An environmental assessment of insulation materials and techniques for exterior period timber-frame walls

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ABSTRACT: The French government has instigated an ambitious renovation programme aimed at the thermal insulation of existing housing stock to combat climate change and cut CO_2 *emissions. This will have a considerable effect on the renovation of period timber-frame houses, a rich architectural heritage in France. This study assesses the environmental impact of thermal insulation of exterior timber-frame walls in vernacular timber-frame buildings with brick or daub infill. The 20 wall types studied are based on the outcome of interviews with builders and building experts. A French building assessment tool, Cocon, is used to calculate embodied energy (EE), embodied carbon (EC) and thermal performance for each wall type. 'Conventional' wall types with interior insulation - often mineral wool and plasterboard - generally have the worst overall scores. The highest scores are for wall types with exterior insulation, which make better use of thermal mass. Wall types with interior insulation of plant fibre and binder (e.g. earth/straw) also show good results. Although there is a general lack of technical information on environmental building materials, there is growing evidence that natural and breathable materials are better for the environment, the historic building and the occupant.*

Keywords: energy, carbon, renovation, life cycle analysis.

1. INTRODUCTION

This study focuses on the thermal insulation of period timber-frame houses in the SW of France, a region rich in these historic buildings, the walls of which are traditionally filled with daub or fired brick. The French refurbishment programme, Plan Bâtiment, will have a considerable impact on the renovation of period timber-frame buildings [1]. To combat climate change the French government wants to cut the greenhouse gas (GHG) emissions of the housing sector by almost 40% by 2020 [1]. More than 20 million dwellings will have to be renovated and insulated by 2050 [1].

In the case of housing stock from before 1948, which represents 10 million dwellings in France, this drive for sustainable development may well go against the principles of good conservation [2]. The problem with current thermal regulations is that they are not adapted to historic buildings [3].The building physics of old houses built with traditional materials are very different from those built after 1948, and are often not as well understood [2]. From mistakes made in the past we know how much damage inappropriate renovation and dry lining can do to period timber-frame buildings. Clearly we are only at the beginning of (re)learning about natural and traditional materials and techniques, and their contribution to the energy efficiency of historic buildings [4].

The study aims to answer the question how to renovate historic timber-frame buildings up to modern insulation standards, while preserving the environment and the vernacular qualities of the building, and reducing the embodied energy (EE) and embodied carbon (EC) of the rehabilitation project. The aim of the assessment is not to compare case studies of entire buildings, but to present a more generally applicable model that helps to define the most appropriate environmental insulation techniques for period timber-frame walls. The focus of the study is on building materials and embodied energy and not on 'operational' energy consumption.

Today most of the energy use in buildings is due to heating and only 10% of is associated with the embodied energy in materials [5,6,7]. However, as we move towards highly insulated buildings, EE and EC of building materials will become a major part of a building's energy use and GHG emissions [6].

2. METHODS

2.1. Twenty wall types

The study assesses the environmental impact of several insulation techniques and materials presently used in the renovation of timber-frame buildings. A selection of 20 exterior wall types divided into 4 categories was made based on literature review and interviews with builders and building experts (Table 1). For the general build-up of each of the 20 wall types, see Table 3, p.4.

Table 1 Four categories of wall types in the survey

Wall types	***Number***
I. Conventional wall types with interior insulation : using 'conventional' insulation techniques and materials, generally dry lining with mineral wool and plasterboard or clay blocks.	M1 - M5
II. Ecological wall types with interior insulation : using 'ecological' insulation techniques and materials.	M6 – M10
III. Ecological wall types with plant fibre and binder : using 'ecological' insulation techniques and materials, based on solid walls with infill of plant fibre and mineral binder (clay or lime).	M11 – M15
IV. **Wall types with exterior insulation :** using both conventional and ecological insulation techniques	M16 - M20

The terms 'conventional' and 'ecological' are indicative and not based on strict definitions. 'Conventional' refers to current industrial building techniques which are also common in renovation. 'Ecological' applies to the use of materials and techniques that generally have a low impact on the environment. This does not mean that conventional materials and techniques always have a much higher environmental impact. They can even have a low embodied energy (EE), e.g. glasswool, while providing good thermal insulation, though there may be negative impacts such as pollution, toxicity, resource depletion and health risks. On the other hand, so-called 'ecological' materials can have a high EE (and EC) and therefore do not perform well in the assessment.

