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Broxtowe Housing Decarbonisation Roadmap

Final Report (Version 3.2)

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Delivered by Nottingham University Consultants and Develeco Projects Ltd.

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Executive Summary

In early 2024 Nottingham University Consultants and Develeco Projects Ltd were commissioned to identify cost-effective retrofit opportunities to help decarbonise Broxtowe's housing stock, as part as Broxtowe County Council's commitment to meet 2050 net-zero carbon emission targets.

The team built upon the work developed for Nottingham City Council through the £220 million UK Community Renewal Fund between 2021 and 2022. A significant part of this work was focused on developing a method to look at carbon-cost effectiveness of housing retrofit strategies. This method was further developed, updated and applied to examine Broxtowe's housing stock.

In this report, we present the findings in detail. The report is divided into the following sections:

Section 1. Establishing the status quo: in addition to establishing targets, benchmarks and approaches, this also contain a housing stock characterisation and a fuel poverty analysis.

Section 2. Generic housing performance assessment: this section uses generic dynamic building simulation models representing the main housing typologies as identified in Section 1 to quantify the implications (in terms of energy/carbon reduction and running costs) of fabric retrofit alongside low carbon heating and renewable energy integration.

Section 3. Generic housing embodied carbon calculations: the generic models representing the main housing typologies used in Section 2 were used to calculate the embodied carbon emissions of each retrofit strategy (Life Cycle Stages A1-A5, B1-B5, and C1-C43).

Section 4. Specific housing performance assessment: the method used for the generic models in Section 2 were applied to selected properties to quantify the implications (in terms of energy/carbon reduction and running costs) of fabric retrofit alongside low carbon heating and renewable energy integration.

Section 5. Specific housing embodied carbon calculations: the method used for the generic models in Section 3 were applied to the selected properties in Section 4 to calculate the embodied carbon emissions of each retrofit strategy (Life Cycle Stages A1-A5, B1-B5, and C1-C43.

Section 6. Lifetime capital cost of retrofit: the lifetime capital cost for each typology was calculated using the materials, specifications, and quantities as set out within Section 2.3, 3, 4 and 5.

Section 7. Net lifetime cost of retrofit: the net lifetime cost for each typology was calculated considering the lifetime capital cost of the works minus the lifetime cost savings, using the annual energy costs taken from Sections 2 and 4 and the lifetime capital cost data from Section 6.

Section 8. Carbon-cost effectiveness: the cost of the retrofit investment per tonne of carbon dioxide equivalent saved from the atmosphere over the lifetime of the retrofitted property was calculated for each of the properties studied.

Section 9. Broxtowe housing decarbonisation roadmap: in this section, the key data outputs for each typology are summarised and recommendations are suggested alongside estimated projections.

Section 10 is comprised of appendices and Section 11 is a list of references.

Why retrofit?

Retrofitting UK homes is essential for several reasons. First, it enhances environmental sustainability by reducing carbon emissions and improving the longevity of the housing stock. This is crucial for tackling climate change and preserving the environment for future generations. Second, retrofitting improves household energy efficiency, leading to lower energy bills. By upgrading insulation and installing energy-efficient systems, homes will require less energy to maintain comfortable temperatures, resulting in significant cost savings for homeowners and tenants. Third, retrofitting generates local and domestic economic opportunities. As the demand for retrofitting increases, so does the need for skilled labour and the production of energy-efficient materials. This can stimulate local economies and create new job opportunities within the construction industry. Lastly, retrofitting significantly improves the quality of life for occupants. Energy-efficient homes provide consistent temperatures and better air quality, enhancing health and comfort. This is particularly beneficial for vulnerable groups such as the elderly and disabled. Importantly, lower energy costs can help alleviate fuel poverty, making it easier for households to afford other essentials. *Overall, retrofitting homes in the UK is essential for fighting climate change, cutting energy bills, boosting the economy, and improving living conditions. By investing in retrofitting, the UK can create a more sustainable and comfortable future for everyone.*

What is the quality of the homes in Broxtowe?

An overview of the current condition of Broxtowe's complete housing stock (including owner-occupied, privately rented and socially rented) was established utilising data from the Energy Performance Certificate (EPC) database as of April 2024. The EPC database provides details on a building's energy use, typical energy costs, and recommendations for improving energy efficiency. As is typical to the UK, the most common dwelling types in Broxtowe are detached, semi-detached, mid- and end-terrace houses, flats, and detached bungalows, collectively accounting for approximately 95% of the area's properties. Further analysis of the archetypes showed that houses constructed from 1900–1966, flats constructed from 1900–1929 and 1950–1975, as well as detached bungalows constructed from 1950–1975 are less energy efficient (i.e., have EPC ratings D–G) than homes built during other periods. These homes with lower EPC ratings, which make up approximately 66% of Broxtowe's housing stock, have several key characteristics that need improvement. Characteristically, they often feature no or older insulation, outdated heating systems, and single-glazed windows, all which result in higher energy consumption and costs. These homes typically require substantial retrofit upgrades, including better insulation, more efficient heating systems, and possibly the addition of renewable energy sources, to improve their overall energy efficiency. *As these homes tend to have the highest energy costs and the poorest indoor conditions, and given the estimated number found in Broxtowe, they are a priority for retrofitting.*

Why do we need to consider fuel poverty?

Fuel poverty occurs when a household cannot afford to heat their home to an adequate temperature due to a combination of low-income, high-energy costs, and poor energy efficiency of the property. In the UK, a household is considered to be in fuel poverty if it needs to spend a high proportion of its income on energy to maintain a satisfactory heating regime. The government uses the Low Income Low Energy Efficiency (LILEE) definition for fuel poverty in England. Under this definition, a household is considered fuel poor if it lives in a property with an energy efficiency rating of band D or below and, after spending the required amount on energy, its residual income falls below the official poverty line. Fuel poverty can have serious implications for health and well-being, as cold homes can exacerbate conditions such as respiratory and cardiovascular diseases. It can also lead to higher energy bills, forcing households to make difficult choices between heating their homes and other essential expenses. *The rate of LILEE fuel poverty in Broxtowe is 13.5%, which is slightly higher than the English average of 13.1%, but lower than the typical rate across the East Midlands (15.1%).* To get a better understanding of these fuel poverty statistics, a mapping assessment was undertaken to analyse the spatial distribution of LILEE fuel poverty versus deprivation. The findings indicate that the LILEE definition likely underestimates the true extent of fuel poverty in Broxtowe (and across England), justifying further exploration of subjective fuel poverty rates. Additionally, a rough estimation was done to identify the financially vulnerable households that are omitted by default from LILEE statistics, i.e., those where the main earner is economically inactive and living in a property with an EPC rating of A–C. It was estimated that 1,251 homes fit this description and would likely be categorised as fuel poor according to other fuel poverty definitions. *Knowing the true extent of fuel poverty can drive retrofit initiatives to improve the energy efficiency of homes in Broxtowe, including identifying how to target assistance more effectively.*

What immediate needs does the analysis reveal?

Using data from the EPC database, a housing characterisation review for Broxtowe was conducted to identify key factors to guide the retrofit approach. From this, it was found that 66% of Broxtowe's housing is rated D-G and therefore can be considered energy inefficient and likely need retrofitting to improve performance. Additionally, 88% of Broxtowe's housing stock has gas boilers as the source of heating. The most common wall construction in detached (27.7%), semi-detached (47.5%) and terraced homes (41.9-51.3%) is solid brick with no insulation, and partially/fully insulated cavity walls for flats (30.1%) and filled cavity walls for bungalows (53.5%). Altogether, the proportion of uninsulated and partially insulated cavity walls present a great opportunity for less disruptive fabric improvements across all homes.

EPC data also showed that Broxtowe's housing stock has a large proportion of homes with non-insulated floors – between 44-60% across all typologies. Retrofitting these uninsulated solid ground floors is relatively uncommon because it often requires completely rebuilding the floor, resulting in higher costs and significant disruption for the occupants. Roof insulation is common, but the thickness varies greatly. More than 80% of properties already have double glazing.

We classified retrofit measures as ‘typical’ and ‘deep’. Typical retrofit measures (e.g. adding roof or wall insulation) are those which are generally easier and less expensive to implement, causing minimal disruption to occupants. They typically result in moderate energy savings and performance improvements. Deep retrofit measures, on the other hand, involve comprehensive upgrades across multiple systems, such as the building envelope (e.g., floor insulation), electrical, structural, and mechanical components. These extensive upgrades lead to higher upfront costs and greater disruption for occupants compared to typical retrofits. However, deep retrofit measures can achieve significant performance enhancements and long-term energy savings. *On the whole, the extent to which energy consumption and carbon emissions are reduced depends on the type of retrofit approach implemented and the type of property.*

So, what should be addressed first and why?

Upgrading the building fabric is recommended as the first measure in the retrofit process to improve the energy efficiency of homes. Key measures should include insulating the houses to minimise heat loss through the fabric and improving the airtightness barrier to reduce uncontrolled ventilation between the interior and exterior which is often seen in 'leaky' and draughty homes.

Roof insulation is the easiest retrofit measure and can be one of the first steps in a fabric upgrade. Wall insulation, however, was identified as the most significant fabric measure, proving more effective than other retrofit strategies across all house types. This effectiveness is due to the larger exposed envelope area of the walls compared to other fabric elements. Therefore, retrofitting walls should be prioritised whenever possible.

Installing an air source heat pump (ASHP) proved to be a cost-effective measure for most of the house types tested. Its cost-effectiveness was further enhanced when combined with external wall insulation and draught-proofing.

How much energy could be saved because of implementing the recommended measures?

Overall, the performance analysis indicated that upgrading the fabric and draught-proofing layer could reduce heating demand by up to 86% with extensive fabric measures (deep retrofit). *When fewer, less disruptive, and less expensive fabric measures were considered (typical retrofit), heating demand could be reduced by up to 70% compared to a leaky and non-insulated scenario, depending on the housing archetype.* A breakdown of this is shown for each archetype in Table 0.1.

Table 1: Percentage reduction in heating demand achieved with deep and typical retrofit measures across different heating systems in comparison to a leaky and non-insulated building

Archetype	Deep retrofit measures	Typical retrofit measures
Detached house	81%	61%
Semi-detached	83%	58%
Mid-terrace	86%	70%
End-terrace	86%	70%
Mid-terrace flat	80%	61%
End-terrace flat	81%	52%
Bungalow*	84%	54%

**Bungalow analysis considered a specific housing model, not a generic archetype*.

Greater reductions in total annual energy demand were observed when the traditional gas heating system was replaced with a low-carbon heating system, due to its high efficiency. We assumed a typical efficiency of 0.89 and a seasonal coefficient of performance of 0.8 for a gas boiler and took a realistic approach to the ASHP performance by varying the SCOP from 1.8 to 2.8 for space heating across different retrofit scenarios. Replacing a gas boiler with an ASHP reduced annual energy demand by up to 78% with deep retrofit measures, while maintaining a gas boiler reduced it by up to 61% compared to a leaky and non-insulated building with gas heating. *With typical retrofit measures, total annual energy demand was reduced by up to 73% with an ASHP and up to 49% with a gas boiler, compared to a leaky and non-insulated gas-heated building.* However, it should be noted that the cost-effectiveness of the ASHP compared to the gas boiler will depend on the energy costs of electricity and gas. This breakdown is shown in Table 0.2.

Table 2: Percentage reduction in total energy achieved with deep and typical retrofit measures across different heating systems in comparison to a leaky and non-insulated gas-supplied building

		Deep retrofit measures	Typical retrofit measures
Detached house	Gas boiler	28%	21%
	ASHP	38%	28%
Semi-detached	Gas boiler	22%	15%
	ASHP	42%	32%
Mid-terrace	Gas boiler	33%	27%
	ASHP	33%	20%
End-terrace	Gas boiler	36%	29%
	ASHP	36%	25%
Mid-terrace flat	Gas boiler	27%	20%
	ASHP	38%	31%
End-terrace flat	Gas boiler	30%	19%
	ASHP	41%	29%
Bungalow*	Gas boiler	19%	12%
	ASHP	28%	20%

**Bungalow analysis considered a specific housing model, not a generic archetype*.

Considering the energy price cap that was in place from October to December 2024 (the most recent price cap at the time of the analysis), replacing a gas boiler with an ASHP can reduce annual energy costs by up to 42% when deep retrofit measures are implemented. In comparison, maintaining a gas boiler can lower costs by up to 36% compared to a leaky, non-insulated building. When typical retrofit measures are considered, annual energy costs can be reduced by up to 32% with an ASHP and by up to 29% with a gas boiler, compared to a leaky, non-insulated gas-supplied building. This energy cost analyses suggested that switching to ASHP resulted in marginally lower annual costs compared to a traditional heating system. It is noted that the adoption of ASHP can help transition to net zero greenhouse gases, and energy costs can be further reduced depending on the electricity cost incentives.

What is the impact of implementing retrofit measures on embodied carbon?

Embodied carbon calculations involve assessing the total greenhouse gas emissions associated with the production, transportation, installation, maintenance, and disposal of building materials, measured in carbon dioxide equivalent (CO_2e). In this project, embodied carbon was considered for the key archetypes and for typical versus deep retrofit measures – this is one of a few instances when the embodied carbon of retrofit was considered in the UK. From this, it was determined that - across all property types - implementing a typical retrofit, as opposed to a deep retrofit, results in a saving of roughly 30-40% in embodied carbon. For example, in the case of a detached house, a deep retrofit results in 12.4 tonnes of CO_2e, whereas a typical retrofit generates 8.7 tonnes of CO_2e. This additional 3.7 tonnes of CO2 must be saved in operational carbon emissions over the lifetime of the property to make the deep retrofit scenario worthwhile. This is not unexpected since the deep retrofit utilises more materials and requires more work.

In the specific embodied carbon calculations undertaken for the specific house type, i.e. the bungalow typology, this trend is replicated. The calculations estimated that typical retrofit results in approximately 28% less embodied carbon compared to a deep retrofit. Specifically, a deep retrofit generates 12.9 tonnes of CO_2e, while a typical retrofit produces 9.3 tonnes of CO_2e. Therefore, the additional 3.6 tonnes of CO_2e from a deep retrofit must be offset by savings in operational carbon emissions over the property's lifetime to justify the deep retrofit. *This concludes that while retrofitting aims to reduce operational carbon emissions by improving energy efficiency, it can also introduce embodied carbon due to the materials and processes involved. To some extent, careful selection of materials and a focus on long-term operational savings can help mitigate its impact.*

What are the cost implications of retrofit measures?

The cost implications of retrofit measures can vary significantly based on their *type and extent*. Key factors to review include *initial cost, payback period, operational savings, embodied carbon, and cost effectiveness.* Typical retrofits, which include roof insulation, draught-proofing, and window upgrades, are generally less expensive and less disruptive, offering moderate energy savings. In contrast, deep retrofits involve comprehensive upgrades such as floor insulation and the installation of advanced heating systems like ASHPs. Although these deep retrofits have higher initial costs due to the extensive work required, they provide substantial long-term energy savings – and significantly improved comfort (which was outside the scope of this work). The payback period for retrofit measures depends on the energy savings achieved and the initial investment, with typical retrofits having a shorter payback period due to lower upfront costs, while deep retrofits take longer to pay off but offer greater savings over time. Despite having higher embodied carbon due to the extensive materials and work involved, deep retrofits can offset this through operational carbon savings over the building's lifetime, making them more environmentally beneficial in the long run. Additionally, it is important to note that the cost-effectiveness of retrofit measures can be influenced by factors such as energy prices, government incentives, and the specific characteristics of the building, with the relative costs of electricity and gas playing a role in the cost-effectiveness of ASHPs compared to gas boilers.

What next for Broxtowe?

Based on the findings of this project, that are discussed in detail across this report, the following recommendations can be made:

Recommendation 1 – Take a fabric-first approach. By prioritising improvements to the building's envelope, such as insulation and airtightness improvements, this method can lead to substantial energy savings by reducing the need for supplementary heating and improving overall energy efficiency. Other benefits include healthier and more comfortable indoor conditions for occupants and reduced operational costs and carbon emissions. As a starting point, the implementation of roof and external wall insulation would be the most impactful in any retrofit strategy.

Recommendation 2 – Integrate a comprehensive framework for managing and delivering retrofit projects and initiatives. The quality assurance process in retrofitting, particularly under the PAS 2035 framework, involves several key steps to ensure that retrofit projects are carried out effectively and meet high standards. By following a framework such as PAS 2035, Broxtowe Borough Council can ensure that their retrofit projects and initiatives deliver the desired energy savings and improvements in building performance without compromising on quality or safety.

Recommendation 3 – Consider the distinct characteristics and benefits of typical versus deep retrofit. Overall, while typical retrofits are suitable for achieving moderate improvements with lower upfront costs, deep retrofits are ideal for those seeking significant energy efficiency gains and long-term benefits. However, the comprehensive upgrades required for deep retrofit, such as floor insulation and advanced heating systems, require substantial investment and extensive work. Consequently, the payback period for deep retrofits can be quite long, making them less financially viable. Additionally, the financial benefits of deep retrofits can be influenced by fluctuating energy prices and the availability of government incentives. Without substantial financial support, the high costs and long payback periods make deep retrofits challenging to justify financially.

Recommendation 4 – Review the cost-carbon effectiveness as part of the decision making. From a whole life carbon reduction perspective, typical retrofits are more effective than deep retrofits when assessed over a 20-year period. They consistently cost less and result in greater whole life carbon savings, making them more carbon cost-effective overall.

Recommendation 5 – *When planning a retrofit, consider that costs can vary significantly depending on the type and extent of the measures implemented.* The retrofit process in this report is divided into three key stages. Stage 1 focuses on fabric improvements to reduce operational energy consumption and carbon emissions. Stage 2 builds on Stage 1 by integrating low-carbon heating systems. Stage 3 further enhances Stage 2 by incorporating renewable energy generation. For example, based on the assumptions outlined in this report, the cost for Typical Retrofit Stage 1 is estimated to be between £11,590 and £35,633, depending on the property type and as relates mainly to estimated capital cost for roof and external wall insulation and other factors detailed in the report. Building up on this, for Typical Retrofit Stage 2 (add low carbon heating), will result in energy bills being 8% to 22% lower than the pre-retrofit scenario, at an estimated cost of between £12,200 and £14,118 per property. Regarding Typical Retrofit Stage 3 (renewable energy generation), it was observed that while solar installations offer the most attractive financial payback compared to fabric and low carbon heating improvements, they are not as effective in reducing whole life carbon over a 20-year period.

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Glossary of Terms and Acronyms

ASHP – Air Source Heat Pump
A low-carbon heating system that extracts heat from the outside air to provide space heating and hot water. Efficiency is measured by its Seasonal Coefficient of Performance (SCOP).

BBC – Broxtowe Borough Council
The local authority commissioning the decarbonisation roadmap.

BEIS – Department for Business, Energy & Industrial Strategy
Former UK Government department (functions now largely transferred to DESNZ) responsible for business, industrial strategy, energy, and climate policy.

BRE – Building Research Establishment
UK-based organisation providing research, standards, and guidance on the built environment.

BSI – British Standards Institution
The UK's national standards body, responsible for publishing PAS 2035 and other construction standards.

BUS – Boiler Upgrade Scheme
A UK Government grant scheme providing funding for the installation of low-carbon heating systems, such as heat pumps.

CCE – Carbon Cost Effectiveness
A measure of the cost per tonne of CO_2e saved over the lifetime of a retrofit intervention.

CESP – Community Energy Saving Programme
A now-discontinued UK Government scheme that funded energy efficiency improvements in low-income areas.

CIBSE – Chartered Institution of Building Services Engineers
Professional body that publishes technical guidance for building services, including thermal performance.

CLC – Construction Leadership Council
Industry body that advises UK Government on construction and infrastructure issues.

COP – Coefficient of Performance
Ratio of useful heating or cooling provided by a system to the energy consumed; higher COP indicates greater efficiency.

DESNZ – Department for Energy Security and Net Zero
Current UK Government department responsible for energy policy and net zero delivery.

DHW – Domestic Hot Water
Hot water used for taps, showers, and appliances.

ECO – Energy Company Obligation
A UK Government energy efficiency scheme requiring suppliers to fund measures in eligible homes.

EPC – Energy Performance Certificate
Official UK document rating a property's energy efficiency from A (most efficient) to G (least efficient), with accompanying recommendations.

EUI – Energy Use Intensity
Annual energy consumption per square metre of floor area (kWh/m^2·a), used to benchmark building performance.

EWI – External Wall Insulation
Insulation applied to the outside walls of a building to improve thermal performance and reduce heat loss.

FEES – Fabric Energy Efficiency Standard
A metric for the efficiency of a building's thermal envelope, used in the UK's Future Homes Standard.

FHS – Future Homes Standard
Forthcoming UK regulations aiming to improve energy efficiency and reduce carbon emissions from new homes.

GIA – Gross Internal Area
Total floor area of a building measured to the internal face of perimeter walls.

GLA – Greater London Authority
Regional authority for London, referenced in heat pump performance studies.

GWP – Global Warming Potential
A measure of how much heat a greenhouse gas traps in the atmosphere compared to CO_2.

HVAC – Heating, Ventilation and Air Conditioning
Building systems providing thermal comfort and air quality.

IMD – Index of Multiple Deprivation
A UK measure combining multiple indicators (e.g., income, health, education) to assess relative deprivation.

IWI – Internal Wall Insulation
Insulation installed on the inner face of a wall to improve thermal performance.

LCA – Life Cycle Assessment
An analysis of environmental impacts associated with all stages of a product's life, including embodied carbon.

LETI – London Energy Transformation Initiative
An industry network producing design and performance guidance to achieve net zero buildings.

LILEE – Low Income Low Energy Efficiency
The official definition of fuel poverty in England, combining household income and EPC rating.

LSOA – Lower Layer Super Output Area
A UK geographic unit used for statistical analysis, typically containing 1,000–3,000 residents.

LTHW – Low Temperature Hot Water
Heating water supplied at 35–55°C, typically used with heat pumps for improved efficiency.

MVHR – Mechanical Ventilation with Heat Recovery
A ventilation system that recovers heat from outgoing stale air to warm incoming fresh air.

NDEA – Non-Domestic Energy Assessor
An accredited professional qualified to carry out energy assessments for non-domestic buildings.

PAS – Publicly Available Specification
A type of standard published by BSI; PAS 2035 sets out the framework for domestic retrofit projects.

PER – Primary Energy Renewable
A metric used in Passive House standards, measuring renewable primary energy demand.

PH – Passive House
An ultra-low energy building standard focusing on high insulation, airtightness, and heat recovery.

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1. Establishing the status quo in the UK and Broxtowe

This introductory section starts by setting out the necessity of retrofit for existing homes and identifies the key targets for energy and carbon assessments. Additionally, the results of a review of Broxtowe's housing stock (using EPC data for characterisation purposes) and a fuel poverty analysis are presented.

1.1 Why Retrofit?

Retrofitting homes in the UK is important for several reasons, including:

- Enhancing environmental sustainability, and ensuring the long-term health of the housing stock;
- Bettering household energy efficiency, and consequently lowering energy bills;
- Generating local and domestic economic opportunities; and
- Improving occupants' quality of life.

From an environmental sustainability perspective, retrofitting homes can help reduce greenhouse gas emissions and address climate change. Buildings are responsible for 49% of total greenhouse gas emissions in the UK, with domestic buildings representing 22% of this (LETI, 2020). As its stands (July 2024), new homes tend to fall short of 2030 proposed targets of achieving EPC ratings of C or above for privately rented and social properties (Department for Energy Security and Net Zero, 2025) in support of the Government's 2050 net zero greenhouse gases emissions goals, meaning they will need to be retrofitted further to achieve a suitable energy efficiency standard. Carbon dioxide is the main source of pollution and therefore where efforts are concentrated. Existing homes fair even worse as the majority were built before 1990, which preceded the adoption of more stringent energy standards (Passivehaus Trust, 2022). These existing homes are likely to comprise around 80% of the 2050 housing stock (Passivehaus Trust, 2022). The continued allocation of resources to reduce housing sector emissions is a crucial aspect of efforts to meet the UK's 2050 net zero target.

There are also household-level and broader economic benefits associated with retrofitting. For homeowners and tenants, improved energy efficiency results in lower utility bills. For example, fabric improvements such as insulation can drastically reduce the amount of energy required to keep homes warm in the winter or cool in the summer. Consequently, consumer energy costs should reduce, as should the number of homes experiencing fuel poverty. Additionally, as the UK construction industry adapts to modern retrofitting requirements, there is scope for local economic growth, given the likeliness of a corresponding rise in demand for skilled labour and the manufacture of energy efficient materials.

The energy efficiency benefits of retrofitting are indisputable. An integrated retrofitting approach includes fabric improvements (e.g. upgrading insulation, reduction of air leakage), the installation of energy efficient heating systems (often associated with mechanical ventilation and heat recovery, with air filtering), the adoption of renewable alternatives and the elimination of reliance on fossil fuels. All of these dimensions of retrofitting have the potential to significantly improve the energy efficiency of existing homes and contribute to the decarbonisation of the grid (LETI, 2020). The most crucial implication of having more energy efficient homes is a reduction in overall energy demand, which eases the strain on the national grid and contributes to national energy security.

Improving people's quality of life is also achievable through retrofitting. From a health and comfort perspective, energy efficient homes provide desirable indoor conditions, including consistent temperatures and controlled ventilation, resulting in healthier living conditions. This is especially important for those who are most vulnerable to the negative health consequences of cold living conditions, such as elderly and or disabled people. As previously discussed, retrofitting can contribute to the alleviation of fuel poverty by lowering running costs, however, other factors such as income poverty, inflation and energy market fluctuations are also important. The recent rise in typical energy costs, particularly from 2021–2022, and the coinciding cost of living crisis, placed many households in the UK at increased risk of fuel poverty. In such economic conditions, many low-income homes are forced to make involuntary trade-offs between necessities, often described as the “heat-or-eat dilemma.” Although fuel poverty is a complex multidimensional issue, retrofitting can contribute to the alleviation of fuel poverty in cases where inefficient housing is the root cause.

In summary, retrofitting existing homes in the UK is necessary to address the critical challenges of climate change and fuel poverty. Through ambitious retrofitting projects, the UK can make significant strides towards ensuring a sustainable and resilient housing stock, improving people’s quality of life, and achieving domestic climate change targets.

1.2 Targets and Benchmarks

This section sets out the UK’s current approach to the net zero agenda.

1.2.1 UK Net Zero Approach and Policy

The UK Government aims to achieve net zero greenhouse gases emissions by 2050, legislated under the Climate Change Act 2008 (2050 Target Amendment) Order 2019. In the building sector, the UK Government’s net zero targets have a focus on reducing operational carbon emissions, which requires that buildings reduce the use of non-renewable (i.e., fossil fuel) energy. Operational carbon emissions result from the energy used for standard functions within the building, including heating, cooling, hot water, ventilation, lighting, cooking and any other electrical appliances . Throughout a building’s life cycle, operational carbon emissions constitute the largest direct environmental impact, representing 40–65% of whole life carbon emissions (LETI, 2020).

As renewable energy production increases and the grid is gradually decarbonised, integrating electric heating sources like heat pumps can help buildings reduce carbon emissions sooner. However, as the grid has limited capacity, and because shifting to electric heating systems is only feasible if energy consumption is significantly reduced, prioritising reduced energy consumption through efficient building design strategies (fabric-first principles) is crucial.. Additionally, current electricity costs remain higher than gas. In April 2024, electricity costs were approximately four times higher than gas (Ofgem, 2024). Under the energy price cap running from October 1 to December 31, 2025, electricity costs are set at approximately four times more than gas, (26.3 pence per kWh compared to gas at 6.3 pence per kWh) (Bolton, 2025). This is known as "The Spark Gap” and sadly can hinder the adoption of cleaner energy technologies like heat pumps as hastily transitioning from gas to electric heating would likely raise energy bills for most UK households, unless consumption fell considerably.

The need to reduce carbon emissions becomes significantly more complex when embodied carbon emissions are included. Embodied carbon accounts for emissions generated by the production, transportation, assembly, maintenance, and the disassembly of building materials, components, or entire buildings. The term *whole life carbon* refers to the consideration of both operational and embodied carbon emissions. Approximately 80% of building sector carbon emissions are operational emissions from the existing building stock, while the remaining 20% is attributable to the embodied impact of new constructions . However, as buildings become more energy efficient and electricity generation decarbonises, the operational carbon of new buildings will decrease, hence, embodied carbon will likely contribute a greater proportion of whole life carbon emissions.

The UK net zero agenda was initiated in 2017 with the Government's publication of the 'Clean Growth Strategy,' which aimed to upgrade all existing homes to EPC B and C standards by 2035. This strategy underscores the critical role of local authorities in developing strategic plans to meet carbon and energy targets. Since 2017, the Government has introduced various grants and funding programs to promote housing retrofits and the installation of low-carbon heating systems, some managed by authorities and others by homeowners. However, these programs lack an effective strategy to address the problem comprehensively, as they are not sizeable enough to enable whole-house retrofits (UKGBC, 2021). Instead, most funding schemes focus on isolated home improvements, such as loft insulation or replacement heating systems, which do not necessarily reduce energy bills or carbon emissions, nor enhance energy efficiency or the comfort and health of occupants (see more on this discussion in Section 1.9). Some of the aforementioned programs are listed next.

Warm Homes: Social Housing Fund Wave 3 (DofESNZ, 2024)

- Launched in 2024, the Warm Homes: Social Housing Fund (WH:SHF) Wave 3 aims to upgrade social housing stock in England to at least Energy Performance Certificate (EPC) band C.
- It targets local authorities, combined authorities, registered providers of social housing, and registered charities that own social housing, providing funding to install energy efficiency upgrades and low-carbon heating measures.
- The program offers up to £7,500 per home for energy performance improvements, with an additional £20,000 available for low-carbon heating measures for up to 10% of homes in a bid, requiring no co-funding.
- Eligible improvements include insulation, solar panels, heat pumps, smart controls, and other energy efficiency and low-carbon heating measures.
- The fund seeks to deliver warm, energy-efficient homes, reduce carbon emissions, tackle fuel poverty, support green jobs, and develop the retrofit sector.

Energy Company Obligation (ECO 4) (OFGEM, 2025)

- Launched in 2022, the Energy Company Obligation (ECO4) scheme is a government initiative to improve the energy efficiency of low-income and vulnerable households in Great Britain.
- It requires energy suppliers to fund energy-saving measures, such as insulation and low-carbon heating, in eligible homes to reduce energy bills and carbon emissions.
- ECO4 focuses on upgrading the least energy-efficient homes, targeting properties with an Energy Performance Certificate (EPC) rating of D or below.
- The scheme prioritises households in fuel poverty, social housing, and those receiving certain means-tested benefits.
- Eligible measures include loft and cavity wall insulation, solid wall insulation, heat pumps, solar panels and heating system upgrades.
- ECO4 is part of the UK’s wider strategy to achieve net-zero emissions and alleviate fuel poverty by improving home energy efficiency.

Boiler Upgrade Scheme (Ofgem, 2025)

- Running from 2022 to 2025, this scheme supports homeowners in installing low-carbon heating systems, such as heat pumps.
- It offers £5K for air source heat pumps and biomass boilers and £6K for ground source heat pumps through certified provider. (Ofgem, 2025)
- To be eligible, properties must have an installation capacity of up to 45kWth and a valid EPC with no outstanding recommendations for loft or cavity wall insulation, with exemptions for listed buildings, conservation areas, or specific structural types.

Public Sector Decarbonisation Scheme (BEIS, 2021a), (BEIS, 2021b)

- Launched in 2020, the Public Sector Decarbonisation Scheme (PSDS) provides grant funding to public sector organisations to support energy efficiency upgrades and low-carbon heating measures.
- The scheme has progressed through multiple phases:
- **Phase 1 (2020-2022)**: Provided £1 billion in grants as part of the government's economic recovery plan following COVID-19. It aimed to support up to 30,000 jobs and reduce public sector carbon emissions through a mix of energy efficiency and heat decarbonisation measures.
- **Phase 2 (2021-2022)**: Allocated £75 million with a stronger emphasis on heat decarbonisation, encouraging a 'whole building' approach to retrofit projects.
- **Phase 3 (2022-2026)**: Committed over £1.425 billion in funding across multiple application windows:
    - *Phase 3a* closed in November 2021.
    - *Phase 3b* closed in November 2022.
    - *Phase 3c* closed in November 2023.
- Phase 3 prioritised the replacement of fossil fuel heating systems with low-carbon alternatives, such as heat pumps and district heating, alongside measures like insulation, solar panels, and heating controls.
- **Phase 4 (2025-2026)** has been announced, continuing support for the decarbonisation of public sector buildings, with a strong emphasis on reducing reliance on fossil fuels and improving energy efficiency.

1.2.2 Future Homes and Buildings Standard

The Future Homes and Buildings Standard, set to be implemented in 2025, aims to advance the UK towards net zero by enhancing energy efficiency and transitioning to cleaner heat sources. During its consultation phase in 2021, the standard (Ministry of Housing; Communities and Local Government, 2021) proposed updates to Part L (Conservation of Fuel and Power) and Part F (Ventilation) standards for both non-domestic buildings and dwellings. Additionally, it includes measures to mitigate overheating risks in new residential buildings. The proposed building improvements include improving fabric and services, introducing low-carbon heat, integrating heat recovery technologies and on-site energy generation.

The standard aims to achieve a significant reduction in carbon emissions per building, targeting an improvement of 22-27% compared to the current Part L 2013 standard. This will be accomplished through enhanced building fabric, improved efficiency of building services, and the adoption of low-carbon technologies such as heat pumps and photovoltaic panels (Ministry of Housing; Communities and Local Government, 2021, p. 30). Given that the grid will decarbonise over time and carbon emissions are not a direct measure of energy efficiency, the standard introduces additional performance metrics for new buildings (Ministry of Housing; Communities and Local Government, 2021): primary energy target, CO_2 emission target and minimum standards for fabric and fixed building services.

The Future Homes Standard consultation, launched in 2019 by the Ministry of Housing, Communities, and Local Government, focused on energy standards for newly built domestic buildings. The Future Buildings Standard consultation in 2021 expanded on this by proposing additional changes to Part L for new domestic buildings. These proposals include:

- Setting the level for the Fabric Energy Efficiency Standard (FEES).
- Updating minimum standards for building services.
- Providing guidance on airtightness testing.

Part L 2021 is expected to emphasise a fabric-first approach and serve as a transition to the Future Homes Standard in 2025, with key measures including low-carbon heating systems and improved building fabric. The new standard targets a 31% uplift in energy efficiency for new homes as outlined in the Future Homes Standard consultation, or a FEES adjustment using a 1.15 multiplier (Ministry of Housing; Communities and Local Government, 2021, p. 112). Part L 2021 includes several updates:

- Increasing minimum standards for new and replacement thermal elements (e.g., walls, floors, roofs) and controlled fittings (e.g., windows, rooflights, doors).
- Raising minimum standards for renovated thermal elements.
- Updating minimum standards for building services, including the requirement for self-regulating devices when replacing heating appliances, and incorporating standards from the Building Services Compliance Guides into Approved Document L, volume 1: dwellings.
- Providing guidance on calibrating devices for airtightness testing.

The Future Homes Standard consultation also sets energy efficiency standards for new and replacement parts of existing buildings, aiming to improve the energy efficiency of the existing housing stock. These standards apply when:

- Adding a new element to an existing building (e.g., an extension).
- Replacing a controlled fitting (e.g., windows, doors).
- Completely removing and replacing a thermal element (e.g., walls, floors, roofs).

In addition to improving building fabric energy efficiency, the Future Homes Standard consultation introduces measures to mitigate overheating risks, a relatively new concept in UK regulations. While Part L 2010 addressed overheating, it lacked specific guidance. The proposed requirements focus on limiting solar gains and ensuring adequate ventilation to remove excess heat, though some recommendations may depend on occupant behaviour (e.g., keeping windows open in unoccupied rooms). Guidance on limiting solar gains in summer is provided in Approved Document L1A, Criterion 3, and in Approved Document L, volume 1: conservation of fuel and power in dwellings, sections 4.9 and 4.10.

Following the 2021 consultation, another consultation was initiated in 2023 to cover Part L, Part F and Part O (overheating). This consultation closed in March 2024 and its findings are yet to be released. However, stakeholders such as LETI (section **Error! Reference source not found.**) have r aised concerns about 'how far' the standards go. In particular, they note:

- Developers can 'opt-out of achieving minimum Part L requirements
- Continued use of Carbon emissions and primary energy metrics
- Avoidance of accounting for unregulated energy
- Utilisation of a notational building methodology

Table 3: Summary of limit values of building envelope thermal transmittance (U-values) and air permeability in existing and future standards (Ministry of Housing; Communities and Local Government, 2021, p. 43, 106, 111-113)

	Standards for new thermal elements, windows, doors for existing non-domestic buildings		Standards for new thermal elements, windows, doors for existing dwellings		Upgrading retained thermal elements in existing dwellings		Part L 2021 (HM Government, 2021b)	Part L2021 notional building
	2013	Proposed	Current standard	Proposed Standard	Current standard	Proposed Standard	Current standard	Proposed Standard
U-values	0.16	0.16	0.16	0.16	0.35	0.16	0.16	0.11

Pitched roof – insulation at ceiling level (W/m²K)								
U-values Pitched roof – insulation at rafter level (W/m²K)	0.18	0.16	0.18	0.15	0.35	0.16	0.16	0.11
U-values Flat roof or roof with integral insulation (W/m²K)	0.18	0.18	0.18	0.15	0.35	0.16	0.16	0.11
U-values Wall (W/m²K)	0.28	0.26	0.28	0.18	0.70 for cavity insulation & ext./int. wall insulation	0.55 for cavity insulation 0.30 ext./int. wall insulation	0.26	0.18
U-values Floors (W/m²K)	0.22	0.18	0.22	0.18	0.70	0.25	0.18	0.13
U-values Windows (W/m²K)	1.6 Window Energy Rating Band C	1.6 Window Energy Rating Band B	1.6 Window Energy Rating Band C	1.4 Window Energy Rating Band B	-	-	1.60	1.2
U-values Doors (W/m²K)							1.60	1.0
Air permeability (m^3/hm^2 @50 Pa)							8.0	5.0

1.2.3 Passive House Standard and EnerPHit

EnerPHit is an energy-efficient building retrofit certified under the Passive House (PH) standard, offering more flexible energy, and building envelope targets compared to new PH constructions. It adheres to Passive House principles, emphasising a highly efficient and well-insulated building envelope, enhanced airtightness, minimised thermal bridging, mechanical ventilation with heat recovery, efficient heat generation, and utilisation of renewable energy sources (Passipedia, 2018).

Achieving EnerPHit certification can be pursued through either the building component method or the energy demand method (PHI, 2016). For the UK's cool-temperate climate, the building component method imposes maximum U-values of 0.15 W/m²K for the building envelope, with walls permitted up to 0.35 W/m²K U-values when accounting for internal insulation, considering its impact on usable floor area (PHI, 2016). Also, window installations must not exceed a maximum U-value of 0.85 W/m²K. Alternatively, the energy demand method necessitates a maximum heating demand of 25 kWh/m²a (PHI, 2016).

Regardless of the chosen method, EnerPHit requires adherence to an airtightness limit of 1 air change per hour at 50 Pascal (PHI, 2016) and specific PER (Primary Energy Renewable) demands of ≤ 71 for cool temperate regions or ≤ 65.5 for warm temperate areas (PHI, 2016). Variances in values and targets from standard EnerPHit criteria may be acceptable in certain retrofit areas, provided they are offset by enhanced thermal protection in other areas of the project.

1.2.4 London Energy Transformation Initiative (LETI)

(LETI, 2020) is an independent organisation and network comprising over 1000 professionals in the built environment sector, advocating for energy efficiency and net zero. They focus on energy performance and set targets for building envelope and energy systems to achieve zero carbon. (LETI, 2020) employs the Energy Use Intensity (EUI) metric for new buildings to gauge performance solely based on actual in-use energy consumption, rather than carbon emissions which can be influenced by the carbon intensity of the grid.

For homes, similar to those reviewed as part of this project, LETI recommends a series of design measures and minimum standards for fabric and energy performance, aiming for an EUI equivalent of 35 kWh/m² (LETI, 2020). By comparison, the current average EUI under Part L is estimated to be 140 kWh/m²a (LETI, 2020),highlighting the need for a substantial 75% reduction in energy usage. A summary of the proposed guidance is shown in Table 4.

Table 4: Recommendation on design, building fabric and energy performance according to LETI (2020, p. 26-27)

Metric	Specification	Target
Building fabric U-values	Walls	0.13-0.15 W/m^2K
	Floor	0.08-0.10 W/m^2K
	Roof	0.10-0.12 W/m^2K
	Exposed ceilings/floors	0.13-0.18 W/m^2K
	Windows	0.80 W/m^2K, triple glazing
	Doors	1.00 W/m^2K
Airtightness	Building	< 1 $m^3/h.\ m^2$@50Pa
Energy Use Intensity (EUI)	Building (gross area)	35 $kWh/m^2.a$
Heating demand	Building	15 $kWh/m^2.a$
Window-to-Wall Ratio (WWR)	North	10-15%
	East	10-15%
	South	20-25%
	West	10-15%
Form factor	Building	1.7 – 2.5
Thermal bridging	y-value	0.04
G-value	Glazing	0.6-0.5
MVHR	Ventilation	90% efficiency, duct length from unit to external wall ≤ 2m
Embodied carbon	Material, transport, construction, maintenance, end of life disposal (gross area)	< 500 $KgCO_2/m^2$
Heating system	Building	10 W/m^2 peak load, fossil fuel free
Hot water system	Building	Maximum dead leg of 1 litre for hot water pipework, fossil fuel free
Renewable energy generation	Building	100% of the energy demand
Energy storage	Building	Consider battery storage to smooth energy demand

1.3 Existing Carbon Reporting Data

In the UK, existing carbon reporting data includes comprehensive information on greenhouse gas emissions from various sectors including the built environment sector. This data is crucial for monitoring progress towards meeting carbon reduction goals, informing policy decisions and promoting transparency in sustainability efforts. In the built environment sector, the metric used in determining if buildings meet their specific target is a critical component on the delivery of the retrofit. Next, the key elements that are currently considered have been highlighted.

- Energy performance is considered a core metric, as it can be readily estimated at the design stage and very easily monitored in-use as energy bills are based on kWh of energy used by the building (LETI, 2020) me retrofit housing studies that have used heating demand as the main metric to show improvements. Most of these studies considered heating demands of between 25-50 kWh/m^2a (e.g. EnerPHit standard and LETI). However, it is noted that these projects calculated the area of the heated floor in many ways - this can impact the assumed target.
- A review of current upgrades of retained thermal elements in existing dwellings seem to follow values similar as those suggested by the Future Homes Standard around 0.16 W/m^2K with more flexible values to floors and cavity walls.

- Thermal bridges are identified as areas of focus as their impacts are maximised in highly insulated buildings.
- Airtightness plays a key role on delivering the energy targets. Low levels of airtightness can be achieved when combined with MVHR and this is recommended as the best way forward by the EnerPHit standard (PHI, 2016). MVHR can greatly contribute to reducing energy heating demand, resulting in domestic hot water (DHW) being the most significant demand in the building.

1.4 Fabric-First

Fabric-first is referenced in the UK Net Zero Strategy: Build Back Greener (Department for Business, Energy & Industrial Strategy (BEIS), 2021) and the Retrofit for the Future Guide (Technology Strategy Board, 2014). With a fabric-first approach, building fabric improvement measures are made first, before active retrofit measures are considered.

