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ENERGY ANALYSIS AND OPTIMAL INSULATION THICKNESS.

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ABSTRACT

The problem of optimal insulation thicknesses is one of the simplest that can be addressed by energy analysis. The authors begin with a simple analytical approach, and go on to describe detailed numerical work, based on the definition and parameterisation of a standard dwelling. Sensitivity of the results to large uncertainties in embodied energy data and building lifetime are investigated.

The first conclusion is that insulation thicknesses in UK buildings are sub-optimal in energy terms. This conclusion appears to be robust. Energy-optimised dwellings in the climate of the UK would use more than 90% less energy for space heating than dwellings built to current standards. The authors also show that the penalty for non-optimal design is asymmetric, with much larger penalties for sub-optimal insulation thicknesses, than for super-optimal thicknesses of insulation. This suggests that under conditions of uncertainty, it is rational to install more than the central estimate of optimal insulation thickness.

1 INTRODUCTION

Energy analysis was developed in the 1970's, particularly in the wake of the 1973/4 oil crisis. One of its most important functions then was to explore limits to the development of new energy technologies, which were difficult to establish with more conventional economic analysis. Examples of its use include analyses of the viability of extracting oil from oil shales, and analyses of problems posed by the rapid development of nuclear power.

In the 1970s and early 80s the central problems of energy policy were security of supply and the impending exhaustion of fossil fuels, and energy analysis focussed accordingly on primary energy requirements of goods and services. The over-riding concern since the mid 80s has been climate change. As a result, energy analysis has broadened to include the analysis of CO_2 emissions, and has effectively merged with the larger discipline of environmental impact analysis.

The main aim of this paper is to investigate the problem of insulation thicknesses that minimise i) energy use; and ii) CO_2 emissions over the lifetime of a typical dwelling. Raw data are drawn from a number of published sources, and a combination of analytical and numerical methods is used to explore uncertainties and provide insight into the structure of the problem.

2 METHODOLOGY

2.1 Availability of data

Data for this paper have been taken in the main from West et al [1]. This has been supplemented by data from [2], [3] and [4]. Comparisons between the various available sources must be made with care, not least because of methodological differences. In particular, West et al depart from most other sources by basing their estimates on delivered energy rather than primary energy use, and by excluding the embodied energy of the manufacturing systems used to produce building materials and components.

In spite of this, embodied energy figures from West et al. are broadly comparable with other sources. This may be put down to the fact that i) embodied energy content of manufacturing systems tends to be a small proportion of gross embodied energy, and ii) energy inputs to the production of building materials is primarily in the form of fuels, and the proportion of electricity is low [4].

There is some discussion in the literature over the accounting conventions that should be applied to timber [1],[5]. A proper treatment of timber requires analyses of alternatives to timber, both as a structural material, and increasingly in the future. as a fuel. In order to present a conservative analysis, the present authors have included the calorific value of timber in its energy requirement.

2.2 Optimum insulation thicknesses in masonry walls

In this section we attempt to address the question, when does adding insulation to a building become self-defeating, by consuming more energy or emitting more carbon in the production of the insulation than it saves? Firstly we address the question analytically. Let:

E	lifetime energy use (J/m² of envelope)
ΔT	mean inside-outside temperature difference (K)
t	insulation thickness (m)
e	embodied energy cost of insulation (J/m^3)
λ	conductivity (W/m/K)
L	life of building (s)
C	lifetime carbon emission ($kg(CO_2)/m^2$ of enevelope)
c_i	carbon intensity of thermal insulation ($kg(CO_2)/m^3$)
c_h	carbon intensity of space heat ($kg(CO_2)/J$)

Then ignoring the effects of thermal mass, internal heat gains and seasonality, and all edge and corner effects:

$$E = e.t + \Delta T.L.\lambda/t \qquad 1.$$

$$dE/dt = e - \Delta T.L.\lambda/t^2 \qquad 2.$$

lifetime energy use is minimised when dE/dt = 0; hence

$$t_{min} = \sqrt{(\Delta T.L.\lambda/e)} \qquad 3.$$

and

$$E_{min} = 2\sqrt{(\Delta T.L.\lambda.e)} \qquad \text{(with equal contributions from embodied and annual energy use)} \qquad 4.$$

West et al. [1] give a value for e of about 1 GJ/m^3 at densities appropriate for cavity wall construction. The conductivity of such materials would be approximately 0.04 W/mK. In the UK, $\Delta T \approx 10K$. If we assume a 100 year life for the building, then $t_{min} \approx 1.1$ m.

