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Holistic Assessment of Highly Insulated nZEB Walls

In-situ measurement and embodied energy analysis

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ABSTRACT: Proponents of Passivhaus and nZEB often emphasise a 'fabric first approach' to ensure optimum envelope design, and by extension highest building energy performance. The energy performance of two similar walls, of two separate nZEB-compliant dwellings, are assessed in this paper. The walls have similar construction details, consisting of a layer of 200 mm of mineral wool on the exterior side and a block construction on the interior. The walls are investigated by comparing theoretical and in-situ conductance values while also estimating the embodied energy of both walls. The study found that, although the walls were of similar design and the test was conducted using the same methodology (in accordance with ISO 9869-1), that there was a significant different between the in-situ performance of both walls. One wall performed only slightly worse than the design value while the other performed more than two times worse. This research extrapolates on the findings by comparing theoretical heat loss scenarios with both wall types and calculates A) the potential building energy performance for both walls and B) the carbon and energy payback for the insulation used to achieve such high performance. The results demonstrate the importance of good practice in construction of the building envelopes and in the manufacturing, robustness and quality control of the various building components.
KEYWORDS: U-value, in-situ measurement, embodied energy, nZEB, Walls

1. INTRODUCTION

The U-value and its reciprocal, the R-value, are used globally to quantify the heat loss through the fabric of buildings. They measure the heat transmittance (U-value), or heat resistance (R-value) of a building component; accounting for both the conductive and convective resistances. In near Zero Energy Buildings (nZEB), built to passive house specifications, when calculating the U-value of a component the conductive resistance accounts for more than 97% of the total thermal resistance – this is attributed to the thick insulation layers.

Building regulators are consistently specifying reduced U-values for building components in an effort to reduce the energy consumption of buildings [1]. This consequently means more insulation. But are these regulations sufficient – or indeed are they actually too stringent? And how accurately do these theoretical values describe the in-situ behaviour of building components?

This paper aims to try and address these questions by measuring the heat flow through the walls of two buildings built to nZEB specifications in Ireland and compare these with the theoretical U-values. The operational energy required to heat one of the homes for the design and measured U-values is estimated and compared. Further, the embodied energy required to achieve these low theoretical U-values is examined.

The construction details of the two walls compared in this study are from two completely separate buildings in two separate locations. The construction details are very similar. This work forms part of a larger research project that focuses on the in-use energy monitoring of nZEBs in Ireland (nZEB101 - funded by the SEAI [2]).

2. LITERATURE REVIEW

Two review papers on the topic of in-situ U-value measurements have recently been published. Bienvenido-Huertas et al. [3] conducted a comprehensive literature review of the various methods used to determine building U-values. The authors categorise these into the 5 most common methods – one theoretical method (ISO 6946) and four experimental methods (including The Heat Flow Meter (HFM) method of ISO 9869-1). They outline the benefits and shortcomings of the different methods and conclude that the decision of which method to use is typically determined by the materials and equipment available. Teni et al. [4] also present a comprehensive review of the methods used – they categorise non-destructive in-situ measurements into two groups: those that use a HFM and those that don't. They include the same methods as Bienvenido-Huertas et al. [3] in their study but also include the Natural convection and radiation method (NCaR) method, a method proposed by Jankovic et al [5] which requires inside and outside surface and ambient temperatures as well as the emissivity of the inner surface.

Gaspar et al. [6] identified the temperature difference, the test duration and the equipment accuracy as three critical parameters influencing the accuracy of the in-situ U-value measurement. In their study of a test hut, which was specifically built for purpose, it was found that the average temperature difference between inside and outside has a major role in dictating the required test duration.

