the solid wall
	Vulnerability to microbial growth	-1 to 1	Depends on type of natural stone in the solid wall
Concrete – untreated	Need of inspection	0	
	Need of cleaning	-2 through -1	Assuming that an unpainted concrete wall is cleaned rarely because dirt build-up is more acceptable on an unpainted concrete wall than on a painted wall.
	Need of painting	-2	
	Vulnerability to graffiti	0	
	Vulnerability to pollution	0	
	Vulnerability to microbial growth	-1 through 0	
Concrete – painted	Need of inspection	0	
	Need of cleaning	0	Depends on paint type. If the same type of paint is used (e.g. silicate), then the need of cleaning will be approx. the same. (Plesser 2010)
	Need of painting	0	Depends on paint type. If the same type of paint is used (e.g. silicate), then the need of painting will be approx. the same. (Plesser 2010)

	Vulnerability to graffiti	0	Depends on paint type. If the same type of paint is used (e.g. silicate), then the vulnerability be approx. the same. Vulnerability to microbial growth may increase somewhat because the extra insulation reduces the drying potential of the outside of the wall.
	Vulnerability to pollution	0	
	Vulnerability to microbial growth	-1 through 0	
Cavity wall with outer wythe of brick	Need of inspection	0	
	Need of cleaning	-1	
	Need of repointing	2	New wall does not need repointing
	Need of repairing damages to render	-2	
	Need of painting	-2	
	Vulnerability to graffiti	0	
	Vulnerability to pollution	0	
	Vulnerability to microbial growth	-1	

<u>Frames, insulation and cladding</u>

A metal or timber frame is attached to the facade. Insulation is placed in the cavities between the frames and the insulation is covered with cladding. This type of insulating system can be added to a number of different building types, such as timber framed houses, or houses with concrete or brick walls (Hole 2004, Kvande 2003).

The first step in adding external insulation to a wall that already is timber framed consists of removing old sheathing and breather membrane. Next, wood studs are attached to the existing wood studs, allowing the frame to accommodate a deeper insulation layer. Finally, extra mineral wool or other type of insulation is added and new breather membrane and ventilated sheathing is attached to the wall (Hole 2004), see Figure 90.

External insulation composed of frames, insulation and cladding can also be used on concrete walls. Studs, vertical or horizontal are attached to the existing facade, and insulation is placed in between the studs (Kvande 2003), see Figure 91. The insulation is covered with a breather membrane and a cladding, e.g. ventilated wood sheathing.

Maintenance procedures and intervals are shown in Table 44. The vulnerability to damage is assessed in Table 45. Table 46 summarizes the effects on maintenance and vulnerability to damage of changing the cladding of the facade to frames with insulation and wood cladding.

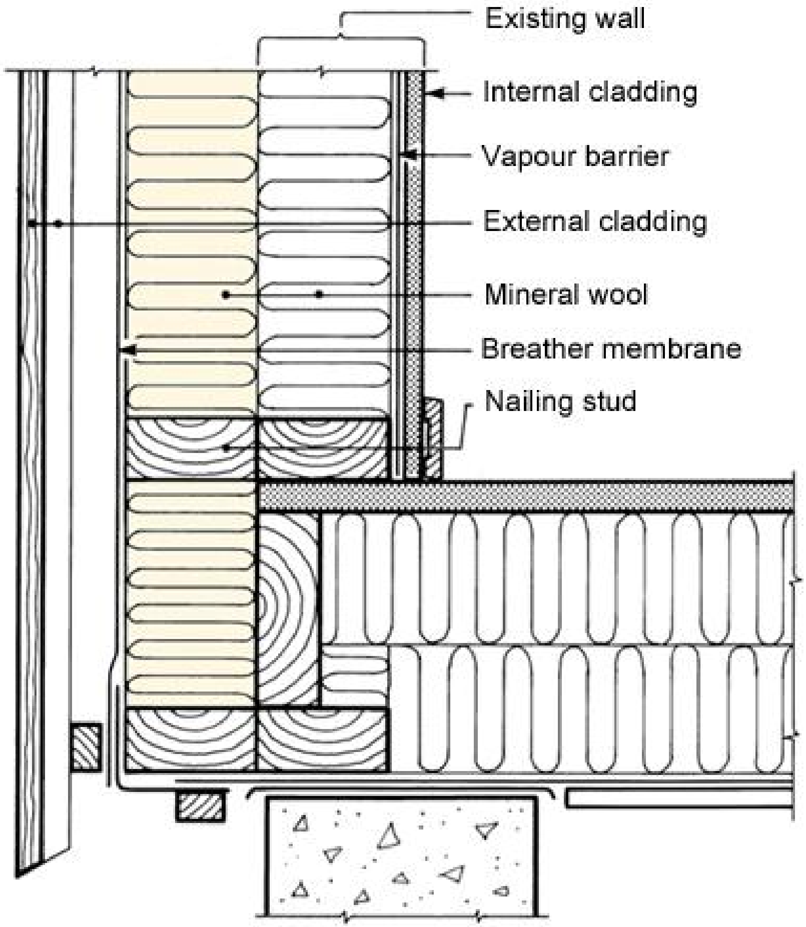


Figure 90. External insulation (light yellow) added to the wall of a load bearing wood structure (Hole 2004).

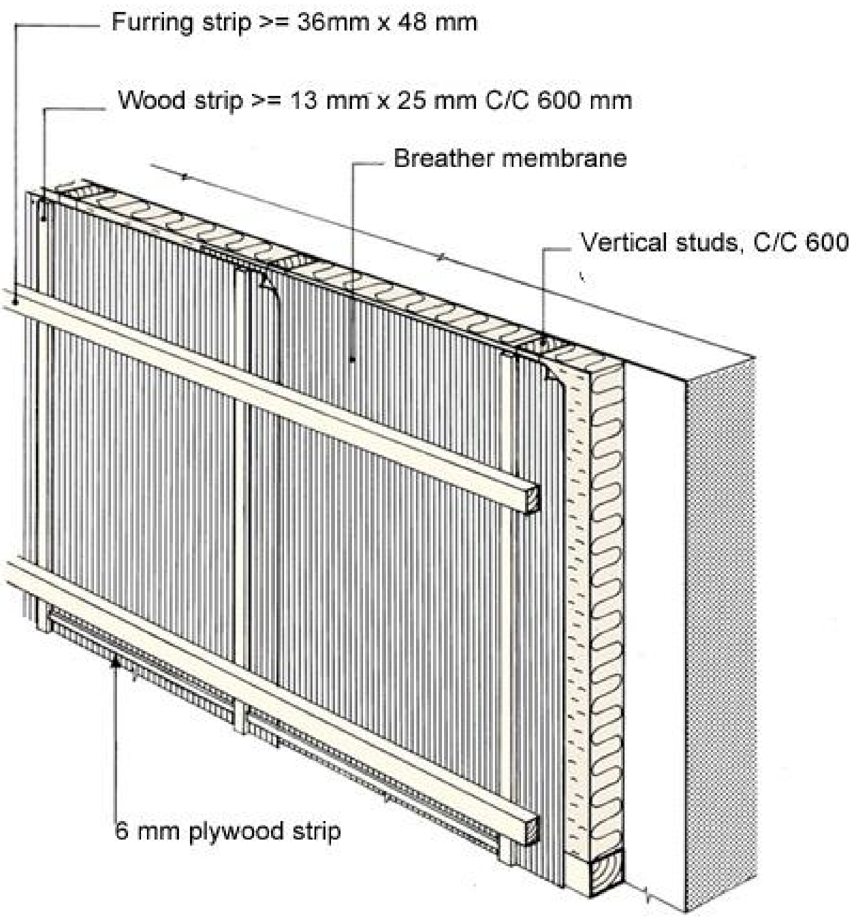


Figure 91. Retrofitting external insulation on a concrete wall. In this example the studs are vertical and wall will receive a ventilated wood siding (Kvande 2003).

Table 44. Maintenance procedures and intervals for timber framed walls with wood cladding.

Maintenance type	**Level**	**Procedure**	**Interval (y)**
Inspection	Light	Visual inspection – damages to wood or paint/stain. (Bøhlerengen and Gåsbak 1995), (Bøhlerengen and Mattson 1995),	1
Cleaning of wood panel	Light	Apply washing agent and rinse with water.	1[1)]
Staining or painting wood panel	Moderate	Clean surface. Remove peeling paint and damaged wood or wood fibers. Treat with fungicidal solution. Apply primer in spots with bare wood. Apply stain or paint	Staining wood panel – transparent stain: 2-4[2)] Staining wood panel semi transparent/solid color stain: 4-8[2)] Painting wood panel: 6-12[2)] (Plesser 2009)
Renewal of wood panel	Heavy	Remove old wood panel and breather membrane. Mount new breather membrane and wood panel. Apply surface treatment.	40–60 (Larsen 2010)

1) Paint manufacturers in Northern Europe typically recommend annual cleaning of painted or stained external surfaces. In reality, cleaning is only performed when the surface is visibly soiled (particle deposits, fungus or algae).

2) Binder based on acrylic, alkyd oil or hybrid acrylic/alkyd oil. The paints/stains may be waterborne (acrylic or hybrids) or solvent borne (most alkyd oils).

Table 45. Vulnerability to damage – timber framed wall with wood cladding.

Damage type	Vulnerability to damage	Comments
Graffiti (aerosol paint)	- Stained wood: Medium/high - Painted wood: Medium (Withford 1992) (Kvande 2002)	
Pollution	*Diluted sulfuric acid (acid rain):* - Stained wood cladding: Low/medium - Painted wood cladding: Low/medium (Lee et al. 2003) (Williams 2002)	Sulfur dioxide (SO_2) is oxidized to sulfuric acid (H_2SO_4). The main component in acid rain is sulfuric acid. The acid may cause the calcium carbonate in paints containing this compound to dissolve (Williams 2002). In recent times the levels of sulfur dioxide as atmospheric pollutant have decreased. Soot and nitrogen compounds now form the main part of pollutants depositing on building surfaces (Grossi, et al., 2007). The photo initiated reaction of atmospheric hydrocarbons with nitric oxide (NO) leads to the formation of ozone. Ozone reacts with nitric oxide and leads, in the end, to the formation of nitrogen dioxide (NO_2) and nitric acid (HNO_3) (Charola, et al., 2002). The effect of nitrogen compounds on building materials is much less studied than the effect of sulfur dioxide/sulfuric acid.
Microbial growth	- Stained wood: Low-high - Painted wood: Low-high (Hjort et al. 2010)	Stained and painted wooden surfaces are vulnerable to fungi. Paint brands differ greatly in their ability to withstand fungal attack. (Hjort et al. 2010)

Table 46. The effect on maintenance parameters and vulnerability to damage of changing the facade to frames with insulation and painted wood cladding.

Old wall	Parameter	Change due to refurbishment	Comments
Solid masonry wall	Need of inspection	0	
	Need of cleaning	-2 through -1	
	Need of repointing	2	New wall does not need repointing
	Need of painting	-2	
	Need for changing cladding	-2	
	Vulnerability to graffiti	0-1	Depends on the type of stone in the solid wall
	Vulnerability to pollution	0 through 1	Depends on the type of stone in the solid wall
	Vulnerability to microbial growth	-1 through 1	Depends on the type of stone in the solid wall and the type of paint used on the wooden cladding.
Concrete – untreated	Need of inspection	0	
	Need of cleaning	-2 through -1	
	Need of painting	-2	
	Need for changing cladding	-2	
	Vulnerability to graffiti	1	
	Vulnerability to pollution	0-1	
	Vulnerability to microbial growth	-1	Depends on the type of paint used on the wooden cladding.
Concrete – painted	Need of inspection	0	
	Need of cleaning	-1 through 0	Some inorganic paints, which can be used with concrete, have less dirt pick-up than organic paints. The high pH of silicate paints (can be used on concrete but not wood) reduces microbial growth. If the concrete is painted with an acrylate type paint, then the dirt accumulation and microbial growth will be approximately equal. (Plesser 2010)

Old wall	Parameter	Change due to refurbishment	Comments
	Need of painting	-1/0	The service lives of silicate and silicone emulsion paints which can be used on concrete are higher than that of typical wood products. If the concrete is painted with an acrylate type paint, then the repaint intervals are approximately equal. (Plesser 2009) (Plesser 2010)
	Need for changing cladding	-2	
	Vulnerability to graffiti	0	
	Vulnerability to pollution	0	
	Vulnerability to microbial growth	-1 through 0	Silicate paint is less vulnerable to microbial growth than organic paints. If the concrete was painted with silicate paint, then the vulnerability to microbial growth increases because wooden claddings are painted with organic paints (Plesser 2010)
Timber framed wall with ventilated wooden cladding	Need of inspection	0	
	Need of cleaning	0	
	Need of painting	0	
	Need for changing cladding	0	
	Vulnerability to graffiti	0	
	Vulnerability to pollution	0	
	Vulnerability to microbial growth	0	

5.1.9 Indoor air quality and acoustics

5.1.9.1 Thermal climate

Changes in internal surface temperatures mainly depends on the change in U-value of the construction, and not on the placement of the insulation. Many insulation materials (e.g. mineral wool, cellulose wool) have a relatively minor effect on airtightness. These materials are often used together with external wind-barriers, or internal moisture barriers or retarders. The retrofit of such barriers may increase airtightness significantly.

Rigid insulation materials like EPS, XPS and others are more or less airtight, but since they do not form a continuous layer, the actual effect on airtightness depends very much on actual construction details being suitably designed.

Spray foams would have a profound effect on airtightness, but are currently hardly used in this application.

In all cases, joints (between walls and windows, doors, roofs, foundations and dividing walls and floors) and penetrations (pipes, cables, etc) are generally at least as important as the airtightness of the wall itself. It is generally recommended that ano examination is undertaken regarding the actual the airtightness as well as the ventilation rate before and after refurbishment.

Effect on moisture content of indoor air will be relatively unaffected by external insulation. The major exception to this is walls with a high thermal mass and with significant moisture transport through the wall, where external insulation will be highly beneficial.

Table 47. Effect of External insulation without air gap on thermal climate.

Concept / Parameter	E1	Note
Air leakage	0 thr 2	Generally little effect, but air leakages around windows, other joints and penetrations may decrease.
Temperature assymetry	-1 thr 2	Normally asymmetry improves, but not in cases where some external walls are opaque and other consists mostly of windows.
Internal surface temperatures	1 thr 2	Insulation reduces extreme temperatures, as internal and external temperatures are more decoupled than originally.
Internal Humidity (buffering)	0	Buffering unchanged, but influx may be reduced. Significant in some compact walls in wet climates.

5.1.9.2 Air quality

Air quality is generally not affected by external insulation except for cases where internal mould risk in original construction is removed.

Table 48. Effect of external insulation without air gap on air quality.

Concept / Parameter	E1	Note
Existing pollution sources	0 thr +2	Internal mold risk may be removed by insulation.
New pollution sources	0	
Ventilation efficiency	-1 thr 0	Reduced infiltration through walls reduces ventilation if no countermeasures applied.
Influx of water	0 thr 2	Irrelevant (0) for most walls, relevant for some massive walls.

5.1.9.3 Acoustics

Continuous layers of external insulation may reduce sound transmission significantly for walls with high thermal mass s. This is highly dependent on actual materials and constructions used. Rigid insulation materials have little or in some cases even negative effect, while some mineral wool products are effective. In practice windows, doors and other building parts will generally be the weakest point, and the reduced transmission through the wall will have no impact on indoor sound levels unless these are remediated simultaneously.

Relatively small changes to the refurbishment system are important for the sound transmission. Type of material, weight of the external layer and the degree of mechanical coupling between layers are of importance.

Table 49. Effect of external insulation without air gap on acoustics.

Concept / Parameter	E1	Note
Noise from outside	0 thr +1	Can be improved if windows, ventilation openings and other weak points also are improved.
Internal sound transmission	0	Rarely affected
Internal acoustics	0	Internal surface unchanged by refurbishment

5.1.10 Disturbance

External insulation is more often than not possible to apply with the building still in use. Methods requiring protection from rain and sun may reduce the ventilation and daylight in the dwellings in the building period, and this may not always be acceptable. Methods utilizing prefabricated elements may be faster and more tolerable to the inhabitants and neighbours.

Table 50. Disturbance evaluation (E1).

Concept / Parameter	E1
Effect on inhabitability	-1-0
Effect on neighbours and site	-1-0

5.1.11 Aesthetic quality and effect on cultural heritage

Refurbishment on the external side of the wall or change of the original finishes can be proposed either to achieve good thermal performance or to improve the aesthetic quality of the building or to inhibit heat and moisture movement in the wall.

Stripping off finishes, such as plaster from brick, rubble stone or timber-framed wall can have an adverse effect on the building's cultural significance through loss of historic materials and original finishes and detract from its aesthetics. In most cases, it is also damaging to the thermal and moisture performance too. Therefore, when proposing the finish on the wall, appropriate building materials need to be used to ensure an authentic or suitable detailed finish is achieved. Improper external finish or insulation will affect the aesthetic quality of the building within a local context.

Insulating the external wall is often controversial for buildings that are listed or within conservation areas. However, for traditional buildings outside these categories, it is important to recognise that the original structure, details, characteristics and finishes of the building are valuable as cultural heritage, even when they are not immediately visible to the casual observer. The interior of the construction should be retained as far as possible.

5.1.12 Impact on renewable energy use potential

No impact.

5.1.13 Fire Safety

Table 51. Fire safety evaluation.

External insulation (E) –- New outer service with retrofit insulation – effect on Fire Safety				
WALL TYPE	BUILDING TYPE	Type of external structure/layer	Type of insulation	Score E1
W1_Solid wall; Brick, natural stone	A	Brick, natural stone or similar	Non-combustible	0
			Combustible	0
		Thin non-combustible	Non-combustible	0
			Combustible	-1
		Combustible	Non-combustible	-1
			Combustible	-2
W2_Sandwich element; concrete panel + concrete panel	C	Concrete or similar	Non-combustible	0
			Combustible	0
		Thin non-combustible	Non-combustible	0
			Combustible	-1
		Combustible	Non-combustible	-1
			Combustible	-2
W4_ Load bearing cavity without insulation; brick + concrete block W5_Insulated load bearing cavity; concrete block + concrete block W6_Non-load bearing cavity; hollow brick + perforated brick W7_Non-load bearing concrete block without insulation; hollow brick + concrete block	A	Brick, natural stone or similar	Non-combustible	0
			Combustible	0
		Thin non-combustible	Non-combustible	0
			Combustible	-1
		Combustible	Non-combustible	-1
			Combustible	-2
	B	Brick, natural stone or similar	Non-combustible	0
			Combustible	0
		Thin non-combustible	Non-combustible	0
			Combustible	-
		Combustible	Non-combustible	-1
			Combustible	-2
	C*	Concrete or similar	Non-combustible	0
			Combustible	0
		Thin non-combustible	Non-combustible	0
			Combustible	-1
		Combustible	Non-combustible	-1
			Combustible	-2

5.2 Concept E2 – External insulation fixed with air gap

5.2.1 Durability

<u>Durability – moisture behaviour</u>

Described in Section 14.1.

<u>Durability – modelling of deterioration</u>

Case study: refurbishment concept E2 assuming that the thermal insulation of the original structure is of expanded polystyrene (ESP) (Krakow)

<u>Original structure</u>

The original wall is a similar sandwich wall as in Concept E1 (Oostende) with a thermal insulation board of expanded polystyrene (ESP). The durability data of the original structure are presented in the following figures.

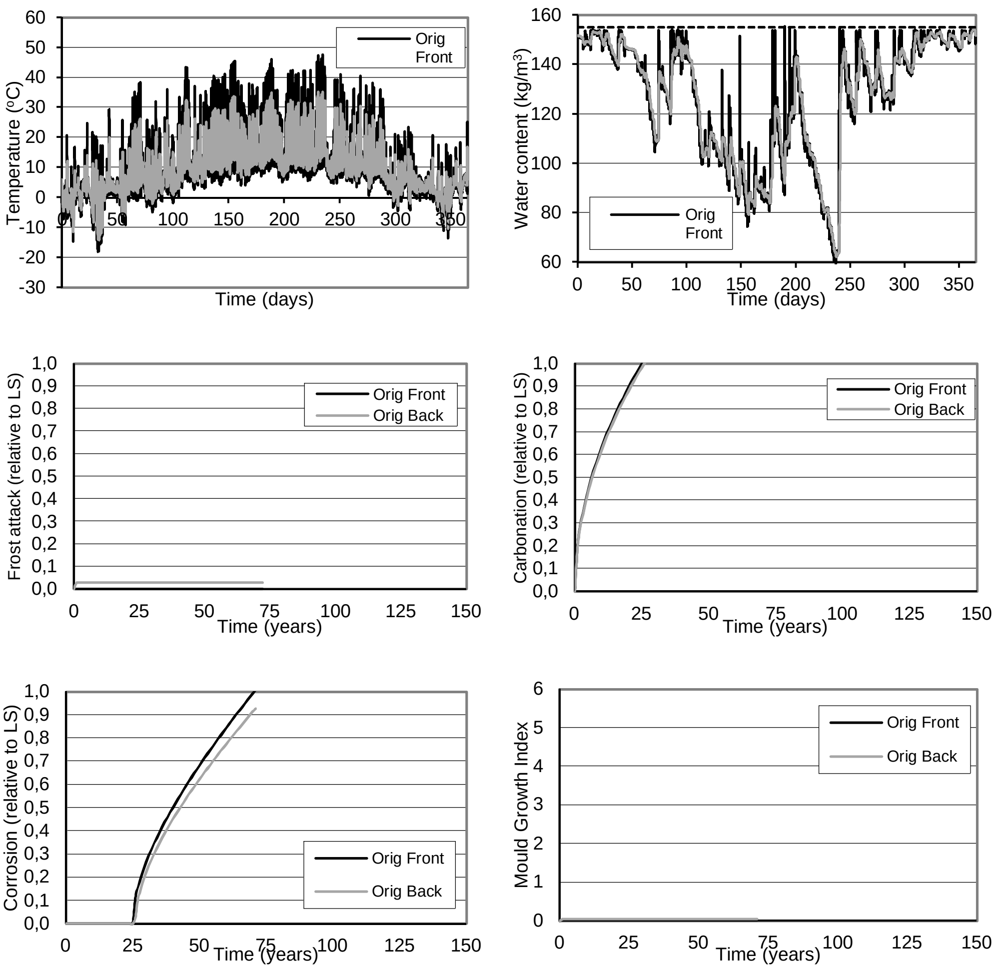


Figure 92. Results for the original unrefurbished outer concrete core faces of the sandwich wall in Krakow, – temperature, water content, frost attack, carbonation, corrosion, mould growth.

A small amount of frost attack is predicted for Krakow. There is a risk of frost attack as the lowest temperature in Krakow was -18 °C. The occurrence of frost attack depends on the quality of the concrete. With very low frost resistance concrete frost attack is possible also in Krakow.

The mould growth index was very small.

The service life with respect to carbonation + corrosion was 71 years.

Refurbishment

Concept E2 was used in refurbishment. In Concept E2 mineral wool or polyurethane thermal insulation boards are installed on the original outer core and the wall is panelled with a masonry board leaving a ventilation gap between the thermal insulation and the panel. A cross section of the system is shown below.

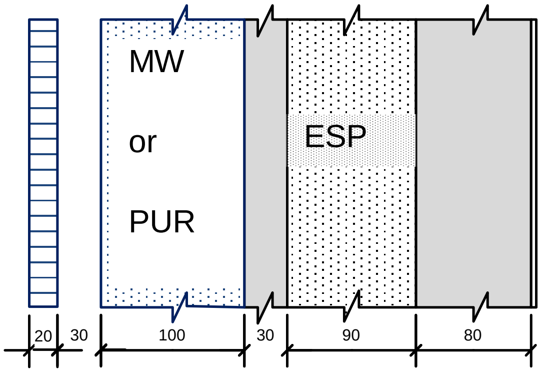


Figure 93. Refurbished sandwich wall, Concept E2.

The time of refurbishment is the time of service life of the original outer core based on corrosion of reinforcement.

For the mineral wool thermal insulation the analysis results were the following:

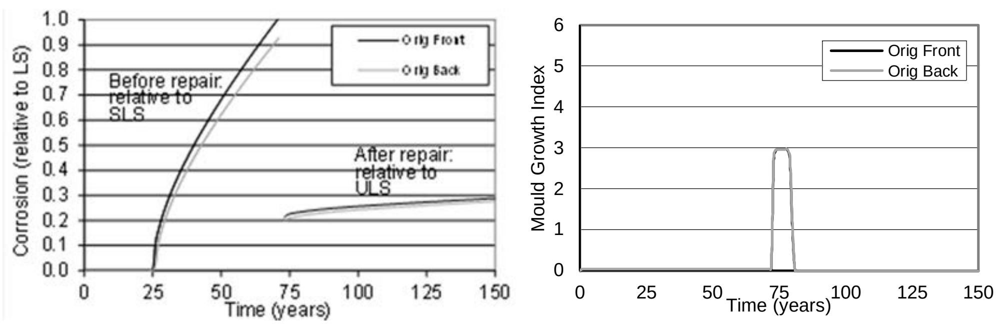


Figure 94. Results for the MW refurbished wall – corrosion and mould growth.

With mineral wool as the additional thermal insulation there seem to be an elevated mould risk although temporary. After the refurbishment the mould growth index increases (as a result of increased temperature) but the peak does not reach the maximum value (3.5) and the risk period is about 8 years. The mould index is reduced when the relative humidity constantly falls below 85%.

With PUR as the additional insulation the results were as presented below:

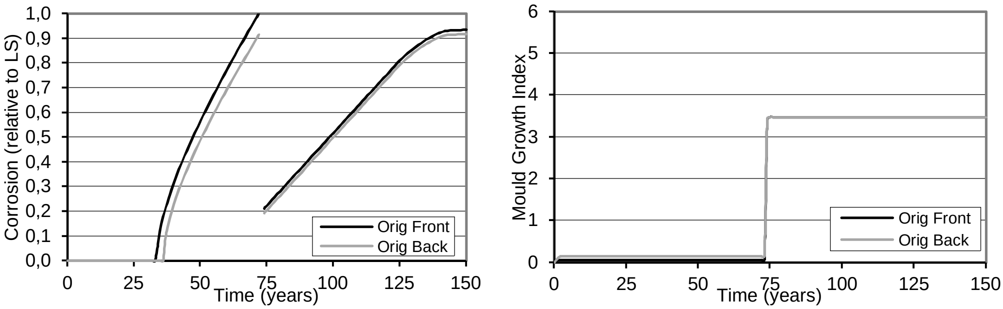


Figure 95. Results for the PUR refurbished wall – corrosion and mould growth.

With polyurethane as the additional thermal insulation the risks are considerable. After the refurbishment the mould growth index rises close to the maximum and stays there several decades (even to the end of the calculated period).

5.2.2 Environmental Impact

External renovation concept with the presence of air gap gives more options for choosing the façade types. Different type of façade boards like polymer based, concrete, wooden, natural stone, clay brick and others are all possible options. As these materials come from different origins the material production processes causing different amount of emissions, raw-materials and energy needs. The example for selected façade types and their carbon footprints is shown in the Figure 96.

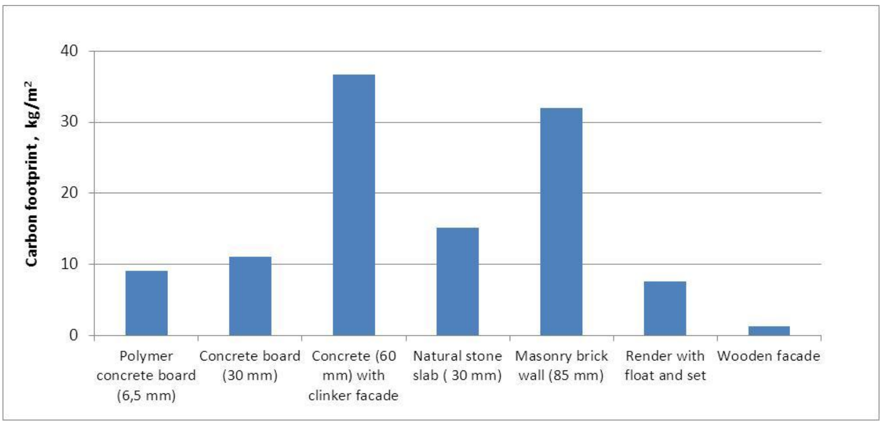


Figure 96. Carbon footprint for different facade materials.

