How far can low emission retrofit of terraced housing in Northern Ireland go?

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PAPER

How far can low emission retrofit of terraced housing in Northern Ireland go?

Ben James[1,*], **Jayanta Mondol**[1], **Trevor Hyde**[1] **and Aoife Houlihan Wiberg**[2]

[1] Belfast School of Architecture and the Built Environment, Ulster University, Belfast, United Kingdom
[2] Department of Architecture and Civil Engineering, Faculty of Engineering and Design, University of Bath, Bath, United Kingdom
[*] Author to whom any correspondence should be addressed.

E-mail: James-b1@ulster.ac.uk

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Abstract
With both global and national targets to reduce greenhouse gas (GHG) emissions the improvement of existing buildings will be key to realising these ambitions. How this can be achieved, and the impact of whole-life emissions from retrofit remains a key question. This paper investigates the potential of retrofit to reduce and limit lifecycle GHG emissions resulting from an existing house, typical of one of the predominant housing typologies in Northern Ireland. Through the use of lifecycle assessment a range of retrofit scenarios are considered for an early 20th century, solid wall, terraced house, to understand the impacts of retrofit on lifecycle emissions. A range of retrofit scenarios were modelled and simulated, considering both embodied and operational emissions over the building's lifetime, to understand how net emissions can be reduced. The results show that although fabric and some technological measures can reduce emissions by over 60% when applied in isolation, a holistic approach is required to achieve the greatest reductions. Although operation remains the largest single source of emissions, the results also show the importance of taking a holistic approach to the assessment of retrofit with varying lifecycle stages responsible for considerable emissions. It is seen that emissions reductions of up to 99% may be possible when taking a holistic approach to retrofit and its assessment, considering whole-life emissions. This study highlights the potential benefits of retrofit and how it could be effectively applied to the existing housing stock in Northern Ireland creating low-emission or net-zero emission buildings.

1. Introduction

Globally buildings and the entire construction sector accounted for 39.65% of greenhouse gas (GHG) emissions in 2022 (IEA 2023), the largest of any single sector. Excluding 'other construction', for example, infrastructure projects, and looking solely at the operation and construction of buildings in 2022 this figure only reduces to 33.5% of global emissions (IEA 2023). As the effects and impacts of climate change become an ever more pressing issue, both globally and locally, there is an increasing urgency to reduce emissions levels and our built environment has a key role to play in this.

In 2021 the United Kingdom contributed 0.89% or 335.36 $MtCO_2$/yr to global CO_2 emissions, down from 1.86% in 2005 (Crippa *et al* 2022), of which 20% came from all buildings (Climate Change Committee 2022, Crippa *et al* 2022). Recent annual reports by the UK's Climate Change Committee (CCC), suggest not enough is being done in the built environment sector to bring about reductions in these figures. Their latest report suggests urgent changes are required in how the UK's existing housing stock uses energy (Climate Change Committee 2022). The observations of the CCC coupled with national emissions statistics reflect an ever-increasing urgency with which emissions from our built environment must be addressed, especially if Net Zero targets are to be met and more importantly global warming slowed.

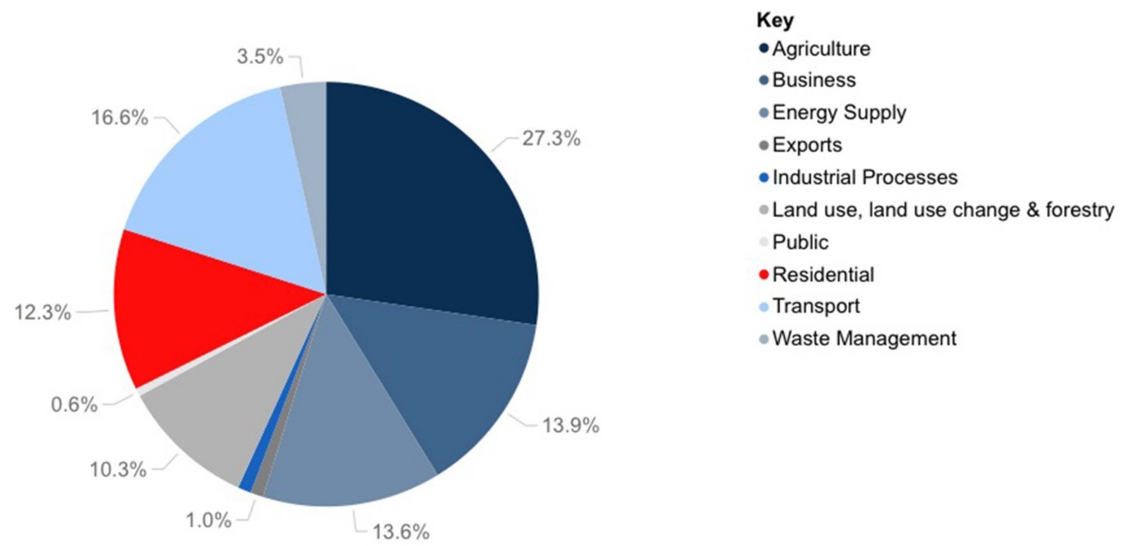


Figure 1. Sources of emissions in Northern Ireland (Source of Data: Department for Energy Security & Net Zero (DESNZ) 2023).

Examination of emissions sources in the UK, as a whole, shows that direct emissions from residential use equated to 15.5% of total UK GHG emissions in 2021 (Department for Energy Security & Net Zero (DESNZ) 2023), almost three times the sectors share globally, at 5.7% (IEA 2022). Whilst this can in part be attributed to lower proportions of emissions coming from other sectors, relative to other countries, the continued use of oil and natural gas to heat homes is one of the biggest sources of building related in the UK (Climate Change Committee 2022). As seen in figure 1, this figure drops slightly to 12.3% of total GHG emissions in Northern Ireland (Department for Energy Security & Net Zero (DESNZ) 2023), with similar percentages in the other nations of the UK. For comparison, direct emissions from residential use in the Republic of Ireland were 18% of total national GHG emissions in 2021 (Sustainable Energy Authority of Ireland 2023).

1.1. Energy performance of existing UK building stock

With emissions from residential use in the UK primarily driven by heating homes (Department for Business, Energy & Industrial Strategy (BEIS) 2023) the energy efficiency of housing has a key role to play in reducing these emissions. In the UK Energy Performance Certificates are used to rate the energy efficiency of houses, with houses given a rating between 1 to 100 correlating to seven lettered bands, from 'A' the most efficient to 'G' the least efficient. These certificates are based upon the estimated energy efficiency of a given house, calculated in accordance with the UK Governments Standard Assessment Procedure. This procedure considers the amount the amount of energy required to heat and use the house, considering the building fabric, heating and cooling systems as well as any renewables present. Whilst the average energy performance in Northern Ireland is the best across the UK (Ogunrin *et al* 2022), this only equates to a 'D' rating. Furthermore, the Northern Ireland Housing Executive (NIHE) reported that in 2016 no houses in Northern Ireland had an EPC rating of 'A', while 50% were in Band 'D' or lower (NIHE 2018). With 28.5 million existing homes in the UK in 2017 (Piddington *et al* 2020), and approximately 780 000 of these in Northern Ireland (NIHE 2018), retrofit across the UK will have a key role to play in reducing emissions. Northern Ireland faces its challenges as it attempts to reduce emissions and address energy efficiency within its existing housing stock.

1.2. Whole-life emissions and retrofit

Historically retrofit has tended to focus on reducing energy use and emissions from operation, (Vavanou *et al* 2022), however in recent years lifecycle assessment (LCA) has increasingly been used to understand the whole-life impacts of retrofit. As outlined in EN 15978:2011 'Sustainability of construction works-Methodology for the assessment of performance of buildings' (British Standards Institute 2012) LCA is used to consider the whole-life impacts of a project, broken down into various lifecycle modules. These modules include the extraction of raw materials and manufacture of products through to the construction, operation and maintenance of the building as well as ultimately the deconstruction and the end of life of materials. Table 1 shows all of the modules and lifecycle stages included within EN 15978:2011 (British

Table 1. Lifecycle stages according to EN 15 978:2011 (British Standards Institute 2012).