The Energy Saving Trust recommend that homes should be heated to temperatures between 18-21°C during winter (EST, 2021). Considering Low Temperature Hot Water (LTHW) supply temperatures, Approved Document G (Sanitation, hot water safety and water efficiency) recommends that delivered temperatures should not exceed 48°C (Government, 2015).

Heat pumps are typically able to generate LTHW at temperatures of between 35-55°C. Heat pumps achieve highest efficiencies when the required flow temperature is lower, since the system needs to do less 'work' to generate heat. According to the Carbon Trust, *'every 1°C reduction in flow temperature typically results in approximately 1.5%-3% increase in heat pump efficiency'*. Figure 1 is taken from a report into 'Low Carbon Heat: Heat Pumps in London,' commissioned by the Greater London Authority.

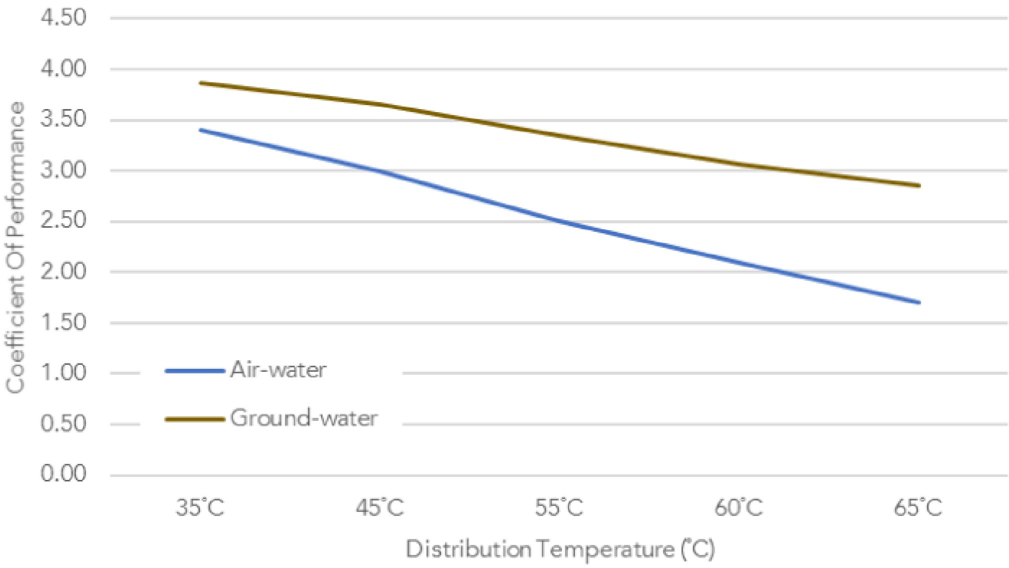


Figure 1: Relationship between flow temperature and heat pump efficiency (GLA, 2018)

Comparatively, gas fired boilers are typically designed to deliver LTHW at temperatures of between 65-75°C (Ducker, 2022). For this reason, with gas fired boilers, it is possible to turn up the heating to high levels for short periods of time. This results in surges in temperature which are often reactive, according to user preference. Gas fired boilers are also able to deliver hot water to radiators at consistently high temperatures for prolonged periods of time. This means that it is possible to heat a room or home with a relatively low number of radiators. The high output temperatures also mean that gas boilers can counteract any heat losses associated with poor performing buildings.

A heat pump produces heat more slowly than a boiler. They are not typically suited to reactive user profiles and are designed to deliver smaller temperature differences at consistent levels. The Carbon Trust state that heat pumps perform most efficiently *'when maintaining a constant temperature in continuous operation'* (Trust, 2020). It is for this reason that underfloor heating solutions work well with heat pumps, where large surface areas mean that lower temperatures can be used to heat more of the building footprint. The radiators used with heat pump systems are also typically larger.

A fabric-first approach will result in immediate reductions in energy demand (regardless of the heat source) and will ensure that the new heating systems installed later perform optimally. There are also other benefits in terms of internal comfort and occupant health. According to the Construction Leadership Council (CLC), a fabric-first approach *'is a 'no regrets one'; reducing the demand for heat, improving the ability to heat the poorest performing homes whilst allowing more time to consider the methods available to heat those homes as the decarbonisation of the electricity supply grid continues. This satisfies fuel poverty eradication as well as net zero carbon emissions'* (CLC, 2016).

Considering energy capacity and security, LETI highlight that at peak demand in winter, the UK's energy requirement is around three times the capacity of the national electricity grid (LETI, 2020). The Greater London Authority (GLA) found that electrification of heat in buildings would require a sharp increase in energy efficiency and concluded that without this, there would be major increases in peak demand necessitating expensive network upgrades through taxpayer funding (GLA, 2018). As well as avoiding unnecessary national spending, reductions in national energy demand through fabric-first principles will aid *'energy security and make us more resilient to global energy shocks'* (Khayatt, 2021).

1.5 Net Zero Readiness

For a property to be 'Net Zero ready', electricity must be the sole source of power for all heating and other energy requirements. This way – regardless of the quantity of electricity consumption – when the national electricity grid eventually becomes fully renewable, the property will produce zero carbon emissions to operate. Clearly, the amount of electricity that the property uses will impact the annual energy bills for the user. This is one of the reasons that 'Fabric-First' is considered best practice, as discussed in detail in Section 1.4.

For the purposes of this Section, it is important to consider the benefit of implementing Fabric First principles, compared to installing electric heating systems with limited fabric upgrades. Some key factors are summarised in Table 5.

Table 5: The pros and cons of implementing Fabric First principles, compared to installing electric heating systems with limited fabric upgrades.

Pros	Cons
▪ Boiler Upgrade Scheme (funding for ASHP and GSHP) requires a valid EPC with no outstanding recommendations for loft or cavity wall insulation. ▪ Energy bills do not increase significantly as a result of heating system electrification. ▪ Climate change benefits prior to electricity grid decarbonisation. ▪ Reduction in the risk of fuel poverty. ▪ Reduction in adverse health impacts of poorly insulated homes.	▪ Increased cost of fabric-first strategies. ▪ Energy bills will increase due to the cost of electricity compared to gas, if energy demand is not reduced. ▪ BUS funding cannot be applied for if limited fabric improvement measures have not been implemented (cavity wall and loft insulation) ▪ Increased programme duration and disruption levels for occupants. ▪ Risk of unintended consequences (moisture issues) associated with

▪ Macro-economic benefits of reduced taxpayer spending on NHS and national grid upgrades. ▪ Increased demand for local skilled labour and specialist retrofit advice, driving positive economic growth. ▪ Appreciation in property value associated with improved EPC Rating and energy performance. ▪ Compliance with upcoming changes to the Minimum Energy Efficiency – landlord benefit.	insulation, if best practice is not followed. ▪ Lack of training and skilled workforce to meet the high demand. ▪ Practical issues associated with 'hard-to-treat' properties, including heritage, ownership, and statutory issues.

1.6 External Wall Insulation: Best Practice

In domestic retrofit terms, External Wall Insulation (EWI) is generally considered to be best practice and is preferred over Internal Wall Insulation (IWI) for several key reasons:

- **Thermal Bridging:** EWI effectively minimises thermal bridging by enveloping the building's exterior, ensuring continuous insulation. In contrast, IWI can leave structural elements like floor joists and internal walls exposed, creating potential thermal bridges. The Building Research Establishment (BRE) notes that *'the most common form of solid wall insulation in the UK is applied externally, as it is less disruptive to the residents and technically less challenging when compared to internal wall insulation'* (BRE, 2016).
- **Moisture Risk:** Applying insulation internally can alter the building's moisture balance, potentially leading to condensation and damp issues if not properly managed. The UK Centre for Moisture in Buildings highlights that *'the unintended consequences of insulating internally are poorly understood, however, and a tendency to regard the installation of internal wall insulation (IWI) as akin to wallpapering can result in defects'* (NBT, 2017).
- **Disruption:** Installing EWI causes minimal disturbance to occupants, as the work is conducted externally. Conversely, IWI requires significant interior work, often necessitating the removal of fixtures and fittings, leading to considerable disruption. The BRE emphasises that EWI is *'less disruptive to the residents and technically less challenging when compared to internal wall insulation'* (BRE, 2016).
- **Cost:** While EWI can be more expensive due to materials and scaffolding requirements, it often provides better long-term value by addressing multiple issues simultaneously, such as thermal performance and moisture control. IWI might have lower upfront costs but can lead to additional expenses if moisture-related problems arise.

It should be noted that even retrofit schemes which utilise EWI can result in unintended consequences, if the proper steps are not taken. The Retrofit Academy, within their publication 'PAS 2035: What is it and what does it mean for you', highlight that defects and unintended consequences are common within poorly delivered retrofit projects. Located in Preston, the 'Fishwick 247 External Wall Insulation Project' is an infamous example of poor-quality retrofit. Delivered in 2013, the scope was to install external wall insulation to 386 terraced dwellings. Fishwick is an inner-city Ward within Preston City Council (PCC), characterised by poor quality 19th century housing. The scheme was delivered under the now discontinued government funding scheme CESP. Within one year of completion, a large proportion of the properties started to report quality issues *"mainly about dampness, mould growth and water penetration"* (PCC, 2022).

Fundamentally, the quality of the housing stock within the Fishwick Ward was very poor prior to commencement of the works. There were existing building defects including poor quality brickwork, defective rainwater goods, and rotting external doors and windows. PCC highlight that these issues were not acknowledged or addressed as part of the retrofit project. Additionally, works were rushed to meet funding deadlines, and the quality of workmanship was poor. Properties were not assessed on an individual basis and a 'one size fits all' approach was taken. The poor-quality work resulted in unintended consequences in most homes, including adverse impacts on health, wellbeing and quality of living. Additionally, the energy performance levels, and associated energy bill reductions are not in line with predictions.

It is vital that Broxtowe Borough Council take the necessary steps to avoid unintended consequences. Within this technical report, External Wall Insulation is recommended, in accordance with best practice.

1.7 BSI Publicly Available Specification (PAS) 2035

During the early 2010's, the Building Research Establishment (BRE) and subsequently BEIS recognised that many retrofit projects were failing. In response to this, BEIS released 'An Independent Review of Consumer Advice, Protection, Standards and Enforcement for Energy Efficiency and Renewable Energy', in coordination with the Department for Communities and Local Government (BEIS, An Independent Review of Consumer Advice, Protection, Standards and Enforcement for Energy Efficiency and Renewable Energy, 2016). The document, released in 2016, was titled 'Each Home Counts' and made 27 key recommendations as to how the industry can better support customers within the energy efficiency sector. Recommendations 1 and 8 are particularly relevant to this report.

Recommendation 1 states that every project should be delivered under a quality mark. This was subsequently agreed to be TrustMark, who are a *'Government Endorsed'* consumer protection scheme (TrustMark, 2022). Recommendation 2 called for a new framework for the construction industry, relating specifically to energy improvement works. In response to this recommendation, the British Standards Institute (BSI) were commissioned to develop and publish a document called the 'BSI Publicly Available Specification (PAS) 2035', or 'PAS 2035' (BSI, 2019). This is an overarching framework for project delivery and it *'addresses the fundamental structural problems that blight many energy efficiency projects'* (Academy, 2019).

For developers and clients that require project delivery under TrustMark, full compliance with the PAS 2035 framework is required. The framework introduces five clear roles to the retrofit process and breaks down each project into six distinct phases, all of which are overseen by the Retrofit Coordinator. The Retrofit Coordinator, one of the five roles, is ultimately responsible for ensuring compliance with PAS 2035 (Academy, 2019). A graphical representation of the *'core principles of PAS 2035'* is provided at Figure 2.

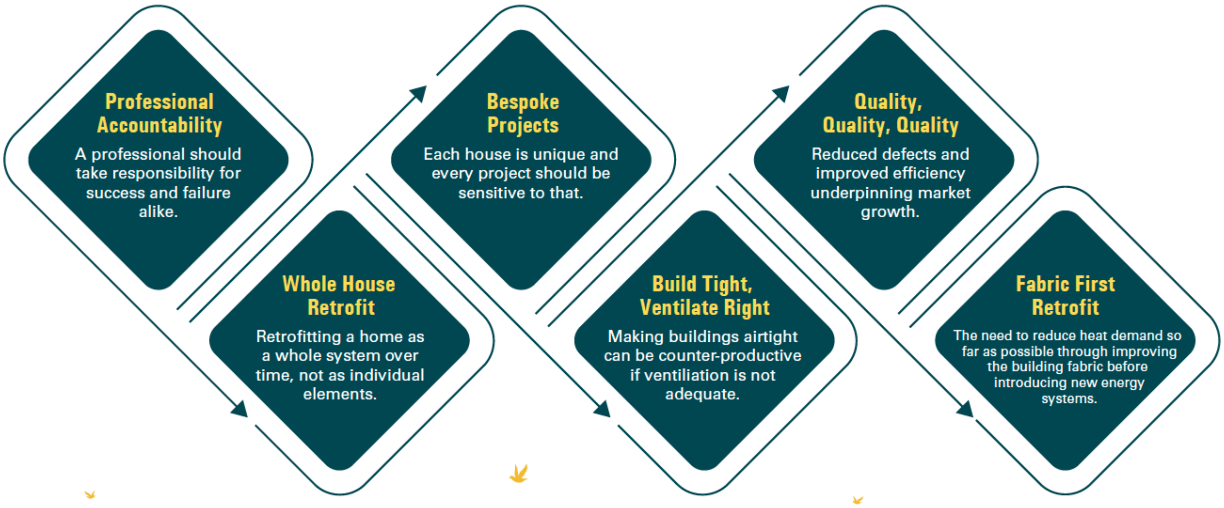


Figure 2: Core principles of PAS 2035 (Academy, 2019)

Whilst retrofit delivery under the TrustMark scheme is voluntary in the UK, there are government funding opportunities that require a commitment to compliance as a prerequisite to funding success. Within this report, it is assumed that PAS2035 principles for best practice are followed by Broxtowe Borough Council.

1.8 Broxtowe Housing Stock Characterisation: Energy Performance Certificate

This section summarises the current condition of Broxtowe's housing stock (including owner-occupied, privately rented and socially rented), based on the Energy Performance Certificate (EPC) database (Department for Levelling Up, Housing & Communities, 2024). The purpose of this section is to identify archetypes that represent the Broxtowe housing stock, ensuring that subsequent building simulations are relevant. To do this, consideration must be given to various property characteristics, including EPCs, Standard Assessment Procedure (SAP) score (which is used to determine EPC bands), property type, building form, construction age, tenure status and the energy efficiency of specific building fabrics (e.g., walls, roof, floors etc.). Unless stated otherwise, all of the information in this section was derived from the EPC database.

Energy Performance: As of April 2024, there are 36,933 unique lodged EPCs in Broxtowe. Of these, 33.8% have an EPC rating of A–C, while the remaining 66.2% are rated D–G. An EPC rating of C is a generally accepted benchmark for energy efficiency. Table 6 shows the total distribution of EPC ratings in Broxtowe; the majority of properties are rated C or D (~68%), which is broadly consistent with the rest of England. EPC banding can be useful for basic comparisons of energy efficiency, but the banding process induces a potentially misleading level of aggregation, for example, there may be a considerable number of D-rated properties that are on the verge of being C-rated or vice-versa.

Table 6: EPC distribution across all Broxtowe homes (n=36,933) (% in parentheses)

EPC	A	B	C	D	E	F	G
Frequency	45 (0.12)	3025 (8.19)	9421 (25.50)	15878 (42.99)	6810 (18.43)	1488 (4.03)	266 (0.72)

To overcome this, Figure 3 shows the distribution of SAP scores (a continuous scale that determines EPC rating) in Broxtowe, disaggregated by the four main property types: bungalows, flats, houses and maisonettes. This allows a more accurate identification of the property types that are most in need of energy efficiency upgrades. SAP scores over 69 correspond to an EPC rating of C or above. Across all homes in Broxtowe the mean SAP score is 62.5 and the median is 64; the median score is probably more informative in this context, as the mean can be overly sensitive to outliers. The figure shows that flats and maisonettes are the most energy efficient property types, with median SAP scores of 72 and 70, respectively. Conversely, houses and bungalows are the least efficient, both with median SAP scores of 62.

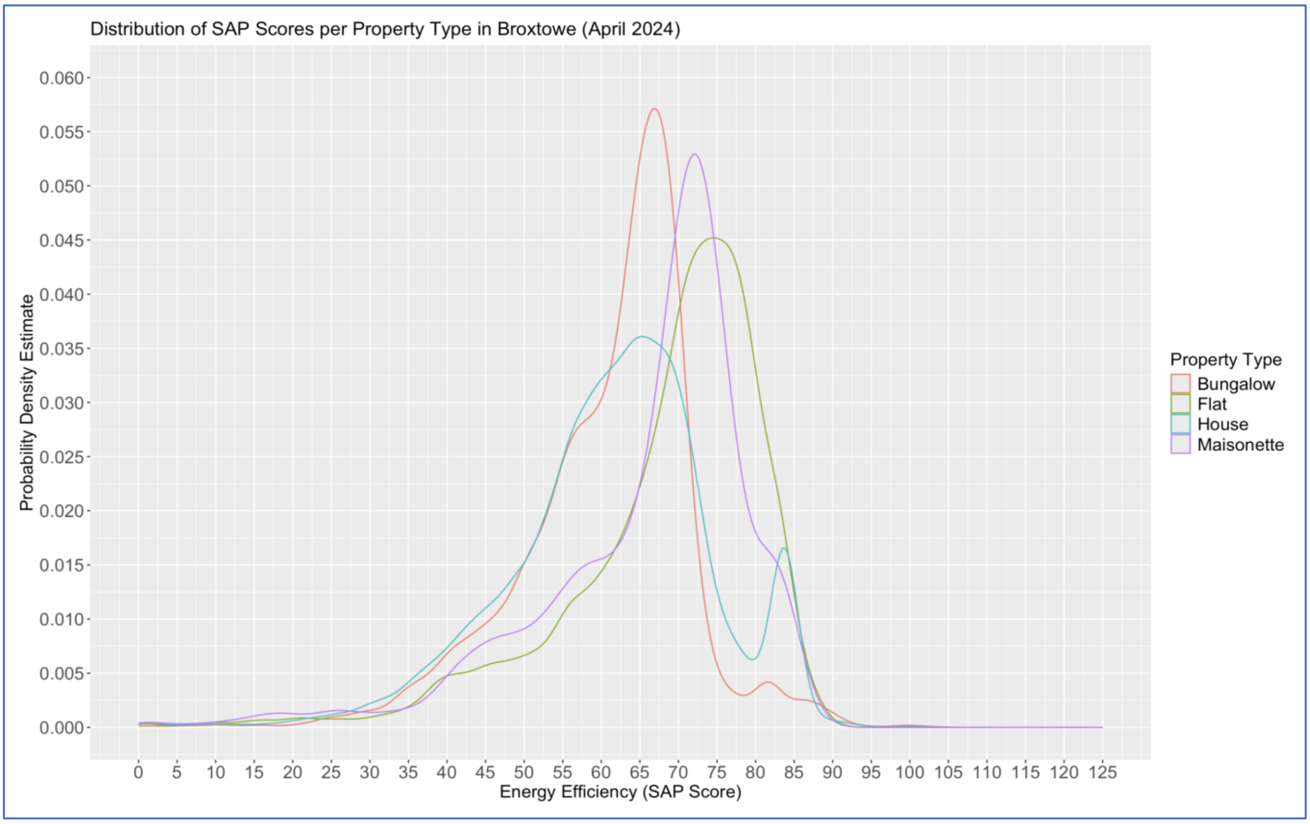


Figure 3: Distribution of SAP scores for all Broxtowe homes, disaggregated by property type (dashed lines = median SAP per property type) (n=36,933)

Construction Age: The construction age of homes often plays a significant role in determining their form, build fabrics and energy efficiency. Figure 4 shows the construction age bands of all homes in Broxtowe, disaggregated by EPC (A–C versus D–G). As expected, homes built before and in the first half of the 20th century are less energy efficient than those built more recently. The irregularity of the x-axis should be noted; the construction age bands are released in this format, so it is not possible to create regular intervals (e.g., builds per decade).

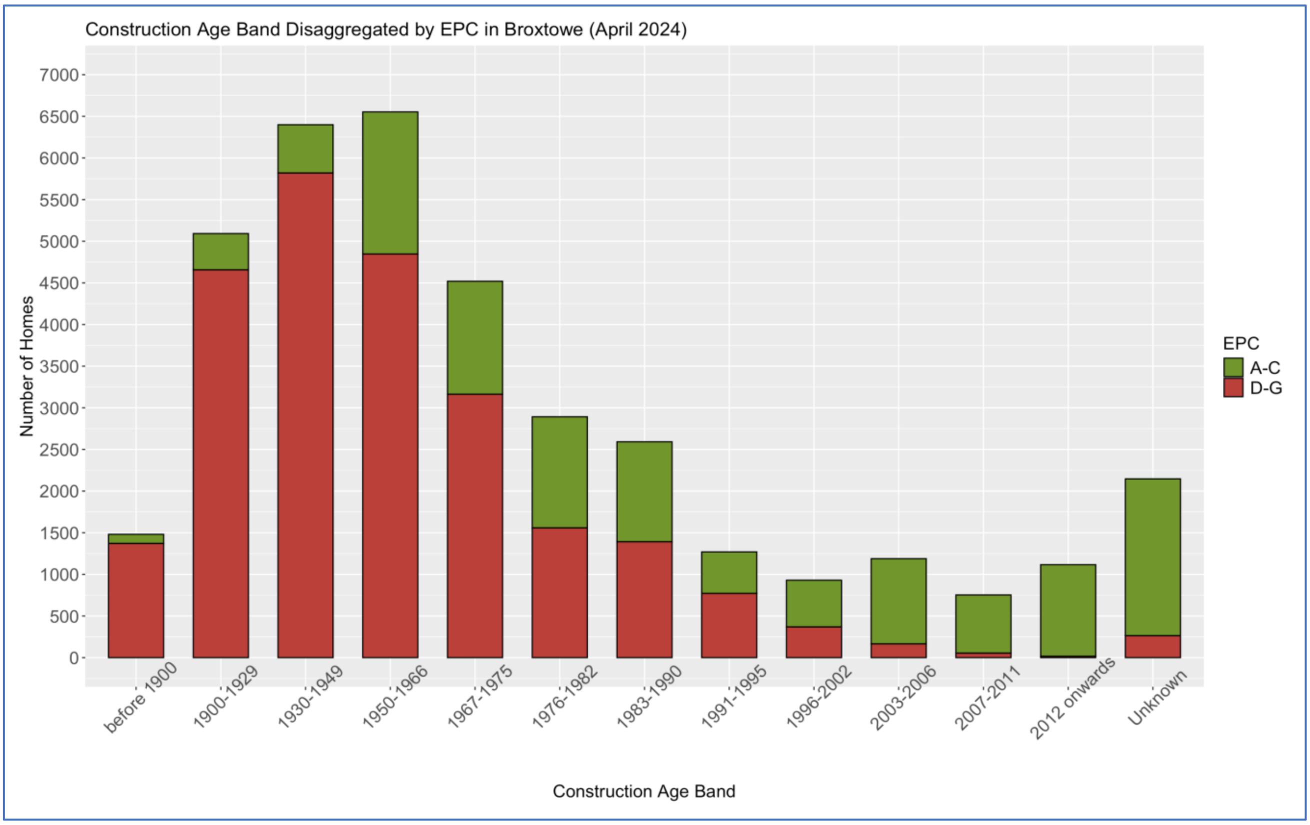


Figure 4: Construction age band for all Broxtowe homes, disaggregated by EPC (n=36,933)

Tenure Status: The tenure status of homes is a crucial factor that can affect the practicalities of retrofitting strategies. In many British cities, including Nottingham, the energy efficiency of socially rented properties tends to be higher than privately rented and owner-occupied homes. This may be due to hesitation among homeowners to see the short or long-term benefits of retrofitting. In Broxtowe, the division of tenure is as follows: 58.35% of homes are owner-occupied, 19.08% are privately rented, 13.96% are socially rented and the remaining 8.20% are unknown. Table 7 shows the proportion of homes within each tenure status that achieve an EPC rating of A–C, as well as the median SAP score. As expected, the energy efficiency of socially rented homes tends to be higher, whereas there is less to separate owner-occupied and privately rented properties.

Table 7: Tenure Status, EPC and SAP in Broxtowe (n=36,933) (% EPC A–C versus D–G within tenure status in parentheses)

Tenure Status	EPC A–C	EPC D–G	Median SAP
Owner-occupied (n=21549)	5070 (23.53)	16479 (76.47)	61
Privately rented (n=7048)	1865 (26.46)	5183 (73.54)	62
Socially rented (n=5157)	2977 (57.73)	2180 (42.27)	70

Property Type & Building Form: Table 8 displays a cross-tabulation of property type and building form in Broxtowe (for the 36,509 properties where this information is available). Houses are the most common property type, accounting for 72.26% of all homes. Flats are the second most common property type (14.78% of all homes). Detached bungalows also account for a considerable proportion of homes (8.26%). In total, houses, flats, and detached bungalows account for around 95% of Broxtowe properties, therefore, the remaining statistics in this section will focus on these home types only.

Table 8: Property type versus building form in Broxtowe (n=36,509) (% in parentheses)

	Detached	Semi-detached	Mid-Terrace	End-Terrace	Total
Bungalow	3016 (8.26)	733 (2.01)	162 (0.44)	168 (0.46)	4079 (11.17)
House	7607 (20.84)	11105 (30.42)	4559 (12.49)	3111 (8.52)	26382 (72.26)
Flat	NA	NA	NA	NA	5395 (14.61)
Maisonette	119 (0.33)	270 (0.74)	127 (0.35)	128 (0.35)	644 (1.76)
Park home	9 (0.02)	NA	NA	NA	9 (0.02)
Total	11795 (31.94)	14184 (38.40)	6172 (16.71)	4358 (11.80)	**36509**

Table 8 also shows the most common building forms for each property type. The four most common property-build combinations are as follows: semi-detached houses (30.42% of all properties); detached houses (20.84%); mid-terrace houses (12.49%), end-terrace houses (8.52%). Note that, although the EPC database does provide information on building form for flats, we do not believe this information to be sufficiently accurate, therefore, we treat flats as a singular build category in this section. In spite of this, retrofitting simulations are provided for mid-terrace and end-terrace flats in later sections.

Property types of interest (houses, flats & detached bungalows) in Broxtowe: Further to houses being the most common property type, Table 9 also showed them to be the least efficient. Table 9, instead, shows energy efficiency characteristics for the property types of interest, disaggregated by building form, allowing us to determine the specific property-build combinations that lead to lower SAP scores. Table 9 shows that all build categories among houses (detached, semi-detached, mid-terrace and end-terrace) are less energy efficient than flats, however, detached bungalows are approximately as inefficient as detached/semi-detached houses. Among houses, detached and semi-detached are both the most numerous and some of the least energy efficient properties in Broxtowe.

Table 9: Further energy efficiency characteristics for houses and flats, disaggregated by building form (n=37,183) (% EPC A–C versus D–G within property-build type in parentheses)

Property type	Building form	EPC A–C	EPC D–G	Median SAP
Houses (n=26382)	*Detached*	2261 (29.72)	5356 (70.28)	62
	Semi-detached	2627 (23.66)	8478 (76.34)	61
	Mid-terrace	1669 (36.61)	2890 (63.39)	65
	End-terrace	1042 (33.49)	2069 (66.51)	63
Flats (n=5395)	*All flats*	3355 (62.19)	2040 (37.81)	72
Bungalows (n=3016)	*Detached*	534 (17.71)	2482 (82.29)	62

Figure 5, Figure 6 and Figure 7 show the distribution of construction age bands for inefficient (i.e., a subset of D–G rated properties only) houses, flats and bungalows, respectively. As before, houses are disaggregated by building form, while flats are treated as a singular build category.

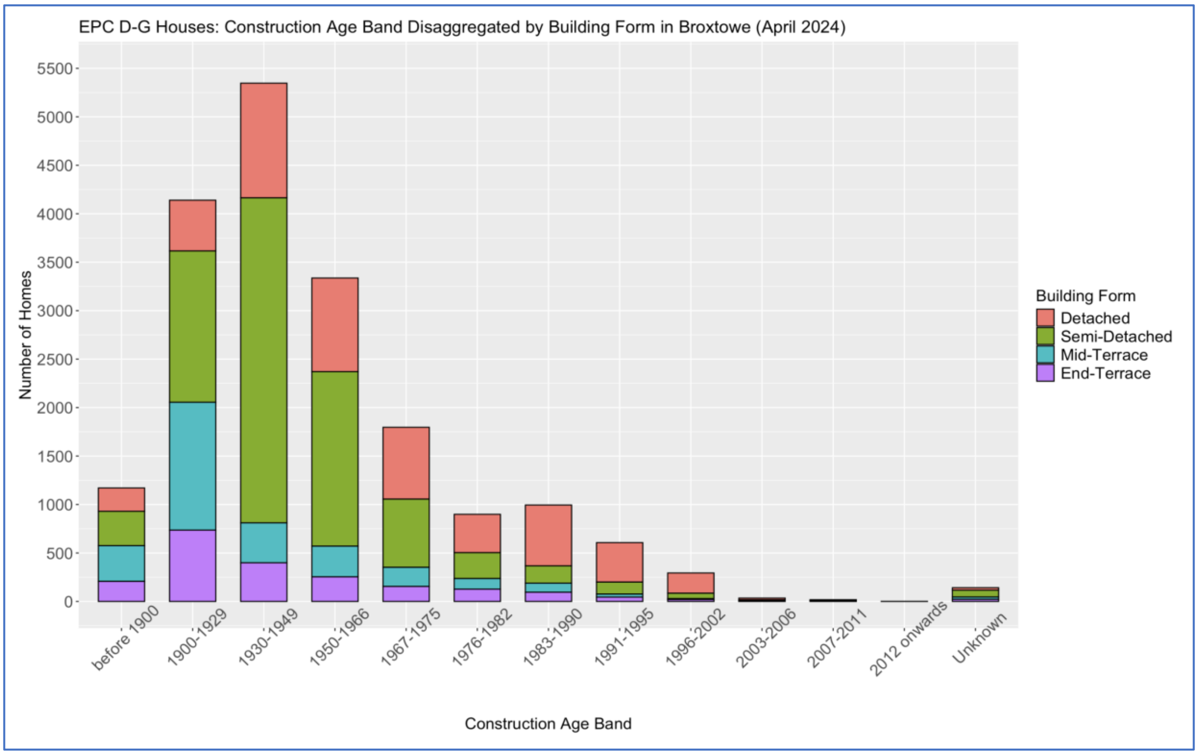


Figure 5: Construction age band for EPC D–G rated houses in Broxtowe, disaggregated by building form (n=18,783)

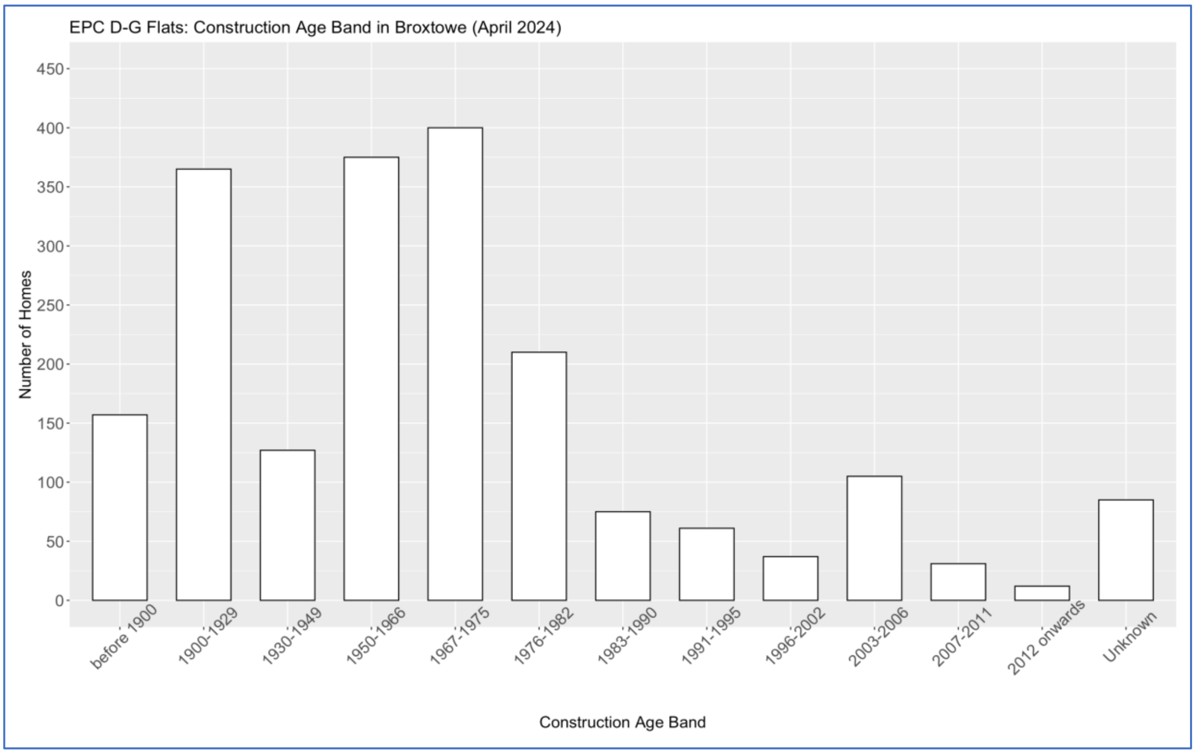


Figure 6: Construction age band for EPC D–G rated flats in Broxtowe (n=2,040)

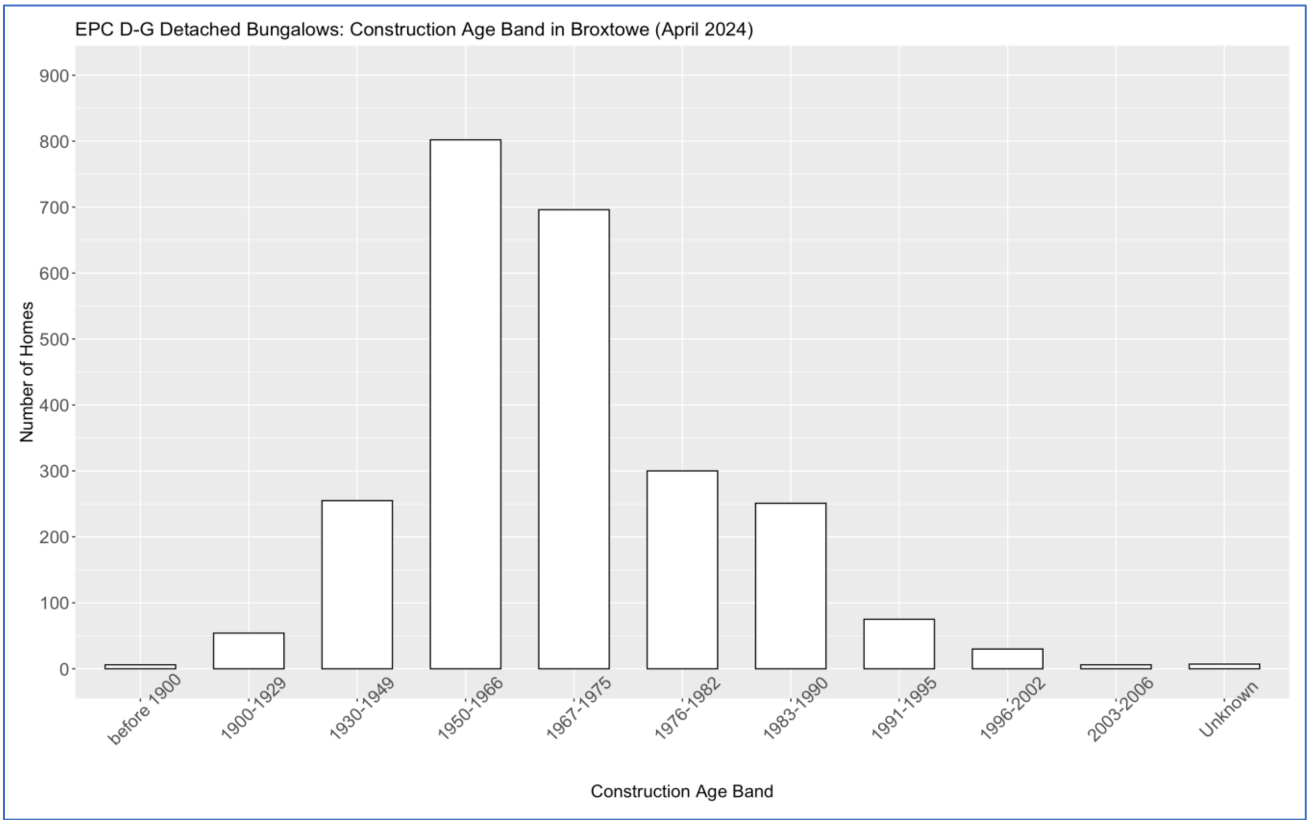


Figure 7: Construction age band for EPC D–G rated detached bungalows in Broxtowe (n=2,482)

Given the information up until this point, suitable archetypal properties in Broxtowe may be any of the following: (i) detached or semi-detached houses built from 1900 to the late 1960s; (ii) flats built from the 1950s to the 1980s; and (iii) detached bungalows built from the 1950s to the 1980s. It may be particularly productive to target privately rented and owner-occupied properties among these categories.

Property dimensions (amongst archetypes): For the property types of interest, it is important to understand typical dimensions, namely the number of habitable rooms and floor area, to enhance the accuracy of the simulations. Table 10 shows the median and mean number of habitable rooms, as well as the median floor area, per property-build type.

Table 10: Number of habitable rooms and median floor area per property-build combination

Property type	Building form	Median (mean) habitable rooms	Median (mean) floor area (m^2)
Houses (n=26382)	*Detached*	6 (5.84)	111 (122.80)
	Semi-detached	5 (4.71)	84 (87.75)
	Mid-terrace	4 (4.26)	76 (78.13)
	End-terrace	4 (4.31)	77 (79.36)
Flats (n=5395)	*All flats*	3 (2.63)	51 (53.85)
Bungalows (n=3016)	*Detached*	4 (4.14)	76 (84.43)

Heating type: The main heating type used within the home has implications for the property's energy efficiency rating, energy costs and the thermal comfort of occupants. In Broxtowe, as is the case in the rest of the UK, the main heating type in the vast majority of homes is a mains gas boiler with radiators. This is the case for more than 88% of properties in Broxtowe, a rate which remains consistent across the house types of interest; hence, no further disaggregation of heating type per property-build combination is provided here.

Build fabrics (Walls; Roof; Floor; Windows [illustrated in* Appendix A: Building Fabric*]): A breakdown of the most common build fabrics per property type of interest in Broxtowe, for all homes and for the inefficient subset (EPC D–G properties), is presented in Table 11 (walls), Table 12 (roof), Table 13 (floor) and Table 14 (windows). Following this, the most common build fabrics across all Broxtowe homes is presented in Table 15, whereas Table 16 displays the equivalent information for EPC D–G rated homes.

