Operational and embodied energy analysis of 8 single-occupant dwellings retrofit to nZEB standard

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ABSTRACT: In line with the Energy Performance of Buildings Directive, Irish dwellings are being retrofit to near Zero Energy Building (nZEB) standards - with a number of the deep energy retrofits classified as A-rated. As a result of the low operational energy, the embodied energy share of an nZEB's life cycle energy is significantly increased. Therefore, to obtain a holistic picture of the change in energy profile of buildings, the embodied energy of the material added to achieve that low performance should also be taken into account. This paper presents results from a case study of 8 single-occupant terrace bungalows retrofit to nZEB standard. The pre- and post-retrofit operational performance is first estimated using the Irish Dwelling Energy Assessment Procedure (DEAP). The post-retrofit operational performance of the space heating and domestic hot water heating system is also measured over a year. The embodied energy is estimated by way of embodied carbon/energy calculations. Monitored results of the 8 similar buildings exhibit a wide variance of operational energy consumption while the embodied energy is (by nature of the calculation) consistent. The average estimated primary energy requirement for the buildings was 674 kWh/(m^2·year) pre-retrofit and 38 kWh/(m^2·year) post-retrofit while the average measured primary energy requirement for space heating and hot water alone was 119 kWh/(m^2·year) – ranging from 74 to 167 kWh/(m^2·year) for the 8 houses. The embodied energy of the materials and technologies used to retrofit the buildings was 676 kWh/m^2. Despite the building performing worse than expected, desirable primary energy and carbon paybacks of 2.0 and 6.1 years were achieved respectively. These positive payback periods are largely due to the very poor operational performance of the buildings pre-retrofit.

KEY WORDS: nZEB; Operational energy; Embodied energy, Air source heat pump

1 INTRODUCTION

In an effort to reduce the carbon intensity of the built environment, the European Parliament issued the Energy Performance of Buildings Directive in 2010 [1], setting out guidelines and requirements for all EU member states to prepare their own near zero energy building (nZEB) plan. According to the European Commission; "Nearly zero-energy buildings (NZEB) have very high energy performance. The low amount of operational energy that these buildings require comes mostly from renewable sources.". This directive allows for flexibility, and subsequently member states define nZEB differently; a concise summary of the different definitions has been described by the Buildings Performance Institute Europe (BPIE) [2].

In Ireland a Building Energy Rating (BER) is used to rate a building's energy performance. This includes the energy required for space heating, domestic hot water, lighting and ventilation and is calculated using the Dwelling Energy Assessment Procedure (DEAP) software [3]. A BER rates the energy performance of a building on a scale of A1 - G. An A1 rated dwelling has an energy requirement of less than 25 kWh/(m^2·year) while a G rated building has an energy performance of more than 450 kWh/(m^2·year). However, the BER does not consider the embodied resources that went into constructing the building and only considers the use stage of a building. A building's life cycle, as defined in EN 15978 [4], consists of four primary stages: the product stage, the construction stage, the use stage and the end of life stage. The Embodied Energy (EE) primarily relates to the product and construction stage i.e. the energy used to produce and install the individual products, materials and technologies used in buildings.

In a review of a comparable sample of 39 case study buildings, Chastas et al. [6] found that the share of Embodied Energy (EE) in the life cycle energy of residential buildings ranged from 6% to 20% for conventional buildings, 11% to 33% for passive houses and 74% to 100% for nZEB. This considered only case study buildings with a 50-year life span for analysis and studies that did not account for waste, transport and disposal were excluded from the analysis. The authors define low energy and Passive House as those building having a primary energy demand less than 120 kWh/(m^2·year) and conventional buildings with a primary energy demand greater than 120 kWh/(m^2·year). The nZEBs are defined by the national reference limit values in the reviewed studies, but it should be noted that Passive House can be classified within the definition of nZEB in some cases.