<table>
<tr><th colspan="15">BUILDING LIFECYCLE STAGES</th></tr>
<tr><th colspan="3">Product Stages</th><th colspan="2">Construction Process Stages</th><th colspan="5">Use Stages</th><th colspan="4">End of Life Stages</th><th>Benefits and Loads beyond the Lifecycle</th></tr>
<tr><td>A1</td><td>A2</td><td>A3</td><td>A4</td><td>A5</td><td>B1</td><td>B2</td><td>B3</td><td>B4</td><td>B5</td><td>C1</td><td>C2</td><td>C3</td><td>C4</td><td>D</td></tr>
<tr><td rowspan="3">Raw Material Supply</td><td rowspan="3">Transport</td><td rowspan="3">Manufacturing</td><td rowspan="3">Transport</td><td rowspan="3">Construction - Installation Process</td><td>Use</td><td>Maintenance</td><td>Repair</td><td>Refurbishment</td><td>Replacement</td><td rowspan="3">Deconstruction</td><td rowspan="3">Transport</td><td rowspan="3">Waste Processing</td><td rowspan="3">Disposal</td><td>Reuse</td></tr>
<tr><td colspan="5">B6 Operational Energy Use</td><td>Recovery</td></tr>
<tr><td colspan="5">B7 Operational Water Use</td><td>Recycling</td></tr>
</table>

Table 2. Summary of EN 15 978:2011 lifecycle modules included in previous studies.

		Lifecycle Modules according to EN 15978:2011														
Study by	Location	A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
(Colli *et al* 2018)	France	X	X	X		X		X		X	X	X	X		X	
(Vavanou *et al* 2022)	UK	X		X				X		X						
(Shibata *et al* 2023)	UK	X	X		X	X	X	X		X						
(Mohammadpourkarbasi *et al* 2023)	UK	X	X		X	X	X	X	X	X						

Standards Institute 2012). Whilst the introduction of EN 15978:2011 provides a standardised approach and methodology for the assessment of emissions the modules reported can vary greatly between projects. It is this variation in the reporting of modules which can make it difficult to understand what Net Zero or Low emission is. Thus, how Net Zero is defined can be key, but as shown by Satola *et al* (2022) Net Zero definitions can not only vary between countries but have differing ambition levels within one country's definition. In the UK Net Zero buildings are defined by the UKGBC in three categories, Net Zero for Construction, Operation and Whole-life.

Whilst (Satola *et al* 2022) argue for the integration of a whole-lifecycle approach to emissions, for both new build and retrofit, this is currently not always the case. Various studies have examined the operational and embodied emissions associated with retrofit as well as the impact retrofit depth can have on emissions (Famuyibo *et al* 2013, Colli *et al* 2018, Vavanou *et al* 2022, Mohammadpourkarbasi *et al* 2023, Shibata *et al* 2023), but the lifecycle stages considered vary. Fewer studies have used EN 15978:2011 as the methodological approach for the LCA and fewer still consider all lifecycle modules within this standard. Table 1 highlights four such studies which have all used EN 15978:2011 to assess the retrofit of a single existing residential building. Although all of these studies follow EN 15978:2011 not all report the same lifecycle modules, making direct comparisons challenging. However, as shown by Sahagun and Moncaster (2012) materials (A1-A3) and transport (A4) are the biggest contributors of emissions, after operation (B6), over the lifecycle of a retrofit project with emissions from other modules negligible in comparison. There is a focus on the product stage and operational energy modules, whilst understandable this excludes potentially key sources of emissions, such as transport. It is also important to note, as highlighted by Colli *et al* (2018), that not all modules are relevant to retrofit, for example, B5 covers refurbishment which could be defined as retrofit. Despite this, there remains progress to be made in understanding whole-life emissions from retrofit and how Net Zero can be achieved.

Regardless of the differences in reporting the various LCA modules the studies highlighted in table 2 some of these also explore the impact retrofit depth can have on lifecycle emissions. The impact of retrofit depth is illustrated in the studies by Vavanou *et al* (2022) and Mohammadpourkarbasi *et al* (2023) where progressively deeper retrofit scenarios reduce lifecycle emissions. It is also apparent, in both of these studies, that increasing retrofit depth shifts the emissions balance from operational emissions towards embodied factors, although operational emissions often remain the largest single source of GHG emissions. It is clear that although shallow retrofit can potentially bring about quick reductions in GHG emissions when Net Zero is concerned ultimately deep retrofit is required in the long term.

1.3. Retrofit guidance

With limited ambition for retrofit coming from either the Northern Irish Building Regulations or those in other parts of the UK, voluntary initiatives can offer more rigorous targets and ambitions for the improvement of existing buildings. One such initiative is the LETI Climate Emergency Retrofit Guide (Low Energy Transformations Initiative 2021) which begins to develop a series of targets and ambitions for retrofit. Although still primarily focused on operational impacts the LETI Retrofit Guide goes further than the Building Regulations in the UK, setting detailed and ambitious targets for retrofit. Offering guidance which takes account of building form and historic value the guide presents targets for energy use targets and use of renewables as well as fabric performance ambitions, tailored to various housing typologies. However, the LETI guidance falls short when considering the lifecycle emissions of retrofit. Despite highlighting embodied emissions as an important factor, and presenting ways in which they can be minimised, the guidance stops short of setting any specific targets. Whilst embodied emissions targets, especially for retrofit, can be problematic this lack of targets is in stark contrast to the extensive operational targets presented, ultimately limiting the impact of the guidance, especially when striving for Net Zero emissions.

1.4. Aims and objectives

A major change is required in how we approach existing buildings and strive for low, and ultimately Net Zero, Emission buildings. Through a case study approach, this paper will examine how far lifecycle emissions can be reduced through the retrofit of a common house typology in Northern Ireland. Specifically, that of an early 20th Century solid wall terrace house. This study explores the theoretical whole-life emissions for both the continued unchanged use of the house and 5 post-retrofit scenarios. This paper aims to understand the scale of the problem faced in individual houses and how whole-life emissions from such buildings can be reduced as part of a pathway to realising Net Zero Emission Buildings. It is intended that this study can be used to identify the constraints and potential opportunities that these housing typologies present when striving for Net Zero Emissions through retrofit.

2. Methodology

The purpose of this case study is to examine lifecycle emissions resulting from a residential property in Northern Ireland and the impacts retrofit could have on these emissions. The case study will be based upon an existing house constructed as a replica of a typical early 20th Century 3-bedroom terraced house in Belfast. LCA will be carried out for the house, considering several different scenarios both pre and post-retrofit. The use of LCA allows for the analysis of GHG emissions in terms of both operational and embodied emissions. This allows for an understanding of the sources of emissions in a retrofit project and how these can be minimised across the lifecycle of a retrofit project.

These LCAs will follow the British version of the European Standard for 'Sustainability of construction works-Methodology for the assessment of performance of buildings' [EN 15978:2011] alongside industry guidance in the form of the RICS Professional Statement on 'Whole-life Carbon Assessment for the Built Environment' and the IEA Annex 56 report on 'LCA for Cost Effective Energy and Carbon Emissions Optimization in Building Renovation'. Whilst EN 15978:2011 (British Standards Institute 2012) sets out the method for calculation to assess the environmental performance of a building, new or existing and the communication of the assessment outcome, the RICS statement (RICS 2017) offers additional guidance for the interpretation and implementation of the British Standard. Further to these documents the IEA Annex 56 report (Lasvaux *et al* 2017) offers further methodological guidance for carrying out LCA's for building renovations, i.e. retrofit.