WALLS

Table 11: Wall fabric breakdown

Property-build type	Wall type	Proportion per house type	Proportion per house type (EPC D–G)
All detached houses (n=7,607) EPC D–G detached houses (n=5,356)	U = 0.13–0.20 W/m2K	1.6%	<0.1%
	U = 0.21–0.30 W/m2K	8.0%	<0.1%
	U = 0.31–0.45 W/m2K	0.2%	<0.1%
	U = 0.46–1.80 W/m2K	<0.1%	<0.1%
	Cavity wall, as built – partially/fully insulated*	24.6%	21.8%
	Cavity wall, as built – no insulation*	10.4%	14.4%
	Cavity wall, as built – filled cavity	25.1%	23.6%
	Solid brick, as built – no insulation*	**27.7%**	**38.3%**
	Solid brick – internal/external insulation	1.4`%	1.0%
	System built, as built – no insulation*	<0.1%	0.1%
	System built – internal/external insulation	<0.1%	<0.1%
	Other/unknown	0.9%	0.9%
Semi-detached houses (n=11,105) EPC D–G semi-detached houses (n=8,478)	U = 0.13–0.20 W/m2K	1.5%	<0.1%
	U = 0.21–0.30 W/m2K	5.2%	<0.1%
	U = 0.31–0.45 W/m2K	0.1%	<0.1%
	U = 0.46–1.80 W/m2K	0.3%	0.4%
	Cavity wall, as built – partially/fully insulated*	8.2%	5.8%
	Cavity wall, as built – no insulation*	11.0%	13.8%
	Cavity wall, as built – filled cavity	23.2%	17.7%
	Solid brick, as built – no insulation*	**47.5%**	**60.5%**
	Solid brick – internal/external insulation	1.5%	0.7%
	System built, as built – no insulation*	0.2%	0.3%
	System built – internal/external insulation	<0.1%	<0.1%
	Other/unknown	1.1%	0.8%
Mid-terrace houses (n=4,559) EPC D–G mid-terrace houses (n=2,890)	U = 0.13–0.20 W/m2K	1.8%	<0.1%
	U = 0.21–0.30 W/m2K	3.1%	<0.1%
	U = 0.31–0.45 W/m2K	0.9%	<0.1%
	U = 0.46–1.80 W/m2K	0.1%	0.1%
	Cavity wall, as built – partially/fully insulated*	14.0%	7.3%
	Cavity wall, as built – no insulation*	7.5%	9.0%
	Cavity wall, as built – filled cavity	17.2%	9.4%
	Solid brick, as built – no insulation*	**51.3%**	**71.0%**
	Solid brick – internal/external insulation	2.1%	1.2%
	System built, as built – no insulation*	1.0%	1.1%
	System built – internal/external insulation	0.1%	0.1%
	Other/unknown	1.0%	0.8%
End-terrace houses (n=3,111) EPC D–G end-terrace houses (n=2,069)	U = 0.13–0.20 W/m2K	2.7%	<0.1%
	U = 0.21–0.30 W/m2K	6.5%	<0.1%
	U = 0.31–0.45 W/m2K	1.2%	<0.1%
	U = 0.46–1.80 W/m2K	0.1%	0.2%
	Cavity wall, as built – partially/fully insulated*	17.8%	11.0%
	Cavity wall, as built – no insulation*	5.0%	7.2%
	Cavity wall, as built – filled cavity	19.2%	14.2%
	Solid brick, as built – no insulation*	**41.9%**	**62.3%**

	Solid brick – internal/external insulation	2.7%	2.0%
	System built, as built – no insulation*	1.2%	1.6%
	System built – internal/external insulation	0.4%	0.2%
	Other/unknown	1.3%	1.1%
Flats (n=5,395) EPC D–G flats (n=2,040)	U = 0.13–0.20 W/m2K	2.7%	0.4%
	U = 0.21–0.30 W/m2K	6.2%	1.9%
	U = 0.31–0.45 W/m2K	1.3%	1.3%
	U = 0.46–1.80 W/m2K	0.5%	0.3%
	Cavity wall, as built – partially/fully insulated*	**30.1%**	16.7%
	Cavity wall, as built – no insulation*	7.6%	15.1%
	Cavity wall, as built – filled cavity	28.1%	19.6%
	Solid brick, as built – no insulation*	13.9%	**31.6%**
	Solid brick – internal/external insulation	3.5%	3.8%
	System built, as built – no insulation*	1.5%	3.6%
	System built – internal/external insulation	2.6%	3.4%
	Other/unknown	2.0%	2.3%
Detached bungalows (n=2,482) EPC D–G detached bungalows (n=2,482)	U = 0.13–0.20 W/m2K	0.4%	<0.1%
	U = 0.21–0.30 W/m2K	1.5%	<0.1%
	U = 0.31–0.45 W/m2K	<0.1%	<0.1%
	U = 0.46–1.80 W/m2K	<0.1%	<0.1%
	Cavity wall, as built – partially/fully insulated*	14.4%	13.1%
	Cavity wall, as built – no insulation*	13.9%	16.7%
	Cavity wall, as built – filled cavity	**53.5%**	**51.7%**
	Solid brick, as built – no insulation*	13.2%	15.7%
	Solid brick – internal/external insulation	0.6%	0.3%
	System built, as built – no insulation*	0.1%	0.2%
	System built – internal/external insulation	<0.1%	<0.1%
	Other/unknown	2.4%	2.5%

ROOF

Table 12: Roof fabric breakdown

Property-build type	Roof type	Proportion per house type	Proportion per house type (EPC D–G)
Detached houses (n=7,607) EPC D–G detached houses (n=5,356)	U = 0.07–0.15 W/m2K	8.6%	<0.1%
	U = 0.16–0.20 W/m2K	1.2%	<0.1%
	U = 0.21–2.30 W/m2K	0.1%	<0.1%
	Pitched – no insulation*	5.4%	7.6%
	Pitched – insulated (unknown dimensions)	5.6%	5.0%
	Pitched – 12–50mm loft insulation	4.1%	5.5%
	Pitched – 75mm loft insulation	4.6%	5.9%
	Pitched – 100mm loft insulation	13.5%	**16.2%**
	Pitched – 150mm loft insulation	12.8%	14.6%
	Pitched – 200mm loft insulation	14.2%	14.8%
	Pitched – 250mm loft insulation	13.9%	14.6%
	Pitched – over 250mm loft insulation	**14.3%**	13.9%
	Flat – partially/fully insulated*	0.4%	0.5%
	Flat – no insulation*	0.1%	0.1%
	Another dwelling above	<0.1%	<0.1%
	Other/unknown	1.2%	1.2%
Semi-detached houses (n=11,105) EPC D–G semi-detached houses (n=8,478)	U = 0.07–0.15 W/m2K	6.0%	<0.1%
	U = 0.16–0.20 W/m2K	0.9%	0.1%
	U = 0.21–2.30 W/m2K	0.3%	0.3%
	Pitched – no insulation*	10.9%	14.1%
	Pitched – insulated (unknown dimensions)	3.2%	3.0%
	Pitched – 12–50mm loft insulation	5.5%	6.7%
	Pitched – 75mm loft insulation	6.4%	7.5%
	Pitched – 100mm loft insulation	**14.5%**	**16.1%**
	Pitched – 150mm loft insulation	11.5%	12.3%
	Pitched – 200mm loft insulation	13.2%	13.2%

	Pitched – 250mm loft insulation	12.9%	12.7%
	Pitched – over 250mm loft insulation	12.9%	12.1%
	Flat – partially/fully insulated*	0.4%	0.4%
	Flat – no insulation*	0.1%	0.1%
	Another dwelling above	0.1%	<0.1%
	Other/unknown	1.3%	1.3%
Mid-terrace houses (n=4,559)	U = 0.07–0.15 W/m2K	5.3%	<0.1%
	U = 0.16–0.20 W/m2K	0.6%	<0.1%
	U = 0.21–2.30 W/m2K	<0.1%	0.1%
EPC D–G mid-terrace houses (n=2,890)	Pitched – no insulation*	**16.4%**	**25.7%**
	Pitched – insulated (unknown dimensions)	3.9%	3.5%
	Pitched – 12–50mm loft insulation	4.9%	6.4%
	Pitched – 75mm loft insulation	5.9%	6.8%
	Pitched – 100mm loft insulation	13.9%	15.3%
	Pitched – 150mm loft insulation	11.7%	10.6%
	Pitched – 200mm loft insulation	12.5%	10.6%
	Pitched – 250mm loft insulation	12.0%	10.4%
	Pitched – over 250mm loft insulation	11.2%	8.9%
	Flat – partially/fully insulated*	0.4%	0.6%
	Flat – no insulation*	0.2%	0.2%
	Another dwelling above	0.2%	0.1%
	Other/unknown	1.0%	0.9%
End-terrace houses (n=3,111)	U = 0.07–0.15 W/m2K	9.6%	<0.1%
	U = 0.16–0.20 W/m2K	0.7%	<0.1%
	U = 0.21–2.30 W/m2K	0.2%	0.2%
EPC D–G end-terrace houses (n=2,069)	Pitched – no insulation*	11.4%	**17.0%**
	Pitched – insulated (unknown dimensions)	4.4%	3.3%
	Pitched – 12–50mm loft insulation	4.3%	5.9%
	Pitched – 75mm loft insulation	4.9%	6.4%
	Pitched – 100mm loft insulation	**14.0%**	16.8%
	Pitched – 150mm loft insulation	11.2%	12.9%
	Pitched – 200mm loft insulation	11.7%	11.7%
	Pitched – 250mm loft insulation	12.8%	12.5%
	Pitched – over 250mm loft insulation	12.8%	11.8%
	Flat – partially/fully insulated*	0.2%	0.1%
	Flat – no insulation*	0.1%	0.1%
	Another dwelling above	0.2%	0.2%
	Other/unknown	1.4%	0.9%
Flats (n=5,395)	U = 0.07–0.15 W/m2K	3.4%	0.9%
	U = 0.16–0.20 W/m2K	1.5%	0.8%
EPC D–G flats (n=2,040)	U = 0.21–2.30 W/m2K	0.2%	0.2%
	Pitched – no insulation*	3.9%	10.0%
	Pitched – insulated (unknown dimensions)	5.2%	5.6%
	Pitched – 12–50mm loft insulation	1.5%	2.4%
	Pitched – 75mm loft insulation	0.9%	1.5%
	Pitched – 100mm loft insulation	4.4%	5.4%
	Pitched – 150mm loft insulation	3.6%	3.0%
	Pitched – 200mm loft insulation	4.9%	4.4%
	Pitched – 250mm loft insulation	5.8%	4.0%
	Pitched – over 250mm loft insulation	7.5%	3.6%
	Flat – partially/fully insulated*	3.7%	7.5%
	Flat – no insulation*	1.3%	3.3%
	Another dwelling above	**51.3%**	**45.2%**
	Other/unknown	0.8%	1.5%
Detached bungalows (n=2,482)	U = 0.07–0.15 W/m2K	1.7%	<0.1%
	U = 0.16–0.20 W/m2K	0.2%	<0.1%
	U = 0.21–2.30 W/m2K	<0.1%%	<0.1%
	Pitched – no insulation*	4.9%	5.9%
	Pitched – insulated (unknown dimensions)	4.5%	4.5%
	Pitched – 12–50mm loft insulation	4.0%	4.8%

EPC D–G detached bungalows (n=2,482)	Pitched – 75mm loft insulation	4.5%	5.4%
	Pitched – 100mm loft insulation	11.4%	12.8%
	Pitched – 150mm loft insulation	10.9%	11.2%
	Pitched – 200mm loft insulation	16.0%	15.6%
	Pitched – 250mm loft insulation	18.4%	17.6%
	Pitched – over 250mm loft insulation	**22.0%**	**20.9%**
	Flat – partially/fully insulated*	0.3%	0.3%
	Flat – no insulation*	0.1%	0.1%
	Another dwelling above	NA	NA
	Other/unknown	1.2%	1.1%

FLOOR

Table 13: Floor fabric breakdown

Property-build type	Floor type	Proportion per house type	Proportion per house type (EPC D–G)
Detached houses (n=7,607) EPC D–G detached houses (n=5,356)	U = 0.02–0.15 W/m2K	5.7%	<0.1%
	U = 0.16–0.20 W/m2K	2.7%	<0.1%
	U = 0.21–1.20 W/m2K	1.4%	<0.1%
	Solid – partially/fully insulated*	9.0%	3.8%
	Solid – no insulation*	**44.2%**	**49.9%**
	Suspended – partially/fully insulated*	2.3%	1.5%
	Suspended – no insulation*	34.5%	44.6%
	Another premises/dwelling below	0.1%	0.1%
	Other/unknown	0.1%	0.1%
Semi-detached houses (n=11,105) EPC D–G semi-detached houses (n=8,478)	U = 0.02–0.15 W/m2K	4.5%	<0.1%
	U = 0.16–0.20 W/m2K	1.6%	<0.1%
	U = 0.21–1.20 W/m2K	1.1%	0.4%
	Solid – partially/fully insulated*	3.3%	1.1%
	Solid – no insulation*	**47.2%**	48.2%
	Suspended – partially/fully insulated*	1.1%	0.7%
	Suspended – no insulation*	40.8%	**49.2%**
	Another premises/dwelling below	0.1%	0.1%
	Other/unknown	0.3%	0.3%
Mid-terrace houses (n=4,559) EPC D–G mid-terrace houses (n=2,890)	U = 0.02–0.15 W/m2K	3.5%	<0.1%
	U = 0.16–0.20 W/m2K	1.2%	<0.1%
	U = 0.21–1.20 W/m2K	1.2%	0.1%
	Solid – partially/fully insulated*	6.1%	0.8%
	Solid – no insulation*	**57.2%**	**59.5%**
	Suspended – partially/fully insulated*	0.9%	0.3%
	Suspended – no insulation*	28.8%	38.1%
	Another premises/dwelling below	0.2%	0.3%
	Other/unknown	0.9%	0.9%
End-terrace houses (n=3,111) EPC D–G end-terrace houses (n=2,069)	U = 0.02–0.15 W/m2K	6.5%	<0.1%
	U = 0.16–0.20 W/m2K	2.4%	<0.1%
	U = 0.21–1.20 W/m2K	1.6%	0.2%
	Solid – partially/fully insulated*	8.4%	1.6%
	Solid – no insulation*	**52.6%**	**60.5%**
	Suspended – partially/fully insulated*	1.4%	0.5%
	Suspended – no insulation*	25.8%	36.0%
	Another premises/dwelling below	0.4%	0.3%
	Other/unknown	0.7%	0.9%
Flats (n=5,395) EPC D–G flats (n=2,040)	U = 0.02–0.15 W/m2K	3.0%	0.6%
	U = 0.16–0.20 W/m2K	1.1%	0.6%
	U = 0.21–1.20 W/m2K	1.3%	1.5%
	Solid – partially/fully insulated*	4.7%	2.6%
	Solid – no insulation*	23.7%	28.0%
	Suspended – partially/fully insulated*	1.0%	0.8%
	Suspended – no insulation*	4.1%	6.3%
	Another premises/dwelling below	**59.5%**	**56.8%**

	Other/unknown	1.6%	2.7%
Detached bungalows (n=2,482) EPC D–G detached bungalows (n=2,482)	U = 0.02–0.15 W/m2K	0.6%	<0.1%
	U = 0.16–0.20 W/m2K	1.1%	<0.1%
	U = 0.21–1.20 W/m2K	0.1%	<0.1%
	Solid – partially/fully insulated*	2.9%	1.3%
	Solid – no insulation*	**53.0%**	**53.1%**
	Suspended – partially/fully insulated*	1.5%	0.8%
	Suspended – no insulation*	40.6%	44.6%
	Another premises/dwelling below	NA	NA
	Other/unknown	0.1%	0.2%

WINDOWS

Table 14: Window type breakdown

Property-build type	Window (glazing) type	Proportion per house type	Proportion per house type (EPC D–G)
Detached houses (n=7,607) EPC D–G detached houses (n=5,356)	Full single glazing	1.7%	2.3%
	Partial double glazing	10.0%	13.9%
	Full double glazing	**78.6%**	**82.9%**
	High performance glazing	0.5%	0.7%
	Secondary glazing	8.9%	<0.1%
	Other/unknown	0.3%	0.2%
Semi-detached houses (n=11,105) EPC D–G semi-detached houses (n=8,478)	Full single glazing	2.0%	2.5%
	Partial double glazing	10.0%	12.5%
	Full double glazing	**80.7%**	**84.4%**
	High performance glazing	0.3%	0.3%
	Secondary glazing	6.7%	<0.1%
	Other/unknown	0.2%	0.2%
Mid-terrace houses (n=4,559) EPC D–G mid-terrace houses (n=2,890)	Full single glazing	3.3%	5.0%
	Partial double glazing	8.9%	12.8%
	Full double glazing	**82.8%**	**81.8%**
	High performance glazing	0.1%	0.2%
	Secondary glazing	4.8%	0.1%
	Other/unknown	0.1%	0.1%
End-terrace houses (n=3,111) EPC D–G end-terrace houses (n=2,069)	Full single glazing	2.5%	3.7%
	Partial double glazing	7.3%	10.4%
	Full double glazing	**80.6%**	**85.3%**
	High performance glazing	0.4%	0.4%
	Secondary glazing	9.0%	<0.1%
	Other/unknown	0.2%	0.1%
Flats (n=5,395) EPC D–G flats (n=2,040)	Full single glazing	1.6%	2.9%
	Partial double glazing	4.1%	9.2%
	Full double glazing	**84.3%**	**84.1%**
	High performance glazing	0.8%	1.0%
	Secondary glazing	9.0%	2.5%
	Other/unknown	0.2%	0.2%
Detached Bungalows (n=2,482) EPC D–G detached bungalows (n=2,482)	Full single glazing	1.3%	1.5%
	Partial double glazing	7.0%	8.2%
	Full double glazing	**89.4%**	**89.6%**
	High performance glazing	0.4%	0.4%
	Secondary glazing	1.7%	<0.1%
	Other/unknown	0.3%	0.2%

Table 15: Building elements and their common types

Property-build type	Building element	Most common among type
	Walls	Solid brick, as built – no insulation
	Roof	Pitched – over 250mm loft insulation

Detached houses (n=7,607)	Floor	Solid – no insulation
	Windows	Full double glazing
Semi-detached houses (n=11,105)	Walls	Solid brick, as built – no insulation
	Roof	Pitched – 100mm loft insulation
	Floor	Solid – no insulation
	Windows	Full double glazing
Mid-terrace houses (n=4,559)	Walls	Solid brick, as built – no insulation
	Roof	Pitched – no insulation
	Floor	Solid – no insulation
	Windows	Full double glazing
End-terrace houses (n=3,111)	Walls	Solid brick, as built – no insulation
	Roof	Pitched – 100mm loft insulation
	Floor	Solid – no insulation
	Windows	Full double glazing
All flats (n=5,395)	Walls	Cavity wall, as built – partially/fully insulated
	Roof	Another dwelling above
	Floor	Another premises/dwelling below
	Windows	Full double glazing
Detached bungalows (n=2,482)	Walls	Cavity wall, as built – filled cavity
	Roof	Pitched – over 250mm loft insulation
	Floor	Solid – no insulation
	Windows	Full double glazing

Table 16: Building elements and their common types in EPC D-G properties

Property-build type	Building element	Most common among **EPC D–G only**
EPC D–G detached houses (n=5,356)	Walls	Solid brick, as built – no insulation
	Roof	Pitched – 100mm loft insulation
	Floor	Solid – no insulation
	Windows	Full double glazing
EPC D–G semi-detached houses (n=8,478)	Walls	Solid brick, as built – no insulation
	Roof	Pitched – 100mm loft insulation
	Floor	Suspended – no insulation
	Windows	Full double glazing
EPC D–G mid-terrace houses (n=2,890)	Walls	Solid brick, as built – no insulation
	Roof	Pitched – no insulation
	Floor	Solid – no insulation
	Windows	Full double glazing
EPC D–G end-terrace houses (n=2,069)	Walls	Solid brick, as built – no insulation
	Roof	Pitched – no insulation
	Floor	Solid – no insulation
	Windows	Full double glazing
EPC D–G flats (n=2,040)	Walls	Solid brick, as built – no insulation
	Roof	Another dwelling above
	Floor	Another premises/dwelling below
	Windows	Full double glazing
EPC D–G detached bungalows (n=2,482)	Walls	Cavity wall, as built – filled cavity
	Roof	Pitched – over 250mm loft insulation
	Floor	Solid – no insulation
	Windows	Full double glazing

1.9 Broxtowe Housing Stock Characterisation: Fuel Poverty Analysis

This section provides an overview of fuel poverty in Broxtowe, according to the UK Government's Low Income Low Energy Efficiency (LILEE) definition. The most recent data (DESNZ, 2024) show that Broxtowe has a LILEE fuel poverty rate of 13.5%, which is slightly higher than the English average (13.1%), but lower than the typical rate across the East Midlands (15.1%). Figure 8 shows the spatial distribution of LILEE fuel poverty across Lower Super Output Areas (LSOAs) in Broxtowe. LSOAs are a standardised, geographical unit used to divide local authorities into more manageable small areas with approximately consistent populations. The univariate map (i.e., displaying a single variable – LILEE fuel poverty rate per LSOA) shows that LILEE fuel poverty tends to be clustered around the LSOAs with the highest population density (i.e., the LSOAs with the smallest geographical areas). This is to be expected, and similar clustering has been observed in other studied areas, including Nottingham and London. It is also worth noting that the irregularity of the scale (e.g., 4–9.7%) is induced by the division of Broxtowe's LSOAs into five fuel poverty quintiles, hence each colour represents the lowest to highest quintile of fuel poverty compared to the Broxtowe baseline rate (13.5%).

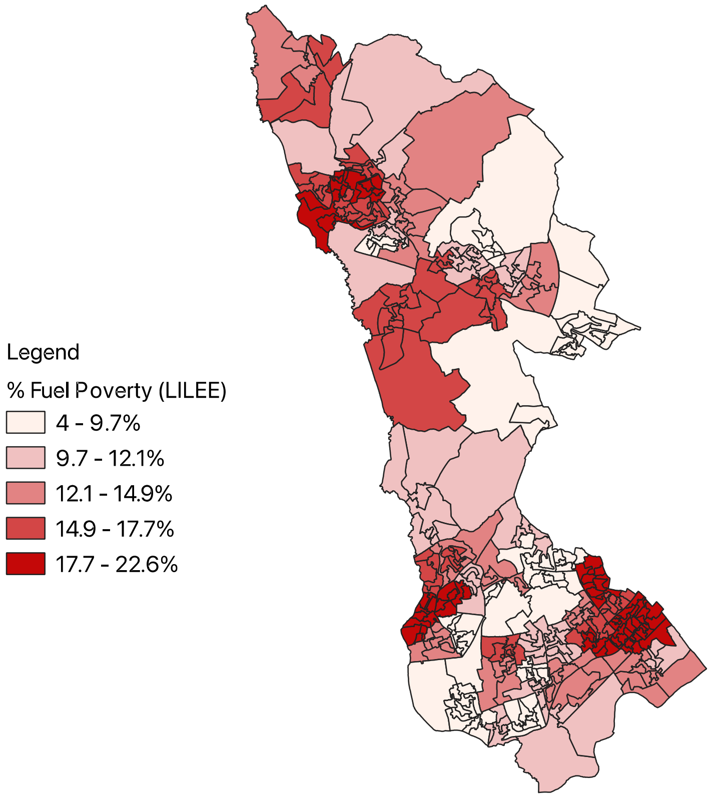


Figure 8: Univariate, quintile-aggregated LILEE fuel poverty map for Broxtowe LSOAs

Due to how the LILEE definition is formulated, there are concerns that the true extent of fuel poverty in England may be trivialised. LILEE, which was adopted as the official definition in 2019, controversially omits homes with Fuel Poverty Energy Efficiency Rating (FPEER) bands of C or above. The FPEER banding system is equivalent to EPC bands in almost all cases. The implication is that homes rated A–C cannot experience fuel poverty; however, our previous research has shown that a considerable proportion of low-income people living in A–C rated properties still experience energy insecurity, which is a form of self-reported or subjective fuel poverty. To partially express this issue in Broxtowe, Figure 9 displays a bivariate map of LILEE fuel poverty versus Index of Multiple Deprivation (IMD), per LSOA. The purpose of this map is to demonstrate that there are a considerable number of LSOAs that have middling to high deprivation but low rates of LILEE fuel poverty; these instances are denoted by light blue (legend code B1) and turquoise (legend code C1). It is highly likely that, within these identified LSOAs, there are many low-income homes that are misclassified as not fuel poor under LILEE.

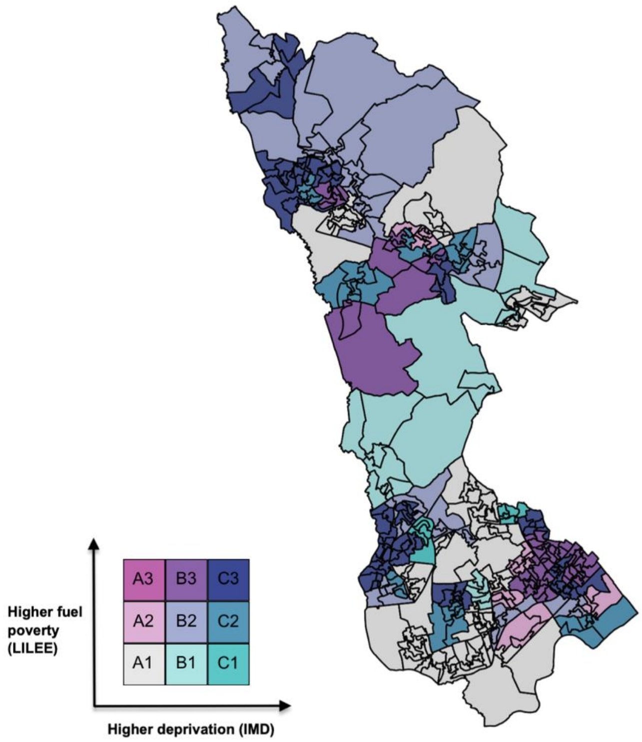


Figure 9: Bivariate map for Broxtowe: LILEE fuel poverty versus deprivation (IMD)

To further illustrate the deficiencies of the LILEE definition, the following calculations provide an estimate of low-income homes (where the main earner is unemployed or economically inactive) with EPC ratings of C or above in Broxtowe. We suggest that homes meeting this description are unlikely to be able to *afford adequate warmth*, which is the typically recognised definition of fuel poverty across Europe and other British nations. In the housing characterisation section, it was shown that 33.8% (n=12,491) of homes in Broxtowe have EPC ratings of A–C. Among this A–C subset, Table 17 displays typical tenure status. The remainder of this section only focuses on socially and privately rented homes, given the likelihood that people living in these tenures are significantly more likely to be in financially vulnerable or precarious situations.

Table 17 Tenure status among EPC A–C rated properties in Broxtowe

Tenure Status	Frequency (among A–C subset, n=12,491) (% of subset in parentheses)
Owner-occupied	5070 (40.6%)
Privately rented	1865 (14.9%)
Socially rented	2977 (23.8%)
Unknown	2435 (19.5%)

Among socially (n=2,977) and privately rented (n=1,865) tenures, there are a combined 4,482 homes. By integrating employment information from the English Housing Survey (DLUHC, 2023), it is possible to roughly estimate the number of EPC A–C-rated, socially or privately rented, financially vulnerable homes in Broxtowe. The proportion of main earners who are unemployed or economically inactive is 31.6% and 16.6% in socially and privately rented properties, respectively. Then, it follows that 31.6% of the 2,977 socially rented homes (~941) are at risk of income-induced fuel poverty, despite their default omission under LILEE. Among privately rented properties, the equivalent figure is around 310 homes. In summary, 1,251 homes (around 3.4% of the entire Broxtowe housing stock) are wrongly omitted from fuel poverty statistics.

2 Retrofit Generic Housing Performance Assessment

For the purpose of this report, the retrofit process is divided into three key stages, as outlined below:

- Retrofit stage 1: consists of fabric improvements to reduce operational energy consumption and carbon emissions
- Retrofit stage 2: considers retrofit stage 1, combined with the integration of low-carbon heating systems
- Retrofit stage 3: consists of retrofit stage 2 with the integration of renewable energy generation

The aforementioned stages can be implemented as part of a typical retrofit or deep retrofit approach. Simply put, typical retrofits are usually easier to implement as they are less costly and less disruptive to occupants. The typical retrofit approach, alone, results in moderate energy savings and performance improvements.

Alternatively, deep retrofit measures involve more comprehensive upgrades. Unlike typical retrofits, deep retrofitting involves the upgrade of multiple systems, including building envelope (e.g. floor insulation) as well as electrical, structural, and mechanical components. As mentioned previously, it is this extensive nature of deep retrofits that incur higher upfront costs and disruptions for occupants, in comparison to less invasive typical retrofits. Despite the longer project duration required for implementation, deep retrofitting can result in significant performance enhancements and long-term energy savings.

In reality, deep retrofitting is often unfeasible, due to financial constraints and the level of disruption to occupants, as previously discussed; in some other cases deep retrofitting is incompatible with the protection of historically significant buildings and/or building features. It is therefore often more realistic to design an approach based on incremental improvements, in which a long-term plan accounts for all the required upgrades. However, if possible, deep retrofitting should be undertaken in a single go, which can maximise quality and reduce costs.

A more pragmatic approach would be to consider the implementation of typical retrofit measures in a scenario where decarbonisation efforts are at the forefront. By decarbonising our energy sources, we can reduce greenhouse gas emissions, lower energy costs, and improve energy efficiency in our homes. Combined with typical retrofit measures, decarbonisation can help us ensure that we provide superior quality homes within a shorter period and at a substantially lower retrofit cost. Other additional benefits include enabling improved energy security by reducing reliance on fossil fuels, promoting the health of citizens because of reduced pollution, and aligning with regulatory requirements.

This section presents the findings of the generic housing stock energy performance assessment. Both typical and deep retrofitting approaches are considered. The performance of retrofitted homes is calculated using thermal dynamic building simulation, based on typical inputs and housing characteristics. The thermal dynamic building simulations were produced in IESVE simulation software. IESVE is a commonly used, industry-standard building simulation tool (Jankovic, 2017).

The optimisation of the building envelope, known as a ‘fabric first’ approach, includes the reduction of overall envelope U-values and improvements to air permeability. The main aim is to get the existing housing stock up to the Future Homes Standard (Ministry of Housing; Communities and Local Government, 2019), which will become mandatory for all new builds from 2025. The U-values that will appear in the updated Building Regulations Part L 2021 will show a minimum value (higher U-value) that must be achieved for each building component, e.g., roof, walls, windows, plus a stricter ‘notional value’ that needs to be reached across all elements to achieve compliance. In other words, there is a degree to which some elements can be offset against others by going over that minimum value where it is easy to do so (in the roof, for instance).

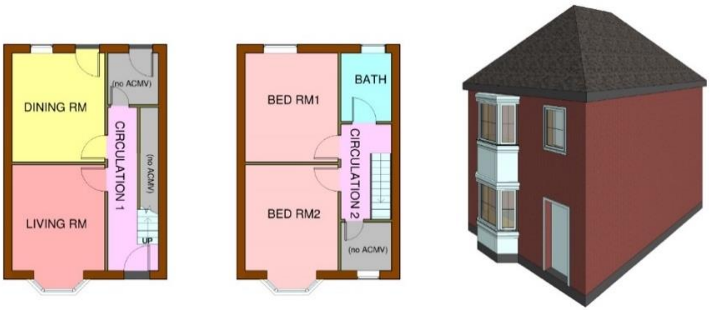
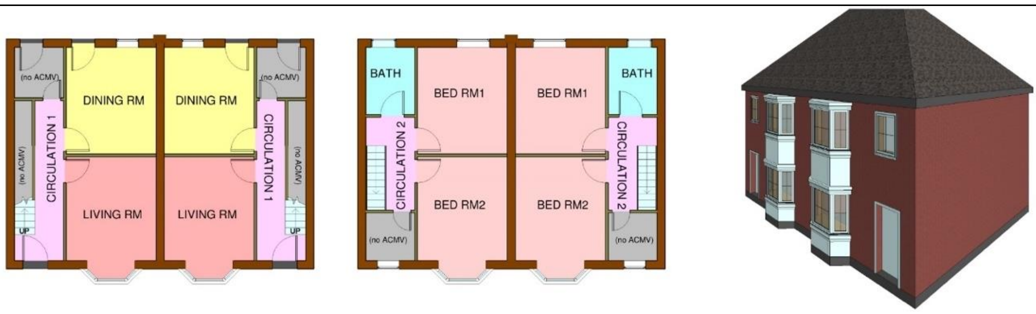
2.1 Simulation Models, Stages and Assumptions

This section presents the building models (or archetypes), retrofit stages and assumptions used in the simulations.

Models

For the simulations to be realistic and relevant to the current Broxtowe housing stock, five models were developed to represent the most typical house types identified in Section 1.8. The property types of interest in Broxtowe are detached, semi-detached, mid-terrace and end-terrace houses, and flats. Table 18 illustrates these, along with the corresponding geometric data, shown in Table 19. Each of these models varies in layout, floor area, number of bedrooms, and occupancy, with the number of occupants determined by the number of bedrooms. These factors all contribute to differences in energy consumption and performance levels. While this approach provides a more accurate representation of the energy use and performance levels of the different archetypes, it is crucial to understand these differences; therefore, each model needs to be assessed separately.

Table 18: Housing archetypes – floor plans and perspectives

Detached Bedrooms: 2 Occupancy: 3	
Semi-detached Bedrooms: 2 Occupancy: 3	
Mid-terrace & End-terrace Bedrooms: 3 Occupancy: 4	

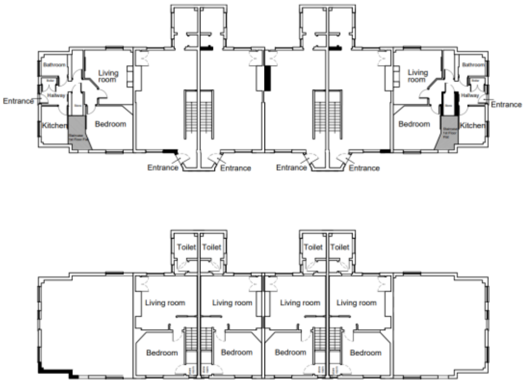
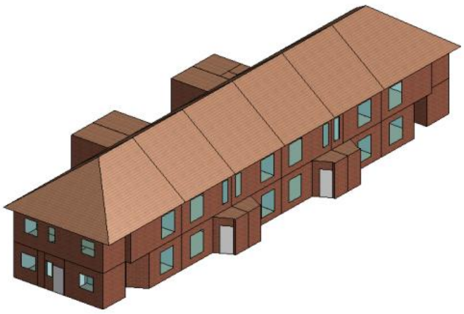
	
Flats Bedrooms: 1 Occupancy: 2	 

Table 19: Housing archetypes – Building geometry data and air permeability assumptions

Building Components	Detached house	Semi-Detached house	Mid-terrace house	End-terrace house	Mid-terrace Flat_FF	End-terrace Flat_GF
	Area (m^2)	Area (m^2)	Area (m^2)	Area (m^2)	Area (m^2)	Area (m^2)
Ground Floor Area	48.72	48.72	50.28	50.28	50.9	62
Total Floor Area	89.9	89.9	89.7	89.7	50.9	62
Roof (ceiling level)	57.6	53.84	53.2	53.2	50.9	62
Roof (if sloped)	76	62.74	83.07	83.07	62	
Wall (External walls + party walls as they are considered permeable)	159	112	115.36	152.32	81.6	79.2
Window	9.3	9.3	10.68	10.68	7.3	8.07
External Door	5.67	5.67	5.67	5.67	1.8	1.8
Roof Volume (m^3)	60.92	52.2	68.74	72.1	85.54	107
All internal air volume (m^3) (for infiltration calculation)	333.76	325	343.58	346.94	122.16	148.8
Wall + Roof + Ground Floor Area (Building Fabric area used for infiltration calculation)	265.32	214.56	218.84	255.8	183.4	203.2
ACH if airtight test (very leaky type) is 15 m^3/hm^2 @ 50Pa (and 1/20 rule) -Test / Base	0.60	0.50	0.48	0.55	1.13	1.02

ACH if airtight test is 8 m^3/hm^2 @ 50Pa (and 1/20 rule) - Optimised to Part L 2021 max. permitted	0.32	0.26	0.25	0.29	0.60	0.55
ACH if airtight test is 5 m^3/hm^2 @ 50Pa (and 1/20 rule) - Optimised to Part L 2021 notional	0.20	0.17	0.16	0.18	0.38	0.34

Retrofit Stage 1

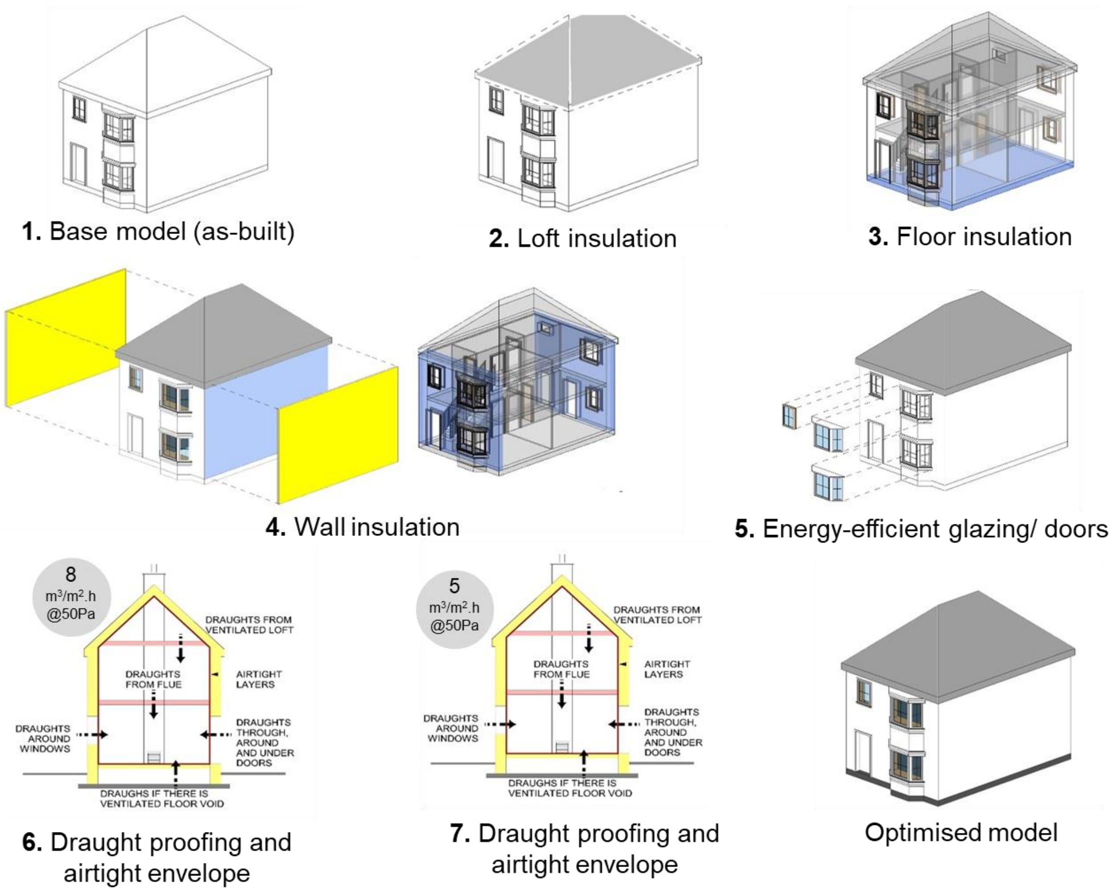
Retrofit stage 1 is exclusively limited to fabric improvements to reduce operational energy consumption and carbon emissions. A total of six simulation scenarios (base scenario plus five levels of building fabric improvements) were investigated, as outlined in Table 20. The key 'fabric first' measures included in this stage are loft insulation, floor insulation (when viable and affordable), wall insulation, triple glazing, and air tightness.

The scenarios considered in this investigation accounted for the likelihood and feasibility of the changes and these are:

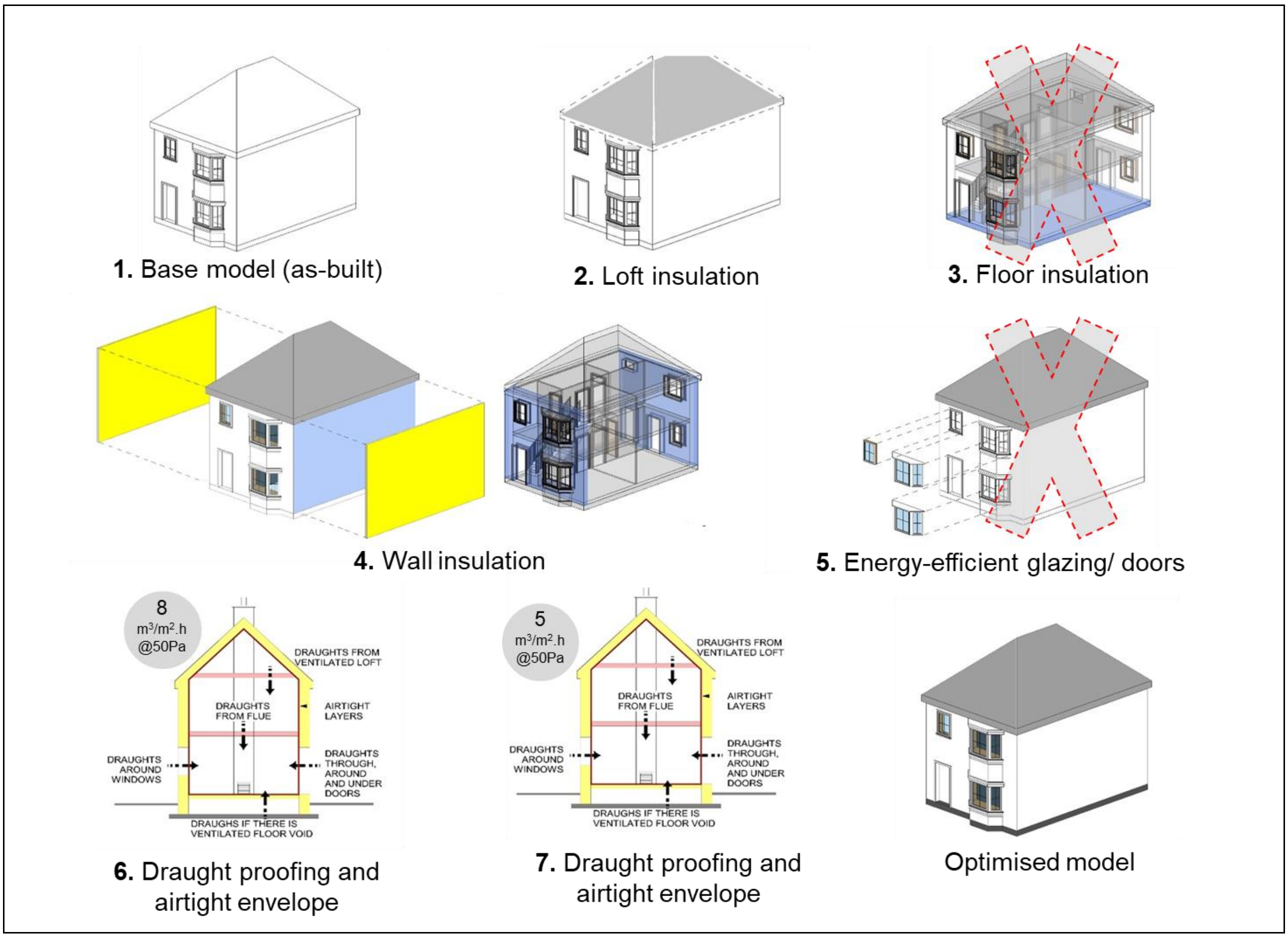
- Loft insulation, measured in W/m^2K
- Floor insulation, measured in W/m^2K
- Wall insulation, measured in W/m^2K
- Triple glazing, measured in W/m^2K
- Airtightness (Draught Proofing), measured in m^3/hm^2 @ 50Pa

Table 20: Retrofit stage 1 – building fabric improvement – simulation scenarios analysed

1	Base case as-built (scenario 1) – with highly infiltrated (15 m^3/m^2h), poorly or non-insulated building envelope.
2	Added loft Insulation to scenario #1 (Part L 2021 notional levels)
3	Added loft insulation + solid floor insulation to scenario #2 (based on the most feasible and less destructive option)
4	Added loft insulation + floor insulation + external insulation on the walls to scenario #3 (Part L 2021 notional levels)
5	Added loft insulation + floor insulation + wall insulation + energy-efficient glazing and doors (low U-value glazing) to scenario #4 (Part L 2021 notional levels)
6	Added loft insulation + floor insulation + wall insulation + energy-efficient glazing and doors + draught-proofing and airtight layer (8 m^3/m^2h) to scenario #5 (Part L 2021)
7	Added loft insulation + floor insulation + wall insulation + energy-efficient glazing and doors + additional draught-proofing and airtight layer (5 m^3/m^2h) to scenario #6 (Part L 2021 notional levels)
An illustration of the simulation's steps for a detached house for deep retrofit.	



An illustration of the simulation's steps for a detached house for typical retrofit.



Retrofit Stage 2 & 3

Retrofit Stage 2 (Table 21) and Stage 3 (Table 22) compare the impacts of passive measures through fabric improvements when combined with low-carbon heating systems and energy generation, respectively. ASHPs and solar photovoltaics (PV) were proposed to investigate potential reductions in energy consumption, carbon emissions, and energy prices after the passive energy measures are added.

Table 21: Retrofit Stage 2 – integration of low-carbon heating systems – simulation scenarios analysed

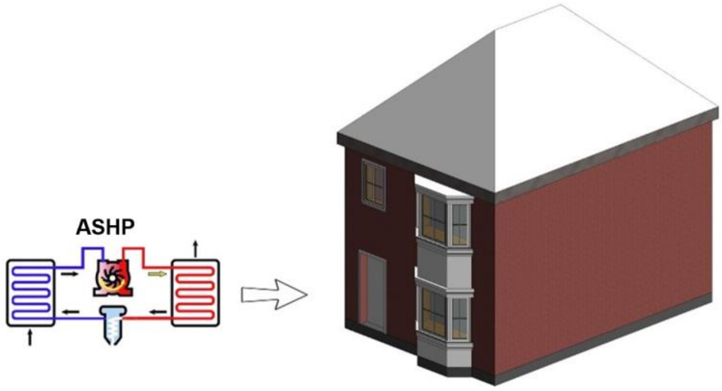
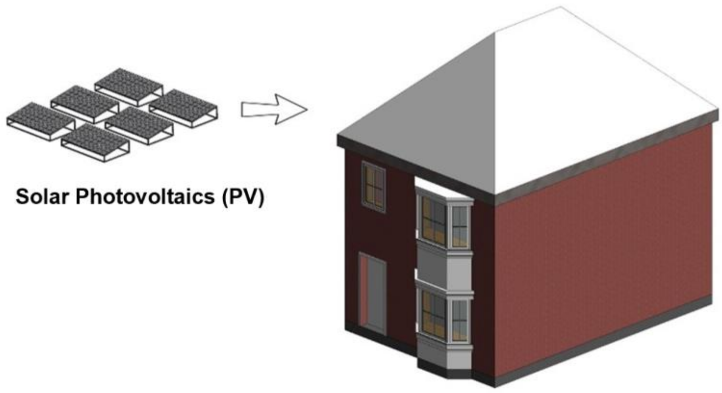
Scenario 2.1	ASHP
	

Table 22: Retrofit Stage 3 – renewable energy generation – simulation scenarios analysed

Scenario 3.1	solar photovoltaics (PV)
	

Simulation Assumptions

The assumptions adopted in the simulations are described in Table 23. Heating and cooling setpoints were based on CIBSE (2019b). Cooling indoor temperature limits, window opening regimes and duration of the cooling season were based on TM59 (CIBSE, 2017). Windows in each room were set to be controlled separately and modelled as open when both the internal dry bulb temperature exceeds 22°C and the room is occupied (CIBSE, 2017). A detailed heat gain profile is shown in the appendices. Internal doors can be included and left open in the model in the daytime but should be assumed closed when the occupants are sleeping (23 to 8h).