Throughout the literature, the deviation (ΔU) between theoretical (U_{th}) and experimental (U_{exp}) U-values is documented and is defined by Equation 1.

$$\Delta U\ (\%) = ((U_{exp} - U_{th})/U_{th}) \times 100 \qquad (1)$$

A deviation greater than zero indicates a building performing worse than what was calculated theoretically. Nardi et al. [7] found that the in-situ U-value could deviate from -6% to 83%. They showed an example historic building (U = 1.17 W/m^{2}K) as performing slightly better than what was estimated theoretically and a heavily insulated wall of a private house performing 83% worse than the design U-value. A study conducted in Dublin (Ireland) found that the deviation in wall U-value ranged from 4% to 61% in a study of 6 walls, noting that all performed worse than designed [8]. Albatici et al. [9] also found that in none of the 5 walls they investigated did the experimentally measured U-value outperform the design, with deviations ranging from 0 to 43%.

The purpose of insulation is to reduce heat loss and thereby reduce the energy consumption (and associated carbon emissions) required to achieve and maintain a particular temperature for a desired thermal comfort setting. If, as outlined in the literature, some walls are not providing the amount of heat resistance as per design calculations, the question of the insulation's effectiveness is then raised. Can we justify the amount of energy that has been consumed in producing the thick insulation layers which remains embodied in the buildings fabric?

Whether the discrepancies between the real and design U-value are due either to misleading/inaccurate manufacturer specified values or due to poor installation during construction and the consequential effects (e.g. thermal looping [10]), the insulation itself remains the same. If the purpose of insulation is to save on energy and carbon then the energy and carbon that has gone into producing that insulation must also be considered.

An introduction to the embodied energy of insulation materials and their associated performance can be found on the GreenSpec® website [11] while individual Life Cycle Analysis (LCA) of specific products can be obtained on publicly available Environmental Product Declaration (EPD) databases – such as that of the Institut Bauen und Umwelt e.V. [12]. In a review and comparative study of insulation materials for the building sector, Schiavoni et al. [13] compared the embodied carbon and energy of different insulation materials. They used a functional unit (f.u. = the amount of insulation required to achieve a thermal resistance of 1 m^{2}K/W for a 1m^2 area) to compare the different materials. As an example, they observed that that the embodied energy of a selection of stone wool based insulation products ranged from 5 to 18 kWh/f.u. while the embodied energy of expanded polystyrene base insulation products ranged from 32 to 36 kWh/f.u.; in terms of carbon these values were 1.45 to 3.62 KgCO2eq /f.u. and 5.05 to 8.25 KgCO2eq /f.u respectively – these values are dependent on the fuel mix in the location where the materials were processed. The insulation material used in the buildings assessed in this paper is a commercially available stone wool.

3. METHODOLOGY

Prior to the embodied energy/carbon analysis, the thermal and operational performance of two walls of similar construction are investigated. First the theoretical U-values are calculated, and the heat loss is estimated over a one-year period. These results are compared with experimental results from in-situ monitoring of two nZEB dwelling walls in Dublin (Ireland) of typical construction. Finally, the embodied energy of the wall is calculated and compared with the operational energy savings/losses.

3.1 Theoretical values

The theoretical (or design) thermal conductance values, U_{con} (W/m^{2}K), are calculated using resistance networks as per ISO 6946 [14] for the two nZEB walls. The convective surface resistances add an additional and complex (if estimated accurately) variable to the problem which accounts for a small percentage of the thermal resistance of heavily insulated walls and so are omitted from this study. The thermal conductance is therefore calculated according to Equation 2.

$$U_{con} = 1/(t_1/k_1 + t_2/k_2 + \ldots\ t_n/k_n) \qquad (2)$$

Where t_n and k_n are the thicknesses and conductivities of the nth layers in a multi-layer wall build-up.

3.2 Whole building energy modelling

For contextual relevance, the annual heat requirements (kWh) are estimated for a hypothetical nZEB with different wall U-values. The hypothetical case study building considered for this part of the analysis is a detached two storey dwelling with a floor area of 113 m^2 (average dwelling size in Ireland in 2016 [15]) and constructed to nZEB standards (U-values for the walls, windows and roof are built to passive house specifications) with a glazing to opaque surface ratio of 20%. Real weather data from the year

2012 for Dublin, Ireland, is taken from the Met Eireann database and used for the analysis.

