ENERGY EMBODIED IN, AND TRANSMITTED THROUGH, WALLS OF DIFFERENT TYPES WHEN ACCOUNTING FOR THE DYNAMIC EFFECTS OF THERMAL MASS

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ABSTRACT

Embodied energy is a measure of the energy used in producing, transporting and assembling the materials for a building. Operational energy is the energy used to moderate the indoor environment to make it functional or comfortable—primarily, to heat or cool the building. For many building geometries, the walls make the most significant contribution to the embodied energy of the building, and they are also the path of greatest heat loss or gain through the fabric, as they often have a greater surface area than the roof or floor. Adding insulation reduces the heat flow through the wall, reducing the energy used during operation, but this adds to the embodied energy. The operational energy is not only a function of the wall buildup, but also depends on the climate, occupancy pattern, and heating strategy, making an optimisation for minimum overall energy use non-trivial. This study presents a comparison of typical wall construction types and heating strategies in a temperate maritime climate. The transient energy ratio method is a means to abstract the heat flow through the walls (operational energy for heating), allowing assessment of the influence of walls in isolation (i.e. in a general sense, without being restricted to particular building geometries). Three retrofit scenarios for a solid wall are considered. At very low U-values, overall energy use can increase as the embodied energy can exceed the operational energy; current best practice walls coupled with low building lifetimes mean that this point may be reached in the near future. Substantial uncertainty is present in existing embodied energy data, and given its contribution to total energy use, this is a topic of urgent concern.

KEYWORDS

energy use, lifetime energy use, embodied energy, operational energy, thermal mass, heating, intermittent occupancy, transient energy ratio, uncertainty

1. THE ENERGY USE OF BUILDINGS

Current assessments predict a mean global temperature rise in excess of 3 K by the end of the century[1]. Much energy is devoted to creating and maintaining comfortable thermal

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environments in buildings; even in mild climates heating and cooling combined can account for a third of energy use. Besides energy use, building construction and use accounts for a large proportion of resource consumption and pollution.

Life cycle assessment (LCA) of buildings generally fall into the category of 'bottom up' approaches: quantities of materials are measured, inputs and outputs are assessed, and the impact of a building as a whole is construed from the impact of its parts (and the process of assembling them into a building). By contrast, industry-wide studies tend to take a 'top down' view: looking at, for example, the total amount of fuel used in concrete production, and comparing this to the total output. In practice, both methods are needed. Often, LCA studies published in the literature are case studies of particular buildings, for example the same building in different locations to look at the effects of climate.[2] Most of these are, however, carried out on exemplary low energy buildings.[3] Despite this limitation, a number of authors have reviewed the literature relevant to LCA in construction, generally examining a large number of case studies (see, for example, [4][5][6]—a more comprehensive list of review articles is contained in [7], Table 1).

Cradle-to-gate, cradle-to-site, and cradle-to-cradle are common terms used to define the extent of the boundaries of the analysis. Cradle-to-cradle is the most comprehensive, and takes into account the reuse and recycling of building materials; this can make a significant difference to the impact of a building. Nevertheless, cradle-to-gate figures are the most common, for reasons of practicality; gate-to-site transport figures can vary substantially between projects.

The combined total of embodied energy and operational energy is termed the *lifetime energy consumption*. (Demolition and disposal also contributes to the total energy use, but this contribution is smaller than the errors in most estimates of the other contributions—of the order of 1%[8]). Substantial difficulties arise in applying this methodology to the construction

TABLE 1. Nomenclature.

k	Thermal conductivity (Wm^{-1} K^{-1})
ρ	Material density (kgm^{-3})
c_p	Specific heat capacity (Jkg^{-2} K^{-1})
L	Thickness of materal (m)
T	Temperature (K unless specified)
T_0	Air temperature (K unless specified)
h	Heat transfer coefficient (W/K)
$\overline{\upsilon}$	Mean wind speed (m/s)
ϵ	Emissivity (dimensionless)
σ_0	5.67×10^{-8} W m^{-2} K^{-4}
U	U value ($Wm^{-2}K^{-1}$)
U_e	Effective U value (Wm^{-2} K^{-1})
TER	Transient Energy Ratio (dimensionless)

sector due to the bespoke nature of the product, the lack of an agreed framework, and the difficulties in attributing 'hidden' contributions from services.

The construction sector faces particular challenges as buildings are very long-lived products: the UK building stock is growing at a rate of about 0.5% per annum; many houses are in use for over a century, while the replacement rate for commercial buildings is about 2% per annum[9]. Data is often unavailable for extant buildings, which may have been constructed using very different processes to modern construction. Buildings are diverse, and often change owners several times during the life of the building—particularly so for domestic buildings.[10] For all these reasons, there is substantial uncertainty in estimates of lifetime energy use for buildings, despite the existence of standards for lifecycle assessment.[11–16] This situation has been summarised by several authors:

> "Current embodied energy calculations exhibit problems of variation, inaccuracy and incompleteness"[17]
>
> "The majority of the studies cited are not comparative, lack the level of detail required to make any comparisons and have inconsistent boundaries."[18]
>
> "The differences from case to case are, indeed, simply too great to allow any further general conclusion."[19]
>
> "A lack of comparable methodologies, data, and regulation still hinder the reduction of the embodied impacts."[20]
>
> Most embodied energy studies are carried out on "exemplary buildings" in urban settings in developed countries, with few studies looking at traditional buildings or other sites.[3]

Consequently, there is need for a more general understanding, with an approach applicable to a wide range of materials; that can be used earlier in the design stage of buildings, before major decisions are taken concerning building form, orientation, etc. A consideration of the error in values is also important; uncertainty values are given in very few case studies [4], and as will be seen later in this work, the uncertainty associated with embodied energy values (in particular) can be large.

This work uses the transient energy ratio (TER) method to analyse the use energy due to particular wall configurations. This 'use energy' is the heat energy flowing into the wall; that stored and lost through it. A natural consequence of the TER method is that operational energy use can be conveniently expressed in MJ/m^2 of wall area per year (rather than floor area). In this way, the analysis is more general, as it not restricted to individual buildings or specific geometries. A sample of representative walls are examined, and this is followed by an analysis comparing different insulation materials.

2. METHODOLOGY

This paper presents an examination of the contribution of embodied energy to total energy use, and the variation in embodied energy between some sample walls. Typical wall sections are presented, and examined both in terms of use energy and embodied energy. Subsequently, a retrofit scenario is examined in a similar manner.

Changing building geometry, glazing ratio, air permeability among many other parameters significantly impact the proportional heat loss of a building and are all different for different buildings. Changing these other parameters do not, however, significantly change the steady state heat loss through the wall for a given U-value, and so this paper isolates the wall as a focus of this study. This method, of isolating the heat flow through the walls alone, is used in the Transient Energy Ratio method previously validated.[21] The wall is selected as it makes up the greatest area of the building envelope, and consequently makes the greatest contribution to both embodied energy and heat loss. Examples of the wall buildups used in this study are shown in Figure 1.

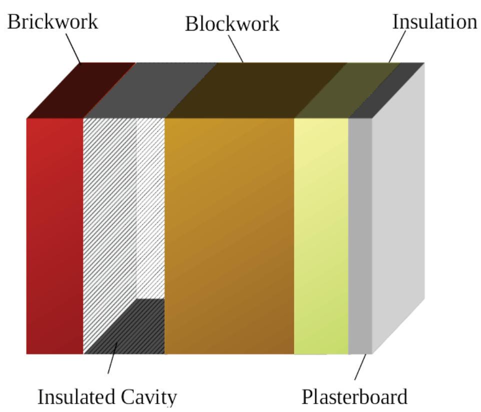
2.1 Wall types

Four wall types are chosen: a solid blockwork wall, an insulated brick and blockwork cavity wall (as is common in, for example, the UK and Ireland), an insulated concrete formwork wall, and a straw bale wall. These walls have been chosen to illustrate very different construction techniques. They are representative of walls requiring energy-efficiency retrofit (solid blockwork), common construction (cavity wall), newer wall types (ICF) and biobased alternatives (straw bale). The walls studied here are representative of actual walls in each material; consequently, they have different thicknesses and different U-values. By using the TER, the relative magnitudes of the embodied and operational energy contributions can be calculated, while using an accurate, dynamic calculation of the heat flow. It would not be practical, for example, to make a solid blockwork wall with a U-value of 0.21 $Wm^{-2} K^{-1}$ without insulation, as it would be impractically thick. Likewise, it would not be representative to consider a solid wall and a cavity wall of the same thickness. By comparing the figures on a MJ/m^2 basis, a direct comparison can be made between embodied energy and use energy for each of these walls. Between them, the walls cover a wide range of thermal performance and embodied energy. There is a further reason for including the solid blockwork wall: although uninsulated walls are not common in contemporary construction in heating-dominated climates, such walls are widespread in existing building stock, and a target for renovation. Renovation strategies for this wall are covered later in this paper.