2.1. Case study house

As seen, there is a clear need to address poor energy performance in housing in Northern Ireland, as such this study takes an inefficient house and examines how retrofit can be used to improve the energy efficiency and reduce emissions. The selection of house for this case study, a replica of an early 20th Century mid terrace in Belfast, is also one of the predominant housing typologies in Northern Ireland as identified in the 2016

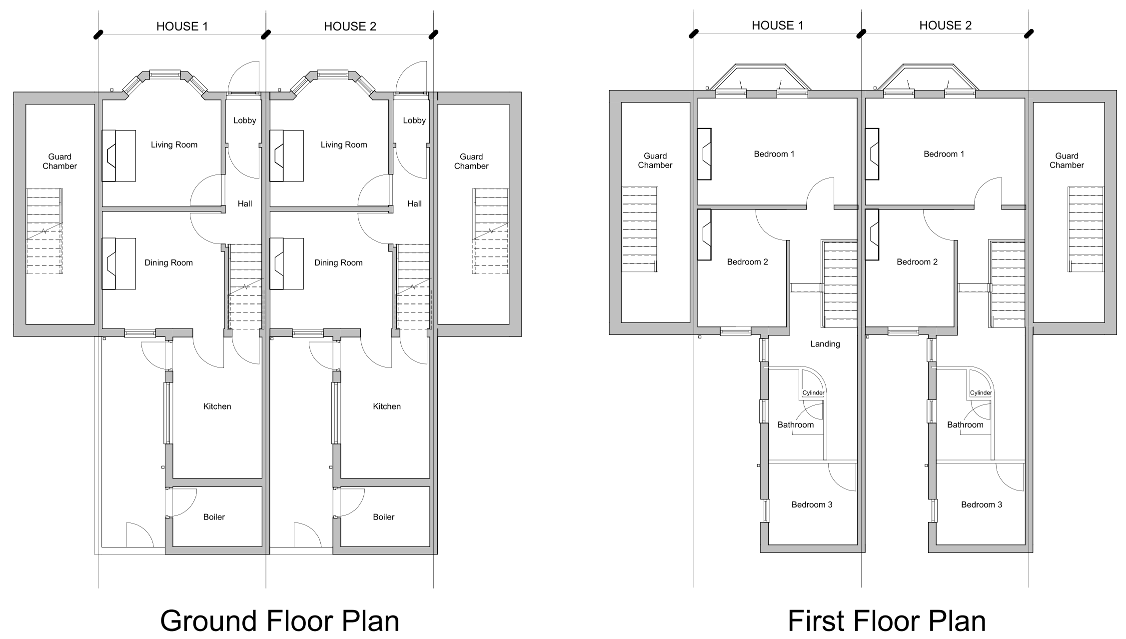


Figure 2. Floor plans of the case study 'test houses'.

Figure 3. Image of the Revit model of the individual case study house.

Northern Ireland Housing Condition Survey (NIHE 2018). Although not an original house from the era, it was constructed in 2012 as a replica of the typology, in both form and fabric, with a treated internal floor area of 91.3 m^2. The 'test houses' at Ulster University's Jordanstown campus offer the chance to understand and assess the constraints and opportunities such house types present when considering retrofit. Comprising two dwellings built with brick solid wall construction the test houses replicate the construction techniques of the period, and a common construction type in Northern Ireland as well as other parts of the UK. Constructed as a 'living lab' the development consists of two identical houses in a terrace with climate-controlled 'guard chambers' on either side, as seen in figure 2, to best replicate a continuous terrace of houses. The form and massing of the house is highlighted in figure 3, showing modelling of one of the test houses in isolation.

Deliberate use of minimal insulation in the houses further reflects the nature of this type of property and the challenges it presents. The houses consist of uninsulated floor and wall constructions, typical of the original housing on which the houses are modelled, while the roof spaces contain minimal 100 mm of quilt insulation further replicating the original house type. The windows are double-glazed, although this does not truly reflect the nature of houses from the early 20th century it does reflect the fact that one of the first and most common changes made to this type and age of house is to replace existing single-glazed windows. In fact, as of 2016 89% of all homes in Northern Ireland have double glazing installed (NIHE 2018), thus it is assumed to be a reflection of what could be expected to be found presently in such a property. The heating of the house consists of a central heating system with a condensing natural gas boiler, with radiators in each room, and a hot water storage cylinder at first floor. There are no renewable technologies considered as part of the existing scenario and the electricity supply is from the national grid.

2.2. LCA goal and scope

The following section outlines the boundaries and criteria for the LCAs used to compare the various retrofit scenarios which will be examined here. These will follow the industry standard as set out in EN 15978:2011 (British Standards Institute 2012), with additional supporting guidance from the RICS professional statement on whole-life carbon (RICS 2017). The goal for these calculations and assessments is to explore any potential benefits retrofit may bring in reducing the emissions from a building over its lifetime. With a focus on achieving Net Zero Emissions, all scenarios will be assessed for their global warming potential, as this is the most relevant metric when considering how buildings can impact climate change and the warming of the planet. With different gases having different potentials for global warming, CO_2 is commonly used as a reference point, therefore reporting here will be in the amount of CO_2 equivalent emissions, reported in kilograms i.e. $kgCO_2e$. Given the small and domestic nature of the case study the functional unit will be 1 m^2 of gross internal floor area including ground and first floors. There are no spaces which are not used or are 'untreated' therefore the boundary is to include all spaces, including storage. The physical boundaries for the assessments will be formed by the external envelope of the existing building, including the entirety of the party walls. It is presumed that the existing building has already been fully constructed in its current form, as per the RICS guidance (RICS 2017). The reference study period for all scenarios will be 60 years in line with the aforementioned RICS guidance. Results will be presented in terms of CO_2 equivalent emissions per 1 m^2 on an annual basis i.e. $kgCO_2e/m^2/yr$ across the 60 year reference study period. Assessments will account for both embodied and operational emissions with the criteria for these outlined in section 2.4 for each scenario.

2.2.1. Operational emissions–energy use

Operational energy demand, and ultimately operational emissions, were calculated through computer modelling, using IESVE 2021 (IES Virtual Environment), for both the existing and retrofit scenarios. A tool for dynamic building simulation, IESVE can be used to assess the energy and thermal performance of a building as modelled by the user, with an interface called Apache sitting at the centre of the simulation processing. IESVE comprises several applications within the software to assist with the modelling of a given building and the input of data and information regarding the construction, systems and use of the building. Figure 4 details the processes and applications used within IESVE for the creation and input of data to the model of the case study house along with the subsequent running of the dynamic simulations for each of the scenarios considered here. Annual energy use results from IESVE were generated from each of the dynamic simulations, broken down into monthly totals, in kilowatt hours, for both electricity and natural gas use. For some scenarios, where renewable heat sources are used the totals for gas are reported as zero, while generation from PV's are reported as a negative figure showing as an energy input rather than energy use. These annual energy use totals were subsequently exported to an MS Excel spreadsheet where operational emissions could be calculated from these results using the relevant emissions factors for Northern Ireland.

The house as existing, based upon original drawings, was initially modelled in IESVE (figure 5) using the 'ModelIt' application. Data for location, weather, use profiles and construction properties was subsequently added to this model to form both the model for the existing scenario as well as a baseline model which could be adapted for each of the retrofit scenarios. Data for weather and location is based upon the closest location to the site for which data is available, namely Belfast, Aldergrove (Latitude: 54.66°, Longitude: 6.22°) which is approximately 22 km due west of the case study house. Given the close proximity between the two locations, it was not expected that this would significantly impact upon the simulation results. To comply with standardised assessment criteria the UK National Calculation Methodology (UK NCM) (Building Research Establishment 2013) for dwellings was followed where applicable in the input of data to the IESVE model as well as the running of the simulations.

