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Demolish or reuse? – The balance between operational and embodied emissions in the retrofit of commercial buildings

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Abstract. There are two clear options for reducing the emissions of poorly-performing buildings: refurbishment of the space to a higher standard or demolition and replacement with a better performing building. Non-residential buildings are subject to the latter of these options more than dwellings due to higher rates of ownership changes. This study assesses the carbon emissions of each of the above options for a poorly-performing retail building in Sheffield, UK. The embodied carbon and operational performance of each scenario are calculated to identify the most sustainable option over a 50 year lifespan. The scenario with the lowest emissions is found to be a retrofit case study relying upon electricity as its sole fuel source. The new build scenarios emitted significantly more carbon over the building's lifespan despite performing better operationally than the refurbishment scenario. It was also found that, due to the decarbonisation of the national grid, relying on gas boilers instead of electric fuel sources would make carbon emissions approximately 2.5x bigger in the refurbishment model, despite being legal under UK building regulations.

Key Words: Embodied Carbon, Operational Energy, Whole life Carbon, Retrofit, Demolition

1. Introduction

The operational energy use of buildings accounts for 30% of the UK's total emissions showing the need for major improvements to building stock efficiency [1]. Retrofit is one option to reduce a property's energy use, where the building's fabric and systems are improved through refurbishment. However, this can be costly and complex, often making the alternative of demolition and replacement with a better performing building more attractive to developers. Typically non-residential buildings have been found to have higher replacement rates than domestic buildings [2]. This could be attributed to the higher rates of change of use and ownership, with the question of demolition or refurbishment being presented at each occurrence of these [2]. A building's embodied carbon refers to the emissions associated during the extraction, production, transportation, construction, maintenance and eventual deconstruction and waste disposal of each material used. It is important to assess the carbon emissions of both scenarios, to help understand the significance of embodied carbon within a demolition vs refurbishment case study.

Both Marique & Rossi [3] and Pittau et al. [4] calculated the total embodied carbon of both a refurbishment and reconstruction scenario for a non-domestic case study. Marique & Rossi [3] found that the retrofit case study emitted 56.6% of the carbon compared to the rebuild scenario. Pittau et al. [4] also found that refurbishment was the most sustainable option. However, in both these studies the two different scenarios were assumed to have the same operational energy performance, which is unlikely to be the case in a real life case study. For example, UK building regulations require less efficient HVAC equipment in refurbishment projects compared to new buildings [5]. Studies where this performance difference is accounted for are much less common. Dilsiz et al. [6] performed a literature review which identified 100 comparable case studies to be analysed (a mixture of residential & commercial buildings) and compared the operational and embodied energy use of a retrofit case alongside low energy, passive and net zero energy new builds. It was concluded that focus should lie in conventional retrofit, as the majority of buildings have already been built and big changes to the embodied energy are only found in new constructions and deep retrofit [6].

Currently in the UK there are no laws enforcing the assessment or regulation of embodied carbon emissions within buildings, making their impacts difficult to quantify. Within literature, the embodied carbon of retrofit has been found to have wide ranging impacts. Ardente et al. [7] study the effects of different retrofit measures on 6 public buildings in Europe. In the majority of cases, each measure repaid its embodied carbon debt within 5 years - well below the typical predicted extended lifespan of each building. However, in the case of Provenhallen in Copenhagen, it took 30 years before insulation started to have a positive environmental impact [7]. Pomponi et al. [8] also found that, when studying the impacts of double-skin facades (DSF's), there was a wide range of results between case studies. In some cases, despite the DSF reducing operational energy use, the retrofit measure would cause higher whole life carbon emissions over the building's lifespan as a result of its associated embodied carbon. This shows the importance of assessing embodied carbon within retrofit design for non-residential buildings. With whole life carbon assessments of retrofit shown to be so important and the embodied emissions of new builds being considerably higher, it is clear that these emissions in a demolition vs refurbishment assessment could be highly significant.