Façade types and energy efficiency

Concept E2 includes renovation methods with an air gap, where no removal of an old wall structure is needed. The case contains insulation materials, wooden or steel battens, wind protection material and new façade. E2 assessment is made for solid lightweight concrete wall, where U-value for existing building is 0.82 W/m^2. This structure represents concrete buildings which need urgently energy renovations and are typical structures in Easter Europe and Russia. It is assumed that the walls with the same U-value existing also in Central and Southern Europe.

- Case 1 – solid lightweight concrete renovation with 100 mm rock wool and 30 mm concrete board (Moscow, Berlin, Barcelona)
- Case 2 – solid lightweight concrete renovation with additional 100 mm rock wool and wooden panel (Moscow, Berlin, Barcelona)
- Case 3 – solid lightweight concrete renovation with additional 100 mm rock wool and clay brick façade (Moscow, Berlin, Barcelona)
- Case 4 – solid lightweight concrete renovation with additional 200 mm rock wool and 30 mm concrete board (Moscow, Berlin, Barcelona)
- Case 5 – solid lightweight concrete renovation with additional 300 mm rock wool and 30 mm concrete board (Moscow, Berlin, Barcelona)
- Case 6 – solid lightweight concrete renovation with additional 300 mm rock wool and clay brick façade (Moscow, Berlin, Barcelona).

Table 52. Energy consumption for external renovation concepts with rock wool and different façade materials. Existing wall type is solid lightweight concrete wall and location is Moscow, Berlin and Barcelona.

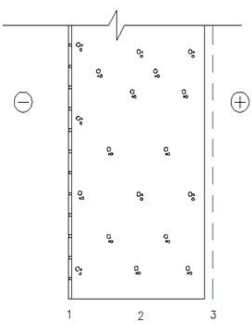
Existing wall 400 mm lightweight concrete, no insulation	Studied cases and façade type	Rock wool, thickness	U-value.	Energy. kWh/wall-m^2/a		
		mm	W/mK	Moscow	Berlin	Barcelona
	Existing wall		0.86	96	65	29
	Case 1 (30 mm concrete board)	100	0.28	31	21	9
	Case 2 (wooden facade	100	0.28	31	21	9
	Case 3 (85 mm clay brick facade)	100	0.28	31	21	9
	Case 4 (30 mm concrete board)	200	0.16	18	12	6
	Case 5 (30 mm concrete board)	300	0.12	13	9	4
	Case 6 (clay brick façade)	300	0.12	13	9	4

Table 53. Carbon footprint for concrete element renovation with external insulation and three layer rendering. Heating energy type for Helsinki, Berlin and Barcelona is gas.

Carbon footprint				
	Façade,	Insulation,	Heating,	Total,
	kg/wall-m²/ 20 year	kg/wall-m²/ 20 year	kg/wall-m²/ 20 year	kg/wall-m²/ 20 year
Existing, Moscow			523	523
Case 1(100 mm wool + 30 mm concrete)	11	6	167	184
Case 2 (100 mm wool + wooden panel)	1.2	6	167	174
Case 3 (100 mm wool + 85 mm brick)	32	6	167	205
Case 4 (200 mm wool +30 mm concrete)	11	12	98	136
Case 5 (300 mm wool +30 mm concrete)	11	19	70	108
Case 6 (300 mm wool + 85 mm brick)	32	19	70	121
Existing Berlin			354	354
Case 1(100 mm wool + 30 mm concrete)	11	6	113	130
Case 2 (100 mm wool + wooden panel)	1.2	6	113	120
Case 3 (100 mm wool + 85 mm brick)	32	6	113	151
Case 4 (200 mm wool +30 mm concrete)	11	12	67	105
Case 5 (300 mm wool +30 mm concrete)	11	19	47	85
Case 6 (300 mm wool + 85 mm brick)	32	19	47	98
Existing, Barcelona			159	159
Case 1(100 mm wool + 30 mm concrete)	11	6	51	68
Case 2 (100 mm wool + wooden panel)	1.2	6	51	58
Case 3 (100 mm wool + 85 mm brick)	32	6	51	89
Case 4 (200 mm wool +30 mm concrete)	11	12	30	68
Case 5 (300 mm wool +30 mm concrete)	11	19	21	59
Case 6 (300 mm wool + 85 mm brick)	32	19	21	72

Table 54. Fossil energy consumption for concrete element renovation with external insulation and three layer rendering. Heating energy type for Helsinki, Berlin and Barcelona is gas.

Fossil energy consumption				
	Façade,	Insulation,	Heating,	Total,
	kg/wall-m^2/ 20 year	kg/wall-m^2/ 20 year	kg/wall-m^2/ 20 year	kg/wall-m^2/ 20 year
Existing, Moscow			7,664	7,664
Case 1(100 mm wool + 30 mm concrete)	60	78	2,445	2,583
Case 2 (100 mm wool + wooden panel)	16	78	2,445	2,539
Case 3 (100 mm wool + 85 mm brick)	467	78	2,445	2,990
Case 4 (200 mm wool +30 mm concrete)	60	156	1,440	1,656
Case 5 (300 mm wool +30 mm concrete)	60	238	1,022	1,320
Case 6 (300 mm wool + 85 mm brick)	467	238	1,022	1,727
Existing Berlin			5,196	5,196
Case 1(100 mm wool + 30 mm concrete)	60	78	1,658	1,795
Case 2 (100 mm wool + wooden panel)	16	78	1,658	1,752
Case 3 (100 mm wool + 85 mm brick)	467	78	1,658	2,203
Case 4 (200 mm wool +30 mm concrete)	60	156	976	1,192
Case 5 (300 mm wool +30 mm concrete)	60	238	693	991
Case 6 (300 mm wool + 85 mm brick)	467	238	693	1,398
Existing, Barcelona			2,337	2,337
Case 1(100 mm wool + 30 mm concrete)	60	78	745	883
Case 2 (100 mm wool + wooden panel)	16	78	745	840
Case 3 (100 mm wool + 85 mm brick)	467	78	745	1,291
Case 4 (200 mm wool +30 mm concrete)	60	156	439	655
Case 5 (300 mm wool +30 mm concrete)	60	238	312	610
Case 6 (300 mm wool + 85 mm brick)	467	238	312	1,017

Table 55. Non-renewable raw material consumption for concrete element renovation with external insulation and three layer rendering. Heating energy type for Helsinki, Berlin and Barcelona is gas.

Non- renewable raw-material consumption				
	Façade,	Insulation,	Heating,	Total,
	kg/wall-m^2/ 20 year	kg/wall-m^2/ 20 year	kg/wall-m^2/ 20 year	kg/wall-m^2/ 20 year
Existing, Moscow			169	169
Case 1(100 mm wool + 30 mm concrete)	72	11	54	137
Case 2 (100 mm wool + wooden panel)	0.05	11	54	65
Case 3 (100 mm wool + 85 mm brick)	172	11	54	237
Case 4 (200 mm wool +30 mm concrete)	72	21	32	125
Case 5 (300 mm wool +30 mm concrete)	72	33	23	127
Case 6 (300 mm wool + 85 mm brick)	172	33	23	228
Existing Berlin			115	115
Case 1(100 mm wool + 30 mm concrete)	72	11	37	120
Case 2 (100 mm wool + wooden panel)	0.05	11	37	47
Case 3 (100 mm wool + 85 mm brick)	172	11	37	219
Case 4 (200 mm wool +30 mm concrete)	72	21	22	115
Case 5 (300 mm wool +30 mm concrete)	72	33	15	120
Case 6 (300 mm wool + 85 mm brick)	172	33	15	220
Existing, Barcelona			52	52
Case 1(100 mm wool + 30 mm concrete)	72	11	16	99
Case 2 (100 mm wool + wooden panel)	0,05	11	16	27
Case 3 (100 mm wool + 85 mm brick)	172	11	16	199
Case 4 (200 mm wool +30 mm concrete)	72	21	10	103
Case 5 (300 mm wool +30 mm concrete)	72	33	7	112
Case 6 (300 mm wool + 85 mm brick)	172	33	7	212

5.2.3 Life cycle costs

It has been calculated life cycle cost of three structures in case of

- Concrete sandwich
- Wooden wall
- Solid cavity wall

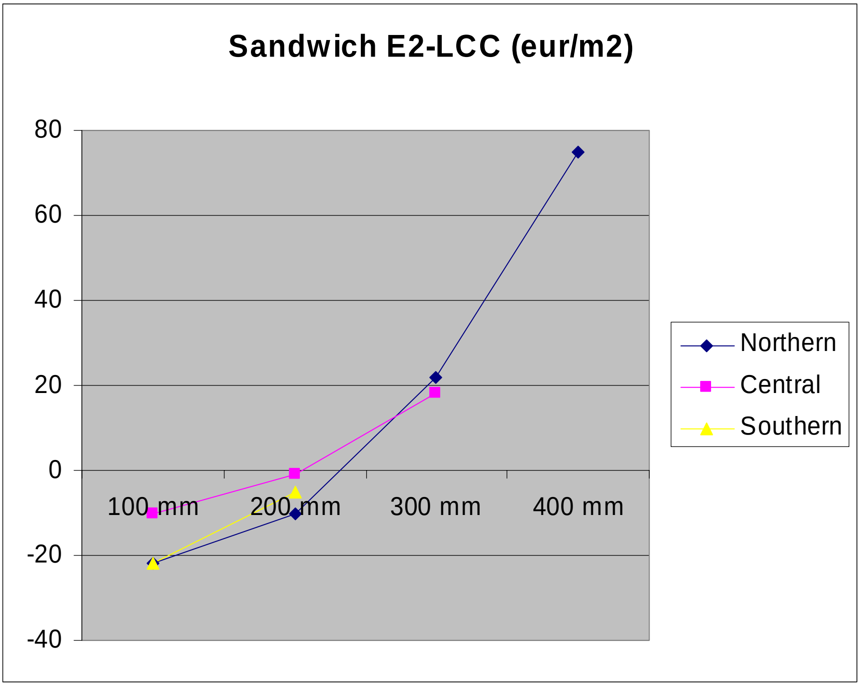


Figure 97. Life cycle costs of concrete sandwich by weather zone and insulation thickness.

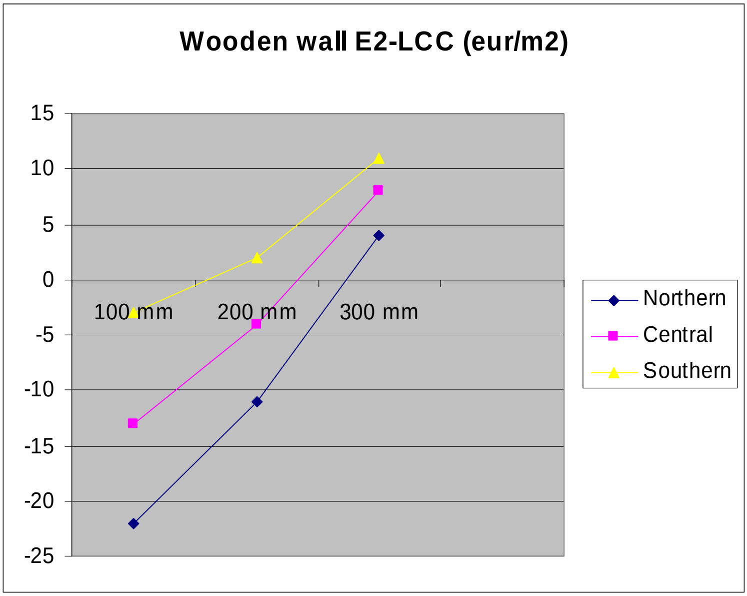


Figure 98. Life cycle costs of wooden wall by weather zone and insulation thickness.

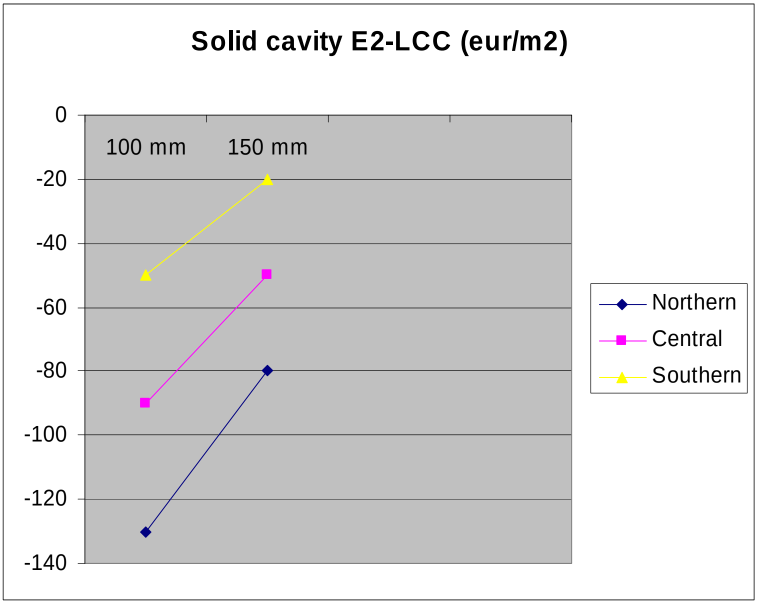


Figure 99. Life cycle costs of solid cavity wall by weather zone and insulation thickness.

The results show that in all cases the thickness of 100 mm is most economical, the thickness of 200 mm is life cycle economical too, but thickness of 300 mm is not economical in the case of a concrete sandwich. However the economy of insulation fixed with air gap is more economical in case of wooden wall and solid cavity than in case of concrete sandwich.

5.2.4 Energy demand for heating and cooling

Table 56. Calculated monthly and yearly heat flow through façade E2 on the selected climates.

Q_E2 [kWh/m^2]

Month	Paris	Lyon	Bilbao	Barcelona	Almeria	Catania
1.00	0.00	0.00	0.00	0.00	0.00	0.00
2.00	0.00	0.00	0.00	0.00	0.00	0.00
3.00	0.00	0.00	0.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00	0.00	0.00	0.00
5.00	0.00	0.00	0.00	0.00	0.01	0.00
6.00	0.00	0.03	0.00	0.04	0.08	0.14
7.00	0.06	0.12	0.05	0.27	0.47	0.73
8.00	0.06	0.10	0.04	0.20	0.62	0.72
9.00	0.00	0.00	0.03	0.04	0.25	0.15
10.00	0.00	0.00	0.00	0.00	0.01	0.00
11.00	0.00	0.00	0.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00	0.00	0.00	0.00
Whole year	0.12	0.25	0.12	0.55	1.43	1.75

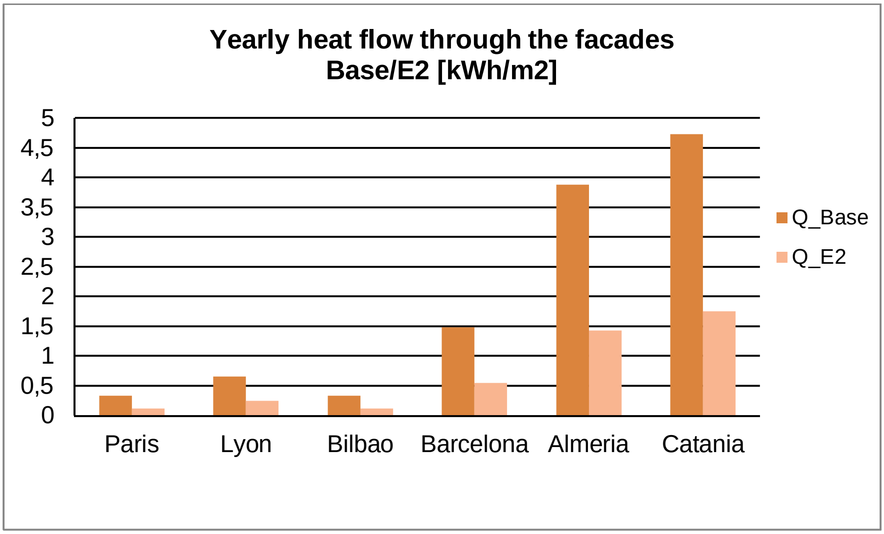


Figure 100. Yearly heat flow through the facades (E2).

5.2.5 Impact on daylight

Same as for E1.

5.2.6 Structural stability

Structural performance of the wall and the building (load bearing capacity)

The structural performance of the different types of walls (W1–W6) will normally remain unchanged for this type of light-weight insulation system.

Mounting of fastening points in the existing wall

The possibilities for sufficient anchor to the wall must be assessed closely. The load bearing capacity of the brick wall W4 and W6 might need fastening in the more durable underlying wall (see also restriction under buildability).

Changes in water drainage, changes in humidity and danger of frost heave

Risks for negative effects that can reduce the quality of the wall must be assessed. External insulation will normally have no negative effect on changes in humidity and will give no danger of frost heave. The water drainage with E2 will normally be secured as a part of the refurbishment system itself.

Sensitivity for seismic loads

External light weight insulation system are normally not sensitive for seismic loads, but the wall system itself may be more or less sensitive (see descriptions of the wall systems).

Table 57. Rating of E2 vs. wall type W1-W6 for structural stability.

Concept / Parameter	E2 + W1	E2 + W2	E2 + W3	E2 + W4[3)]	E2 + W5	E2 + W6[2)]	Note
Structural performance of the wall and the building (load bearing capacity)	0	0	0	0	0	0	The structural stability will normally remain unchanged
Mounting of fastening points in the existing wall	2	1	-1	1	1	1	Sufficient anchor to the wall may be limited for wood structures (W3)
Changes in water drainage, changes in humidity and danger of frost heave	2	2	2	2	2	2	Normally no negative effects that can reduce the quality of the wall
Sensitivity for seismic loads	0	0	1	0	0	0	Normally of low importance

2) Conditional suitable according to main table (total judgement), see appendix 8
3) Not suitable according to main table (total judgement), see appendix 8.

5.2.7 Buildability

Current condition of the existing wall

For some types of insulation materials it may be necessary that the surface is even to avoid air gaps between the insulation and the wall or to close then with weatherstrip etc. insulation materials.

Constructional feasibility

External insulation system are conditionally buildable for W3, W4 and W6 due to unsuitable insulation system outside a ventilated cavity.

The flexibility of EPS and XPS is lower than for mineral wool due to the feasibility to irregularities of the surface of the existing wall. The flexibility of vacuum panels are low since they cannot be cut to fit in any direction.

Access to the building site

Any kind of external insulation system requires scaffolding. Some kind of outer surface/cladding, e.g. external insulation composite systems (ETICS) are more sensitive to rainfall, hence a tarpaulin is needed. Exterior refurbishment to be painted requires tarpaulin.

Domestic factors

Factors that may restrict the refurbishment alternative must be assessed. Such factors may be cultural and conservation measures that causes a distinction between interior and exterior insulation.

Climate zones

Dependency of weather conditions and climate zones is important. The choice of cladding and drainage system is of great importance when you have wind driven rain.

Table 58. Rating of E2 vs. wall type W1-W6 for buildability.

Concept / Parameter	E2 + W1	E2 + W2	E2 + W3	E2 + W4[4)]	E2 + W5	E2 + W6[3)]	Note
Current condition of the existing wall	0 through -1	0 through -1	0 through -1	0 through -1	0 through -1	0 through -1	Depending of insulation materials. EPS and XPS need even surface or extra tightening (-1)
Constructional feasibility	1 through -1	1 through -1	1 through -1	1 through -2	1 through -2	1 through -2	Depending of insulation materials. Mineral wool (1), EPS/XPS (-1), Vacuum panels (-2)
Access to the building site	-1	-1	-1	-1	-1	-1	All external insulation need scaffolding, also small houses
Domestic factors	-2 through +2	-2 through +2	-2 through +2	-2 through +2	-2 through +2	-2 through +2	Domestic factors may restrict the refurbishment alternative stongly
Climate zones[2)] Cfb Cfbw Csa Dfb Dfc	 2 2 2 2 2	 2 2 2 2 2	 2 2 2 2 2	 2 2 2 2 2	 2 2 2 2 2	 2 2 2 2 2	Ratings for different climate zones are all good with cladding ventilation and draining.

2) Conditional suitable according to main table (total judgement), see appendix 8

3) Not suitable according to main table (total judgement), see appendix 8.

5.2.8 Need for care and maintenance

External insulation with brick veneer

External insulation with brick veneer can be mounted on a concrete wall, on an existing frame made of wood or metal (Kvande 2003, Kvande 2009) or on an existing brick wall. The brick veneer is connected to the studs in the frame using wall ties, see Figure 101 and Figure 102. The cavity between the brick layer and the insulation must be at least 15 mm wide, preferably 30 mm or more, since it difficult to prevent at least some excess mortar from extending into the cavity. Water repelling mineral wool insulation batt is placed between the cavity and the substructure. The batt facilitates the water draining ability of the cavity.

Maintenance procedures and intervals are given in table Table 59. The vulnerability to damage is assessed in Table 60. Table 61 summarizes the effects on maintenance and vulnerability to damage of changing the cladding of the facade to brick veneer.

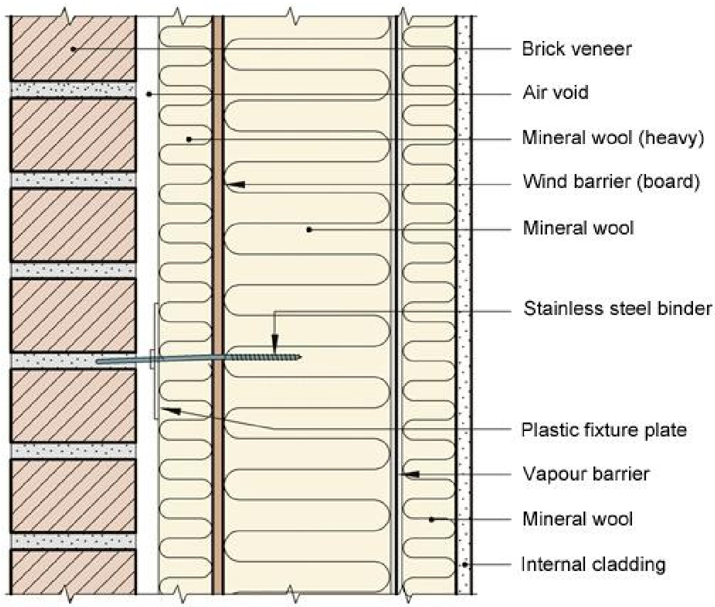


Figure 101. Brick veneer on a framework wall (Kvande 2009).

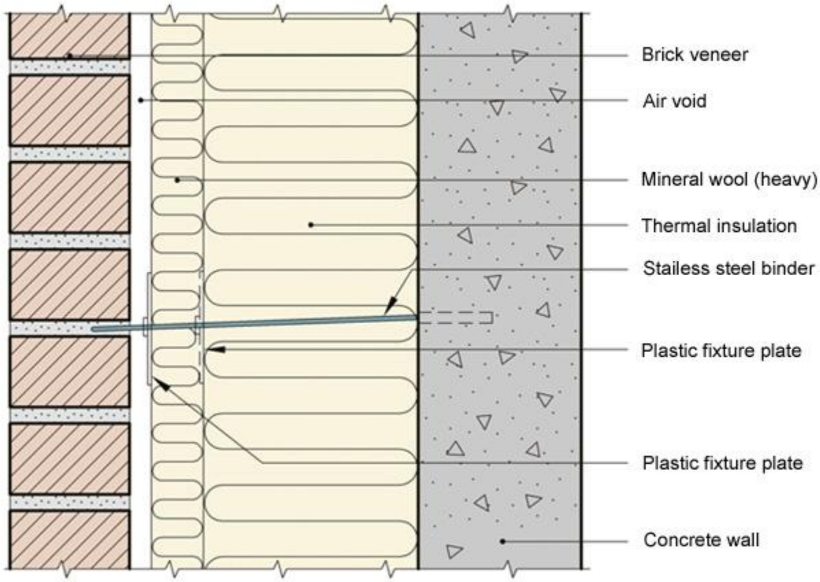


Figure 102. Brick veneer on concrete wall (Kvande 2009).

Table 59. Maintenance procedures and intervals for brick veneer.

Maintenance type	**Level**	**Procedure**	**Interval (y)**
Inspection	Light	Visual inspection. Check that drainage holes and vent openings are open. Check for signs that wall-ties or metal reinforcements are corroding. Check joints. Check for signs of moisture build-up in wall structure. (Askeland 1992)	1
Cleaning outer surface	Light	Cleaning with water and washing agent or other suitable cleaning method. (Nilsen 2006)	Depends on rate of dirt deposits and microbial growth. The rate is highly climate and pollution dependent. Salt deposits may be sign of moisture problems.
Repointing joints (brickwork without surface treatment)	Light-Moderate	Remove loose mortar. Apply new mortar.	30–60 (Larsen 2010)

Table 60. Vulnerability to damage – external insulation with brick veneer (untreated).

Damage type	**Vulnerability to damage**	**Comments**
Graffiti (aerosol paint)	- Brick – untreated: High (Withford 1992) (Kvande 2002)	
Pollution	*Diluted sulfuric acid (acid rain):* - Brick: Medium	Sulfur dioxide (SO_2) is oxidized to sulfuric acid (H_2SO_4). The main component in acid rain is sulfuric acid. The diluted sulfuric acid reacts with calcium carbonate ($CaCO_3$) in the brick and gypsum (hydrated $CaSO_4$) is formed. In recent times the levels of sulfur dioxide as atmospheric pollutant have decreased. Soot and nitrogen compounds now form the main part of pollutants depositing on building surfaces (Grossi et al. 2007). The photo initiated reaction of atmospheric hydrocarbons with nitric oxide (NO) leads to the formation of ozone. Ozone reacts with nitric oxide and leads, in the end, to the formation of nitrogen dioxide (NO_2) and nitric acid (HNO_3) (Charola, et al., 2002). The effect of nitrogen compounds on building materials is much less studied than the effect of sulfur dioxide/sulfuric acid.
Microbial growth	- Brick (low porosity): Low (Guilitte et al. 1995)	Some algae growth (Guilitte et al. 1995).

Table 61. The effect on maintenance parameters and vulnerability to damage of changing the facade cladding to untreated brick veneer.

Old wall	**Parameter**	**Change due to refurbishment**	**Comments**
Solid masonry wall	Need of inspection	0	
	Need of cleaning	0	
	Need of repointing	0	
	Vulnerability to graffiti	-1 through 0	Depends on the type of stone used in the solid wall
	Vulnerability to pollution	-1 through 1	Depends on the type of stone used in the solid wall

	Vulnerability to microbial growth	0 through 2	Depends on the type of stone used in the solid wall
Concrete - untreated	Need of inspection	0	
	Need of cleaning	0	
	Need of repointing	-2	
	Vulnerability to graffiti	0	
	Vulnerability to pollution	0	
	Vulnerability to microbial growth	0	
Concrete – painted	Need of inspection	0	
	Need of cleaning	1	
	Need of painting	2	
	Vulnerability to graffiti	0	Assuming that an inorganic paint is used on the concrete.
	Vulnerability to pollution	0	
	Vulnerability to microbial growth	0	
Timber framed wall with ventilated wooden cladding	Need of inspection	0	
	Need of cleaning	1	
	Need of repointing	-2	
	Need of painting	2	
	Need for changing cladding	2	
	Vulnerability to graffiti	-1	
	Vulnerability to pollution	0	
	Vulnerability to microbial growth	1	

5.2.9 Indoor air quality and acoustics

5.2.9.1 Thermal climate

Changes in internal surface temperatures mainly depends on the change in U-value of the construction, and not on the placement of the insulation. Many insulation materials (e.g. mineral wool, cellulose wool) have a relatively minor effect on airtightness. These materials are often use together with external wind-barriers, or internal moisture barriers or retarders. The retrofit of such barriers may increase airtightness significantly.