2.2 Life cycle analysis

For each wall type the environmental impact of the thermal insulation was assessed using the Excel-based tool Cocon [8][1]. Cocon gives each wall an overall score based on the calculation of six parameters: embodied energy, embodied carbon, resource depletion, thermal resistance, decrement delay and thermal inertia (Table 2).

Table 2 Scores and values for six parameters, wall type M1 (brick, glasswool, plasterboard)

Summary Table *M 1*	**Embodied Energy**		**Embodied Carbon**		**Resource Depletion**	
Overall Score	*kWh /m²*	*Score*	*kg eq CO2/m²*	*Score*	*kea*	*Score*
8.5	**177.5**	**8.2**	**39.7**	**7.4**	**0.0281**	**10.3**
Carbon tax	**Thermal resistance**		**Decrement delay**		**Thermal Inertia**	
€ / m²	(m²K/ W)	*Score*	h	*Score*	(kJ/ m²K)	*Score*
0.67 €	**2.65**	**13.6**	**5.7**	**9.5**	**24**	**1.9**

The scores for the environmental impact parameters are based on official data from life cycle analysis (LCA), and the scores for the building physics parameters are based on values from French or international thermal regulations[2].

Cocon can be directly linked to the French database INIES which contains Environmental Product Declarations (EPDs) and industry data for building products based on LCA [10][3]. For product data that are not included in INIES, Cocon uses its own database developed at the LRA, which contains data from the Swiss Oekobilanzdaten or from extrapolations based on other sources [11].

There is a possibility in Cocon to choose 'with' or 'without' renewable energy (RNE). The reason for including RNE in this assessment is that most data are based on EPDs in INIES [10] which include RNE, despite the fact that this is controversial because these include feedstock energy and cause a bias against renewable materials [12].

2.3 Thermal performance of a functional unit

The functional unit in LCA is usually 1 m^2 of building element for a certain life time (e.g. 50 years). To be able to compare the environmental impact of the 20 wall sections it is better to compare functional units with a similar thermal resistance. In this study an average R-value of approximately 2.7 m^2K/W was chosen, based on the insulation standard RT-2007, which corresponds with 8 cm of glasswool [9]. To achieve a similar R-value for other insulation materials sometimes required adding an extra centimetre.

Most builders interviewed do not apply a vapour control layer (VCL) but leave a cavity of 4cm or 5cm which should be fully ventilated to allow humidity to escape, though often is not. Therefore in the assessment of the conventional wall types (M1-M6) VCLs are not included. Instead a non-ventilated air gap of 4 cm (λ = 0.23 W/m.C) is added to be true to existing renovation practice in SW France. Obviously this hardly influences the outcome in the assessment which does not take vapour transport into account.

The timbers are not accounted for in the assessment and therefore considered as 'accessories', and are not included in the calculations for thermal performance. In most cases the original timbers are kept or reused, which means they are considered 'existing' and therefore not included in the impact assessment either. When bricks or daub are reused or left in place as infill one considers them 'existing' as well. Again this means they are not included in the impact assessment, though they are included in the thermal calculations because they are not considered accessory. Other accessories, e.g. metal or wood frames for boards and infill are excluded

[1] COCON - Comparaison de solutions Constructives de Confort et d'emissions de CO_2 - is in the process of being approved by the CSTB.