Table 23: Assumptions adopted in the simulation models

Parameter	Description	Assumption	Ref / Profile
Weather	Nottingham	Typical weather year	Nottingham_CIBSE-TRY
Air permeability	Base case	15 m^3/hm^2 @ 50Pa	
	Improved scenario	8 m^3/hm^2 @ 50Pa	
	Further improved scenario	5 m^3/hm^2 @ 50Pa	Future Homes Standard (Ministry of Housing; Communities and Local Government, 2021)
Heating profile	Base case heating setpoint	Lower thermal comfort temperature limits in dwellings according to CIBSE (2019b, p. 1-10): Bathrooms: 20°C Bedroom: 17°C Circulation: 19°C Kitchen: 17°C Living: 22°C	Extended from October to March
Cooling profile and window opening	Base case	No cooling	
	Test scenario for summer cooling (window opening)	Start to open when the internal temperature exceeds 22°C, fully opened when the internal temperature exceeds 26°C. Start to close when the internal temperature falls below 26°C, fully closed when the internal temperature falls below 22°C (HM Government, 2021a, p. 8). Closed if the outdoor temperature > 26°C	From May to September (CIBSE, 2017)
	Test scenario for summer cooling (mixed-mode)	Window is closed. Same cooling set point as above.	From May to September (CIBSE, 2017)
	Cooling set points	Lower summer operative temperature limits in dwellings when conditioned according to CIBSE (2019b, p. 1-10): Bathrooms: 23°C Bedroom: 23°C Circulation: 21°C Kitchen: 21°C Living:23°C	Whenever summer cooling was considered.
Internal gains, based on TM59 (CIBSE, 2017, p. 6-9)	Bedroom Occupancy	Sensible 75 W/person, Latent 55 W/person, Density 2; 70% during sleep activity	As per schedule
	Bedroom Lighting	2 W/m^2, Radiant Fraction 0.45,	18-23 hour
	Bedroom Equipment	Sensible 80 Watts, Radiant Fraction 0.22	As per schedule
	Living Room Occupancy	Sensible 75 W/person, Latent 55 W/person, Density 2	As per schedule
	Living Room Lighting	2 W/m^2, Radiant Fraction 0.45	18-23 hour
	Living Room - Equipment	Sensible 150 Watts, Radiant Fraction 0.22	As per schedule
	Kitchen - Occupancy	Sensible 75 W/person, Laten 55 W/person, Density 2	As per schedule
	Kitchen - Lighting	2 W/m^2, Radiant Fraction 0.45	18-23 hour
	Kitchen - Equipment	Sensible 300 Watts, Radiant Fraction 0.22	As per schedule
	Circulation area and	2 W/m^2, Radiant Fraction 0.45	18-23 hour

	bathroom - Lighting -		
	Bedroom Equipment	Sensible 1.75 W/m^2, Radiant Fraction 0.22	18-23 hour
Heating system	Base case / Improved scenarios	Seasonal efficiency: 0.89 SCoP (kW/kW): 0.8 No ventilation heat recovery No CH(C)P	Normal natural gas metre
	Test scenarios for ASHP	Central heating system through radiators. SCoP for Space heating – 1.8 for non-retrofit and increased to 2.8 at later stages SCoP for Domestic hot water - 1.5 for non-retrofit and increased to 2 at later stages (see Section 2.4)	ASHP (electricity)
Cooling system	Test scenarios for summer cooling	Air conditioning	Electricity: Meter

In this study, the air permeability of the building envelope (measured at @50Pa) was converted to infiltration using the 'divided by 20' rule and normalised by the envelope area of each typology. For example, a building with an area of 130m^2, with a volume of 230m^3 and measured air permeability of 15m^3/m^{2}h @50Pa, would have an infiltration calculated as: $[(15\ \frac{m^3}{m^2.\ h}\ @50Pa \times \frac{130\ m^2}{230\ m^3}) \div 20] = 0.42\ ach$. Please note that dynamic building simulation software requires an input as infiltration.

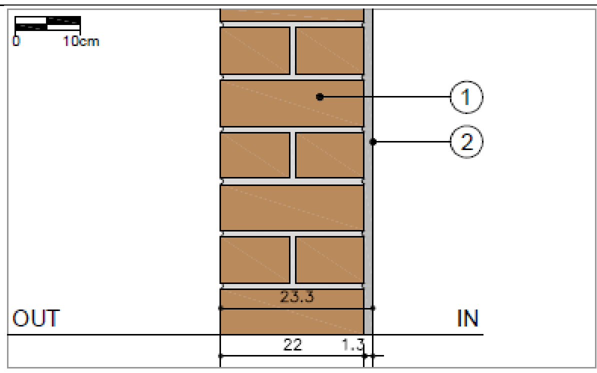
2.2 Building Fabric

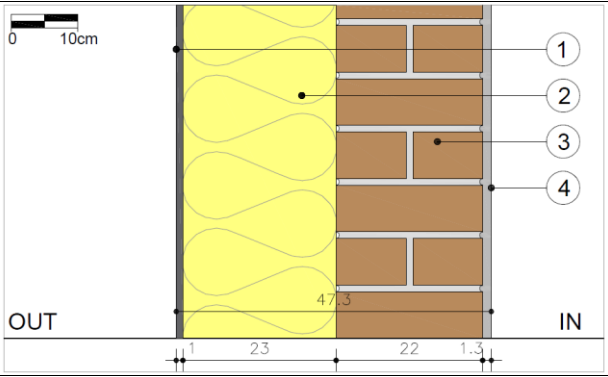
In this section, each construction component (walls, roof, floor, glazing and doors) is reviewed in terms of its material composition and typical U-value. An optimised component is then proposed, based on national standards, and best retrofit practices (as shown in Section 1.2). Please note that notional Part L2021 U-value limits were adopted.

Walls

Wall construction type (as-built and optimised) is illustrated in Table 24

Table 24: Wall construction type – as-built and optimised, based on CIBSE (2019a, p. 3-50 - 3-51)

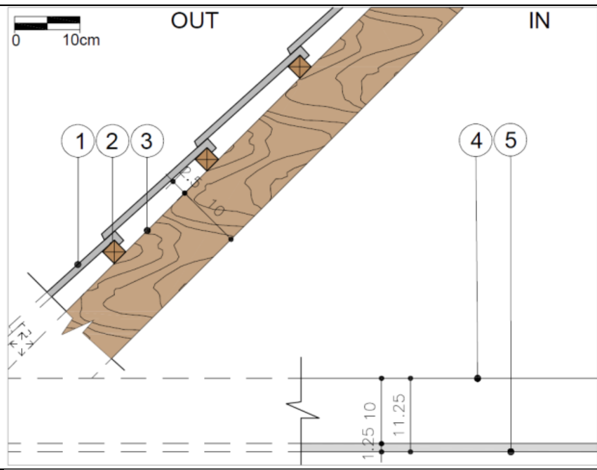
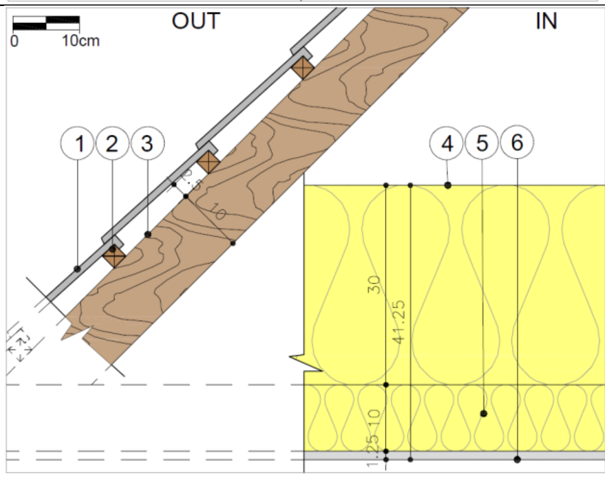
	Wall construction type (Thickness and layers)	U-value (W/m^{2}K)	Section
As-built	Non-insulated solid brick walls Total thickness: 233mm Layers from outside to inside: 1. 220mm solid brick 2. 13mm dense plaster	2.08	

Optimised	Externally insulated solid brick walls Total thickness: 473 mm Layers from outside to inside: 1. 10 mm basecoat/mesh/render 2. 230mm EWI Mineral wool 3. 220mm solid brick 4. 13mm dense plaster	0.16 (U-value (W/m²K) (≤ 0.18)	

Roofs

Roof construction type (as-built and optimised) is illustrated in Table 25.

Table 25: Roof construction type – as-built and optimised, based on CIBSE (2019a, p. 3-54)

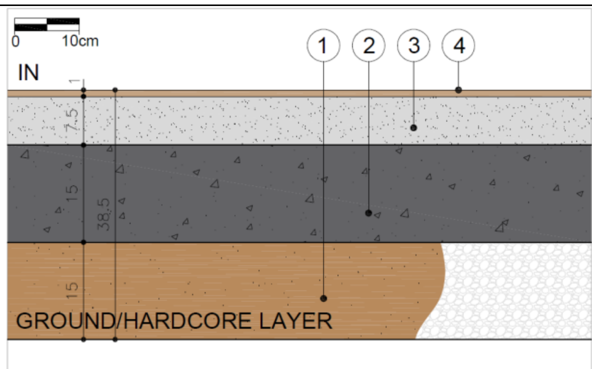
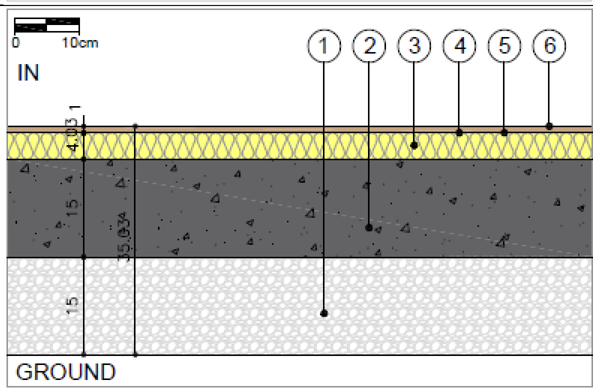
	Roof construction type (Thickness and layers)	U-value (W/m²K)	Section
As-built	Non-insulated pitched roof Total thickness: 112.5mm Layers from outside to inside: 1. 20mm tiles (ventilated) 2. 25mm roof space – battens (ventilated) 3. - mm windtight barrier above the rafters 4. 100mm ceiling joists 5. 12.5mm plasterboard	2.24	
Optimised	Highly insulated pitched roof (insulated at ceiling level) Total thickness: 412.5mm Layers from outside to inside: 1. 20mm tiles (ventilated) 2. 25mm roof space – battens (ventilated) 3. - mm windtight barrier above the rafters 4. 300mm mineral wool over ceiling joists 5. 100mm mineral wool between 100mm ceiling joists 6. 12.5mm plasterboard	0.10 (U-value (W/m²K) (≤ 0.11)	

Floors

Ideally, proposed improvements to solid floors would aim to comply with Part L 2021 notional building (Ministry of Housing; Communities and Local Government, 2021), which specifies a U-value of 0.13W/m²K or less. However, this may necessitate a full rebuild, resulting in higher costs and significant disruption to occupants. For this reason, a more feasible alternative was selected for simulations under the deep retrofit approach. Consequently, a high-performance aerogel insulation mat with a low thermal conductivity of 0.015 W/mK was chosen for the thermal upgrade of solid floors. This slim insulation mat can be placed over a solid concrete floor, conserving interior space, and offering a less disruptive option compared to full rebuilding (Thermablok, 2023).

Ground floor construction type (as-built and optimised) is illustrated in Table 26.

Table 26: Floor construction type – as-built and optimised, based on CIBSE (2019a, p. 3-55 - 3-56)

	Floor construction type (Thickness and layers)	U-value (W/m^2K)	Section
As-built	Non-insulated solid floor Total thickness: 235mm Layers from outside to inside: 1. Ground/Hardcore Layer 2. 150mm cast concrete 3. 75mm screed 4. 10mm carpet	1.59	
Optimised	Highly insulated solid floor- Aerogel insulation mat Layers from outside to inside: 1. Ground/Hardcore Layer 2. 150mm cast concrete 3. 40mm Aerogel insulation mat 4. 3mm high-density untreated chipboard 5. Damp-proof membrane 6. 10mm carpet	0.30 (U-value (W/m^2K) (> 0.13)	

Glazing and doors

Proposed improvements to glazing and doors aimed to comply with Part L2021 notional building (Ministry of Housing; Communities and Local Government, 2021) and should be smaller than or equal to 1.20 (6+12+6+12+6mm, 0.98 W/m^2K) and 1.00W/m^2K, respectively.

2.3 Retrofit Stage 1: Building Fabric Optimisation

Typical building fabrics were initially examined across each archetype (as described in Section 1.8) to explore the achieved heating energy demands. Following this, a series of simulations were conducted to measure the energy efficiency resulting from cumulative changes in the fabric. These changes aimed to reach the notional levels of Part L 2021, considering a deep retrofit approach. Additionally, a typical retrofit approach was adopted that excluded the more costly and disruptive strategies (as explained in Table 20). The purpose of this investigation was to determine the extent to which energy demand can be reduced by optimising the building fabric. This stage of assessment only involved improved fabric energy efficiency and airtightness levels. There were no active system improvements such as the use of ASHP.

The results, analysed per archetype, are shown in Figure 10-Figure 15.

Detached house

Deep Retrofit
▪ In the initial as-built scenario, the estimated heating demand was 107 kWh/m². Following the implementation of a series of retrofit measures based on Part L notional levels, the heating demand was reduced to 20 kWh/m², marking an overall reduction of 81%. It is noted that loft insulation only resulted in a 5% decrease in heating demand compared to the base case, while solid floor insulation reduced the demand by 7% in scenario 3, compared to scenario 2. ▪ The addition of external wall insulation in scenario 4 had the most significant impact, reducing heating demand by 47% compared to the previous scenario. This is due to its larger exposed envelope area compared to the other fabric elements. ▪ Opting for energy-efficient glazing and doors also proved beneficial, leading to an additional 7% improvement in comparison to the previous scenario, due to a significant improvement in the U-values. However, it is important to note that implementing this measure is both costly and disruptive. ▪ The addition of airtightness and draught-proofing in scenario 6 reduced the heating demand by 10%. Further improvement in airtightness (scenario 7) from 8 to 5 m³/m²h @50 Pa resulted in an additional 5% reduction.
Typical retrofit
▪ The initial heating demand was estimated to be 107 kWh/m². After implementing a series of typical retrofit measures, the heating demand was reduced to 42 kWh/m², representing a significant reduction of 61%. ▪ According to the results presented in Figure 10, loft insulation only reduced the heating demand by 5% in scenario 2 compared to the base case (scenario 1). While this had a relatively small impact on reducing heating demand, it is also one of the easiest strategies to implement. ▪ Furthermore, external wall insulation was found to be the most impactful measure, reducing the heating demand by 45% in scenario 3, compared to scenario 2. This is due to its larger exposed envelope area compared to the other fabric elements. ▪ The addition of airtightness and draught-proofing in scenario 4 decreased the heating demand by 8%. Further improvement in airtightness (scenario 5) from 8 to 5 m³/m²h @50 Pa resulted in an additional 3%.

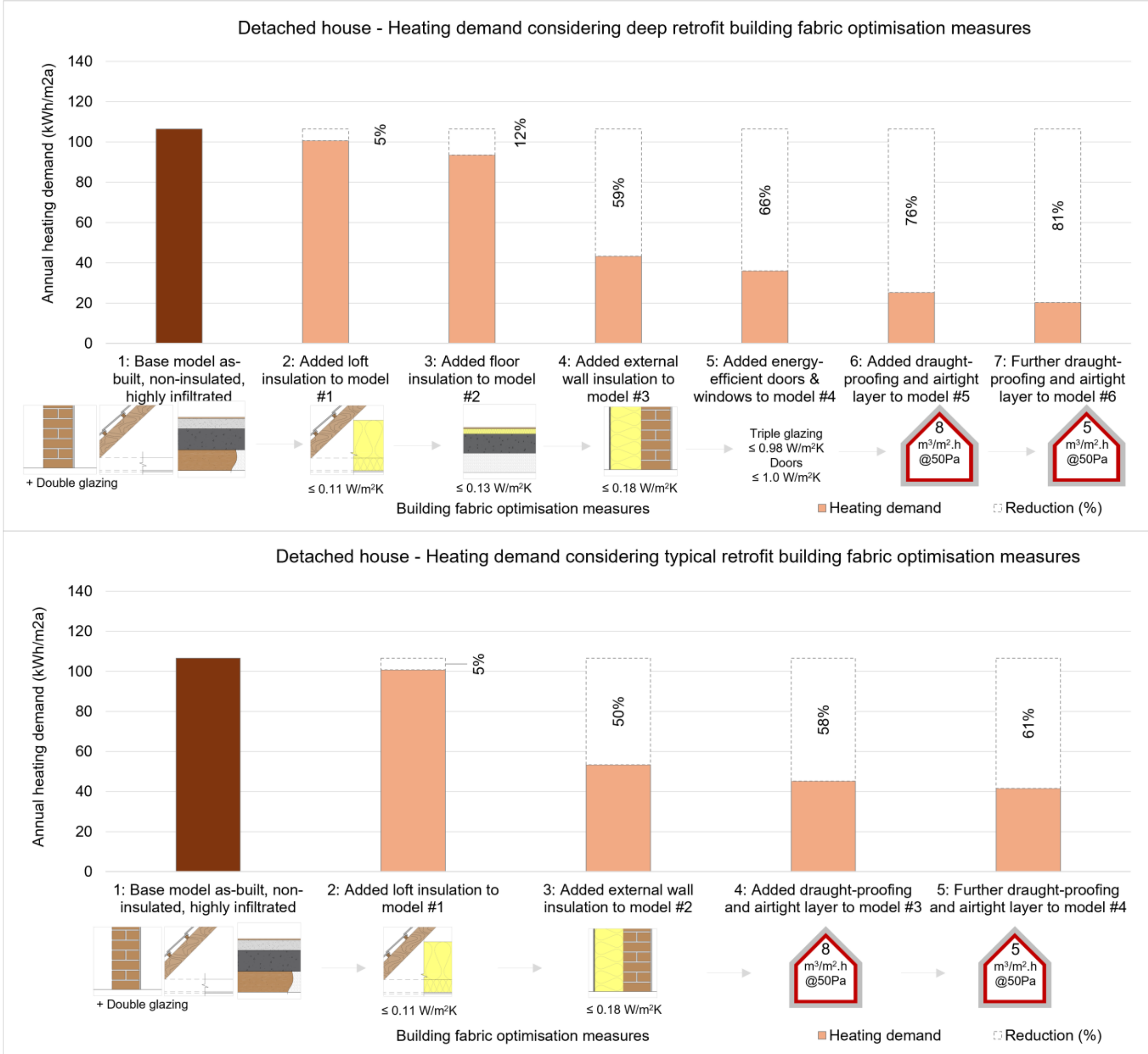


Figure 10: Deep & typical retrofit fabric measures – Detached house

Semi-detached house

Deep Retrofit
▪ In the initial as-built scenario, the estimated heating demand was 87 kWh/m^2. Following the implementation of all the fabric retrofit measures based on Part L notional levels, the heating demand was reduced to 15 kWh/m^2, marking a substantial overall reduction of 83%. It is noteworthy that loft insulation resulted in a 9% decrease in heating demand compared to the base case, while solid floor insulation reduced the demand by 10% in scenario 3 when compared to scenario 2. ▪ The addition of external wall insulation in scenario 4 had the most significant impact, reducing heating demand by 40% compared to the previous strategy. This is due to its larger exposed envelope area compared to the other fabric elements. ▪ Opting for energy-efficient glazing and doors also proved beneficial, leading to an additional 9% improvement in comparison to the previous strategy due to a significant improvement in the U-values. However, it is important to note that implementing this measure is both costly and disruptive. ▪ The addition of airtightness and draught-proofing in scenario 6 reduced the heating demand by 11%. Further improvement in airtightness (scenario 7) from 8 to 5 m^3/m^2h @50 Pa resulted in an additional 4% reduction.
Typical retrofit
▪ The initial heating demand was estimated to be 87 kWh/m^2. After implementing a series of typical retrofit measures, the heating demand was reduced to 37 kWh/m^2, representing a significant reduction of 58%. ▪ According to the results presented in Figure 11, loft insulation only reduced the heating demand by 9% in scenario 2, compared to the base case (scenario 1). While this had a relatively small impact on reducing heating demand, it is also one of the easiest strategies to implement. ▪ Furthermore, external wall insulation was found to be the most impactful measure, reducing the heating demand by 38% in scenario 3 compared to scenario 2. This is due to its larger exposed envelope area compared to the other fabric elements. ▪ The addition of airtightness and draught-proofing in scenario 4 decreased the heating demand by 8%. Further improvement in airtightness (scenario 5) from 8 to 5 m^3/m^2h @50 Pa resulted in an extra 3% reduction.

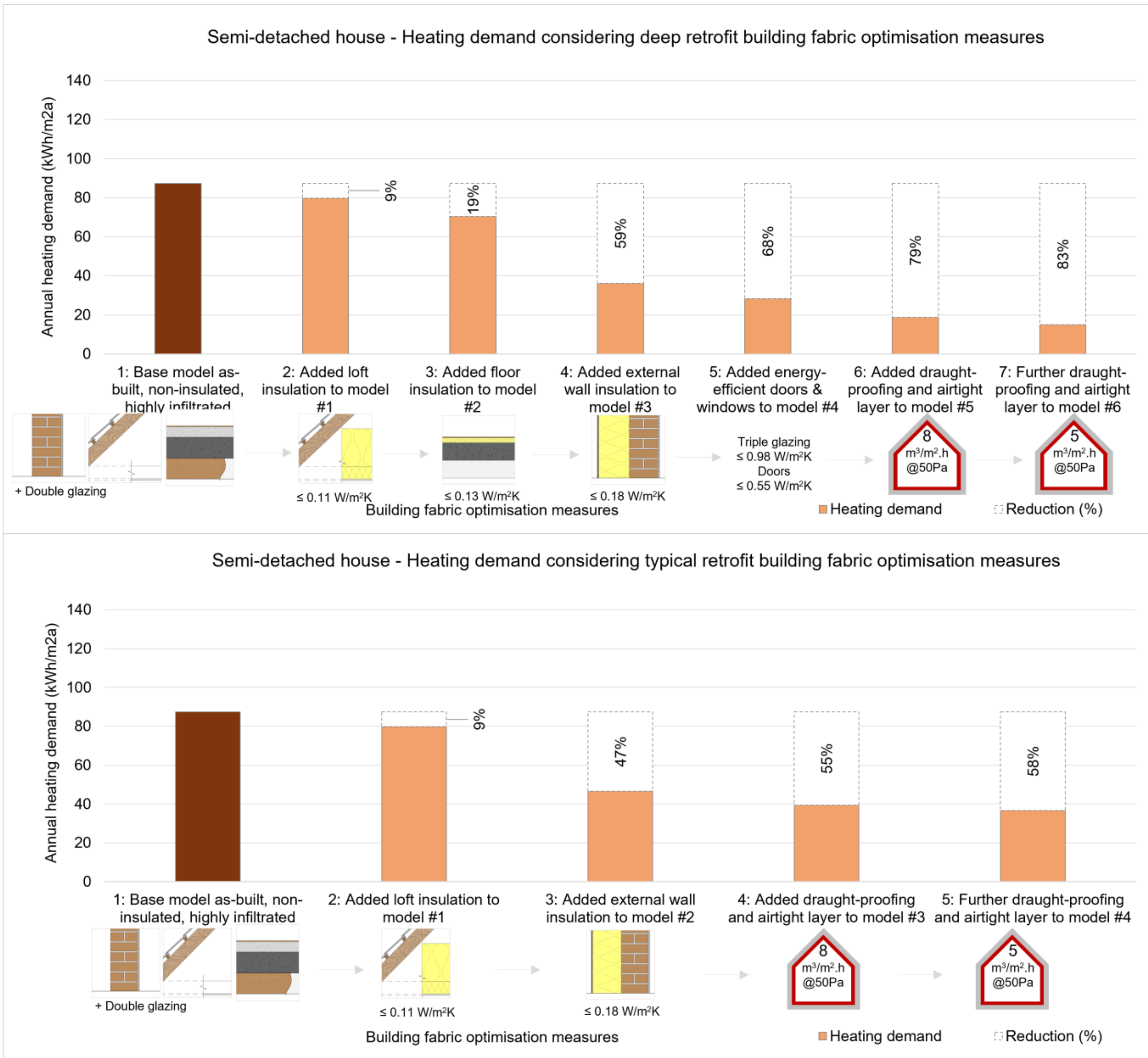


Figure 11: Deep & typical retrofit fabric measures – Semi-detached house

Mid-terrace house

Deep Retrofit
▪ In the initial as-built scenario, the estimated heating demand was 125 kWh/m². Following the implementation of all deep retrofit measures based on Part L notional levels, the heating demand was reduced to 17 kWh/m², marking a reduction of 86%. It is noteworthy that loft insulation resulted in an 8% decrease in heating demand compared to the base case, while solid floor insulation reduced the demand by 14% in scenario 3 compared to scenario 2. ▪ The addition of external wall insulation in scenario 4 had the most significant impact, reducing heating demand by 42% compared to the previous strategy. This is due to its larger exposed envelope area compared to the other fabric elements. ▪ Opting for energy-efficient glazing and doors also proved beneficial, leading to an additional 9% improvement in comparison to the previous strategy due to a significant improvement in the U-values. However, it is important to note that implementing this measure can be costly and disruptive. ▪ The addition of airtightness and draught-proofing in scenario 6 reduced the heating demand by 9%. Further improvement in airtightness (scenario 7) from 8 to 5 m³/m²h @50 Pa resulted in an additional 4% reduction.
Typical retrofit
▪ The initial heating demand was estimated to be 125 kWh/m². After implementing a series of typical retrofit measures, the heating demand was reduced to 37 kWh/m², representing a significant 70% reduction. ▪ According to the results presented in Figure 12, loft insulation only reduced the heating demand by 8% in scenario 2 compared to the base case (scenario 1). While this had a relatively small impact on reducing heating demand, it is also one of the easiest strategies to implement. ▪ Furthermore, external wall insulation was found to be the most impactful measure, reducing the heating demand by 51% in scenario 3 compared to scenario 2. This is due to its larger exposed envelope area compared to the other fabric elements. ▪ The addition of airtightness and draught-proofing in scenario 4 decreased the heating demand by 8%. Further improvement in airtightness (scenario 5) from 8 to 5 m³/m²h @50 Pa resulted in an extra 3% reduction.

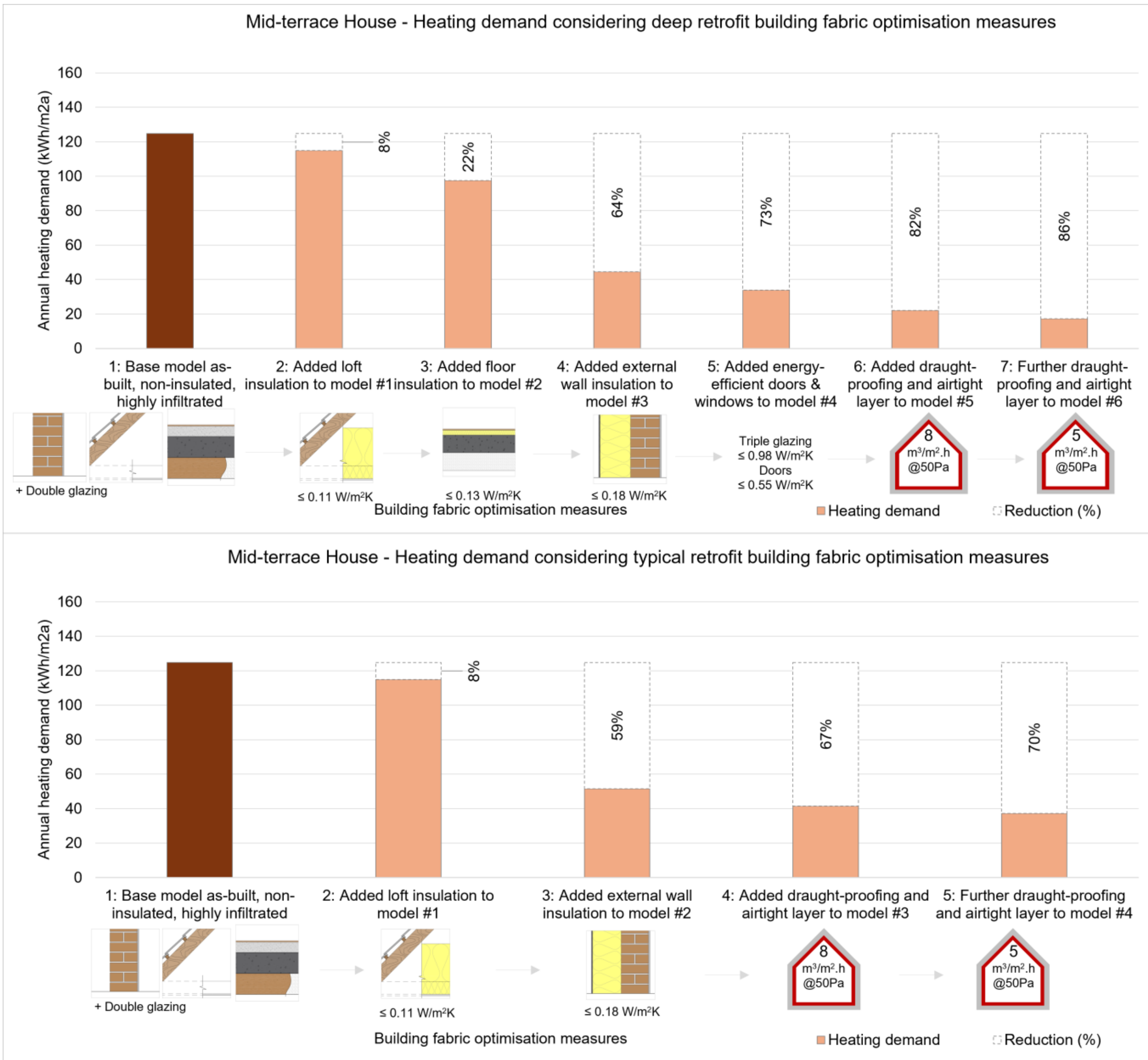


Figure 12: Deep & typical retrofit fabric measures – Mid-terrace house

End-terrace house

Deep Retrofit
- In the initial as-built scenario, the estimated heating demand was 143 kWh/m². Following the implementation of the deep retrofit measures based on Part L notional levels, the heating demand was reduced to 20 kWh/m², marking an overall substantial 86% reduction. It is noteworthy that loft insulation resulted in a 5% decrease in heating demand, compared to the base case, while solid floor insulation reduced the demand by 11% in scenario 3, compared to scenario 2.   - The addition of external wall insulation in scenario 4 had the most significant impact, reducing heating demand by 51% compared to the previous strategy. This is due to its larger exposed envelope area compared to the other fabric elements.   - Opting for energy-efficient glazing and doors also proved beneficial, leading to an additional 7% improvement in comparison to the previous strategy due to a significant improvement in the U-values. However, it is important to note that implementing this measure can be costly and disruptive.   - The addition of airtightness and draught-proofing in scenario 6 reduced the heating demand by 9%. Further improvement in airtightness (scenario 7) from 8 to 5 m³/m²h @50 Pa resulted in an additional 3% reduction.
Typical retrofit
- The initial heating demand was estimated to be 143 kWh/m². After implementing a series of typical retrofit measures, the heating demand was reduced to 44 kWh/m², representing a significant 70% reduction.   - According to the results presented in Figure 13, loft insulation only reduced the heating demand by 5% in scenario 2, compared to the base case (scenario 1). While this had a relatively small impact on reducing heating demand, it is also one of the easiest strategies to implement.   - Furthermore, external wall insulation was found to be the most impactful measure, reducing the heating demand by 54% in scenario 3 when compared to scenario 2. This is due to its larger exposed envelope area compared to the other fabric elements.   - The addition of airtightness and draught-proofing in scenario 4 decreased the heating demand by 7%. Further improvement in airtightness (scenario 5) from 8 to 5 m³/m²h @50 Pa resulted in an additional 4% reduction.

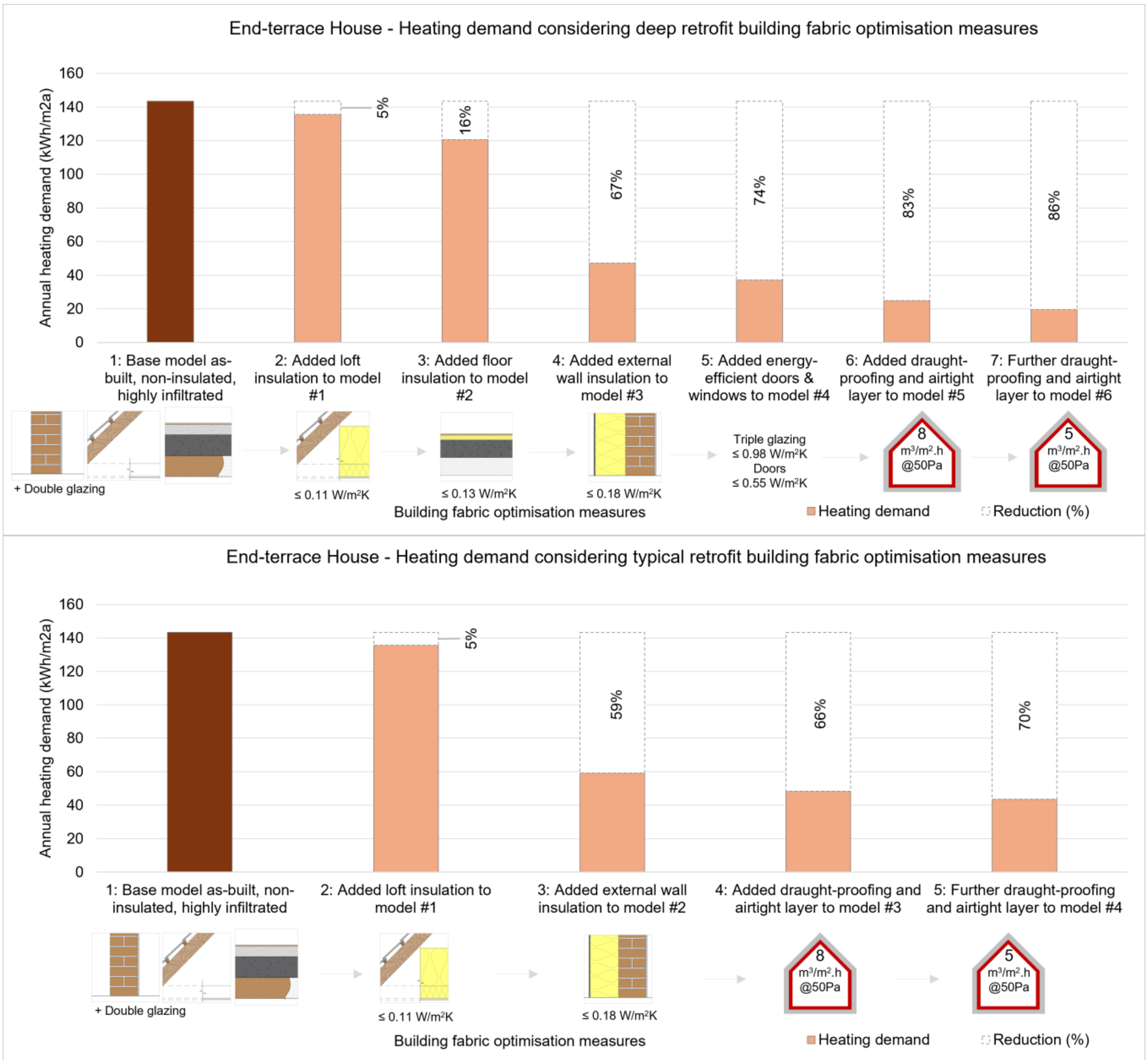


Figure 13: Deep & typical retrofit fabric measures – End terrace house

Flat- Mid-terrace

Deep Retrofit
▪ In the initial as-built scenario, the estimated heating demand was 148 kWh/m². Following the implementation of a series of retrofit measures based on Part L notional levels, the heating demand was reduced to 29 kWh/m², marking an overall substantial 80% reduction. The simulation involved a Mid-terrace first-floor flat, and the use of loft insulation contributed significantly, resulting in a 16% decrease in heating demand compared to the base case. ▪ The addition of external wall insulation in scenario 4 had the most significant impact, reducing heating demand by 36% compared to the previous strategy. This is due to its larger exposed envelope area compared to the other fabric elements. ▪ Opting for energy-efficient glazing and doors also proved beneficial, leading to an additional 5% improvement in comparison to the previous strategy due to a significant improvement in the U-values. However, it is important to note that implementing this measure is both costly and disruptive. ▪ The addition of airtightness and draught-proofing in scenario 6 reduced the heating demand by 16%. Further improvement in airtightness (scenario 7) from 8 to 5 m³/m²h @50 Pa resulted in an additional 7% reduction. This means that with all the deep retrofit measures in place, there was an overall 80% reduction in heating demand.
Typical retrofit
▪ The initial heating demand was estimated to be 148 kWh/m². After implementing a series of retrofit measures, the heating demand was reduced to 57 kWh/m², representing a significant 61% reduction. ▪ According to the results presented in Figure 14, loft insulation reduced the heating demand by 16% in scenario 2 compared to the base case (scenario 1). While this had a relatively small impact on reducing heating demand, it is also one of the easiest strategies to implement. ▪ Furthermore, external wall insulation was found to be the most impactful measure, reducing the heating demand by 24% in scenario 3 compared to scenario 2. This is due to its larger exposed envelope area compared to the other fabric elements. ▪ The addition of airtightness and draught-proofing in scenario 4 decreased the heating demand by 15%. Further improvement in airtightness (scenario 5) from 8 to 5 m³/m²h @50 Pa resulted in an overall 61% reduction in heating demand, bringing it down to 57 kWh/m².

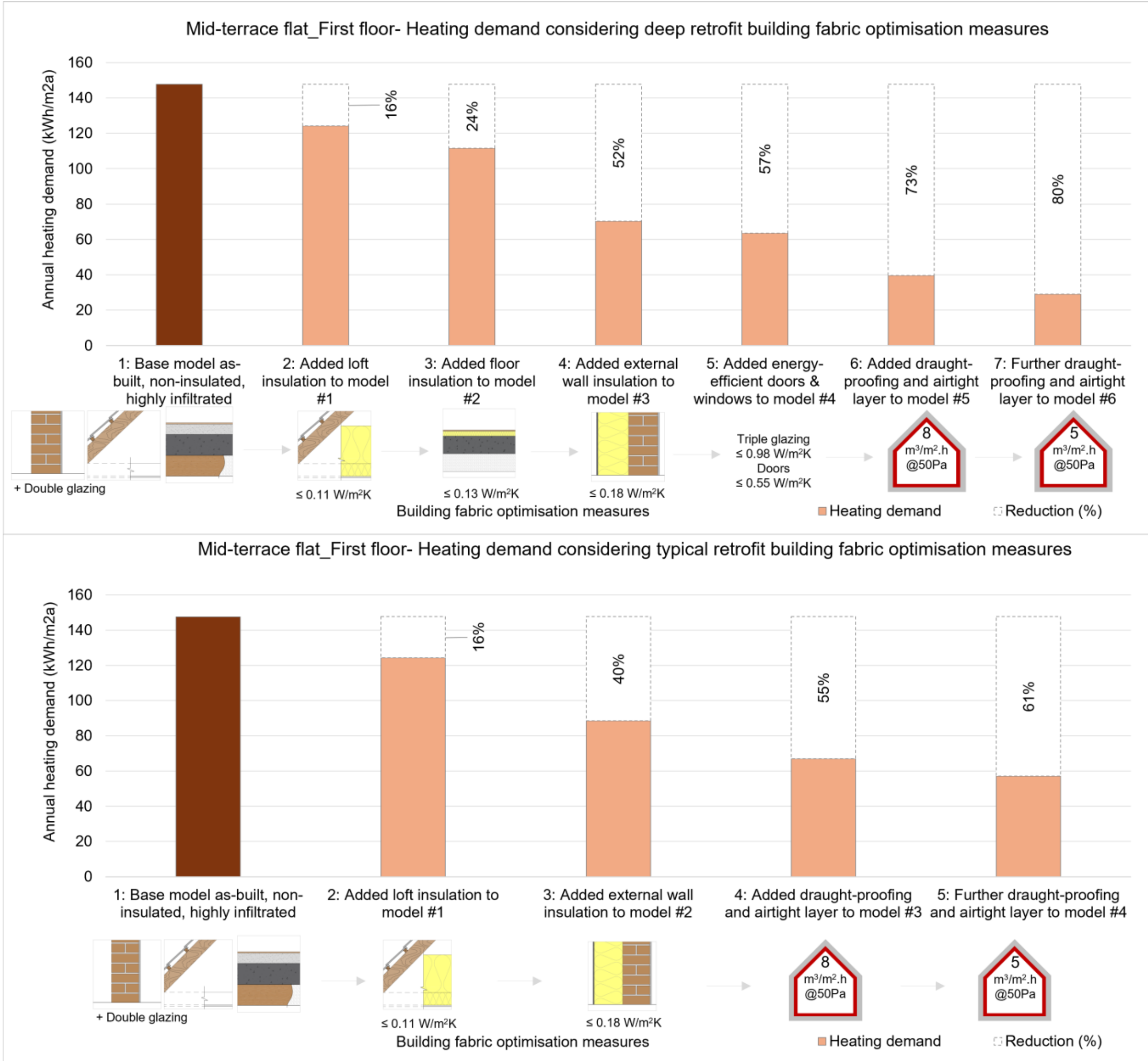


Figure 14: Deep & typical retrofit fabric measures – Flat- Mid-terrace

Flat- End-terrace

Deep Retrofit
▪ In the initial as-built scenario, the estimated heating demand was 149 kWh/m². Following the implementation of a series of deep retrofit measures based on Part L notional levels, the heating demand was reduced to 29 kWh/m², representing a substantial 81% reduction overall. The simulation involved an end-terrace ground floor flat, and the use of solid floor insulation contributed significantly to a 25% reduction in demand in scenario 3. ▪ The addition of external wall insulation in scenario 4 had the most significant impact, reducing heating demand by 33% compared to the previous strategy. This is due to its larger exposed envelope area compared to the other fabric elements. ▪ Replacing windows/doors by energy-efficient glazing and doors also proved beneficial, leading to an additional 5% improvement compared to the previous strategy due to a significant improvement in the U-values. However, it is important to note that implementing this measure is both costly and disruptive. ▪ The addition of airtightness and draught-proofing in scenario 6 reduced the heating demand by 12%. Further improvement in airtightness (scenario 7) from 8 to 5 m³/m²h @50 Pa resulted in an additional 6% reduction.
Typical retrofit
▪ The initial heating demand was estimated to be 149 kWh/m². After implementing a series of typical retrofit measures, the heating demand was reduced to 72 kWh/m², representing a significant 52% reduction. ▪ The external wall insulation was found to be the most impactful measure, reducing the heating demand by 37% in scenario 3. This is due to its larger exposed envelope area compared to the other fabric elements. ▪ The addition of airtightness and draught-proofing in scenario 4 decreased the heating demand by 10%. Further improvement in airtightness (scenario 5) from 8 to 5 m³/m²h @50 Pa resulted in a further 5% reduction.