A number of assumptions and simplifications are made to obtain the building's heat demand. It is assumed that the only source of heat loss is through the fabric of the building and thermal bridging is neglected. A very simple heating schedule is also assumed whereby the daily heating schedule is from 06:00 to 09:00 and 18:00 to 23:00 and where the seasonal heating period starts on the 4th of October and ends on the 30th of April. The heating system considered is a 91% efficient gas boiler. The heat requirement, Q (Wh), is estimated at hourly average intervals which is calculated using Equation 3. The heat requirement is accumulated over a year for values within the assumed heating period and season.

$$Q = \sum U_x A_x (T_b - T_o) \qquad (3)$$

U_x (W/m^{2}K) and A_x (m^2) are the thermal transmittances and areas of the different components of the building and T_b is the assumed base temperature of 16°C. T_o is the outdoor averaged ambient temperature.

The primary energy and carbon emission factors are taken from the Sustainable Energy Authority of Ireland (SEAI) [17], which are 1.1 (Primary Energy Factor) and 204.7 gCO2/kWh (Emissions factor) for natural gas.

3.3 In-situ thermal monitoring

In-situ conductance values, U_{con} [W/ m^{2}K] are used as inputs to the model. These are obtained using quasi-steady thermal analysis of the building's envelope as per ISO 9869-1 [16]. To obtain these in-situ values heat flux and temperature sensors are installed on interior and exterior surfaces of the building's fabric. A schematic of the test set-up is presented in Figure 1. It also outlines the conductance calculation where *HF* is the heat flow density (W/m^2), *Tsi* (°C) is the internal surface temperature and *Tse* (°C) is the external surface temperature. The test is conducted at two locations so as to get two sets of results for each test site. The equipment therefore contains four surface temperature sensors (± 0.2 K) and two heat flux sensors (± 3 %). Before every test is initiated a thermal image is taken to identify a suitable test location free from thermal bridging. An image of an example test setup is presented in Figure 2.

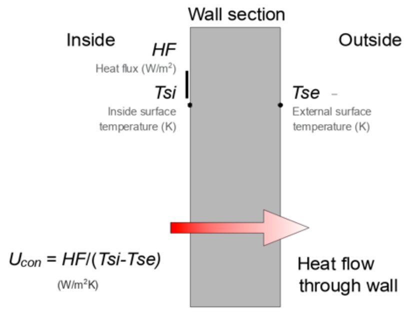

Figure 1. In-situ U-value measurement schematic.

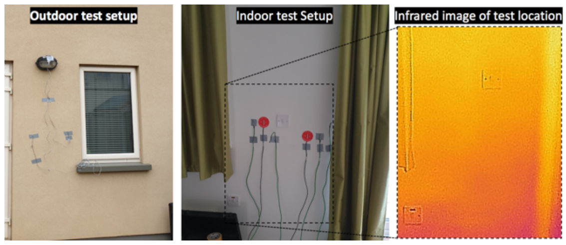

Figure 2. In-situ U-value measurement set-up for example wall.

3.4 Embodied energy & carbon analysis

The embodied energy and carbon of the insulation in the walls is quantified by simply cradle-to-gate boundary conditions. The data used to assess this is taken from the manufacturer's Environmental Product Declaration (EPD) for the high density stone wool; the results of which are presented in Table 1.

Table 1: Summary of environmental indicators for a commercially available stone wool

Parameter	value
Embodied carbon [kgCO2eq/m^3]	197
Embodied primary energy [kWh/m^3]	589
Conductivity [W/mK]	0.032-0.05
Density [kg/m^3]	155

This data will be used to first compare the effectiveness of the insulation, by comparing the theoretical performance with the real in-situ performance. Secondly, the balance between the operational energy and embodied energy of the insulation will be compared. The carbon and energy payback as a result of the operational energy savings associated with incremental increases in the insulation thickness will be quantified assuming simple payback method as per Equation (4).