[2] The scores are a simple linear interpolation on a somewhat arbitrary scale with an upper and lower limit, taking the real values from the LCA or thermal regulations (RT-2007 and ISO13786).

[3] FDES Fiche de Déclaration Environnementale et Sanitaire, based on NF P01-010.

from the thermal calculations, though they are included in the impact assessment because they are considered 'new'.

Building physics parameters, e.g. air tightness, thermal bridging and vapour control, require simulation software and are therefore not included in the assessment. Qualitative aspects that are hard to quantify, e.g. health issues related to building materials, and above all architectural interest and vernacular qualities, were not included in the assessment. However, the study clarifies whether certain insulation techniques and materials are considered 'appropriate' for exterior period timber-frame walls.

3. RESULTS AND DISCUSSION

3.1. Overall scores of wall types

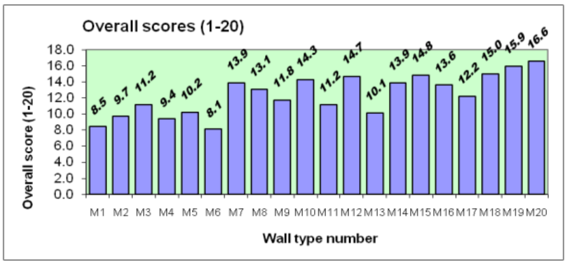

Fig. 1 Overall scores for 20 wall types (for the results per parameter, see Table 3, p. 4)

The three wall types with the highest overall scores all have exterior insulation, which gives much better scores for thermal inertia (Fig. 1). The walls with woodfibre board on the outside (M20) give the best overall results, whereas more conventional wall types with exterior insulation, e.g. polystyrene (M17), do not achieve a satisfactory overall score due to their high environmental impact.

When exterior insulation is out of the question for conservation reasons the earth/straw wall types give the best overall results (M15,M12)[4]. They are probably more compatible with historic timber-frame walls than woodfibre board, especially in the case of wattle and daub walls. Beside their hygrothermal qualities, timber-frame walls with plant fibre infill (e.g. hempcrete, woodchip/lime and earth/straw) provide an excellent decrement delay and are a good solution for thermal bridging and achieving air tightness in leaky old timber-frame buildings [13]. Several studies, e.g. Evrard, show how the dynamic thermal performance of insulation materials can be very different from the 'steady state' situations used for thermal regulations, which makes hempcrete walls perform better than expected from simple R-values, due to the benefits of hygroscopicity and reduction of thermal bridging [13].

3.2. Earth/straw or hempcrete?

Amongst French builders earth and straw is less well known than hempcrete, a mix of hemp and lime. Looking at Table 3 (p.4) the hempcrete wall (M11) does not get a satisfactory score in the assessment due to its high EE (152 kWh/m^2), even though it is virtually carbon neutral (EC = -3.5 kgCO_2eq/m^2). Changing the lime binder for clay would considerably lower its environmental impact, though hemp and clay is still at an experimental stage and needs more research. With more accurate data for the two lime renders (3 cm each) that take re-carbonation into account, the hempcrete wall would perform better, especially for EE (92 kWh/m^2) and EC (-30 kgCO_2eq/m^2). Though this is the case for most wall types that include lime renders. The data for the lime binder in the hempcrete (M11) are from the French LCA and show a particularly high EE because the lime is imported from Spain [14].

Another advantage of earth/straw over hempcrete is that the materials can be found cheaply and locally. At present earth/straw is mainly used for the infill of new timber-frame buildings, though it can be an excellent solution for renovation, especially in combination with the repair of old daub (M15).