High efficiency gas boilers are still often seen as a viable option for retrofit. The Net Zero Whole Life Carbon Roadmap [9] does not expect to phase out gas boilers in non-domestic buildings until 2028 and current building regulations still allow for gas boilers to be installed in both new builds and retrofit [5]. However, the national grid is currently in a decarbonisation process meaning the emissions released in the production of electricity will get lower and lower [10]. The carbon factor of fossil fuels will never change significantly, meaning that proportionally those buildings relying on fuels like gas will account for higher carbon emissions. Ghose et al. [11] studies three different grid mixes within their retrofit case study. The carbon payback time was shown to change by up to 5 years depending on which grid scenario was assessed [11]. This difference between each scenario shows why it is important to model future grid mix predictions. Gonzalez-Prieto et al. [12] found that the most sustainable grid mix would reduce the effectiveness of retrofit measures by up to 40%. This can be explained as a grid mix with a lower carbon factor would reduce the building's pre-retrofit emissions and therefore less carbon would be saved. It is clear that the faster, and more effectively, the UK manages to decarbonise the national grid, the lower our emissions will be. Therefore, as very low operational carbon emissions are achieved, the embodied carbon of a project will take up a larger proportion of the building's total emissions [9].

2. Methodology

The building case study is situated in Sheffield, UK. It was built in the 1960s and has served as a retail space until 2020 (See Figure 1). The building is currently vacant citing a need for either refurbishment or demolition. Therefore, as the building is currently not in use, no information is required on the pre-retrofit performance and only future scenarios have been assessed. Four possible scenarios were created - one retrofit scenario with gas heating, one retrofit which ran on only electricity and two new build scenarios to differing standards. These options have been explored to understand typical building scenarios but within a demolition vs refurbishment context. The future use of the building will still be considered as retail, and the new build studies will be said to have exactly the same floor area (14300m^2) as the original building. Both the extended lifespan of the retrofit models and the lifespan of the new build scenarios was assumed to be 50 years, which is the British Standard's designated design life for a typical building [13].

2.1. *Operational energy calculations*

2.1.1. Retrofit case studies. Two retrofit models were created within Design Builder [14] both of which performed to a Part L2B standard which is the UK building regulation of the improvement of existing buildings other than dwellings (See model in Figure 2) [15]. Though both models use mechanical ventilation and cooling, they differ with the type of HVAC system used. One model is seen as an upgrade of existing systems which means it still relies on gas as the primary fuel source. The other model is completely electrified and uses an air source heat pump (ASHP) air handling unit alongside solar thermal and electric boiler to provide the hot water. The appendices (Table 4) gives the inputs specific to a Part L2B refurbishment which were input into the DesignBuilder model. This model was then run through the EnergyPlus simulator which provided the yearly site energy use. Primary energy factors were used to convert this into source energy use, as these factors take the transformation process of the fuel used into account [16]

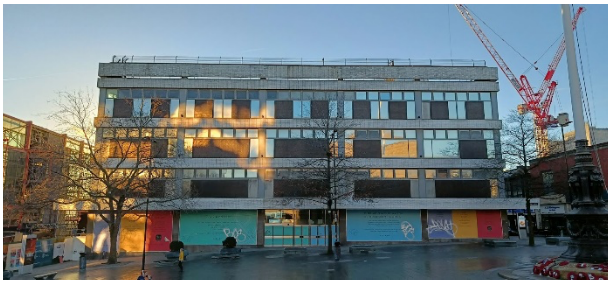

Figure 1. External view of building case study.

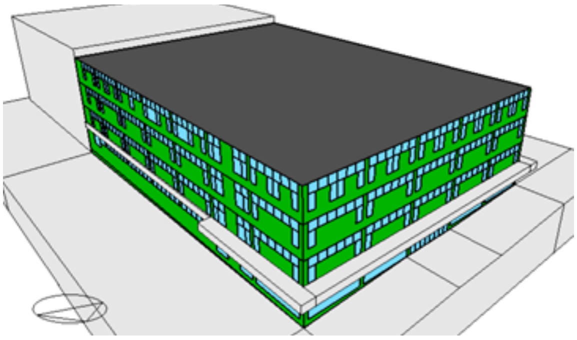

Figure 2. DesignBuilder model of building.