Payback = Embodied carbon and energy of the additional insulation / savings in operational energy by adding the extra insulation (4)

4. RESULTS AND DISCUSSION

4.1 Theoretical results

The theoretical thermal conductance values for the two nZEB walls presented in Figure 3 are 0.145

and 0.165 W/m^{2}K for nZEB A and B respectively; calculated using Equation 2.

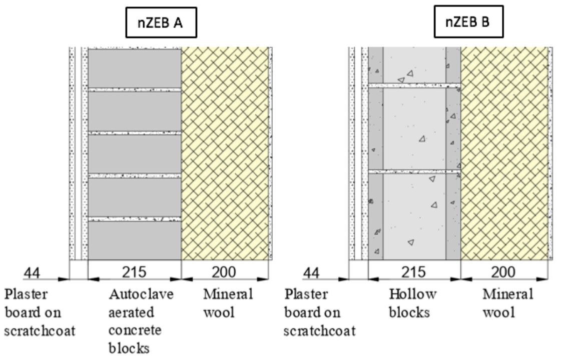

Figure 3. Wall sections for the two nZEB walls

The heat requirements for the theoretical case study described in Section 3.2. with these calculated U-values are presented in Table 2, along with the associated primary energy consumption and carbon emissions. The primary energy consumption associated to the heating per year per m^2 would be 12 kWh/m^2/a for nZEB A and 13 kWh/m^2/a for nZEB B.

Table 2: Summary of a case study nZEB performance with the theoretical wall conductance values of nZEB A and B. – based on the 113m2 dwelling described in Section 3.2.

	nZEB A	nZEB B
Theoretical U_{con} [W/m²K]	0.145	0.165
Heat requirement [kWh/a]	1145	1188
Primary Energy requirement [kWh/a]	1384	1436
Carbon emission [kgCO2eq/a]	158	267

4.2 In-situ monitoring results

The actual thermal conductance of the two walls of nZEB A and B are measured following the procedure of ISO 9869-1, as outlined in Section 3.3. The tests were conducted at two different sites at different times of the year but with the same equipment and methodology. The results of both sets of sensors at both locations are presented in Figure 4. As the test for nZEB A was conducted in summer, the indoor temperature was boosted to 30 °C in order to obtain a sufficient temperature difference greater than 10 °C as per recommendations of Gaspar et al. [6] (Table 3).

It is evident that the two sets of monitoring sensors (*HF*, *Tse* and *Tsi*) follow the same temperature and heat flux profiles for both tests, verifying the validity of the precise test locations at the two test sites.