Ramesh et al. (2010) found that embodied energy accounted for 10-20% of a building's life cycle energy in a review of 73 case study buildings. 46 of the buildings assessed Ramesh et al. (2010) are residential, which have an average embodied energy of 32.3 kWh/(m^2·year). Figure 1 presents the percentage share of the embodied energy to life cycle energy of the case study buildings from the study by Ramesh et al. (2010). The case study buildings in Figure 1 are presented in order of increasing energy consumption (i.e. Building (A) has the lowest operational energy consumption). But good operational energy doesn't necessarily have to be a result of high embodied energy. While Building (A) in Figure 1 does have a high embodied energy (due to the installation of the renewable energy technologies required to achieve its net zero operational energy), Building (B) has a low EE of 12 kWh/(m^2·year) (which did not include any renewables and was built using light construction materials). Likewise, poor operational performance does not mean low embodied energy – e.g. Building (C) from Figure 1.

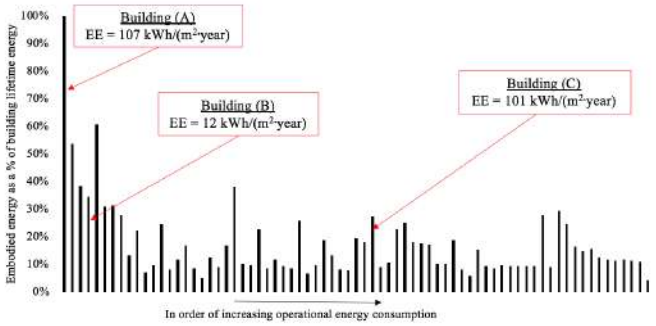

Figure 1. Embodied energy as a % of building lifetime energy. Data is extracted from [7].

Chastas et al. [8] reviewed the EE for a range of different buildings including 23 nZEBs (19 of which are defined as Passive House). EE values ranged from 9 - 135 kWh/(m^2·year) with an average of 42 kWh/(m^2·year) for the nZEB typologies. Goggins et al. [9] investigated the life cycle environmental performance of six case study dwellings in Ireland, which included two nZEBs. The two nZEBs measured EE values of 19.5 and 21.2 kWh/(m^2·year), making for a 33% and 31% share of the total energy over a 60-year lifespan.

In relation to the balance between the OE savings and EE of retrofit scenarios there is significantly less data available. In a recent study, Hurst and Donovan [5] noted that because of the scarcity of this data the life cycle energy savings of retrofit scenarios are not well understood. They reference a total of 12 retrofit buildings. Asdrubali et al. [10] found that the embodied energy invested in an nZEB retrofit was paid back in 6.6 and 6.9 years and the embodied carbon in 5.9 and 6.5 years for two case study buildings. Moran et al. [11] recently published a paper assessing different retrofit solutions for the Irish housing stock using multiple life cycle economic and environmental indicators. Results from the life cycle energy and carbon analysis indicated that it would be beneficial to introduce grants to retrofit more air source heat pumps.

This paper contributes to the scientific literature by adding a further study focused on the balance between operational energy savings and embodied energy of nZEB retrofits. Specifically, it evaluates the nZEB retrofit of 8 terrace bungalows in Ireland using estimated energy calculations pre-retrofit and monitored energy measurements post-retrofit.

2 METHODOLOGY

In this section, the retrofit scheme is first described. The Operational Energy (OE) is estimated pre- and post- retrofit using the DEAP software, it is also monitored for a full year (April 2019 – March 2020) post-retrofit and is then discussed. Finally, the embodied energy and carbon of the materials added during the retrofit to the building are quantified using simple cradle to gate boundary conditions for the individual materials.

The OE as per DEAP calculations include the space heating, domestic hot water, lighting and ventilation. In this work the space heating and hot water loads are only measured with the LED lighting and demand control ventilation assumed to be minimal energy contributors in comparison.

2.1 Description of scheme

The materials and technologies used in the retrofit are outlined in Table 1. The scheme consisted of 12 terrace bungalows in Wexford Ireland. An image of some of the homes before and during retrofit are presented in Figure 2. An image of all 12 buildings after the completion of the retrofit works is presented in Figure 3.

Table 1. Details of the retrofit for the 12 homes.