The analysis is easy to modify to minimise carbon emissions:

$$C = c_i.t + \Delta T.L.\lambda.c_h/t \qquad 5.$$

so

$$t_{C\,min} = \sqrt{(\Delta T.L.\lambda.c_h/c_i)} \qquad 6.$$

and

$$C_{min} = 2\sqrt{(\Delta T.L.\lambda.c_h.c_i)} \qquad \text{(again, with equal contributions from embodied and annual energy use)} \qquad 7.$$

The ratio c_i/e is the carbon intensity of energy used to make thermal insulation. In much of Europe, marginal space heating demand is supplied by natural gas with the lowest carbon intensity of all fossil fuels. Energy used to make thermal insulation includes electricity and other more carbon intensive vectors, and it appears from the published data that $c_i/c_h \approx 1.5$ e. Thus one would expect that carbon-optimised insulation thicknesses would be less than energy optimised insulation thicknesses by a factor of about 1.2 ($\approx\sqrt{1.5}$).

The limitations of the above analysis are obvious, but it has the advantage of clarifying some important structural features of the problem. In the next section we present a numerical analysis of two options for constructing the walls of a typical UK dwelling: i) a cavity wall, with an inner leaf of dense concrete blocks, an outer leaf of brick, tied with HDPE ties at a rate of 8 m^{-2}, and with the cavity fully filled with mineral fibre at a density of 30 kg/m^3; and ii) an externally insulated masonry wall, with a single structural leaf of 200 mm high density concrete blocks, an external layer of high density (140 kg/m^3) mineral fibre, and an outer weathering layer of stainless steel reinforced render, tied back to the masonry with HDPE ties at a rate of 8 m^{-2}.

The dwelling used as the basis for the calculations is semi-detached, two-storey, 50 m^2 plan with 15 m^2 of window and door openings. The total height is assumed to be 5 metres. The physical life of the dwelling is assumed to be 100 years. In the analysis, we have excluded the energy used directly, on site in the construction process, and to transport materials to site. Chapman [6] estimates direct energy used in construction of a dwelling as just under 20% of the total.

In estimating embodied energy of wall, E_c, we have assumed that gross floor area measured to the inside face of the external walls remains constant as wall thickness increases. We have accounted for the following geometrical effects:

* increased area of roof required to cover thicker walls;
* increased width of foundations required for thicker cavity walls;
* increased perimeter length of external leaf/render;
* additional insulation required at corners;
* longer wall ties;
* deeper window reveals (cavities are assumed to be closed with 25 mm thick timber carcassing, with no masonry return at window and door reveals).

The annual heating energy required by a wall of a given level of insulation has been estimated as E_r = U. D. 0.0864 MJ/m^2a, where D is the degree day total to an appropriate base temperature. This base temperature is in turn estimated using a version of BREDEM [7] which has subsequently been incorporated into the Standard Assessment Procedure [8].

Although the focus of this paper is on optimal insulation thicknesses in walls, the performance of the rest of the building envelope has an important second order effect through its impact on degree day base temperature. A U value of 0.085 W/m^2K has been assumed for the opaque parts of the building envelope other than the walls, and a U value of 0.6 W/m^2K for glazing. These figures are low, even compared with low energy construction in the UK, but neither is unobtainable. To assume a worse performance for the rest of the building envelope, would artificially increase the savings in heating energy due to the improved wall.

3 RESULTS

Figure 1 shows the marginal lifetime energy and carbon payback ratios for each of the two constructions, as a function of insulation thickness. The marginal lifetime energy payback ratio is the ratio of the reduction in space heating energy brought about by the last millimetre of insulation added to the construction, over the lifetime of the dwelling, to the additional construction cost of adding that last millimetre. A ratio greater than 1 implies that the last millimetre of insulation saves more energy than it costs. A ratio equal to 1 is the break-even point, where running and embodied energy requirements exactly balance. If energy (or CO_2) were the only criterion by which insulation thicknesses were decided, one would continue adding insulation until this point were reached.

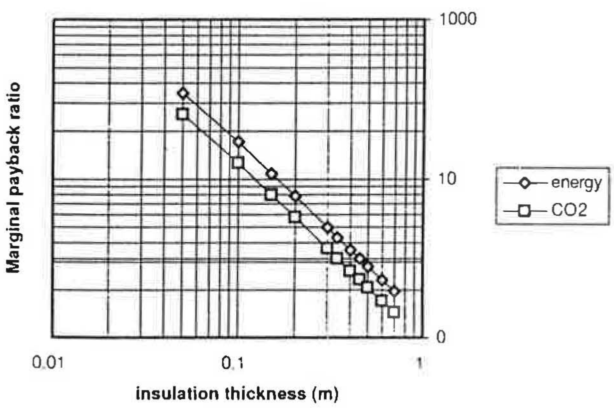

Figure 1. Marginal payback ratio for insulated cavity wall.