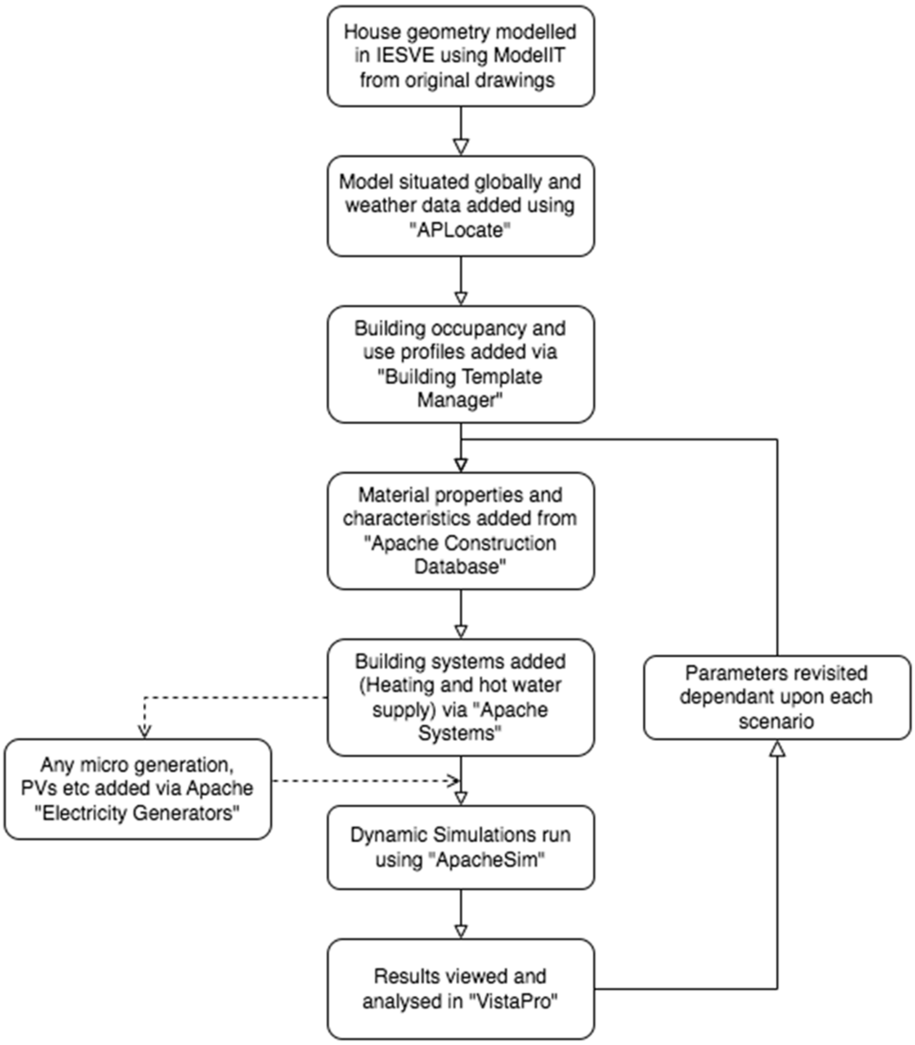


Figure 4. Flow chart showing workflow using IESVE.

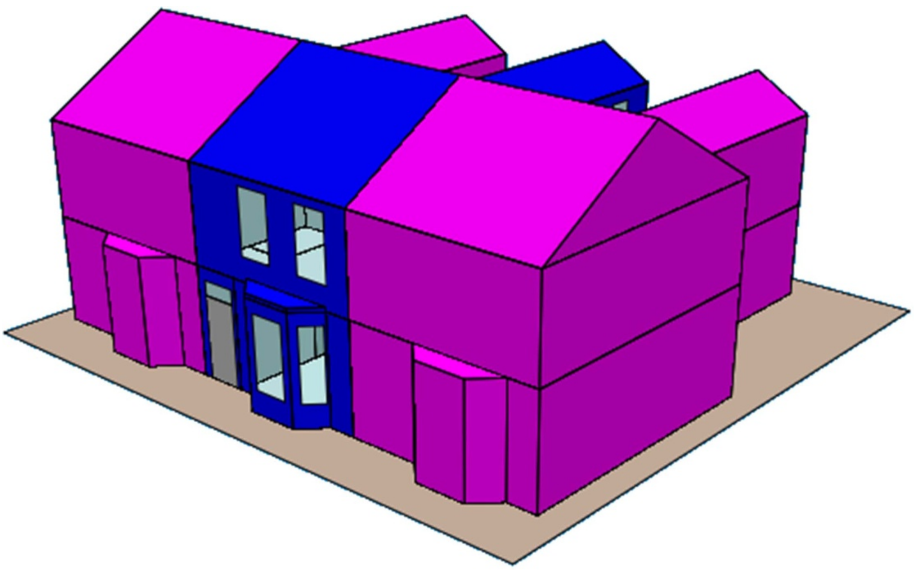


Figure 5. Image of the IESVE model with the case study house (highlighted) and adjoining properties.

Table 3. Energy related emission factors to be used in the life-cycle assessments.

	Electricity (kWh)	Gas (kWh)
Emission factor $kgCO_2$/unit	0.258	0.201

Table 4. Water related emission factors to be used in the life-cycle assessments.

	Water supply (litres)	Waste Water (litres)
Emission factor $kgCO_2$/unit	0.000 113	0.000 184

2.2.2. Operational emissions—emissions factors

Whilst the simulations offered an understanding of the energy demand of the various scenarios the resultant GHG emissions from this demand will be calculated using reported CO_2 emissions per kilowatt hour in Northern Ireland as shown in table 3. Given that emission factors can vary year on year as decarbonisation of the grid continues for this study the most recently reported emissions factors will be used to ensure consistency. Furthermore, with both electricity and gas grids in Northern Ireland also reliant on supply from other jurisdictions there is a degree of variation in emissions and potential change for sources of supply in the future.

Emissions from electricity supply in Northern Ireland are reported on a 'whole island' basis, including data from the Republic of Ireland. As such CO_2 emissions from electricity production in 2021 were 258 gCO_2/kWh (SEM Committee 2022). It is worth noting that this is down from 481 gCO_2/kWh in 2012 (SEM Committee 2022).

In the absence of data for CO_2 emissions from natural gas specific to the Northern Ireland market, along with the fact that the supply of gas in Northern Ireland is via pipelines from the UK and the Republic of Ireland, an average of the reported emission factors in each of these jurisdictions will be used. In the UK the emissions factor per kWh of gas in 2022 was 200 gCO_2/kWh (Department for Energy Security & Net Zero (DESNZ) 2023), while in the Republic of Ireland, it was 202.9 gCO_2/kWh in 2022 (Sustainable Energy Authority of Ireland 2023). Therefore the average of these two figures, 201.5 gCO_2/kWh, will be used.

2.2.3. Operational emissions—water

Further to operational energy use and emissions, emissions resulting from water use and wastewater has been calculated for each scenario, module B7 in LCA calculations (British Standards Institute 2012). In the absence of regulation or guidance on water efficiency in Northern Ireland water use is estimated based upon the National Calculation Methodology for assessing water efficiency in new dwellings in line with Approved Document G of the Building Regulations in England and Wales (The Building Regulations 2010). The existing water use and wastewater scenario is based on specification documents and drawings for the house, while the retrofit scenario uses data from new products with a focus on improved water efficiency.

Calculation of emissions resulting from the supply water and subsequent wastewater treatment have been based upon the latest reported emissions from NI water, namely 0.113 tCO_2e/MegaLitre for water supply and 0.184 tCO_2e/MegaLitre for wastewater treatment in 2021/22 (Northern Ireland Water 2022). As with electricity supply, this figure has reduced over the preceding years as the grid has begun to decarbonise, but again it is difficult to project forward, so these current figures are used as the basis for these assessments. Multiplication of the estimated water usage by the relevant emissions factors for both water supply and wastewater, as shown in table 4, has been used to calculate the resultant emissions.

2.2.4. Embodied emissions

As well as analysis of the operational emissions the embodied emissions of the materials used for the retrofit are also considered within the LCA's. The calculation of embodied emissions is to be carried out in MS Excel using material quantities exported from BIM (Autodesk Revit) modelling of the house, for both the existing and proposed scenarios, alongside product-specific environmental product declarations (EPDs). All EPDs used are third-party verified and are predominantly sourced from either 'Eco-platform' (Eco Platform 2023) or the BRE's (Building Research Establishment) GreenBookLive EPD verification scheme's search tool (BRE Global 2022). The quantities sourced from the BIM model are multiplied by the relevant emissions per module from the EPDs for each material or product, the quantities used in these calculations are driven by the functional unit reported in each EPD. A total emissions value for each module is calculated from the sum of each of the relevant individual emission values for each material or product. Calculations for the

Table 5. Lifecycle stages included within each scenario (refer to section 2.4 for further details of scenarios).