Item	Description	Quantities [unit]
Roof	0.4 m Mineral wool	136 [m^3]
Walls	0.1 m EPS (Ext)	34 [m^3]
Ground	No work done	-
Doors	Double glazed PVC	24 units
Windows	Triple glaze low e	50 [m^2]
PV	11.6 m^2 per dwelling	139 [m^2]
HP	4 kW split unit per dwelling	12 units
Lighting	All LED lighting	-

Figure 2. (a) Image of one block of terraces before retrofit [Source: SEAI] and (b) image of another block of terraces during retrofit [Source: 3CEA].

Figure 3. Panoramic Image of the 12 dwellings post-retrofit.

2.2 Operational Energy

Of the 12 homes in the scheme 8 are monitored - 4 end-terrace and 4 mid-terrace. In order to anonymize the occupants. a lettered labelling scheme (A to H) is used for the 8 monitored homes.

The primary operational energy consumption is first estimated pre- and post- retrofit using the Dwelling Energy Assessment Procedure (DEAP) – software version 3.2.1. This analysis was conducted by 3CEA (a project partner of nZEB101) [12].

In addition, the space heating and Domestic Hot Water (DHW) demand has been monitored after the retrofit has been completed and the homes occupied. The measured data for this paper is based on data collected from April 2019 to March 2020.

The heat pump is a split unit with an indoor hot water cylinder that contains a separate immersion used for top up heating. The electricity consumption of the heat pump as well as the immersion boost heater of each of the dwellings is measured using Current Transformer (CT) clamps with a 0.05 – 100 Amp measurement range.

To obtain the primary energy consumption from the electrical loads, all secondary electricity consumption data is multiplied by a primary energy requirement factor of 1.963. To obtain the associated CO_2 equivalent emissions, a conversion factor of 436.6 gCO_2/kWh was also applied. These conversion factors are taken from the most recently published Sustainable Energy Authority of Ireland (SEAI) energy conversion factors for electricity [14].

2.3 Embodied Energy

Hurst and Donovan [5] note that Embodied Energy (EE) impacts occur throughout the building's life but that numerous different definitions are used in the literature. Here, the embodied energy of the product stage is only considered. The data for transport and construction is not available and is hence not included in the EE calculation.

The embodied energy (kWh) and carbon ($kgCO_2e$) of the nZEB retrofit is estimated by accumulating the EE and EC of the various quantities listed in Table 1. A full LCA is outside the scope of this paper and instead individual EE/EC intensity values are taken from Environmental Product Declarations (EPDs) where possible and from the academic literature where an EPD does not exist. All source data references are clearly indicated in Table 2. The results are used to provide an estimate of the amount of energy and carbon that was required to achieve the upgrade. Lighting and ventilation upgrades are ignored as they are not included in the operational energy measurement.

3 RESULTS

The estimated operational energy performance is first presented. The measured operational energy is then analysed. And finally, the embodied energy is investigated.

3.1 Operational performance – estimated

The estimated performance pre- and post- retrofit is presented in Figure 4 for the space heating as per the DEAP calculations. The predicted space heating after retrofit ranged from 13 - 23 kWh/(m^2·year), multiple times less than before (225 – 690 kWh/(m^2·year)). It is interesting to note the high energy loads before retrofitting due to poor technical characteristics of the building (i.e. high fabric U-values, inefficient boilers and poor air tightness before retrofit).

Using the same DEAP software, the average total regulated load (space heating, hot water, lighting and ventilation) after retrofit was estimated to be 38 kWh/(m^2·year) – indicating a BER of A2. Before retrofitting the same average total load was estimated to be 674 kWh/(m^2·year) – indicating a BER of G.

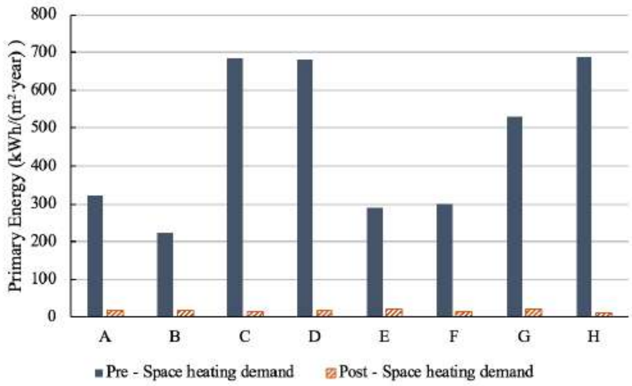

Figure 4. Primary energy requirement for space heating before and after retrofit.