Rigid insulation materials like EPS, XPS and others are more or less airtight, but since they do not form a continuous layer, the actual effect on airtightness depends very much on actual details. Application of a windbarrier on the outside of the insulation may increase airtightness considerably, if applied in an unbroken layer and tightly connected to joints and penetrations.

In all cases, joints (between walls and windows, doors, roofs, foundations and dividing walls and floors) and penetrations (pipes, cables, etc) are generally at least as important as the airtightness of the wall itself. It is generally recommended to examine the airtightness as well as the ventilation rate before and after refurbishment.

Effect on moisture content of indoor air will be relatively unaffected by external insulation. The major exception to this is walls with high thermal mass with significant moisture transport through the wall, where external insulation will be highly beneficial.

Table 62. Effect of external insulation with air gap on thermal climate.

Concept / Parameter	E2	Note
Air leakage	0 thr 2	Generally little effect, but leakages around windows and other joints and penetrations may decrease air leakage
Temperature assymetry	-1 thr 2	Normally asymmetry improves, but not in cases where some external walls are opaque and other consists mostly of windows.
Internal surface temperatures	1 thr 2	Insulation reduces extreme temperatures, as internal and external temperatures are more decoupled than originally.
Internal Humidity (buffering)	0	Buffering unchanged, but influx may be reduced. Significant in some compact walls in wet climates.

5.2.9.2 Air quality

Air quality is generally little affected by external insulation except for cases where internal mould risk in original construction is removed.

Table 63. Effect of external insulation with air gap on air quality.

Concept / Parameter	E2	Note
Existing pollution sources	0 thr 2	Internal mould risk may be removed by insulation.
New pollution sources	0	
Ventilation efficiency	-2 thr 0	Reduced infiltration through walls reduces ventilation if no countermeasures applied. Need for additional ventilation should always be considered.
Influx of water	0 thr 2	Irrelevant (0) for most walls, relevant for some massive walls.

5.2.9.3 Acoustics

Continuous layers of external insulation may reduce sound transmission significantly for walls with high thermal mass. This is highly dependent on actual materials and constructions used. Rigid insulation materials have little or in some cases even negative effect, while some mineral wool products ere effective. In practice windows, doors and other building parts will generally be the weakest point, and the reduced transmission through the wall will have no impact on indoor sound levels unless these are remediated simultaneously.

Table 64. Effect of external insulation with air gap.

Concept / Parameter	E2	Note
Noise from outside	0 thr 2	Can be improved if windows, ventilation openings and other weak points also are improved.
Internal acoustics	0	Internal surface unchanged by refurbishment

5.2.10 Disturbance

External insulation is more often than not possible to apply with the building still in use. Methods requiring protection from rain and sun may reduce the ventilation and daylight in the dwellings in the building period, and this may not always be acceptable. Methods utilizing prefabricated elements may be faster and more tolerable to the inhabitants and neighbours.

Table 65. Disturbance assessment (E2).

Parameter \ Concept	E2
Effect on inhabitability	-1–0
Effect on neighbours and site	-1–0

5.2.11 Aesthetic quality and effect on cultural heritage

Same as for concept E1.

5.2.12 Impact on renewable energy use potential

No impact.

5.2.13 Fire Safety

Table 66. Fire Safety Assessment (E2).

External insulation (E) – New outer service with retrofit insulation – effect on Fire Safety				
WALL TYPE	BUILDING TYPE	Type of external structure/layer	Type of insulation	Score E2
W1_Solid wall; Brick, natural stone	A	Brick, natural stone or similar	Non-combustible	0
			Combustible	-1
		Thin non-combustible	Non-combustible	0
			Combustible	-2
		Combustible	Non-combustible	-1
			Combustible	-2
W2_Sandwich element; concrete panel + concrete panel	C	Concrete or similar	Non-combustible	0
			Combustible	-1
		Thin non-combustible	Non-combustible	0
			Combustible	-2
		Combustible	Non-combustible	-2
			Combustible	-2
W4_ Load bearing cavity without insulation; brick + concrete block W5_Insulated load	A	Brick, natural stone or similar	Non-combustible	0
			Combustible	0-1
		Thin non-combustible	Non-combustible	0
			Combustible	-2

bearing cavity; concrete block + concrete block		Combustible	Non-combustible	-1
			Combustible	-2
W6_Non-load bearing cavity; hollow brick + perforated brick	B	Brick, natural stone or similar	Non-combustible	0
			Combustible	-1
		Thin non-combustible	Non-combustible	0
W7_Non-load bearing concrete block without insulation; hollow brick + concrete block			Combustible	-1
		Combustible	Non-combustible	-1
			Combustible	-2
	C*	Concrete or similar	Non-combustible	0
			Combustible	-1
		Thin non-combustible	Non-combustible	0
			Combustible	-2
		Combustible	Non-combustible	-2
			Combustible	-2

5.3 Concept I – Internal thermal insulation of the envelope

5.3.1 Durability

Durability – moisture behaviour

Refurbishment

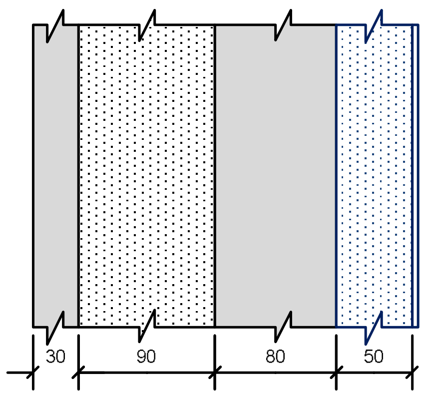


Figure 103. Retrofit insulation on inner surface of a concrete sandwich wall.

Retrofit insulation on inner surface of a wall was studied without the possibility of water leaking. The original wall structure is type of concrete sandwich element structure. In Table 67 the maximum water content in the inner concrete wall (CMAX) and the new insulation (INS2 that was EPS) was recorded.

Table 67. The moisture content of different walls when there is no water leakage.

			Water content (kg/m^3)					
Case	**Location**	**Ref.met.**	**Leaking**	**CMAX**	**INS1**	**INS2**	**Result**	**Note**
1.4	Frankfurt	Int.EPS	0.00%	147.75	4.76	1.79	OK	
1.4	Krakow	Int.EPS	0.00%	147.16	3.83	1.79	OK	
1.4	Jyväskylä	Int.EPS	0.00%	148.04	4.02	1.79	OK	

When comparing the moisture curves in Figure 104 it shows that inserting thermal insulation on the inner surface of a wall decrease the temperatures and increases moisture content of the original wall. Decreased temperatures in the outer layer of the wall increases the number of freeze-thaw cycles and may lead to frost damage. Increased moisture content may also lead to frost damage and may cause other kind of damages, too. When adding thermal insulation on an inner surface of a wall it must be taken care that the positioning of the water vapour barrier is close to the inner surface of a wall and the thermal insulation is not too thick. A good thumb rule is that the thinner thermal insulation the better.

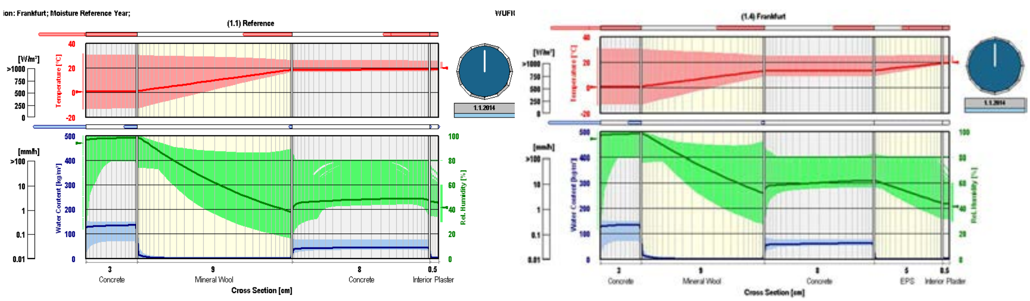


Figure 104. Moisture and temperatures levels in concrete element sandwich wall. Left image is without retrofit insulation and right one is retrofitted with EPS insulation on inner surface of the wall.

Results show that moisture accumulation is not a problem, as long as wind driven rain cannot penetrate the wall. If retrofit insulation on the inner surface of a wall is used, extra attention must be paid to joints with retrofit insulation and partition wall and retrofit insulation and floors. If the joints are not air and water vapour tight, there will probably be moisture condensation on the boundary of the old inner surface and new retrofit insulation. The condensation risk comes more increased the thicker the retrofit insulation. The connecting walls and floors are also thermal bridges and they reduce the effectiveness of retrofit insulation if not detailed properly.

Durability – modelling of deterioration

Case study: Refurbishment Concept I (Modena/Italy)

Original structure

The original wall is a sandwich wall as in Case study E1. The thermal insulation between the concrete cores is of mineral wool. The dimensions and other material properties are as in Case study E1.

The monitoring points for carbonation and corrosion were the front and back surface of the original concrete core. The monitoring points for mould growth were the front and back surface of the original insulation.

The durability data of the original structure is the same as in Case study E1.

Because of high temperature in Modena no frost attack was observed. The lowest temperature was about -4 °C. The dry conditions of Modena cause the carbonation rate to be relatively rapid. The service life with regard to corrosion of reinforcement was 57 years.

Refurbishment

Concept I was applied for the case in Modena. An internal insulation board is provided on the inner core of the original sandwich. The insulation may be of mineral wool or polyurethane. To improve the aesthetic appearance of the original façade a polymer coating was applied on the surface of the outer core.

Variables in the analyses

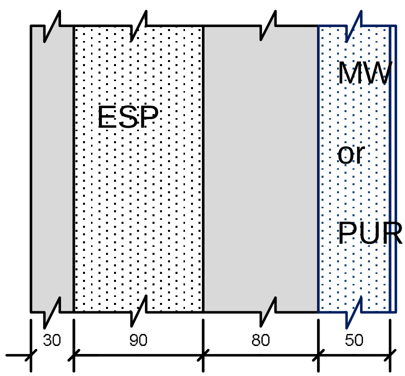


Figure 105. Refurbished sandwich wall, concept I.

For the mineral wool thermal insulation the analysis results were the following:

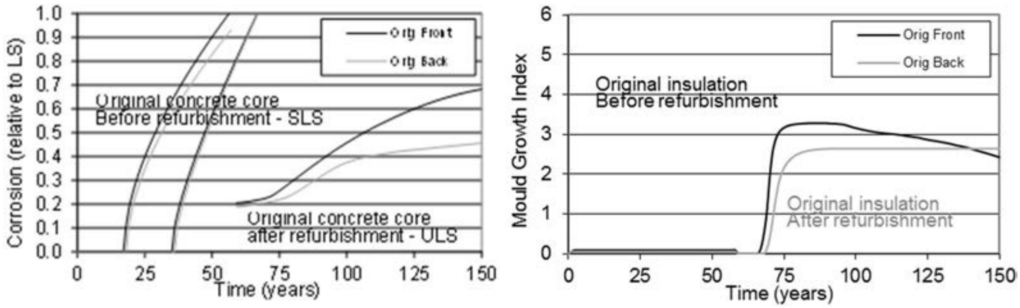


Figure 106. Results for the MW refurbished wall – corrosion and mould growth.

The risk of frost attack is small and the risk of reaching the ultimate limit state of reinforcement corrosion after the repair in the original concrete core is small. However, by time the risk of corrosion increases as the permeability of the coating increases.

There is an elevated mould growth risk after the repair around the original thermal insulation. As long as the coating is able to prevent rain water outside the wall the mould growth index is 0. With increasing permeability (after some 10 years) the mould growth index increases on both sides of the insulation and stays high long.

For polyurethane insulation the results were as following.

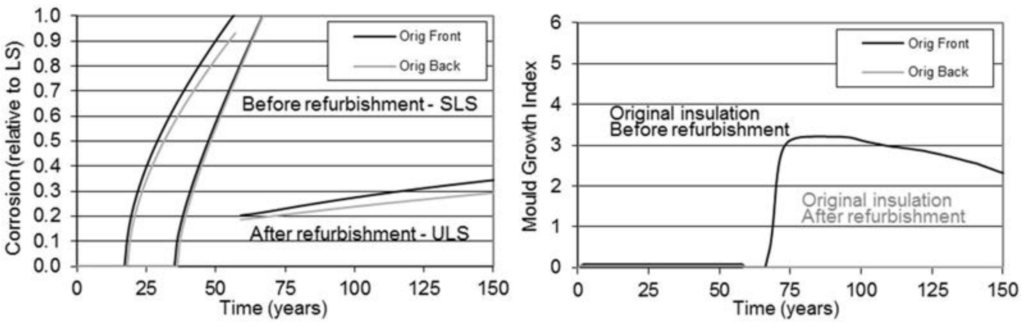


Figure 107. Results for the PUR refurbished wall – corrosion and mould growth.

With polyurethane insulation as the additional internal thermal insulation the performance of the wall is much similar as that with mineral wool insulation. However the risk of reinforcement corrosion is smaller and the risk of mould growth is only at the front side of the thermal insulation. At the back side of the thermal insulation (in touch with the inner concrete core) the risk is 0.

5.3.2 Environmental Impact

<u>Insulation material type</u>

Main insulation materials are mineral based rock- or glass wool, polymer based expanded polystyrene or polyurethane, and natural based insulations like cellulose fibres or lamb wool. Carbon footprint for different insulation materials depend on their origin, production method, use of recycling materials and also their insulation capacity. Figure 108 illustrates the carbon footprint value for different insulation materials and thicknesses. Lamb wool is given as an example for the utilization of waste material. The assumption for lamb wool was: that this material is not suitable for fabric production and because of that lamb breeding impacts allocated to the meat industry and insulation industry gets lamb wool with no emissions from production.

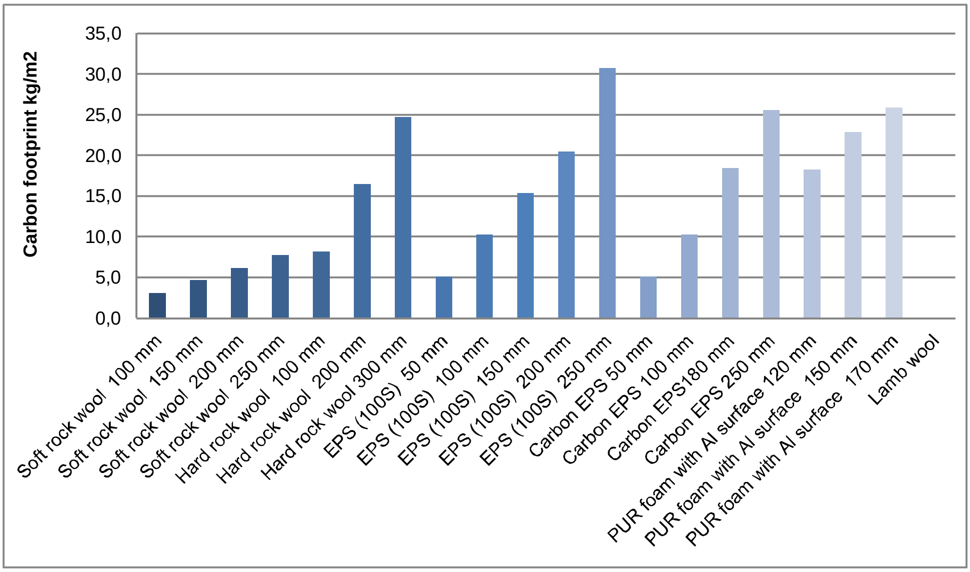


Figure 108. Carbon footprint for different insulation materials.

Environmental impact from the use of different insulation materials is illustrated with the help of stone wall renovation concepts where insulation fixed to the inner wall layer. This renovation method is suitable for historically protected buildings or for the buildings where outside widening is impossible because of the city planning. Solid wall cases are not typical in Northern Europe and because that this example deals with Eastern, Central and Southern Europe cases.

This example is given for the renovation case where target U-value was 0.17 W/m^2K. Thermal conductivity of different insulation materials is taken into account which results to the different insulation thicknesses.

Renovation cases for different insulation types are:

- Case 1 – rock wool with wooden studs and gypsum board
- Case 2 – polystyrene with gypsum board
- Case 3 – polyurethane with gypsum board
- Case 4 – lamb wool with wooden studs and gypsum board.

Table **68**Table 68 gives the result for external renovation cases for different insulation materials.

Table 68. Energy consumption for stone wall internal renovation concept where insulation types for different cases are rock wool, EPS, PUR and lamb wool. Inside finishing is gypsum board.

	Studied cases	Insulation thickness mm	U-value W/m^2K	Energy. $kWh/m^2/a$		
				Moscow	Berlin	Barcelona
Existing wall: solid stone wall, brick wall etc. were U-value is 1.5 W/m^2K)	Existing wall		1.5	168	114	51
	Case 1 (Mineral wool with gypsum board)	180	0.17	19	13	6
	Case 2 (EPS with gypsum board)	180	0.17	19	13	6
	Case 3 (PUR with gypsum board)	115	0.17	19	13	6
	Case 4 (Lamb wool with gypsum board)	195	0.17	19	13	6

Table 69. Carbon footprint for internal renovation with different insulation materials. Inside finishing is gypsum board. Heating energy type for Helsinki, Berlin and Barcelona is gas.

Carbon footprint				
	Gypsum board,	Insulation,	Heating,	Total,
	kg/wall-m^2/ 20 year	kg/wall-m^2/ 20 year	kg/wall-m^2/ 20 year	kg/wall-m^2/ 20 year
Existing Moscow			910	910
Case 1 (Mineral wool with gypsum board)	4.0	5.6	103	113
Case 2 (EPS with gypsum board)	4.0	18.0	103	125
Case 3 (PUR with gypsum board)	4.0	17.8	103	125

Case 4 (Lamb wool with gypsum board)	4.0	0.029	103	107
Existing, Berlin			617	617
Case 1 (Mineral wool with gypsum board)	4.0	5.6	70	79
Case 2 (EPS with gypsum board)	4.0	18.0	70	92
Case 3 (PUR with gypsum board)	4.0	17.8	70	92
Case 4 (Lamb wool with gypsum board)	4.0	0.029	70	74
Existing, Barcelona			277	277
Case 1 (Mineral wool with gypsum board)	4.0	5.6	31	41
Case 2 (EPS with gypsum board)	4.0	18.0	31	54
Case 3 (PUR with gypsum board)	4.0	17.8	31	53
Case 4 (Lamb wool with gypsum board)	4.0	0.029	31	36

Table 70. Fossil energy consumption for internal insulation renovation with different insulation materials. Inside finishing is gypsum board. Heating energy type for Helsinki, Berlin and Barcelona is gas.

Fossil energy consumption				
	Gypsum board,	Insulation,	Heating,	Total,
	kg/wall-m^2/ 20 year	kg/wall-m^2/ 20 year	kg/wall-m^2/ 20 year	kg/wall-m^2/ 20 year
Existing Moscow			13,337	13,337
Case 1 (Mineral wool with gypsum board)	59	70	1,511	1,640
Case 2 (EPS with gypsum board)	59	486	1,511	2,056
Case 3 (PUR with gypsum board)	59	407	1,511	1,977
Case 4 (Lamb wool with gypsum board)	59	0.61	1,511	1,571
Existing, Berlin			9,041	9,041
Case 1 (Mineral wool with gypsum board)	59	70	1,025	1,154

Case 2 (EPS with gypsum board)	59	486	1,025	1,569
Case 3 (PUR with gypsum board)	59	407	1,025	1,490
Case 4 (Lamb wool with gypsum board)	59	0.61	1025	1,084
Existing, Barcelona			4,066	4,066
Case 1 (Mineral wool with gypsum board)	59	70	461	590
Case 2 (EPS with gypsum board)	59	486	461	1,005
Case 3 (PUR with gypsum board)	59	407	461	926
Case 4 (Lamb wool with gypsum board)	59	0.61	461	520

Table 71. Fossil raw material consumption for internal insulation renovation with different insulation materials. Inside finishing is gypsum board. Heating energy type for Helsinki, Berlin and Barcelona is gas.

Non- renewable raw-material consumption				
	Gypsum board,	Insulation,	Heating,	Total,
	kg/wall-m^2/ 20 year	kg/wall-m^2/ 20 year	kg/wall-m^2/ 20 year	kg/wall-m^2/ 20 year
Existing Moscow			295	295
Case 1 (Mineral wool with gypsum board)	10	9.6	33	53
Case 2 (EPS with gypsum board)	10	12	33	56
Case 3 (PUR with gypsum board)	10	15	33	59
Case 4 (Lamb wool with gypsum board)	10	0	33	44
Existing, Berlin			200	200
Case 1 (Mineral wool with gypsum board)	10	9.6	23	43
Case 2 (EPS with gypsum board)	10	12	23	45
Case 3 (PUR with gypsum board)	10	15	23	48
Case 4 (Lamb wool with gypsum board)	10	0	23	33

Existing, Barcelona			90	90
Case 1 (Mineral wool with gypsum board)	10	9.6	10	30
Case 2 (EPS with gypsum board)	10	12	10	32
Case 3 (PUR with gypsum board)	10	15	10	36
Case 4 (Lamb wool with gypsum board)	10	0	10	21

5.3.3 Life cycle costs

– solid concrete

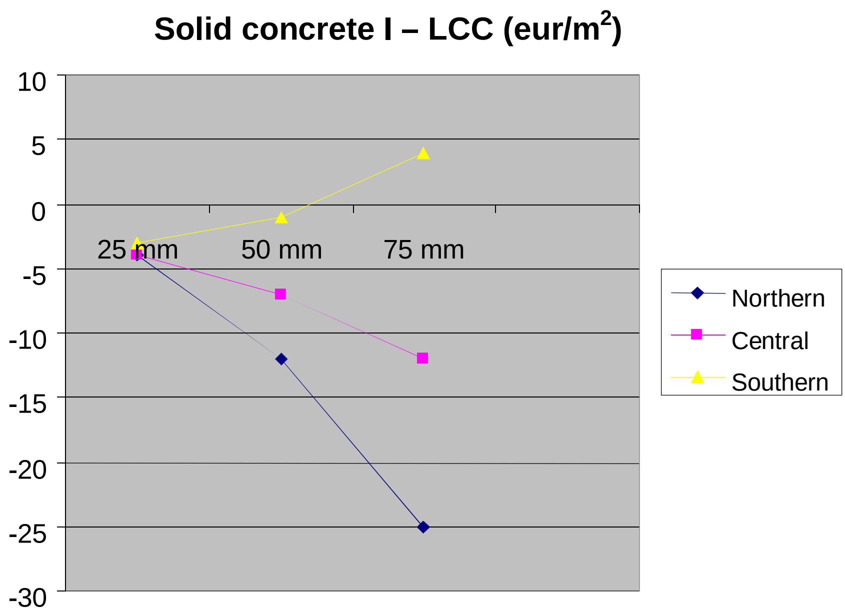


Figure 109. Life cycle Costs of solid concrete wall by weather zone and insulation thickness.

The results show that in case of new inner layer the life cycle economics is better as the thickness of insulation increases.

5.3.4 Energy demand for heating and cooling

Table 72. Calculated monthly and yearly heat flow through façade I on selected climates.

Q_I [kWh/m²]

Month	Paris	Lyon	Bilbao	Barcelona	Almeria	Catania
1.00	0.00	0.00	0.00	0.00	0.00	0.00
2.00	0.00	0.00	0.00	0.00	0.00	0.00
3.00	0.00	0.00	0.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00	0.00	0.00	0.00
5.00	0.00	0.00	0.00	0.00	0.01	0.00
6.00	0.00	0.03	0.00	0.04	0.08	0.14
7.00	0.06	0.12	0.05	0.27	0.47	0.73
8.00	0.06	0.10	0.04	0.20	0.62	0.72
9.00	0.00	0.00	0.03	0.04	0.25	0.15
10.00	0.00	0.00	0.00	0.00	0.01	0.00
11.00	0.00	0.00	0.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00	0.00	0.00	0.00
Whole year	0.12	0.25	0.12	0.55	1.44	1.76

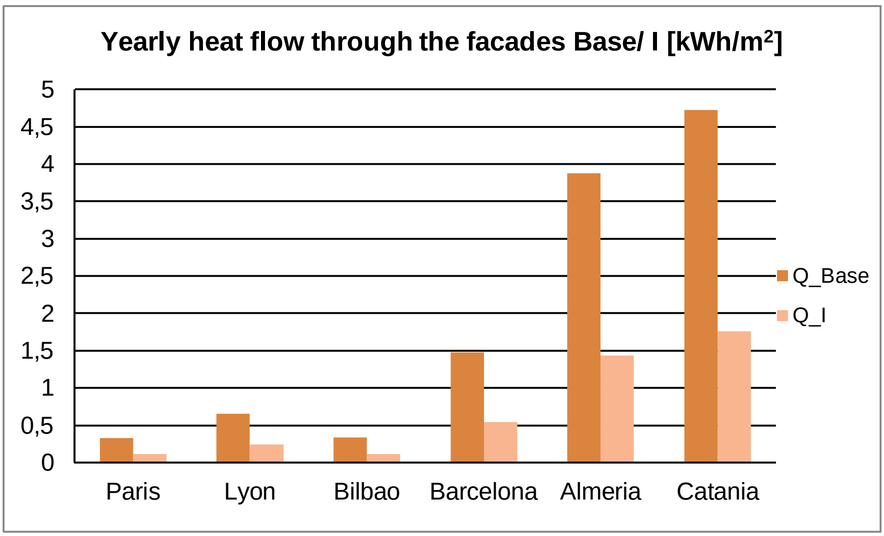


Figure 110. Yearly heat flow through the facades (I).

5.3.5 Impact on daylight

Minor impact.

5.3.6 Structural stability

Structural performance of the wall and the building (load bearing capacity)

The structural performance of the different types of walls (W1–W6) will normally remain unchanged for this type of light-weight insulation system.

Mounting of fastening points in the existing wall

The possibilities for sufficient anchor to the wall must be assessed closely, and assessed by undertaking a pull test.

Changes in water drainage, changes in humidity and danger of frost heave

Internal insulation will have no effect.

Sensitivity for seismic loads

Internal light-weight insulation system are normally not sensitive for seismic loads, but the wall system itself may be more or less sensitive (see descriptions of the wall systems).

Table 73. Rating of I vs. wall type W1-W6 for structural stability.

Concept / Parameter	I + W1[2)]	I + W2	I + W3[2)]	I + W4	I + W5[2)]	I + W6[2)]	Note
Structural performance of the wall and the building (load bearing capacity)	0 through -1	0	0	0	0	0	The structural stability will normally remain unchanged
Mounting of fastening points in the existing wall	1	1	2	1	1	1	Sufficient anchor to the wall is easy for wood structures (W3), else acceptable
Changes in water drainage, changes in humidity and danger of frost heave	-2	0	0 through -1	0 through -1	0 through -1	0 through -1	Risks for frost heave in mortar in massif brick wall (W1) and for vapour barrier problems in timber frame walls (W3)
Sensitivity for seismic loads	0	0	0	0	0	0	Normally of low importance

5.3.7 Buildability

Current condition of the existing wall

The condition of the wall and the suitability prior to refurbishment must be assessed.

Any kind of lead-in wires or penetrations must be planned carefully and can only be implemented where no cold drafts can occur. No holes must be made in the vapour barrier.

Constructional feasibility

The flexibility of EPS and XPS is lower than for mineral wool due to the feasibility to irregularities of the surface of the existing wall. The flexibility of vacuum panels is low since they cannot be cut to fit in any direction.

Access to the building site

Internal insulation system requires no scaffolding.

Domestic factors

Normally not relevant for internal insulation system.

Climate zones

Dependency of weather conditions and climate zones is not relevant for this insulation system.

Table 74. Rating of I vs. wall type W1-W6 for buildability.