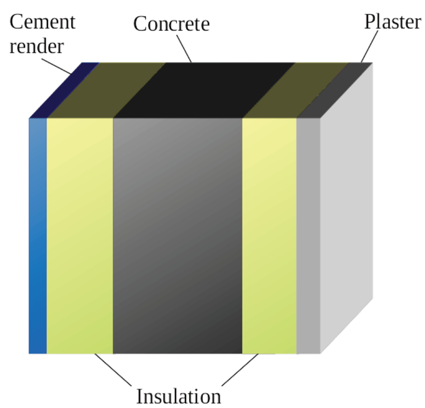
2.2 Embodied energy

The embodied energy for each wall was calculated based on published values for materials. Embodied energy values were taken from [22]. The embodied energy values provided are

FIGURE 1. a) Buildup of the cavity wall showing thickness and position of the wall layers; b) Buildup of the insulated concrete formwork (ICF) wall.



a.



b.

‘cradle-to-gate’ values; consequently, transport to site and the energy used during construction are excluded. Transport and on-site construction together are estimated to add around 2% to the total embodied energy of buildings [23]; for present purposes, a constant factor of 2% has been assumed for transport and on-site work for all materials.

Thermal properties and density were generally taken from [24] and [25], and the density of polyisocyanurate was taken from [26]. Material data was also taken from [27] and [28].

2.3 Use energy

The use energy was calculated using the Transient Energy Ratio (TER) method [21]. This energy is more specifically the heat energy and does not include energy related to for example appliances or other unregulated loads in the building. The TER method allows a calculation of the heat flow through a wall over an entire year, again without assuming a particular building form. However, in contrast to using the thermal conductivity alone, the TER method accurately captures the effect of thermal mass and transient heating/cooling cycles. Importantly, this also takes account of occupancy patterns—a naive assumption that energy use scales with occupied hours is incorrect, due to the heat stored in the building fabric at the start and end of each heating period. Under certain control strategies and weather conditions, heat storage can significantly alter the energy use compared to an assumption of steady-state conditions. In some cases, the difference between an accurate dynamic calculation (using the TER) and a pseudo-steady-state calculation is greater than a factor of 3.[21]

The transient energy ratio is a parameter that quantifies the departure from steady-state thermal conditions during building heating and cooling. It incorporates the detail of the construction, dynamic material properties, and building occupancy schedule, but in such a way as knowledge of the building geometry is not needed. The method is described in summary below (from [29]):

Calculate the U-value for the wall section in question (U)

Simulate the thermal behaviour of the wall, using boundary conditions representative of the climate and indoor occupancy pattern of interest

Use the actual energy flow through the wall in the dynamic simulation to calculate an effective U-value (termed U_e)

Divide U_e by U to find the transient energy ratio (TER)

The dynamic simulation is necessary to capture the true behaviour of the walls. In conditions of changing surface temperatures, heat may be stored and returned to the indoor and outdoor environment: this is the basis of thermal mass. A dynamic simulation attempts to capture these effects by modelling the response of a wall to varying temperatures. The effective U-value is the quantity which, when used with the mean temperatures, gives the actual energy flow through the wall.

This actual energy flow may be greater or less than that predicted based on the static U-value, and this ratio is termed the TER. If the TER is less than one, the thermal mass of the wall offers energy savings, over and above any savings purely due to a low conductivity. On the other hand, if the TER is greater than one, the wall is leading to greater energy use than predicted by a static analysis.

Static Analysis The static analysis is simply an evaluation of each wall’s U-value, calculated in the standard manner as in Equation1 below (where L is the thickness of each material, k is the conductivity, and the subscript indicates the material).

$$\frac{1}{U} = \frac{L_1}{k_1} + \frac{L_1}{k_1} + \ldots + \frac{L_n}{k_n} \tag{1}$$

Dynamic Analysis The principle of the TER method is to use a dynamic simulation of a wall section. To comply with the method, any simulation method that accurately predicts internal wall temperatures may be used.

The output from the model is a heat flux on the interior surface of the wall (Wm^{-2}). This average heat flux per unit area is divided by the mean temperature difference to give the effective U-value (U_e). In this way, the effective U-value accurately reflects the heat loss/gain through the wall, but has units of $Wm^{-2} K^{-1}$, making it directly comparable with the standard U-value calculated through a static analysis.

In the present work, heat flow through the wall is calculated using a one dimensional finite element model. The air temperature on both sides of the wall is treated as an ideal heat source/sink with no thermal mass of its own, and the operative temperature (the mean of the air and surface temperature) results from the interaction between this source/sink and the wall, as in [21].

Heat transfer at the wall surfaces was modelled according to ISO 6946[30], as in Equation 2 below.

$$h = 4 + 4\overline{v} + 4\epsilon\sigma_0 T_0^3 \tag{2}$$

2.4 Numerical model

Finite element model A finite element (FE) model was used to calculate the energy flow through the wall. The FE model allows for accurate treatment of the dynamic properties of the wall, including the thermal mass, and the interfaces between different layers in the wall, and between wall and air. The external temperature was applied using recorded climate data[31]. The indoor temperature had a setpoint of 294 K (21°C), on a schedule defined by the occupancy pattern (see below). These temperatures were applied to the FE model as the temperatures of infinite air volumes: the actual temperature at the wall surface depended on the interaction between the wall and air, with the interaction defined by a heat transfer coefficient. This was calculated according to either indoor conditions, or for the external wall, using mean wind speeds for the locality according to a standard method[32].

Two software platforms were used: the commercial desktop FE package Abaqus CAE, and the online platform SimScale running on the open-source software Code Aster. A variety of cases were used to check the reliability of the results, by comparing (a) simple steady-state or periodic conditions to analytic solutions, and (b) by comparing cases between the two software platforms. (For the analytic solutions, functions were used in place of climate data for the temperature, and direct contact was assumed rather than convective heat transfer.) These results were in agreement. Further details of the model validation are given in [21].

Treatment of cavity ventilation Modelling the ventilation inside a cavity wall is a topic of ongoing research effort. Despite many studies, authors disagree about the extent of cavity ventilation and its effects on hygrothermal conditions in the wall (both in the cavity itself, and as a result, in the material of the wall)[33]. Studies of the effects of a cavity range from positive[34] to negligible[35] and even negative[36]. Many simplified models and indices have been developed but there is poor agreement between these models[37], although in specific cases these models can show good agreement with experimental data[38]. Karagiozis and Ku¨nzel proposed a simplified model which has seen comparatively widespread adoption through its use in a commercially-available model (WUFI)[39]). A similar approach is taken here by neglecting the coupling between ventilation rates and outdoor conditions, modifying the thermal conductivity of the cavity and assuming a constant averaged ventilation rate.

2.5 Climate and indoor environment control strategy

The most significant factor affecting indoor energy use is the control strategy and temperature setpoint: at one extreme, if a building's occupants decide to turn off any active heating or cooling systems, no energy will be used for heating or cooling, regardless of the system efficiency and the performance of the walls. The local climate has a similarly strong effect, as the optimum wall design and pattern of energy use will obviously vary with outdoor conditions. The present analysis is restricted to buildings with winter heating and no air conditioning in oceanic temperate climates, i.e. those corresponding to Koppen Cfb climate zones; this includes much of northern Europe [40]. Whilst mean outdoor temperatures, and hence building energy demand, may vary substantially within these areas, the *pattern* of energy use varies much less [41]. Consequently, the differences in energy use may be adequately modelled by consideration only of the degree-day differences between locations; this would not be the case when comparing, for example, a hot desert city with a cool oceanic one. In order to avoid presentation of a large mass of data, results are presented for a single, representative city (Belfast, Northern Ireland). Energy use values may be adjusted for other regions with a Cfb climate by comparing the degree-days of heating for Belfast and the location of interest. Belfast weather data was obtained from the UK Met Office (Belfast, Newforge) and is broadly representative of wider UK and Irish weather. Annual sunshine hours total 1246.9 (UK avg. 1372.8), averaged over the period 1981–2010. Average max (13.4°C) and min (6.3°C) temperatures are slightly higher than the UK average (12.4 and 5.3), and monthly rainfall is lower 994 vs 1154mm. Further detail on Belfast climate characteristics are listed in Appendix B. Wall heat energy flow, for light and heavy constructions, accounting for the varying heat storing impacts of thermal mass for warmer climates are reported in [21]. Given space constraints the climate of Belfast is focused on in this study for which a TER of 2.65 was previously reported for a cavity wall construction [21]. TERs of 0.93 and 0.58 are reported for light and heavy constructions for the climate Madrid [21].