As no solar contribution measurements are made at this site, an estimate is required. Using the EU's PVGIS tool [15] and taking account of orientation and inclination, it is estimated that the average 1.7 kW solar array generates 1400 kwh per year - or 45 kWh per m^2 of the building's floor area per year. The individual monthly contributions are presented in Figure 5.

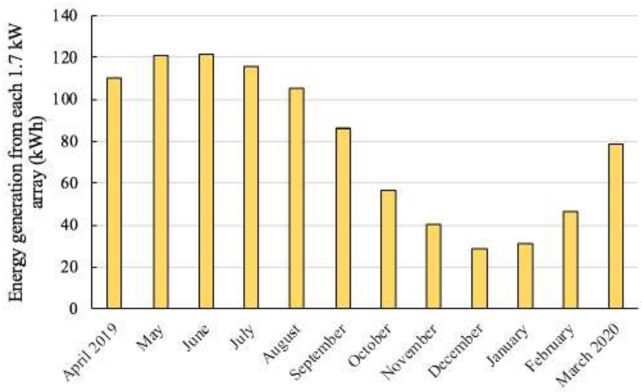

Figure 5. Monthly average energy contribution from each 1.7kW solar array – as per PVGIS calculations [15].

3.2 Operational performance - measured

An overview of the measured monthly energy consumption is presented in Figure 6. The median value for each month is emphasised by a larger circle in the figure, displaying an obvious trend of greater energy consumption in the winter months – as expected.

The immersion has a greater energy load in the summer. This is more apparent in Figure 7 where the average energy consumption per m^2 for a given month of the eight homes is compared. The heat pump used in each of the homes is a split system with a hot water storage tank that includes a separate immersion booster heater. Thus, if the HP is not operating in the summer months less energy is supplied to the tank and a greater boost would be required to achieve adequate tank temperature for domestic hot water applications. Detailed analysis of the heat pump system is subject to ongoing research by the nZEB101 project.

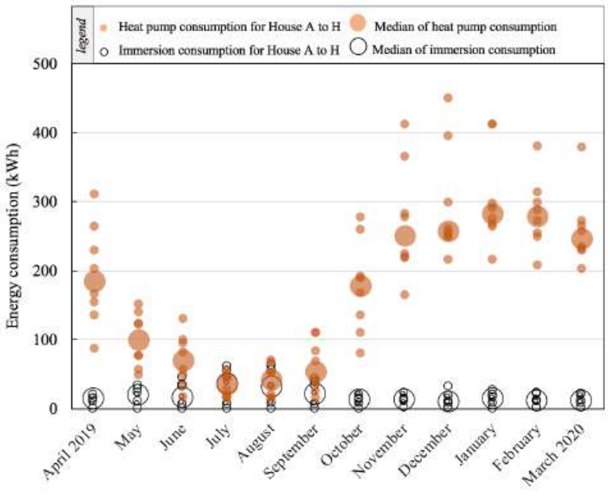

Figure 6. Breakdown of space heating and immersion consumption of the 8 homes.

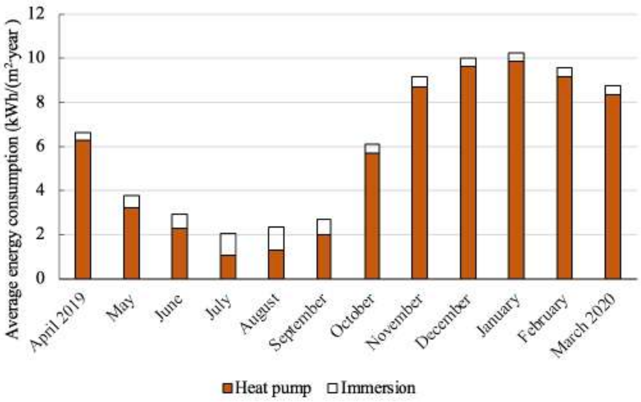

Figure 7. Average monthly energy consumption for homes A to H.