Concept / Parameter	I + W1 3)	I + W2	I + W3 3)	I + W4	I + W5 3)	I + W6 3)	Note
Current condition of the existing wall	0 through -2	0	0	0	0	0	More or less independent of the condition, but brick walls are vulnerable for changes in temperature and danger of frost heave.
Constructional feasibility	1 through -2	1 through -2	1 through -2	1 through -2	1 through -2	1 through -2	Depending of the insulation material: mineral wool (1), EPS/XPS(-1), vacuum panels (-2).

Access to the building site	0	0	0	0	0	0	No need for scaffolding etc.
Domestic factors	0	0	0	0	0	0	No factors that may restrict the refurbishment alternative.
Climate zones Cfb Cfbw Csa Dfb Dfc	 0 -1 -1 0 -2	 0 0 0 0 0	 0 0 0 0 0	 0 -1 0 0 -1	 0 -1 0 0 -1	 0 0 0 0 0	 Rating according to different climate zones. Danger of frost heave (W1, W4 and W5)

2) Conditional suitable according to main table (total judgement), see appendix 8

3) Not possible according to main table (total judgement), see appendix 8.

5.3.8 Need for care and maintenance

On a timber framed structure, the first step consists of removing the internal cladding and vapor barrier. Additional insulation, new vapor barrier and new internal cladding is then added, see Figure 111 (Hole 2004). The new vapor barrier is placed between the internal cladding and the insulation.

If the original wall is concrete or masonry a similar procedure may be used. Normally a framework of timber studs is fastened to the inside of the existing walls and insulation is packed into the space between the studs (Kvande 2003). If the wall is above ground a vapor barrier is placed between the internal cladding and the insulation.

The temperature of the original wall drops as a result of retrofitting with internal insulation and the wall drying potential may decrease, particularly in the winter (Ogley et al. 2010) (Saïd et al. 2003). As a result moisture may collect in the original wall and cause increased maintenance due to moisture related damage. The material in the outer wall may also suffer frost damage. The effect of internal insulation on the cladding may be less pronounced when the cladding is ventilated, but no data was found on this particular topic.

The vulnerability to damage is assessed in Table 75 and Table 76 summarizes the effects on maintenance and vulnerability to damage of adding internal insulation.

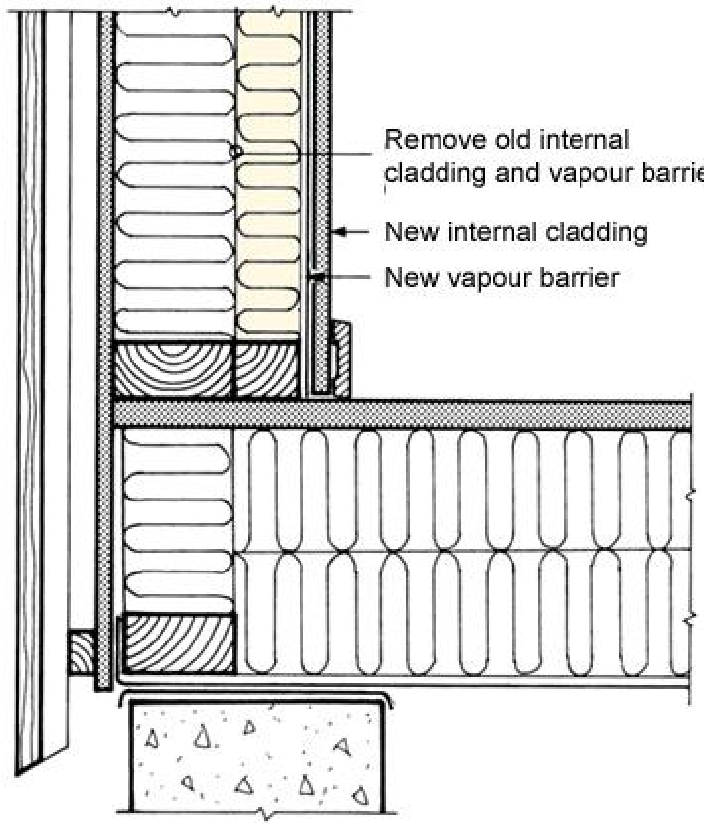


Figure 111. Internal insulation (light yellow) added to a timber framed wall with ventilated cladding (Hole 2004).

Table 75. Vulnerability to damage – internal insulation.

Damage type	Vulnerability to damage	Comments
Graffiti (aerosol paint)	- Stained wood cladding: High - Painted wood cladding: Medium/high - Untreated brick: High (Withford 1992) (Kvande 2002)	
Pollution	*Diluted sulfuric acid (acid rain):* - Stained wood cladding: Low/medium - Painted wood cladding: Low/medium	Sulfur dioxide (SO_2) is oxidized to sulfuric acid (H_2SO_4). The main component in acid rain is sulfuric acid. The diluted sulfuric acid reacts with calcium carbonate ($CaCO_3$) in the brick and gypsum (hydrated $CaSO_4$) is formed (Pavía et al. 2000). The

	- Brick: Medium (Pavía et al. 2000) (Lee et al. 2003) (Williams 2002)	acid may cause the calcium carbonate in paints containing this compound to dissolve (Williams, 2002). In recent times the levels of sulfur dioxide as atmospheric pollutant have decreased. Soot and nitrogen compounds now form the main part of pollutants depositing on building surfaces (Grossi et al., 2007). The photo initiated reaction of atmospheric hydrocarbons with nitric oxide (NO) leads to the formation of ozone. Ozone reacts with nitric oxide and leads, in the end, to the formation of nitrogen dioxide (NO_2) and nitric acid (HNO_3) (Charola, et al., 2002). The effect of nitrogen compounds on building materials is much less studied than the effect of sulfur dioxide/sulfuric acid.
Microbial growth	- Stained wood: Low-high - Painted wood: Low-high - Brick (low porosity): Low (Hjort et al. 2010) (Guilitte et al. 1995)	Stained and painted wooden surfaces are vulnerable to fungi. Paint brands differ greatly in their ability to withstand fungal attack (Hjort et al. 2010). Brick: Some algae growth (Guilitte et al. 1995).

Table 76. The effects on maintenance and vulnerability to damage of adding internal insulation.

Old wall	**Parameter**	**Change due to refurbishment**	**Comments**
Timber framed wall with ventilated wooden cladding	Need of inspection	-1/0	Check for moisture and/or temperature related problems.
	Need of cleaning	0	
	Need of painting	0	Colder outer surface may lead to decreased drying rate for outer wall and moisture build up
	Need of renewing wood panel	0	
	Vulnerability to graffiti	0	
	Vulnerability to pollution	0	
	Vulnerability to microbial growth	0	
Solid masonry wall	Need of inspection	-1	Check for moisture and/or temperature related problems.
	Need of cleaning	0	

	Need of repointing	-1	Colder outer surface may lead to decreased drying rate for outer wall and subsequent moisture build up. In cold climates freeze-thaw cycles may cause problems
	Need of repainting wall with render	-1	
	Need of new render	-1	
	Vulnerability to graffiti	0	
	Vulnerability to pollution	0	
	Vulnerability to microbial growth	0	

5.3.9 Indoor air quality and acoustics

5.3.9.1 Thermal climate

Changes in internal surface temperatures mainly depends on the change in U-value of the construction, and not on the placement of the insulation.

Internal insulation generally needs an airtight inside layer, often in the form of a vapour barrier or -retarder. This can increase the airtightness of the construction considerably.

Expanding foams are sometimes used for internal insulation, and may have a profound effect on airtightness.

In all cases, joints (between walls and windows, doors, roofs, foundations and dividing walls and floors) and penetrations (pipes, cables, etc) are generally at least as important as the airtightness of the wall itself, and both the original airtightness as well as the effect by the refurbishment solution will depend much on the building construction detail.

Effect on the indoor humidity will depend mostly on buffering by the internal layer, and be relatively unrelated to the refurbishment method in other aspects. If vapour barriers are used, the refurbished solution generally has lower water buffering capacity, and RH fluctuations will increase.

Walls with high thermal mass with significant moisture transport through the wall should never be internally insulated because of risk of water accumulation and mould growth.

Table 77. Effect of inernal insulation on thermal climate.

Concept / Parameter	I	Note
Air leakage	0 thr 2	Most concepts will reduce air leakage, details of methods most important.
Temperature assymetry	-1 thr 2	Normally asymmetry improves, but not in cases where some external walls are opaque and other consists mostly of windows.
Internal surface temperatures	0 thr 2	Insulation reduces extreme temperatures, as internal and external temperatures are more or less decoupled, but thermal bridges may be more pronounced after internal insulation.
Internal Humidity (buffering)	-1 thr 1	Internal buffer capacity normally decreases with internal insulation.

5.3.9.2 Air quality

A serious concern with internal insulation is the risk of interstitial condensation, which may have a grave effect on indoor air quality. Internal insulation implies a new internal surface. If the materials and surface treatment emits gases or particles, the indoor climate will be (negatively) affected. Materials fulfilling criteria for low-emitting buildings in EN 15251 Annex C is recommended. This is more important in dwellings than other buildings, as these would normally have lower ventilation rates.

If existing wall has defective material in or on it, this can and should be removed. The same applies for high-emitting materials or surface treatments. Internal layers may reduce exposure, but should not be considered an alternative to removal.

Table 78. Effect of internal insulation on air quality.

Concept / Parameter	I	Note
Existing pollution sources	0 thr 2	Remove all infected or smelly material.
New pollution sources	-2 thr 0	Select low-emitting materials. NB! Avoid moisture problems.
Ventilation efficiency	-1 thr 0	Reduced infiltration through walls reduces ventilation if no countermeasures applied. Consider increasing ventilation.
Influx of water	-2 thr 0	Irrelevant (0) for most walls, relevant for some massive walls which should never be internally insulated.

5.3.9.3 Acoustics

Windows, doors and other building parts will generally be the weakest point, and the reduced transmission through the wall will have no impact on indoor sound levels unless these are remediated simultaneously.

Internal insulation is generally less efficient than external in reducing noise from outside, as there will often be flanking transmission connected to dividing walls and floors.

Table 79. Effect of internal insulation on acoustics.

Concept / Parameter	I	Note
Noise from outside	0 thr 1	
Internal acoustics	-1 thr 1	Internal surfaces are changed

5.3.10 Disturbance

Internal insulation will make the dwelling more or less uninhabitable for longer or shorter periods. The period depends more on building characteristics than details of the insulation method. The neighbours and site will be less affected.

Concept / Parameter	
Effect on inhabitability	-2- -1
Effect on neighbours and site	0-1

5.3.11 Aesthetic quality and effect on cultural heritage

In some cases the interior details contribute greatly to understanding the building's history more than its exterior fabric. When refurbishing the external wall with internal insulation, the aesthetic quality of the interior should not be sacrificed, provided there is no harmful disruption of the delicate thermal and moisture distribution within the wall. In many traditional buildings, however, the cultural heritage values of a building's internal features are of historic importance and need to be preserved. In such cases, there is seldom an alternative but to avoid changing the interior construction at all. Advances in the development of new insulation materials, particularly in aerogels, are creating new opportunities for more sensitive interventions in building interiors, for example, by reducing the thickness of insulation required around window reveals, thus maintaining access to daylight through the windows. Changes to the interior are seldom satisfactory in traditional buildings, and usually involve compromise between improved thermal energy performance and protecting cultural heritage.

By preserving past alterations as well as original internal features, the social and architectural history of the building can be conserved. The internal structural system and interior details such as iron columns, sill and lintel details, and cornice detail and purlin roofs are examples of features to be preserved rather than removed or hidden during renovation. If the building is of historic interest, than the maintenance of the physical and visual presence of internal details should be considered at the earliest opportunity before proposing or suggesting any refurbishment option.

5.3.12 Impact on renewable energy use potential

No impact.

5.3.13 Fire Safety

Table 80. Fire Safety (I).

Internal insulation (I) – New inner insulation with new inner layer – effect on Fire Safety				
WALL TYPE	BUILDING TYPE	Type of inner layer	Type of insulation	Score
W1_Solid wall; Brick, natural stone	A	Non-combustible	Non-combustible	0
			Combustible	0…-1
		Combustible	Non-combustible	-1
			Combustible	-2
W2_Sandwich element; concrete panel + concrete panel	C	Non-combustible	Non-combustible	0
			Combustible	0…-1
		Combustible	Non-combustible	-1
			Combustible	-2
W3_Load bearing wood structure; Wooden frame	A	Non-combustible	Non-combustible	2
			Combustible	1
		Combustible	Non-combustible	0
			Combustible	-1
W4_ Load bearing cavity without insulation; brick + concrete block W5_Insulated load bearing cavity; concrete block +	A	Non-combustible	Non-combustible	0
			Combustible	0…-1
		Combustible	Non-combustible	-1
			Combustible	-2
	B	Non-combustible	Non-combustible	0

concrete block			Combustible	0…-1
W6_Non-load bearing cavity; hollow brick + perforated brick		Combustible	Non-combustible	-1
			Combustible	-2
	C*	Non-combustible	Non-combustible	0
			Combustible	0…-1
W7_Non-load bearing concrete block without insulation; hollow brick + concrete block		Combustible	Non-combustible	-1
			Combustible	-2

5.4 Concept C – Cavity insulation

5.4.1 Durability

Durability – moisture behaviour

The typical cavity wall with an external brick layer and the inner leaf built from concrete block was studied in combination with cavity wall insulation. The base case, cavity without thermal insulation, was simulated as a reference in Modena and Oostende. The cities were selected as this structure is common in those cities. Because of the poor thermal insulation of this type of construction detail it is not used in a cold climate, e.g. in Finland.

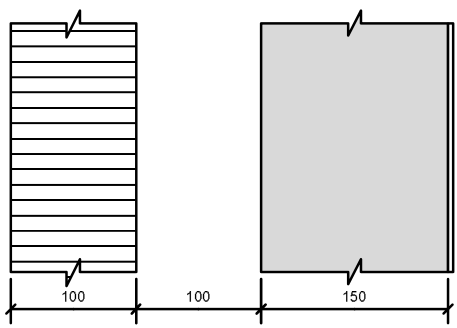


Figure 112. Unfurbished cavity wall.

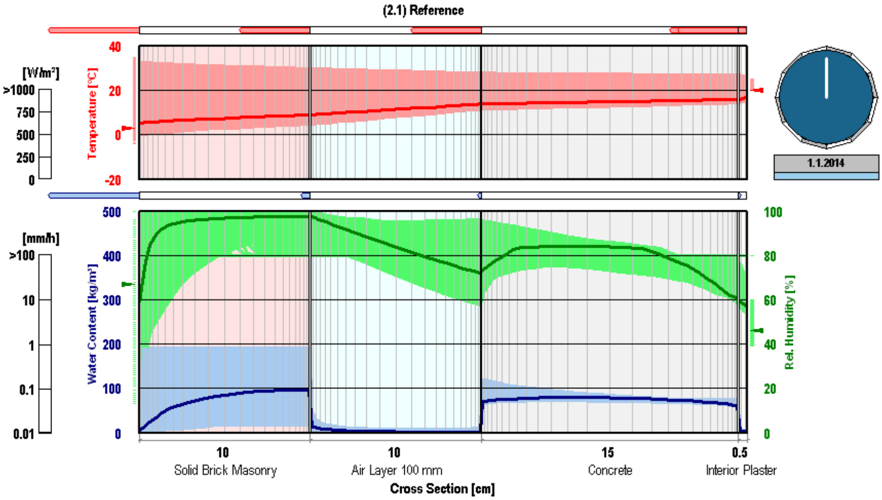


Figure 113. Moisture and temperatures levels in unrefurbished cavity wall.

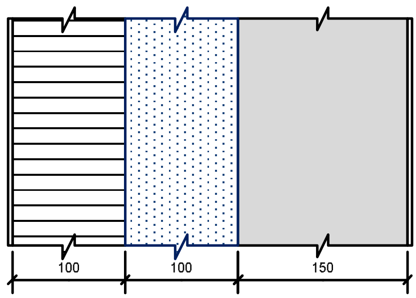


Figure 114. Refurbishing cavity wall by adding thermal insulation (EPS beads, mineral wool or PUR foam) in the cavity of a wall.

The insulation modelled was either sprayed polyurethane foam or blown mineral wool, in some countries. Polystyrene beads are also used, but they were not studied in WUFI simulations because their material data was not available. The actual moisture and thermal properties of thermal insulation used in cavity walls may vary in reality due to the storage conditions and method of application on a building site. Therefore the material properties of thermal insulation materials used in the simulations were selected from WUFI database.

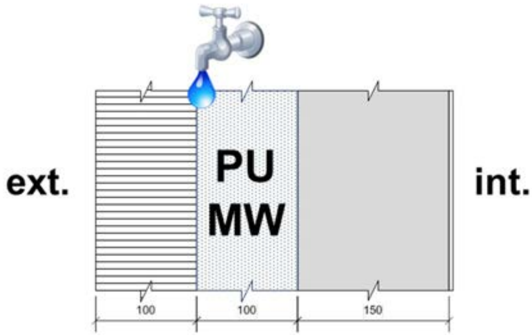


Figure 115. Water leakage point in a cavity wall.

The modelling indicated that the maximum possible water leaking varies from 4.71 to 19.5%. In the following table the maximum water content in the inner concrete wall (INTW), external brick wall (EXTW) and the new insulation (INS that was PUR foam and mineral wool fibres) was recorded. Concerning the moisture transport, these walls did not indicate any significant risk of damage when the leaking position was located at the inner face of the outer leaf. However, this study does not take into account the damage caused by repositioning of mineral wood fibres due to the increased moisture content the corrosion of connecting elements and salt migration.

Table 81. The maximum possible water leaking rate of different walls.

				Water content (kg/m^3)				
Case	**Location**	**Insulation**	**Leaking**	**EXTW**	**INTW**	**INS**	**Result**	**Note**
2.1	Oostende		0.00%	189.99	75.0	-	OK	
2.1	Modena		0.00%	189.91	75.0	-	OK	
2.2.1	Oostende	PU	0.00% 12.2%	191.20 222.02	75.0 75.0	4.46 19.06	OK	
2.2.1	Modena	PU	0.00% 19.5%	189.99 204.75	75.0 75.0	4.02 19.35	OK	
2.2.1	Oostende	MW	0.00% 12.3%	190.96 221.45	75.0 75.0	5.10 19.22	OK	
2.2.1	Modena	MW	0.00% 4.71%	189.98 189.99	75.0 75.66	5.36 6.30	OK	

The results in Table 81 and moisture level curves in Figure 116 show that adding thermal insulation into a wall cavity does not cause moisture problems, on the contrary adding thermal insulation can even reduce the moisture levels in the inner layer. The main reason for reduction of moisture level is better insulation of filled cavity, which increases the temperature of the inner layer.

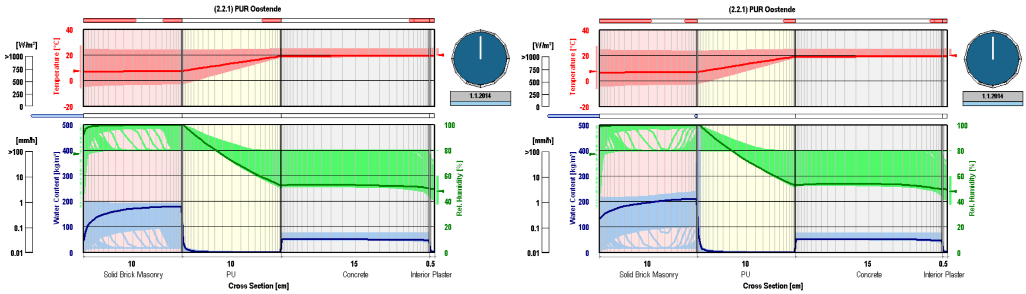


Figure 116. Moisture and temperatures levels in PUR retrofitted wall structures. The left image is with no water leakage and the right image is with maximum water leakage rate.

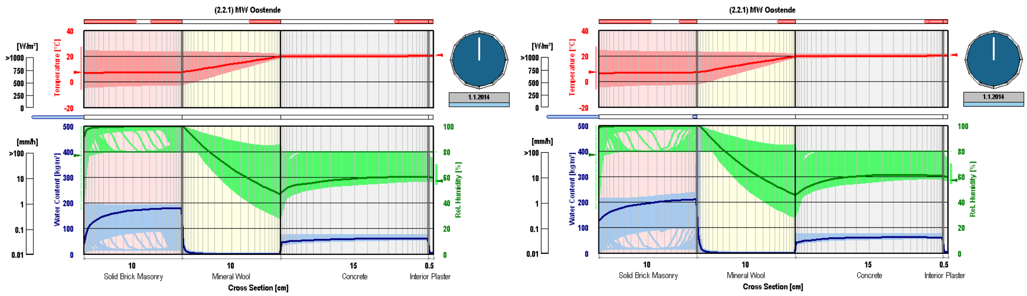


Figure 117. Moisture and temperatures levels in mineral wool retrofitted wall structures. The left image is with no water leakage and the right image is with maximum water leakage rate.

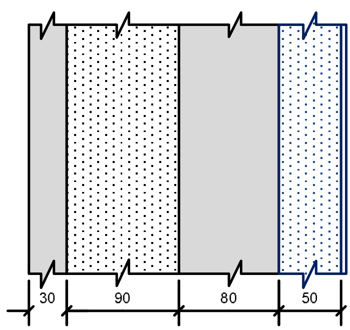


Figure 118. Retrofit insulation on inner surface of a concrete sandwich wall.

Retrofit insulation on inner surface of a wall was studied without the possibility of water leaking.

Table 82. The moisture content of different walls when there is no water leakage.

			Water content (kg/m^3)					
Case	**Location**	**Ref.met.**	**Leaking**	**CMAX**	**INS1**	**INS2**	**Result**	**Note**
1.4	Frankfurt	Int.EPS	0.00%	147.75	4.76	1.79	OK	
1.4	Krakow	Int.EPS	0.00%	147.16	3.83	1.79	OK	
1.4	Jyväskylä	Int.EPS	0.00%	148.04	4.02	1.79	OK	

When comparing the moisture curves in Figure 119 it shows that inserting thermal insulation on the inner surface of a wall decrease the temperatures and increases moisture content of the original wall. Decreased temperatures in the outer layer of the wall increases the number of freeze-thaw cycles and may lead to frost damage. Increased moisture content may also lead to frost damage and may cause other kind of damages, too. When adding thermal insulation on an inner surface of a wall it must be taken care that the positioning of the water vapour barrier is close to the inner surface of a wall and the thermal insulation is not too thick. A good thumb rule is that the thinner thermal insulation the better.

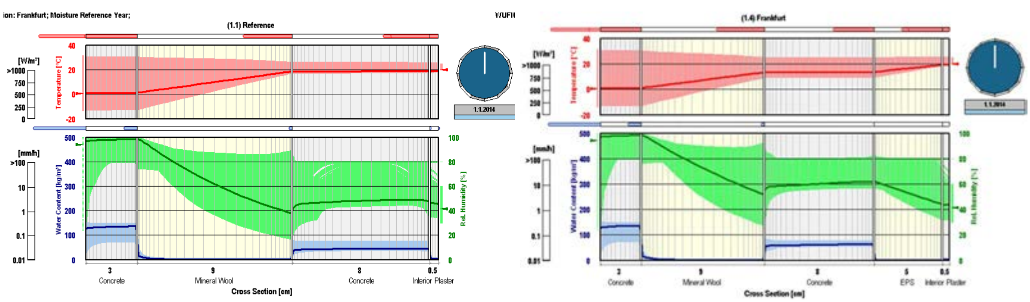


Figure 119. Moisture and temperatures levels in concrete element sandwich wall. Left image is without retrofit insulation and right one is retrofitted with EPS insulation on inner surface of the wall.

Both results show that moisture accumulation is not a problem, as long as wind driven rain cannot penetrate the wall. If retrofit insulation on the inner surface of a wall is used, extra attention must be paid to joints with retrofit insulation and partition wall and retrofit insulation and floors. If the joints are not air and water vapour tight, there will probably be moisture condensation on the boundary of the old inner surface and new retrofit insulation. The condensation risk comes more increased the thicker the retrofit insulation. The connecting walls and floors are also thermal bridges and they reduce the effectiveness of retrofit insulation if not detailed properly.

5.4.2 Environmental Impact

No data available.

5.4.3 Life Cycle Costs

The economics of insulation into cavity is as more economical as width of the cavity is. It is economical almost in all cases when taking the technical boundaries in account.

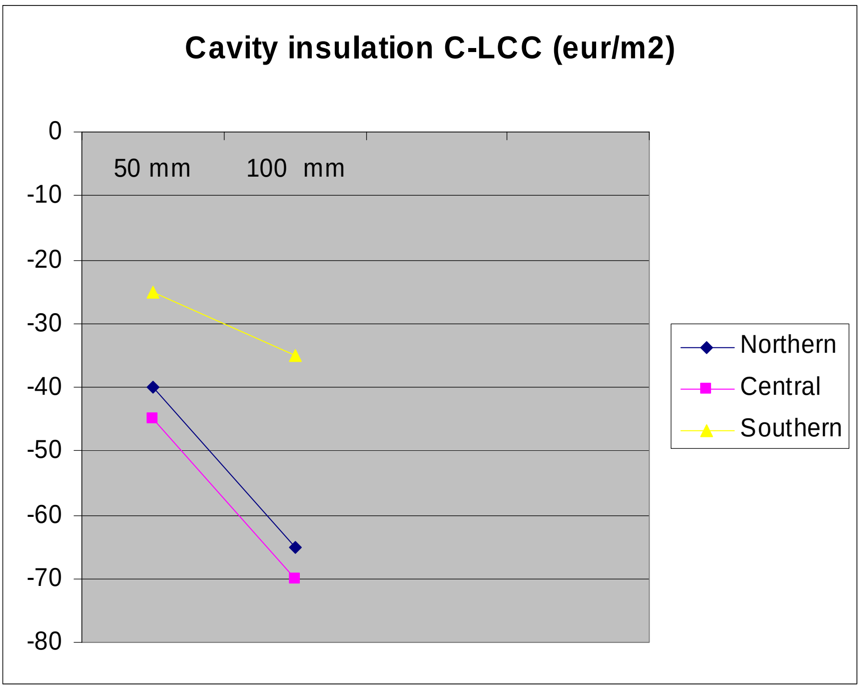


Figure 120. Life cycle Costs of cavity insulation by weather zone and insulation thickness.

5.4.4 Energy demand for heating and cooling

Table 83. Calculated monthly and yearly heat flow through façade C on the selected climates.

Q_C [kWh/m^2]

Month	Paris	Lyon	Bilbao	Barcelona	Almeria	Catania
1.00	0.00	0.00	0.00	0.00	0.00	0.00
2.00	0.00	0.00	0.00	0.00	0.00	0.00
3.00	0.00	0.00	0.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00	0.00	0.00	0.00
5.00	0.00	0.00	0.00	0.00	0.01	0.00
6.00	0.00	0.03	0.00	0.04	0.08	0.13
7.00	0.06	0.11	0.05	0.25	0.44	0.68
8.00	0.05	0.09	0.04	0.19	0.58	0.67
9.00	0.00	0.00	0.03	0.04	0.23	0.14
10.00	0.00	0.00	0.00	0.00	0.01	0.00
11.00	0.00	0.00	0.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00	0.00	0.00	0.00
Whole year	0.11	0.23	0.12	0.51	1.35	1.64

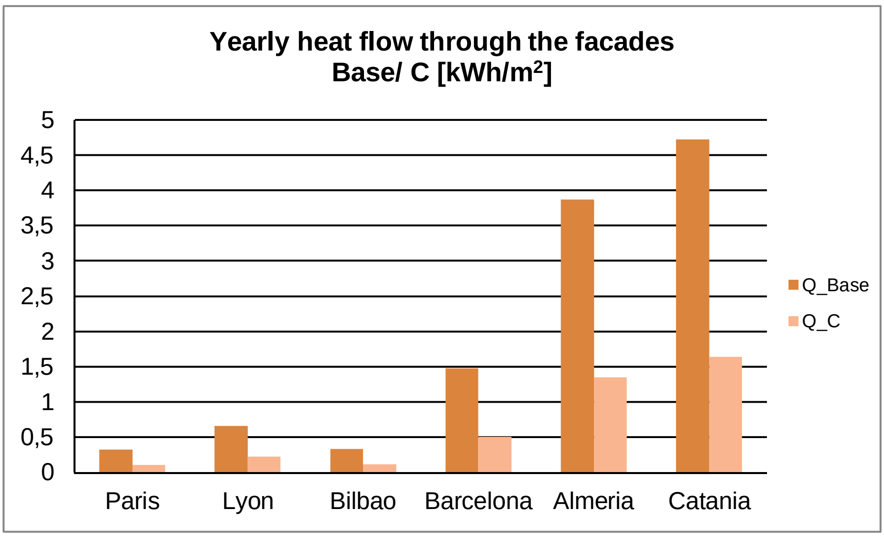


Figure 121. Yearly heat flow through the facades Base/C [kWh/m^2].