A number of heating strategies are presented, although again, these are limited to an illustrative selection of cases. Three cases are presented; all use a setpoint during occupied hours of 294 K (21°C). The first case assumes 24 hour heating, every day, to maintain this setpoint; the second assumes that the building is occupied from 9am to 5pm and unheated outside these hours (simulating a typical office), and the third case assumes heating from 6am to 8am and 6pm to 10pm (simulating a domestic building with occupants away during the day and turning the heating off at night). Values of use energy in all cases assume that active heating is only employed between October and March. Although the indoor temperature falls below 294 K outside these months, from April to September heating energy use is much more variable. Some occupants will not use active heating at all, some may maintain 294 K as a minimum year-round, and the energy needed to maintain any particular setpoint will be more dependent on building form and airtightness during periods of high solar gain and greater ventilation.

3. RESULTS

3.1 Embodied energy as a contribution to total lifetime energy use of walls

Values of the embodied energy for each material are mostly taken from[22], except where noted. These values are used to produce a value of embodied energy for each wall, with a factor (2%) applied to account for site work, fixings, etc[23]. The calculation of the embodied energy for each is shown in Table 2, where only the mean values are shown for clarity. Full material

TABLE 2. Embodied energy material data and wall buildups; the first two embodied energy columns are for the materials, provided on a per-mass and per-volume basis. 2% was added to the final value for all walls to account for site work. The sources for all material data are given in Appendix A.

Wall (U-value)	Material	Thickness	Embodied Energy (mean)	Embodied Energy	Embodied Energy (wall)
$Wm^{-2} K^{-1}$		mm	MJ/kg	MJ/m^3	MJ/m^2
Solid blockwork (3.3)	Plaster Blockwork Cement render	12.5 250 20	1.81 2.18 1.33	2353 3052 2657	867
	Total	*282.5*			
Cavity (0.23)	Brick Mineral wool Blockwork Polystyrene (XPS)	102 150 100 40	3 21.3 2.18 92.9	4724 1708 3052 3112	1280
	Plaster	12.5	1.81	2353	
	Total	*404.5*			
Straw bale (0.15)	Plaster Straw Lime Render	12.5 450 40	1.81 0.24 1.05	2353 42 1680	117
	Total	*502.5*			
Insulated concrete formwork (0.21)	Plaster Polystyrene (XPS) Concrete XPS Cement render	12.5 120 320 120 20	1.81 92.9 2.18 92.9 1.33	2353 3112 4478 3112 2657	2306
	Total	*592.5*			

data used, including the minimum and maximum values, and the data sources, is given in Appendix A.

The use energy for each wall is calculated using a finite element model, as described in the methodology section. Initially, heat flow through the walls is modelled assuming that they are used in a building with a 24 hours per day heating regime over winter. In this case, a pseudo-steady-state model, based on the U-value, gives the correct result for heat loss through the wall (although the dynamic properties affect the peak power requirements, they do not affect the total energy flow—see [21].) The U-value for each wall is presented in Table 2.

The embodied energy values are shown in Figure 2. Two things are striking about this chart: first, the difference in embodied energy between the lowest value (straw bales) and the highest (insulated concrete formwork); and secondly, the huge range of uncertainty for each wall type: a factor of 6 for the cavity wall, 4.5 for the ICF wall, and nearly 10 for the solid blockwork wall. These uncertainties are based on the maximum and minimum values of embodied energy found in [22], and reasonably conservative maximum and minimum values of density (i.e. not especially extreme values). Error bars are not shown for the straw wall as the ICE database contains only one value. (As a point of note, the ICE database for straw contains an error concerning the maximum value and the standard deviation; it is not within the remit of this paper to redo the embodied energy analysis for these materials.) It is unclear at present if the range displayed represents the genuine range of embodied energies, or if it reflects fundamentally incompatible methodologies between different studies; but what is clear, is that much more robust methods of assessment and standardisation are needed for embodied energy analysis (whether based on [14] or another method).[2]

The difference between the wall types is dramatic when compared on any basis: whether mean, minimum or maximum embodied energy values. The mean value for the ICF wall is 20 times that of the straw wall, and the straw wall also has a lower U-value. The low value of the straw wall does not include an allowance for framing (nor does it for the other wall types, but greater framing might be needed for this wall type than for the others). Adding a timber frame[3] would add 85 MJ/m^2 of embodied energy to the wall.[4] Even with such a substantial frame, the render and plaster together would be the largest contribution to the overall embodied energy. The straw itself contributes only a small fraction, and it could be made thicker with little impact on the embodied energy. By contrast, with the ICF wall, the concrete layer contributes the greatest part (seen in Table 2), and a reduction in concrete thickness would substantially reduce the impact of this wall type.

The heat loss through each wall is shown in Table 3. Clearly, the operational energy for the solid wall is very much higher than for the other wall types. The other wall types exhibit slight differences, as is expected from the difference in U-values. Of most interest, however, is the comparison between these values and the embodied energy: this comparison is given in Figure 3, which shows the total energy use against time, and in Figure 4, which shows how the contributions of embodied and use energy vary. The latter figure is particularly instructive: whilst the operational energy dominates the total energy consumption for the straw wall and the solid masonry wall in less than 10 years, to reach the same point takes around 25 years for the cavity wall, and nearly 60 years for the ICF wall.

2. As an example, the values for embodied energy of general concrete quoted in [22] range from 0.07 MJ/kg to 92.5 MJ/kg; surely such a range reflects errors with the data, since such a large range does not seem feasible. In this work, the ICF wall is modelled using the figures for precast concrete.

3. Using data for red fir, Oregon fir, and assuming a frame comprising 150 mm square timbers at 1 m centres

4. Mean value 85, minimum 8.5, maximum 153 MJ/m^2

FIGURE 2. Embodied energy values for sample walls, showing the very wide range of energies embodied by these construction types, and the uncertainty in the values.

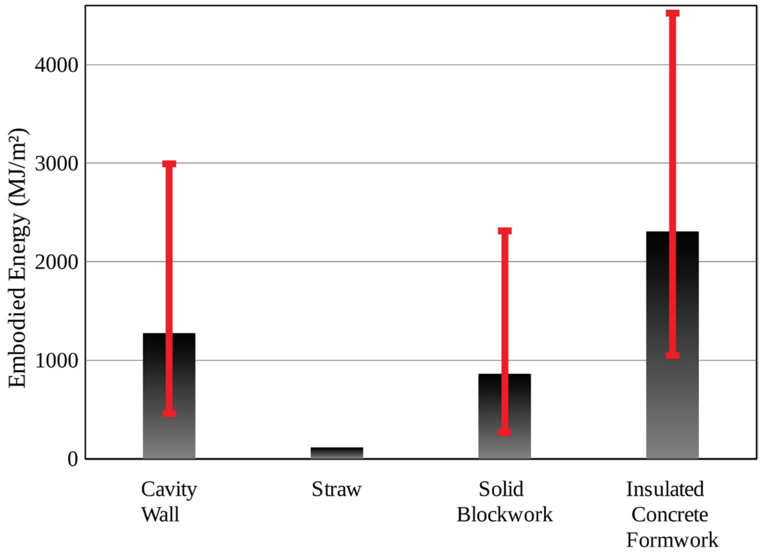


TABLE 3. Annual operational energy loss through sample walls.

Wall type	Operational energy (MJm^{-2}/year)	
	24 hour heating	am-pm heating
Cavity	48	32
Straw bale	31	18
Solid masonry	673	186
Insulated concrete formwork	44	27

These graphs show useful information about optimising the design of the wall build-ups with respect to the design lifetime. For 24 hour heating each winter and a building lifetime of 100 years, these walls would all benefit from enhanced insulation. However, for a lifetime of less than 50 years, adding insulation to the ICF wall would increase the total energy use, as the greater embodied energy would not be outweighed by the savings in heating. For a lifetime of less than 25 years, the same thing would be true for the cavity wall.

This analysis, indicating substantial benefits of extra insulation for all walls at medium to long timescales, is perhaps not surprising; but the figures change significantly once more realistic heating schedules are modelled. For instance, modelling morning and evening heating only, such as might be typical of a working household,[5] means the contribution from operational energy is lower. This scenario is shown in Figure 5: with the wall thicknesses modelled, at 100 years the contribution of embodied energy in the case of the solid masonry and straw walls is less than 10%, but still in the region of 50% for the ICF wall.

5. Assuming the heating is on from 06:00–08:00 and 18:00–22:00 each day

FIGURE 3. Total energy use over a building's lifetime per square metre of wall area (use case 1: 24 hour occupancy).