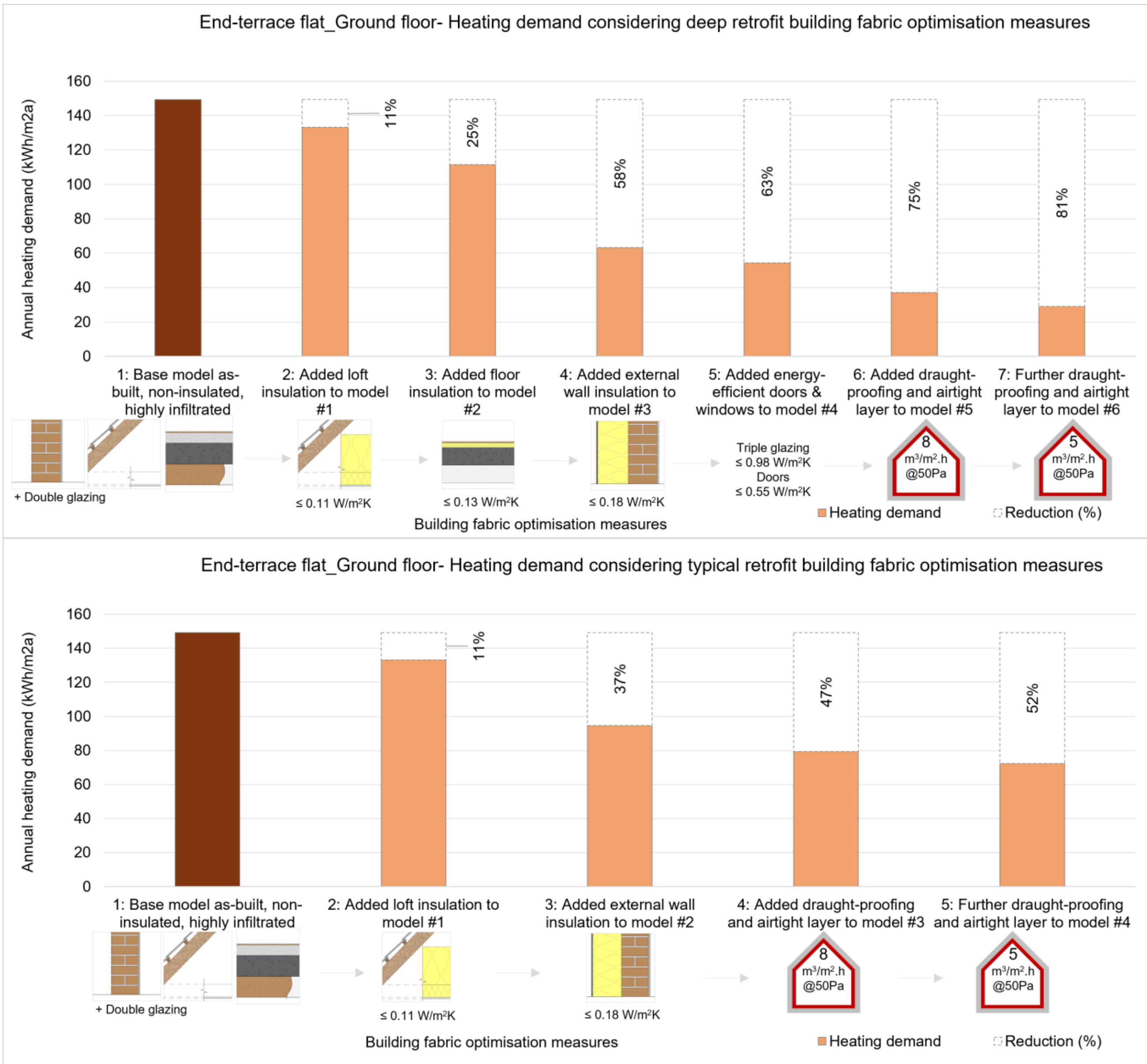


Figure 15: Deep & typical retrofit fabric measures – Flat- End-terrace

2.4 Retrofit Stage 2 & Stage 3: Low-Carbon Heating & Renewable Energy Generation

This section examines the simulated archetypes further to determine the energy and carbon impact achieved by the adoption of a low-carbon heating system compared to a typical gas heating baseline. This was achieved by adding an ASHP and solar photovoltaic (PV) panels to the model. One of the main aims was to better understand the stage of building fabric optimisation that is most beneficial to install an ASHP, i.e., conditions where ASHP performance is not diminished by low-quality fabric. Retrofit stages 2 and 3 were assessed on the deep retrofit and typical retrofit scenarios across all the archetypes.

For space heating and domestic hot water (DHW), typical gas boiler and ASHP heating systems were adopted for comparative purposes. Heating inputs were considered, as mentioned in Table 23, and DHW mean consumption was assumed as 112.2 litres/day for a two-person occupancy and 133 litres/day for a three-person occupancy (Hot water assumptions in the Home Energy Model: FHS assessment wrapper, 2023).

For the gas boiler, the seasonal efficiency was 0.89; the seasonal coefficient of performance (SCOP), which identifies how much kW of heat a system can generate for every kW of electricity, was 0.8; there was no ventilation heat recovery effectiveness. The ASHP in combination with radiators was considered as the central heating system. A realistic approach to the ASHP performance was implemented by varying the SCOP from 1.8 to 2.8 for space heating across different retrofit scenarios, with a SCOP of 1.8 assumed for a leaky building, and gradually increasing across the retrofit scenarios. Similarly, a varying ASHP SCOP from 1.5 to 2 was assumed for domestic hot water (Heat Pumps and UK's Decarbonisation, 2021 & Interim Heat Pump Performance Data Analysis Report, 2023). This means that for a well-insulated house with a well-installed ASHP, a typical SCOP for space heating would be 2.8 and the SCOP for water heating would be 2. This is because water heating requires a higher temperature to be achieved, upwards of a 45°C gain, and the ASHP is less efficient when delivering these higher temperatures (works at a maximum 50-55°C). Space heating can be operated with lower temperature gains, typically 30-35°C (ideal for underfloor heating).

A solar PV system was adopted for renewable energy generation. For simulation purposes, the number of solar panels (5 units) was considered the same across all the archetypes. The panel type was monocrystalline silicon, and the other specifications include a panel size of 2m², module nominal efficiency of 0.20, nominal cell temperature (NOCT) of 42°C, and temperature coefficient for module efficiency Pmax as -0.36%/°C (Jinko Solar, 2020). All the panels were inclined at 34° and oriented southwards.

The total energy demand was calculated by considering the energy needed to run the house over a year, based on space heating, electricity (lighting and appliances), and hot water inputs.

The total carbon emissions from heating were calculated using the Future Home Standard Fuel factors within the Home Energy Model (HEMFHS). The HEMFHS emissions factor for electricity used the Green Book Supplementary Guidance grid average consumption-based electricity emissions factors. These figures were generated by the DESNZ Dynamic Dispatch Model (DDM), which considers electricity supply and demand up to 2050. It was assumed that natural gas and electricity have carbon emission factors equivalent to 0.21 $kgCO_2e/kWh$ and 0.086 $kgCO_2e/kWh$ respectively (Fuel factors within the Home Energy Model: FHS assessment, 2023).

The comparative annual running costs of gas and low-carbon heating systems were calculated, considering the cumulative building fabric optimised changes targeting the Part L 2021 notional levels. For the cost analyses, the daily standing charge was considered for both gas and electricity.

This was based on the fact that the majority of the houses in the UK typically use both electricity (i.e., lighting and equipment) and gas (i.e., heating and cooking if not electrical) as energy sources. However, considering that the adoption of the ASHP will cease gas consumption in these households, a scenario was adopted accounting for the electricity daily standing charge only (considering that cooking will not be sourced by gas anymore).

The assumptions concerning the energy tariffs and carbon emissions factors are mentioned in Table 27. The energy tariffs are average and use direct debit payment as a reference (Ofgem, 2024). This was adopted as the current national energy prices have increased and follow an uptrend.

Table 27: Emissions and tariffs of the heating sources

Gas	Gas price cap (October 2024 to December 2024) (Ofgem, 2024)	0.06 GBP per kWh
	Gas daily standing charge (Ofgem, 2024)	0.31 GBP
	Natural gas carbon emission factor (HEM, 2023)	0.210 $kgCO_2e/kWh$
Electricity	Electricity price cap (October 2024–December 2024) (Ofgem, 2024)	0.24 GBP per kWh
	Electricity daily standing charge (Ofgem, 2024)	0.60 GBP
	Electricity grid carbon emission factor (HEM, 2023)	0.086 $kgCO_2e/kWh$

From 2025 the government plans to ban gas boilers for new homes as a measure to meet carbon neutral targets by 2050. This will make electric systems the only viable alternative to deliver heating and DHW demands in the residential sector. The Future Homes Standard (Ministry of Housing; Communities and Local Government, 2021) specification has been developed with this in mind, as heat pumps, the preferred option for single dwellings, require an environment where temperatures can be kept consistent, rather than requiring a rapid response. The ideal scenario is therefore an insulated and airtight indoor environment that can reduce overall and peak demand.

This rapid transition will in all likelihood take place in the new-build market. For the retrofit market, however, the approach taken here is to list the pros and cons of low-carbon heating systems to show why this is far less likely to be rolled out as a mainstream solution.

Pros:

- ASHPs will deliver a potentially carbon-neutral source of heating and DHW, dependent on the UK energy mix and the rate at which that decarbonises.
- ASHPs will reduce energy demand significantly due its COP of approximately 3, but energy bills are not necessarily reduced if not combined with PVs and a robust building fabric.
- The replacement of boilers by ASHP will generate many thousands of jobs for the region.

Cons:

- Each property will first have to be refurbished to Future Homes Standard or Part L 2021 notional levels in terms of thermal efficiency and airtightness, otherwise the risk of higher energy bills is likely to occur as electricity costs more than gas.
- The local electricity grid will, according to Western Power, require substantial and immediate investment to supply the electricity demand, which cannot be currently met.
- All gas boilers and radiators, irrespective of their age and efficiency would have to be removed, the embodied carbon footprint of which would need to be calculated and added to that of the manufacture of all replacement systems.
- The embodied energy of the gas central heating system being removed (7000$kgCO_2e$ plus radiators) plus that of an ASHP installation (1563 $kgCO_2e$) equates to approximately 10 years of carbon savings in a typical house complying with current regulations*.

- ASHPs costs nearly 15 thousand pounds are currently around three to four times the cost of a conventional gas boiler.
- The external space required, and the location of the water tank internally will create additional cost and disruption for many households.
- ASHPs cannot face each other on adjoining properties which would require alternative internal layouts on semi-detached units.
- The change in occupants' lifestyle necessitated by the adoption of a low-temperature heating system will by met with resistance, which could also impact overall efficiency.
- The risks associated with an unknown future climate and the likelihood of unprecedented cold weather spells have not been accounted for.
- Running a hot bath requires a quick response heat load that ASHPs cannot provide.
- The lack of a robust supply chain for manufacture and a skilled workforce for installing has yet to be addressed, currently resulting in excessive installation costs of up to 10x that of a gas boiler.
- (*total embodied carbon = 8563kgCO_2 (7000+1563) / energy saved = 3840kWh/yr (66% of 5760kWh/yr. / carbon emission due to gas energy saved = 806kgCO_2 (3840*0.21) / payback time = 10 years (8563/806).

The results, analysed by archetype, present the total annual energy demand and carbon emissions for both, deep retrofit and typical retrofit scenarios. These findings are represented in Figure 16 to Figure 27.

Detached house

Figure 16 illustrates a comparison of simulation results for energy consumption and carbon emissions between ASHP and a conventional gas heating system for deep retrofit and typical retrofit scenarios. A consistent trend is evident across both retrofit scenarios, prompting a detailed explanation of the simulation results for deep retrofit scenarios for better comprehension.

The energy consumed by gas boiler heating systems was much higher in leaky, non-insulated buildings. However, when fabric optimisation measures were considered, energy consumption was significantly reduced. In the initial, as-built scenario, the total annual energy consumption (including gas and electricity) was 18 MWh. After implementing fabric optimisation measures, the overall energy consumption dropped by 53% to 8.5 MWh. When renewable energy sources were added, the energy demand decreased further to 7 MWh. When using an ASHP, the total energy consumption was significantly lower than a gas boiler heating system. This was due to the efficiency of the system and inputs adopted. The building fabric's sequential improvement could further reduce energy consumption. The total annual energy consumption for the uninsulated envelope using an ASHP corresponded to 9MWh. Once the fabric optimisation measures were considered, the energy demand was reduced by 54%, reaching nearly 4.3MWh. Renewable energy further reduced the total annual energy consumption to 2.8 MWh.

In terms of carbon emissions, a considerable difference in the results was observed when considering a traditional gas boiler as a heating system compared to an ASHP. As expected, the carbon emissions attributable to the gas boiler system were significantly higher than the low-carbon heating system. The carbon emission values when considering a traditional gas boiler heating system corresponded to 3.4 tonnes CO_2/yr, reducing to 1.3 tonnes CO_2/yr once the fabric optimisation measures were considered. Comparatively, when adopting ASHP, the carbon emissions corresponded to 0.8 tonnes CO_2/yr and were reduced to half when the fabric optimisation measures were considered, respectively. Renewable energy further reduced the total carbon emissions to 0.2 tonnes CO_2/yr, equivalent to a 69% reduction. It is noteworthy that the external wall insulation of the fabric optimisation measures contributed significantly to reducing energy consumption and carbon emissions.

The overall energy and carbon simulation results indicated that implementing fabric optimisation measures led to more than a 50% reduction in both energy consumption and carbon emissions. Furthermore, it was also observed that simply switching to a low-carbon heating system without adopting any fabric measures led to a 76% decrease in carbon emissions, when compared to the emissions produced by gas heating systems. This shows that replacing fossil fuels-based systems with low-carbon heating, most likely ASHPs, in combination with the decarbonisation of the electricity grid, can achieve significant carbon emission reductions. However, it is crucial that fabric retrofit measures precede the installation of low-carbon alternatives to ensure consumer energy bills remain affordable and demand can be met. This reiterates the finding that the replacement of gas boilers should be considered following a certain degree of fabric improvement, therefore ensuring that occupants' quality of life is not negatively affected. ASHPs are most suited to installation in better-insulated, quality-built homes that demand lower heat output due to its operation at lower temperatures. Its adoption in leaky homes means that ASHP runs continuously and is likely to negatively impact the thermal comfort of the occupants, assuming radiators are kept at the typical sizes.

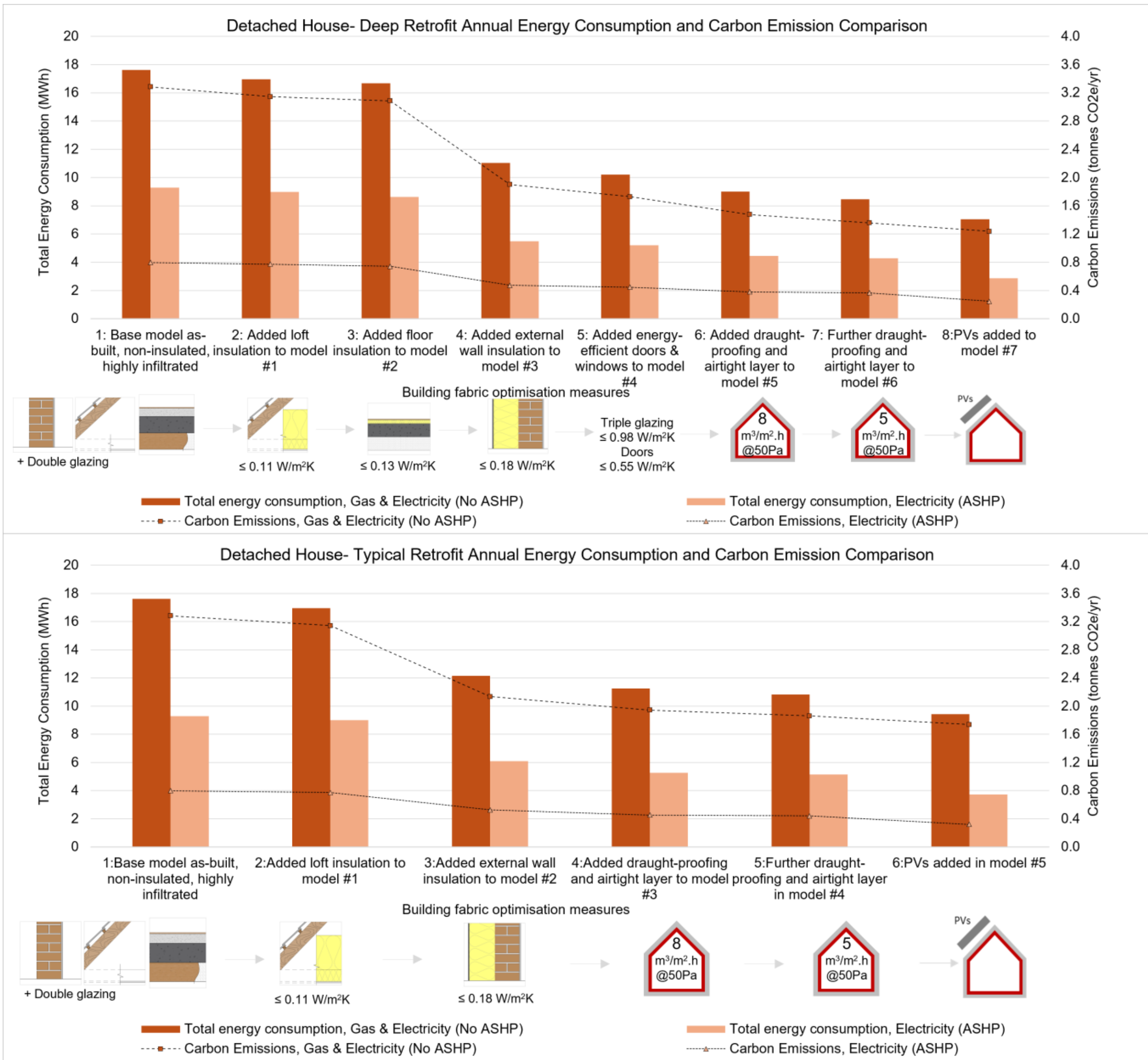


Figure 16: Deep & typical retrofits – heating systems annual energy demand & carbon emission – Detached

Annual running energy costs- Cap period October–December 2024

Figure 17 illustrates the comparative annual energy costs between ASHP and a conventional gas heating system for deep retrofit and typical retrofit scenarios. The annual running costs calculated for winter 2024 (October–December 2024 cap period) showed a gradual reduction across the sequential fabric optimisation scenarios, independent of the heating system adopted.

With all the deep retrofit measures adopted (up to Scenario 7), the annual energy cost while considering the gas heating system was reduced by 28% compared to the base case scenario. Comparatively, with a low-carbon heating system adopted , the energy cost was reduced by 49% compared to the base case, non-retrofit scenario.

Similarly, after implementing all typical retrofit measures up to Scenario 5, the annual energy cost using a gas heating system was reduced by 21% compared to the base case scenario.

Comparatively, with a low-carbon heating system adopted , the energy cost was reduced by 41% compared to the base case, non-retrofit scenario.

This highlights the suitability of heat pumps for installation in well-insulated, high-quality homes that have lower heat output demands. Additionally, the cost analyses comparing ASHP to gas heating systems for deep and typical retrofit scenarios indicated that the optimal stage to install an ASHP is after the adoption of wall insulation, i.e., Scenario 4 of deep retrofit and Scenario 3 of typical retrofit, thereby ensuring that the ASHP performance is not diminished by low-quality fabric.

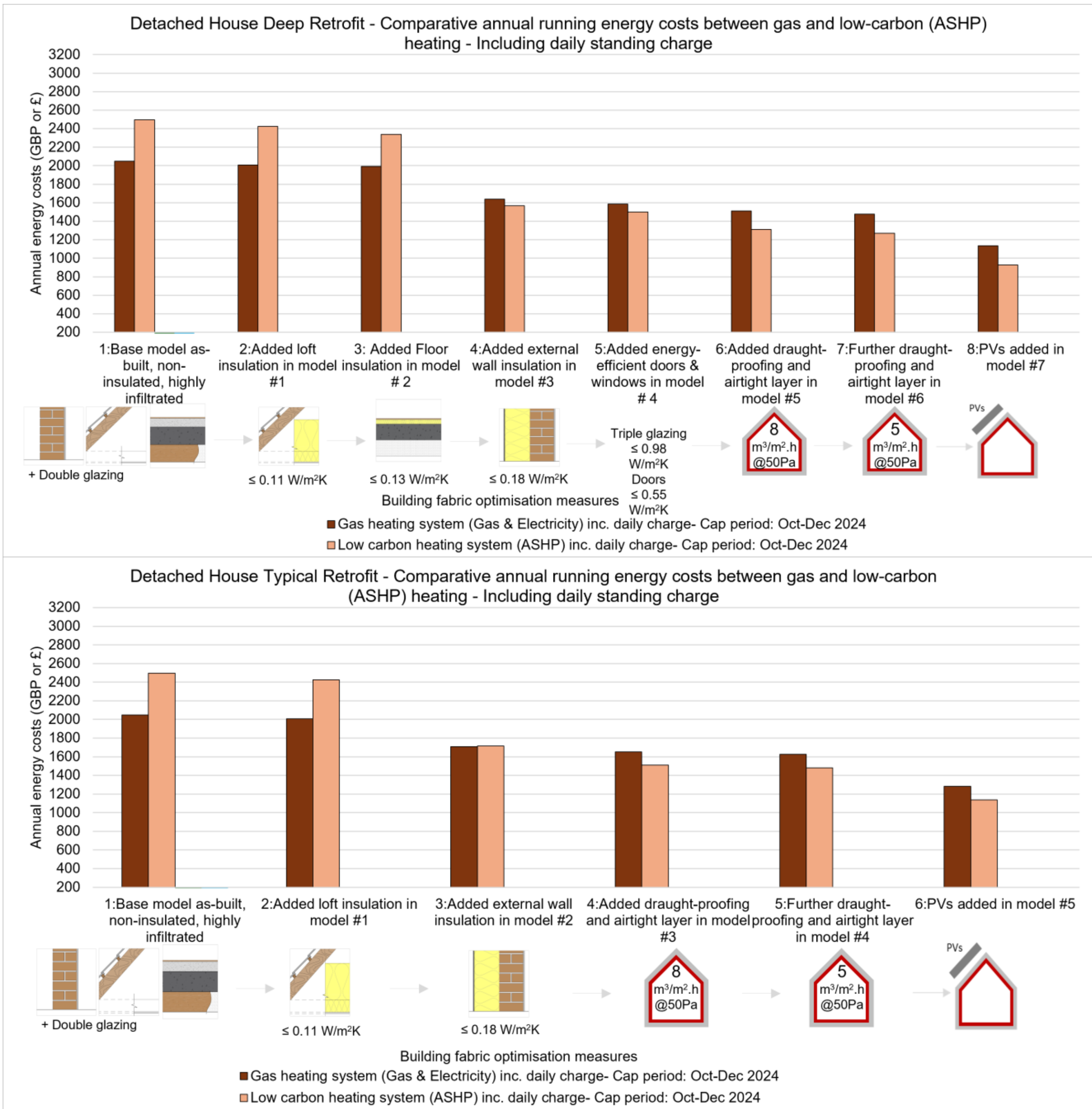


Figure 17: Deep & typical retrofits – heating systems annual costs – Detached

Semi-detached house

Figure 18 illustrates a comparison of simulation results for energy consumption and carbon emissions between an ASHP and conventional gas heating system for deep retrofit and typical retrofit scenarios. A consistent trend is evident across both retrofit scenarios, prompting a detailed explanation of the simulation results for deep retrofit scenarios for better comprehension.

The energy consumed by gas boiler heating systems was much higher in leaky, non-insulated buildings. However, when fabric optimisation measures were considered, energy consumption was significantly reduced. In the initial, as-built scenario, the total annual energy consumption (including gas and electricity) was 16 MWh. After implementing fabric optimisation measures, the overall energy consumption dropped by 48% to 8.7 MWh. When renewable energy sources were added, the energy demand decreased further to 7 MWh. When using an ASHP, the total energy consumption was significantly lower than a gas boiler heating system. This was due to the efficiency of the system and inputs adopted. The building fabric's sequential improvement could further reduce energy consumption. The total annual energy consumption for the uninsulated envelope using an ASHP corresponded to 8.3MWh. Once the fabric optimisation measures were considered, the energy demand was reduced by 51%, reaching nearly 4.1MWh. Renewable energy further reduced the total annual energy consumption to 2.7 MWh.

In terms of carbon emissions, a considerable difference in results was observed when considering a traditional gas boiler as a heating system compared to an ASHP. As expected, the carbon emissions with the gas boiler system were significantly higher than the low-carbon heating system. The carbon emission values when considering a traditional gas boiler heating system corresponded to 3 tonnes CO_2/yr, reducing to 1.3 tonnes CO_2/yr once the fabric optimisation measures were considered. Comparatively, when adopting an ASHP, the carbon emissions corresponded to 0.7 tonnes CO_2/yr and were reduced to half when the fabric optimisation measures were considered, respectively. Renewable energy further reduced the total carbon emissions to 0.2 tonnes CO_2/yr, resulting in an overall reduction of carbon emissions by 68%. It is noteworthy that the external wall insulation of the fabric optimisation measures has contributed significantly to reducing energy consumption and carbon emissions.

The overall energy and carbon simulation results indicated that implementing fabric optimisation measures led to more than a 50% reduction in both energy consumption and carbon emissions. Furthermore, it was also observed that switching to a low-carbon heating system without adopting any fabric measures led to a significant 76% decrease in carbon emissions compared to the emissions produced by gas heating systems. This shows that by replacing fossil fuels with low-carbon heating, primarily ASHPs (ASHPs), along with the decarbonisation of the electricity grid, can achieve significant carbon emission reductions. However, fabric retrofit measures are necessary alongside this switch to ensure bills remain affordable, and power supplies and infrastructure can meet demand. This highlights the fact that gas boiler replacement by low-carbon heating systems should be considered when a certain degree of improvement has been carried out on the fabric. ASHP is most suited to installation in better-insulated, quality-built homes that demand lower heat output due to its operation at lower temperatures. Its adoption in leaky homes means that ASHP runs continuously and is likely to negatively impact the thermal comfort of the occupants, assuming radiators are kept at the typical sizes.

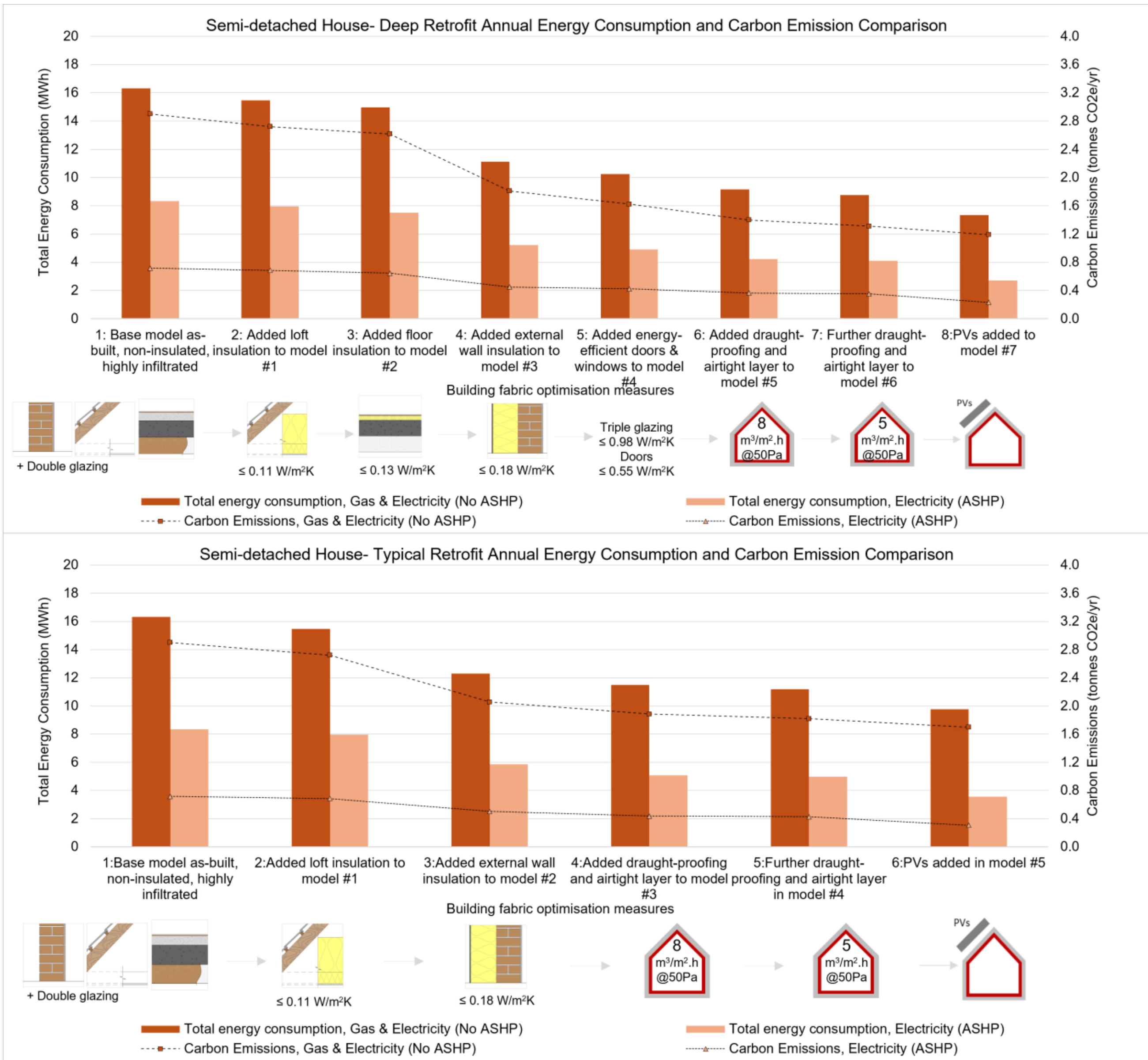


Figure 18: Deep & typical retrofits – heating systems annual energy demand & carbon emission – Semi-detached

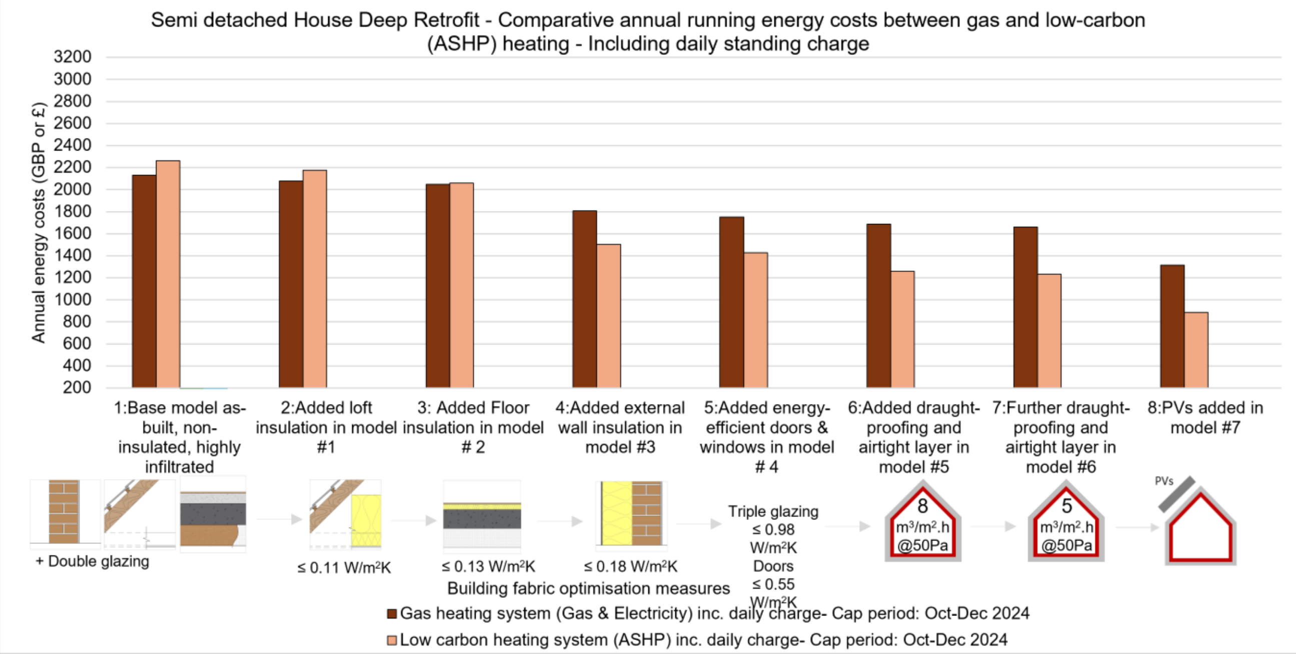
Annual running energy costs- Cap period October–December 2024

Figure 19 illustrates the comparative annual energy costs between ASHP and a conventional gas heating system for deep and typical retrofit scenarios. The annual running costs calculated for winter 2024 (October–December 2024 cap period) showed a gradual reduction across the sequential fabric optimisation scenarios, independent of the heating system adopted.

With all the deep retrofit measures adopted (up to Scenario 7), the annual energy cost while considering the gas heating system was reduced by 22% compared to the base case scenario. Comparatively, with a low-carbon heating system adopted , the energy cost was reduced by 46% compared to the base case, non-retrofit scenario.

Similarly, after implementing all typical retrofit measures up to Scenario 5, the annual energy cost using a gas heating system was reduced by 15% compared to the base case scenario. Comparatively, with a low-carbon heating system adopted , the energy cost was reduced by 36% compared to the base case, non-retrofit scenario.

This highlights the suitability of heat pumps for installation in well-insulated, high-quality homes that have lower heat output demands. Additionally, the cost analyses comparing ASHP to gas heating systems for deep and typical retrofit scenarios indicated that the optimal stage to install an ASHP is after the adoption of wall insulation, i.e., Scenario 4 of deep retrofit and Scenario 3 of typical retrofit, thereby ensuring that the ASHP performance is not diminished by low-quality fabric.



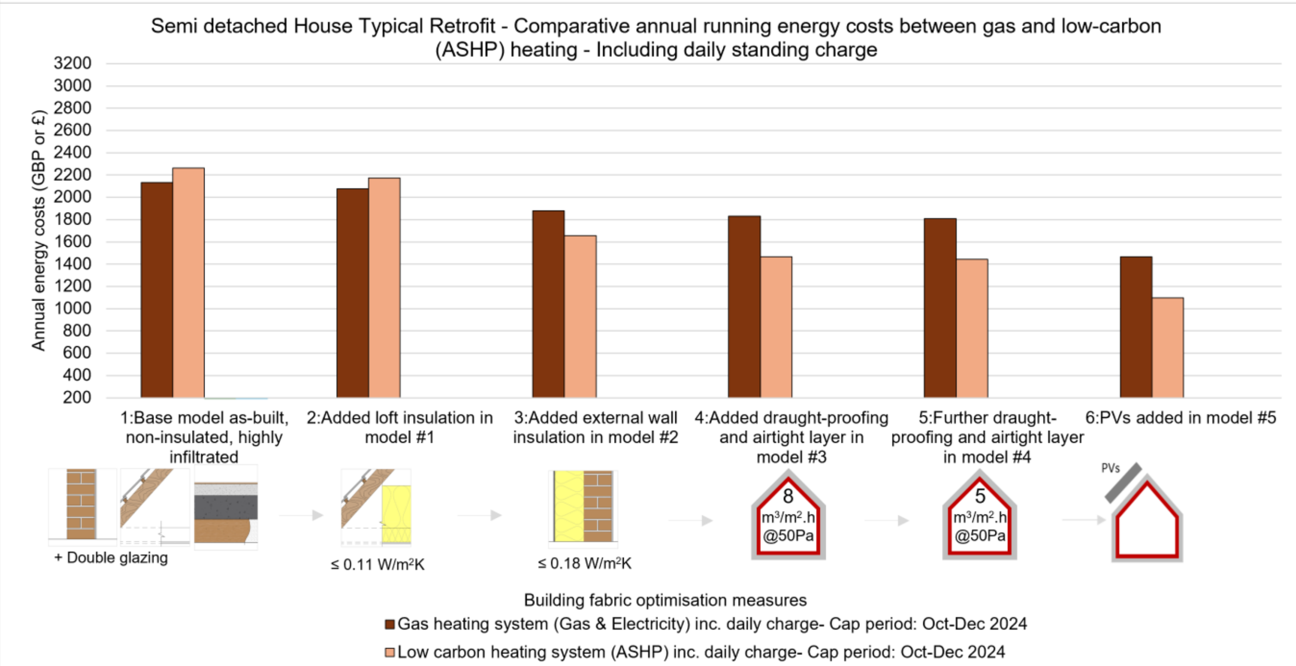


Figure 19: Deep & typical retrofits – heating systems annual costs – Semi-detached

Mid-terrace house

Figure 20 illustrates a comparison of simulation results for energy consumption and carbon emissions between ASHP and a conventional gas heating system for deep retrofit and typical retrofit scenarios. A consistent trend is evident across both retrofit scenarios, prompting a detailed explanation of the simulation results for deep retrofit scenarios for better comprehension.

The energy consumption from using a gas boiler for heating was much higher in leaky, non-insulated buildings. However, when fabric optimisation measures were considered, the consumption was significantly reduced. In the initial, as-built scenario, the total annual energy consumption (including gas and electricity) was 20 MWh. After implementing fabric optimisation measures, the overall energy consumption dropped by 58% to 8.7 MWh. When renewable energy sources were added, the energy demand further decreased to 7 MWh. When using an ASHP, the total energy consumption was significantly lower than a gas boiler heating system. This was due to the efficiency of the system and inputs adopted. The building fabric's sequential improvement could further reduce energy consumption. The total annual energy consumption for the uninsulated envelope using an ASHP corresponded to 11 MWh. Once the fabric optimisation measures were considered, the energy demand was reduced by 53%, reaching nearly 5.3MWh. Renewable energy further reduced the total annual energy consumption to 4 MWh.

In terms of carbon emissions, a considerable difference in the results was observed when considering a traditional gas boiler as a heating system compared to ASHP. As expected, the carbon emissions with the gas boiler system were significantly higher than the low-carbon heating system. The carbon emission values when considering a traditional gas boiler heating system corresponded to 4 tonnes CO_2/yr, reducing to 1.4 tonnes CO_2/yr once the fabric optimisation measures were considered. Comparatively, when adopting ASHP, the carbon emissions corresponded to 0.9 tonnes CO_2/yr and were reduced to half when the fabric optimisation measures were considered, respectively. Renewable energy further reduced the total carbon emissions to 0.3 tonnes CO_2/yr, resulting in an overall reduction of carbon emissions by 65%. It is noteworthy that the external wall insulation of the fabric optimisation measures has contributed significantly to reducing energy consumption and carbon emissions.

The overall energy and carbon simulation results indicated that implementing fabric optimisation measures led to more than a 50% reduction in both energy consumption and carbon emissions. Furthermore, it was also observed that just switching to a low-carbon heating system without adopting any fabric measures led to a significant 75% decrease in carbon emissions compared to the emissions produced by gas heating systems. This shows that by replacing fossil fuels with low-carbon heating, primarily ASHPs (ASHPs), along with the decarbonisation of the electricity grid, can achieve significant carbon emission reductions. However, fabric retrofit measures are necessary alongside this switch to ensure bills remain affordable, and power supplies and infrastructure can meet demand. This highlights the fact that gas boiler replacement by low-carbon heating systems should be considered when a certain degree of improvement has been carried out on the fabric. ASHP is most suited to installation in better-insulated, quality-built homes that demand lower heat output due to its operation at lower temperatures. Its adoption in leaky homes means that ASHP runs continuously and is likely to negatively impact the thermal comfort of the occupants, assuming radiators are kept at the typical sizes.

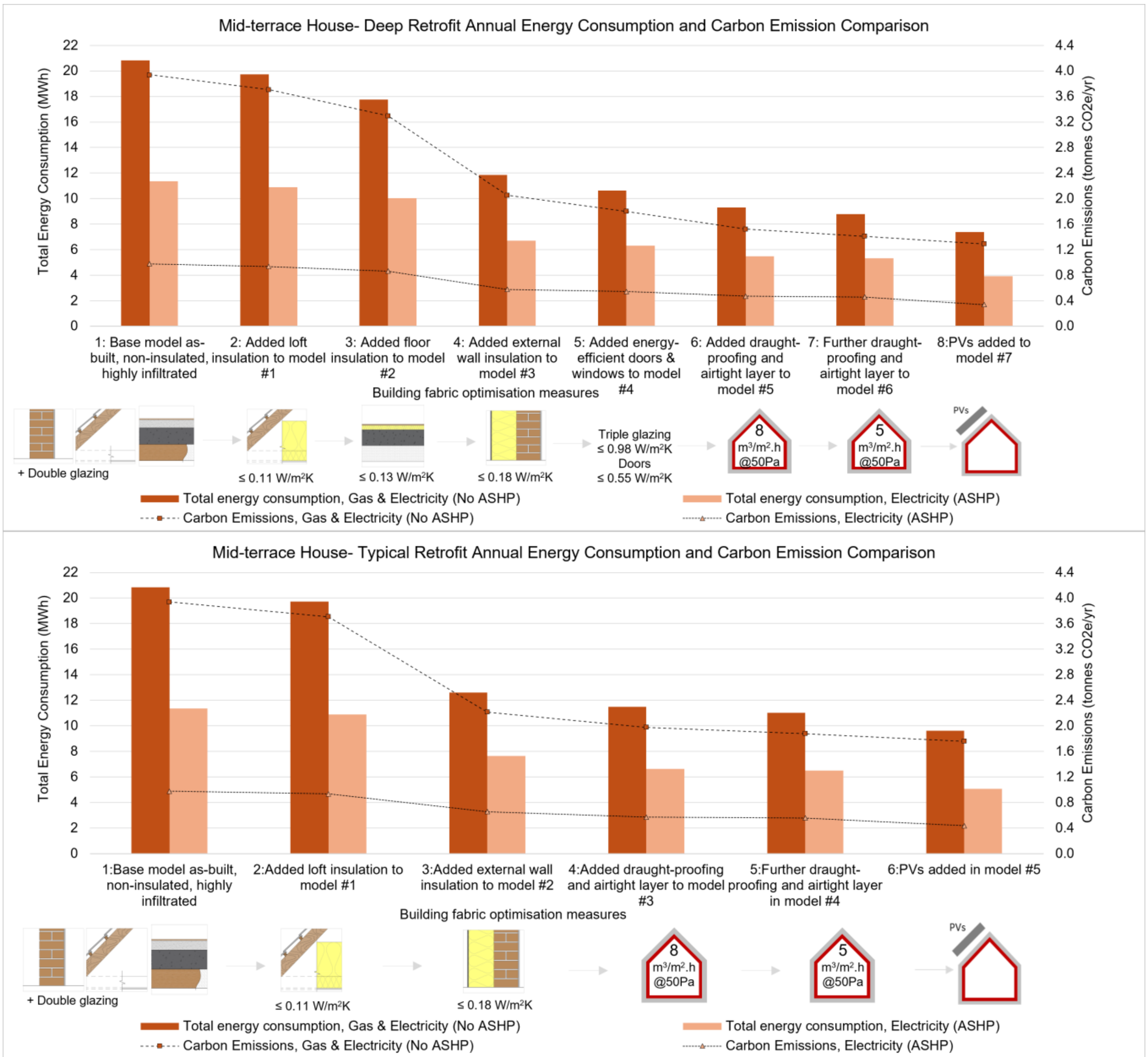


Figure 20: Deep & typical retrofits – heating systems annual energy demand & carbon emission – Mid-terrace House

Annual running energy costs- Cap period October–December 2024

Figure 21 illustrates the comparative annual energy costs between ASHP and a conventional gas heating system for deep and typical retrofit scenarios. The annual running costs calculated for winter 2024 (October–December 2024 cap period) showed a gradual reduction across the sequential fabric optimisation scenarios, independent of the heating system adopted.