5.4.5 Impact on daylight

No impact.

5.4.6 Structural Stability

Structural performance of the wall and the building (load bearing capacity)

The structural performance of the different types of walls (W1–W6) will normally remain unchanged for Cavity wall insulation system.

Mounting of fastening points in the existing wall

Not relevant.

Changes in water drainage, changes in humidity and danger of frost heaver

Cavity wall insulation will have no effect.

Sensitivity for seismic loads

Cavity wall insulation system is normally not sensitive for seismic loads, but the wall system itself may be more or less sensitive (see descriptions of the wall systems).

Table 84. Rating of C vs. wall type W1-W6 for structural stability.

Concept / Parameter	C + W1[3)]	C + W2[3)]	C + W3[3)]	C + W4[2)]	C + W5[3)]	C + W6[2)]	Note
Structural performance of the wall and the building (load bearing capacity)	0	0	0	0	0	0	The structural stability will normally remain unchanged
Mounting of fastening points in the existing wall	0	0	0	0	0	0	Normally no need for anchor to the wall
Changes in water drainage, changes in humidity and danger of frost heave	0	0	0	0	0	0	No risks for negative effects that can reduce the quality of the wall
Sensitivity for seismic loads	0	0	0	0	0	0	Low sensitivity

2) Conditional suitable according to main table (total judgement), see appendix 8

3) Not possible according to main table (total judgement), see appendix 8.

5.4.7 Buildability

Current condition of the existing wall

Any kind of lead-in wires or penetrations must be planned carefully and can only be implemented where no cold drafts can occur. No holes must be made in the vapour barrier.

Constructional feasibility

The flexibility of EPS and XPS is lower than for mineral wool due to the feasibility to irregularities of the surface of the existing wall. The flexibility of vacuum panels are low since they cannot be cut to fit in any direction. Insulation type C, automatically excluding wall type 1, 2, 3 and 5. Furthermore it excludes insulation types that cannot be blown into the cavity, like EPS, XPS and vacuum panels.

Access to the building site

Cavity wall insulation system requires normally scaffolding (outside work is normal).

Domestic factors

Normally not relevant for internal insulation system.

Climate zones

Dependency of weather conditions and climate zones is not relevant for this insulation system.

Table 85. Rating of C vs. wall type W1-W6 for buildability.

Concept / Parameter	C + W1[4)]	C + W2[4)]	C + W3[4)]	C + W4[3)]	C + W5[4)]	C + W6[3)]	Note
Current condition of the existing wall	-2	-2	-2	0	0	0	More or less independent of the condition
Constructional feasibility	-2	-2	2 through -2	-2	-2	-2	Insulation of cavities leads to risk of increased moisture and reduced drainage. The system requires to tear down part of the construction, alternatively blowing of granulated mineral wool.
Access to the building site	-1	-1	-1	-1	-1	-1	Assessment of need for scaffolding etc.

Domestic factors	0	0	0	0	0	0	Assessment of factors that may restrict the refurbishment alternative.
Climate zones[2)] Cfb Cfbw Csa Dfb Dfc	 0 -1 -1 0 -2	 0 0 0 0 0	 0 0 0 0 0	 0 -1 0 0 -1	 0 -1 0 0 -1	 0 0 0 0 0	Rating according to different climate zones. Danger of frost heave (W1, W4 and W5)

3) Conditional suitable according to main table (total judgement), see appendix 8

4) Not possible according to main table (total judgement), see appendix 8.

5.4.8 Need for care and maintenance

It is possible to place insulation into wall cavities if these exist. Normally the insulation is blown into the cavities through holes drilled through the exterior layer (Holøs et al. 2010). This solution leaves the appearance of interior and the exterior unchanged, except for the holes drilled in the exterior walls.

Older, uninsulated wood structures may have a cavity in the wall. Insulation may be filled into the cavity if it is sufficiently wide (Hole 2004). The insulation is blown through holes that are drilled through the outside or inside wall into the cavity. As a result of the insulation the outer wall will become colder and more vulnerable to moisture damage if there is no cavity between the siding and the insulation. In this case the maintenance intervals for the surface treatment, as given in chapter 4.1, may be shortened, particularly in areas with driving rain.

Cavity walls are constructed with a cavity that separates the inner and outer layers. The cavity in the masonry cavity wall provides a means for moisture entering the wall, whether is moisture from wind-driven rain entering through the outer or water vapor from the inside of the building that enters the cavity through the innerlyer, to exit without causing damage to the wall structure. If the cavity is partially ventilated or not ventilated, the cavity also provides a limited contribution to the insulating ability of the wall. It is common practice to increase the insulating value of the cavity in previously uninsulated cavity walls, by injecting an insulation material, such as mineral wool or expanded polystyrene beads into the cavity (Baker 2009). Introducing insulation into the cavity of a cavity wall may, however, cause moisture problems because the cavity is blocked and water no longer drains out (Saïd et al. 2003). The insulation can provide a way for the moisture that has entered from the outside (wind-driven rain or faulty construction leading to water being directed towards the wall) through the outerlayer to travel across the cavity to the inner wythe (Ogley et al. 2010). The moisture problems can manifest themselves in damp spots and mold on the inside wall as well as increased corrosion rate for wall ties. Buildings must meet a strict set of technical requirements for cavity infill to be a suitable insulation method. It is also important that the workmanship of the installer is adequate; otherwise unfilled areas will be left in the wall, causing lower insulation effect.

The vulnerability to damage is assessed in Table 86 and Table 87 summarizes the effects on maintenance and vulnerability of injecting insulation into wall cavities.

Table 86. Vulnerability to damage – insulation injected into wall cavities.

Damage type	**Vulnerability to damage**	**Comments**
Graffiti (aerosol paint)	- Stained wooden cladding: High - Painted wooden cladding: Medium/high - Untreated brick: High (Withford 1992) (Kvande 2002)	
Pollution	*Diluted sulfuric acid (acid rain):* - Stained wood cladding: Low/medium - Painted wood cladding: Low/medium - Brick: Medium (Pavía et al. 2000) (Lee et al. 2003) (Williams 2002)	Sulfur dioxide (SO_2) is oxidized to sulfuric acid (H_2SO_4). The main component in acid rain is sulfuric acid. The diluted sulfuric acid reacts with calcium carbonate ($CaCO_3$) in the brick and gypsum (hydrated $CaSO_4$) is formed (Pavía et al. 2000). The acid may cause the calcium carbonate in paints containing this compound to dissolve (Williams 2002). In recent times the levels of sulfur dioxide as atmospheric pollutant have decreased. Soot and nitrogen compounds now form the main part of pollutants depositing on building surfaces (Grossi et al. 2007). The photo initiated reaction of atmospheric hydrocarbons with nitric oxide (NO) leads to the formation of ozone. Ozone reacts with nitric oxide and leads, in the end, to the formation of nitrogen dioxide (NO_2) and nitric acid (HNO_3) (Charola, et al., 2002). The effect of nitrogen compounds on building materials is much less studied than the effect of sulfur dioxide/sulfuric acid.
Microbial growth	- Stained wooden cladding: Low-high - Painted wooden cladding: Low-high - Brick (low porosity): Low (Hjort et al. 2010) (Guilitte et al. 1995)	Stained and painted wooden surfaces are vulnerable to fungi. Paint brands differ greatly in their ability to withstand fungal attack (Hjort et al. 2010). Brick: Some algae growth (Guilitte et al. 1995).

Table 87. The effect on maintenance parameters and vulnerability of damage of injecting insulation into wall cavities.

Old wall	**Parameter**	**Change due to refurbishment**	**Comments**
Traditional wood structures with cavity	Need of inspection	-1	Check for moisture and/or temperature related problems.
	Need of cleaning	0	
	Need of painting	-1	Colder outer surface may lead to decreased drying rate for outer wall and moisture build up
	Need of renewing wood panel	-1	
	Vulnerability to graffiti	0	
	Vulnerability to pollution	0	
	Vulnerability to microbial growth	0	
Cavity wall	Need of inspection	-1	Check for moisture and/or temperature related problems.
	Need of cleaning	0	
	Need of repointing	-1	Colder outer surface may lead to decreased drying rate for outer wall and subsequent moisture build up. In cold climates freeze-thaw cycles may cause problems
	Need of repainting wall with render	-1	
	Need of new render	-1	
	Vulnerability to graffiti	0	
	Vulnerability to pollution	0	
	Vulnerability to microbial growth	-1 through 0	

5.4.9 Indoor air quality and acoustics

5.4.9.1 Thermal climate

Changes in internal surface temperatures mainly depends on the change in U-value of the construction, and not on the placement of the insulation.

Most insulation materials used for cavity insulation (e.g. mineral wool, cellulose wool) have a minor effect on airtightness as measured by a pressure test. Some reduction of air infiltration may still occur. Expanding foams may increase air tightness. Internal moisture content of air will mostly be unaffected by cavity insulation.

Table 88. Effect of cavity insulation on thermal climate.

Concept / Parameter	C	Note
Air leakage	0 thr 1	Only small effects are likely.
Temperature assymetry	-1 thr 2	Normally asymmetry improves, but not in cases where some external walls are opaque and other consists mostly of windows.
Internal surface temperatures	1 thr 2	Insulation reduces extreme temperatures, as internal and external temperatures are more or less decoupled.
Internal Humidity	0	Internal buffer capacity unaffected.

5.4.9.2 Air quality

Effect of cavity insulation on indoor air quality will be negligible provided that moisture problems are avoided (consult criterion 1- durability) and high-emitting insulation materials are avoided. Some expanding foams may emit isocyanate which is a risk factor for asthma, during and after application.

Table 89. Effect of cavity insulation on air quality.

Concept / Parameter	C	Note
Existing pollution sources	0	Removal of infected material etc with impact on IAQ rarely affected by cavity insulation.
New pollution sources	0 thr 1	Normally no or minor effects. Avoid materials emitting isocyanates.
Ventilation efficiency	-1 thr 0	Some reduction possible, consider increasing ventilation.
Influx of water	-2 thr 0	Method not suitable in situations with high water influx.

5.4.9.3 Acoustics

The effect of filling a cavity with insulation of sound transmission is normally limited, and internal acoustics are not affected.

Table 90. Effect of cavity insulation on air quality.

Concept / Parameter	C	Note
Noise from outside	0 thr 1	Only marginal effects can be expected for most constructions.
Internal acoustics	0	Internal surface unchanged by refurbishment

5.4.10 Disturbance

Cavity insulation can normally be performed with relatively minor disturbance to inhabitants or site. If not correctly controlled, insulation materials can be blown into indoor spaces.

Table 91. Disturbance assessment (C).

Concept / Parameter	
Effect on inhabitability	0-1
Effect on neighbours and site	0-1

5.4.11 Aesthetic quality and effect on cultural heritage

Inserting insulation into the external cavity wall should not affect the cultural heritage or the aesthetic quality of the wall because the insulation is unseen to anyone from inside or outside surface of the wall. However, while inserting the insulation from external side of the wall, care should be taken that the part of the existing wall through which insertion has been done it should not get damaged, as it will deteriorate from the appearance of the building. Through SUSREF, however, we have seen that in some countries cavity insulation is inserted by removing the outer leaf of the wall completely, insulating and then reinstating the outer leaf. This method raises issues that are not so different to those discussed above for external insulation. Once again, the question of constructional authenticity arises.

5.4.12 Impact on renewable energy use potential

No impact.

5.4.13 Fire Safety

<table>
<tr><td colspan="4">Cavity wall insulation (C) – Insulation into cavity – effect on Fire Safety</td></tr>
<tr><td>WALL TYPE</td><td>BUILDING TYPE</td><td>Type of insulation</td><td>Score</td></tr>
<tr><td rowspan="6">W4_Load bearing cavity without insulation; brick + concrete block
W5_Insulated load bearing cavity; concrete block + concrete block
W6_Non-load bearing cavity; hollow brick + perforated brick
W7_Non-load bearing concrete block without insulation; hollow brick + concrete block</td><td rowspan="2">A</td><td>Non-combustible</td><td>0…1</td></tr>
<tr><td>Combustible</td><td>0…-1</td></tr>
<tr><td rowspan="2">B</td><td>Non-combustible</td><td>0…1</td></tr>
<tr><td>Combustible</td><td>0…-1</td></tr>
<tr><td rowspan="2">C*</td><td>Non-combustible</td><td>0…1</td></tr>
<tr><td>Combustible</td><td>0…-1</td></tr>
</table>

*Not applicable for wall types W6 and W7

5.5 Concept R – Technologies for replacing existing walls

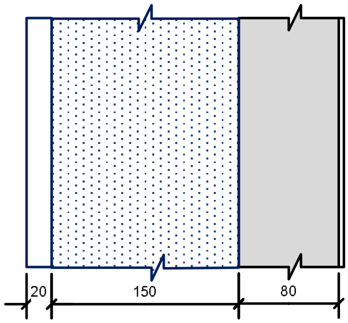
5.5.1 Durability

<u>Durability – Moisture behaviour</u>

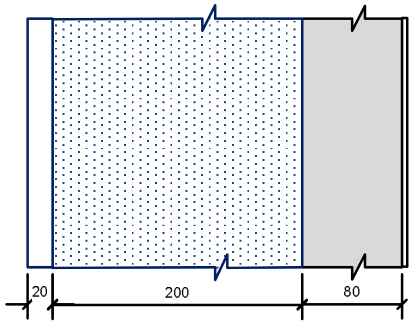
Following concepts of replacing existing walls were used.

Table 92. Refurbishment methods of a concrete sandwich element wall. The thermal insulation is replaced with thicker one and outer layer is replaced with a new one.

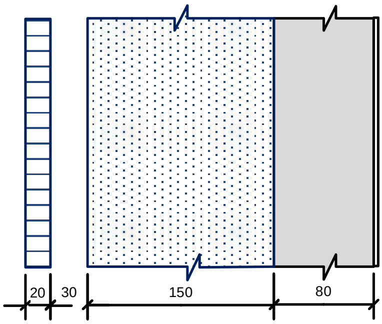
(R) 150 mm PUR + 20 mm rendering in Frankfurt, Krakow



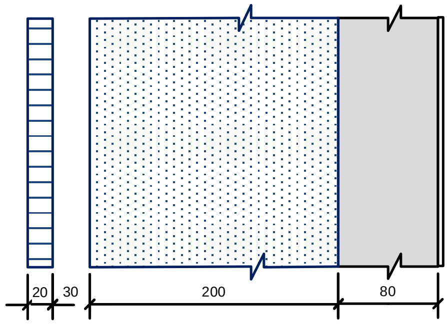
(R) 200 mm PUR + 20 mm rendering in Jyväskylä



(R) 150 mm MW + brick boards in Frankfurt, Krakow



(R) 200 mm MW + brick boards in Jyväskylä



The maximum possible water leaking varies from 10.3 to 18.3%. In the following table the maximum water content in the inner concrete wall (CMAX) and the new insulation (INS2 that uses PUR/mineral wool in cases) was recorded. It was identified that the leaking position was different in the PUR compared to the mineral wool cases, also the increase of water content was observed in different locations in the wall. In the case of the PUR panels, the failure was in the inner concrete wall while in case of external mineral wool with the air gap, the highest increase in water content was observed in the external insulation.

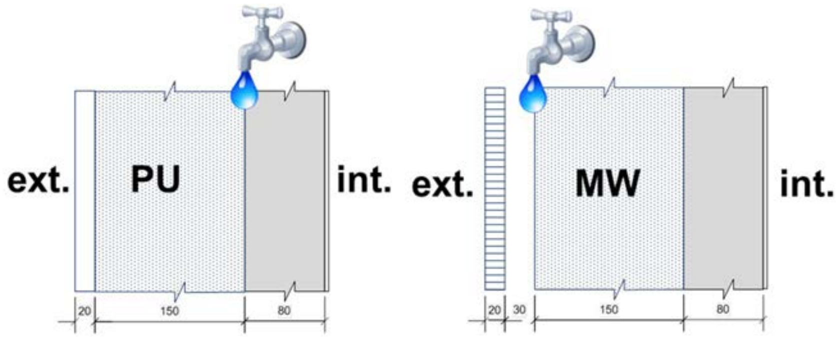


Figure 122. Water leakage points in different kind of walls.

Table 93. The maximum possible water leaking rate of different walls.

			Water content (kg/m³)				
Case	**Location**	**Ref.met.**	**Leaking**	**CMAX**	**INS2**	**Result**	**Note**
1.3.1	Frankfurt	Rem.PU	0.00% 10.47%	75.0 145.92	2.32 14.76	OK Fail	Inner concrete layer
1.3.1	Krakow	Rem.PU	0.00% 10.34%	75.0 139.13	2.42 16.01	OK Fail	Inner concrete layer
1.3.2	Jyväskylä	Rem.PU	0.00% 18.31%	75.0 147.24	2.40 16.60	OK Fail	Inner concrete layer
1.3.3	Frankfurt	Rem.MW	0.00% 6.07%	75.0 75.0	3.30 4.27	OK Fail	External mineral wool insulation
1.3.3	Krakow	Rem.MW	0.00% 11.91%	75.0 75.0	3.36 19.48	OK OK	
1.3.4	Jyväskylä	Rem.MW	0.00% 12.79%	75.0 75.0	2.68 24.10	OK Fail	External mineral wool insulation

The simulations showed that if the wind driven rain leakage rate is 0%, there will be no problem with refurbished concrete sandwich element structure, if the outer surface layer and possibly the original thermal insulation were replaced with new insulation material.

When a new outer layer enables wind driven rain to penetrate into a wall, there are greater risks with the structures when using plastic foam thermal insulation as a retrofit insulation on the exterior surface of the existing wall, than structures using mineral wool insulation. The maximum possible leaking rates are higher in mineral wool insulated walls than in polyurethane foam insulated walls. The results of the modelling indicate if the thermal insulation is polyurethane foam, then the problem will be the moisture content of the inner concrete layer, the construction detail used for the calculations were made with a water vapour permeable layer on the inner surface of the wall, but it was noted that if this layer is water vapour tight, the maximum allowable rain water leakage is much lower. In this case the leaked

rain water can evaporate only slowly by diffusion through the inner surface layer and plastic foam insulation. The tighter the inner layer and the thicker the thermal insulation is, the lower is the allowable rain water leakage.
In case of the PUR panels, the typical ranges of temperature, relative humidity and water content are shown in the following images for the case without any leaking (left) and with the maximum possible leaking (right).

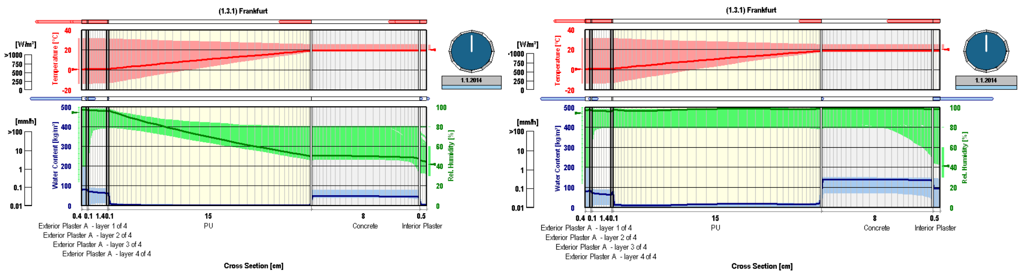


Figure 123. Moisture and temperatures levels in PUR retrofitted wall structures. The left image is with no water leakage and the right image is with maximum water leakage rate.

In case of mineral wool insulation, the typical ranges of temperature, relative humidity and water content are on the following pictures for the case without any leaking (left) and with the maximum possible leaking (right).

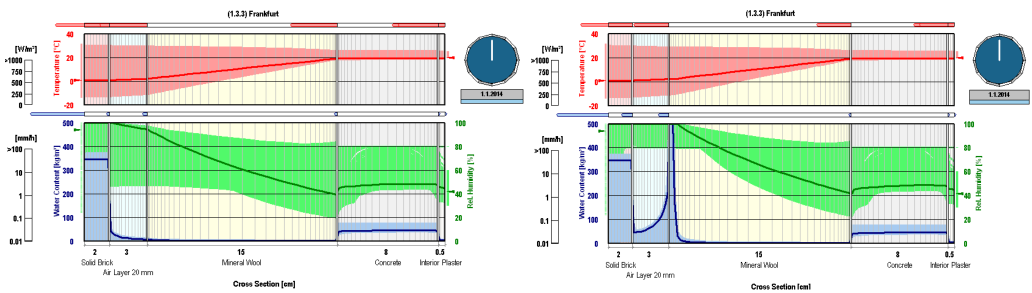


Figure 124. Moisture and temperatures levels in mineral wool retrofitted wall structures. The left image is with no water leakage and the right image is with maximum water leakage rate.

Durability – modelling of deterioration of refurbished concrete facades

Case study 1: Refurbishment Concept R (Jyvaskyla/Finland)

Refurbishment

Concept R was applied in the refurbishment. The old outer core and the old thermal insulation are removed and replaced by a new thermal insulation and rendering on top of the insulation. The insulation board may be of mineral wool or polyurethane.

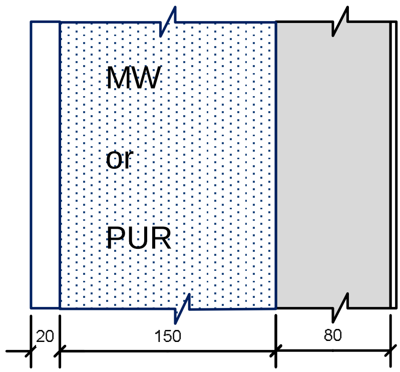


Figure 125. Refurbished sandwich wall, concept R.

The rendering material was the same as in Case study E1. However, now it is assumed that the reinforcement of the rendering is not zinc coated steel. So, corrosion of this reinforcement is possible in carbonated rendering in this case.

The monitoring points of carbonation and corrosion are front and back side of the rendering. The monitoring points of mould growth are both sides of the thermal insulation (original and new).

With mineral wool thermal insulation the results are presented below.

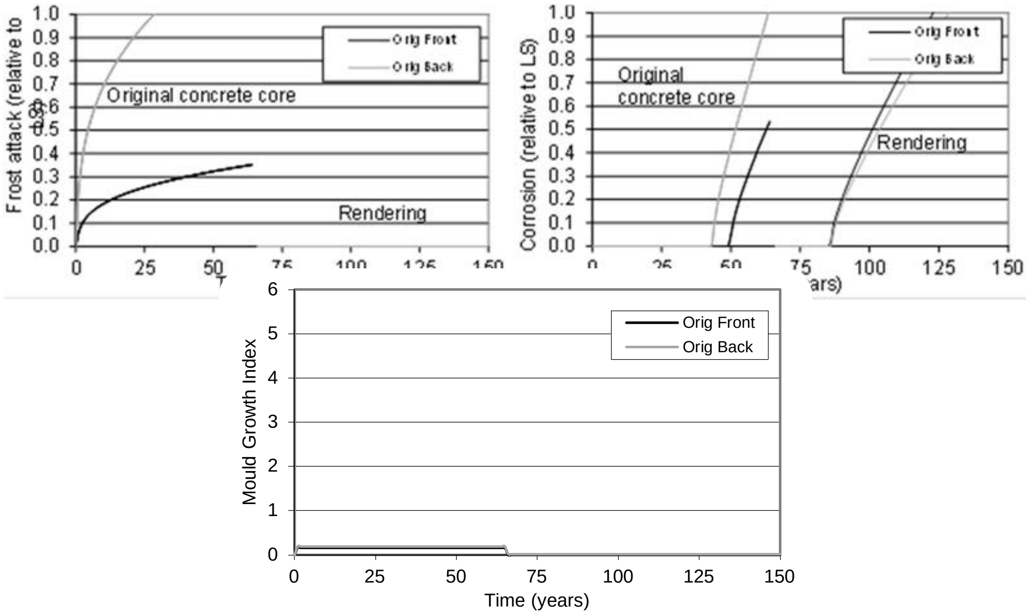


Figure 126. Results for the MW refurbished wall – frost attack, corrosion and mould growth.

There are no serious moisture risks with the applied refurbishment Concept R. The only risk is the result of the assumed reinforcement of the rendering which was not zinc coated. Because of that the service life of the repair is limited to about 60 years (average). The reinforcement of the rendering should always be zinc coated.

With polyurethane thermal insulation the results are presented below.

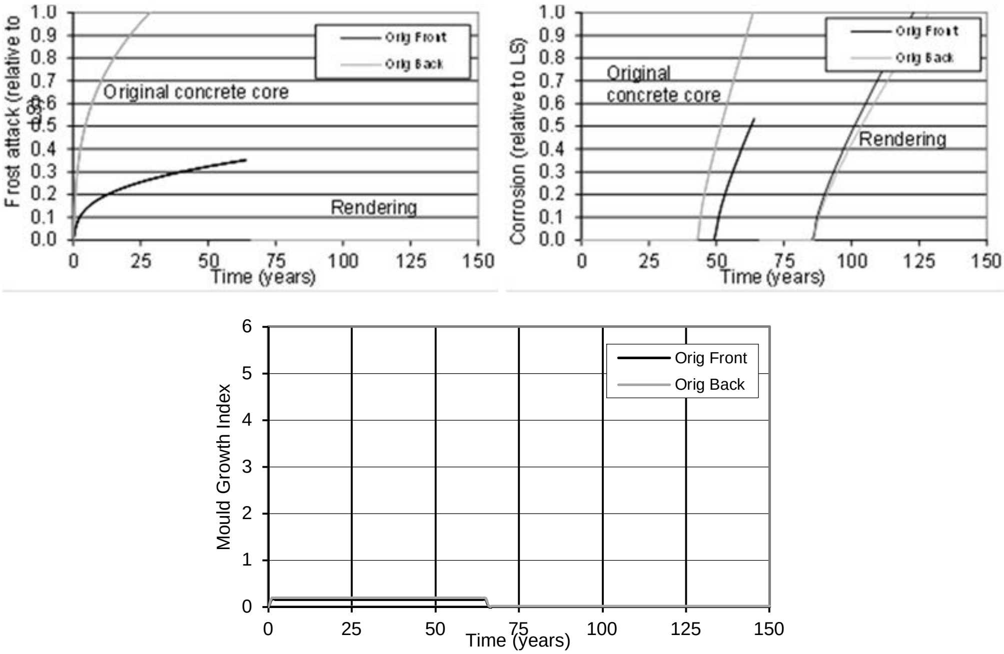


Figure 127. Results for the PUR refurbished wall – frost attack, corrosion and mould growth.

The degradation curves with polyurethane thermal insulation the degradation curves are almost identical with those of mineral wool. No special risks exist except in this case the uncoated reinforcement net of the rendering.

Case study 2: Refurbishment Concept R (Oostende/Belgium)

The original unrefurbished wall is the same as in Case study 1.

<u>Refurbishment</u>

Concept R was applied for the refurbishment. The old outer core and the old thermal insulation are removed and replaced by a new thermal insulation. The insulation board may be of mineral wool or polyurethane. The wall is covered with masonry panelling leaving a ventilation gap between the thermal insulation and panelling.