2.1.2. New build case studies. Table 1 shows the operational energy benchmarks that will be used in the study. These will be multiplied by the floor area of the original building. One case will perform to current 'good practise' while the other to standards that are expected to be achieved by 2030 [17, 18]. Both benchmarks are said to run on only electricity.

Table 1. Yearly operational energy benchmarks for New Builds

	Operational Energy (kWh/m^2.yr)
2020 Standard New Build	89 [a]
2030 Standard New Build	55 [b]

[a] Benchmark provided by BBP [17]
[b] Benchmark provided by RIBA[18]

2.2. *Operational carbon calculations*

Two national grid decarbonisation scenarios were taken from the UK's national grid Future Energy Scenarios report [10]. Carbon capture was excluded from this study as the technology and infrastructure needed does not yet exist in the UK [19]. The best and worst performing scenarios were adopted and shown in Figure 3. As predictions after 2050 have not yet been made, in this study the carbon factor will remain constant after 2050.

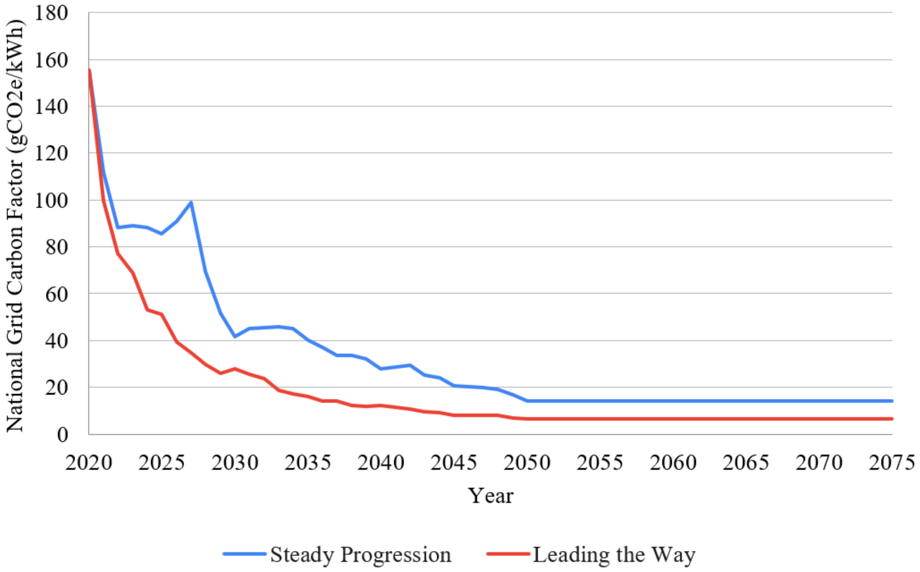

Figure 3. Two National Grid future scenarios for the grid carbon factor [10].

The yearly operational carbon emissions of each scenario could then be calculated by multiplying the operational energy use by the carbon factor of that year. This was then totalled over the 50 year lifespan of the building as shown in equation 1.

$$\text{Operational Carbon (KgCO2e)} = \sum_{n=1}^{50} \text{Carbon Factor}_n \left(\frac{\text{KgCO2e}}{\text{kWh}}\right) \times \text{Yearly Operational Energy(kWh)} \quad (1)$$

2.3. *Embodied carbon calculations*

The available benchmarks used in the new build study only allow for a cradle-to-site embodied carbon assessment to be performed (Stages A1 - A5 as stipulated in BS EN 15978:2011 [20]). This refers to the carbon release during the production (A1-A3), transportation to site (A4) and installation (A5) of materials.

2.3.1. Retrofit case studies. Only the fabric measures, i.e. excluding internal finishes and mechanical systems, have been included in this embodied carbon assessment. This is due to large uncertainties within the design of the HVAC systems adopted, making it very difficult to assess the embodied carbon without detailed building services design. There is also evidence of a lack of data, especially for the embodied carbon of building systems due to their complexity [21]. Section 2.3.2 outlines how a fair comparison is made between the retrofit and new build case studies given this exclusion of HVAC systems in the retrofit embodied carbon assessment.