	Product Stages			Construction Stages		Use Stages							End of Life Stages				Benefits and Loads beyond the Lifecycle
Scenario	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
1									X		X	X					
2	X	X	X	X	X				X		X	X		X	X	X	X
3									X		X	X					
4	X	X	X	X	X				X		X	X		X	X	X	X
5	X	X	X	X	X				X		X	X		X	X	X	X
6	X	X	X	X	X				X		X	X		X	X	X	X

replacement of materials (Module B4) are based upon the reference service life of products as reported in individual EPDs, where this information may not be available the reference service life is based upon lifespans for elements as presented in the RICS guidance (RICS 2017).

The specific lifecycle modules covered vary between the different scenarios being examined. Table 5 details the lifecycle modules, as per EN 15978:2011 (British Standards Institute 2012), which are included within each scenario. This section will outline which of these modules are relevant to this study and why some are excluded. Where applicable modules for product stages to practical completion [A1-A5] are included as are end-of-life impacts, including removal [C2], processing [C3] and disposal of waste [C4], as well as any product replacements [B4] required during the reference study period, where relevant any benefits beyond system boundaries [D] are also included to help inform end of life situations. Where module C2 is not reported in EPD's emissions are instead based on BEIS (Department for Business, Energy & Industrial Strategy (BEIS) 2022) emissions factors for Freighting Goods by 'all HGV's' per tonne km^{-1} based on being 50% loaded, (Department for Business, Energy & Industrial Strategy (BEIS) 2022) allowing for arriving at site empty and leaving loaded as per the RICS guidance (RICS 2017). Whilst included to understand the complete picture, module D assumes best-case scenarios for the end-of-life treatment of materials, if treated differently at end-of-life these benefits may not be present. Modules for use, maintenance, repair, refurbishment and deconstruction [B1-B3, B5, C1] are excluded due to the difficulty in quantifying any energy use during these processes, and a lack of reporting in some EPDs. Furthermore, given the building type, it is not anticipated that any planned refurbishment [B5] will occur in the building's lifetime. Retrofit itself arguably fits into this module, B5, however, to fully understand the impact of retrofit a full LCA is required, as being carried out here.

2.3. Proposed retrofit measures

The retrofit proposals will address both fabric and technological solutions to reduce lifecycle emissions and understand the offsetting, or energy export, required to achieve Net Zero Emissions. With regulatory targets for the thermal performance of retrofit being limited in ambition, the LETI Climate Emergency Retrofit guide (Low Energy Transformations Initiative 2021) will be used to offer benchmarks for the thermal performance of individual elements. This guidance presents U-Value based ambitions on a building element basis tailored to either 'constrained' or 'unconstrained' properties. As a replica, it is assumed that the case study house falls into the unconstrained category, with no limiting factors such as heritage value or size, impacting the scope of the retrofit. Table 6 presents the existing construction with estimated U-values alongside the proposed retrofit measure for that element and the resultant U-values together with the relevant LETI targets. Table 7 further outlines the existing technology and systems alongside the proposed retrofit measures.

2.4. Assessment scenarios

Various scenarios will be considered to understand the benefits of retrofit and the role both fabric and technology have in reducing emissions. As well as considering the benefits a fabric-based approach can have, further scenarios also considered increasingly common technological, or active, measures such as photovoltaic panels and an air source pump as well as combinations of these. With the UK Government's 'Heat and Buildings Strategy' (Department for Business, Energy and Industrial Strategy 2021) intending to phase out gas boilers by 2035 the use of alternative heat sources will become more prolific. This is reflected in the number of air source heat pumps being installed in the UK, with 30 000 installed in 2022 versus around 8000 in 2017 (Microgeneration Certification Scheme 2023). Similarly, microgeneration can be seen to be

Table 6. Summary of fabric-based retrofit measures.

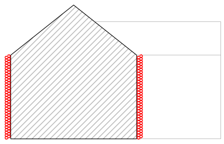
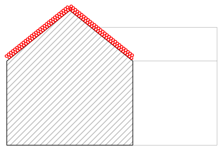
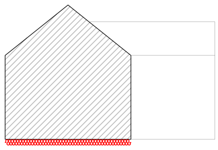
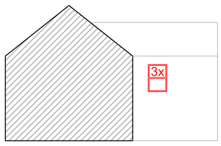
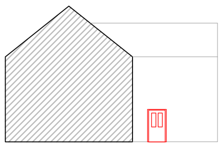
Building Element	Existing Construction	Existing Approx. U-Value W $m^{-2}K^{-1}$	Proposed Construction	Proposed Approx. U-Value W $m^{-2}K^{-1}$		LETI Target U-Value (W $m^{-2}K^{-1}$)
External Walls	Solid brick walls 215 mm	2.19	Existing 215 mm solid brick wall, 100 mm Kingspan K5 Insulation, Brick slips on adhesive	0.18		0.18
Roof	100 mm rockwool insulation at ceiling joist level	0.25	350 mm Sheepswool insulation at ceiling joist level	0.12		0.12
Ground Floor	Part uninsulated ground-bearing concrete slab, part uninsulated raised timber floor	1.93 (solid floor) 2.53 (raised timber floor)	150 mm Ground bearing concrete slab, Damp Proof Membrane, 125 mm Kingspan Thermafloor TF70 insulation, 75 mm sand cement screed	0.15		0.18
Windows	Softwood double-glazed windows	1.93	NorDan Aluclad triple-glazed windows	0.82		1.00
Doors	Hardwood double-glazed doors	1.98	Composite external doors	0.90		0.80

Table 7. Summary of technology and systems-based retrofit measures.

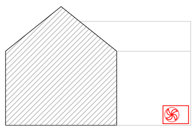
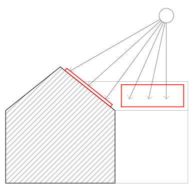
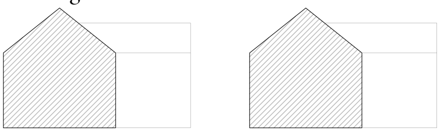
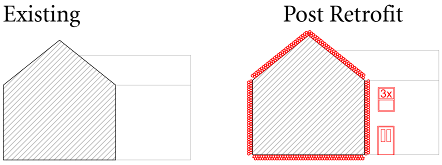
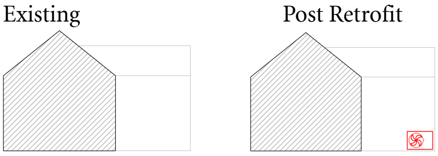
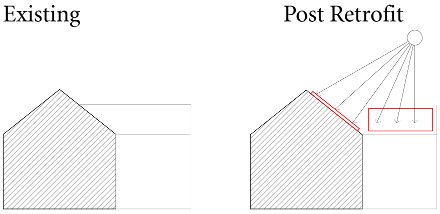
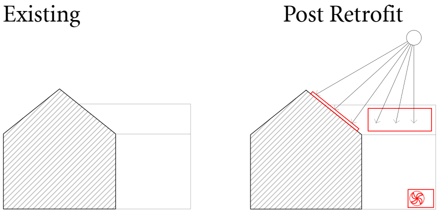
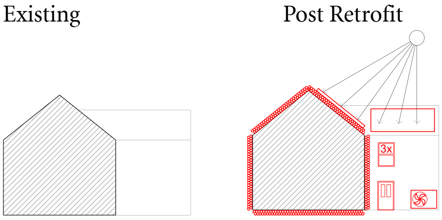
System	Existing System type	Existing Fuel	Proposed System type	Proposed Fuel		LETI Targets
Heating/Hot water source	Gas boiler with hot water storage cylinder	Gas (22 kW output)	Air Source Heat pump with hot water storage cylinder	Electric (6 kW output)		Fossil fuel free home
Electricity Supply	National grid	N/A	PV and National Grid	50% of existing roof area (19no 400Wp panels)		PV to 40% of roof area

Table 8. Summary of retrofit measures implemented for each scenario.