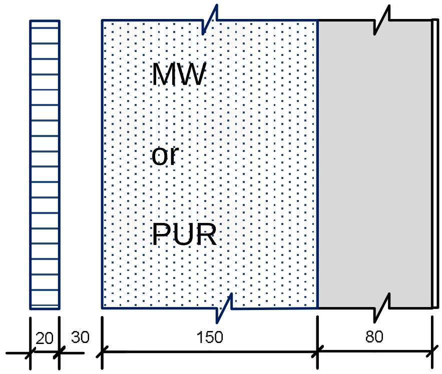


Figure 128. Refurbished sandwich wall, concept R.

The possible degradation of the masonry panel is not considered in this analysis. So, the only possible threat in this case is mould growth. The monitoring points of mould growth are both sides of the thermal insulation (original and new).

With mineral wool thermal insulation the results are presented below.

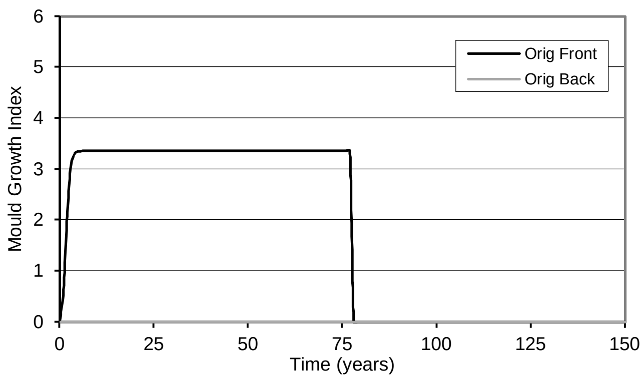


Figure 129. Results for the MW refurbished wall for mould growth.

With polyurethane thermal insulation the results are presented below.

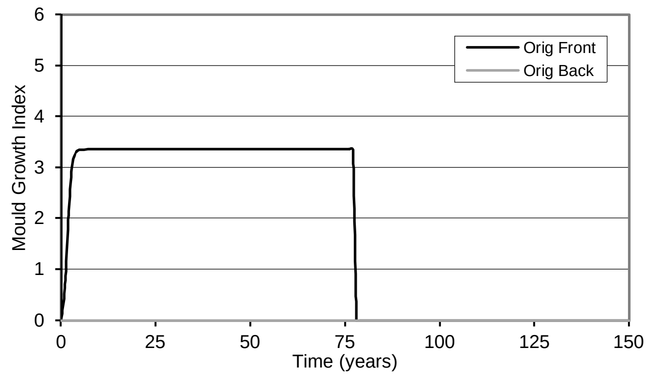


Figure 130. Results for the PUR refurbished wall for mould growth.

After the repair the mould growth is reduced rapidly to 0 with both thermal insulation options. No risks were observed in this refurbishment concept.

5.5.2 Environmental Impact

Concept R includes renovation methods, in which part of the external walls are removed, before installation of new insulation and façade. One example is concrete sandwich element, where the façade is deteriorated into such content that outer element and insulation should be removed before new installations. Replaced renovation is applicable also for load bearing or non-load bearing wooden- and cavity walls. Environmental impact result for replaced renovation is quite similar to external renovations where insulation can fix without or with air gap. Replaced renovation enables to change façade materials or keep exterior features.

- Case 1 changes façade features and insulation thickness. Outer concrete layer and old insulation is replaced with 3-layer rendering façade and with the 210 mm rock wool insulation.
- Case 2 keeps the façade features. Outer concrete layer and old insulation is replaced with new similar 60 mm concrete layer and with the 210 mm rock wool insulation.

For energy source alternatives gas and district heat (Finland) is used.

Table 94. Energy consumption for replaced renovation concepts with rock wool and three layer rendering or new concrete outer leaf. Existing wall type is concrete sandwich element and location is Helsinki.

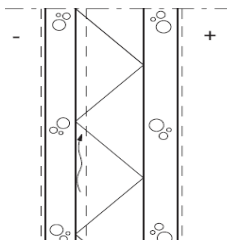
Existing wall (60 mm concrete + 80 mm rock wool + 120 mm concrete)	Studied cases for outer concrete layer and insulation replacement	Insulation thickness. mm	U-value. W/mK	Energy, kWh/wall-m^2/a
				Helsinki
	Existing wall	80	0.44	50
	Case 1 (rock wool + 3-layer rendering)	210	0.17	19
	Case 2 (rock wool + 60 mm outer concrete leaf)	210	0.17	19

Table 95. Carbon footprint for concrete element renovation with replacement concept. Façade type is three layer rendering or 60 mm concrete outer leaf. Heating energy type for Helsinki is a gas or average district heat (Finland).

Carbon footprint				
	Façade, kg/wall-m^2/20 year	Insulation, kg/wall-m^2/20 year	Heating, Gas/district (Finland) kg/wall-m^2/20 year	Total, gas/district Finland kg/wall-m^2/20 year
Existing sandwich element, Helsinki			270/209	270/209
Case 1 (rock wool + 3-layer rendering)	8	12	104/81	124/101
Case 2 (rock wool + 60 mm outer concrete leaf)	36	12	104/81	153/129

Table 96. Fossil energy consumption for concrete element renovation with replacement concept. Façade type is three layer rendering or 60 mm concrete outer leaf. Heating energy type for Helsinki is a gas or average district heat (Finland).

Fossil energy consumption				
	Façade, MJ/wall-m²/20 year	Insulation, MJ/wall-m²/20 year	Heating, Gas/district Finland MJ/wall-m² /20 year	Total, Gas/district Finland MJ/wall-m² /20 year
Existing sandwich element, Helsinki			3,961/3,085	3,961/3,085
Case 1 (rock wool + 3-layer rendering)	40	156	1,530/1,192	1,727/1,388
Case 2 (rock wool + 60 mm outer concrete leaf)	263	156	1,530/1,192	1,949/1,611

Table 97. Non-renewable raw material consumption for concrete element renovation with replacement concept. Façade type is three layer rendering or 60 mm concrete outer leaf. Heating energy type for Helsinki is a gas or average district heat (Finland).

Non-renewable raw material consumption				
	Façade, kg/wall-m²/20 year	Insulation, kg/wall-m²/20 year	Heating, Gas/district Finland, kg/wall-m²/ 20 year	Total, Gas/district Finland, kg/wall-m² /20 year
Existing, Helsinki			88 / 103	88 / 103
Case 1 (rock wool + 3-layer rendering)	61	21	34 / 40	116 / 122
Case 2 (rock wool + 60 mm outer concrete leaf)	147	21	34 / 40	202 / 208

5.5.3 Life cycle costs

The economics of the old outer layer being removed and a new layer with additional insulation installed has been calculated in the case of a concrete sandwich. The results show that additional insulation is in all cases life cycle economical.

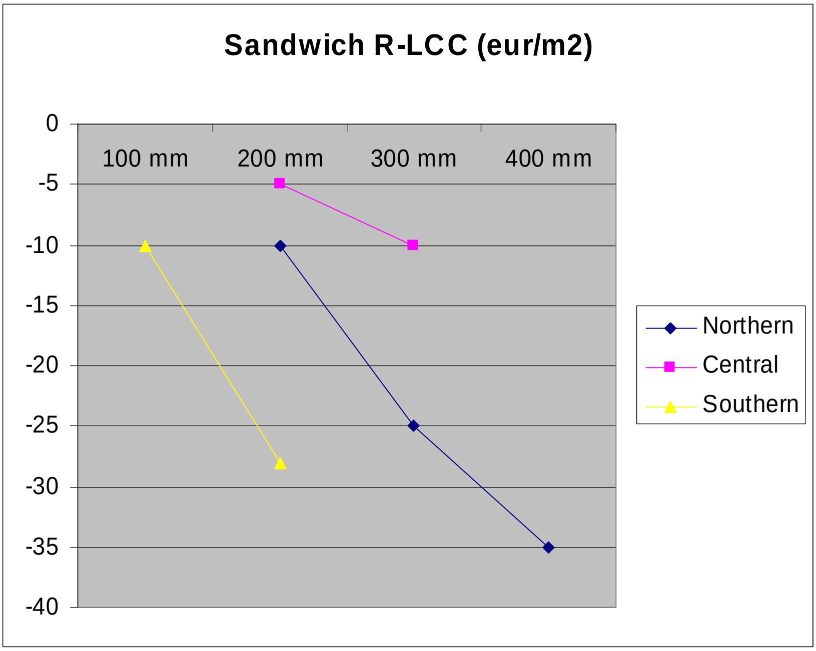


Figure 131. Life cycle Costs of additional insulation in new layer by weather zone and insulation thickness.

Table 98. Energy demand for heating and cooling.

Q_R [kWh/m^2]

Month	Paris	Lyon	Bilbao	Barcelona	Almeria	Catania
1.00	0.00	0.00	0.00	0.00	0.00	0.00
2.00	0.00	0.00	0.00	0.00	0.00	0.00
3.00	0.00	0.00	0.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00	0.00	0.00	0.00
5.00	0.00	0.00	0.00	0.00	0.01	0.00
6.00	0.00	0.03	0.00	0.04	0.09	0.16
7.00	0.07	0.13	0.05	0.30	0.51	0.80
8.00	0.06	0.11	0.05	0.22	0.68	0.79
9.00	0.00	0.00	0.03	0.05	0.27	0.17
10.00	0.00	0.00	0.00	0.00	0.01	0.01
11.00	0.00	0.00	0.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00	0.00	0.00	0.00
Whole year	0.13	0.27	0.14	0.60	1.58	1.92

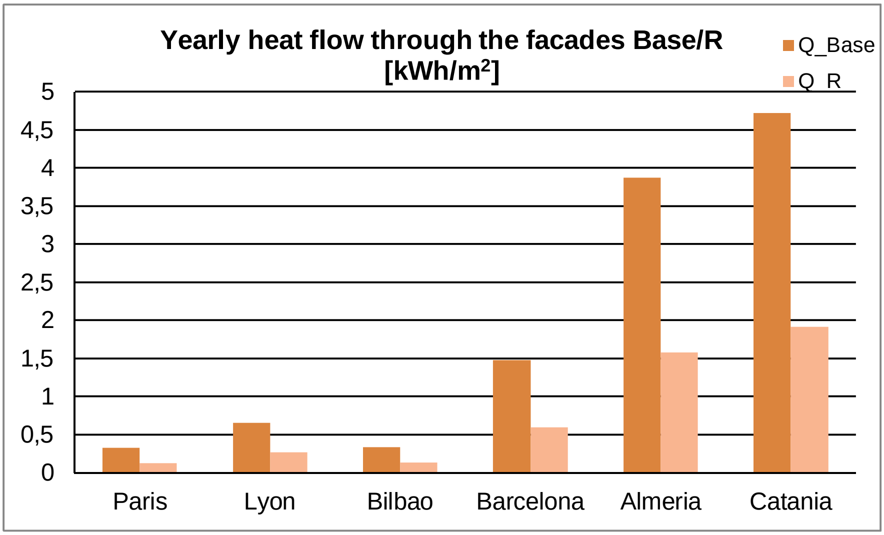


Figure 132. Yearly heat flow through the facades Base/R [kWh/m^2].

5.5.4 Impact on daylight

No impact.

5.5.5 Structural stability

<u>Structural performance of the wall and the building (load bearing capacity)</u>

The structural performance of the different types of walls (W1–W6) will normally remain unchanged for this type of replacement insulation system. This is the only type of insulation that may affect the structural stability since it entails removing part of the building and replacing it with different material.

<u>Mounting of fastening points in the existing wall</u>

The possibilities for sufficient anchor to the wall must be assessed closely. The load bearing capacity of the brick wall W4 and W6 might need fastening in the more durable underlying wall (see also restriction under buildability).

<u>Changes in water drainage, changes in humidity and danger of frost heave</u>

Replacement insulation will have no effect.

Sensitivity for seismic loads

Replacement insulation are normally not sensitive for seismic loads, but the wall system itself may be more or less sensitive (see descriptions of the wall systems).

Table 99. Rating of R vs. wall type W1-W6 for structural stability.

Concept / Parameter	R + W1[4)]	R + W2[2)]	R + W3	R + W4[4)]	R + W5[3)]	R + W6[4)]	Note
Structural performance of the wall and the building (load bearing capacity)	0 (-1)	0 (-1)	0 (-1)	0 (-1)	0 (-1)	0 (-1)	The structural stability will normally remain unchanged. Temporary Removal of one part of the wall may affect the structural stability.
Mounting of fastening points in the existing wall	0	0	0	0	0	0	Normally no need for anchor to the wall
Changes in water drainage, changes in humidity and danger of frost heave	0	0	0	0	0	0	Normally of low importance
Sensitivity for seismic loads	0	0	0	0	0	0	No sensitivity

2) Conditional suitable according to main table (total judgement), see appendix 8

3) Unsuitable according to main table (total judgement), see appendix 8

4) Not possible according to main table (total judgement), see appendix 8.

5.5.6 Buildability

Current condition of the existing wall

The condition of the wall and the suitability prior to refurbishment must be assessed.

Any kind of lead-in wires or penetrations must be planned carefully and can only be implemented where no cold drafts can occur. No holes must be made in the vapour barrier.

Constructional feasibility

The flexibility of EPS and XPS is lower than for mineral wool due to the feasibility to irregularities of the surface of the existing wall. The flexibility of vacuum panels are low since they cannot be cut to fit in any direction. It is not possible to change insulation in sandwich elements. To change insulation in wall type 5 and 7 requires that you tear down one leaf of the wall. Wall type 1 is a solid stone/brick wall. There is no possibility for replacements.

Access to the building site

Internal insulation system requires no scaffolding.

Domestic factors

Normally not relevant for internal insulation system.

Climate zones

Dependency of weather conditions and climate zones is not relevant for this insulation system.

Table 100. Rating of R vs. wall type W1-W6 for buildability.

Concept / Parameter	R + W1 5)	R + W2 3)	R + W3	R + W4 5)	R + W5 4)	R + W6 5)	Note
Current condition of the existing wall	0	0	0	0	0	0	No influence
Constructional feasibility	-2	-2	+1	-2	-2	-2	Replacement possible for wood structure (W3), but not for sandwich element (W2) and not for W5 that require to tear down one leaf of cavity walls.
Access to the building site	0	0	0	0	0	0	Assessment of need for scaffolding etc.
Domestic factors	0	0	0	0	0	0	Assessment of factors that may restrict the refurbishment alternative.
Climate zones 2) Cfb Cfbw Csa Dfb Dfc	 0 0 0 0 0	 0 0 0 0 0	 0 0 0 0 0	 0 0 0 0 0	 0 0 0 0 0	 0 0 0 0 0	Rating according to different climate zones. May be a problem with vapor barrier with high quality insulation materials.

3) Conditional suitable according to main table (total judgement), see appendix 8

4) Unsuitable according to main table (total judgement), see appendix 8

5) Not possible according to main table (total judgement), see appendix 8.

5.5.7 Need for care and maintenance

No data available.

5.5.8 Indoor air quality and acoustics

5.5.8.1 Thermal climate

The effect on thermal climate will generally be as with external insulation with or without air-gap, depending on the resulting construction.

As the renovation is normally thorough, it may be possible to improve airtightness significantly.

Table 101. Effect of replacement insulation on thermal climate.

Concept / Parameter	R	Note
Air leakage	0 thr 2	Possible to improve
Temperature assymetry	-1 thr 2	Normally asymmetry improves, but not in cases where some external walls are opaque and other consists mostly of windows.
Internal surface temperatures	1 thr 2	Insulation reduces extreme temperatures, as internal and external temperatures are more decoupled than originally.
Internal Humidity (buffering)	0	Buffering normally unchanged, but influx may be reduced. Significant in some compact walls in wet climates.

5.5.8.2 Air quality

One likely motivation for performing replacement insulation is the need to remove infected or high-emitting (e.g. creosote impregnated wood) from the construction. This may improve indoor air quality considerably. As the internal surface is normally left intact, it is unlikely that significant new pollution sources are introduced, as long as the refurbished solution is moisture safe.

As infiltration rates may decrease significantly, the air quality may deteriorate if ventilation is not improved.

Where also the internal part of the wall is replaced, considerations as explained under internal insulation apply.

Table 102. Effect of replacement insulation on air quality.

Parameter \ Concept	R	Note
Existing pollution sources	0 thr 2	Infected or high-emitting can (and should) be replaced
New pollution sources	-1 thr 0	If interior surface is replaced, low emitting materials should be used.
Ventilation efficiency	-2 thr 0	Reduced infiltration through walls reduces ventilation if no countermeasures applied. Consider balanced ventilation or additional vents.

5.5.8.3 Acoustics

The replacement refurbishment would normally imply that also windows, doors and penetrations will be exchanged or remediated, giving better possibilities to improve noise reduction. The actual effect depends highly on the refurbished wall and the component (e.g. window) quality.

Table 103. Effect of replacement insulation on acoustics.

Parameter \ Concept	R	Note
Noise from outside	-1 thr 2	A significant improvement is possible, but decreased sound insulation is also possible depending on the chosen solution
Internal acoustics	1 thr 1	Affected if heavyweight walls are changed to lightweight walls
Internal sound transmission	-2 thr 1	An improvement is possible, but increased internal sound transmission is also possible if construction at inside side is changed

5.5.9 Disturbance

Replacement insulation is normally extensive with major disturbance to inhabitants, neighbours and site. If only exterior cladding is removed, the disturbance will be more like for external insulation.

Table 104. Disturbanse assessment (R).

Concept / Parameter		Note
Effect on inhabitability	-2- -1	Normally the buildings are not suitable for use for longer periods.
Effect on neighbours and site	-2- -1	Removal of existing affects surrounding space, and generates noise and dust.

5.5.10 Aesthetic quality and effect on cultural heritage

Replacement of the refurbished fabric is not that complicated in the buildings outside conservation areas and those which are not listed. However, by replacing the fabric with something significantly different to existing finishes or character of the neighbourhood, buildings might lose the historic interest and appearance of that building. If the building is listed and of historic interest then the prior advice should be taken from the local planning authority or relevant body.

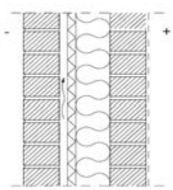
Replacement of historic fabric with alternative materials may adversely affect the appearance and authenticity of the building, and reduce its value as a source of historical information. For example the replacement of the internal insulation on the exposed pointed stone wall with external insulation, which change the appearance and authenticity of the building. Another example, the replacement of original timber sash and case windows with modern PVC frames. This causes a serious loss of authenticity, even when the replacement windows attempt to duplicate the appearance of the original. Possibly a good repair of the original window could have prolong its life for many years. Minimum interference should be done to the fabric. That means the historic fabric or refurbishment is replaced only where there has been a loss of function. Any changes and interference should appreciate the existing fabric and involve the least possible loss of that which is culturally significant.

5.5.11 Impact on renewable energy use potential

No impact.

5.5.12 Fire Safety

Table 105. Fire safety assessment.

Replacing renovation (R) – Old outer layer removed and new layer with additional insulation installed – effect on Fire Safety				
WALL TYPE	BUILDING TYPE	Type of external structure/layer	Type of insulation	Score
W2_Sandwich element; concrete panel + concrete panel	C	Concrete, brick or similar	Non-combustible	0
			Combustible	-1
		Thin non-combustible	Non-combustible	0
			Combustible	-1
		Combustible	Non-combustible	-1
			Combustible	-2
W3_Load bearing wood structure; Wooden frame	A	Concrete, brick or similar	Non-combustible	2
			Combustible	1
		Thin non-combustible	Non-combustible	1
			Combustible	0
		Combustible	Non-combustible	0
			Combustible	-2
	A	Brick, natural stone or similar	Non-combustible	0
			Combustible	0…-1
		Thin non-combustible	Non-combustible	0
			Combustible	0…-1
		Combustible	Non-combustible	-1
			Combustible	-2

6 Summary table

The following table is a summary table including selected aspects for the different refurbishment technologies.

	E1	E2	I	C	R
Structural Stability					
Structural performance of the wall and the building (load bearing capacity)	0	0	-1 thr 0	0	-1 thr 0
Mounting of fastening points in the existing wall	0 thr 2	-1 thr 2	1 thr 2	0	0
Changes in water drainage, changes in humidity and danger of frost heave	2	2	-2 thr 0	0	0
Sensitivity for seismic loads	0 thr 1	0 thr 1	0	0	0
Buildability					
Current condition of the existing wall	-2 thr 0	-1 thr 0	-2 thr 0	-2 thr 0	0
Constructional feasibility	-2 thr 1	-1 thr 1	-2 thr 1	-2 thr 2	-2 thr 1
Access to the building site	-1	-1	0	-1	0
Domestic factors	-2 thr 2	-2 thr 2	0	0	0
Climate zones Cfb Cfbw Csa Dfb Dfc	 1 -2 2 0 -1	 2 2 2 2 2	 0 -1 thr 0 -1 thr 0 0 -2 thr 0	 0 -1 thr 0 -1 thr 0 0 -2 thr 0	 0 0 0 0 0
Thermal climate					
Air leakage	0 thr 2	0 thr 2	0 thr 2	0 thr 1	0 thr 2
Temperature assymetry	-1 thr 2	-1 thr 2	-1 thr 2	-1 thr 2	-1 thr 2
Internal surface temperatures	1 thr 2	1 thr 2	0 thr 2	1 thr 2	1 thr 2
Internal Humidity (buffering)	0	0	-1 thr 1	0	0
Air quality					

Existing pollution sources	0 thr 2	0 thr 2	0 thr 2	0	0 thr 2
New pollution sources	-1 thr 2	0	-2 thr 0	0 thr 1	-1 thr 0
Ventilation efficiency	1 thr 2	-2 thr 0	-1 thr 0	-1 thr 0	-2 thr 0
Influx of water	0	0 thr 2	-2 thr 0	-2 thr 0	xxx
Acoustics					
Noise from outside	0 thr +1	0 thr 2	0 thr 1	0 thr1	-1 thr 2
Internal sound transmission	0	x	x	x	-1 thr 1
Internal acoustics	0	0	-1 thr 1	0	-2 thr 1
Fire					
Brick, natural stone or similar/Concrete or similar	0	-1 thr 0	x	x	-1 thr 2
Non-combustible	-1 thr 0	-2 thr 0	-1 thr 2	0 thr 1	-1 thr 1
Combustible	-1 thr -2	-2 thr 1	-2 thr 0	0 thr 1	-2 thr 0
Distrurbance					
Effect on inhabitability	-1 thr 0	-1 thr 0	-2 thr -1	0 thr 1	-2 thr -1
Effect on neighbours and site	-1 thr 0	-1 thr 0	0 thr 1	0 thr 1	-2 thr -1

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Appendix A: Aesthetic quality and cultural heritage

1 Aesthetic quality

Many buildings and groups of buildings are valued as much for their aesthetics as for their functional characteristics. Aesthetics distinguish one building from another, often controversially, and establish the character of buildings, towns and cities. Unlike many of the criteria discussed elsewhere in this report, aesthetic quality is notoriously difficult to measure or reach a consensus view on, which often means these qualities are neglected and absent from legislation and guidance. Aesthetic quality is more of a judgement than a calculation, which makes it difficult to define parameters let alone limiting values.

In most conversations about architecture, the term “aesthetics” is reserved for matters relating to the visual appearance of a building. However, it refers to more than this; it means the appreciation of beauty or the pleasure given from beauty. This is a much wider definition than is normally adopted. The beauty in older buildings is often obvious in their appearance, but for some beauty can be perceived in the acoustics, the thermal conditions, tactile experience of elements and components, the construction materials and how they are assembled, and even the smell of a building. Assessing refurbishment options for their aesthetic qualities, therefore, is a complex affair.

1.1 Dimensions for assessing aesthetic quality

The assessment of aesthetics is often described as being “purely subjective” with the implication that there can be no agreed criteria against which different designs or solutions can be assessed. However, this view is misleading. It is true that for any given building it will be possible to find detractors and admirers and the arguments of both will often be couched in terms that seem opaque to those not familiar with this type of debate. But, for a large number of cases, it is possible to achieve some level of consensus about the aesthetic merits of a piece of architecture. Judgments about architecture, rather than being “purely subjective”, are usually “intersubjective”: there is agreement within a social or cultural group. These groups often hold very similar views about the beauty of a building or city, but may be wildly divergent from those of other groups. This makes a quantitative treatment of aesthetic quality difficult.

Despite this intrinsic difficulty, we can still identify aspects of aesthetics that groups will have a view on. These are: visual appearance, tactile properties, and acoustic properties. Each of these is discussed below. It should be remembered, however, that these are not experienced as discreet sensations in everyday life. They overlap such that properties assigned to one category are often manifest in others. For example, things that are shiny in appearance are often hard to the touch. The converse is also true and can be manipulated by designers—things that look hard to the touch may be soft, etc. In short, for ease of discussion we tend to distinguish between these properties but in reality we should consider them within the totality of our experience. This is another feature of experience that makes it difficult to assess aesthetic qualities.

1.2 Visual appearance

As noted previously, visual appearance is the most commonly associated interpretation for the term “aesthetics”. The following properties have a direct bearing on visual appearance:

Form. Strictly speaking, form deserves separate treatment because it defines more than an object’s visual appearance. Form—or shape, or geometry—determines not just visual appearance. It represents a set of mathematical relations that have an aesthetic dimension of their own.

Colour. The way in which colour has been used in specific locations is often linked to the history of the particular place. Many pigments refer to locations, such as Burnt Sienna, because they are derived from local materials. Welsh slates are often called “Bangor blues”, for example. Thus particular areas will have an indigenous palette of materials and colours. Introducing new materials (and colours) will extend the palette available to designers, which can be good or bad.

There is a large body of research about the perception of colour and the use of colour in architecture. The results are inconclusive except to agree that colour is an important property of architecture and has a major influence on how it is perceived not just by architects and other built environment professionals, but by the general public.

Light reflectance. In addition to colour, materials are often described according to their light reflecting properties, as having gloss or matte finishes. The type of finish has implications not just for aesthetics but on the light and thermal properties, most obvious in the extreme case of mirrored finishes seen in glass and ceramics.

Texture. The beauty of an object or place often depends on the texture of the materials. As with colour, the character of places is often a reflection of the properties of local materials. Regions gain character and distinctiveness through

1.3 Tactile properties of materiality

Tactile experience is often overlooked in discussions about aesthetics, but it is not difficult to identify architecture that is known for its tactility as much as for its appearance.

The Finnish architectural theorist, Juhani Pallasmaa, in The Eyes of the Skin, emphasises that hands not only sense materials through touch, but that they are also organs for thought, which eventually develop the feelings, moods and wishes in us (1996). He further notes that the skin of the hand reads the texture, weight, density and temperature of the material. It connects us with time and tradition through impressions of touch. Pallasmaa's book has become a standard text for students of architecture and emphasises the contribution touch makes to the total experience of buildings and the environment.

The importance of tactile experience has been highlighted generally in philosophy and in phenomenology in particular. Architects have adopted the work of philosopher Maurice Merleau-Ponty as a key supporter of the tactile approach to design based on his comprehensive phenomenological account of everyday life offered in Phenomenology of Perception (1962).

Texture. In addition to its visual appearance, texture is an important aspect of tactile experience. Indeed, the tactile properties of a given texture are often more directly perceived through touch than visually.

Hardness. A different aspect of tactile experience is the degree to which a surface yields to pressure from the human hand, for example. The hardness or softness of a surface material can also be manifest in the visual appearance thereby colouring the perception of an element or environment. Though this may feature in architectural debate about the aesthetics of a building, it is unlikely to have a major impact.

1.4 Acoustic properties

Buildings have acoustic properties that are often central to the aesthetic experience they offer their occupants. For some this is more important than others. Obviously, concert halls, recording studios, swimming pools and other spaces serving specialised purposes have specific functional requirements that are crucial to their success as a building, but for others, such as churches, changes to the acoustic environment alter the "beauty" of the space. "Every building or space has its characteristics sound of intimacy or monumentality, invitation or rejection, hospitality or hostility. A space is understood and appreciated through its echo as much as through its visual shape, but the acoustic percept usually remains as an unconscious background experience" (Pallasmaa, 1996). This can occur mainly through changes to the following properties.