With all the deep retrofit measures adopted (up to Scenario 7), the annual energy cost while considering the gas heating system was reduced by 33% compared to the base case scenario. Comparatively, with a low-carbon heating system adopted , the energy cost was reduced by 49% compared to the base case, non-retrofit scenario.

Similarly, after implementing all typical retrofit measures up to Scenario 5, the annual energy cost using a gas heating system was reduced by 27% compared to the base case scenario. Comparatively, with a low-carbon heating system adopted , the energy cost was reduced by 40% compared to the base case, non-retrofit scenario.

This highlights the suitability of heat pumps for installation in well-insulated, high-quality homes that have lower heat output demands. However, the cost analyses across all the retrofit scenarios suggested that adopting ASHP had marginally higher annual energy costs than the traditional gas heating system.

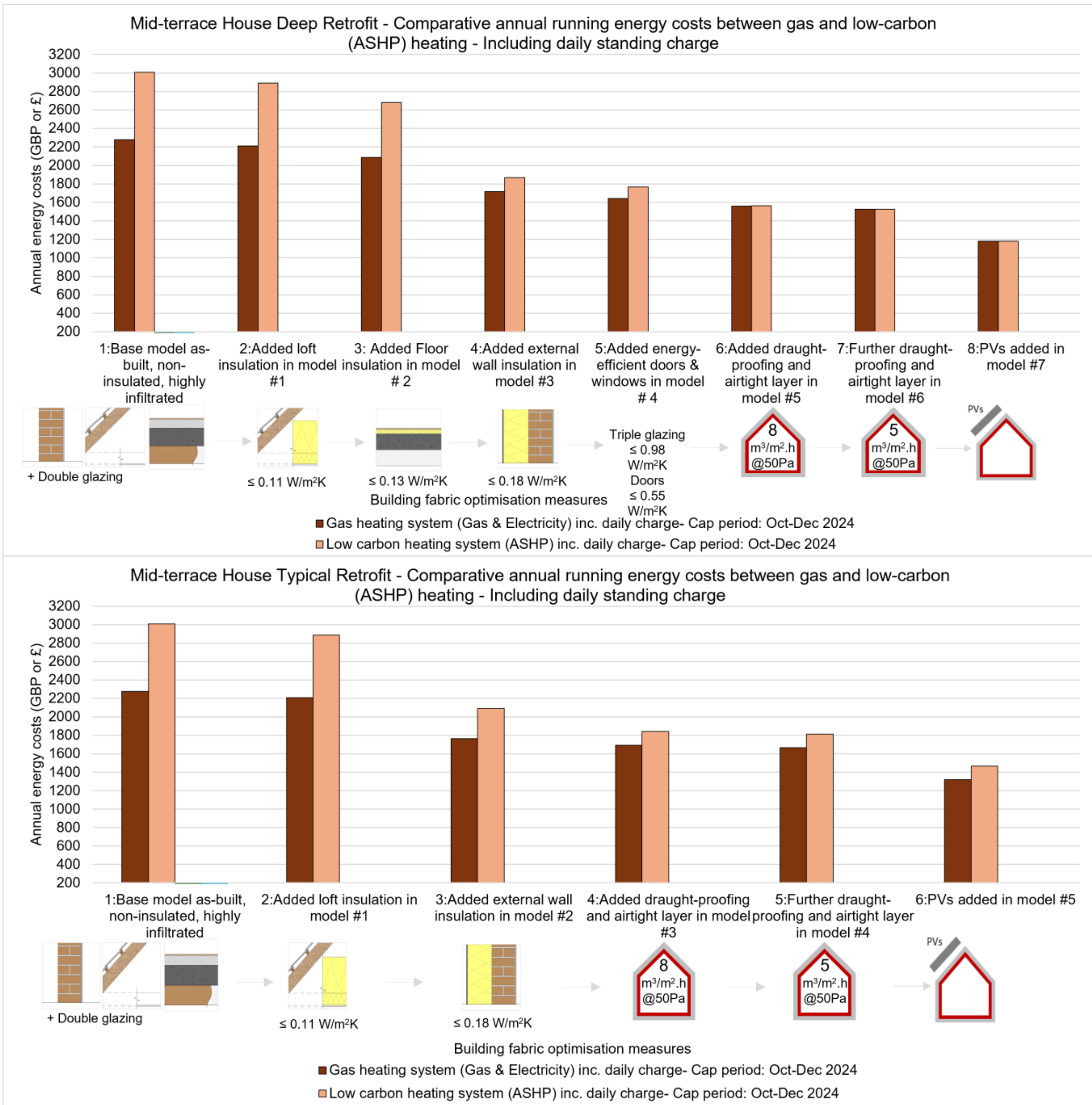


Figure 21: Deep & typical retrofits – heating systems annual costs – Mid-terrace House

End-terrace house

Figure 22 illustrates a comparison of simulation results for energy consumption and carbon emissions between ASHP and a conventional gas heating system for deep retrofit and typical retrofit scenarios. A consistent trend is evident across both retrofit scenarios, prompting a detailed explanation of the simulation results for deep retrofit scenarios for better comprehension.

The energy consumption from using a gas boiler for heating was much higher in leaky, non-insulated buildings. However, when fabric optimisation measures were considered, the consumption was significantly reduced. In the initial, as-built scenario, the total annual energy consumption (including gas and electricity) was 23 MWh. After implementing fabric optimisation measures, the overall energy consumption dropped by 61% to 9 MWh. When renewable energy sources were added, the energy demand further decreased to 7.6 MWh. When using an ASHP, the total energy consumption was significantly lower than a gas boiler heating system. This was due to the efficiency of the system and inputs adopted. The building fabric's sequential improvement could further reduce energy consumption. The total annual energy consumption for the uninsulated envelope using an ASHP corresponded to 12 MWh. Once the fabric optimisation measures were considered, the energy demand was reduced by 56%, reaching nearly 5.4MWh. Renewable energy further reduced the total annual energy consumption to 4 MWh.

In terms of carbon emissions, a considerable difference in the results was observed when considering a traditional gas boiler as a heating system compared to ASHP. As expected, the carbon emissions with the gas boiler system were significantly higher than the low-carbon heating system. The carbon emission values when considering a traditional gas boiler heating system corresponded to 4 tonnes CO_2/yr, reducing to 1.4 tonnes CO_2/yr once the fabric optimisation measures were considered. Comparatively, when adopting ASHP, the carbon emissions corresponded to 1 tonne CO_2/yr and were reduced to half when the fabric optimisation measures were considered, respectively. Renewable energy further reduced the total carbon emissions to 0.3 tonnes CO_2/yr, resulting in an overall reduction of carbon emissions by 67%. It is noteworthy that the external wall insulation of the fabric optimisation measures has contributed significantly to reducing energy consumption and carbon emissions.

The overall energy and carbon simulation results indicated that implementing fabric optimisation measures led to more than a 50% reduction in both energy consumption and carbon emissions. Furthermore, it was also observed that just switching to a low-carbon heating system without adopting any fabric measures led to a significant 76% decrease in carbon emissions compared to the emissions produced by gas heating systems. This shows that by replacing fossil fuels with low-carbon heating, primarily ASHPs (ASHPs), along with the decarbonisation of the electricity grid, can achieve significant carbon emission reductions. However, fabric retrofit measures are necessary alongside this switch to ensure bills remain affordable, and power supplies and infrastructure can meet demand. This highlights the fact that gas boiler replacement by low-carbon heating systems should be considered when a certain degree of improvement has been carried out on the fabric. ASHP is most suited to installation in better-insulated, quality-built homes that demand lower heat output due to its operation at lower temperatures. Its adoption in leaky homes means that ASHP runs continuously and is likely to negatively impact the thermal comfort of the occupants, assuming radiators are kept at the typical sizes.

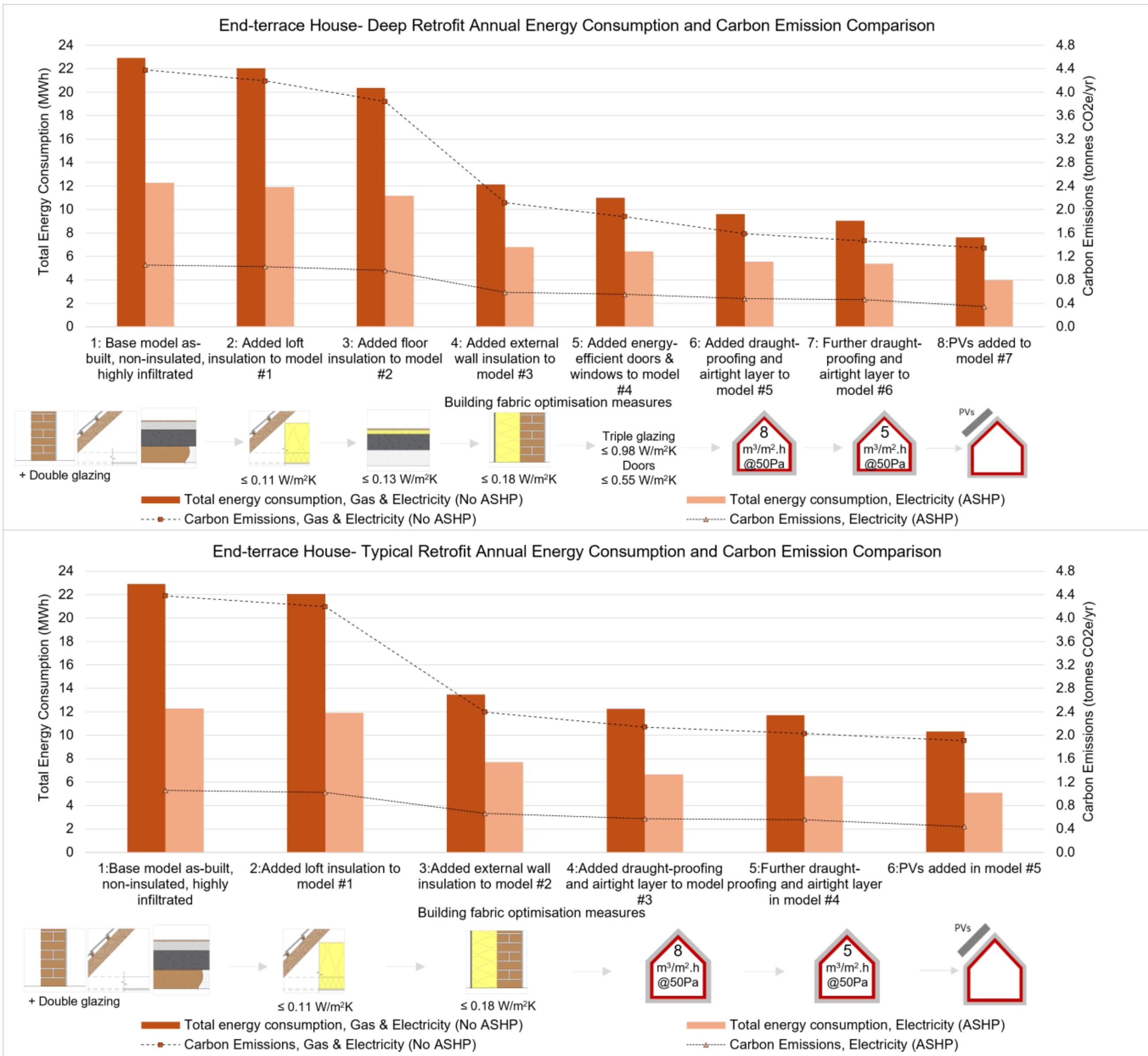


Figure 22: Deep & typical retrofits – heating systems annual energy demand & carbon emission – End-terrace House

Annual running energy costs- Cap period October–December 2024

Figure 23 illustrates the comparative annual energy costs between ASHP and a conventional gas heating system for deep and typical retrofit scenarios. The annual running costs calculated for winter 2024 (October–December 2024 cap period) showed a gradual reduction across the sequential fabric optimisation scenarios, independent of the heating system adopted.

With all the deep retrofit measures adopted (up to Scenario 7), the annual energy cost while considering the gas heating system was reduced by 36% compared to the base case scenario. Comparatively, with a low-carbon heating system adopted , the energy cost was reduced by 52% compared to the base case, non-retrofit scenario.

Similarly, after implementing all typical retrofit measures up to Scenario 5, the annual energy cost using a gas heating system was reduced by 29% compared to the base case scenario.

Comparatively, with a low-carbon heating system adopted , the energy cost was reduced by 44% compared to the base case, non-retrofit scenario.

This highlights the suitability of heat pumps for installation in well-insulated, high-quality homes that have lower heat output demands. However, the cost analyses across all the retrofit scenarios suggested that adopting ASHP had marginally higher annual energy costs than the traditional gas heating system.

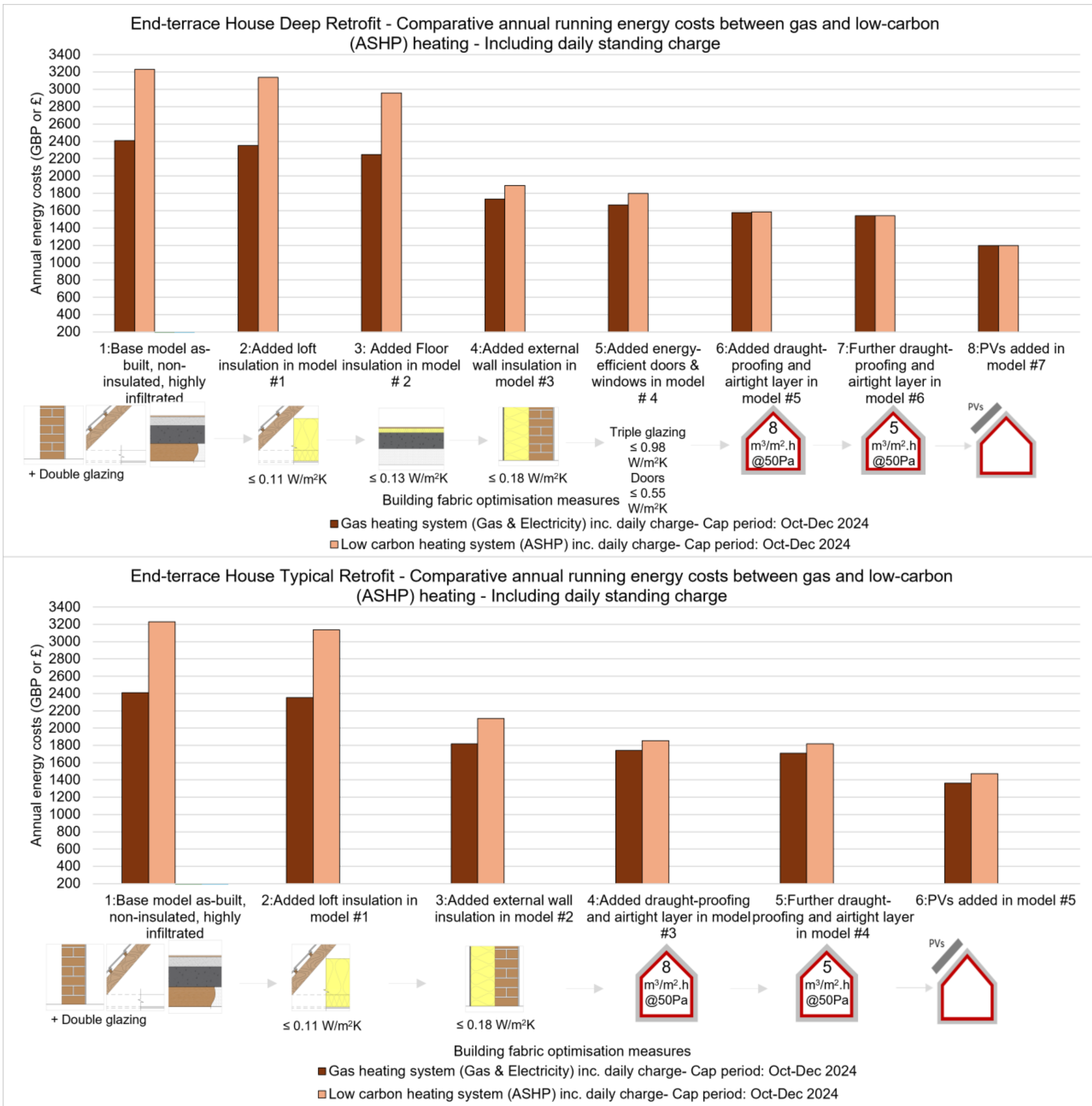


Figure 23: Deep & typical retrofits – heating systems annual costs – End-terrace House

Flat - Mid-terrace

Figure 24 illustrates a comparison of simulation results for energy consumption and carbon emissions between ASHP and a conventional gas heating system for deep retrofit and typical retrofit scenarios. A consistent trend is evident across both retrofit scenarios, prompting a detailed explanation of the simulation results for deep retrofit scenarios for better comprehension.

The energy consumption from using a gas boiler for heating was much higher in leaky, non-insulated buildings. However, when fabric optimisation measures were considered, the consumption was significantly reduced. In the initial, as-built scenario, the total annual energy consumption (including gas and electricity) was 15 MWh. After implementing fabric optimisation measures, the overall energy consumption dropped by 51% to 7.3 MWh. When renewable energy sources were added, the energy demand further decreased to 6 MWh. When using an ASHP, the total energy consumption was significantly lower than a gas boiler heating system. This was due to the efficiency of the system and inputs adopted. The building fabric's sequential improvement could further reduce energy consumption. The total annual energy consumption for the uninsulated envelope using an ASHP corresponded to 7.5 MWh. Once the fabric optimisation measures were considered, the energy demand was reduced by 53%, reaching nearly 3.5MWh. Renewable energy further reduced the total annual energy consumption to 2.1 MWh.

In terms of carbon emissions, a considerable difference in the results was observed when considering a traditional gas boiler as a heating system compared to ASHP. As expected, the carbon emissions with the gas boiler system were significantly higher than the low-carbon heating system. The carbon emission values when considering a traditional gas boiler heating system corresponded to 2.8 tonnes CO_2/yr, reducing to 1.2 tonnes CO_2/yr once the fabric optimisation measures were considered. Comparatively, when adopting ASHP, the carbon emissions corresponded to 0.6 tonnes CO_2/yr and were reduced to half when the fabric optimisation measures were considered, respectively. Renewable energy further reduced the total carbon emissions to 0.2 tonnes CO_2/yr, resulting in an overall reduction of carbon emissions by 72%. It is noteworthy that the external wall insulation of the fabric optimisation measures has contributed significantly to reducing energy consumption and carbon emissions.

The overall energy and carbon simulation results indicated that implementing fabric optimisation measures led to more than a 50% reduction in both energy consumption and carbon emissions. Furthermore, it was also observed that just switching to a low-carbon heating system without adopting any fabric measures led to a significant 77% decrease in carbon emissions compared to the emissions produced by gas heating systems. This shows that by replacing fossil fuels with low-carbon heating, primarily ASHPs (ASHPs), along with the decarbonisation of the electricity grid, can achieve significant carbon emission reductions. However, fabric retrofit measures are necessary alongside this switch to ensure bills remain affordable, and power supplies and infrastructure can meet demand. This highlights the fact that gas boiler replacement by low-carbon heating systems should be considered when a certain degree of improvement has been carried out on the fabric. ASHP is most suited to installation in better-insulated, quality-built homes that demand lower heat output due to its operation at lower temperatures. Its adoption in leaky homes means that ASHP runs continuously and is likely to negatively impact the thermal comfort of the occupants, assuming radiators are kept at the typical sizes.

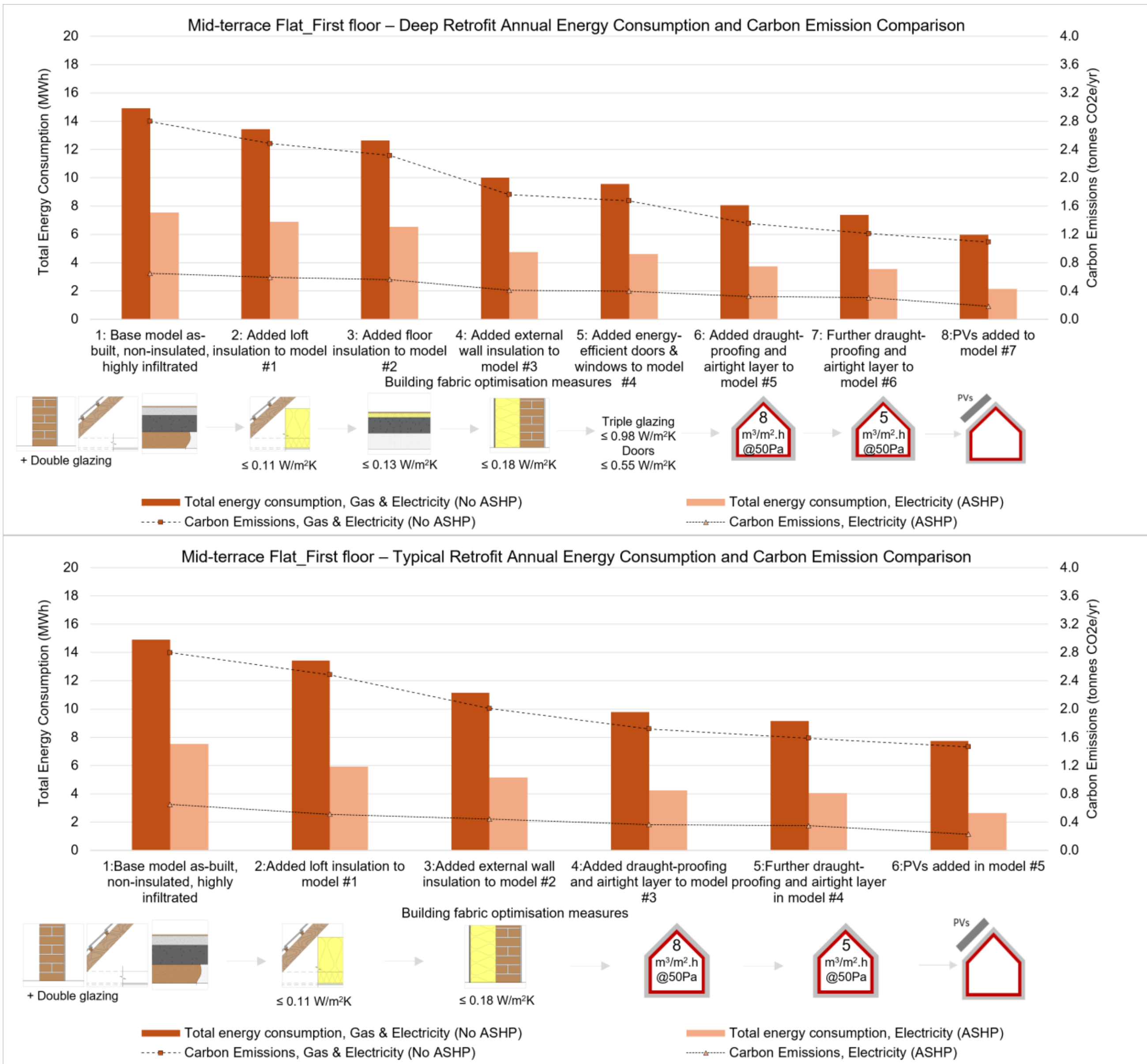


Figure 24: Deep & typical retrofits – heating systems annual energy demand & carbon emission – Mid-terrace Flat

Annual running energy costs- Cap period October–December 2024

Figure 25 illustrates the comparative annual energy costs between ASHP and a conventional gas heating system for deep and typical retrofit scenarios. The annual running costs calculated for winter 2024 (October–December 2024 cap period) showed a gradual reduction across the sequential fabric optimisation scenarios, independent of the heating system adopted.

With all the deep retrofit measures adopted (up to Scenario 7), the annual energy cost while considering the gas heating system was reduced by 27% compared to the base case scenario. Comparatively, with a low-carbon heating system adopted , the energy cost was reduced by 47% compared to the base case, non-retrofit scenario.

Similarly, after implementing all typical retrofit measures up to Scenario 5, the annual energy cost using a gas heating system was reduced by 20% compared to the base case scenario. Comparatively, with a low-carbon heating system adopted , the energy cost was reduced by 41% compared to the base case, non-retrofit scenario.

This highlights the suitability of heat pumps for installation in well-insulated, high-quality homes that have lower heat output demands. Additionally, the cost analyses comparing ASHP to gas heating systems for deep and typical retrofit scenarios indicated that the optimal stage to install an ASHP is after the adoption of wall insulation, i.e., Scenario 4 of deep retrofit and Scenario 3 of typical retrofit, thereby ensuring that the ASHP performance is not diminished by low-quality fabric.

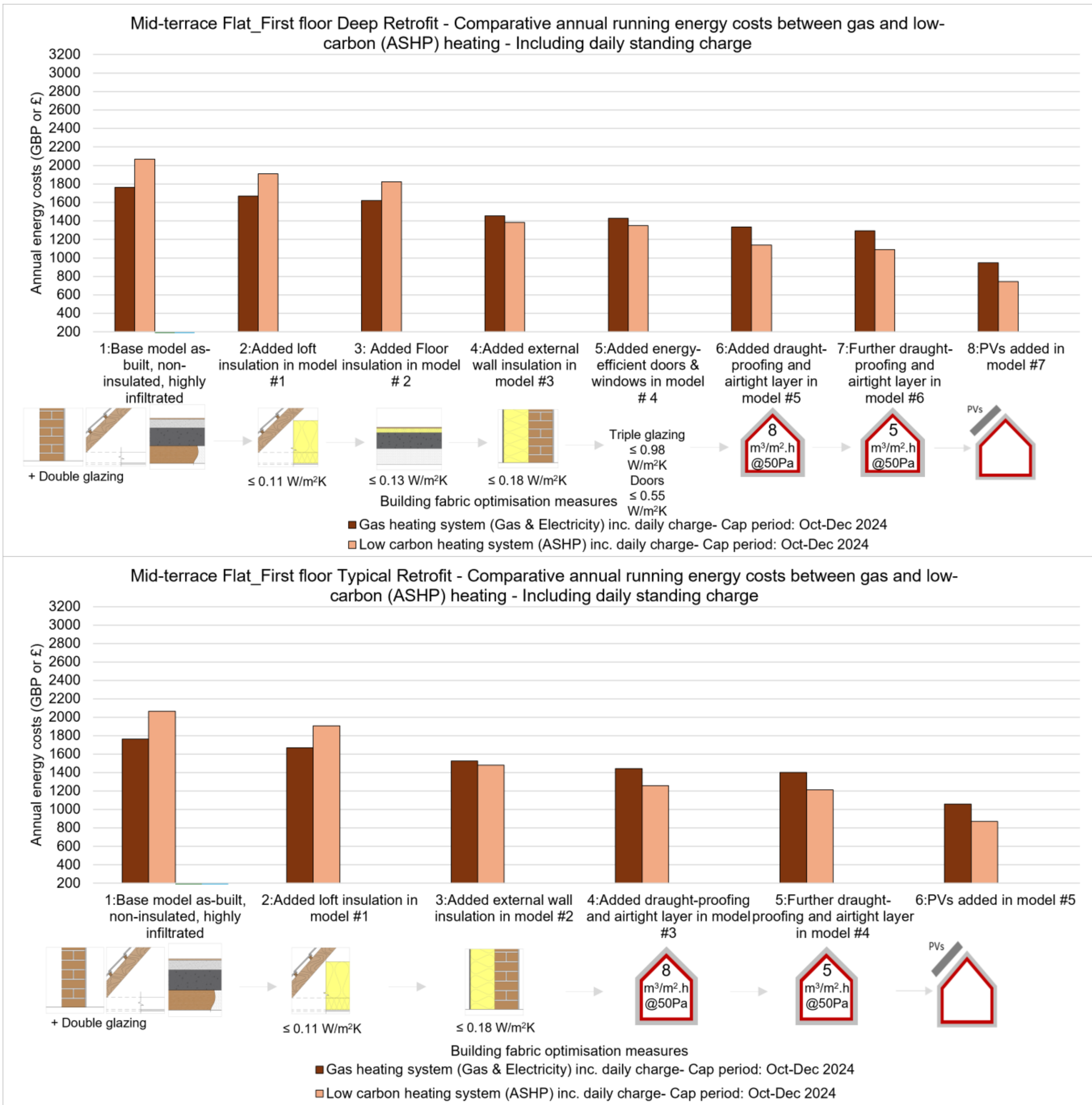


Figure 25: Deep & typical retrofits – heating systems annual costs – Mid-terrace Flat

Flat - End-terrace

Figure 26 illustrates a comparison of simulation results for energy consumption and carbon emissions between ASHP and a conventional gas heating system for deep retrofit and typical retrofit scenarios. A consistent trend is evident across both retrofit scenarios, prompting a detailed explanation of the simulation results for deep retrofit scenarios for better comprehension.

The energy consumption from using a gas boiler for heating was much higher in leaky, non-insulated buildings. However, when fabric optimisation measures were considered, the consumption was significantly reduced. In the initial, as-built scenario, the total annual energy consumption (including gas and electricity) was 17 MWh. After implementing fabric optimisation measures, the overall energy consumption dropped by 54% to 7.8 MWh. When renewable energy sources were added, the energy demand further decreased to 6.4 MWh. When using an ASHP, the total energy consumption was significantly lower than a gas boiler heating system. This was due to the efficiency of the system and inputs adopted. The building fabric's sequential improvement could further reduce energy consumption. The total annual energy consumption for the uninsulated envelope using an ASHP corresponded to 8.5 MWh. Once the fabric optimisation measures were considered, the energy demand was reduced by 57%, reaching nearly 3.7MWh. Renewable energy further reduced the total annual energy consumption to 2.3 MWh.

In terms of carbon emissions, a considerable difference in the results was observed when considering a traditional gas boiler as a heating system compared to ASHP. As expected, the carbon emissions with the gas boiler system were significantly higher than the low-carbon heating system. The carbon emission values when considering a traditional gas boiler heating system corresponded to 3.2 tonnes CO_2/yr, reducing to 1.3 tonnes CO_2/yr once the fabric optimisation measures were considered. Comparatively, when adopting ASHP, the carbon emissions corresponded to 0.7 tonnes CO_2/yr and were reduced to half when the fabric optimisation measures were considered, respectively. Renewable energy further reduced the total carbon emissions to 0.2 tonnes CO_2/yr, resulting in an overall reduction of carbon emissions by 73%. It is noteworthy that the external wall insulation of the fabric optimisation measures has contributed significantly to reducing energy consumption and carbon emissions.

The overall energy and carbon simulation results indicated that implementing fabric optimisation measures led to more than a 50% reduction in both energy consumption and carbon emissions. Furthermore, it was also observed that just switching to a low-carbon heating system without adopting any fabric measures led to a significant 77% decrease in carbon emissions compared to the emissions produced by gas heating systems. This shows that by replacing fossil fuels with low-carbon heating, primarily ASHPs (ASHPs), along with the decarbonisation of the electricity grid, can achieve significant carbon emission reductions. However, fabric retrofit measures are necessary alongside this switch to ensure bills remain affordable, and power supplies and infrastructure can meet demand. This highlights the fact that gas boiler replacement by low-carbon heating systems should be considered when a certain degree of improvement has been carried out on the fabric. ASHP is most suited to installation in better-insulated, quality-built homes that demand lower heat output due to its operation at lower temperatures. Its adoption in leaky homes means that ASHP runs continuously and is likely to negatively impact the thermal comfort of the occupants, assuming radiators are kept at the typical sizes.

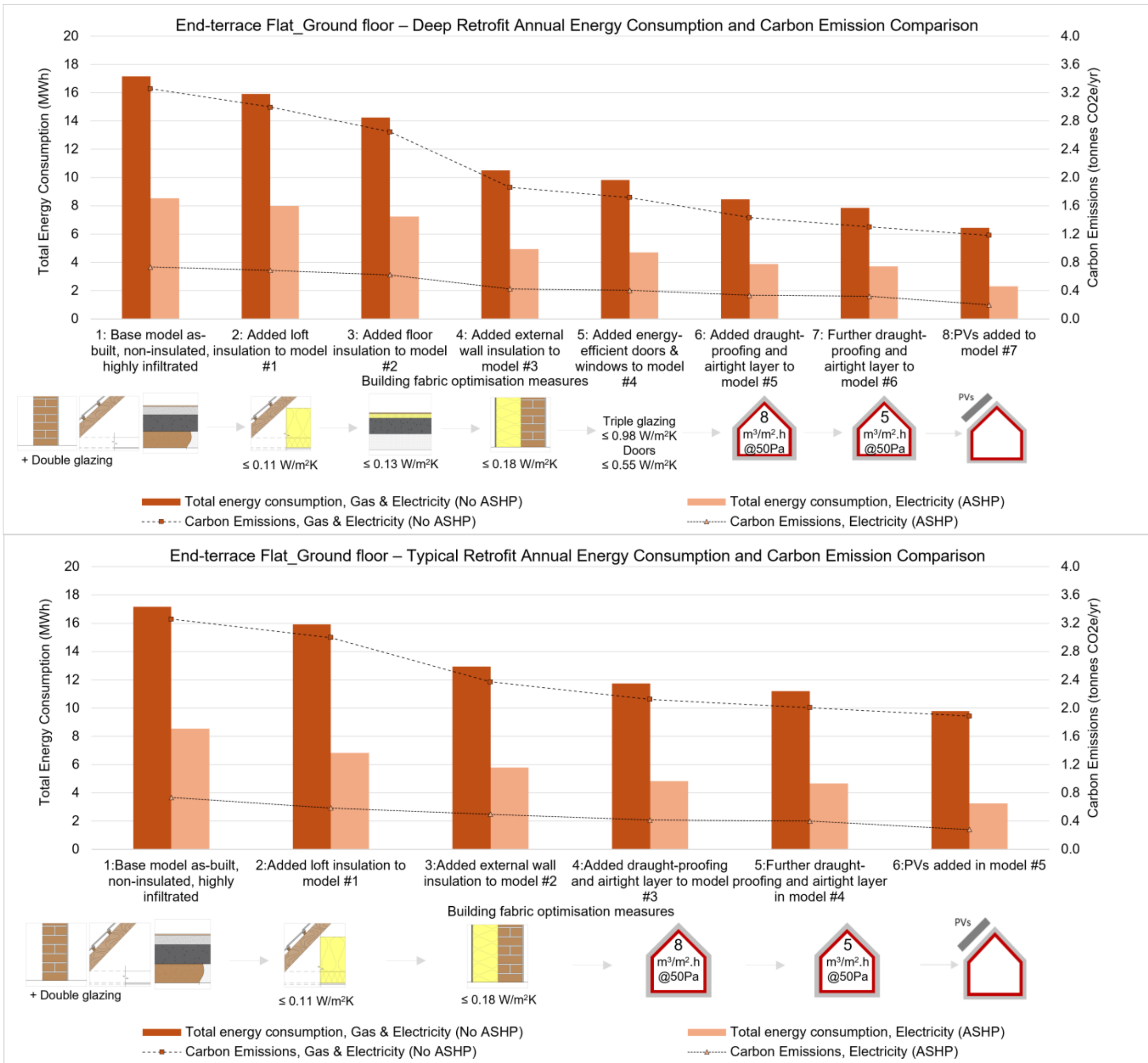


Figure 26: Deep & typical retrofits – heating systems annual energy demand & carbon emission – End-terrace Flat

Annual running energy costs- Cap period October–December 2024

Figure 27 illustrates the comparative annual energy costs between ASHP and a conventional gas heating system for deep and typical retrofit scenarios. The annual running costs calculated for winter 2024 (October–December 2024 cap period) showed a gradual reduction across the sequential fabric optimisation scenarios, independent of the heating system adopted.

With all the deep retrofit measures adopted (up to Scenario 7), the annual energy cost while considering the gas heating system was reduced by 30% compared to the base case scenario. Comparatively, with a low-carbon heating system adopted , the energy cost was reduced by 51% compared to the base case, non-retrofit scenario.

Similarly, after implementing all typical retrofit measures up to Scenario 5, the annual energy cost using a gas heating system was reduced by 19% compared to the base case scenario. Comparatively, with a low-carbon heating system adopted , the energy cost was reduced by 41% compared to the base case, non-retrofit scenario.

This highlights the suitability of heat pumps for installation in well-insulated, high-quality homes that have lower heat output demands. Additionally, the cost analyses comparing ASHP to gas heating systems for deep and typical retrofit scenarios indicated that the optimal stage to install an ASHP is after the adoption of wall insulation, i.e., Scenario 4 of deep retrofit and Scenario 3 of typical retrofit, thereby ensuring that the ASHP performance is not diminished by low-quality fabric.

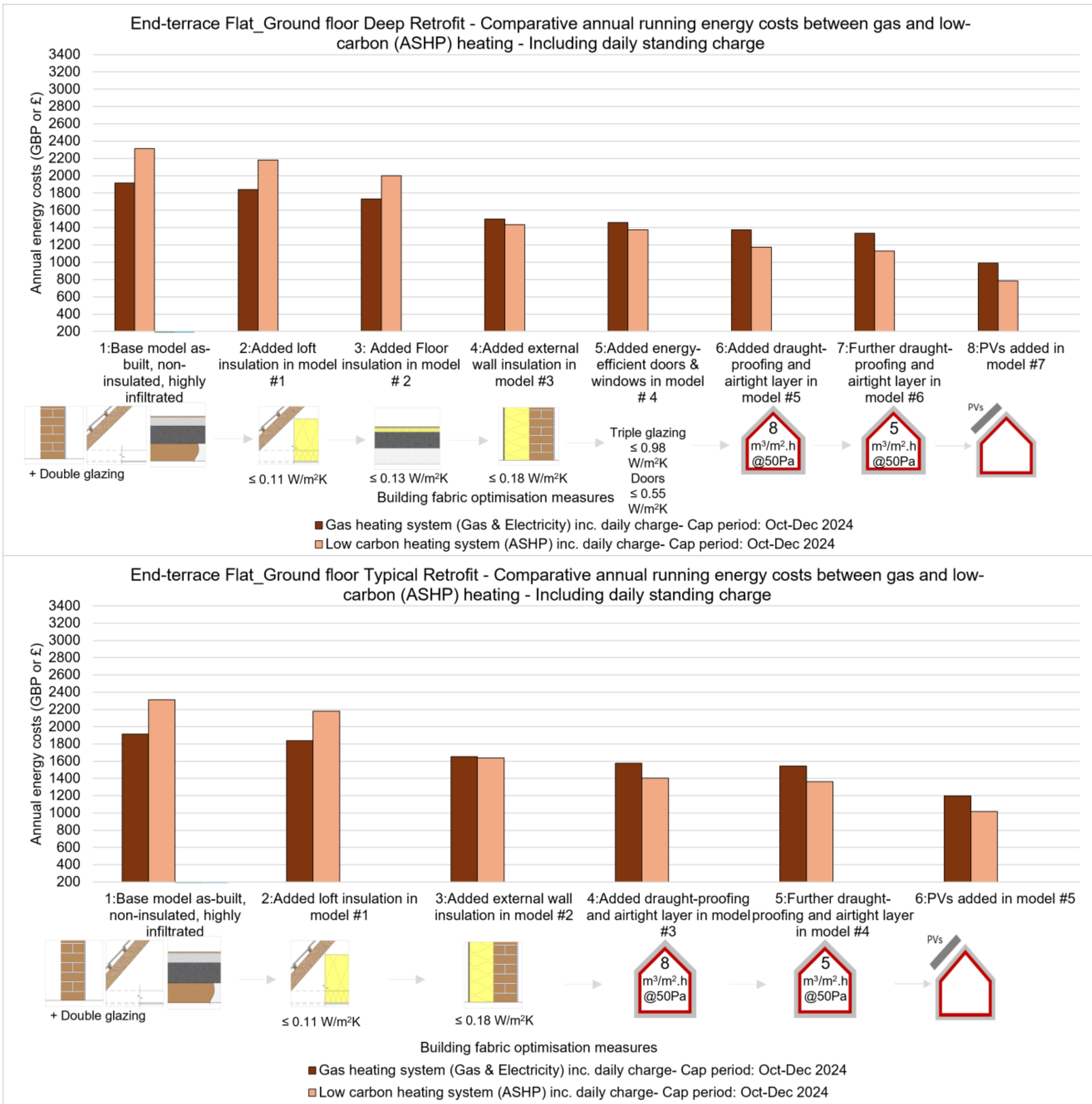


Figure 27: Deep & typical retrofits – heating systems annual costs – End-terrace Flat

2.5 Summary

This section presents a summary of the energy and carbon performance assessment for the generic housing stock, along with a comparative analysis between 'deep retrofit' and 'typical retrofit' scenarios.

The 'deep retrofit' scenario consistently resulted in greater reductions in energy consumption and operational carbon emissions. This is primarily due to the implementation of more extensive fabric upgrades. These upgrades, such as the installation of floor insulation and triple-glazed windows were excluded from the 'typical retrofit' scenario.

Overall energy consumption across all archetypes showed that the 'deep retrofit' scenario achieved a further reduction of approximately 20-34% from the 'typical retrofit' measures. Additionally, adopting low-carbon heating systems has demonstrated lower energy consumption across all archetypes than traditional gas heating systems. The cost analyses also suggested that they had marginally lower annual costs when compared to the traditional heating system. Moreover, with the UK transitioning to a decarbonised energy system by around 2050, renewable costs are expected to become cheaper than fossil fuels in the coming years, and so will the energy costs.

The most significant fabric measure identified was the implementation of wall insulation, which proved more effective than other retrofit strategies across all archetypes. This reduction can be attributed to the larger exposed envelope area of the wall insulation compared to other fabric elements.

Table 28-
Table 31 present a summary of the key results related to annual heating demand, total energy consumption, carbon emissions and estimated annual running costs for the generic housing stock in both 'deep retrofit' and 'typical retrofit' scenarios.

Table 28: Summary of the key results related to annual heating demand.