The contribution from each of the 1.7kW PV arrays is presented in Figure 8, along with the total measured energy consumption for space heating and DHW – indicating a clear mismatch between energy generated and heat required. It is assumed that the full generation from the PV is contributed to the heat pump and immersion heater so that, for example, in May through to September the primary energy factor would be 1.0 and the carbon emissions would be 0 gCO_2e/kWh. In winter however the contribution is much lower - for example in December the PV contribution is only 9% and the associated primary energy factor is 1.87 while the associated carbon intensity factor would be 396 gCO_2e/kWh.

The primary energy requirement of the 8 dwellings are presented in Figure 9, grouped as mid-terrace and end-terrace. The BER rating for the end-terrace dwellings ranged from C1 to A3 with an average BER of B3 whereas the mid-terrace all achieved a B2 rating. This small sample set indicates a slightly lower and more stable energy consumption in the mid-terrace dwellings.

3.3 *Embodied energy and carbon analysis*

A summary of the embodied carbon and energy of the retrofit scheme is presented in Table 2, along with references to the source data. The results show the different contributors to the embodied carbon and energy. In relation to the insulation it is interesting to note that although more roof insulation overall was used than wall insulation (11.3 m^3 vs 2.8 m^3 per dwelling), the embodied energy and carbon of the wall is more impactful. This is because of the mineral wool used in the roof has a much lower EE and EC per m^3 than expanded polystyrene insulation used in the wall. For the mineral wool the EE = 108 kWh/m^3 and EC = 16 $kgCO_2e/m^3$ whereas the expanded polystyrene has an EE and EC of 576 kWh/m^3 and 87 $kgCO_2e/m^3$ respectively. A summary of the breakdown of the EE and EC per m^2 of floor area is illustrated in Figure 10.

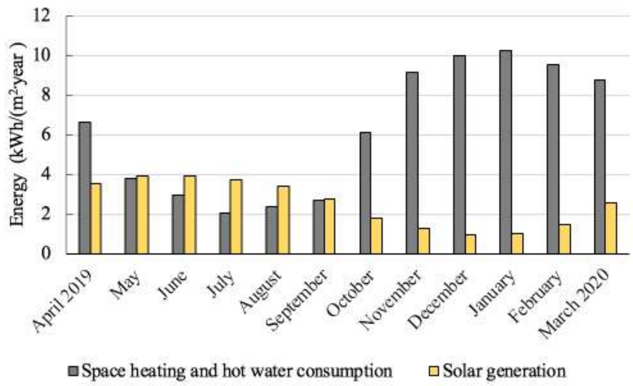

Figure 8. Average combined space heating and hot water consumption per m^2 and estimated solar contribution from each 1.7 kW PV array.

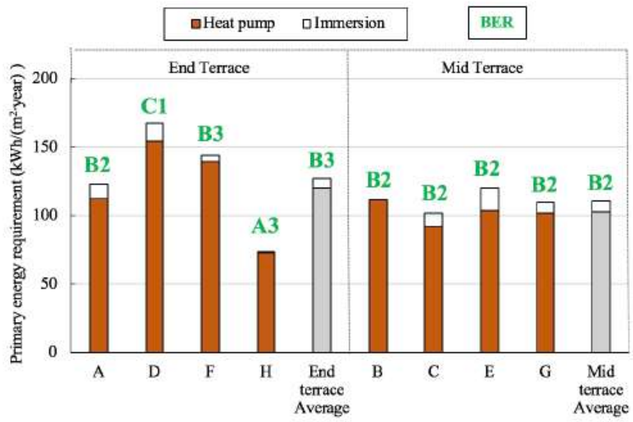

Figure 9. Difference in primary energy requirement for house A – H and their associated minimum BERs.