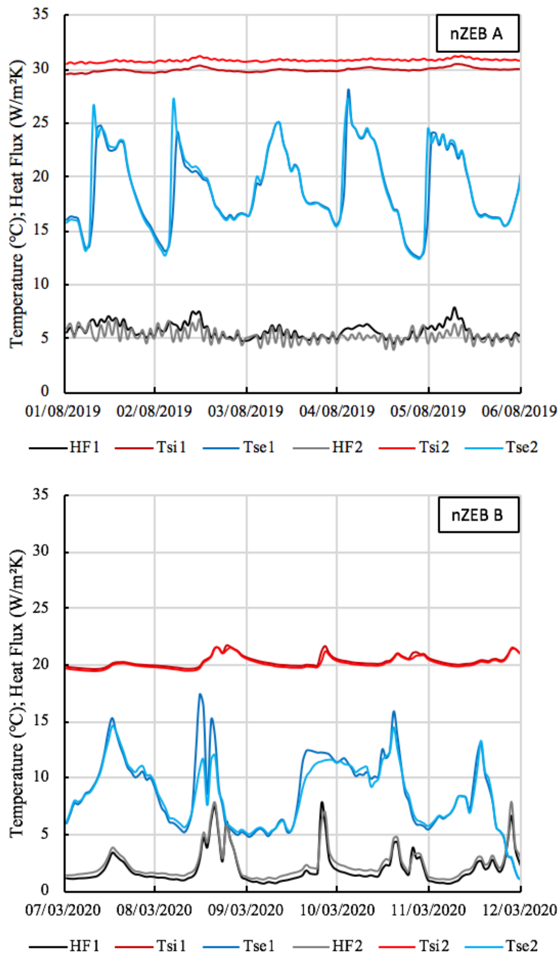

Figure 4. In-situ monitoring results for the two case study buildings - nZEB A (Top) and B (Bottom)

The thermal conductance, U_{con} (W/m^{2}K), at a given time is calculated for both case study walls using results from the average of the sensor pairs. The actual thermal conductance of the walls is then calculated by cumulating these values over time as shown by the equation in Figure 5. The result is only valid once the three check criteria, outlined in Figure 5, are met. It is immediately evident from Figure 5 that the value of nZEB A is significantly greater than that of nZEB B as well as its theoretically calculated design value. A summary of these findings is presented in Table 3.

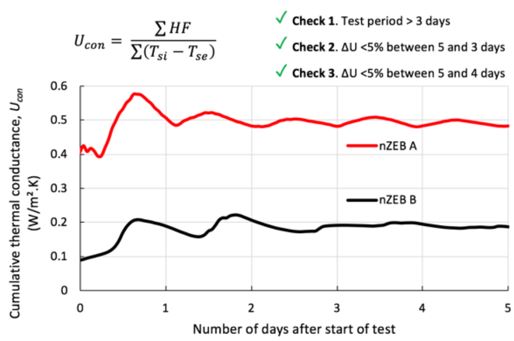

Figure 5. The cumulative thermal conductance over a 5 days test period for both wall tests.

Table 3: Summary of results from the two case study walls

	nZEB A	nZEB B
Average (Tsi - Tse) [°C]	11.3	11.6
Theoretical U_{con} [W/m^{2}K]	0.145	0.165
In-situ U_{con} [W/m^{2}K]	0.482	0.187
Deviation (Equation 1) [%]	232%	13%

Considering the similarity of the two walls the difference in performance is stark. Possible explanations for the significant difference in the performance of the two walls could be due to any or a combination of wet/damaged insulation or inadequate/discontinuous wall construction.

Considering the first theory, that the insulation is either wet or damaged, it should be remembered that the high thermal resistance of most insulation materials is due to the small pockets of stagnant air within the material. Unlike most foam based insulation materials, stone wool is an open structure and so is susceptible to moisture ingress. If this moisture replaces the air, the insulation's performance can be significantly reduced [18].

The other potential cause for such a reduction in the thermal performance of the wall is a discontinuous layer of insulation. Such discontinuities formed from e.g. cyclic shrinkage and expansion or poor initial placement (not staggering the insulation layers or leaving gaps around the edges) could result in air gaps between the layers of insulation layer and the adjacent block layer which could result in thermal looping, which can significantly compromise the performance of the wall [10].

The precise reason for the variation in in-situ thermal conductance is subject to continued investigation in the nZEB101 project. But whether the higher-than-expected values arise from poor construction or inadequate insulation materials, the knock-on effect on the building energy performance is considerable. Table 4 presents a copy of Table 2 but with the experimentally measured values used to model the building in place of the theoretical ones – these results represent a 63% increase in the primary heat requirement for nZEB A and a 4% increase for nZEB B.