Heating demand (kWh/m²a) Deep retrofit/ Typical retrofit							
	1 Base model as-built, non-insulated, highly infiltrated	2 Added loft insulation to model #1	3 Added floor insulation to model #2	4 Added external wall insulation to model #3	5 Added energy-efficient doors & windows to model #4	6 Added draught-proofing and airtight layer to model #5	7 Further draught-proofing and airtight layer to model #6
Detached house	107	101/ 101	94/ -	43/ 53	36/ -	25/ 45	20/ 42
Semi-detached house	87	80/ 80	70/ -	36/ 47	28/ -	19/ 39	15/ 37
Mid-terrace house	125	115/ 115	97/ -	45/ 52	34/ -	22/ 41	17/ 37
End-terrace house	143	136/ 136	121/ -	47/ 59	37/ -	25/ 48	20/ 44
Mid-terrace flat	148	124/ 124	112/ -	70/ 89	64/ -	40/ 67	29/ 57
End-terrace flat	149	133/ 133	112/ -	63/ 95	55/ -	37/ 79	29/ 72

Table 29: Summary of the key results related to total energy consumption.

Total energy consumption (kWh) Deep retrofit/ Typical retrofit									
		1 Base model as-built, non-insulated, highly infiltrated	2 Added loft insulation to model #1	3 Added floor insulation to model #2	4 Added external wall insulation to model #3	5 Added energy-efficient doors & windows to model #4	6 Added draught-proofing and airtight layer to model #5	7 Further draught-proofing and airtight layer to model #6	8 PVs added to model #7
Detached house	Gas heating	17,617	16,954/ 16,954	16,676/ -	11,028/ 12,153	10,207/ -	9006/ 11,238	8452/ 10,834	7049/ 9431
	ASHP	9276	8991/ 8991	8636/ -	5496/ 6100	5213/ -	4441/ 5253	4283/ 5135	2881/ 3733
Semi-detached house	Gas heating	16,320	15,463/ 15,463	14,970/ -	11,126/ 12,299	10,240/ -	9167/ 11,484	8752/ 11,171	7342/ 9762
	ASHP	8333	7966/ 7966	7500/ -	5221/ 5845	4916/ -	4233/ 5069	4114/ 4978	2705/ 3568
Mid-terrace house	Gas heating	20,831	19,725/ 19,725	17,763/ -	11,839/ 12,617	10,640/ -	9307/ 11,481	8782/ 11,018	7372/ 9608
	ASHP	11,369	10,885/ 10,885	10,027/ -	6712/ 7638	6299/ -	5469/ 6625	5320/ 6490	3910/ 5080
End-terrace house	Gas heating	22,919	22,044/ 22,044	20,361/ -	12,131/ 13,471	11,009/ -	9624/ 12,250	9033/ 11,720	7623/ 10,310
	ASHP	12,282	11,900/ 11,900	11,164/ -	6813/ 7707	6426/ -	5559/ 6660	5391/ 6509	3981/ 5099
Mid-terrace flat	Gas heating	14,913	13,425/ 13,425	12,624/ -	9994/ 11,153	9566/ -	8047/ 9777	7369/ 9149	5961/ 7742
	ASHP	7530	6880/ 6880	6529/ -	4744/ 5144	4597/ -	3734/ 4226	3541/ 4048	2133/ 2640
End-terrace flat	Gas heating	17,158	15,913/ 15,913	14,232/ -	10,502/ 12,923	9814/ -	8465/ 11,743	7841/ 11,189	6434/ 9781
	ASHP	8532	7987/ 7987	7251/ -	4945/ 5780	4707/ -	3883/ 4816	3705/ 4658	2297/ 3250

Table 30: Summary of the key results related to carbon emissions.

Annual carbon emissions (kgCO_2e/yr) Deep retrofit/ Typical retrofit									
		1 Base model as-built, non-insulated, highly infiltrated	2 Added loft insulation to model #1	3 Added floor insulation to model #2	4 Added external wall insulation to model #3	5 Added energy-efficient doors & windows to model #4	6 Added draught-proofing and airtight layer to model #5	7 Further draught-proofing and airtight layer to model #6	8 PVs added to model #7
Detached house	Gas heating	3284	3144/ 3144	3086/ -	1900/ 2136	1727/ -	1475/ 1944	1359/ 1859	1239/ 1739
	ASHP	798	773/ 773	743/ -	473/ 525	448/ -	382/ 452	368/ 442	247/ 321
Semi-detached house	Gas heating	2900	2720/ 2720	2617/ -	1810/ 2056	1624/ -	1398/ 1885	1311/ 1819	1190/ 1698
	ASHP	717	685/ 685	645/ -	449/ 503	423/ -	364/ 436	354/ 428	232/ 306
Mid-terrace house	Gas heating	3940	3707/ 3707	3295/ -	2051/ 2215	1800/ -	1520/ 1976	1409/ 1879	1288/ 1758
	ASHP	978	936/ 936	862/ -	577/ 657	542/ -	470/ 570	458/ 558	336/ 437

End-terrace house	Gas heating	4378	4194/ 4194	3841/ -	2113/ 2394	1877/ -	1586/ 2138	1462/ 2026	1341/ 1906
	ASHP	1056	1023/ 1023	960/ -	586/ 663	553/ -	478/ 573	464/ 560	342/ 438
Mid-terrace flat	Gas heating	2796	2483/ 2483	2315/ -	1763/ 2006	1673/ -	1354/ 1717	1211/ 1585	1091/ 1465
	ASHP	648	592/ 592	562/ -	408/ 442	395/ -	321/ 364	305/ 348	183/ 227
End-terrace flat	Gas heating	3259	2997/ 2997	2644/ -	1861/ 2369	1716/ -	1433/ 2121	1302/ 2005	1181/ 1884
	ASHP	734	687/ 687	624/ -	425/ 497	405/ -	334/ 414	319/ 401	197/ 279

Table 31: Summary of the key results related to annual running costs.

Total annual running costs (GBP or £) Deep retrofit/ Typical retrofit									
		1 Base model as-built, non-insulated, highly infiltrated	2 Added loft insulation to model #1	3 Added floor insulation to model #2	4 Added external wall insulation to model #3	5 Added energy-efficient doors & windows to model #4	6 Added draught-proofing and airtight layer to model #5	7 Further draught-proofing and airtight layer to model #6	8 PVs added to model #7
Detached house	Gas heating	2049	2008/ 2008	1991/ -	1638/ 1708	1587/ -	1512/ 1651	1477/ 1626	1134/ 1282
	ASHP	2495	2425/ 2425	2338/ -	1569/ 1717	1499/ -	1310/ 1509	1272/ 1480	928/ 1137
Semi-detached house	Gas heating	2131	2078/ 2078	2047/ -	1807/ 1881	1752/ -	1685/ 1830	1659/ 1810	1314/ 1465
	ASHP	2264	2174/ 2174	2060/ -	1502/ 1654	1427/ -	1259/ 1464	1230/ 1442	885/ 1097
Mid-terrace house	Gas heating	2278	2208/ 2208	2086/ -	1716/ 1765	1642/ -	1558/ 1694	1526/ 1665	1180/ 1320
	ASHP	3008	2889/ 2889	2679/ -	1867/ 2094	1765/ -	1562/ 1845	1526/ 1812	1180/ 1467
End-terrace house	Gas heating	2408	2353/ 2353	2248/ -	1735/ 1818	1665/ -	1578/ 1742	1541/ 1709	1196/ 1364
	ASHP	3231	3138/ 3138	2957/ -	1891/ 2110	1797/ -	1584/ 1854	1543/ 1817	1198/ 1472
Mid-terrace flat	Gas heating	1763	1670/ 1670	1620/ -	1456/ 1528	1429/ -	1334/ 1442	1292/ 1403	947/ 1058
	ASHP	2067	1908/ 1908	1822/ -	1385/ 1482	1348/ -	1137/ 1258	1090/ 1214	745/ 869
End-terrace flat	Gas heating	1915	1838/ 1838	1733/ -	1500/ 1651	1457/ -	1373/ 1578	1334/ 1543	989/ 1198
	ASHP	2313	2179/ 2179	1999/ -	1434/ 1638	1376/ -	1174/ 1402	1130/ 1363	785/ 1019

3 Retrofit Generic Housing Embodied Carbon Calculations

The built environment accounts for roughly 40% of total UK carbon emissions (UKGBC, 2023) Carbon emissions associated with the built environment are attributable not only to the use of built assets (operational carbon emissions) but also to their construction (embodied carbon emissions). Operational emissions are attributable to the everyday running of a building whereas embodied emissions result from the production, procurement and installation of the building's materials and components (construction). Embodied emissions also include the lifetime emissions from maintenance repair, replacement, demolition, and disposal. Both operational and embodied emissions are assessed according to their Global Warming Potential (GWP), measured in kilograms or tons of carbon dioxide equivalent per square metre floor area (kgCO_2e/m2 or TCO_2e/m2).

Operational emissions relate to Life Cycle stages B6 and B7 (see Figure 28). Embodied emissions are calculated at Life Cycle Stages A1-A5, B1-B5, and C1-C4. This section focuses on the embodied emissions associated with both the deep and typical retrofit scenarios for the 'generic' house-types, as defined within Section 0.

Figure 28: Whole Life Carbon Stages

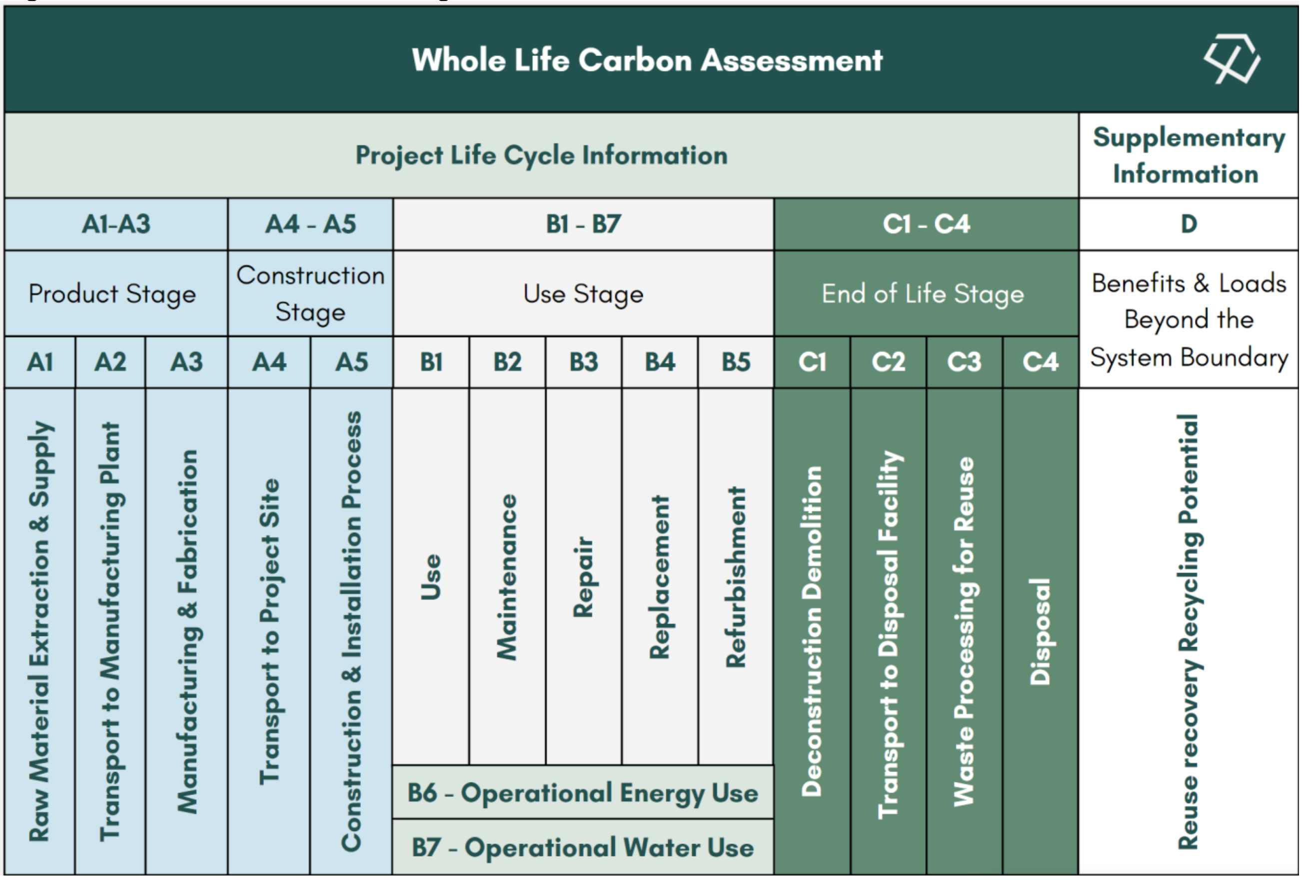


Figure 28: Whole Life Carbon Stages (Develeco, 2025)

3.1 Methodology and Assumptions

The embodied carbon calculations were undertaken Using OneClick LCA in accordance with RICS guidance 2024 (2^{nd} Edition) (RICS, 2024).

Reference Study Period (RSP)

The Reference Study Period (RSP) is the period of analysis for the embodied carbon assessment. Non-domestic projects must be analysed over a 60-year RSP, in order to be considered compliant with the RICS Professional Standard. For domestic projects, the requirements are less strict, and there are no industry-specific standards for retrofit.

For this analysis, we have assumed a 20-year RSP for all data analysis and associated outputs. According to a study conducted by the Ministry of Housing, Communities and Local Government, UK owner-occupiers live in the same home for an average of 17.2 years (Ministry of Housing, 2024) . Life expectancy has therefore been set at 20 years in order to simplify calculations. We determined that a 60-year period was an excessively long timeframe for evaluating total payback, as it is unlikely to align with typical stakeholder concerns. Furthermore, this duration would necessitate the replacement of systems such as ASHPs and solar panels at least twice within the assessment period. Such replacements would have introduced significant variability in the results, potentially skewing the overall payback analysis.

Product Stage (A1-A3)

Product Stage modules include the $kgCO_2e$ released during extraction, processing, manufacture (including prefabrication of components or elements) and transportation of materials between these processes, until the product leaves the factory gates to be taken to site. Note that recycled content of a product affects the $kgCO_2e$ released in modules A1-A3.

Construction Process Stage (A4-A5)

Construction Process modules include the $kgCO_2e$ released during transportation of materials and products to site, energy usage due to activities on site (site huts, machinery use etc.) and the $kgCO_2e$ associated with the production, transportation, and end-of-life processing of materials used on site.

Use Stage (B1-B5)

Use Stage modules (excluding B6-B7) include the $kgCO_2e$ released due to use, maintenance, repair, replacement, and refurbishment while the building is in use. Module B4 (replacement) is often a key focus of the use stage when embodied carbon is being considered.

End of Life Stage (C1-C4)

End of Life modules include the $kgCO_2e$ released during decommissioning, stripping out, demolition, deconstruction, transportation of materials away from the site, waste processing and the disposal of materials.

Benefits and Loads Beyond the System Boundary (D)

Module D is an additional stage beyond the life cycle of the asset that is intended to provide a broader view of its environmental impacts. Module D emissions have been excluded from this assessment, subject to further information being provided.

Assumptions

Table 32: Breakdown of assumptions (RICS, 2024)

Lifecycle Stage	**Assumptions**
Product Stage (A1 – A3)	Calculated using EPDs which align with the exact product and/or material specification or the most applicable similar product.
Construction Stage (A4 – A5)	Transportation to site (A4) – calculated using RICS assumptions: 50 km (locally sourced materials such as concrete-mix), 300 km (national sourced materials such as steel), 1,500 km (internationally sourced within the EU). Site operations including construction waste (A5) – based on 40 $kgCO_2e/m2$ (as per RICS 2024 guidance).
Use Stage (B1 – B5)	Refrigerant leakage is accounted for. Maintenance (B2) and Repair (B3) have been accounted for in the results, expressed as a % of material repaired per year based on RICS guidance estimates for these modules (i.e., 1% of A1-A5) For B2 and 25% of B2 for B3. Replacement (B4) and Refurbishment (B5) is based on the product specific service life and where applicable, RICS defaults.
Operational Energy Use (B6)	Excluded.
Operational Water Use (B7)	Excluded.
End of Life Stage (C1-C4)	Based on End of Life (EoL) Market Scenarios as noted in RICS 2017. C1 has been accounted for each building element based on a % contribution of each element to the embodied carbon figure, this percentage has then been applied to the GIA and distributed accordingly.
Module D	Excluded.
Pre-Demolition Assumptions	The emissions associated with preconstruction demolition are reported using the GLA and RICS standard assumptions in addition to the Pre-demolition Audit quantities.

3.2 Results

Using the base building assumptions as defined within Section 2, embodied carbon models have been created for each property-build type. In Table 33, a summary results table is provided for each property build-type, comparing the deep and typical retrofit scenarios.

Table 33: Embodied Carbon Results Summary - All House Types (Deep and Typical)

Property-build type	**Type of Retrofit**	**A1-A5, B1-B5,C1-C4 ($kgCO_2e/m2$)**	**GIA (m2)**	**A1-A5, B1-B5,C1-C4 (TCO_2e)**
Detached	Deep	138.42	89.90	12.44
	Typical	97.05	89.90	8.73
Semi-detached	Deep	136.45	89.90	12.27
	Typical	86.99	89.90	7.82
Mid-terrace	Deep	118.99	89.70	10.67
	Typical	72.57	89.70	6.51
End-terrace	Deep	128.07	89.70	11.49
	Typical	85.00	89.70	7.62
Mid-terrace Flat (Whole)	Deep	108.95	112.90	6.26
	Typical	108.95	112.90	7.60
	Deep	108.95	112.90	12.30

End-terrace Flat (Whole)	Typical	108.95	112.90	7.60
Mid-terrace Flat	Deep	123.04	50.90	6.26
	Typical	81.53	50.90	4.15
End-terrace Flat	Deep	118.34	62.00	7.34
	Typical	76.82	62.00	4.76

Full data exports are provided in Appendix B: Embodied Carbon Data Exports. Table 33 provides a summary of total embodied carbon emissions only. Table 34 and 35 provide a detailed breakdown of GWP according to resource type, across the varied house types.

Table 34: Combined Global Warming Potential across all house types (kgCO_2e/m2) (Typical Retrofit Scenario)

House Type	Detached	Semi Detached	Mid Terrace	End Terrace	Mid Terrace Flat	End Terrace Flat
Stone wool insulation	39.52	35.09	25.19	32.20	24.37	24.37
Energy production systems from renewable energy	14.89	14.89	14.93	14.93	26.30	21.59
HVAC equipment with refrigerant	13.21	13.21	13.24	13.24	10.52	10.52
Mortar (masonry/bricklaying)	16.14	11.32	7.40	12.01	9.25	9.24
Other site operation	5.50	5.50	5.51	5.51	5.50	5.50
Refrigerant fluids	4.51	4.51	4.52	4.52	3.59	3.59
Textiles and wallpapers	2.76	1.95	1.27	2.06	1.59	1.59
Plastic profiles and products	0.32	0.32	0.32	0.32	0.25	0.25
HVAC components and equipment	0.21	0.21	0.21	0.21	0.16	0.16
Total	97.05	86.99	72.57	85.00	81.53	76.82

Table 35: Combined Global Warming Potential across all house types (kgCO_2e/m2) (Deep Retrofit Scenario)

House Type	Detached	Semi Detached	Mid Terrace	End Terrace	Mid Terrace Flat	End Terrace Flat
Stone wool insulation	39.52	35.16	28.53	32.20	26.67	27.56
Other insulation	26.45	26.46	27.56	27.56	24.37	25.19
Energy production systems from renewable energy	16.14	14.94	14.93	14.93	26.30	22.31
HVAC equipment with refrigerant	14.89	13.28	13.24	13.24	11.15	11.52
Mortar (masonry/bricklaying)	13.21	11.40	9.92	12.01	10.07	9.55
Other site operation	8.95	10.47	8.25	9.92	9.24	8.52
PVC frame windows	8.25	9.10	7.40	8.25	8.25	10.41
Refrigerant fluids	4.51	9.01	4.52	4.52	3.59	3.71
Textiles and wallpapers	2.76	2.48	1.47	2.06	1.59	1.64
Other resource types	3.74	4.14	3.19	3.39	1.80	1.86
Total	138.42	136.45	118.99	128.07	123.04	122.28

Note: This CGWP is calculated on a per square meter basis, therefore resulting in a higher rate for the smaller mid-terrace flat compared to the end terrace flat.

To understand the specific embodied carbon impact at Retrofit Stages 1, 2 and 3 (as defined within Section 0), a more detailed breakdown is required, as provided within Table 36 and Table 37.

Table 36: Breakdown by Retrofit Stage across all house types (Typical Retrofit Scenario)

House Type	**Detached**		**Semi**		**Mid Terrace**		**End Terrace**		**Mid Terrace Flat**		**End Terrace Flat**	
	GWP	%	GWP	%	GWP	%	GWP	%	GWP	%	GWP	%
Retrofit Stage 1 - Fabric	64.24	66%	54.17	62%	39.69	55%	52.11	61%	40.96	50%	40.96	53%
Retrofit Stage 2 - Low Carbon Heating	17.92	18%	17.92	21%	17.96	25%	17.96	21%	14.27	18%	14.27	19%
Retrofit Stage 3 - Renewable Technology	14.89	15%	14.89	17%	14.93	21%	14.93	18%	26.30	32%	21.59	28%
Total	97.05	100%	86.99	100%	72.57	100%	85.00	100%	81.53	100%	76.82	100%

Table 37: Breakdown by Retrofit Stage across all house types (Deep Retrofit Scenario)

House Type	**Detached**		**Semi**		**Mid Terrace**		**End Terrace**		**Mid Terrace Flat**		**End Terrace Flat**	
	GWP	%	GWP	%	GWP	%	GWP	%	GWP	%	GWP	%
Retrofit Stage 1 - Fabric	105.82	76%	99.22	73%	86.32	73%	95.39	74%	82.00	67%	82.00	69%
Retrofit Stage 2 - Low Carbon Heating	17.71	13%	22.29	16%	17.75	15%	17.75	21%	14.74	12%	14.74	12%
Retrofit Stage 3 - Renewable Technology	14.89	11%	14.94	11%	14.93	13%	14.93	18%	26.30	21%	21.59	18%
Total	138.42	100%	136.45	100%	118.99	100%	128.07	113%	123.04	100%	118.34	100%

Using the output data, a series of graphical representations of the results are provided at Figure 29, Figure 30, Figure 31 and Figure 32

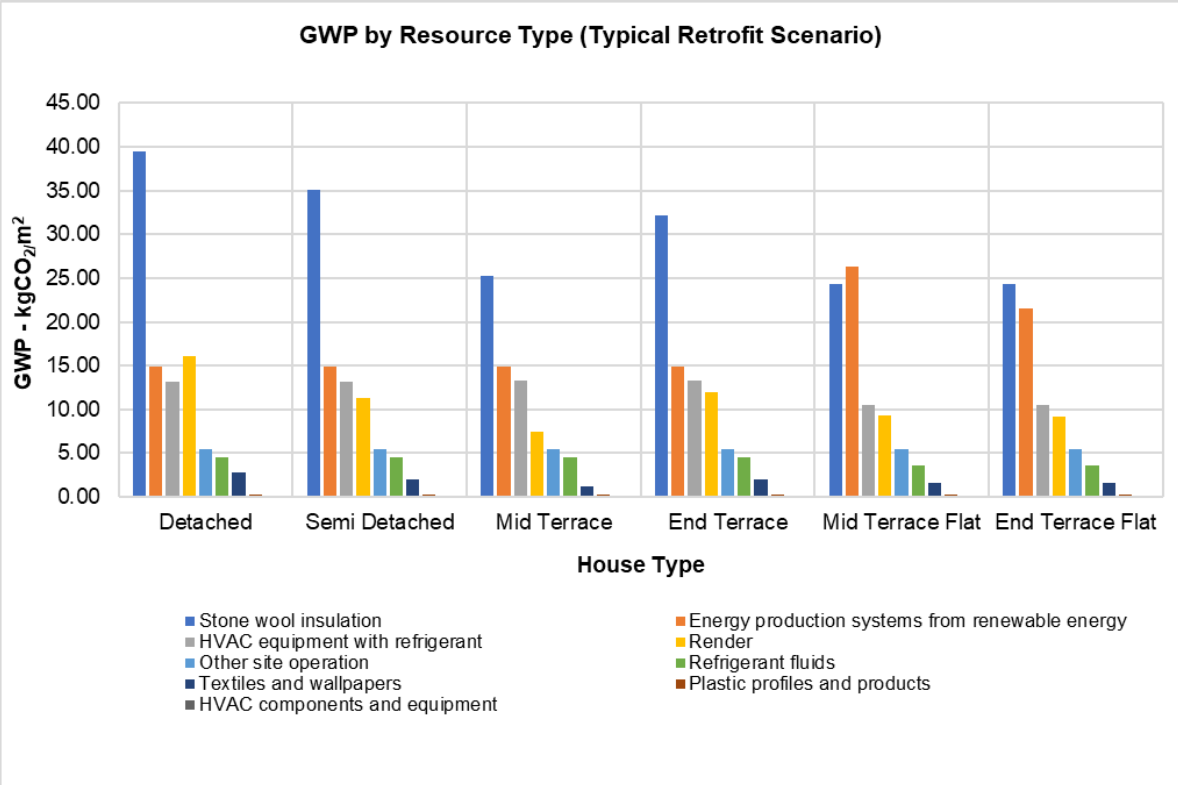


Figure 29: Global Warming Potential by Resource Type (Typical Retrofit Scenario)

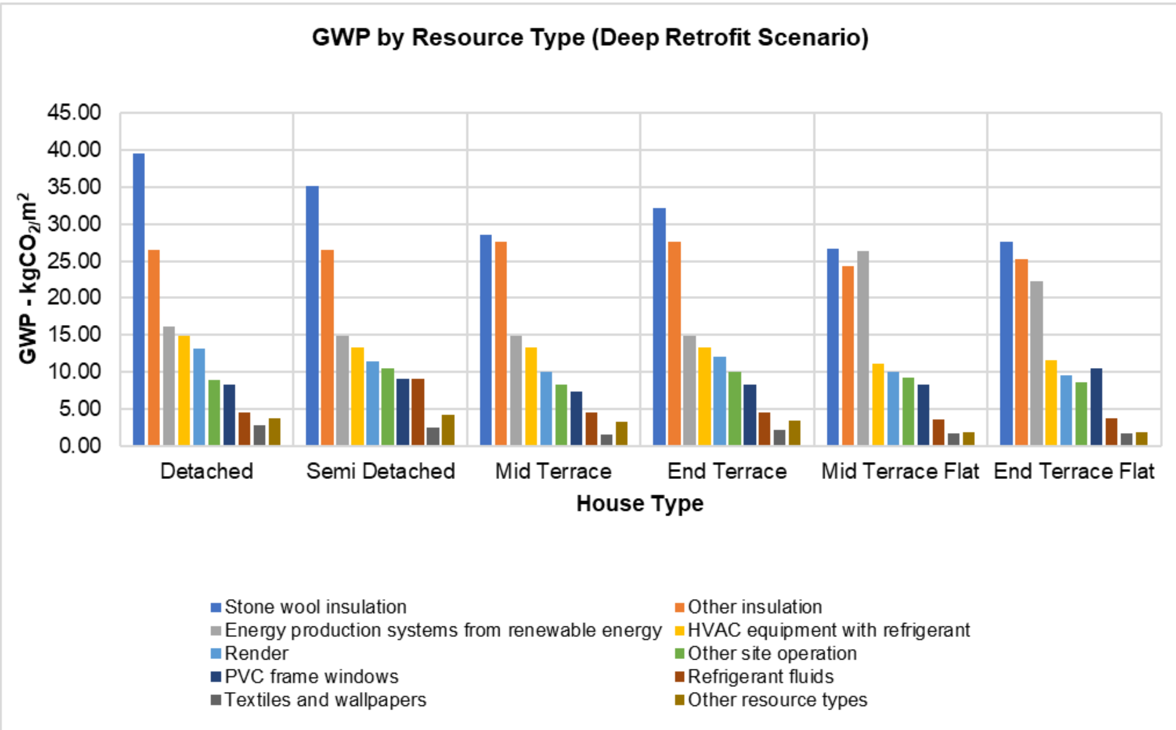


Figure 30: Global Warming Potential by Resource Type (Deep Retrofit Scenario)

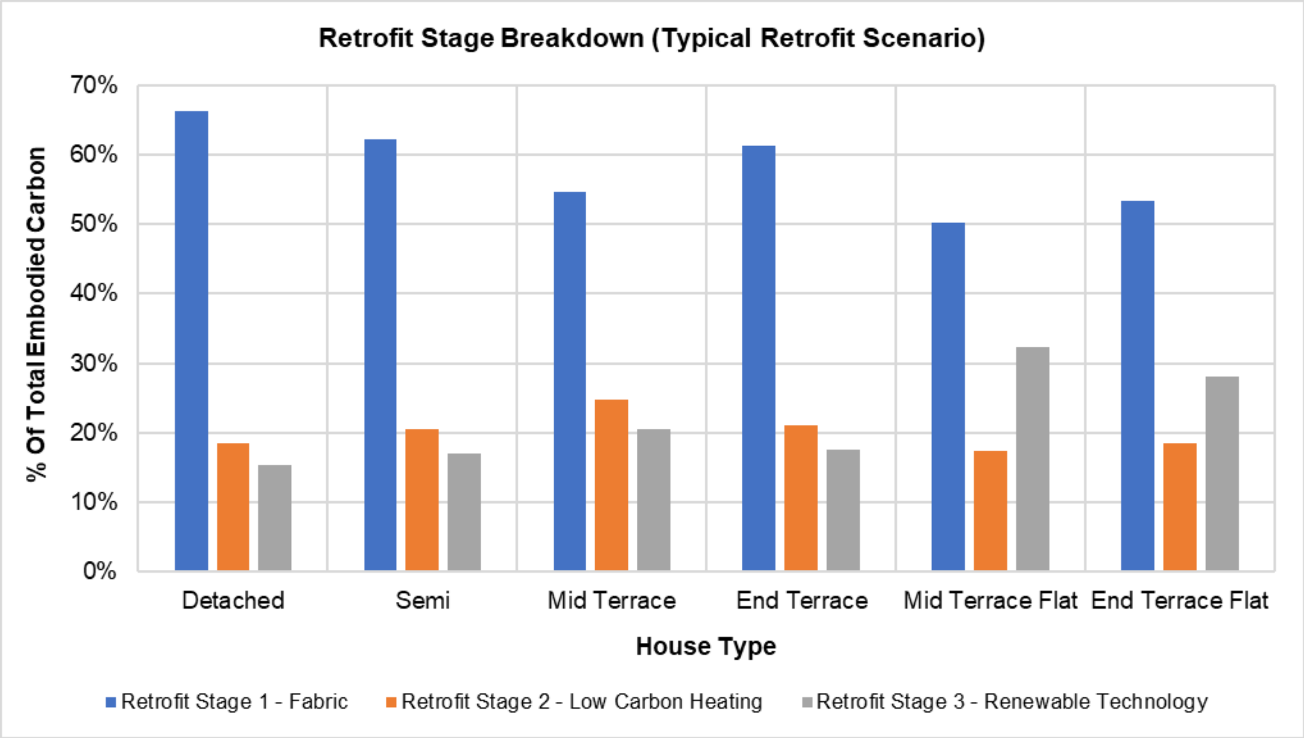


Figure 31: Retrofit Stage Breakdown across all house types (Typical Retrofit Scenario)

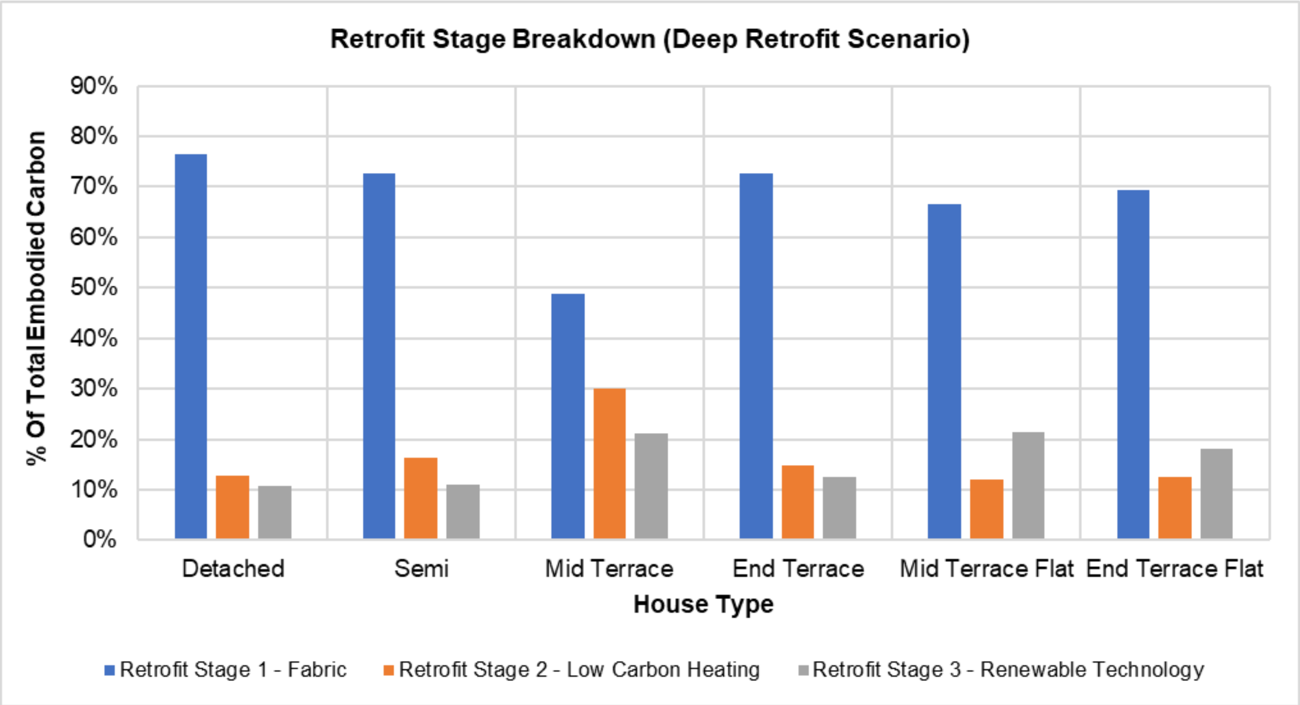


Figure 32: Retrofit Stage Breakdown across all house types (Deep Retrofit Scenario)

3.3 Summary

A comparative analysis has been undertaken between 'Deep retrofit' and 'Typical retrofit' scenarios. The 'Deep retrofit' scenario consistently results in higher total embodied carbon emissions, primarily due to the inclusion of more extensive fabric upgrades. These upgrades, such as the installation of floor insulation and new triple-glazed windows, are omitted from the 'Typical retrofit' scenario, leading to the observed differences in carbon footprint.

In terms of overall emissions, the 'typical retrofit' measures account for approximately 60-70% of the total emissions generated from a 'deep retrofit' approach. The analysis further reveals that detached houses exhibit the highest embodied carbon emissions per square meter, at 138.4kgCO_2e/m^2 and 97.1kgCO_2e/m^2 for the deep and typical scenarios, respectively. Despite the Gross Internal Area (GIA) remaining consistent with other house types, the Detached House is comprised of an increased number of heat loss perimeter walls, necessitating a larger surface area of external wall insulation. Conversely, the lowest emissions per square meter were observed in end-terrace flats, where only two of the four external walls are insulated, contributing to a lower figure of 118.3kgCO_2e/m^2 for the 'deep retrofit' scenario.

Across all property types, fabric improvements are the most significant contributor to embodied carbon emissions, accounting for between 39.7 and 64.2kgCO_2e/m^2 across the property types. The next largest contributor is the HVAC equipment, which includes heat pumps and cylinders, which contribute 18.0kgCO_2e/m^2 to the total. With the exception of the flats, these figures remain constant across the property types, reflecting uniformity in the type and size of the HVAC equipment installed. The GWP for each flat has been calculated on a pro-rata basis, based on GIA as a percentage of the whole property. This follows the principle that flats would not be retrofitted individually or in isolation, but as part of a 'whole building' approach.

Among the additional measures introduced exclusively in the 'Deep retrofit' scenario, new floor insulation emerged as the most carbon intensive. For detached house type, floor insulation contributes 26.5kgCO_2e/m^2 to the overall emissions. This is followed by the installation of triple-glazed PVC windows, which contributes a further 8.3kgCO_2e/m^2.

In conclusion, across all property types, implementing a typical retrofit, as opposed to a deep retrofit, results in a saving of roughly 30-40% in embodied carbon. In the case of a detached house, a deep retrofit results in 12.4tonnes of CO_2e whereas a typical retrofit generates 8.7tonnes of CO_2e. This additional 3.7tonnes of CO_2e is what must be saved in operational carbon emissions over the lifetime of the property to make the deep retrofit scenario worth pursuing. This will be evaluated in detail as part of subsequent analysis.

4 Retrofit Specific Housing Performance Assessment

This section presents the results of the energy performance assessment of specific housing stock. It examines real case studies from Broxtowe housing stock to determine whether the projects and their specifications achieve the predicted performance outcomes. Both typical and deep retrofitting approaches are considered for the performance assessment. The performance of retrofitted homes is calculated using thermal dynamic building simulation, based on typical inputs and housing characteristics.

4.1 Simulation Models, Stages and Assumptions

This section presents the building model (or archetype), retrofit stages and assumptions used in the simulations.

Model

Building on our previous exploration of various property types (archetypes) under the general housing performance assessment, the bungalow housing type was selected for a detailed evaluation in the specific housing assessment. For this case study, a detached bungalow was chosen from the Broxtowe housing stock, constructed in the early 1980s. This housing typology represents 11.2% of the Broxtowe's housing stock. Table 38 illustrates the property type, alongside the corresponding geometric data, shown in Table 39. The retrofit stages (Stages 1, 2 & 3) and the assumptions used in the simulation were the same as outlined in Section 2.1.

Table 38: Housing archetype – Floor plan and perspective

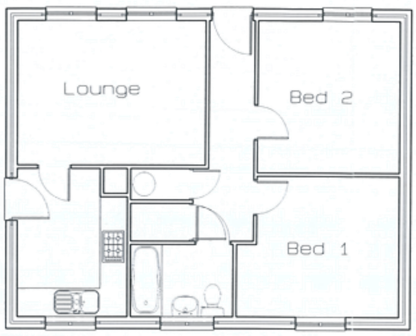
Bungalow	 

Table 39: Housing archetype – Building geometry data and air permeability assumptions

Detached Bungalow - Building Components	Area (m^2)
Ground Floor Area	53.5
Total Floor Area	53.5
Roof (ceiling level)	57.8
Roof (if sloped)	69
Wall (External walls)	86.7
Window	8.1
External Door	3.8
Roof Volume (m^3)	63.5
All internal air volume (m^3) (for infiltration calculation)	130
Wall + Roof + Ground Floor Area (Building Fabric area used for infiltration calculation)	198
ACH if airtight test (very leaky type) is 15 m^3/hm^2 @ 50Pa (and 1/20 rule) -Test / Base	1.14

ACH if airtight test is 8 m^3/hm^2 @ 50Pa (and 1/20 rule) - Optimised to Part L 2021 max. permitted	0.61
ACH if airtight test is 5 m^3/hm^2 @ 50Pa (and 1/20 rule) - Optimised to Part L 2021 notional	0.38

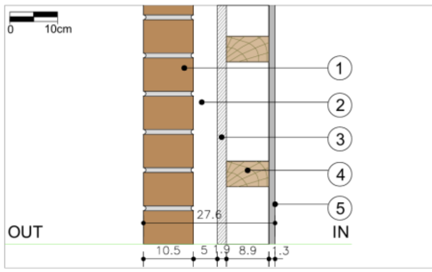
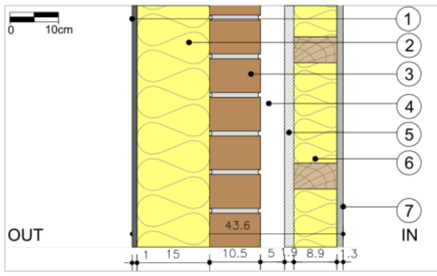
4.2 Building Fabric

In this section, each construction component (walls, roof, floor, glazing and doors) is explored in terms of its material composition and typical U-value. An optimised component is then proposed, based on national standards, and best retrofit practices (as shown in Section 1.2). Notional Part L2021 U-value limits were adopted.

Walls

Wall construction type (as built and optimised) is illustrated in Table 40.

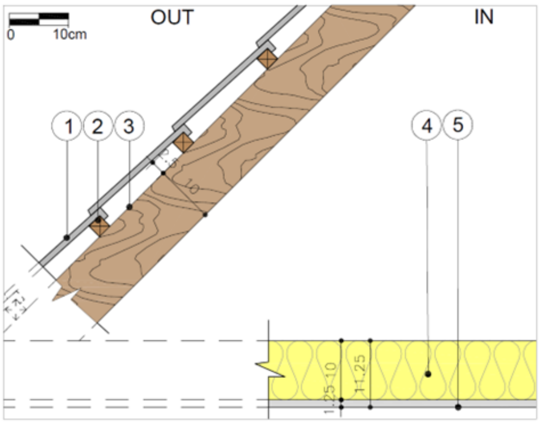
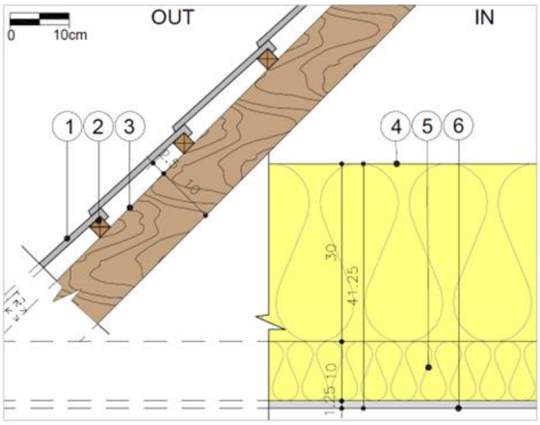
Table 40: Wall construction type – As-built and optimised, based on CIBSE (2019a, p. 3-52, 3-12)

External Wall	Construction specification	U-value (W/m^2K)	Section
As-built based on CIBSE (2019a, p. 3-52, 3-12) Complies with 1976 build. reg ≤ 1.00 W/m^2K	Non-insulated timber frame wall, 50mm cavity Total thickness: 276mm Layers from outside to inside: 1. 105mm solid brick 2. 50mm airspace 3. 19mm plywood sheathing 4. 89mm timber framework/ studding 5. 13mm plasterboard	1.10	
Optimised Target: Part L 2021 notional U-value (W/m^2K) ≤ 0.18	Externally insulated timber frame wall, cavity between timber framework filled with insulation Total thickness: 436mm Layers from outside to inside: 1. 10mm basecoat/mesh/render 2. 150mm EWI Mineral wool 3. 105mm solid brick 4. 50mm airspace 5. 19mm plywood sheathing 6. 89mm mineral wool insulation between timber frameworks 7. 13mm plasterboard	0.16	

Roof

Roof construction type (as built and optimised) is illustrated in Table 41

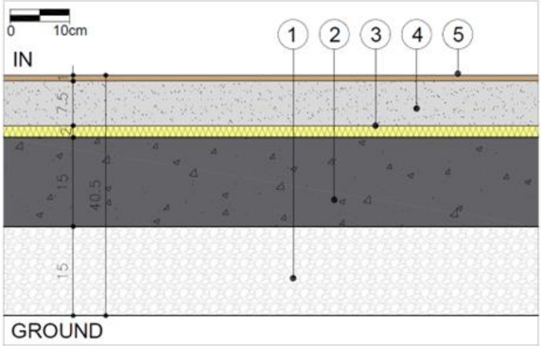
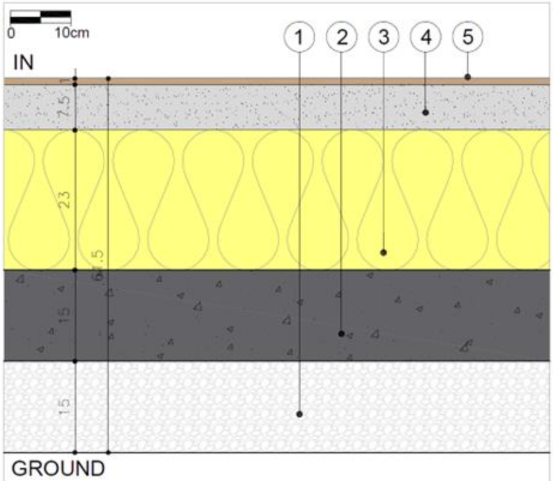
Table 41: Roof construction type – As-built and optimised, based on CIBSE (2019a, p. 3-54)

Roof	Construction specification	U-value (W/m²K)	Section
As-built Based on CIBSE (2019a, p. 3-54) Complies with 1976 build. reg ≤ 0.60 W/m²K	Low insulated pitched roof (cold roof) Total thickness: 112.5mm Layers from outside to inside: 1. 20mm tiles (ventilated) 2. 25mm roof space – battens (ventilated) 3. mm windtight barrier above the rafters 4. 100mm mineral wool between 100mm ceiling joists 5. 12.5mm plasterboard	0.35	
Optimised Target: Part L 2021 notional U-value (W/m²K) ≤ 0.11	Highly insulated pitched roof (insulated at ceiling level) Total thickness: 412.5mm Layers from outside to inside: 1. 20mm tiles (ventilated) 2. 25mm roof space – battens (ventilated) 3. windtight barrier above the rafters 4. 300mm mineral wool over ceiling joists 5. 100mm mineral wool between 100mm ceiling joists 6. 12.5mm plasterboard	0.10	

Floor

Floor construction type (as built and optimised) is illustrated in Table 42.