It is clear from Figure 10, that the renewable technologies have a significant contribution to the embodied energy (81%) and carbon (91%) of this particular retrofit, with the fabric part of the upgrade having a significantly smaller environmental impact.

4 DISCUSSION

The average primary energy requirement for the space heating was estimated to be 453 $kWh/(m^2 \cdot year)$ pre-retrofit and 18 $kWh/(m^2 \cdot year)$ post-retrofit using the DEAP software while the measure primary energy requirement post-retrofit was 119 $kWh/(m^2 \cdot year)$. This is significantly higher than the estimated performance as shown in Figure 11.

Although measured and estimated columns in Figure 11 are not directly related (the measured data includes some contribution to domestic hot water), it is clear (also from Figure 9) that the dwellings did not meet the target performance as per the DEAP estimates. Estimated BER ratings of A2 were assumed for the total regulated load (including lighting and ventilation) yet the primary energy requirement as per the measured space heating and hot water load indicate an average BER of B2.

Table 2. Total EC and EE per dwelling.

	Source data	EC ($kgCO_2e$)	EE (kWh)
Roof	EPD [16][a]	182	942
Walls	EPD [17][a]	243	1,247
Doors	[18][b]	16	24
Windows	EPD [19][a]	315	1,816
PV	EC [20]; EE [21]	2,888	7,726
HP	EC [22]; EE [23]	4,927	9,203
Totals		8,571	20,958

[a] EPD references is from a representative product – not the exact product used.
[b] Limited data on precise type of door. This reference is for general PVC doors.

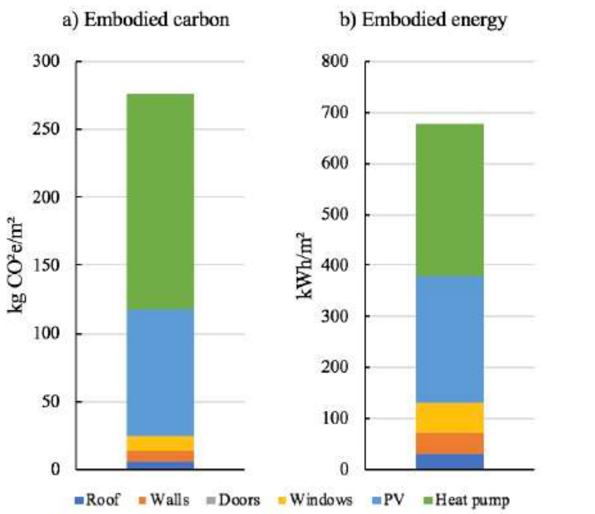

Figure 10. a) Embodied carbon ($kgCO_2e$) and b) embodied energy (kWh) per m^2 of building floor area used to complete the upgrade of the 8 homes.

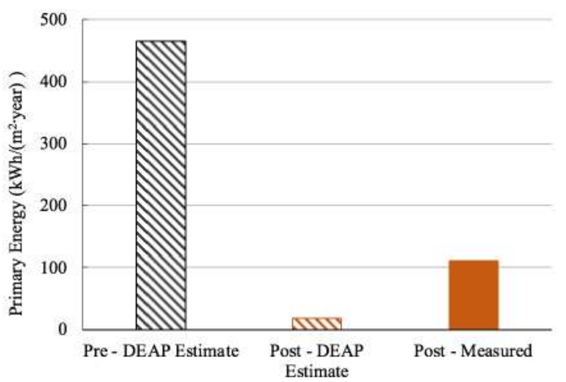

Figure 11. Average primary energy requirement for space heating.

The higher than expected energy loads is due partly to the underperformance of the heat pump. The heat pumps did not perform as was expected from the design estimates. This is likely due to lower-than-expected Coefficient of Performances (COPs). A detailed investigation of the heat pump's performance is outside the scope of this paper but is subject to continued research by the nZEB101 project. For context an example of one of the heat pumps monitored daily performance is illustrated in Figure 12.