A worst case scenario was assumed, which meant aluminium cladding (highly polluting) was adopted and a concrete screed was needed when installing the ground floor insulation. The DesignBuilder model was used to work out the total amount of insulation, cladding and concrete required as well as the area of windows. Embodied carbon calculations for each stage of the LCA included are explained below.

Stages A1 – A3 - Product specific EPDs (Environmental Product Declaration) were used to find the carbon factor (CF) for either 1m^2 or 1kg of the material used [22-24]. This was multiplied by the quantity of material as shown in equation 2a and 2b.

$$\text{Embodied Carbon, A1-A3 (KgCO2e)} = \text{CF}_{\text{A1-3}}\ (\text{KgCO2e/m}^2) \times \text{Material Area (m}^2) \times \text{WR} \qquad (2a)$$

$$\text{Embodied Carbon, A1-A3 (KgCO2e)} = CF_{A1-3}\ (\text{KgCO2e/kg}) \times \text{Material Mass (Kg)} \times \text{WR} \qquad (2b)$$

Stage A4 - A carbon factor (CF) was utilized, as in equation 3, which was dependent on the distance transported to site and the mode of transportation [25].

$$\text{Embodied Carbon Stage A4 (KgCO2e)} = \text{CF}_{A4}\text{(kgCO2e/kg)} \times \text{Material Mass (kg)} \times \text{WR} \quad (3)$$

Stage A5 – A wastage rate (WR) was assumed for the amount of material wasted onsite, which is shown in equation 2 & 3 to be accounted for. A benchmark for emissions during construction was found from literature and added to the total embodied carbon [20, 25].

The embodied carbon of stages A1-A5 was totalled to find the predicted embodied carbon for both retrofit case studies.

2.3.2. New build case studies. Due to a lack of available data, the embodied carbon of internal finishes & mechanical systems was not included in the retrofit case studies. Mechanical systems have been found to account for up to 75% of a retrofit project's embodied carbon emissions, showing their significance [26]. Therefore, comparing only the embodied carbon of fabric retrofit measures to the embodied carbon of a whole new building would not be fair. This meant that two benchmarks for each new build scenario were found, shown in Table 2.

One benchmark gives the predicted embodied carbon of the whole building while the other only predicts the embodied carbon for the structure. This provides a range within which the fair comparison lies. If, as expected, the new build scenarios perform better operationally, these benchmarks will provide an accurate range of the payback period between the refurbishment model and the new build.

Table 2. Stages A1 – A5, embodied carbon benchmarks for new builds.

	Embodied Carbon (kgCO2e/m^2)	
	Structure [a]	Whole Building [b]
2020 Standard New Build	350	550
2030 Standard New Build	225	300

[a] Benchmark provided by Institute of Structural Engineers [27]
[b] Benchmark provided by LETI [28]

In addition, an estimation of the carbon emissions released during demolition (stage C1) of the original building was calculated and added to the total embodied carbon (see equation (4)) [25].

$$\text{Embodied carbon, stage C1 (tCO}_2\text{e)} = 3.4\ (\text{kgCO}_2\text{e/m}^2) \times \text{Floor area (m}^2) \times 0.001 \quad (4)$$

3. Results

3.1. Comparison of retrofit models

Figure 4 shows the predicted carbon emissions from the two different retrofit models, using the 'steady progress' grid scenario.

Over the building's extended lifespan, using only electricity would reduce the total carbon emissions by 58% in comparison to using gas. The yearly emissions from the ASHP model reduce significantly, by 84%, after the national grid undergoes decarbonisation, while that of the gas model only reduces by 50%.