Scenario	Existing / Post Retrofit	Measures
Scenario 1 As Existing	Existing; Post Retrofit 	- Continued use of the house in its existing form with no retrofit - Consideration of emissions from the replacement of existing materials at end of their lifespan only
Scenario 2 Fabric Only	Existing; Post Retrofit 	- Existing fabric improved - Existing gas-fired boiler retained, no on-site electricity generation - Includes emissions from retrofit materials, including any replacements required over the reference study period
Scenario 3 Heat Pump Only	Existing; Post Retrofit 	- Existing gas-fired boiler replaced with new air-source heat pump for heating and hot water, fabric retained as existing - Includes emissions from the replacement of existing materials at end of their lifespan only
Scenario 4 Photovoltaics Only	Existing; Post Retrofit 	- Introduction of PV panels on the existing roof (19 panel array), fabric retained as existing - Electricity generation used to offset demand - Includes emissions from PV panels as well as the replacement of existing materials at end of their lifespan.
Scenario 5 Renewables Only (Heat Pump and Photovoltaics)	Existing; Post Retrofit 	- Existing gas-fired boiler replaced with new air-source heat pump for heating and hot water, PV panels installed on the existing roof (19 panel array), fabric retained as existing - Electricity generation used to offset demand - Includes emissions from PV panels and the replacement of existing materials at the end of their lifespan.
Scenario 6 Fabric and renewables (Heat Pump and Photovoltaics)	Existing; Post Retrofit 	- Existing fabric improved, existing gas-fired boiler replaced with new air-source heat pump for heating and hot water, PV panels installed on the roof (19 panel array) - Electricity generation used to offset demand - Includes emissions from retrofit materials and PVs, including any replacements required over the reference study period

becoming more prevalent with almost 140 000 UK-wide installations of solar PV in 2022, in comparison to just under 37 000 in 2017 (Microgeneration Certification Scheme 2023). Whilst it is hard to track fabric-based retrofit statistics, it is clear that renewable technologies are becoming an increasingly common measure for households in the UK. Table 8 outlines the scope of these various scenarios, while table 9 describes the assessment parameters for the LCA of each scenario.

Table 9. Summary of parameters for LCA's of each retrofit scenario.

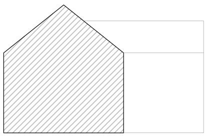
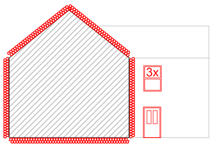
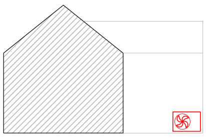
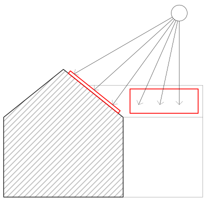
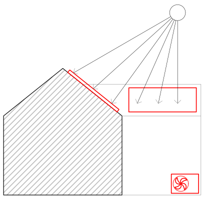
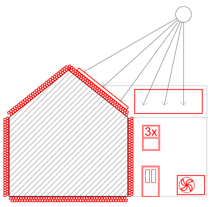
Scenario		1	2	3	4	5	6
System Boundaries	A1-A3 Product Stage		X		X (PV's only)	X (PV's only)	X (all new materials)
	A4-A5 Construction Stage		X		X (PV's only)	X (PV's only)	X (all new materials)
	B1-B5 Use Stage	X (B4)	X (B4)	X (B4)	X (B4)	X (B4)	X (B4)
	B6 Operational Energy	X	X	X	X	X	X
	B7 Operational Water	X	X	X	X	X	X
	C1-C4 End of Life Stage		X (C2-C4)		X (C2-C4, PV's only)	X (C2-C4, PV's only)	X (C2-C4) (all new materials)
	D-Benefits and Loads Outside System Boundary		X		X (PV's only)	X (PV's only)	X (all new materials)
Reference Study Period		60 years					
Natural Gas Grid Mix		0.201 $kgCO_2/kWh$					
Electricity Grid Mix		0.258 $kgCO_2/kWh$					
Supply Water		0.000113 $kgCO_2e/l$					
Waste Water		0.000184 $kgCO_2e/l$					
Summary Description		Baseline-No Retrofit, continued use as is (B4-replacement of existing materials)	Fabric based retrofit only—(B4-replacement of existing and retrofit materials)	Heat pump only-No fabric retrofit, (B4-replacement of existing materials)	PV's only-No fabric retrofit, (B4-replacement of existing materials and PV's)	Renewables only (PV and Heat pump)-No fabric retrofit, (B4-replacement of existing materials and PV's)	Retrofit Fabric + Renewables (B4-replacement of existing and retrofit materials)

3. Results

The results of the various LCA's show that retrofit offers the potential to significantly impact emissions from existing buildings over their lifecycle, through the use of technological and fabric-based approaches. It is also clear from the results that energy demand and the resultant emissions from operation remain the biggest drivers of emissions across a building's lifecycle. Despite operational emissions being the biggest contributor to net emissions embodied impacts should not be forgotten and it can be seen from an examination of the LCA results that certain elements of the retrofit are key drivers to overall levels of embodied emissions.

As expected, the biggest reductions in net emissions are seen where a holistic approach is taken (Scenario 6), where both fabric and renewable technology approaches are used in tandem. This approach has the potential to offer annual emissions savings of almost 100%, or near Net Zero, but is the most invasive of the scenarios considered. Whilst this holistic approach leads to the most significant reductions, shallower retrofit scenarios still have the potential to reduce emissions, albeit to a much lesser extent, as shown in table 10. The implementation of a solely fabric-based retrofit (Scenario 2) or the introduction of renewable heating (Scenario 3) both offer emissions reductions of over 50%, however introducing PV panels in isolation has a much more limited impact (Scenario 4). The use of photovoltaic panels offers the greatest benefit when the energy demand is first lowered through the implementation of other measures (Scenarios 5 and 6). When striving for Net Zero emission buildings, however, it is Scenario 6 which comes closest to achieving this target.

Table 10. Summary of LCA net GHG emissions results per scenario.

Scenario	Scenario Diagram	Net Emissions ($kgCO_2e/m^2/yr$)	Reduction in Net Emissions from Baseline (%)	Emissions relative to Baseline
1 (Baseline)		62.21	0.0	 100%
2		27.29	56.1	 43. 9%
3		25.79	58.5	 41.5%
4		47.26	24.0	 76.0%
5		10.84	82.6	 17.4%
6		0.54	99.1	0.9%

In the UK context when assessed against the UKGBC's 'Net Zero Carbon Buildings: A Framework Definition' it can be seen that through retrofit the house can achieve 'Net Zero Carbon—Operational energy' or 'Net Zero Carbon—Construction' (Richard Twinn *et al* 2019). With either operational emissions (B6) or emissions from product and construction stages (A1-A5) able to be offset by the generation of onsite electricity both of these definitions are achievable, however the retrofit falls just short of offsetting all embodied and operational emissions as required by the 'Net Zero Carbon—Whole-life' definition (Richard Twinn *et al* 2019). A closer examination of the two scenarios where the greatest emissions reductions are seen (Scenarios 5 and 6) shows how emissions can be balanced through on-site generation (see table 11 and figures 6 and 7). Whilst there remains a considerable difference in the emissions balance in Scenario 5, where a holistic approach is considered in Scenario 6 this balance becomes closer. Whilst showing the significance of onsite generation in balancing emissions the results show the scale of the problem with operational emissions, which remain over five times greater than embodied emissions (Scenario 6). This highlights the importance of lowering operational demand and emissions if net zero retrofit is to be achievable.