The hempcrete wall is not the only 'ecological' wall that gets a mediocre score in the assessment. The cellulose wall (M9) and the monomur of fired clay insulation blocks (M6) do not get satisfactory results either. Blown cellulose is still one of the cheapest and widely used environmental insulation materials, also in renovation. However, due to its low density it has little thermal mass, which brings down the overall score in the assessment. Bringing other parameters into account, e.g. hygroscopicity and thermal bridging, would give cellulose certainly a better overall score than in the present assessment. The monomur may provide a very good decrement delay of 22.5 hours, but shows a very high EE (355 kWh/m^2) and EC (135 kgCO_2eq/m^2), and is the worst solution of all the 20 wall types (Table 3.).

3.3. Dry lining and thermal mass

The assessment shows that the widely used 'conventional' insulation techniques are amongst the worst performers from a thermal and environmental point of view, with overall scores below 10 out of 20 (M1,M2, M4). This is mainly due to the high EE of new fired bricks and the very low scores for thermal inertia.

This is also the reason why the wall with no insulation (M5) gets a better overall score, simply because it does not have an added environmental impact, while it preserves the building's thermal mass. Some experts therefore believe that it is often preferable not to compromise a building's vernacular qualities by applying dry lining, but use an insulation render, e.g. hemp and lime, for 'thermal improvement' [3].

When the old daub (M3) is kept, dry lining wall types get a slightly better result, especially if glasswool is replaced by woodwool, which is more hygroscopic and therefore more compatible with 'breathing' and 'capillary' timber-frame constructions. When used in combination with interior clay blocks it achieves a good decrement delay and acceptable overall score of 13.6 (M3*b*).

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[4] *Terre-paille* or 'light earth', a mix of straw and clay earth in very low densities of around 400 kg/m^3.

Table 3 Results all parameters for the 20 wall types

Wall type	Wall number	Overall score	Width	Embodied Energy		Embodied Carbon		Resource depletion		Thermal Resistance		Decrement delay		Thermal inertia	
		1 to 20	*cm*	*kWh per m²*	*Score*	*kg CO2eq per m²*	*Score*	*kea per m²*	*Score*	*m² K/w per m²*	*Score*	*h / m²*	*Score*	*kJ/m²K per m²*	*Score*
Brick, glasswool, plasterboard	M1	8.5	26.5	177	8.2	40	7.4	0.02814	10.3	2.65	13.6	5.7	9.5	24	1.9
Clay block, glasswool, plasterboard	M2	9.7	27.5	144	10.4	36	7.6	0.00528	15.2	2.72	14.0	5.6	9.3	24	1.9
Old daub, glasswool, plasterboard	M3	11.2	29.5	100	13.4	32	7.9	0.00124	19.4	2.67	13.7	6.5	10.9	24	1.9
Brick, glasswool, clay block	M4	9.4	32.0	201	6.6	50	6.7	0.02960	10.2	2.75	14.2	7.9	13.2	71	5.7
Old daub, no insulation	M5	10.2	13.0	30	18.0	13	9.1	0.00000	20.0	0.40	1.1	4.6	7.6	70	5.6
Brick and monomur	M6	8.1	49.0	355	0.0	135	1.0	0.10341	6.6	3.13	16.3	22.5	20.0	61	4.9
New daub, woodwool, clay block	M7	13.9	32.0	72	15.2	-3	10.2	0.00203	18.0	2.70	13.9	12.4	20.0	77	6.2
Brick (reuse), cork board	M8	13.1	26.0	60	16.0	-3	10.2	0.00000	20.0	2.70	13.9	9.4	15.7	36	2.8
Old daub, cellulose, Fermacell	M9	11.8	28.0	144	10.4	18	8.8	0.00010	20.0	2.69	13.9	8.3	13.8	45	3.6
Old daub, wood fibre board	M10	14.3	28.0	37	17.5	-13	10.9	0.00000	20.0	2.62	13.5	11.8	19.6	54	4.3
Hempcrete	M11	11.2	31.0	152	9.9	-4	10.2	0.03250	9.9	2.79	14.4	10.8	17.9	58	4.6
Earth and straw	M12	14.7	36.0	85	14.3	-39	12.6	0.00008	20.0	2.77	14.3	16.0	20.0	86	6.9
Woodchip and lime	M13	10.1	45.0	290	0.7	-47	13.1	0.06818	7.8	2.77	14.3	18.6	20.0	62	5.0
Earth/straw, woodwool, Fermacell	M14	13.9	25.0	70	15.4	-15	11.0	0.00001	20.0	2.74	14.1	10.6	17.6	63	5.0
Old daub, earth and straw	M15	14.8	38.0	35	17.6	-22	11.5	0.00000	20.0	2.62	13.5	15.3	20.0	81	6.5
Wood cladding, glasswool, old daub	M16	13.6	29.7	147	10.2	17	8.9	0.00076	20.0	2.80	14.5	8.4	14.0	177	14.1
Polystyrene, old daub	M17	12.2	26.0	124	11.7	39	7.4	0.00522	15.2	2.57	13.2	7.0	11.6	175	14.0
Slate cladding, woodwool, old daub	M18	15.0	27.5	120	12.0	-10	10.6	0.00026	20.0	2.68	13.8	10.6	17.7	198	15.9
Woodfibre board, unfired bricks	M19	15.9	25.0	36	17.6	-18	11.2	0.00001	20.0	2.65	13.7	11.4	19.0	176	14.1
Woodfibre board, old daub	M20	16.6	28.0	28	18.1	-20	11.3	0.00000	20.0	2.71	13.9	12.3	20.0	202	16.1
	Average	12.4	30.1	120	12.2	9.3	9.4	0.01384	16.6	2.61	13.4	10.8	15.9	88	7.1