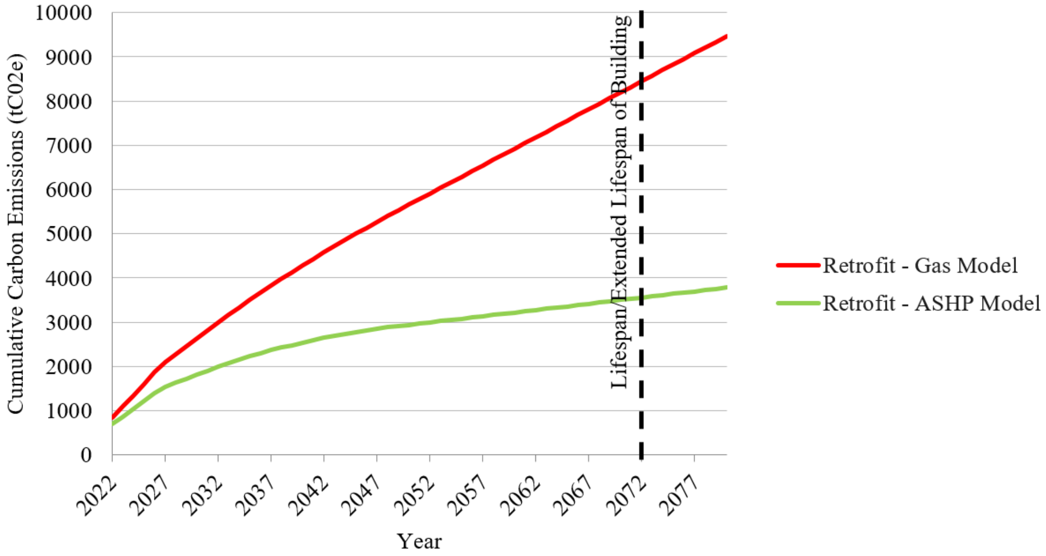

Figure 4. Cumulative carbon emissions for the two retrofit scenarios over the building's lifespan.

3.2. *Refurbishment vs. Demolition & rebuild*

The three scenarios which ran on only electricity have been compared. Table 3 shows that the scenario with the highest operational emissions is the ASHP retrofit model. Over the 50 year lifespan, the retrofit model is shown to emit 1.5x and 2.5x more operational carbon than the 2020 and 2030 new build models respectively.

Table 3. Total operational carbon emissions over the building's lifespan

Model Type	Total Operational Emissions (tCO2e)
Retrofit Model - ASHP	3180
2020 Standard - New Build	2070
2030 Standard - New Build	1280

However, once embodied carbon emissions are accounted for, the scenario with the lowest cumulative carbon emissions would be the retrofit model as shown in Figure 5. In fact, it would take between 112-176 years for the retrofit model to accumulate higher carbon emissions than the 2030 standard new build - which is well over the stipulated lifespan of either building. By 2072, the 2030 model is shown to perform considerably better than the 2020 model, as it would emit 4400 less tonnes of carbon dioxide.

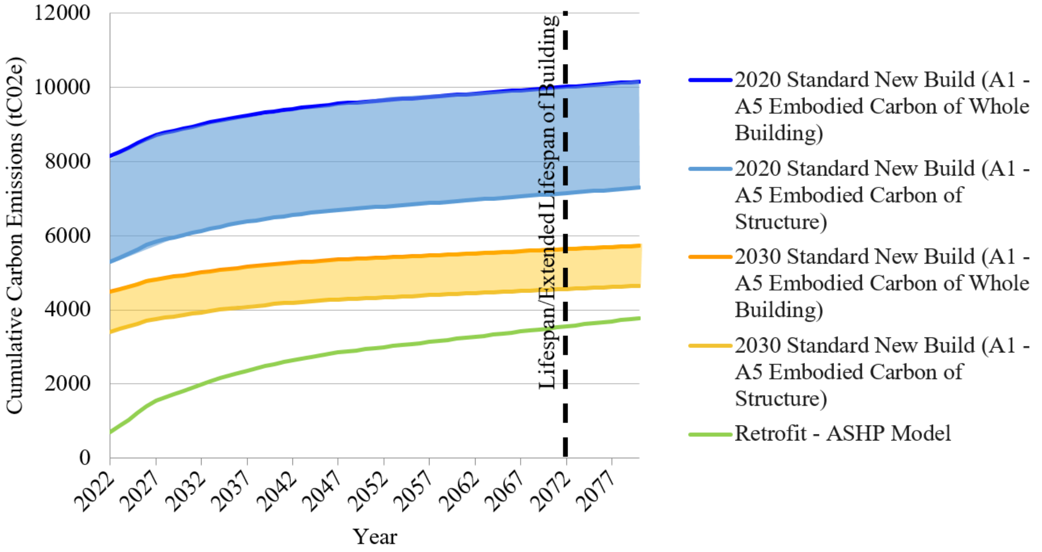

Figure 5. Cumulative carbon emissions over the building's lifespan, using the National Grid's 'Steady Progress' future scenario.