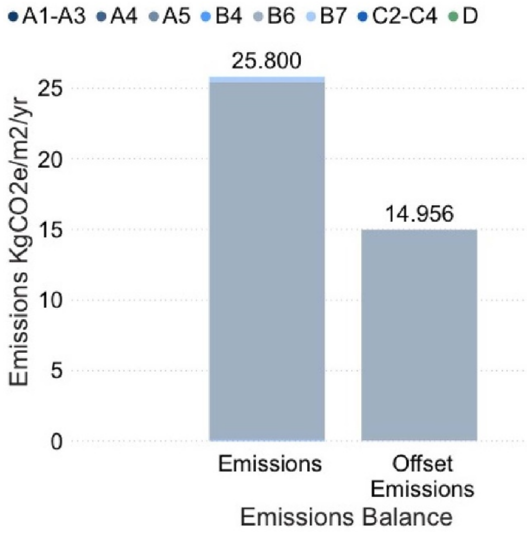


Figure 6. Graph showing emissions balance for Scenario 5.

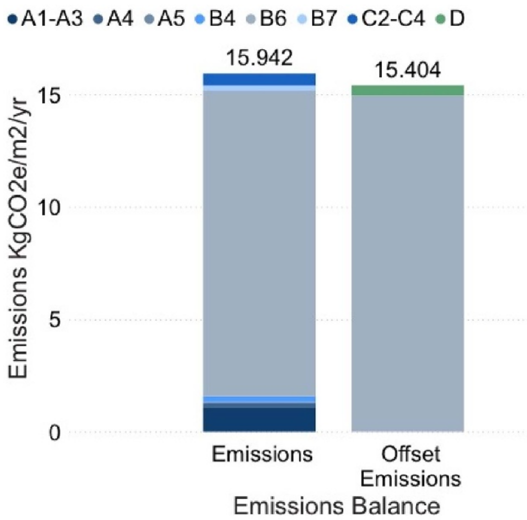


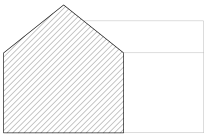
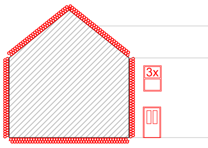
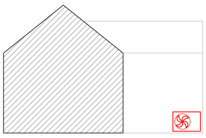
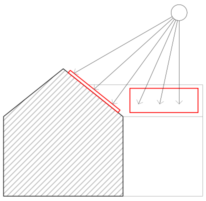
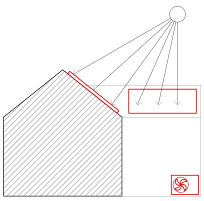
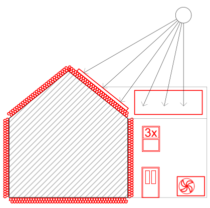
Figure 7. Graph showing emissions balance for Scenario 6.

Table 11. Summary of emissions and emissions offsets for scenarios 4 and 5.

		A1-A3	A4	A5	B4	B6	B7	C2-C4	D	Total
Scenario 5	Emissions ($kgCO_2/m^2/yr$)	0.0021	0.01	0.000 0053	0.07	25.38	0.34	0.000 027	N/A	25.80
	Offset Emissions ($kgCO_2/m^2/yr$)	N/A	N/A	N/A	N/A	−14.96	N/A	N/A	0.00	−14.96
Scenario 6	Emissions ($kgCO_2/m^2/yr$)	1.10	0.17	0.05	0.25	13.59	0.23	0.55	N/A	15.94
	Offset Emissions ($kgCO_2/m^2/yr$)	N/A	N/A	N/A	N/A	−14.96	N/A	N/A	−0.45	−15.40

As previously seen emissions from operation remain a key driver of overall emissions across a building's lifecycle, therefore reductions in energy demand are key to realising low-emission buildings. Each scenario explored how this energy demand can be reduced, offset or both, through retrofit. It can be seen in table 12 that the most successful methods of reducing net energy use are those where demand is lowered, be that through fabric-based intervention or the use of active measures, with further emissions savings possible through generation and offsetting. As seen in table 12 energy reductions of more than 85% are possible solely through the use of renewable technologies and generation (Scenario 5) however, it is not until fabric improvements are considered alongside renewables (Scenario 6) that energy use reduces significantly. It is also important to understand the source of this energy demand. Figure 8 highlights the significance of

Table 12. Summary of energy use results per scenario.

Scenario	Scenario Diagram	Total Energy Use (kWh yr^{-1})	Reduction in Net Energy Use from Baseline (%)	Emissions relative to Baseline
1 (Baseline)		27 068.9	0.0	 100%
2		10 497.7	61.2	 38.8%
3		8977.4	66.8	 33.2%
4		21 778.8	19.5	 80.5%
5		3687.3	86.4	 13.6%
6		−481.8	101.8 (energy export)	-1.8% (export)

emissions from heating demands. It can be seen in figure 8 that while emissions from gas usage far outstrip emissions from electricity use (Scenarios 1, 2 and 4), where renewable heating is used (Scenarios 3, 5 and 6) emissions from electricity use increased. It can be seen that it is only in Scenario 6, where a holistic approach is taken, that emissions from energy use see a significant reduction. There is only a 38% increase in total emissions from electricity use from the baseline scenario where heating was from a gas-fired boiler to this Scenario (6) where heat is now provided from an electrically powered renewable source.

Examination of the embodied emissions from materials in Scenario 6, (see figure 9), shows that the biggest contributor is insulating the ground floor. Whilst being a driver of high embodied emissions and one of the most intrusive elements of the retrofit, insulating the ground floor offers some of the greatest improvements in the thermal efficiency of the existing fabric (see table 6). These high embodied emissions can primarily be put down to the need for replacement concrete. Through substitution of the component parts of the concrete by alternatives, such as ground granulated blast-furnace slag (GGBS), this impact can be

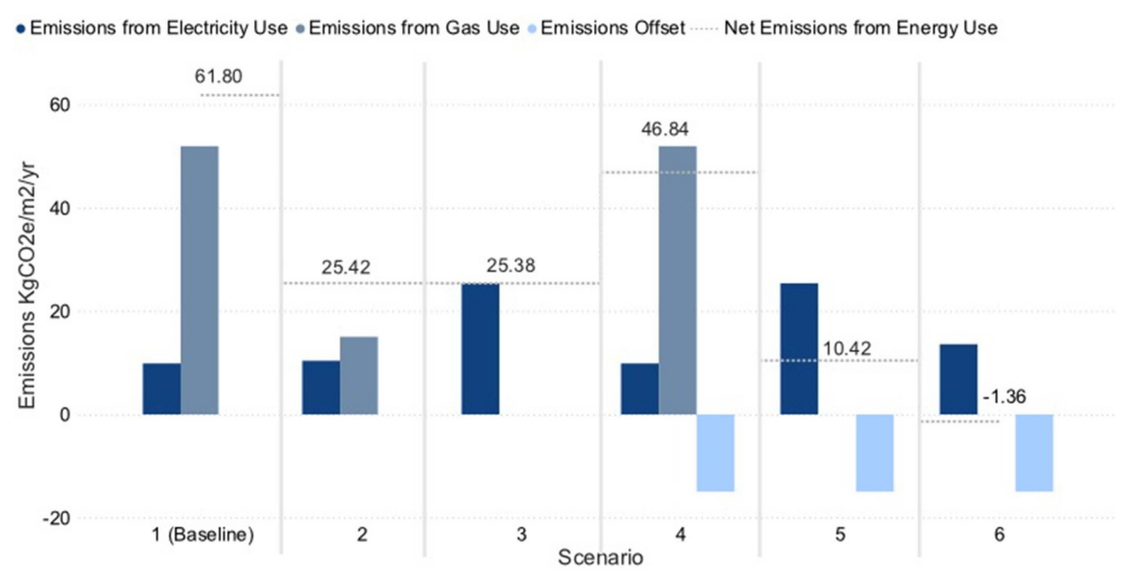


Figure 8. Graph showing comparisons of emissions from energy demand.