Table 4: Summary of a case study nZEB performance with the experimental wall conductance values of nZEB A and B.

	nZEB A	nZEB B
Experimental U_{con} [W/m^{2}K]	0.482	0.187
Primary Energy requirement [kWh/a]	2263	1494
Carbon emission [kgCO2eq/a]	421	278

4.3 Embodied Energy and Carbon

The differences in U-values as a result of potentially poor construction, improper preparation of insulation materials on site and/or inadequate insulation has a significant and negative impact on the operational performance. But unfortunately the material used to obtain the design criteria, remains embodied in the building. This results in insulation material that effectively has a reduced functionality – the same amount of insulation no longer provides the same level of thermal resistance. A comparison of the amount of energy used to produce the different amount of insulation for a given functionality is presented in Figure 6. It is evident from the logarithmic-scaled figure that the functionality of insulation has reduced substantially. Similar comparisons could be drawn for the embodied carbon where a different multiplier is used.

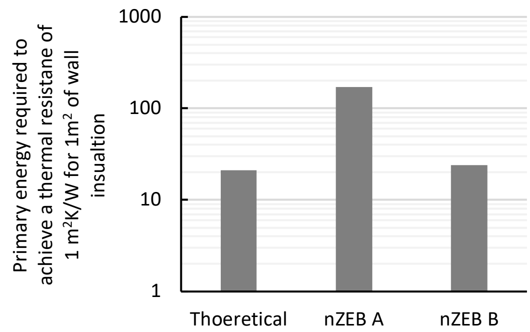

Figure 6. Comparing the effectiveness of the different case scenarios.

Based on the observed results it would be safe to assume that the theoretical case would likely provide the optimum results in most scenarios. And that, although it is likely the performance will be worse in reality (as shown by the results in this study and throughout the literature cited in this paper), it would be interesting to investigate the balance between operational energy and embodied energy for this best case scenario. To do this, the hypothetical case study described in Section 3.2 is used again and the theoretical wall build-up of nZEB A is assumed.

The amount of time, in years, required to pay back the primary energy and carbon associated with different incremental increases in insulation is presented in Figure 7. It is evident that there are diminishing returns as the thickness of the insulation is increased. This is because the heat loss is inversely proportional to the thickness of the insulation. This is a simple analysis and, as our grid electricity becomes greener, the carbon payback periods will increase; likely stretching beyond the life of the building. With other foam insulations which embody more energy and carbon the payback periods would be longer.

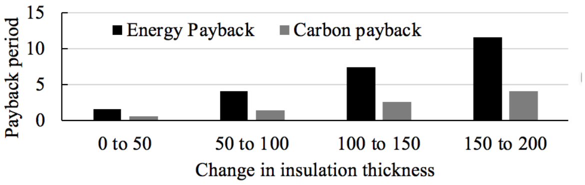

Figure 7. The number of years it would take to pay back incremental increases in thickness of the mineral wool insulation layer in terms of carbon and primary energy.

CONCLUSIONS

There exists a clear and unnerving discrepancy between the design and actual thermal performance of walls. The cause of which is subject to continued research, but the effect of which is significant.

In addition to potential concerns outside the scope of this paper (such as the consequential under-sizing of mechanical system within a building) the deviations mean that the functionality of insulation material is significantly reduced. Not only does this add an unnecessary extra cost to the building, which in countries with housing shortages (such as Ireland) can lead to less homes being built for a given pot of money, it also means there is unnecessary extra energy and carbon embodied in the building. Even when the theoretical performances are met, diminishing returns on the effectiveness of the insulation means that the carbon and energy payback periods need to be considered.

It is further interesting to remember that as our electricity becomes less carbon intensive – which European legislation is enforcing – the amount of carbon embodied in the walls will remain and the payback period on carbon will increase. We need to stand back from the “target” of low u-values, outlined in standards, and instead focus on the target of lower carbon. Implementation of such a broad target is of course challenging and more detailed targets are needed; but pushing the boundaries without addressing the current discrepancies between design and actual is not conducive to a low-carbon built environment. Our efforts might currently be better focused on building strategy rather than insulation quantity.

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