3.3. *Using 'leading the way' National Grid predictions*

Figure 6 shows the change to the results if the UK were to follow the best possible decarbonisation scenario. If this were achieved, then in all cases there would be a 40% decrease in operational emissions over the 50 year lifespan compared to the 'steady progress' scenario.

Figure 6 shows it would also increase the carbon payback period between the new build scenarios and the retrofit case study. It would take between 156 - 220 years before the retrofit model would start to emit more carbon than the 2030 standard new build.

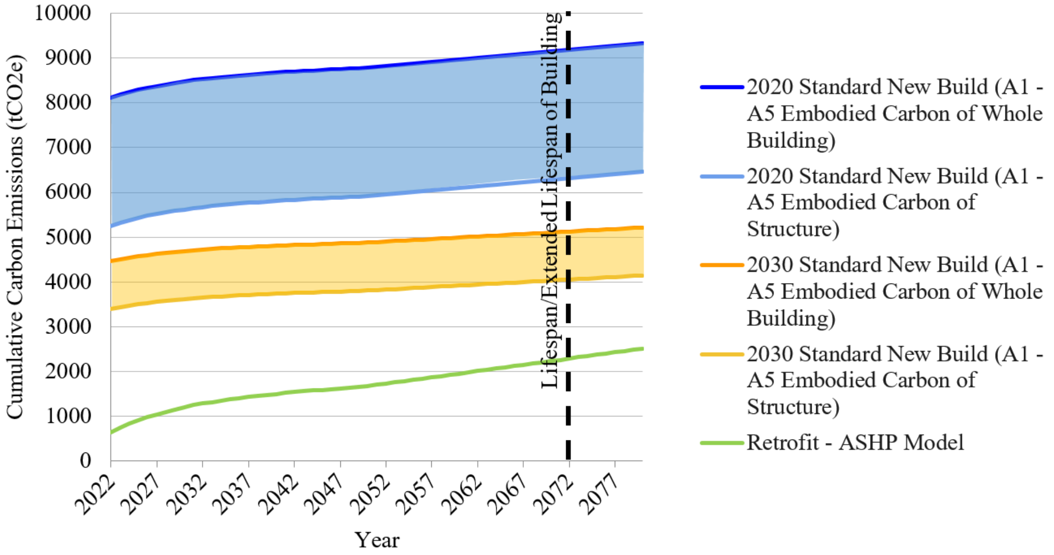

Figure 6. Cumulative carbon emissions over the building's lifespan, using the National Grid's 'Leading the way' future scenario.

4. Discussion and conclusions

The overall worst performing scenario was the retrofit model which relied on gas. Despite both retrofit models having the exact same thermal standards, the gas model emitted considerably more carbon. As the national grid carbon factor reduces, the ASHP model is shown to emit less and less carbon while the gas model continues to emit carbon at a much higher rate. If the UK did manage to achieve net zero national grid emissions, eventually the ASHP could emit no new carbon emissions. This is unlikely to ever be achieved through the gas boiler model, and indicates that relying on on-site fossil fuels in refurbishment projects will not allow the UK to cut carbon emissions at the pace required to meet national and international climate commitments [29].

This study shows that grid decarbonisation reduces the effect of lowering operational energy, and increases the carbon payback time between the new build and retrofit scenarios. This shows the importance of including grid decarbonisation scenarios within demolition vs refurbishment case studies, as the impacts of the larger embodied carbon footprint on whole life carbon from the new build scenario could be being underestimated.