1.4.1 Reverberation time

This is the most widely discussed acoustic property of a space, when considering the experience of those in the space. The reverberation time is a measure of how long a sound will take to decay in a given space. It varies according to the frequency of the sound and is the result of the absorption and reflective properties of the enclosing surfaces. The most extreme examples are church interiors which tend to have long reverberation times that enhance performance of particular types of music but are less kind to speech, which may be unintelligible in the worst cases.

Refurbishment is likely to have a significant impact on reverberation times if it alters the internal surfaces of a space. Replacing hard, reflective surfaces with more absorbent materials (fabrics) and constructions (such as plasterboard mounted on timber battens). This is only likely to create problems in spaces where the reverberation time is critical, such as for the intelligbility of speech, but from an aesthetic point of view it may alter the character of the space. This suggests that reverberation time may be an important variable to calculate before proceeding with a particular refurbishment option if the acoustics are an intrinsic part of the space's character.

1.4.2 Sound distribution

Changes to the fabric of a building can alter the distribution of sound. In extreme cases, the form of a wall or similar structure can focus sounds in such a way that they can be heard more intensely at some points in the space rather than others. This is most obvious in the case of curved surfaces which, deliberately or otherwise, can create concentrations of sound at a given point in a space.

1.5 Thermal properties

Another overlooked aspect of experience is the thermal environment. Discussions about thermal experience are usually limited to considerations of thermal comfort criteria. But as Lisa Heschong (1980) established some years ago, thermal conditions carry an aesthetic component. There is an obvious thermal delight in entering a cool, shaded courtyard with a fountain on a hot sunny day in an arid climate. Although most cases are less extreme than this, changes to buildings, both internally and externally, can have tangible effects on the thermal environment and the occupants' experience of it. It is perhaps less of an issue as far as walls are concerned, but could be important if a proposed refurbishment were to alter temperature distribution across the surfaces in a space. As with many of these criteria, there are no readily available measures, other than those normally used to assess thermal comfort. In this case, the thermal environment is typically judged according to the split between mean radiant temperature (the weighted average of surface temperatures) and the air temperature. Comfort conditions favour a small gap between these two variables and, preferably, a slightly higher mean radiant temperature. However, radiant heat delivered from ceilings is generally considered to be less conducive to achieving thermal comfort, as is asymmetric delivery of heat through warmed surfaces.

Heat exchange also takes place through direct contact when people touch elements of a building. This aspect of the environment can be significant, but usually only when there is a large temperature difference between the person and the surface of the element.

The thermal environment also includes the hygrothermal conditions. Moisture and humidity are frequently evident in building interiors and other research within the SUSREF project suggests that refurbishment can result in a redistribution of moisture that will lead to a change in the indoor climate.

1.6 Aesthetic quality at a larger scale

At a larger scale, groups of buildings contribute to the aesthetics of entire areas, towns and cities.

The previous criteria apply at any scale. Visual appearance criteria can be used to assess building construction details just as easily as whole buildings, and even configurations of buildings. There are, however, some criteria that are emergent and so only become relevant to discussions about groups of buildings in various configurations. There is no doubt that refurbishment can alter the aesthetics of an entire street as well as individual buildings. Perhaps more importantly, there are significant aesthetic issues if only some buildings in a group are refurbished while others are left alone. Figure 133 shows an extreme example of the external refurbishment of a single apartment in a block.

Figure 133: home alone – one apartment externally insulated and rendered. (Photo credit: Andres Järvan).

1.7 Assessing Refurbishment concepts along the parameters impacting aesthetic quality

The assessment of refurbished constructions for their impact on aesthetic quality is very similar to assessing their impact on cultural heritage. These are discussed below.

2 Effect on cultural heritage

The built environment represents an important part of human culture. It reflects the artistic, technological and spiritual achievements and values of cultures that persist and evolve politically, socially and economically. Buildings also reflect the effects of climate and locality in the materials that have been used and how they have weathered over time. In many cases (and places), they are recognised as embodiments of our core values and meanings and as such are essential to defining who we are. Not surprisingly, proposals that seek to change the character of the built environment often meet resistance from citizens who have a keen interest in the character of their environments. This is most vigorous when there are plans to demolish, replace or extend existing buildings, but can be equally vocal against plans to alter existing buildings even in seemingly minor ways. The purpose of this section is to consider how refurbishment proposals for external walls might be assessed for the possible impact on built cultural heritage.

2.1 Assessment criteria and background

The criteria relevant to assessing the impact of refurbishment on cultural heritage and aesthetic quality are:

- Value as an historical architectural work
- Value for its construction engineering
- Value as cultural heritage
- Value to the settlement history, neighbourhood and environment

1. Value as an historical architectural work

The invisible attributes of architecture and places are often as important as the visible. Knowing that an artefact or place has a history and knowing something of that history alters the way in which it is perceived. There have been heated debates in cultural heritage about the importance of authenticity. Interpretations of authenticity also vary with culture. In the Far East, for example, a timber structure such as a temple of shrine may be regarded as thousands of years old because there has been a building on the site for that period of time. The actual building may only be two hundred years old. The fact that the present building is not the same building as the original seems to have little impact on the authenticity of the relic. Conservationists, and particularly preservationists, in the West are less flexible in their allowing authenticity, which is applied as an honorific term of approval.

There is justifiable reason for this as the physical form, scale and layout of the building embodies the architectural history of the building and the way it was built reflects societal and cultural values and knowledge of that period. Many interesting facts about our past can be determined from, for example, the contents of thick stone walls.

2. Value for its construction engineering

All traditional/historic buildings can contribute to present quality of life by reminding us of our past and adding visual interest to the environment. Traditional buildings are of historic interest because they reflect the lives and achievements of our predecessors. Traditional buildings are usually constructed from locally sourced materials that are rarely used in the majority of buildings constructed today. Also, traditional construction puts a value on all historic buildings in terms of cultural heritage and as an irreplaceable resource. With sensitive alterations and repairs, the resource continues to be useful and fulfils a new role as a cultural object. An important value of such buildings is how they represent the abilities of the crafts people of a particular time and the knowledge and skills they possessed. The engineering of traditional buildings is often a function of the available tools and technologies too. Thus, they tell us more about those times than about the building alone.

3. Value as cultural heritage

Historic/traditional buildings differ greatly in how much they can be changed without losing their specific interest. Some buildings are sensitive to the slightest alteration, especially when done externally. Others may have changed drastically several times during their life and can adapt changes quite comfortably.

Before deciding refurbishment measure for any building, it is important to identify to what extent the building is sensitive to alteration. What are the important elements that are significant to that building in term of the special character and the interest of the building? Sufficient survey, investigation and studies of the physical, documentary and on the cultural value should be done in advance of design work to ensure that the building is well understood before proposing any alteration work.

It is important to identify the characteristics that significant at local, regional and national scale. Some features may not be important at regional and national level but are very important at a local level. They could be the most valuable elements within a local context and have particular value to local stakeholders.

It may be the local representative of its own period and local cultural heritage. Most existing residential buildings are capable of describing their period by having a special characteristics or features from their era. These help us to understand those periods in greater detail (such as Victorian, Edwardian etc). While proposing refurbishment, it would also be appropriate to include the help from specific interest groups with specialised knowledge of the period to make sure that the sense of place and that period is not lost.

4. Value to settlement history, neighbourhood and environment

The historical settlement, townscape and the environment of the area or town reflects the local identity of that place. The special architectural features of the traditional building or conservation area give a character to the building or the area. To enhance the character and appearance of the building or the settlement either for the aesthetic reason or to meet the changing needs of the occupiers, there should be complete understanding of the importance of a building character and its originality which reflects the history of its settlement.

With the external wall refurbishment the particular focus should be on the selection of the external materials and its density including building lines and corner features which should relate to the neighbouring buildings and should be sympathetic to the local area. Also the landscaping and the external boundary and surface treatment should be included as an integral element of the overall design of the proposal. Proper refurbishment of the external wall will maintain the valuable environmental and cultural unity of the area and will form systematic landscape scenery.

3 Assessing refurbishment concepts along the parameters impacting aesthetic quality and cultural heritage

The following section will explain how those parameters of cultural heritage and aesthetic quality will affect the different types of refurbishment concepts.

3.1 External insulation fixed with air gap/without air gap

Refurbishment on the external side of the wall or change of the original finishes can be proposed either to achieve good thermal performance or to improve the aesthetic quality of the building or to inhibit heat and moisture movement in the wall.

Stripping off finishes, such as plaster from brick, rubble stone or timber-framed wall can have an adverse effect on the building's significance through loss of historic materials and original finishes and detract from its aesthetics. In most cases, it is also damaging to the thermal and moisture performance too. Therefore, when proposing the finish on the wall, appropriate building materials need to be used to ensure an authentic or suitable detailed finish is achieved. Improper external finish or insulation will affect the aesthetic quality of the building within a local context.

Insulating the external wall is often controversial for buildings that are listed or within conservation areas. However, for traditional buildings outside these categories, it is important to recognise that the original structure, details, characteristics and finishes of the building are valuable as cultural heritage, even when they are not immediately visible to the casual observer. The interior of the construction should be retained as far as possible.

3.2 Internal insulation

In some cases the interior details contribute greatly to understanding the building's history more than its exterior fabric. When refurbishing the external wall with internal insulation, the aesthetic quality of the interior should not be sacrificed, provided there is no harmful disruption of the delicate thermal and moisture distribution within the wall. In many traditional buildings, however, the cultural heritage value of a building's internal features are of historic importance and need to be preserved. In such cases, there is seldom an alternative but to avoid changing the interior construction at all. Advances in the development of new insulation materials, particularly in aerogels, are creating new opportunities for more sensitive interventions in building interiors, for example, by reducing the thickness of insulation required around window reveals, thus maintaining access to daylight through the windows. Changes to the interior are seldom satisfactory in traditional buildings, and usually involve compromise between improved thermal energy performance and protecting cultural heritage.

By preserving past alterations as well as original internal features, the social and architectural history of the building can be conserved. The internal structural system and interior details such as iron columns, sill and lintel details, and cornice detail and purlin roofs are examples of features to be preserved rather than removed or hidden during renovation. If the building is of historic interest, than the maintenance of the physical and visual presence of internal details should be considered at the earliest opportunity before proposing or suggesting any refurbishment option.

3.3 Replacement of the refurbishment

Replacement of the refurbished fabric is not that complicated in the buildings outside conservation areas and which are not listed. However, by replacing the fabric with something significantly different to existing finishes or character of the neighbourhood, buildings might lose the historic interest and appearance of that building. If the building is listed and of historic interest then the prior advice should be taken from the local planning authority.

Replacement of historic fabric with alternative materials may adversely affect the appearance and authenticity of the building, and reduce its value as a source of historical information. For example the replacement of the internal insulation on the exposed pointed stone wall with external insulation, which change the appearance and authenticity of the building. Another example, the replacement of original timber sash and case windows with modern PVC frames. This causes a serious loss of authenticity, even when the replacement windows attempt to duplicate the appearance of the original. Possibly a good repair of the original window could have prolong its life for many years. Minimum interference should be done to the fabric. That means the historic fabric or refurbishment is replaced only where there has been a loss of function. Any changes and interference should appreciate the existing fabric and involve the least possible loss of that which is culturally significant.

3.4 Cavity insulation

Inserting insulation to the external cavity wall should not affect the cultural heritage or the aesthetic quality of the wall because the insulation is unseen to anyone from inside or outside surface of the wall. However, while inserting the insulation from external side of the wall, care should be taken that the part of the existing wall through which insertion has been done it should not get damaged, as it will deteriorate from the appearance of the building. Through SUSREF, however, we have seen that in some countries cavity insulation is inserted by removing the outer leaf of the wall completely, insulating and then reinstating the outer leaf. This method raises issues that are not so different to those discussed above for external insulation. Once again, the question of constructional authenticity arises. (English Heritage, 2012) (The Heritage of Historic Resources Sub-Objective TAG Unit 3.3.9, 2003)

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Appendix B: Impact on energy demand for cooling

Applied Criteria

Cooling energy demands in residential buildings are common in Southern-European climates, in Greece and in the southern parts of Portugal, Spain and Italy.

Cooling loads in other European locations are uncommon, and mainly created by un-proper building design, excessive solar gains without shading and insufficient ventilation rate.

Cooling loads are highly dependent on thermal inertia of buildings and façade constructions. This dependency is even greater than that of heating performance of buildings. Thus cooling thermal loads should be calculated individually for different building refurbishments.

Although good and adequate calculations should be made on building, a simplified approach is proposed here. The heat gain calculation can be done based on the degree-period method for cooling and the thermal transmittance of the wall, U.

The heating degree-period method for cooling can be calculated in a time base according to the inertia of the building type:

- 4h for light-wheight buildings: timber frame,
- 8h for heavy-wheight buildings: brick walls, concrete slabs,
- 24h for heavy-wheight buildings: Stone buildings.

This degree-period will be then transposed to degree-days. This is done in the following way:

Where:

Text: External temperature [ºC]

t : Instantaneous time [h]

P: Cooling degree calculation time base [h]

CDt: Cooling degrees for instant t [ºC*h]

CDY: yearly cooling degrees [ºC*h]

The U value of a wall is the basic reference value for different walls. This parameter is calculated according to the UNE-EN ISO 6946 Standard. The value is a linear coefficient that relates the heat transfer across the wall and the temperature difference between both sides of it.

The final heat transfer, Q [kWh/m2year], is calculated in the following way:

$$Q = \frac{24}{1000} * CDD * U$$

It has to be noted that only heat flows that cause a heating load increment are calculated as the cooling degree day method is used to assess the thermal state difference (interior-exterior).

Calculation of Cooling Degree Periods

Selection of climates

6 European climates were selected in the present study. As the impact of the refurbishment on cooling loads is mainly relevant in southern-European Countries, the selection focused on those cases. Some extreme climates have been added to evaluate the impact for the southern edges of the European mainland and the Mediterranean sea.

The selected climates are the following:

1. Paris
2. Lyon
3. Bilbao
4. Barcelina

5. Almeria
6. Catania

Figure 1: Geographic location of the selected climates.

Results

For each selected climate the cooling degree method has been applied for the specified three time bases: 4, 8 and 24h.

Yearly cooling degree days for 4, 8 and 24h time-bases in the selected climates.

Whole year Cooling Degree Days

	CDD_4h	CDD_8h	CDD_24h
Paris	14.34	10.36	4.60
Lyon	31.23	20.94	7.92
Bilbao	18.40	10.56	2.21
Barcelona	56.98	46.75	23.89
Almeria	138.80	122.24	90.04
Catania	175.90	149.08	71.04

Monthly and yearly cooling degree days for 4, 8 and 24h time-bases in Paris.

Paris			
Month	CDD_4h	CDD_8h	CDD_24h
1.00	0.00	0.00	0.00
2.00	0.00	0.00	0.00
3.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00
5.00	0.26	0.00	0.00
6.00	0.78	0.23	0.00
7.00	6.40	5.33	2.50
8.00	6.83	4.80	2.09
9.00	0.08	0.00	0.00
10.00	0.00	0.00	0.00
11.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00
Whole year	14.34	10.36	4.60

Monthly and yearly cooling degree days for 4, 8 and 24h time-bases in Lyon.

Lyon			
Month	CDD_4h	CDD_8h	CDD_24h
1.00	0.00	0.00	0.00
2.00	0.00	0.00	0.00
3.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00
5.00	0.01	0.00	0.00
6.00	5.07	2.40	0.00
7.00	14.60	10.30	3.70
8.00	11.10	8.16	4.22
9.00	0.45	0.08	0.00
10.00	0.00	0.00	0.00
11.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00
Whole year	31.23	20.94	7.92

Monthly and yearly cooling degree days for 4, 8 and 24h time-bases in Bilbao.

Bilbao			
Month	CDD_4h	CDD_8h	CDD_24h
1.00	0.00	0.00	0.00
2.00	0.00	0.00	0.00
3.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00
5.00	0.72	0.00	0.00
6.00	1.07	0.29	0.00
7.00	4.84	4.20	1.72
8.00	5.40	3.51	0.45
9.00	4.05	2.43	0.04
10.00	2.32	0.14	0.00
11.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00
Whole year	18.40	10.56	2.21

Monthly and yearly cooling degree days for 4, 8 and 24h time-bases in Barcelona.

Barcelona			
Month	CDD_4h	CDD_8h	CDD_24h
1.00	0.00	0.00	0.00
2.00	0.00	0.00	0.00
3.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00
5.00	0.00	0.00	0.00
6.00	4.03	3.36	1.75
7.00	26.36	23.06	13.51
8.00	21.35	16.83	8.04
9.00	5.24	3.50	0.59
10.00	0.00	0.00	0.00
11.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00
Whole year	56.98	46.75	23.89

Monthly and yearly cooling degree days for 4, 8 and 24h time-bases in Almeria.

Almeria			
Month	CDD_4h	CDD_8h	CDD_24h
1.00	0.00	0.00	0.00
2.00	0.00	0.00	0.00
3.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00
5.00	1.38	0.76	0.00
6.00	8.86	7.09	3.15
7.00	43.48	39.95	29.33
8.00	56.72	52.75	42.85
9.00	26.10	21.06	14.70
10.00	2.27	0.63	0.00
11.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00
Whole year	138.80	122.24	90.04

Monthly and yearly cooling degree days for 4, 8 and 24h time-bases in Catania.

Catania			
Month	CDD_4h	CDD_8h	CDD_24h
1.00	0.00	0.00	0.00
2.00	0.00	0.00	0.00
3.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00
5.00	2.01	0.06	0.00
6.00	19.52	12.18	2.52
7.00	65.84	62.22	31.65
8.00	64.33	61.09	32.84
9.00	20.96	13.12	4.03
10.00	3.24	0.42	0.00
11.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00
Whole year	175.90	149.08	71.04

The results show that, cooling is only relevant in Almeria and Catania while the other 4 climates would not require cooling systems due to their envelope.

Residential buildings in Bilbao, Barcelona, Paris and Lyon would not require specific cooling equipment. An adequate ventilation and blocking of solar gains through windows should be enough to avoid cooling as residential buildings do not usually have high internal loads.

Calculation of façade U-values

A base façade was selected for all climates corresponding to a brick cavity wall.

The following configurations have been evaluated:

- E1: External addition of 5 cm insulation (EPS), with no air-gap.
- E2: External addition of 5 cm insulation (EPS), with 1cm air-gap.
- I: Internal addition of 5 cm insulation (EPS).
- C: Cavity insulation with Polyurethane (Full cavity, 4 cm).
- R: Replacement of external layer with internal insulation (5 cm EPS).

The following results were obtained:

U values of the evaluated façades.

Reference	U
	[W/m2K]
BASE	1.32
E1	0.49
E2	0.49
I	0.49
C	0.46
R	0.54

U value calculation procedure for the base case.

	BASE: Façade 2		
		Thickness [m]	Conductivity [W/mK]
1	Perforated Face brick, 11,5 cm (exterior)	0.115	0.567
2	Cement mortar, 1 cm	0.01	1.3
3	Cavity, 4cm	0.03	0.17
4	Hollow brick, 7 cm	0.07	0.432
5	gypsum plaster, 1,5 cm (interior)	0.015	0.4
6			
	U	1.32	W/m2K

U value calculation procedure for case E1.

	E1: Façade 2, Externally refurbished		
		Thickness [m]	Conductivity [W/mK]
1	EPS	0.05	0.039
2	Perforated Face brick, 11,5 cm (exterior)	0.115	0.567
3	Cement mortar, 1 cm	0.01	1.3
4	Cavity, 4cm	0.03	0.17
5	hollow brick, 7 cm	0.07	0.432
6	gypsum plaster, 1,5 cm (interior)	0.015	0.4
	U	0.49	W/m2K

U value calculation procedure for case E2.

	E2: Façade 2, Externally refurbished		
		Thickness [m]	Conductivity [W/mK]
1	EPS	0.05	0.039
2	Air gap	0.01	
3	Perforated Face brick, 11,5 cm (exterior)	0.115	0.567
4	Cement mortar, 1 cm	0.01	1.3
5	Cavity, 4cm	0.03	0.17
6	hollow brick, 7 cm	0.07	0.432
7	gypsum plaster, 1,5 cm (interior)	0.015	0.4
	U	0.49	W/m2K

U value calculation procedure for case I.

	I: Façade 2, Internally insulated refurbished

		Thickness [m]	Conductivity [W/mK]
1	Perforated Face brick, 11,5 cm exterior)	0.115	0.567
2	Cement mortar, 1 cm	0.01	1.3
3	Cavity, 4cm	0.03	0.17
4	hollow brick, 7 cm	0.07	0.432
5	EPS	0.05	0.039
6	gypsum plaster, 1,5 cm (interior)	0.015	0.4
	U	0.49	W/m2K

U value calculation procedure for case C.

	C: Façade 2, Refurbished by cavity insulation		
		Thickness [m]	Conductivity [W/mK]
1	Perforated Face brick, 11,5 cm (exterior)	0.115	0.567
2	Cement mortar, 1 cm	0.01	1.3
3	PU	0.04	0.025
4	hollow brick, 7 cm	0.07	0.432
5	gypsum plaster, 1,5 cm (interior)	0.015	0.4
	U	0.46	W/m2K

U value calculation procedure for case R.

	R: Façade 2, Refurbished by replacing of external layer		
		Thickness [m]	Conductivity [W/mK]
1	Perforated Face brick, 11,5 cm (exterior)	0.115	0.567
2	Cement mortar, 1 cm	0.01	1.3
3	EPS	0.05	0.039
4	hollow brick, 7 cm	0.07	0.432
5	gypsum plaster, 1,5 cm (interior)	0.015	0.4
	U	0.54	W/m2K

Impact on cooling demand

According to the typical massive buildings in southern-European countries, the most appropriate Cooling degree day time-base selection is 8h. The selected building façade is a brick façade, thus a massive construction, which is usually placed in concrete structured buildings, with massive concrete slabs on them.

Results show that the refurbishment techniques provide a yearly thermal gain reduction of 2 kWh in Almeria and 3kWh in Catania, per square metre of opaque façade.

Tese results are conditioned by the thermal dynamic response of the whole building to external conditions. The provided results could be applied in the case of external refurbishment actions. Internal refurbishment reduces the capacity of the building to absorb peak loads, and thus increases the cooling demand during the central hours of the day. This effect can not be considered at façade level, and has not been considered, but leads to an improper result for this kind of insulation placement.

Calculated yearly heat flow through the façades on the selected climates.

[kWh/m2]	Paris	Lyon	Bilbao	Barcelona	Almeria	Catania
Q_Base	0.33	0.66	0.34	1.48	3.88	4.73
Q_E1	0.12	0.25	0.12	0.55	1.44	1.76
Q_E2	0.12	0.25	0.12	0.55	1.43	1.75
Q_I	0.12	0.25	0.12	0.55	1.44	1.76
Q_C	0.11	0.23	0.12	0.51	1.35	1.64
Q_R	0.13	0.27	0.14	0.60	1.58	1.92

Calculated monthly and yearly heat flow through the base façade on the selected climates.

Q_Base [kWh/m2]

Month	Paris	Lyon	Bilbao	Barcelona	Almeria	Catania
1.00	0.00	0.00	0.00	0.00	0.00	0.00
2.00	0.00	0.00	0.00	0.00	0.00	0.00
3.00	0.00	0.00	0.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00	0.00	0.00	0.00
5.00	0.00	0.00	0.00	0.00	0.02	0.00
6.00	0.01	0.08	0.01	0.11	0.22	0.39
7.00	0.17	0.33	0.13	0.73	1.27	1.97
8.00	0.15	0.26	0.11	0.53	1.67	1.94
9.00	0.00	0.00	0.08	0.11	0.67	0.42
10.00	0.00	0.00	0.00	0.00	0.02	0.01
11.00	0.00	0.00	0.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00	0.00	0.00	0.00
Whole year	0.33	0.66	0.34	1.48	3.88	4.73

Calculated monthly and yearly heat flow through façade E1 on the selected climates.

Q_E1 [kWh/m2]

Month	Paris	Lyon	Bilbao	Barcelona	Almeria	Catania
1.00	0.00	0.00	0.00	0.00	0.00	0.00
2.00	0.00	0.00	0.00	0.00	0.00	0.00
3.00	0.00	0.00	0.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00	0.00	0.00	0.00
5.00	0.00	0.00	0.00	0.00	0.01	0.00
6.00	0.00	0.03	0.00	0.04	0.08	0.14
7.00	0.06	0.12	0.05	0.27	0.47	0.73
8.00	0.06	0.10	0.04	0.20	0.62	0.72
9.00	0.00	0.00	0.03	0.04	0.25	0.15
10.00	0.00	0.00	0.00	0.00	0.01	0.00
11.00	0.00	0.00	0.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00	0.00	0.00	0.00
Whole year	0.12	0.25	0.12	0.55	1.44	1.76

Calculated monthly and yearly heat flow through façade E2 on the selected climates.

Q_E2	[kWh/m2]					
Month	Paris	Lyon	Bilbao	Barcelona	Almeria	Catania
1.00	0.00	0.00	0.00	0.00	0.00	0.00
2.00	0.00	0.00	0.00	0.00	0.00	0.00
3.00	0.00	0.00	0.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00	0.00	0.00	0.00
5.00	0.00	0.00	0.00	0.00	0.01	0.00
6.00	0.00	0.03	0.00	0.04	0.08	0.14
7.00	0.06	0.12	0.05	0.27	0.47	0.73
8.00	0.06	0.10	0.04	0.20	0.62	0.72
9.00	0.00	0.00	0.03	0.04	0.25	0.15
10.00	0.00	0.00	0.00	0.00	0.01	0.00
11.00	0.00	0.00	0.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00	0.00	0.00	0.00
Whole year	0.12	0.25	0.12	0.55	1.43	1.75

Calculated monthly and yearly heat flow through façade I on the selected climates.

Q_I	[kWh/m2]					
Month	Paris	Lyon	Bilbao	Barcelona	Almeria	Catania
1.00	0.00	0.00	0.00	0.00	0.00	0.00
2.00	0.00	0.00	0.00	0.00	0.00	0.00
3.00	0.00	0.00	0.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00	0.00	0.00	0.00
5.00	0.00	0.00	0.00	0.00	0.01	0.00
6.00	0.00	0.03	0.00	0.04	0.08	0.14
7.00	0.06	0.12	0.05	0.27	0.47	0.73
8.00	0.06	0.10	0.04	0.20	0.62	0.72
9.00	0.00	0.00	0.03	0.04	0.25	0.15
10.00	0.00	0.00	0.00	0.00	0.01	0.00
11.00	0.00	0.00	0.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00	0.00	0.00	0.00
Whole year	0.12	0.25	0.12	0.55	1.44	1.76

Calculated monthly and yearly heat flow through façade C on the selected climates.

Q_C	[kWh/m2]					
Month	Paris	Lyon	Bilbao	Barcelona	Almeria	Catania
1.00	0.00	0.00	0.00	0.00	0.00	0.00
2.00	0.00	0.00	0.00	0.00	0.00	0.00
3.00	0.00	0.00	0.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00	0.00	0.00	0.00
5.00	0.00	0.00	0.00	0.00	0.01	0.00
6.00	0.00	0.03	0.00	0.04	0.08	0.13
7.00	0.06	0.11	0.05	0.25	0.44	0.68
8.00	0.05	0.09	0.04	0.19	0.58	0.67
9.00	0.00	0.00	0.03	0.04	0.23	0.14
10.00	0.00	0.00	0.00	0.00	0.01	0.00
11.00	0.00	0.00	0.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00	0.00	0.00	0.00
Whole year	0.11	0.23	0.12	0.51	1.35	1.64

Calculated monthly and yearly heat flow through façade R on the selected climates.