3.4. 'Biosourced' materials

Now both France and Germany have their government incentives for renewable building materials, it is interesting to look at the percentage of materials in the wall sections that are 'bio sourced', i.e. derived from plant-based sources (Fig 2). The plant-fibre-filled walls have the highest percentages 'bio sourced' for both weight and volume.

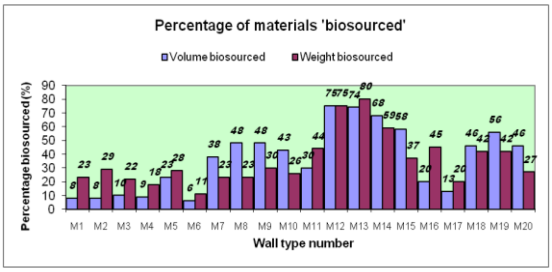

Fig. 2 Percentage of materials 'biosourced' per wall type

This corresponds with Fig. 3 which shows that all plant fibre walls store carbon, with the woodchip and lime wall (M13) storing 47 kg CO_2eq/m^2 and the earth/straw wall (M12) storing 39 kg CO_2eq/m^2.

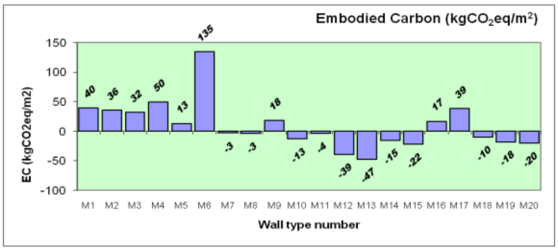

Fig 3 Embodied carbon per wall type

4. CONCLUSION

4.1 Appropriate techniques

The aim of the study was to find out what the most appropriate and sustainable insulation techniques are for the renovation of period timber-frame buildings. This means techniques and materials that do not have a negative impact on the environment, or on the structure of a building and its aesthetic and vernacular qualities. The assessment shows there is no one optimum solution which is satisfactory for all these criteria. Though some insulation techniques may be satisfactory from an energy-saving viewpoint, they are not considered appropriate solutions when they have a negative impact on the environment or the building itself. However, despite the reservations of conservationists, exterior insulation may be a solution for walls that are not of great architectural interest.