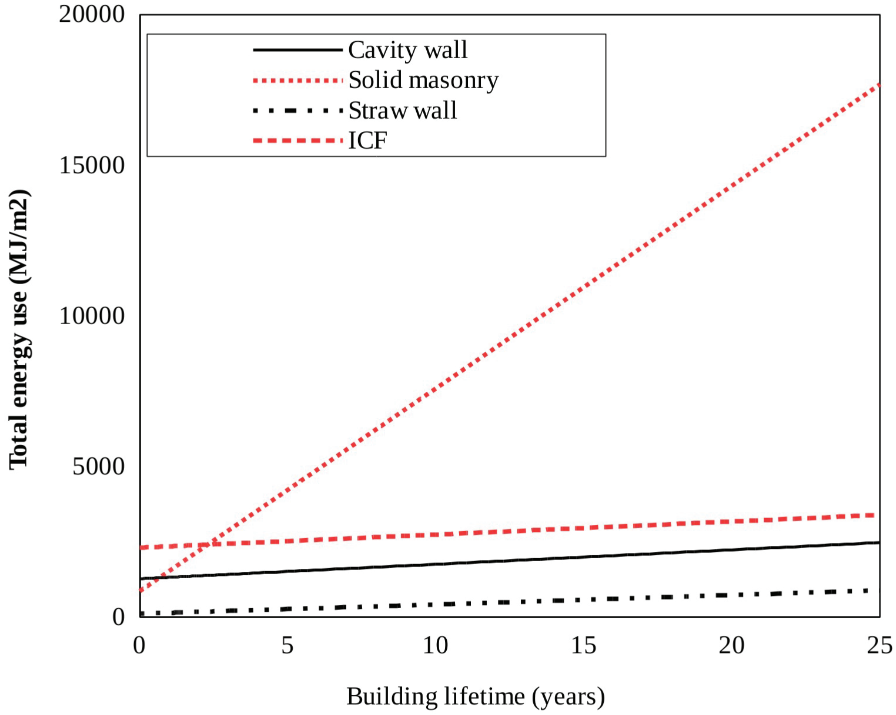
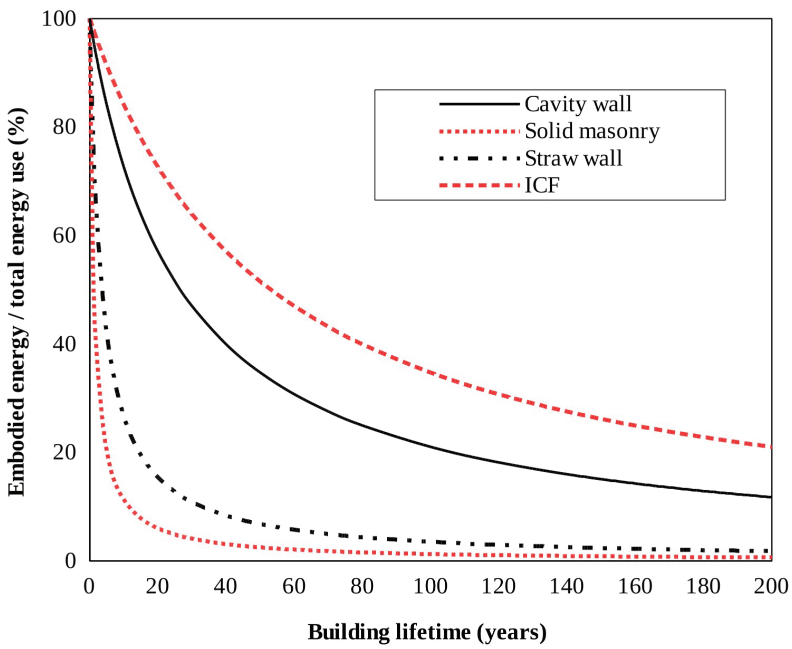


FIGURE 4. Variation of embodied energy as a proportion of total energy use over a building's lifetime (24 hour occupancy). This assumes no renovation or retrofit (this would result in an upwards spike/steep upwards slope during renovation).



In finding an optimum balance between embodied and operational energy, this work agrees with the qualitative conclusions from case study approaches, which generally have found that zero-operational-energy buildings often have greater lifetime energy use than low-energy-buildings, owing to the very large embodied energy requirements for zero-energy or self-sufficient buildings. [4][42]

The precise results will clearly vary substantially, and the exact values for any particular building should be calculated at the design stage, but it is not accurate to neglect the embodied energy as a minimal contribution to the overall impact of a building. As an illustration of the uncertainty in the results, as a consequence of the range of data regarding embodied energy (and to a lesser extent, thermal properties), Figure 6 shows a similar calculation to Figure 4, but showing instead the maximum and minimum curves calculated for the cavity wall. (These are based on the maximum annual operational energy coupled with the minimum embodied energy value, and vice versa—the minimum operational energy is found by using values at the lower end of the range for thermal conductivity, etc.) Figure 6 shows the building lifetime at which the heat lost through the wall becomes equal to the energy embodied in the wall, indicated by the blue line: based on the data available in the literature, this could range from 15 years to nearly 80 years. Unfortunately, few individual studies present estimates of the uncertainty in their data; some of this range likely reflects errors rather than genuine variance in material properties.

3.2 Embodied energy in the context of wall retrofit

This section examines the interaction between embodied energy and operational energy in the context of retrofit. The old wall example is the solid blockwork wall from the previous section; three proposals are modelled that might be suggested to improve the thermal performance of this wall. These are:

FIGURE 5. Variation of embodied energy as a proportion of total energy use over a building's lifetime: morning and evening occupancy (again, assuming no renovation or retrofit).

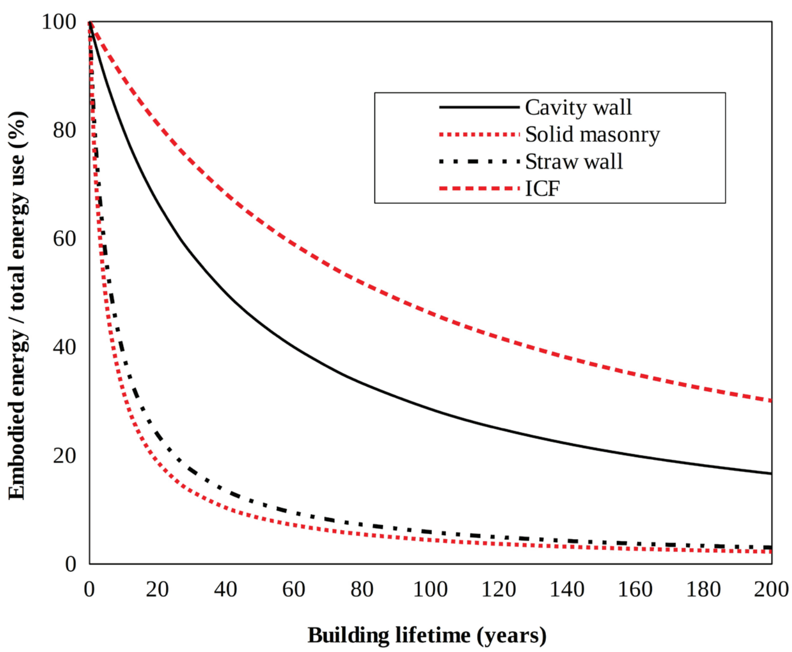
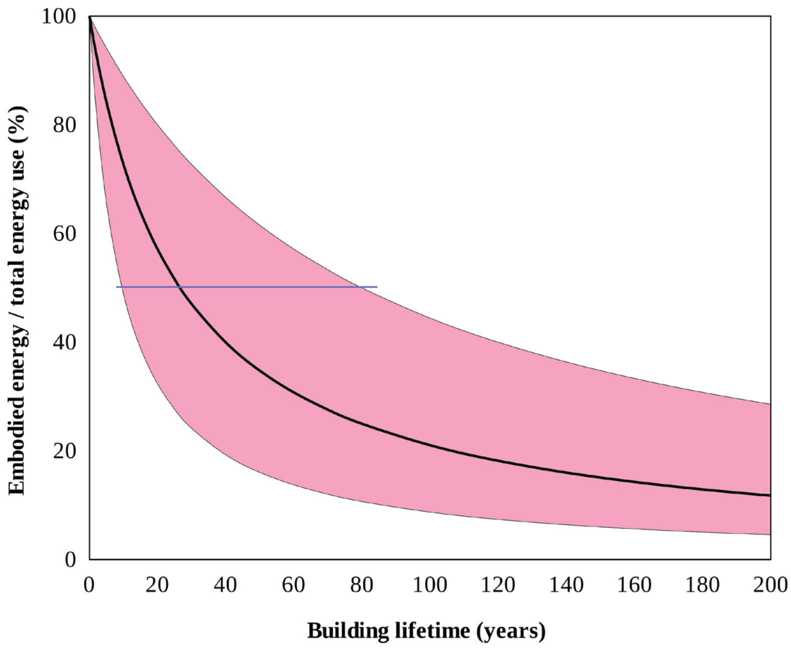


FIGURE 6. Uncertainty in data. Shaded area covers the range of possible values for the cavity wall, given literature data for thermal properties and embodied energy.