Q_R	[kWh/m2]					
Month	Paris	Lyon	Bilbao	Barcelona	Almeria	Catania
1.00	0.00	0.00	0.00	0.00	0.00	0.00
2.00	0.00	0.00	0.00	0.00	0.00	0.00
3.00	0.00	0.00	0.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00	0.00	0.00	0.00
5.00	0.00	0.00	0.00	0.00	0.01	0.00
6.00	0.00	0.03	0.00	0.04	0.09	0.16
7.00	0.07	0.13	0.05	0.30	0.51	0.80
8.00	0.06	0.11	0.05	0.22	0.68	0.79
9.00	0.00	0.00	0.03	0.05	0.27	0.17
10.00	0.00	0.00	0.00	0.00	0.01	0.01
11.00	0.00	0.00	0.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00	0.00	0.00	0.00
Whole year	0.13	0.27	0.14	0.60	1.58	1.92

Conclusions

The selected calculation method shows that façade insulation reduces the heat gain during cooling periods, up to a 75%. For hot Mediterranean climates such reductions can be directly converted into cooling load reductions.

Nevertheless, this method does not take into account that walls also increase the thermal capacity of the building, and thus, internal insulation can lead to a reduction of the effective thermal capacity of the building.

Care should be taken in this case, as this can result into higher peak cooling loads in Mediterranean climates. These cases can only be properly addressed by direct dynamic modelling and simulation of the whole building.

Appendix C: Impact on energy demand for heating

Introduction

SUSREF project considers different refurbishment techniques for extra insulation of facades. The extra insulation can be installed on the exterior surface or on the inside surface or in some cases in the cavity of the external and internal walls.

The placement of the insulation has different influence on the heating energy use even if the thermal conductance (U-value) of the walls were the same. This results from fact that the extra insulation changes the active thermal inertia and capacity of the wall. The thermal capacity of the wall determines the property of the wall to store heat. In general, internal insulation decreases the active thermal capacity in regard to varying internal heat loads like heat from home equipment, heat from people and solar heat load that comes to the room trough windows. This decreased heat storage capacity reduce the utilization of internal heat loads in heating especially during spring and autumn when the heat loads are big compared to the heat demand. Whereas, cavity and external insulation doesn't change the thermal inertia of the wall and the effects on the heating energy consumption are smaller. The effect of the placement of the thermal insulation on the heating demand can only be studied with dynamic simulation but it is possible to estimate roughly the effect of the insulation on the heating demand with simple stationary calculation technique like we have done here using the heating degree day method (HDD).

The heating degree day method gives in most cases rather reliable and easy way to estimate in theory the effects of extra insulation on the heating demand. And because the HDD method can't make difference in heating demand between the placements of the insulation in regard to the changes in thermal capacity, the refurbishment cases (external, cavity and internal) are treated as one and the same case. The Influence of the possible thermal bridges can be included in the HDD method by taking them into account in the U-value and differences between insulated areas can be treated as well by the surface area.

Parameters of extra insulation that effect on the heating energy demand of a building are:

- Insulation thickness and heat conductivity of the insulation material
- Placement of the insulation
    - internal
    - external
    - in between
- Cold bridges
- Assembling
- Effect on air tightness of the envelope
- Effect on heat gains (solar heat, internal loads)

Heating degree day analysis on the heating energy demand

A simple way to estimate the impacts of extra insulation of the walls on the heating energy demand is to use the heating degree day calculation method. Heating degree day reflects the heating energy demand for heating a building. The heating requirements for a given structure at a specific location are considered to be directly proportional to the number of heating degree days at that location. The heating degree day is defined as the number of degrees that a day's average temperature is below chosen base temperature. The base temperature is certain outdoor air temperature below which the building needs to be heated. The base temperature is actually specific for each building depending on the heat losses (walls, roof, floor, windows, air change) and the heat loads (solar, people, devices). Heating degree days are often available with base temperature of 18 °C which is also used in this presentation. The HDD data source for different locations is the Energy Plus weather data files (http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data2.cfm/).

Heating degree day calculation does not take into account the effect of the extra insulation on the utilization of internal heat loads in the heating. There are two physical phenomena that are ignored; namely the change in the relation of heat losses versus internal heat loads and the change in the thermal inertia of the renovated structures. For these reasons it is recommended in careful analysis to use calculation methods or software that can handle these physical aspects.

The heat loss of a wall is directly dependent on the heating degree days and the U-value of the wall, equation 1.

$$Q = \frac{HDD \cdot A \cdot U \cdot 24}{1000} \quad (1)$$

where

Q	is heat loss of wall, kWh
HDD	is heating degree days, -
A	is surface area of the wall, m^2
U	is the thermal conductivity of the wall construction, W/m^2K
24	is hours of the day, h
1000	is conversion factor, Wh -> kWh

Heating degree days for analyzed locations are presented in the following.

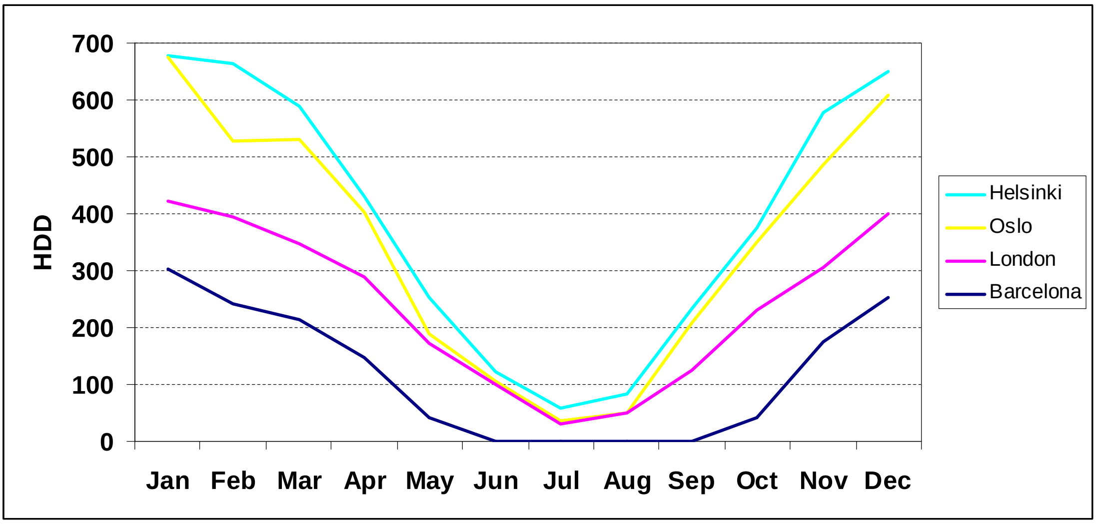

Figure 1. Monthly heating degree days (HDD) of different locations. Heating degree days are calculated using the base temperature of 18 °C.

Table. 1 Yearly heating degree days for different locations Heating degree days are calculated using the base temperature of 18 °C.

	HDD			
	Barcelona	London	Oslo	Helsinki
January	304	422	676	678
February	242	394	528	663
March	213	346	530	589
April	147	290	402	430
May	43	172	189	252
June	1	101	105	123
July	0	31	37	57
August	0	50	51	83
September	0	125	209	233
October	41	231	350	376
November	176	306	487	578
December	252	400	608	650
Year	1419	2868	4172	4712

The bigger the HDD is the higher is also the heat loss for same structure. In Oslo and Helsinki the HDD is three times higher than in Barcelona and in London two times higher.

Specific heat losses (Q/A, $kWh/wall\text{-}m^2$) for analyzed locations are presented in the following.

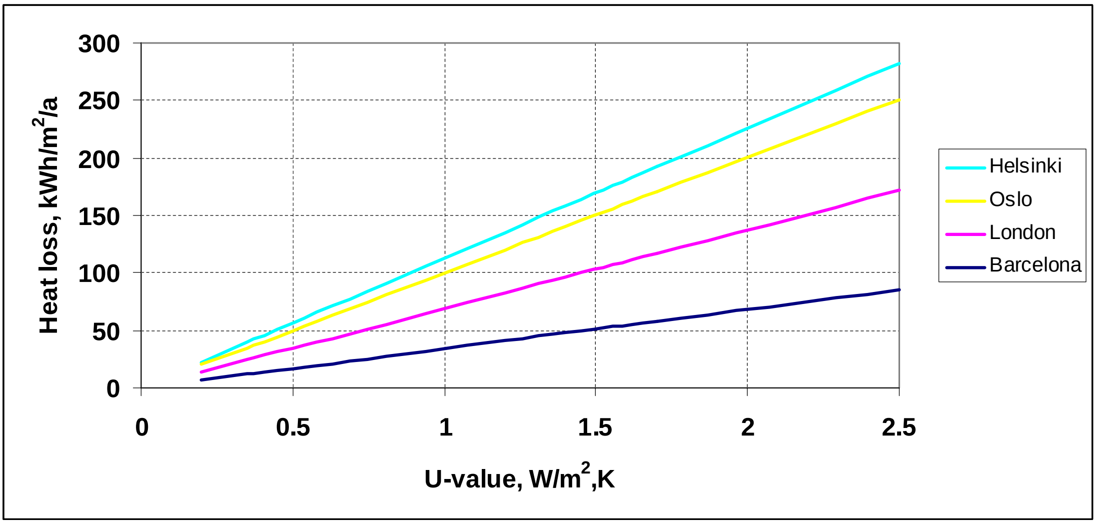

Figure 2. Specific heat loss of the wall as function of the U-value of the wall.

In general the extra insulation of wall decreases the heat demand and the effect on heating energy saving can be roughly estimated by heating degree day calculation, equation 2.

$$\Delta Q = \frac{HDD \cdot A \cdot (U_{ref} - U_{ren}) \cdot 24}{1000} \tag{2}$$

where

ΔQ	is energy saving, kWh
HDD	is heating degree days,-
A	is surface area of the wall, m^2
U_{ref}	is the thermal conductivity of the reference (=original) wall construction, W/m^2K
U_{ren}	is the thermal conductivity of the renovated wall construction, W/m^2K
24	is hours of the day, h
1000	is conversion factor, Wh -> kWh

Heating energy saving coefficients for studied locations are presented in table 2. The heating energy saving coefficient is the term HDD·24/1000 in equation 2.

Table 2. Heating energy saving coefficients (HDD·24/1000) for different locations.

Location	Barcelona	London	Oslo	Helsinki
Saving coefficient	34.1	68.8	100.1	113.1

Heating energy saving coefficients concretize the fact that a equal improvement in U-value means double savings in London, triple in Oslo and nearly four times in Helsinki compared to the savings in Barcelona.

Case studies

The potential of heating energy savings is analyzed based on the renovation cases of WP3 in Spain and England and the example is calculated for the climate of Barcelona and London, tables 3-4.

Table 3. Estimated heating energy savings of facade refurbishments in Barcelona based on HDD method.

Building type	Floors, number	Dimensions: Length x width x floor height, m	Glazing: percentage from floor area, %	Wall area, M^2	U, old, $W/m^2,K$	U, new $W/m^2,K$	Savings, kWh	Savings per floor area, kWh/m^2
Single family	2	10x9x3	25 (frame factor 1,1)	179	1,50	0,52	5957	33
Terraced	2	60x9x3	25 (frame factor 1,1)	531	1,50	0,52	17722	16
Apartment	5	32x12x3	25 (frame factor 1,1)	792	1,50	0,52	26433	14

Table 4. Estimated heating energy savings of facade refurbishments in London based on HDD method.

Building type	Floors, number	Dimensions: Length x width x floor height, m	Glazing: percentage from floor area, %	Wall area, M^2	U, old, $W/m^2,K$	U, new $W/m^2,K$	Savings, kWh	Savings per floor area, kWh/m^2
Single family	2	10x9x3	25 (frame factor 1,1)	198	2,10	0,35	2798	155
Terraced	2	60x9x3	25 (frame factor 1,1)	531	2,10	0,35	91690	85
Apartment	5	32x12x3	25 (frame factor 1,1)	792	2,10	0,35	141557	74

Heating energy savings are calculated for the same kind of wall structure and same renovation measure to show the differences between building types. The results reveal that the biggest saving potential is in single family houses which arise from the fact that in the single family house the wall area compared to the floor area is bigger than in the other building types. The heating energy saving potential is substantially bigger in England than in Spain due to the differences in climate and refurbished cases used in the examples. In all cases the heating energy saving potential is substantial.

Discussion

It should be reminded that heating degree day analysis gives usually the maximum saving potential that can be achieved with conventional extra insulation refurbishment. In practise the savings are in most cases lower because the extra insulation affects the utilization of internal heat loads (sun, appliances, people) that can not be taken into account with HDD method. Dynamic simulations show that usually external insulation gives somewhat higher savings than internal insulation and cavity insulation is somewhere between when the change of the conductance (UA-value) is the same.

There are also practical details that define the success of the extra insulation. Only with external insulation it is possible to cover the whole shell of the building unbrokenly. In wall cavities there are usually bonds between the external and internal walls that form thermal bridges in cavity insulation thus weakening the heat resistance of the wall. Moreover the insulation work of the cavities is technically difficult to carry out so that all the cavities are really insulated according to the specifications. Internal insulation is practically impossible to install without breaks in the insulation because of the internal walls and ceilings which decreases the effect of the thermal insulation. The internal and cavity insulation are also sensitive to errors in design and in installation in regard to condensation problems. Moisture in insulation not only ruins the thermal behaviour of the insulation but also incurs severe indoor air problems.

Assessment criteria

Heating demand of a building is characterized by transmission and ventilation heat losses and on the other hand heat gains of solar radiation and other heat loads like people and electrical appliances. Only part of the heat gains can be used to compensate the heat losses. Equation form of this looks like (equivalent to EN ISO 13790):

$$Q_H = Q_{losses} - \eta \cdot Q_{gains} \qquad (3)$$

where

Q_H is heat demand of the building, kWh
Q_{losses} is heat losses of conduction, infiltration and ventilation, kWh
η is utilization factor for heat gains
Q_{gains} is internal and solar heat gains

The utilization factor for the internal and solar heat gains, η, take into account that only part of the internal and solar heat gains can be utilized to decrease the energy need for heating, the rest of the heat gains only increase the internal temperature above the set-point. The utilization factor depends on the ratio of the heat gains and the heat losses as well as the thermal inertia (= heat capacity) of the building.

The transmission losses of the wall have role not only in the transmission heat losses through a wall but also in the utilization factor. This is by affecting the ratio of heat gains and losses and on the other hand by affecting the thermal inertia of the building. This is illustrated in figure x which is drawn according to the functions given in standard EN ISO 13790.

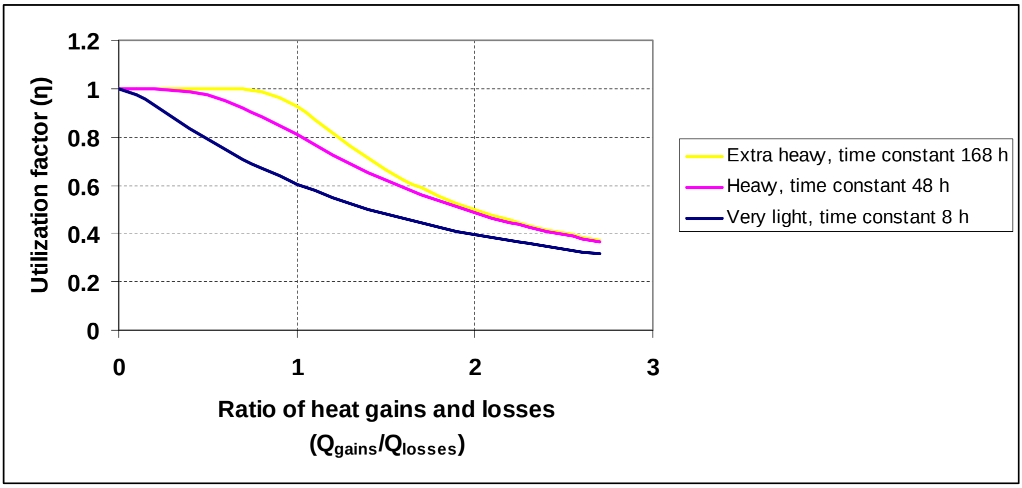

Figure 3. Utilization factor, η, of heat gains according to standard EN ISO 1390.

It can bee seen (figure 3) that the bigger the heat gains are compared to the losses the lesser is the utilization factor. Obvious is also the fact that the smaller the inertia is (light construction and short time constant) the poorer the capability to utilize the heat gains is. In most cases the inertia of the buildings range from light to heavy and the insulation of walls plays very little role in this and so the effect on the utilization factor is also rather insignificant. The biggest influence on the inertia of a building is with internal insulation when the time constant and utilization factor are lowered somewhat. External and cavity insulation usually don't have any influence to the inertia at all. Bigger effect on utilization factor of extra insulation can be seen through the ratio of heat gains and losses; losses are decreased and so does utilization factor. This is independent of where the insulation is installed (internal, external or cavity).

Another way that the installation of extra insulation can affect the heating demand of the building is by air infiltration. Air infiltration is uncontrolled ventilation through cracks and openings in the constructions caused by pressure differences between indoor and outdoor. Pressure difference results from wind and stack forces. The effect of the extra insulation on air infiltration and heating demand is case specific and hard to predict but in general the more covering the insulation is the bigger the effect is. From that point of view the external insulation has most potential in reducing the infiltration and thus also heating demand.

The biggest effect of extra insulation on heating demand is accessible through improving the heat conductance of the wall. Heat conductance is product of the U-value and the surface area of the insulation. The smaller the U-value is the more heating energy is saved and the more of the walls are covered with insulation the smaller the heat demand is. The easiest way to cover all the external walls with thermal insulation is with external insulation. Whereas with cavity insulation and especially with internal insulation there are the possibility of heat bridges that weakens the heat saving potential. Heat bridges are parts of constructions that penetrate the insulating layer, like ceilings and partition walls.

The chosen assessment criteria, based on the facts above, are:

1. Conductance of the wall, AU
2. Utilization factor of heat gains, η
3. Effect on the air infiltration

Table 5. Qualitative scale for refurbishment effect on conductance and utilization factor of heat gains.

Score	General effect of refurbishment	Effect on conductance (insulated area, insulation thickness, thermal bridges)	Effect on utilization factor (*
-2	Significant aggravation	Not relevant	Decreases the heat storage capacity significantly, time constant <8 h
-1	Minor aggravation	Not relevant	Decrease of the heat storage is moderate, time constant <1 d
0	No change	Not relevant	No change
1	Minor improvement	Conductance is decreased by >30 % and effect of thermal bridges is moderate	Increases the storage capacity moderately, time constant <2 d
2	Significant improvement	Conductance is decreased by > 60 % and thermal bridges insignificant	Increases the storage capacity significantly, time constant <7 d
*) utilization factor is defined in standard EN ISO 13790			

Table 6. Qualitative assessment of effect on infiltration rates.

Score	General effect of refurbishment	Effect of refurbishment on infiltration rates
-2	Significant aggravation	Infiltration rates increased by > 0,1 h^{-1}
-1	Minor aggravation	Infiltration rates increased by < 0,1 h^{-1}
0	No change	Infiltration rates not changed.
1	Minor improvement	Infiltration rates likely to be reduced by < 0,1 h^{-1}
2	Significant improvement	Infiltration rates likely to be reduced by > 0,1 h^{-1}
*) n_{50} is the calculated number of air leaks per hour at 50 Pa pressure difference between indoor and outdoor air, see EN 13829. Not to be confused by infiltration rate.		

Case 1 - External insulation without air gap.

Heating demand

The major impact on heating demand depends on the change in U-value of the construction as well as the insulated area. With external insulation it is possible to cover the walls continuously with minor heat bridges so the effect on the heating demand is remarkable.

The external insulation does not affect the heat capacity of the wall in respect to internal loads but it will affect the proportion of internal heat loads to heat losses. The ratio will increase and thus the utilization factor of internal loads will decrease.

Many insulation materials, like mineral wool and cellulose wool, have a relatively minor effect on airtightness. These materials are often used together with external wind-barriers, or internal moisture barriers or retarders. The retrofit of such barriers may increase airtightness significantly. Rigid insulation materials like EPS, XPS and others are more or less airtight, but if they do not form a continuous layer, the actual effect on airtightness depends strongly on actual details. Spray foams would have a profound effect on airtightness, but are currently hardly used in this application.

In all cases, junctions (between walls and windows, doors, roofs, foundations and dividing walls and floors) and penetrations (pipes, cables, etc.) are generally at least as important as the airtightness of the wall itself, and both the original airtightness as well as the effect by the refurbishment solution will depend much on building detail.

Table 7. Effect of External insulation without air gap on heating demand.

Concept / Parameter	E1	Note
Conductance, AU	1 thr 2	Significant effect, and only minor thermal bridges.
Utilization factor	-1 thr 0	Ratio between internal heat loads and heat demand will increase and this may decrease the utilization factor.
Air leakage	0 thr 1	Air leakage through walls is decreased but air leakages around windows, other joints and penetrations may increase unless no measures are made

Case 2 - External insulation with air gap

Heating demand

The major impact on heating demand depends on the change in U-value of the construction as well as the insulated area. With external insulation it is possible to cover the walls continuously with minor heat bridges so the effect on the heating demand is remarkable.

The external insulation does not affect usually the heat capacity of the wall in respect to internal loads but it will affect the proportion of internal heat loads to heat losses. The ratio will increase and thus the utilization factor of internal loads will decrease.

Many insulation materials, like mineral wool and cellulose wool, have a relatively minor effect on airtightness. These materials are often used together with external wind-barriers, or internal moisture barriers or retarders. The retrofit of such barriers may increase airtightness significantly. Rigid insulation materials like EPS, XPS and others are more or less airtight, but if they do not form a continuous layer, the actual effect on airtightness depends strongly on actual details. Spray foams would have a profound effect on airtightness, but are currently hardly used in this application.

In all cases, junctions (between walls and windows, doors, roofs, foundations and dividing walls and floors) and penetrations (pipes, ducts, cables, etc.) are generally at least as important as the airtightness of the wall itself, and both the original airtightness as well as the effect by the refurbishment solution will depend much on building detail.

Table 8. Effect of External insulation with air gap on heating demand.

Concept / Parameter	E2	Note
Conductance, AU	1 thr 2	Significant effect, and only minor thermal bridges..
Utilization factor	-1 thr 0	Ratio between internal heat loads and heat demand will increase and this will decrease the utilization factor.
Air leakage	0 thr 1	Air leakage through walls is decreased but air leakages around windows, other joints and penetrations may increase unless no measures are made

Case 3 - Internal insulation

Heating demand

The major impact on heating demand depends on the change in U-value of the construction as well as the insulated area. With internal insulation it is not possible to cover the walls continuously. In general there will remain uninsulated areas like in the junctions between ceilings and partition walls to the outer wall. These heat bridges will decrease the effect of the wall insulation on the heating demand.

The available space for internal insulation is in many cases limited, which affects the insulation thickness that can be used and this affects directly to the efficiency of the insulation.

The internal insulation decreases the heat capacity of the wall (especially this is the case with massive walls) and also increases the proportion of internal heat loads to heat losses which both will decrease the utilization factor of the internal heat loads and leads to increasing heating demand.

Internal insulation generally needs an airtight inside layer, often in the form of a vapour barrier or –retarder. The insulation and vapour barrier should be seamless to avoid the risk of condensation and to minimize air leakage through the wall. This is important especially at the junctures between walls and between walls and ceilings. However, this might prove difficult and require detailed studies for the junction points. Vapour barrier can increase the airtightness of the construction considerably. Expanding foams, like polyurethane (PU) and phenolic foam (PF), are not permeable and may have a profound effect on airtightness.

In all cases, cracks, junctions (between walls and windows, doors, roofs, foundations and dividing walls and floors) and penetrations (pipes, ducts, cables, etc.) are generally at least as important as the airtightness of the wall itself, and both the original airtightness as well as the effect by the refurbishment solution will depend much on building detail.

Table 9. Effect of Internal insulation on heating demand.

Concept / Parameter	I	Note
Conductance, AU	1	There will be heat bridges (floor and wall joints) left so the result is poorer than with external insulation.
Utilization factor	-2 thr -1	The thermal inertia of the wall will decrease drastically with massive structures and this will decrease the utilization factor. Also the ratio of internal heat loads and heat losses will increase and this will further decrease the utilization factor.
Air leakage	0 thr 1	Air leakage through walls is decreased but air leakages around windows, other joints and penetrations may increase unless no measures are made

Case 4 - Cavity insulation

Heating demand

The major impact on heating demand depends on the change in U-value of the construction as well as the insulated area. With cavity insulation in most cases it is not possible to insulate the walls continuously. The reason for this is that installation techniques are not perfect so most likely there will remain uninsulated spots in the walls. The other reason is heat bridges of the bonds and junctures in the construction. These factors will decrease the effect of the cavity wall insulation on the heating demand.

The cavity wall insulation usually doesn’t have any effect on the heat capacity of the wall but it will decrease heat losses and thus increase the proportion of internal heat loads to heat losses which will decrease the utilization factor of the internal heat loads and leads to increasing heating demand.

If porous insulating materials, such as mineral wool, are not protected with an airtight layer, then the insulation have a minor effect on airtightness. Most insulation materials used for cavity insulation (e.g. mineral wool, cellulose wool) have a minor effect on airtightness. Some reduction of air infiltration may still occur. Expanding foams may increase airtightness.

Table 10. Effect of Cavity insulation on heating demand.

Concept / Parameter	C	Note
Conductance, AU	1	Significant effect, but heat bridges and poor installation may vitiate the result.
Utilization factor	-1 thr 0	Ratio between internal heat loads and heat demand will increase and this will decrease the utilization factor.
Air leakage	0	Air leakage through walls may decrease slightly but air leakages around windows, other joints and penetrations may increase unless no measures are made.

Case 5 - Replacement insulation.

Heating demand

The effect on heating demand is of the same kind as with external insulation and because the refurbishment is normally thorough it is possible to improve the airtightness significantly.

Table 11. Effect of Cavity insulation on heating demand.

Concept / Parameter	C	Note
Conductance, AU	1 thr 2	Significant effect, and only minor thermal bridges.
Utilization factor	-1 thr 0	Ratio between internal heat loads and heat demand will increase and this will decrease the utilization factor.
Air leakage	0 thr 1	Air leakage through walls is decreased but air leakages around windows, other joints and penetrations may increase unless no measures are made

References:

Energy Plus weather data files:
(http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data2.cfm/)

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Title

Sustainable refurbishment of exterior walls and building facades

Final report, Part B

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Abstract

This report is the second part of the final report of Sustainable refurbishment of building facades and exterior walls (SUSREF).

SUSREF project was a collaborative (small/medium size) research project within the 7th Framework Programme of the Commission and it was financed under the theme Environment (including climate change) (Grant agreement no. 226858).

The project started in October 1st 2009 and ended in April 30th 2012.
The project included 11 partners from five countries. The coordinator of the project was Tarja Häkkinen, VTT.

SUSREF developed sustainable concepts and technologies for the refurbishment of building facades and external walls. This report together with SUSREF Final report Part B and SUSREF Final Report Part C introduce the main results of the project. Part A focuses on methodological issues. The descriptions of the concepts and the assessment results of the developed concepts are presented in SUSREF Final report part B (generic concepts) and SUSREF Final report Part C (SME concepts).

The following list shows the sustainability assessment criteria defined by the SUSREF project.

16) Durability
17) Impact on energy demand for heating
18) Impact on energy demand for cooling
19) Impact on renewable energy use potential
20) Impact on daylight
21) Environmental impact of manufacture and maintenance
22) Indoor air quality and acoustics
23) Structural stability
24) Fire safety
25) Aesthetic quality
26) Effect on cultural heritage
27) Life cycle costs
28) Need for care and maintenance
29) Disturbance to the tenants and to the site
30) Buildability.

This report presents sustainability assessment results of general refurbishment concepts and gives recommendations on the basis of the results.

The report covers the following refurbishment cases

- External insulation
- Internal insulation
- Cavity wall insulation
- Replacement Insulation during renovation.

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