In fact, despite having a worse operational energy performance than either new build benchmark, the ASHP retrofit model emitted the least amount of carbon over the building's lifespan. This indicates that embodied carbon cannot be ignored when it comes to deciding the fate of existing buildings. When looking purely at operational emissions, as allowed in UK building regulations, the logical conclusion from these results would be to demolish the original building. The results from this paper, if representative of other commercial buildings in the UK, suggest that embodied emissions must be regulated, alongside operational emissions, if the best whole life carbon solutions are to be identified and pursued, resulting in the prevention of a considerable quantity of carbon emissions.

To quantify this potential saving, the results from this study are scaled up across the UK. Currently, in the UK there are approximately 19 million m^2 of retail floor space in England & Wales of a similar age to the case study assessed (built 1940 - 1970) [30]. Though it is understood that this is just one specific study, if the results were able to be scaled up, you could save between 1.3 - 8.6 million tCO2e by choosing to retrofit this space instead of demolition and new construction of either a 2020 or 2030 standard building. This is equivalent to up to 1.6% of the UK's current annual emissions [31].

5. Limitations and future research

Despite the positive findings in favour of choosing refurbishment in this paper, it is clear that cost would play a huge role in these decisions. Currently, cost benchmarking for commercial retrofit projects is limited. A future survey into the cost implications of choosing retrofit over demolition would be highly useful to understand possible barriers to retrofit uptake in the UK. If major cost hurdles are found, this survey could help inform industry what needs to be changed to help encourage retrofit.

Also, in this study the building's occupancy patterns have not been predicted to change after refurbishment or reconstruction. In the UK, retail and office buildings are predicted to have periods of negative growth rate over the next thirty years, while residential buildings are predicted to increase steadily by 5 million dwellings in 2050 [9]. In the future, detailed research into the adaptability of commercial buildings could be completed as the effects of change of use on operational carbon output could be very different. Adaptation of an existing building could also be found to increase the initial embodied carbon of the refurbishment project. If repurposing these buildings is found to be favourable it could save a significant number of structures from being demolished despite having no need for the building's original purpose. Assessment into the effects of future weather patterns due to climate change could also change the operational carbon output of the building, and would be useful to investigate in the future.

One limitation to the conclusions made in this paper is that it has only studied one specific case study. This means that these results are not necessarily applicable to other buildings around the UK. Future research into how representative this research is of the wider UK building stock is critical to truly understand the best whole life carbon solutions. For example, if it was discovered that portions of the UK's commercial stock could be grouped into similar building typologies it might make it easier to design retrofit measures for multiple buildings at scale and therefore increase uptake.

It would also be useful to undertake this research using wider retrofit and new build scenarios to understand the effects of different environmental design approaches, including the impact of using different forms of renewable energy.

6. Appendices

Table 4. Inputs into the retrofit model required to meet UK building regulations.

Component	Details	Building Regulation Standard [a]
Replacement windows	Double glazing, air filled (1307m^2)	U-Value: 1.8 W/m^2.K
External wall insulation	Stone wool – external wall, 110 – 120mm Cladding – Aluminium (1565m^2)	U-Value: 0.3 W/m^2.K
Internal wall insulation	Stone wool – roll, 110 – 120mm (2084m^2)	U-Value: 0.3 W/m^2.K
Flat roof insulation	Stone wool – rollbatt, 200mm	U-Value: 0.18 W/m^2.K
Floor insulation	Stone wool – insulation slab, 120mm (2864m^2) (Screed – 75mm)	U-Value: 0.25 W/m^2.K
Solar Shading	External blind (80% solar transmittance)	Solar load reduced by 20%
Lighting	500 lux [b]	60 Lumens per Watt
<u>Gas model, building systems</u>		
DHW system	Gas boiler	Efficiency: 0.8
Heating system	Gas boiler	Efficiency: 0.84
Cooling system	Air-source chiller	EER: 2.65
AHU	Inc. plate heat exchanger	Efficiency: 0.5
<u>ASHP model, building systems</u>		
DHW system	Solar thermal (175m^2)	
	Electric water heater	Efficiency: 1
Heating system	Air-source heat pump	COP: 2.5
Cooling system	Air-source heat pump	COP: 2.5
AHU	Inc. plate heat exchanger	Efficiency: 0.5

[a] [15]
[b] [32]

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