1. the addition of 190 mm of mineral wool to the interior of the wall, bringing the U-value down to 0.21 $W/m^2/K$ (as would comply, for example, with UK and Irish building codes);
2. the addition of 332 mm of mineral wool to the interior (U-value 0.13, below the Passivhaus backstop standard);
3. addition of 332 mm of extruded polystyrene insulation to the exterior of the wall (U-value 0.10, keeping the same thickness as the previous case for comparison).

Figure 7 shows the embodied energy of these three suggested retrofits. (The figure shows the total embodied energy, including 862 MJm^{-2} for the original wall.) As in the first study, the range of values is dramatic. It is also clear that the polystyrene insulation has a higher embodied energy than the mineral wool.

Adding insulation increases the embodied energy, but also reduces the energy used in heating. The most important aim is not to simply lower the in-use energy consumption of buildings, but to lower the total energy use over the building's life. The use energy depends on the occupancy pattern of the building, as most buildings are not occupied continuously. In such cases, the dynamic thermal performance also enters into the calculation. This has been incorporated into these studies using the transient energy ratio method (described in the Methodology section). The operational energy for these walls is shown in Table 4.

The total energy use (i.e. the embodied energy plus annual heat loss) is plotted in Figures 8 and 9.

In Figure 8, even though the XPS insulation results in a significantly lower U-value than the mineral wool, thanks to its higher embodied energy the total energy use of the two walls only becomes equal at around 75 years.

The difference in performance between these two walls essentially disappears when intermittent heating schedules are considered (21.2 vs. 19.8 MJm^{-2}/year), and mineral wool has a lower total energy than XPS for any building lifetime (at least until 4000 years).

With a morning and evening heating schedule, even going from a U-value of 0.21 to 0.13 with mineral wool appears to offer only a marginal benefit, if any. Figure 9 shows these two cases, and they offer essentially identical overall performance, within the margin of error of the data; the total energy consumption of these two retrofit strategies differs by less than 5% after 100 years.

Of course, compared to no a solid wall, any retrofit is worthwhile. A comparison between the pre- and post-retrofit cases is shown in Figure 10, showing that compared to the solid blockwork wall, any insulation at all will be beneficial, even over 10 years or less.

Frequency of refurbishment and impact on embodied energy Whilst it is apparent that refurbishment of the solid wall in this example would be beneficial, the optimum choice of refurbishment strategy is not at all clear. This analysis shows that increasing the thickness of

FIGURE 7. Embodied energy values for a solid masonry wall, and two examples of retrofit to reduce the U-value of this wall.

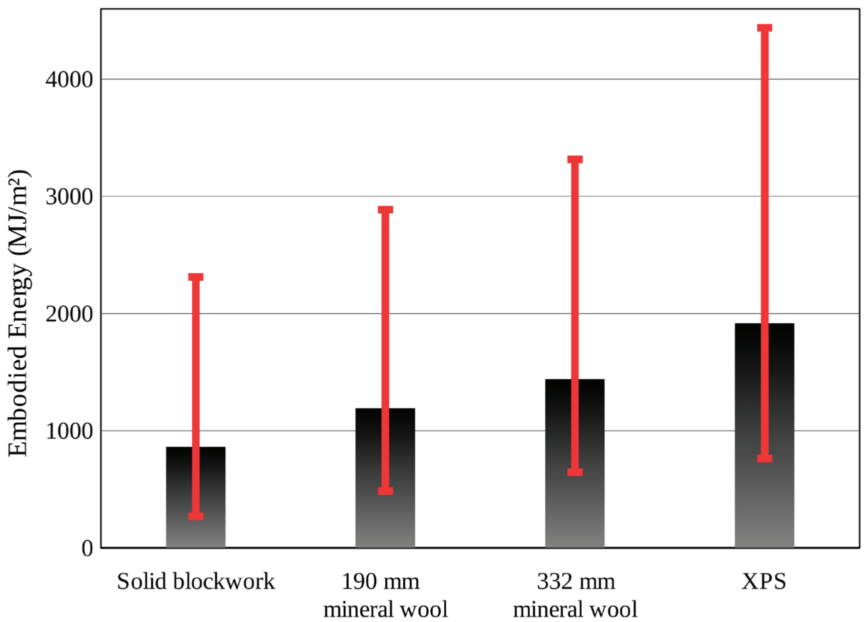


TABLE 4. Operational energy use before and after retrofit.

Wall type	Use energy: 24-hour heating (MJm^{-2}/year)	Use energy: am-pm heating (MJm^{-2}/year)
Solid masonry	673	186
190 mm mineral wool	43.4	23.6
332 mm mineral wool	26.8	21.2
332 mm XPS	20.7	19.8

FIGURE 8. Total energy use over a building's lifetime per square metre of wall area (use case 1: 24 hour occupancy; U-values for each wall are given after the key in the legend).

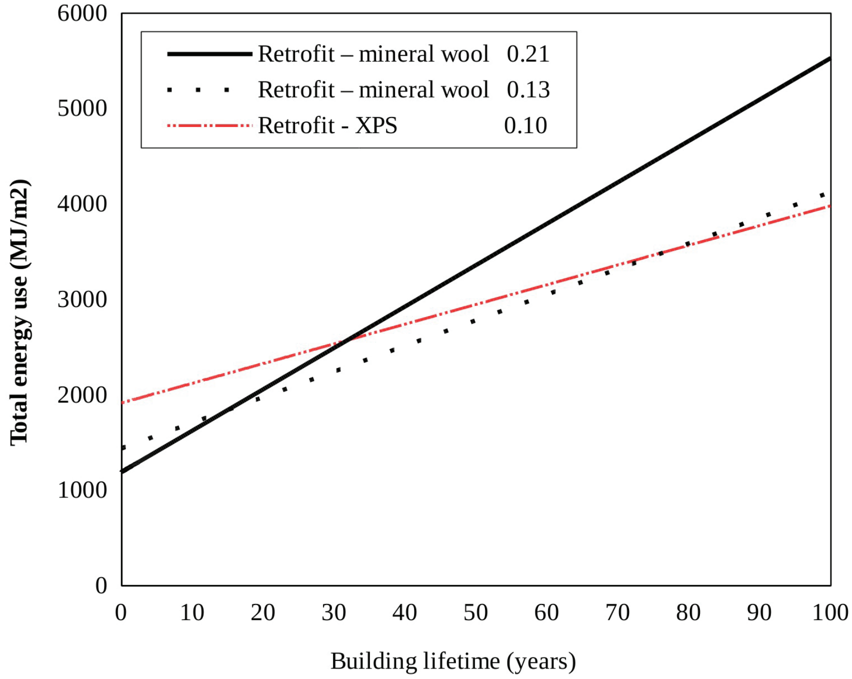


FIGURE 9. Total energy use over a building's lifetime per square metre of wall area (use case 2: am-pm occupancy (06:00–08:00 and 18:00–22:00)).