An appropriate material for the exterior insulation of period timber-frame walls is woodfibre board, due to its low thermal conductivity and EE and a good density (168 kg/m^3) and vapour-openness. When exterior insulation is not possible earth/straw insulation gives the best overall results. Because this technique is more labour intensive and requires longer drying times (up to several months), it would be interesting to study the wider applications of earth and straw in thermal retrofits of existing buildings, as was done for straw bale in the UK [15]. Furthermore, the labour-intensity factor proposed by Floissac et al. [16] deserves further study and is an interesting socio-economic concept for the development of a locally sourced and sustainable construction industry using renewable materials.

There still is a general lack of reliable technical information on manufactured environmental building materials, and producers of these 'new' materials find it difficult to get their products certified [17], e.g. in this study it was hard to find reliable data for expanded cork board insulation. EE and EC figures for cork boards from different sources varied so much it was hard to interpret them. This lack of reliable and comparable data is even more apparent for 'non-manufactured' local materials, e.g. earth, straw and other agro fibres.

4.2. Towards consensus on LCA and carbon storage

The assessment shows that walls with plant fibre and binder insulation (M12-15) store considerable amounts of carbon. Carbon storage in building materials has a great GHG-mitigation potential, which applies to both renovation and new build [7,12,13,18]. However, further research and scientific debate on calculation methods are needed to establish scientific consensus in the LCA community. Some authors maintain that the inclusion of carbon sequestration only makes sense in a wholly sustainable state of production and consumption [19]. Furthermore, carbon storage in building materials is temporary and depends on what happens at the 'end-of-life' of a product. Still, a several centuries old timber-frame houses is probably one of the best examples of a quasi-permanent carbon store.

The general problem with LCA-based assessment tools like Cocon is the different weighting methods and system boundaries used for LCA data. This can lead to rather different results for the same materials and functional units studied. Future European harmonisation of LCA procedures might resolve some of these problems. However, despite the limitations of LCA and the lack of LCA data for environmental materials, the Cocon database provides reliable figures which have been checked and compared with industry data and other sources [7, 11]. The cross-checking has contributed to the continuous updating process of the database.

4.3. Risks of dry lining in historic buildings

It is clear that the currently used dry lining techniques have the worst scores in the assessment. This is not only due to their environmental impact, but also because dry lining completely cancels out the benefits of thermal mass. Furthermore, these techniques annihilate the hygrothermal qualities of daub walls and can put the building at risk when condensation and other humidity issues are not properly addressed, as seen in the interviews [20].

When trying to achieve higher levels of thermal insulation and air tightness in historic buildings, inappropriate materials that do not 'breathe' can bring huge perils to both the health of the building and the occupant [4]. Builders and architects name humidity control as the main problem in old buildings [20]. However, the study shows that the solutions they provide for thermal insulation and vapour control are often inappropriate.

Further research and hygrothermal simulation of different wall types and insulation materials must be carried out to assess which materials are appropriate for historic buildings from a hygrothermal point of view. Hygroscopic materials such as clay and plant fibres can play an important role in moisture buffering [21]. However, the main problem, especially for environmental materials, is to find reliable hygrothermal data which can be used for these simulations [22].

A lot of the results from the assessment are also applicable to new timber-frame buildings and the research model can be adapted to other renovation projects that take the vernacular qualities of buildings into account. Cocon can be used for all types of construction and is normally used to assess a whole building, including its operational energy. In a further case study of several period timber-frame buildings it would be interesting to look at whole buildings, testing several wall types and insulation techniques from the current assessment. Comparing case studies and including hygrothermal simulation could confirm which techniques are more appropriate. Each wall has to be considered individually, also taking climatic parameters (e.g.orientation, solar gain, wind and rain) into account. And building materials should not only be studied for the environmental impact, or the effect they have on the building, but should also be analysed for their influence on indoor air quality and other occupant-related health issues. At present the health issue is largely ignored in the French EPDs.

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