Several things are immediately apparent from these curves. First, marginal payback ratios at the level of current UK Building Regulations are large. For cavity wall under current regulations, an additional millimetre of insulation repays its embodied energy 70 to 90 times, and its embodied CO_2 40 to 50 times, over a 100 year life. There appears to be no argument from analysis of energy or carbon dioxide impacts, against increasing the level of insulation required by the building regulations. Nevertheless, the marginal payback ratios fall very quickly, for both constructions, as insulation thickness increases. Payback ratios are lower for the externally insulated wall. The reason for this is that the external insulation assumed here has a density, and therefore energy intensity per cubic metre, nearly 5 times as high as the insulation normally used in wall cavities.

The approximate break-even thicknesses for wall insulation are shown in table 1. These thicknesses are substantially in excess of thicknesses currently considered normal. though a small number of buildings come within a factor of two and at least one building in the UK (the Wates House at Macchynlleth) exceeds the level implied.

Table 1 Optimal insulation thicknesses (m)

	carbon dioxide	energy
cavity wall	0.34	0.45
externally insulated wall	0.23	0.29

There are three principal sources of error and uncertainty in the calculations that lead to the above results. The first, relating to uncertainties in energy intensities for building materials, has been discussed above. The second relates to the estimation of annual space heating energy consumption. The third stems from uncertainties in the lifetime of a typical dwelling.

The result of doubling the energy cost of construction materials is to reduce the carbon-optimised thickness of insulation in a cavity masonry wall from 340 mm to 250 mm, and the energy optimised thickness from 450 to 330 mm. These comparatively small reductions are due to the very rapid fall in marginal payback ratio with insulation thickness. The reduction factors in both cases are close to the value of $\sqrt{2}$ predicted by the simple analytical model described earlier.

The value chosen for the lifetime of the dwelling in the above calculations is, in our view, likely to significantly underestimate the actual physical lifetime for well designed and constructed masonry dwellings. A lifetime of 100 years does, however, reflect broadly the relaxation time for a pulse of CO_2 injected into the atmosphere [9], and the possible duration of an effective global politico-technical response to the problem of global warming. We therefore feel that a value significantly greater than 100 years is hard to justify for the purposes of the calculations presented here. We will merely note that the effect of halving the physical lifetime is mathematically the same as that of doubling the embodied energy cost of the dwelling.

We are unable to address the question of possible errors in the estimation of space heating energy in this paper, except to note that they are unlikely to be greater than the uncertainties of lifetime and embodied energy and carbon values already discussed.

The reason for the comparative insensitivity of break-even insulation thickness to quite large changes in the values of the parameters discussed above, is the very rapid fall in space heating energy consumption with increasing insulation level. This means that substantial changes in the values of the main parameters lead only to modest changes in the break-even insulation thickness. The most important factor in the determination of break-even thicknesses of insulation is the fact that wall U value is inversely related to insulation thickness. Everything else is rather unimportant.

As far as the designer is concerned a question of some interest is the size of the penalty involved in specifying an thickness of insulation that is either greater than or less than the optimum. This penalty is shown in figure 2. The shape of this "regret" function is essentially determined by equation 1 above. The most striking fact about this graph is its asymmetry - the penalty for putting in too little insulation is much greater than the penalty for putting in too much. As a result, under conditions of uncertainty, the insulation thickness needed to minimise the expectation value of lifetime energy cost is actually greater than the unbiassed estimate of the optimal thickness.

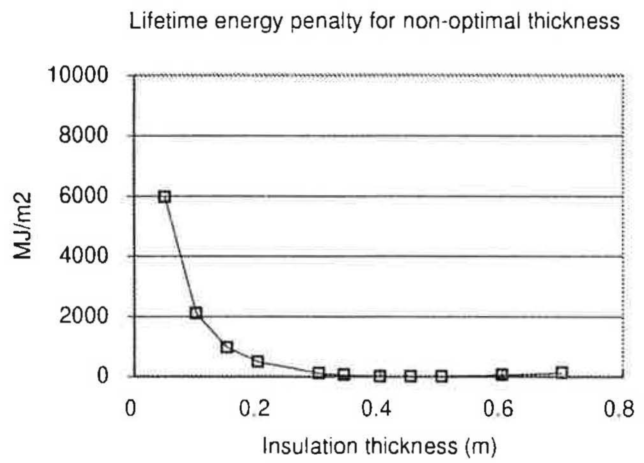

Figure 2. Regret function for non-optimal insulation thickness.

4 CONCLUSIONS

The main conclusions of this paper are:

1. insulation thicknesses in UK domestic wall construction are not currently limited by energy or carbon considerations;

2. that optimum insulation thicknesses are over 300 mm for cavity masonry walls and 250 mm for externally insulated walls;

3. that optimum insulation thicknesses appear to vary more slowly than the square root of embodied energy and/or CO_2, and that predicted thicknesses are therefore reasonably robust to changing assumptions;

4. that the lifetime penalties for non-optimality are higher for thicknesses less than optimal, than for thicknesses greater.

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