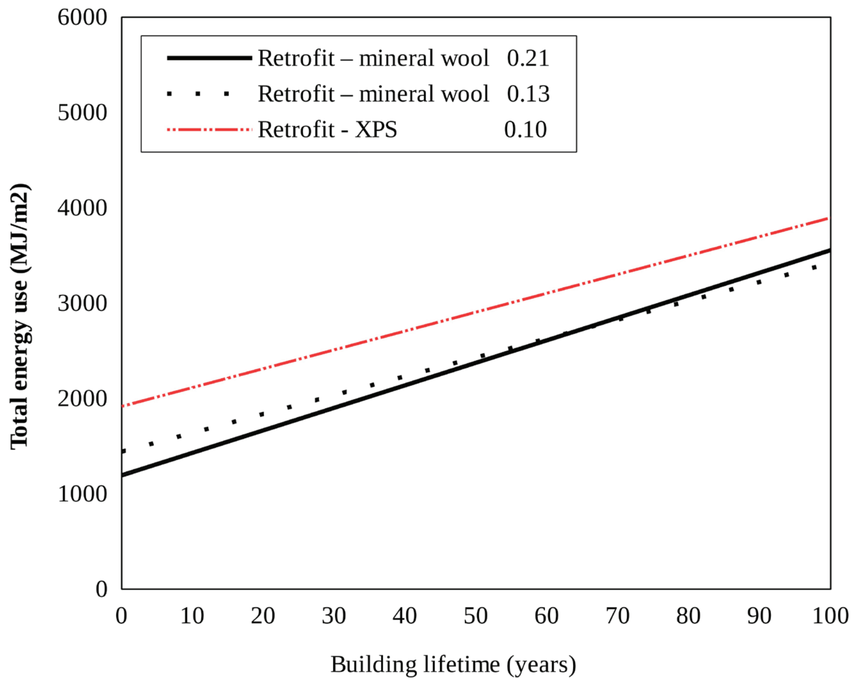
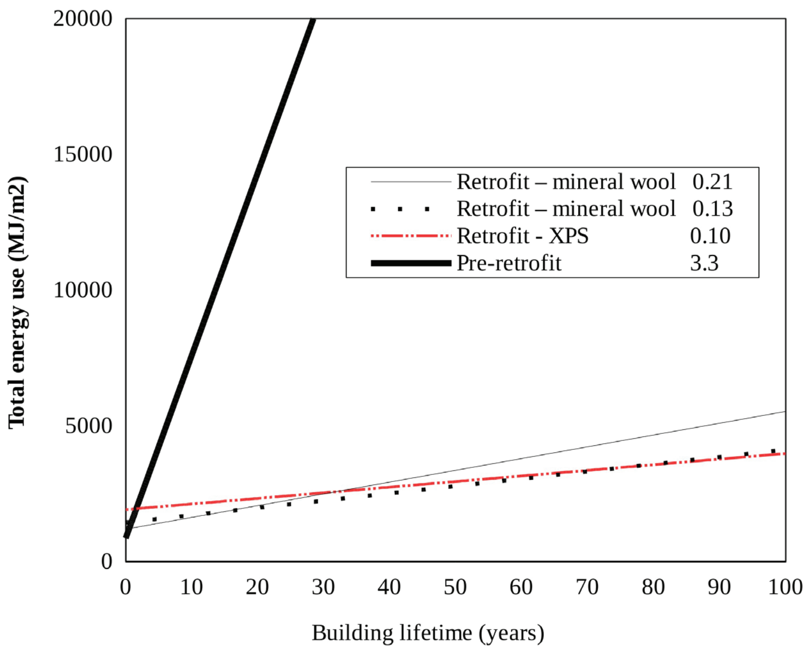


FIGURE 10. Total energy pre- and post-retrofit (use case 1: 24 hour occupancy.



mineral wool from 190 mm might only be of benefit after 65 years or so (in the case of morning and evening occupancy), while switching to XPS insulation would have a higher overall energy consumption than using mineral wool for the first 80 years, even with 24 hour/day heating. 30 years is sometimes taken as the lifetime of refurbishment for commercial property[43]; and a study looking at the 2050 carbon reduction targets in the UK suggests that multi-stage refurbishments are likely before then (for residential property)[44]. Based on the data used in this study, with morning and evening heating, it would take nearer 200 years for the overall energy use of the XPS retrofit to be lower than that of the 190 mm mineral wool retrofit—which is very likely to be longer than the lifetime of the building, and certainly longer than the lifetime of the insulation without further refurbishment.

The lifetime and degradation of the insulation materials may be a factor in the frequency of refurbishment; sources claim everything from lifetimes of less than 20 years to more than 100. Many studies of insulation products mention the service life as a key concern but then do not go on to address the matter again[45]. Authors conducting rapid aging tests have concluded that XPS and fibreglass insulation retains 97% of its performance over time[46]; however, others have found performance losses in expanded foams of around one third after only 10 years[47]. If the building is refurbished on even a moderately frequent basis—say, every 100 years—then it appears likely (from Figure 9) that XPS would result in greater energy use than mineral wool, even given its superior performance.

4. CONCLUSIONS AND EVALUATION

4.1 Evaluation of present study

Embodied energy/carbon has gained prominence in recent years as a building energy research topic. Review of a selection of recent literature [48–54], highlights a wide and varied range of methodologies used for the calculation of embodied values. The review paper by Azari and Abbasabadi [51] attests to this and underscores the challenge in reporting definite representative values of embodied energy for buildings. Variation in embodied energy content is often and rightly ascribed to inconsistent system boundaries, different embodied energy estimation methods, inconsistent technological and geographical representativeness, and data sources and quality variations [51]. However, a driving motivation for this study is to develop a methodology of embodied energy quantification for a component of building—in this case the building envelope. It thereby enables more focused evaluation of the embodied and operational energy balance within a localised area of the building, and hence can inform (in this case, envelope) design decisions.

Values per m^2 of wall are in a comparable range to values reported per m^2 building, but are not directly comparable. Envelope embodied energy values (listed in this study) quantify the embodied energy of the materials in a m^2 of wall area whereas the embodied energy values for the whole building encompass values averaged for the envelope as well as finishes, floors, roofing and sub and possible envelop-separate superstructure. A previous whole building energy analysis from Ireland [56] reports walls as representing approximately 30–40% of the overall building EE total, for a number of variations of a case study home and a value of 3.62 GJ/m^2 for the base case. Aktas and Bilec report values in the range 1.7–7.3 GJ/m^2 [55] and Ding and Ying report values in the range 3.6–8.76 GJ/m^2 [52] for whole building embodied energy conventional and existing residences. This study reports values 0.1–2.3 GJ/m^2 (107–2306 MJ/m^2 in Table 2) for the range of different wall types, with those values for cavity (1.28 GJ/m^2) wall and ICF (2.3 GJ/m^2) construction being more representative of conventional and contemporary low energy designs. Low energy buildings, designed to more stringent standards than those adhered to in this study, commonly report higher embodied energy. This is typically attributed to increased thickness of building skins, and necessary additional insulation [55].

The studies here show the energy use per metre squared of wall area. It is important to stress what this is not: it is not an energy use per square metre of floor area for the building, nor is it a total energy use from all sources. It does not include heating energy due to heat lost through floors and roofs, nor does it account directly for ventilation losses and infiltration. It also makes no allowance for not-heating sources of energy use such as lighting and other services. However, by abstracting the embodied and heat flow losses for the walls alone, these values provide a direct comparison between the different wall construction methods. As a result, these values can be used to compare the influence of wall type directly: for example, the likely impact of changing XPS to glass wool insulation in a retrofit. Of course, other components of the building may change, the assumptions made in making these calculations may be wrong for a particular building, and for any design purposes or other comparisons of individual buildings, more detailed calculations must be made. Where manufacturers have carried out embodied energy studies, greater visibility of these at the design stage would allow designers to include embodied energy as a factor in the design process, rather than adding it on as an analysis once all the major design decisions have been taken.

4.2 Conclusions

For the typical cavity wall analysed in this study, in this use case, about 50% of the total energy is in the form of embodied energy at 50 years. This would be a typical design lifetime for commercial buildings, and this result shows that the embodied energy is not necessarily a secondary concern. For buildings with shorter lifetimes, the search for ever lower U-values and 'better-performing' walls may, in fact, be counter-productive. For a design lifetime of 40 years or less, it may in fact be better to build a wall with less insulation rather than more, as this could lead to a lower total energy use over the expected lifetime of the building. This calls into question the appropriateness of revisions to building regulations (such as Part L in the UK and Ireland), which are frequently revised to specify lower U-values, without (at present) any consideration of embodied energy.

Building form is dictated by many things besides thermal comfort and energy use. Form, security, aesthetics, cost and many other factors are involved, and many of these often take precedence over thermal comfort and energy use. While such constraints may prevent a design team from considering the energy use benefits of, for example, a straw bale wall, there is usually much greater freedom to specify the insulation type, even if the overall construction methodology is fixed by other constraints. While the best wall form, insulation thickness, and insulating materials, will all vary between projects and depend on project-specific factors, a few general conclusions can be drawn. Although synthetic polymer insulation performs very well, and enables very low U-values to be achieved with minimal thicknesses of insulation, the embodied energy costs can be very high. Other insulating materials such as rock wool may offer 'good enough' performance, coupled with lower embodied energy values (and hence, lower carbon dioxide emissions associated with construction). For many buildings, it is very likely that the energy use savings achievable through the use of large quantities of synthetic polymers may not offset the greater energy that goes into their construction, at least for many commercial buildings with comparatively short lifetimes. Rather than chasing ever lower U-values, a better solution might be to ensure that buildings are adaptable and may be easily reused for different purposes, thus extending their likely lifetimes. Unfortunately, this is often beyond the remit of the design team, and changes to taxes and legislation are probably needed to see much progress in this area.

Similar considerations apply when considering the benefits and drawbacks of retrofit. While some retrofits are very worthwhile, others will be questionable, or even demonstrably a waste of resources. For example, pulling out mineral wool in good condition and replacing it with an equal thickness of extruded polystyrene might result in a slight reduction in U-value, but will probably never recoup the embodied energy cost. Similarly, there are likely some buildings that are structurally sound and have undergone multiple retrofit projects in the past, being updated to reflect more stringent standards each time. If this is done, say, every 20 years, it is likely that the embodied energy costs of the retrofit outweigh the gains; and the contribution of embodied energy to the total energy use of such a building could be greater than the contribution from operational energy.