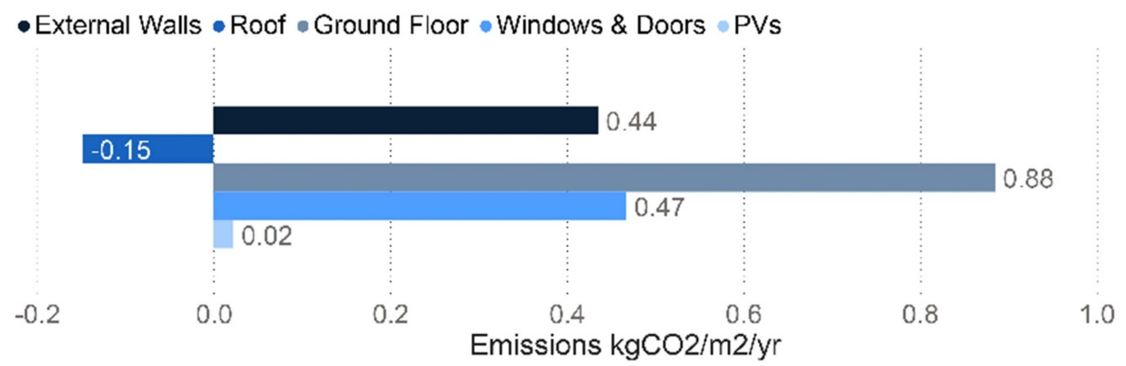


Figure 9. Graph showing embodied emissions per building element for retrofit.

lowered. For example, the Inventory of Carbon and Energy database (Jones and Hammond 2019) gives embodied carbon figures of 0.832 $kgCO_2e$ per kg of general concrete based upon a UK average, whilst a concrete mix with 50.5% of GGBS results in 0.475 $kgCO_2e$ per kg (Jones and Hammond 2019). This shows the potential for reducing embodied emissions further and alongside consideration of alternative insulation and use of natural materials, such as wood fibre, this can make insulating the ground floor more viable when targeting low embodied emissions.

Overall, these results show the benefits of taking a holistic approach to retrofit in reducing net emissions from this type of house. Furthermore, the results show the continuing dominance of operational emissions and the importance of taking a fabric-first approach to initially lower energy demand before considering how that energy or heat is generated. It is important to recognise that variabilities in climatic conditions year on year mean that these results present a 'current' view of both emissions from demand but also the ability to offset emissions through onsite generation. Future variations in climate may further impact these results across the 60 year reference study period, highlighting difficulties in defining Net Zero when the study period is so long. These results present a snapshot based on current data and the information currently available and regardless show that retrofit has the potential to offer significant reductions in emissions and offer a potential route to Net Zero buildings through retrofit.

3.1. Comparison of results

The direct comparison of results to other published LCA studies can be challenging due to variations in the methodological approaches and assessment criteria used. For example, the system boundaries, functional unit and reference study period can all vary between studies. As seen the study by Colli *et al* (2018) considers additional lifecycle modules in comparison to the study by Vavanou *et al* (2022), as well as using a shorter reference study period, with the two studies using 50 and 60 years respectively.

In the study by Vavanou *et al* (2022) a house of similar form and representative of the same era, undergoing deep retrofit, reports similar reductions in overall emissions when considering the same lifecycle modules. Vavanou *et al* (2022) report annual emissions of 17.85 $kgCO_2m^2$ compared to 14.99 $kgCO_2m^2$ presented here when considering the same lifecycle modules, A1-A3, A5, B4 and B6. It should, however, be cautioned that Vavanou *et al* (2022) consider the use of gas heating with mechanical ventilation and heat recovery in their scenario as well as alternative fabric choices. Despite this, both of these studies highlight the potential benefits of retrofit in reducing emissions from existing housing.

4. Discussion

With a need to reduce emissions from housing, it is clear that industry can no longer afford to take the path of least resistance and carry on as usual. This case study shows that significant emissions reductions can be achieved through a range of retrofit scenarios. Whilst fabric or technological approaches result in notable improvements and emissions reductions, in an environment where Net Zero or low emissions buildings will be essential, a holistic approach is key to making a significant impact.

Although the use of renewable heat sources is seen to lower emissions, it is not until demand is reduced through fabric improvements that these reductions become substantive. One of the challenges with the use of technology such as an air source heat pump is the current makeup of the electricity supply in Northern Ireland. The continued reliance on fossil fuel power stations results in a grid mix which results in noticeable emissions through the use of these technologies, with on-site micro generation insufficient to meet the demand. In a situation where up to 80% of UK buildings in 2050 have already been built (Richard Twinn *et al* 2019), it is hard to see how retrofit using renewables alone will be a viable solution in Northern Ireland, or even across the UK.

One challenge of retrofit, particularly of older buildings, is that of aesthetics and appearance. There becomes a careful balance required between the preservation of aesthetics and heritage values and reductions in emissions. While the use of external wall insulation here coupled with brick slips preserves the general appearance of the house, ornate detailing and decoration commonly seen on original properties would be lost with such an approach. With such properties often limited in size, internal insulation can also be problematic, as well as much more invasive. As seen in other studies such as Gupta and Gregg (2016) examination retrofit in a Victorian end terrace. Gupta and Gregg (2016) found that in preserving only the front façade problems were encountered when insulation was added internally to one wall and externally to another. As we strive for lower emissions where is the value in an existing building? Is it not better to retrofit and change a building's appearance whilst preserving its fabric than demolish it and replace it with a modern equivalent, potentially creating more emissions in the process?

How far can retrofit of this type of terraced housing go? With further consideration of the design of the retrofit and further reflection on material choices, Net Zero emissions may be achievable for this house. The substitution of materials with natural, or lower carbon, alternatives may be one way of reducing embodied emissions further, with the benefits of such approaches highlighted by Mohammadpourkarbasi *et al* (2023). Furthermore, with double glazing already installed is there a benefit in replacing these windows with new triple-glazed units or are operational savings undone by the embodied carbon costs? Whilst beyond the scope of this study the use of a phased approach and consideration of the financial implications may offer some answers to these dilemmas.

5. Conclusions

Given the scale of the existing housing stock in the UK and Northern Ireland, and its current energy efficiencies, the retrofit of existing houses will be vital in reducing GHG emissions. This study aimed to understand how far lifecycle emissions could be reduced in an inefficient house, typical of common housing typologies in Northern Ireland. Through the use of LCA whole-life emissions were calculated for various scenarios, with the results showing that retrofit can bring about substantial emission reductions.

Results show that when applied in isolation some retrofit measures produce similar reductions in emissions, as each other, however, it is not until these measures are applied together that substantial reductions are feasible. Although the implementation of retrofit requires new materials and consideration of embodied emissions the largest single source of emissions remains those from operation. Therefore, the depth of retrofit plays a significant part in reducing both operational and whole-life emissions. The findings show that operational emissions will remain an important factor in achieving low or Net Zero emission buildings, but how these are reduced and retrofit implemented becomes increasingly important.

The findings highlight the importance of embodied emissions when considering retrofit. The introduction of new materials shifts some of the overall emissions balance away from operational impacts towards embodied emissions. Thus, when striving for the greatest reductions in emissions, and ultimately Net Zero, the selection of materials can have a significant impact. Whilst one of the much vaunted benefits of retrofit is the retention of existing building fabric, limiting embodied emissions in comparison to new build construction, this study shows that the embodied impact of new materials required in a retrofit must not be forgotten or ignored when seeking to reduce whole-life emissions.

This study shows that a holistic approach to not only retrofit itself but also the assessment of retrofit is vital to realising meaningful GHG emission reductions from existing buildings. Whilst the product stages of the LCA, A1-A3, remain the largest contributor to embodied emissions where materials are sourced and how they are treated at the end-of-life stages can have a significant impact on whole-life emissions. End-of-life decisions are seen to result in either additional emissions or have the opportunity to bring benefits and offset emissions from other lifecycle stages. The variabilities possible across all lifecycle stages further highlight the importance of taking a whole-life approach to understanding the true impact and potential benefits of retrofit.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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ORCID iDs

Ben James https://orcid.org/0000-0002-6641-2169
Aoife Houlihan Wiberg https://orcid.org/0000-0001-7975-2229

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