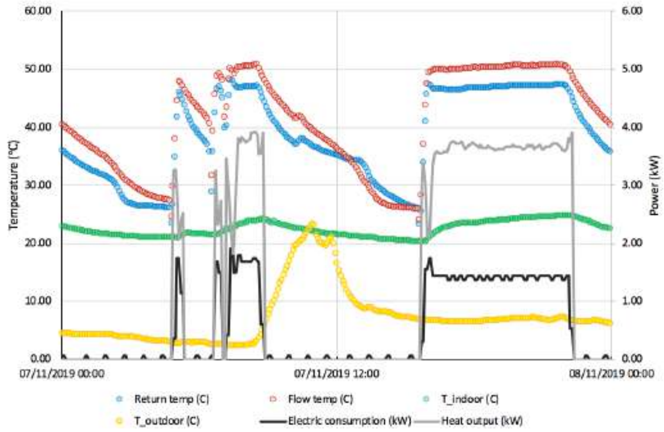

Figure 12. Example daily performance from one of the heat pumps.

The Coefficient of Performance (COP) for this particular day is 2.3 – calculated by dividing the heat output by the electrical input for that day. This is considerably less than what is typically assumed. Using a typically assumed COP of 4.5 in the DEAP software would yield space heating primary energy loads much better than what would be achieved in reality. This is one likely explanation for the difference between estimated and actual performance.

Despite the buildings not meeting their targets, when the savings on energy are compared to the embodied energy of the upgrade, favourable paybacks are observed (Table 3). Considering the average savings on space heating alone, a simple primary energy payback period of 1.97 years and carbon payback period of 6.13 years is estimated. This indicates a valuable upgrade. These favourable payback periods are largely due to the exceptionally high energy requirement pre-retrofit. In the case of very poorly performing buildings retrofits are very worthwhile in terms of energy payback.

Table 3. Average operation and embodied primary energy.

Parameter	Primary Energy	Carbon
Pre-retrofit (DEAP)	453 kWh/(m^2·year)	65 $kgCO_2$/(m^2·year)
Post-retrofit (Measured)	119 kWh/(m^2·year)	20 $kgCO_2$/(m^2·year)
Embodied in retrofit	676 kWh/m^2	276 $kgCO_2$/(m^2)
Simple payback	1.97 years	6.13 years

Finnegan et al. [20] cite life cycles of 15 years for heat pumps and 25 years for PV panels. Assuming that all materials and technologies in this retrofit scenario last 20 years the share between EE and OE-used during those 20 years would be 19% whereas the share between the EE and the OE-saved would be 7%.

For a 20 year lifetime, the EE cost of the retrofit would be 33.8 kWh/(m^2·year), which is lower than the average value for new build nZEBs assessed by Chastas et al. [8] of 44 kWh/(m^2·year), but higher than the EE per year for the new-build nZEBs presented in Goggins et al. [9] (19.5 and 21.2 kWh/(m^2·year)).

Referring back to Figure 10 it is clear that the renewable technologies make up the majority of the embodied energy and carbon for this particular retrofit and hence their EE and EC should be considered during the design stages of both new-build and retrofit.

CONCLUSION

This case study, comparing the operational and embodied energy of 8 similar dwellings retrofit to nZEB standards, has shown that very short energy (< 2 years) and carbon (< 6.2 years) payback periods can be achieved when upgrading buildings with very poor energy performance. These payback periods are based on the energy savings between the estimated average primary energy requirement for space heating pre-retrofit of 453 kWh/(m^2·year) and the monitored average primary energy requirement for space heating and hot water post-retrofit of 119 kWh/(m^2·year).

Despite these positive results, all monitored homes performed considerably worse than the estimated regulated load of 38 kWh/(m^2·year). Poor operational performance in this case study is likely due partly to the inefficient operation of the heat pumps. Early analysis indicates heat pump COPs of less than 2.5 on winter days whereas expectations are that the COP would be 4 or above. Other explanations might be due to the fabric and air tightness not performing as per estimations.

One limitation of this study is that the energy consumption before retrofit was not monitored and instead was estimated. The findings here are based on the assumption that in order to heat the dwelling to a comfortable temperature, the estimated primary energy pre-retrofit would be required. Both the solar and heat pump system's performance are subject to ongoing detailed investigation in this research project.

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