Modelling the embodied energy contributions at the design stage is made more difficult by the lack of reliable, comparable data. The enormous variability of the embodied energy data remains a source of uncertainty; and given the importance of embodied energy and its impacts on climate change, this needs to be addressed. As Figure 6 shows, much more accurate data is needed before general conclusions can be made with reliability.

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APPENDIX

Material name	Key	Density—kg/m3			E.E.—MJ/kg			Conductivity—W/m/K			Spec. heat cap.—J/kg/K		
		min	mean	max	min	mean	max	min	mean	max	min	mean	max
Brick (masonry)	1	1049	1574.5	2100	0.63	3	6	0.32	0.71	1.1	840	840	840
Blockwork	2	600	1400	2300	1.2	2.18	3.8	0.19	0.56	1.63	837	840	1000
Mineral wool	3	80	80	80	14	21.34	37	0.045	0.045	0.045	840	840	840
Extruded polystyrene	4	25	33.5	42	58.4	92.9	149.35	0.027	0.0335	0.04	1340	1405	1470
Concrete	5	1551	2053	2341	1.2	2.18	3.8	0.593	1.5745	3.207	633	840	1000
Plaster	6		1300		1.4	1.81	9.73		0.52			840	
Cement render	7		1998			1.33			0.99			1000	
Lime render	8		1600			1.05			0.7			1000	
Straw	9		175			0.24			0.05			180	
Timber: Red fir, oregon fir, dry, density 524	10		524		0.72	7.2	13		0.14			2280	

Key	Rho—kg/m3		
	min	mean	max
1	[12], p60—Masonry (mediumweight)	mean of < and >	[12], p60—Masonry (heavyweight)
2	[12], p54—Conc., lightweight block	[12], p54—Conc. Block, Mediumweight	[12], p54—Conc., heavyweight block
3	[12], p43—mineral wool, cavity insulation	[12], p43—mineral wool, cavity insulation	[12], p43—mineral wool, cavity insulation
4	[12] p46	mean of < and >	[12] p46
5	[12] p59, Leeds values, min	[12] p59, Leeds values, median	[12] p59, Leeds values, max
6		[12] p50, first value, 'plaster'	
7		[12], p50, Leeds study, cement:sand 1:3	
8			
9		[12], p.67, straw, compressed	
10		Values for samples of timber at this density	
Key	**Ee—MJ/kg**		
	min	**mean**	**max**
1	[14] clay and bricks tab, general clay bricks	[14] clay and bricks tab, general clay bricks	[14] clay and bricks tab, general clay bricks
2	[14] concrete tab, precast	[14] concrete tab, precast	[14] concrete tab, precast
3	[14] miscellaneous tab	[14] miscellaneous tab	[14] miscellaneous tab
4	[14] polystyrene (plastics tab)	[14] polystyrene (plastics tab)	[14] polystyrene (plastics tab)
5	[14] concrete tab, precast	[14] concrete tab, precast	[14] concrete tab, precast
6	[14] plaster tab, min	[14] plaster tab, quoted value for general plaster	[14] plaster tab, max (virgin plaster)—see comments in ICE database
7		[14] cement tab, cement:sand mortar 1:3 ratio	
8			
9		[14] miscellaneous tab	
10	[14] timber tab, sawn softwood	[14] timber tab, sawn softwood	[14] timber tab, sawn softwood
Key	**K—W/m/K**		
	min	**mean**	**max**
1	[12], p60—Masonry (mediumweight)	mean of < and >	[12], p60—Masonry (heavyweight)
2	[12], p54—Conc., lightweight block	[12], p54—Conc. Block, Mediumweight	[12], p54—Conc., heavyweight block
3	[12], p43—mineral wool, cavity insulation	[12], p43—mineral wool, cavity insulation	[12], p43—mineral wool, cavity insulation

Key	K—W/m/K		
	min	mean	max
4	[12] p46	mean of < and >	[12] p46
5	[12] p59, Leeds values, min	[12] p59, Leeds values, median	[12] p59, Leeds values, max
6		[12] p50, first value, ‘plaster’	
7		[12], p50, Leeds study, cement:sand 1:3	
8			
9		[12], p.67, straw, compressed	
10		[12] p68, Red fir, oregon fir	
		Cp—J/kg/K	
Key	min	mean	max
1	[12], p60—Masonry (mediumweight)	[12], p60—Masonry (mediumweight)	[12], p60—Masonry (mediumweight)
2	[12], p.54	[12], p.54	[12], p.54
3	[12], p42—mineral wool	[12], p42—mineral wool	[12], p42—mineral wool
4	[12] p46	Mean of min and max values	[12] p46 (highest value)
5	[12], p58/59, min	[12], p58/59, most common value in terms of records	[12], p58/59, max
6		[12] p50, first value, ‘plaster’	
7		[12] p51, render	
8		[12] p51, render	
9		[12], p.67, straw thatch	
10		[12] p68, Red fir, oregon fir	

Key Comments	
1	
2	ICE database gives a range for EE of 0.07 to 92.5 for general concrete
3	
4	EE data differs from the data in [14] insulation tab; range of density and thermal properties available—single values used for present study
5	ICE data is not specific to extruded—is either expanded or plain polystyrene
6	Using values for precast because the ICE database gives a range for EE of 0.07 to 92.5 for general concrete
7	
8	
9	
10	Straw values contain a clear error in the ICE database, which is probably a typographical error or other error in data entry

B. Weather Data

Representative Belfast data for the period 1981–2010 [57].

January	7.9	2.2	7.5	40.6	90.4	14.7
February	8.3	2.1	7	64.7	64.8	11.4
March	10.2	3.5	3.6	94.7	78	13.8
April	12.4	4.7	1.9	140.2	64.6	11.4
May	15.4	6.9	0.3	181.9	62.9	11.8
June	17.9	9.8	0	151.5	67	11.2
July	19.7	11.7	0	148.8	66	12.1
August	19.3	11.5	0	140.1	86.2	13.4
September	17.1	9.6	0	113.6	77.1	12.3
October	13.6	7	0.8	84.8	98.4	14.4
November	10.3	4.2	4.2	51.7	96.3	14.5
December	8.2	2.3	7.3	34.3	92.2	14.4
Annual	13.4	6.3	32.6	1246.9	944.1	155.5

REFERENCES

1. M. Allen et. al. *Global Warming of 1.5 C*. IPCC, early draft 06-10-2018 edition, 2018.
2. Barbara Rossi, Anne-Fran¸coise Marique, Mauritz Glaumann, and Sigrid Reiter. Life-cycle assessment of residential buildings in three different european locations. *Building and Environment*, 2012.
3. Luisa F. Cabeza, Lidia Rincon, Virginia Vilarino, Gabriel Perez, and Albert Castell. Life cycle assessment (lca) and life cycle energy analysis (lcea) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews*, 29:394–416, JAN 2014.
4. T. Ramesh, Ravi Prakash, and K.K. Shukla. Life cycle energy analysis of buildings: An overview. *Energy and Buildings*, 42(10):1592–1600, 2010.
5. Mahsa Karimpour, Martin Belusko, Ke Xing, and Frank Bruno. Minimising the life cycle energy of buildings: Review and analysis. *Building and Environment*, 2014.
6. Aashish Sharma, Abhishek Saxena, Muneesh Sethi, Venu Shree, and Varun. Life cycle assessment of buildings: A review. *Renewable and Sustainable Energy Reviews*, 15(1):871–875, 2011.
7. Nwodo and Anumba. A review of life cycle assessment of buildings using a systematic approach. *Building and Environment*, 2019.
8. Rosa M. Cu´ellar-Franca and Adisa Azapagic. Environmental impacts of the UK residential sector: Life cycle assessment of houses. *Building and Environment*, 54:86–99, 2012.
9. Luis P´erez-Lombard, Jos´e Ortiz, and Christine Pout. A review on buildings energy consumption information. *Energy and Buildings*, 40(3):394–398, 2008.
10. Michael N. Grussing. Life cycle asset management methodologies for buildings. *Journal of Infrastructure Systems*, 2014.
11. BSI Group. BS EN 15978:2011: Sustainability of Construction Works. Technical report, BSI Group, 2011.
12. RICS Valuation—Professional Standards 2012. Technical report, Royal Institution of Chartered Surveyors, 2012.
13. European Committee for Standardization. TC 350: Sustainability of construction works. Technical report, European Committee for Standardization, 2003.

14. International Organization for Standardization, Geneva, Switzerland. ISO 14040:2006: Environmental management: Life cycle assessment principles and framework, 2006.
15. BS EN 15804:2012+A1:2013: sustainability of construction works. environmental product declarations. core rules for the product category of construction products.
16. International Organization for Standardization, Geneva, Switzerland. ISO 14044:2006: Environmental management—life cycle assessment—requirements and guidelines, 2006.
17. Manish K. Dixit, Charles H. Culp, and Jose L. Ferna´ndez-Sol´ıs. System boundary for embodied energy in buildings: A conceptual model for definition. *Renewable and Sustainable Energy Reviews*, 21:153–164, 2013.
18. J. Monahan and J.C. Powell. An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework. *Energy and Buildings*, 43(1):179–188, 2011.
19. I. Sartori and A.G. Hestnes. Energy use in the life cycle of conventional and low-energy buildings: A review article. *Energy and Buildings*, 39(3):249–257, 2007.
20. Catherine De Wolf, Francesco Pomponi, and Alice Moncaster. Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice. *Energy and Buildings*, 140:68–80, 2017.
21. A. Reilly and O. Kinnane. The impact of thermal mass on building energy consumption. *Applied Energy*, 198:108–121, 2017.
22. G.P. Hammond and C.I. Jones. Inventory of Carbon and Energy. Database, Sustainable Energy Research Team, University of Bath, 2011.
23. IStructE. Building for a Sustainable Future: Construction without Depletion, 1999.
24. J. A. Clarke, P. P. Yaneske, and A. A. Pinney. The Harmonisation of Thermal Properties of Building Materials. BRE publication, BEPAC research report, pub. Energy Simulation Research Unit, Department of Architecture and Building Science, University of Strathclyde, and Building Research Establishment, Watford., 1990.
25. Fernando Dom´ınguez-Mun˜oz, Brian Anderson, Jos´e M. Cejudo-Lo´pez, and Antonio Carrillo-Andr´es. Uncertainty in the thermal conductivity of insulation materials. *Energy and Buildings*, 42(11):2159–2168, 2010.
26. J. Andersons, M. Kirpluks, L. Stiebra, and U. Cabulis. Anisotropy of the stiffness and strength of rigid low-density closed-cell polyisocyanurate foams. *Materials & Design*, 92:836–845, 2016.
27. Callum Hill, Andrew Norton, and Janka Dibdiakova. A comparison of the environmental impacts of different categories of insulation materials. *Energy and Buildings*, 162:12–20, 2017.
28. Farshid Shadram and Jani Mukkavaara. An integrated bim-based framework for the optimization of the trade-off between embodied and operational energy. *Energy and Buildings*, 158:1189–1205, 2018.
29. A Reilly and O Kinnane. An assessment of the thermal storage capacity of hemp-lime using the transient performance ratio method. In *2nd International Conference on Bio-based Building Materials, ClermontFerrand*, 2017.
30. International Organization for Standardization, Geneva, Switzerland. ISO 6946.
31. Met Office. UK Met Office historic data records, 2016.
32. International Organization for Standardization, Geneva, Switzerland. ISO 13786:2017: Thermal performance of building components—dynamic thermal characteristics—calculation methods.
33. Salonvaara M., Karagiozis A. N., and Pazera M. Air cavities behind claddings—what have we learned? In *Proceedings of the thermal performance of the exterior envelopes of whole buildings X*, 2007.
34. J. F. Straube and E. F. P. Burnett. Drainage, ventilation drying and enclosure performance. In *Thermal Performance of the Exterior Envelopes of Buildings VII*, 1998.
35. H. Hens, A. Janssens, W. Depraetere, J. Carmeliet, and J. Lecompte. Brick cavity walls: A performance analysis based on measurements and simulations. *Journal of Building Physics*, 31(2):95–124, 2007.
36. Marnix Van Belleghem, Marijke Steeman, Arnold Janssens, and Michel De Paepe. Heat, air and moisture transport modelling in ventilated cavity walls. *Journal of Building Physics*, 38(4):317–349, 2015.
37. Giacomo Villi, Wilmer Pasut, and Michele De Carli. Cfd modelling and thermal performance analysis of a wooden ventilated roof structure. *Building Simulation*, 2(3):215–228, Sep 2009.
38. A. Moret Rodrigues and L. Aelenei. Thermal performance of a naturally ventilated cavity wall. *International Journal of Energy Research*, 34(4):357–372, 2010.
39. Achilles Karagiozis, Hartwig M. Ku¨nzel, and Andreas Holm. Wufiornl/ibpa north american hygrothermal model. In *Performance of Exterior Envelopes of Whole Buildings VIII*, 2001.

40. M. C. Peel, B. L. Finlayson, and T. A. McMahon. Updated world map of the ko¨ppen-geiger climate classification. *Hydrol. Earth Syst. Sci.*, 11:1633–1644, 2007.
41. A. Reilly and O. Kinnane. A parameter for quantifying the transient response of walls to dynamic thermal loading. In *Advanced Building Skins, Bern, Switzerland*, 2016.
42. Ahmad Faiz Abd Rashid and Sumiani Yusoff. A review of life cycle assessment method for building industry. *Renewable and Sustainable Energy Reviews*, 45:244–248, 2015.
43. Som S. Shrestha, Mahabir S. Bhandari, Kaushik Biswas, and Andre O. Desjarlais. Lifetime energy and environmental impacts of insulation materials in commercial building applications. Technical report, Oak Ridge National Laboratory, USA, 2014.
44. Phil Jones, Simon Lannon, and Jo Patterson. Retrofitting existing housing: how far, how much? *Building Research & Information*, 41(5):532–550, 2013.
45. S. Schiavoni, F. D. Alessandro, F. Bianchi, and F. Asdrubali. Insulation materials for the building sector: A review and comparative analysis. *Renewable and Sustainable Energy Reviews*, 62:988–1011, 2016.
46. L. D. Stephenson, Andrew Heffron, Brenda B. Mehnert, Jedediah B. Alvey, Veera Boddu, Elizabeth J. Gao, Deborah J. Lawrence, and Ashok Kumar. Prediction of long term degradation of insulating materials. Technical report, US Army Corps of Engineers, 2015.
47. H.-J. Choi, J.-S. Kang, and J.-H. Huh. A study on variation of thermal characteristics of insulation materials for buildings according to actual long-term annual aging variation. *International Journal of Thermophysics*, 39(1):2, Nov 2017.
48. S.O. Ajayi, L.O. Oyedele, O.M. Ilori, Changing significance of embodied energy: A comparative study of material specifications and building energy sources, Journal of Building Engineering. 23 (2019) 324–333. https://doi.org/10.1016/j.jobe.2019.02.008.
49. J. Mourão, R. Gomes, L. Matias, S. Niza, Combining embodied and operational energy in buildings refurbishment assessment, Energy and Buildings. 197 (2019) 34–46. https://doi.org/10.1016/j.enbuild.2019.05.033.
50. G. Ding, X. Ying, Embodied and operating energy assessment of existing buildings—Demolish or rebuild, Energy. 182 (2019) 623–631. https://doi.org/10.1016/j.energy.2019.06.056.
51. R. Azari, N. Abbasabadi, Embodied energy of buildings: A review of data, methods, challenges, and research trends, Energy and Buildings. 168 (2018) 225–235. https://doi.org/10.1016/j.enbuild.2018.03.003.
52. F. Shadram, J. Mukkavaara, Exploring the effects of several energy efficiency measures on the embodied/operational energy trade-off: A case study of swedish residential buildings, Energy and Buildings. 183 (2019) 283–296. https://doi.org/10.1016/j.enbuild.2018.11.026.
53. I. Kovacic, J. Reisinger, M. Honic, Life Cycle Assessment of embodied and operational energy for a passive housing block in Austria, Renewable and Sustainable Energy Reviews. 82 (2018) 1774–1786. https://doi.org/10.1016/j.rser.2017.07.058.
54. A. Koezjakov, D. Urge-Vorsatz, W. Crijns-Graus, M. van den Broek, The relationship between operational energy demand and embodied energy in Dutch residential buildings, Energy and Buildings. 165 (2018) 233–245. https://doi.org/10.1016/j.enbuild.2018.01.036.
55. Aktas, C.B., Bilec, M.M. Impact of lifetime on US residential building LCA results. *International Journal of Life Cycle Assessment*, 17, 337–349 (2012). https://doi.org/10.1007/s11367-011-0363-x
56. Goggins, J., Moran, P., Armstrong, A. and Hajdukiewicz, M. Lifecycle environmental and economic performance of nearly zero energy buildings (NZEB) in Ireland. Energy and Buildings, 116, 622–637 (2016)
57. UK Met Office https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-climate-averages/gcey2u2y