Table 42: Floor construction type – As-built and optimised, based on CIBSE (2019a, p. 3-55 - 3-56)

Floor	Construction specification	U-value (W/m²K)	Section
As-built Based on CIBSE (2019a, p. 3-55 - 3-56) Complies with 1976 build. reg ≤ 1.00 W/m²K	Low Insulated solid floor Total thickness: 405mm Layers from outside to inside: Ground 1. 150mm hardcore 2. 150mm cast concrete 3. 20mm EPS 4. 75mm screed 5. 10mm carpet	0.77	
Optimised Target: Part L 2021 notional U-value ≤ 0.13 W/m²K if fully re-built	Highly insulated solid floor (it presupposes that the floor was fully rebuilt) Total thickness: 615mm Layers from outside to inside: 1. 150mm hardcore 2. 150mm cast concrete 3. 230mm EPS 4. 75mm screed 5. 10mm carpet	0.13	

Glazing and doors

Proposed improvements to glazing and doors aimed to comply with Part L2021 notional building (Ministry of Housing; Communities and Local Government, 2021) and should be smaller than or equal to 1.20 (6+12+6+12+6mm, 0.98 W/m²K) and 1.00W/m²K, respectively.

4.3 Retrofit Stage 1: Building Fabric Optimisation

The as-built building fabric was first examined to explore the heating demands achieved across the investigated archetype. Following this, a series of simulations were conducted to measure the energy efficiency resulting from cumulative changes in the fabric. These changes aimed to reach the notional levels of Part L 2021, considering a deep retrofit approach. Additionally, a typical retrofit approach was adopted that excluded the more costly and disruptive strategies (as explained in Table 20). The purpose of this investigation was to determine the extent to which energy demand can be reduced by optimising the building fabric. This stage of assessment only involved improved fabric energy efficiency and airtightness levels. There were no active system improvements such as the use of ASHP.

The results analysed are shown in Figure 33.

Detached Bungalow

Deep Retrofit
▪ In the initial as-built scenario, the estimated heating demand was 89 kWh/m². Following the implementation of a series of retrofit measures based on Part L notional levels, the heating demand was reduced to 14 kWh/m², marking an overall reduction of 84% when all the deep retrofit measures were in place. It is noteworthy that loft insulation only resulted in a 2% decrease in heating demand compared to the base case, while solid floor insulation reduced the demand by 11% in scenario 3 compared to scenario 2. ▪ The addition of external wall insulation in scenario 4 had the most significant impact, reducing heating demand by 33% compared to the previous scenario. This is due to its larger exposed envelope area compared to the other fabric elements. ▪ Opting for energy-efficient glazing and doors also proved beneficial, leading to an additional 11% improvement in comparison to the previous scenario, due to a significant improvement in the U-values. However, it is important to note that implementing this measure is both costly and disruptive. ▪ The addition of airtightness and draught-proofing in scenario 6 reduced the heating demand by 19%. Further improvement in airtightness (scenario 7) from 8 to 5 m³/m²h @50 Pa resulted in an additional 8% reduction.
Typical retrofit
▪ The initial heating demand was estimated to be 89 kWh/m². After implementing a series of retrofit measures, the heating demand was reduced to 41 kWh/m², representing a significant reduction of 54%. ▪ According to the results presented in Figure 33, loft insulation only reduced the heating demand by 2% in scenario 2 compared to the base case (scenario 1). While this had a relatively small impact on reducing heating demand, it is also one of the easiest strategies to implement. ▪ Furthermore, external wall insulation was found to be the most impactful measure, reducing the heating demand by 29% in scenario 3 compared to scenario 2. This is due to its larger exposed envelope area compared to the other fabric elements. ▪ The addition of airtightness and draught-proofing in scenario 4 decreased the heating demand by 16%. Further improvement in airtightness (scenario 5) from 8 to 5 m³/m²h @50 Pa resulted in an overall 54% reduction in heating demand.

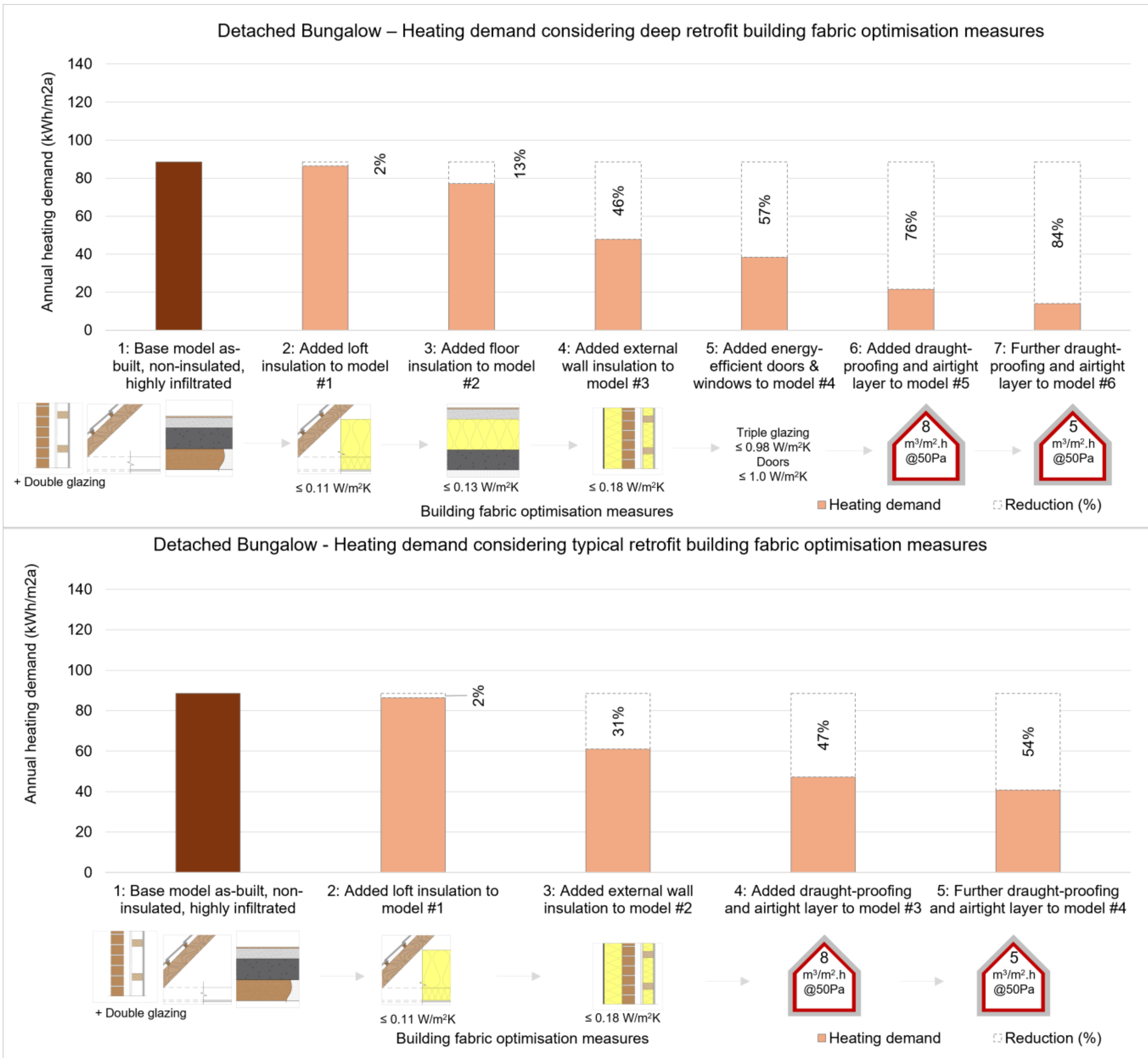


Figure 33: Deep & typical retrofit fabric measures – Detached Bungalow

4.4 Retrofit Stage 2 & Stage 3: Low-Carbon Heating & Renewable Energy Generation

The following section looks at the simulations carried out to measure the energy, carbon and cost impact achieved by the adoption of low-carbon heating system in comparison to typical gas heating system. One of the main aims is to gain an insight into which stage of building fabric optimisation measures, ASHP can be installed without negatively impacting on household energy bills.

For space heating and domestic hot water (DHW), typical gas boiler and ASHP heating systems were adopted for comparative purposes. Heating inputs were considered, as mentioned in Table 23, and DHW mean consumption was assumed as 112.2 litres/day for a two-person occupancy (Hot water assumptions in the Home Energy Model: FHS assessment wrapper, 2023).

The seasonal efficiencies and SCOP for the gas boiler and ASHP were assumed the same as mentioned in Section 2.4

A solar PV system was adopted for renewable energy generation. For simulation purposes, 14 solar panels were considered based on the usable roof size. The panel type was monocrystalline silicon, and the other specifications include a panel size of $2m^2$, module nominal efficiency of 0.20, nominal cell temperature (NOCT) of 42°C, and temperature coefficient for module efficiency Pmax as -0.36%/°C (Jinko Solar, 2020). All the panels were inclined at 33° and oriented southeast.

The total energy demand was calculated by considering the energy needed to run the house over a year, based on space heating, electricity (lighting and appliances), and hot water inputs.

The natural gas and electricity have carbon emission factors equivalent to 0.21 $kgCO_2e$/kWh and 0.086 $kgCO_2e$/kWh respectively (Fuel factors within the Home Energy Model: FHS assessment, 2023).

The comparative annual running costs of gas and low-carbon heating systems were calculated, considering the cumulative building fabric optimised changes targeting the Part L 2021 notional levels. For the cost analyses, the daily standing charge was considered for both gas and electricity. The assumptions concerning the energy tariffs and carbon emissions factors are mentioned in Table 27. The energy tariffs are average and use direct debit payment as a reference (Ofgem, 2024).

Detached Bungalow

Figure 34 illustrates a comparison of simulation results for energy consumption and carbon emissions between ASHP and a conventional gas heating system for deep retrofit and typical retrofit scenarios. A consistent trend is evident across both retrofit scenarios, prompting a detailed explanation of the simulation results for deep retrofit scenarios for better comprehension.

The energy consumption with gas boiler heating systems was much higher in leaky, non-insulated scenario. However, when fabric optimisation measures were considered, energy consumption was significantly reduced. In the initial, as-built scenario, the annual energy consumption (including gas and electricity) was 11.7 MWh. After implementing fabric optimisation measures, the overall energy consumption dropped by 43% to 6.7MWh. When renewable energy sources were added, the energy demand decreased further to 3 MWh. When using an ASHP, the total energy consumption was significantly lower than a gas boiler heating system. This was due to the efficiency of the system and inputs adopted. The building fabric's sequential improvement could further reduce energy consumption. The total annual energy consumption for the uninsulated envelope using an ASHP corresponded to 6.7MWh. Once the fabric optimisation measures were considered, the energy demand was reduced by 43%, reaching nearly 3.8MWh. Renewable energy further reduced the total annual energy consumption to 0.1MWh.

In terms of carbon emissions, a considerable difference in the results was observed when considering a traditional gas boiler as a heating system compared to an ASHP. As expected, the carbon emissions attributable to the gas boiler system were significantly higher than the low-carbon heating system. The carbon emission values when considering a traditional gas boiler heating system corresponded to 2 tonnes CO_2e/yr, reducing to 1.0 tonne CO_2e/yr once the fabric optimisation measures were considered. Comparatively, when adopting ASHP, the carbon emissions corresponded to 0.5 tonnes CO_2e/yr and were reduced to half when the fabric optimisation measures were considered, respectively. Renewable energy further reduced the total carbon emissions to 0 tonnes CO_2e/yr. It is noteworthy that the external wall insulation of the fabric optimisation measures contributed significantly to reducing energy consumption and carbon emissions.

The overall energy and carbon simulation results indicated that implementing fabric optimisation measures led to more than a 50% reduction in both energy consumption and carbon emissions. Furthermore, it was also observed that simply switching to a low-carbon heating system without adopting any fabric measures led to a 72% decrease in carbon emissions, when compared to the emissions produced by gas heating systems. This shows that replacing fossil fuels-based systems with low-carbon heating, most likely ASHPs, in combination with the decarbonisation of the electricity grid, can achieve significant carbon emission reductions. However, it is crucial that fabric retrofit measures precede the installation of low-carbon alternatives to ensure consumer energy bills remain affordable and demand can be met. ASHPs are most suited to installation in better-insulated, quality-built homes that demand lower heat output due to their operation at lower temperatures. Its adoption in leaky homes means that ASHP runs continuously and is likely to negatively impact the thermal comfort of the occupants, assuming radiators are kept at the typical sizes.

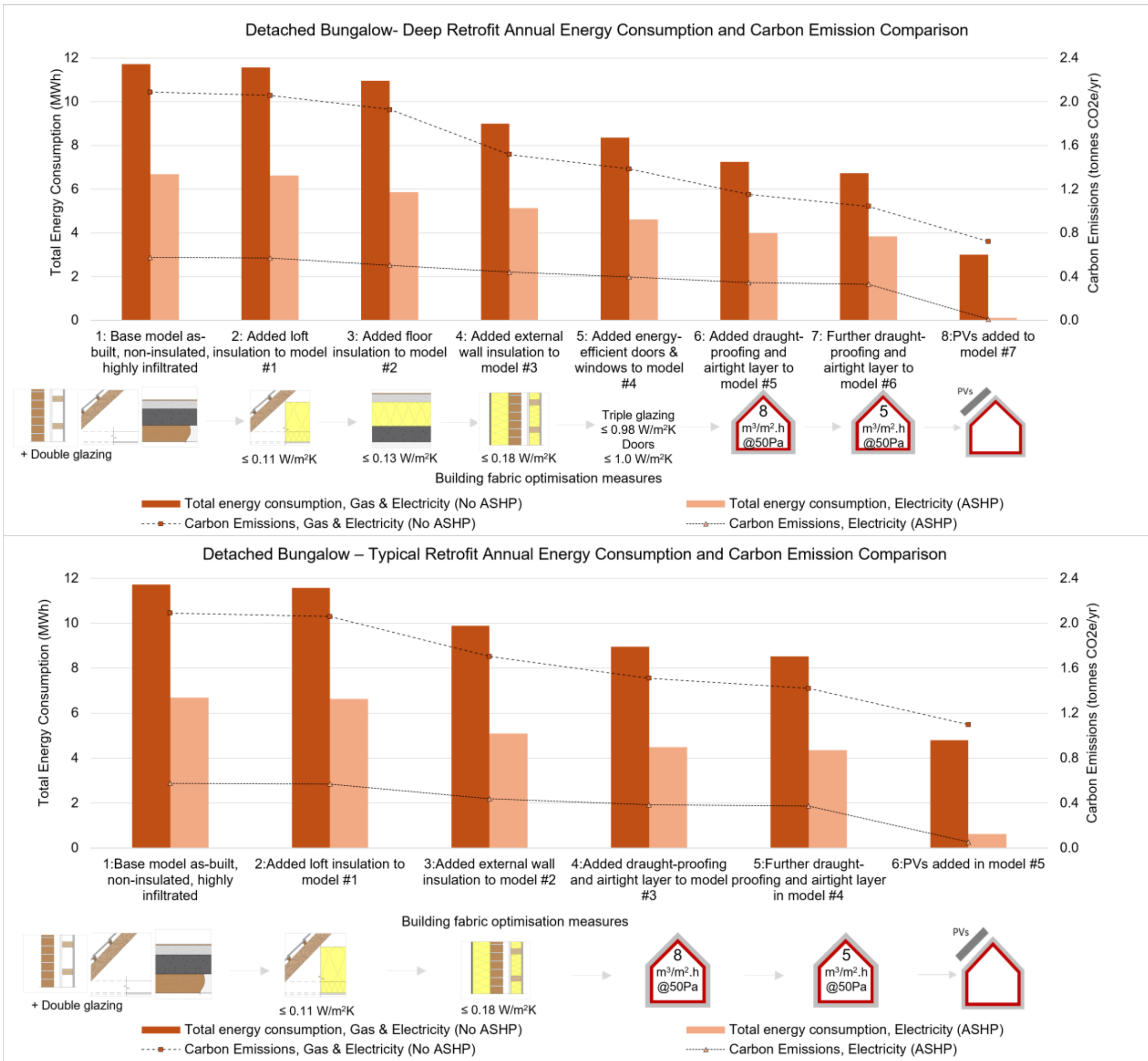


Figure 34: Deep & typical retrofits – heating systems annual energy demand & carbon emission – Bungalow

Annual running energy costs- Cap period October–December 2024

Figure 35 illustrates the comparative annual energy costs between ASHP and a conventional gas heating system for deep retrofit and typical retrofit scenarios. The annual running costs calculated for winter 2024 (October–December 2024 cap period) showed a gradual reduction across the sequential fabric optimisation scenarios, independent of the heating system adopted.

With all the deep retrofit measures adopted (up to Scenario 7), the annual energy cost while considering the gas heating system was reduced by 19% compared to the base case scenario. Comparatively, with a low-carbon heating system adopted, the energy cost was reduced by 37% compared to the base case, non-retrofit scenario.

Similarly, after implementing all typical retrofit measures up to Scenario 5, the annual energy cost using a gas heating system was reduced by 12% compared to the base case scenario. Comparatively, with a low-carbon heating system adopted, the energy cost was reduced by 31% compared to the base case, non-retrofit scenario.

This highlights the suitability of heat pumps for installation in well-insulated, high-quality homes with lower heat output demands. Additionally, the cost analyses comparing ASHP to gas heating systems for deep and typical retrofit scenarios indicated that the optimal stage to install an ASHP is after the adoption of wall insulation, i.e., Scenario 4 of deep retrofit and Scenario 3 of typical retrofit, thereby ensuring that the ASHP performance is not diminished by low-quality fabric.

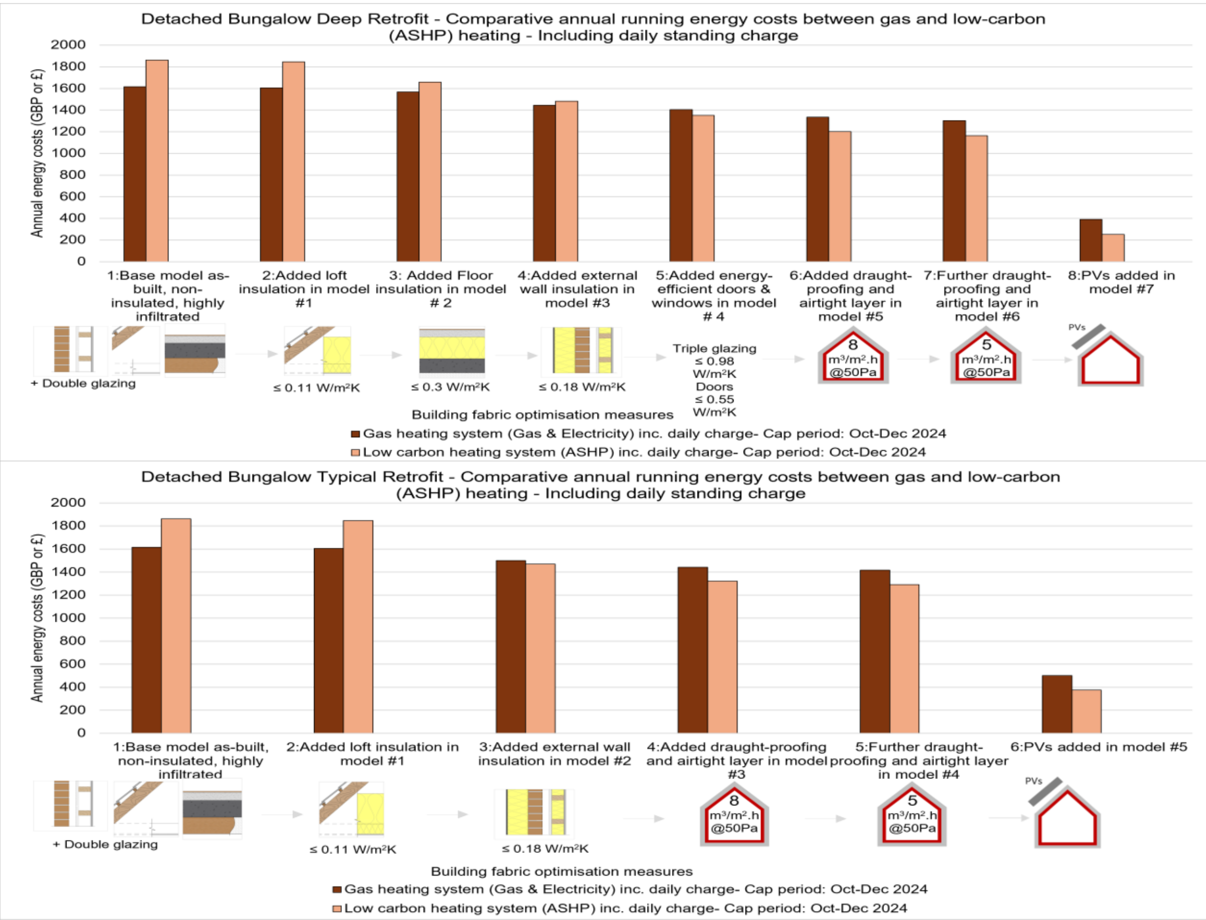


Figure 35: Deep & typical retrofits – heating systems annual costs – Bungalow

4.5 Summary

This section presents a summary of the energy and carbon performance assessment for the specific housing stock, along with a comparative analysis between 'deep retrofit' and 'typical retrofit' scenarios.

The 'deep retrofit' scenario resulted in greater reductions in energy consumption and operational carbon emissions. This is primarily due to the implementation of more extensive fabric upgrades. These upgrades, such as the installation of floor insulation and triple-glazed windows were excluded from the 'typical retrofit' scenario.

Overall energy consumption showed that the 'deep retrofit' scenario achieved a further reduction of approximately 21% from the 'typical retrofit' measures. Additionally, adopting low-carbon heating systems has demonstrated lower energy consumption than traditional gas heating systems. The cost analyses also suggested that they had marginally lower annual costs when compared to the traditional heating system. Moreover, with the UK transitioning to a decarbonised energy system by around 2050, renewable costs are expected to become cheaper than fossil fuels in the coming years, and so will the energy costs.

The most significant fabric measure identified was the implementation of wall insulation, which proved more effective than the other retrofit strategies. This reduction can be attributed to the larger exposed envelope area of the wall insulation compared to other fabric elements.

Table 43 presents a summary of the key results related to annual heating demand, total energy consumption, carbon emissions and estimated annual running costs for the specific housing stock in both 'deep retrofit' and 'typical retrofit' scenarios.

Table 43: Summary of key results related to annual heating demand, total energy consumption, carbon emissions and estimated annual running costs for the detached bungalow archetype.

Detached Bungalow - Deep retrofit/ Typical retrofit									
		1 Base model as-built, non-insulated, highly infiltrated	2 Added loft insulation to model #1	3 Added floor insulation to model #2	4 Added external wall insulation to model #3	5 Added energy-efficient doors & windows to model #4	6 Added draught-proofing and airtight layer to model #5	7 Further draught-proofing and airtight layer to model #6	8 PVs added to model #7
Annual heating demand (kWh/m²a)		89	86/ 86	77/ -	48/ 61	38/ -	22/ 47	14/ 41	-
Total energy consumption (kWh)	Gas heating	11,714	11,569/ 11,569	10,957/ -	8990/ 9877	8364/ -	7244/ 8956	6729/ 8524	2996/ 4791
	ASHP	6692	6627/ 6627	5865/ -	5139/ 5090	4611/ -	3999/ 4484	3846/ 4360	113/ 626
Carbon emissions ($kgCO_{2e}$/yr)	Gas heating	2089	2058/ 2058	1930/ -	1517/ 1703	1385/ -	1150/ 1510	1042/ 1419	721/ 1098
	ASHP	576	570/ 570	504/ -	442/ 438	397/ -	344/ 386	331/ 375	10/ 54
Annual running costs (GBP or £)	Gas heating	1615	1606/ 1606	1567/ -	1445/ 1500	1406/ -	1336/ 1443	1304/ 1416	389/ 501
	ASHP	1862	1846/ 1846	1659/ -	1481/ 1469	1352/ -	1202/ 1321	1165/ 1290	250/ 376

5 Retrofit Specific Housing Embodied Carbon Calculations

In this Section, embodied carbon calculations are undertaken for the specific house-type as defined within Section 4. The same methodology has been adopted, as was specified within Section 3.1.

5.1 Results

Using the base building assumptions as defined within Section 0, an embodied carbon model has been created for the specific house-type. In Table *44* a summary results table is provided, comparing the deep and typical retrofit scenarios.

Table 44: Embodied Carbon Results Summary (Deep and Typical Retrofit)

Property-build type	Generic/ Specific	Type	A1-A5, B1-B5, C1-C4 ($kgCO_2e/m2$)	GIA (m2)	A1-A5, B1-B5, C1-C4 (TCO_2e)
Bungalow	Specific	Deep	240.97	53.50	12.89
	Specific	Typical	173.67	53.50	9.29

Within Table 45, the embodied carbon results for the generic house types (as determined within Section 3) are compared with the results for the specific house-type (bungalow) as set out within Table 44.

Table 45: Embodied Carbon (A1-A5, B1-B5,C1-C4) Results Summary - All House Types (Deep and Typical)

Property-build type	Generic/ Specific	Type	A1-A5, B1-B5,C1-C4 ($kgCO_2e/m2$)	GIA (m2)	A1-A5, B1-B5,C1-C4 (TCO_2e)
Detached	Generic	Deep	138.42	89.90	12.44
	Generic	Typical	97.05	89.90	8.73
Semi-detached	Generic	Deep	136.45	89.90	12.27
	Generic	Typical	86.99	89.90	7.82
Mid-terraced	Generic	Deep	118.99	89.70	10.67
	Generic	Typical	72.57	89.70	6.51
End-terraced	Generic	Deep	128.07	89.70	11.49
	Generic	Typical	85.00	89.70	7.62
Mid-terraced Flat (Whole)	Generic	Deep	108.95	112.90	6.26
	Generic	Typical	108.95	112.90	7.60
End-terraced Flat (Whole)	Generic	Deep	108.95	112.90	12.30
	Generic	Typical	108.95	112.90	7.60
Mid-terraced Flat	Generic	Deep	123.04	50.90	6.26
	Generic	Typical	81.53	50.90	4.15
End-terraced Flat	Generic	Deep	118.34	62.00	7.34
	Generic	Typical	76.82	62.00	4.76

Full data exports are provided in Appendix B: Embodied Carbon Data Exports.Table 45 provides a summary of total embodied carbon emissions only. To understand the embodied carbon impact at Retrofit Stages 1, 2 and 3 (as defined within Section 0), a more detailed breakdown is required. The following Tables and Figures therefore provide the necessary data.

Table 46: Combined Global Warming Potential for Bungalow (Typical Retrofit Scenario)

Category	**Global warming potential - non-decarbonised scenario $kgCO_2e$ - Resource types**
House Type	Bungalow
Stone wool insulation	42.14
Energy production systems from renewable energy	73.49
HVAC equipment with refrigerant	23.26
Render	14.54
Other site operation	9.24
Refrigerant fluids	7.57
Textiles and wallpapers	2.53
Plastic profiles and products	0.54
HVAC components and equipment	0.35
Total	173.67

Table 47: Combined Global Warming Potential for Bungalow (Deep Retrofit Scenario)

Category	**Global warming potential - non-decarbonised scenario $kgCO_2e$ - Resource types**
House Type	Bungalow
Stone wool insulation	42.14
Other insulation	35.83
Energy production systems from renewable energy	73.49
HVAC equipment with refrigerant	22.19
Render	14.54
Other site operation	13.83
PVC frame windows	13.10
Refrigerant fluids	7.57
Textiles and wallpapers	13.19
Other resource types	5.07
Total	240.97

To understand the specific embodied carbon impact at Retrofit Stages 1, 2 and 3 (as defined within Section 0), a more detailed breakdown is required, as provided within Table 48.

Table 48: Breakdown by Retrofit Stage for the specific house type (Typical Retrofit Scenario)

	Global Warming Potential ($kgCO_2e/m2$)	**Percentage of Total**
Retrofit Stage 1 - Fabric	69.00	40%
Retrofit Stage 2 - Low Carbon Heating	31.18	18%
Retrofit Stage 3 - Renewable Technology	73.49	42%
Total	173.67	100%

Table 49: Breakdown by Retrofit Stage for the specific house type (Deep Retrofit Scenario)

	Global Warming Potential ($kgCO_2e/m2$)	**Percentage of Total**
Retrofit Stage 1 - Fabric	137.71	57%
Retrofit Stage 2 - Low Carbon Heating	29.76	12%
Retrofit Stage 3 - Renewable Technology	73.49	30%
Total	240.97	100%

Using the output data, a series of graphical representations of the results are provided at **Error! Reference source not found.**, Figure 37, Figure 38, Figure 39 and Figure 40.

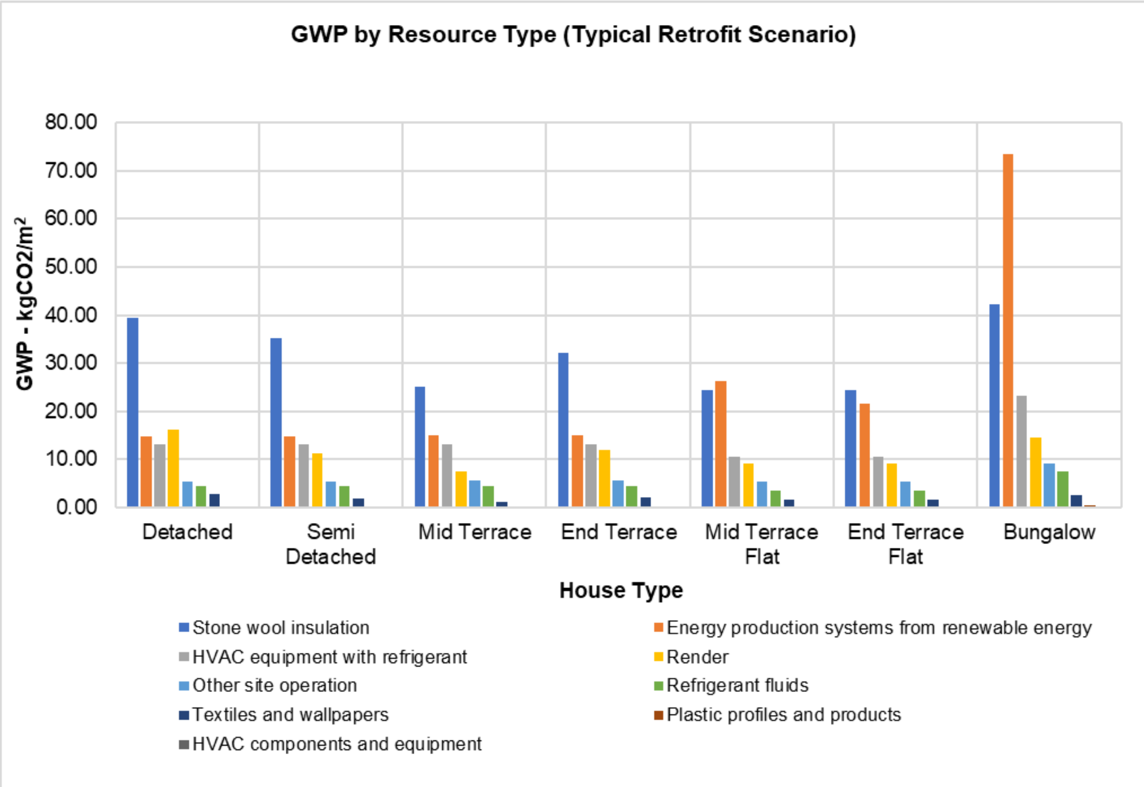


Figure 36: GWP by Resource Type - All House Types (Typical Retrofit)

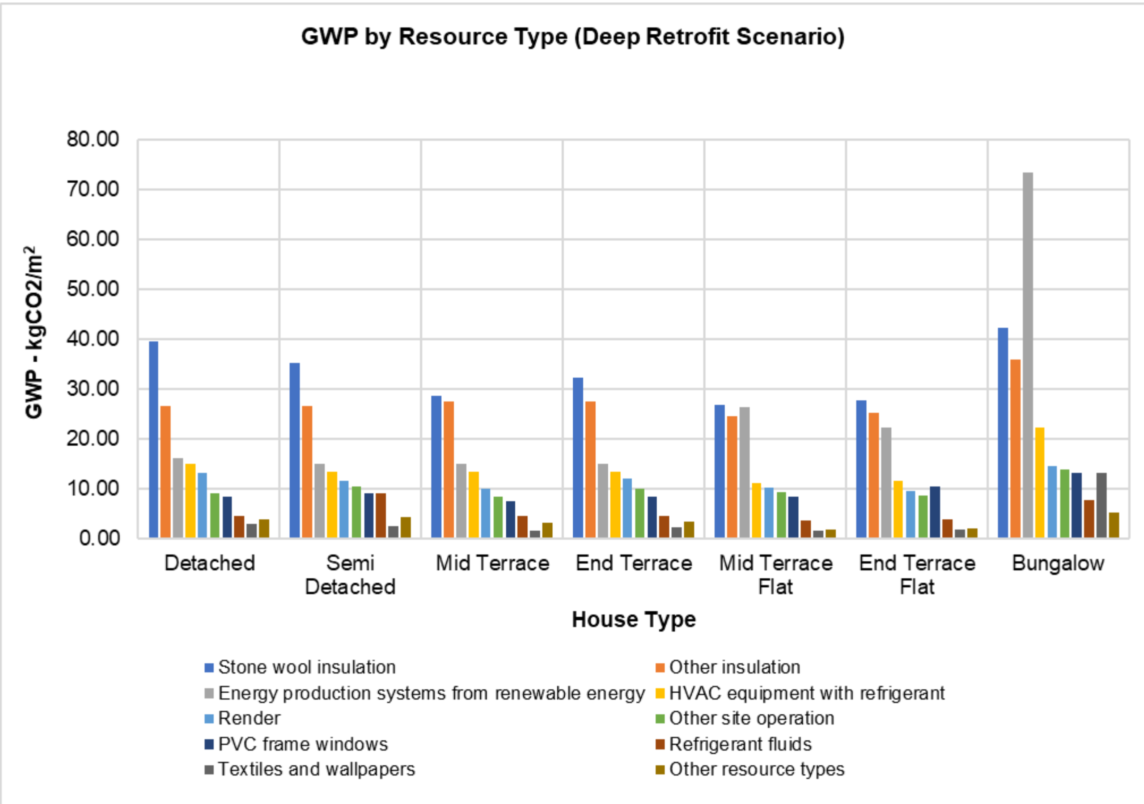


Figure 37: GWP by Resource Type – All House Types (Deep Retrofit Scenario)

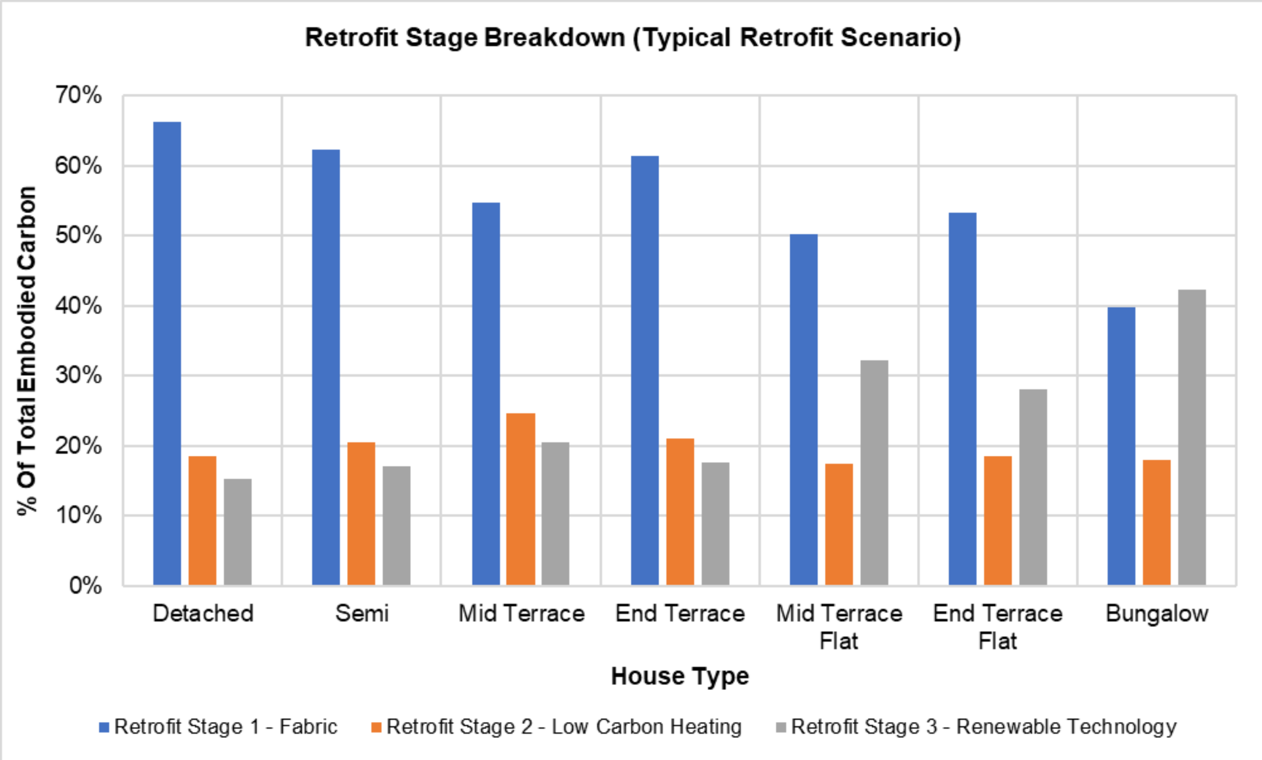


Figure 38: Retrofit Stage Breakdown by Percentage (Typical Retrofit)

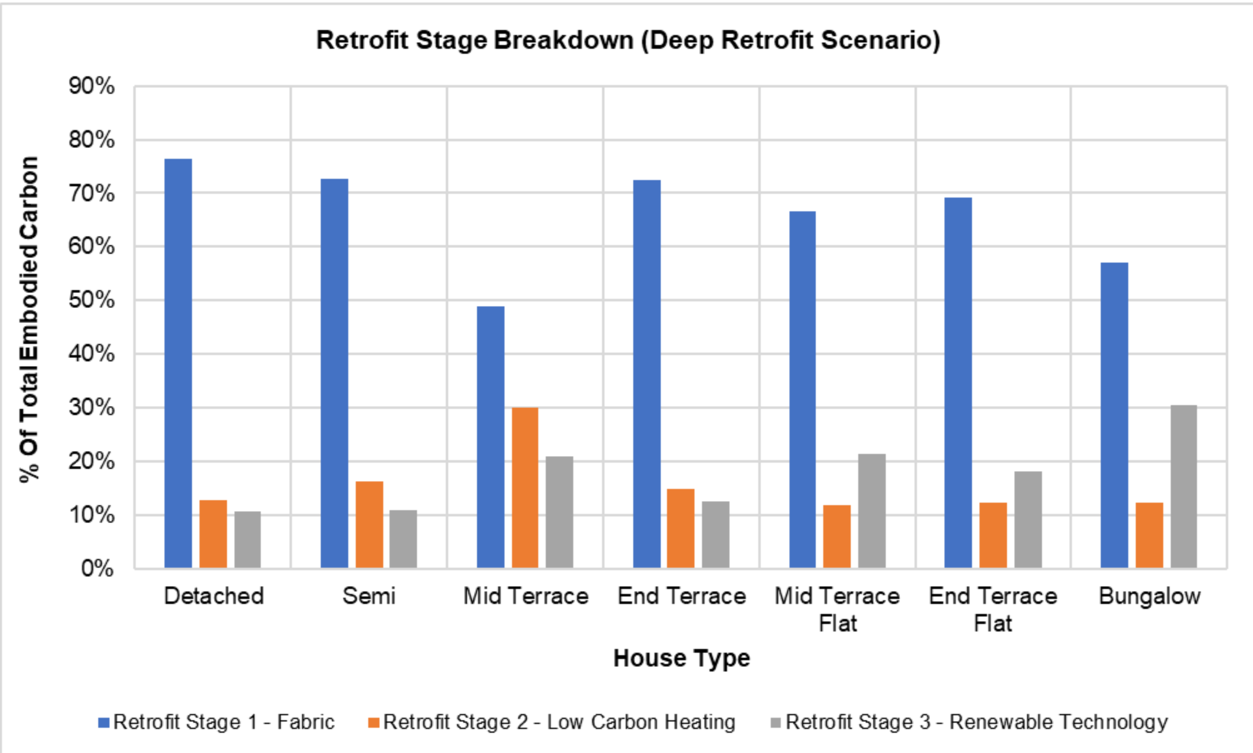


Figure 39: Retrofit Stage Breakdown by Percentage (Deep Retrofit)

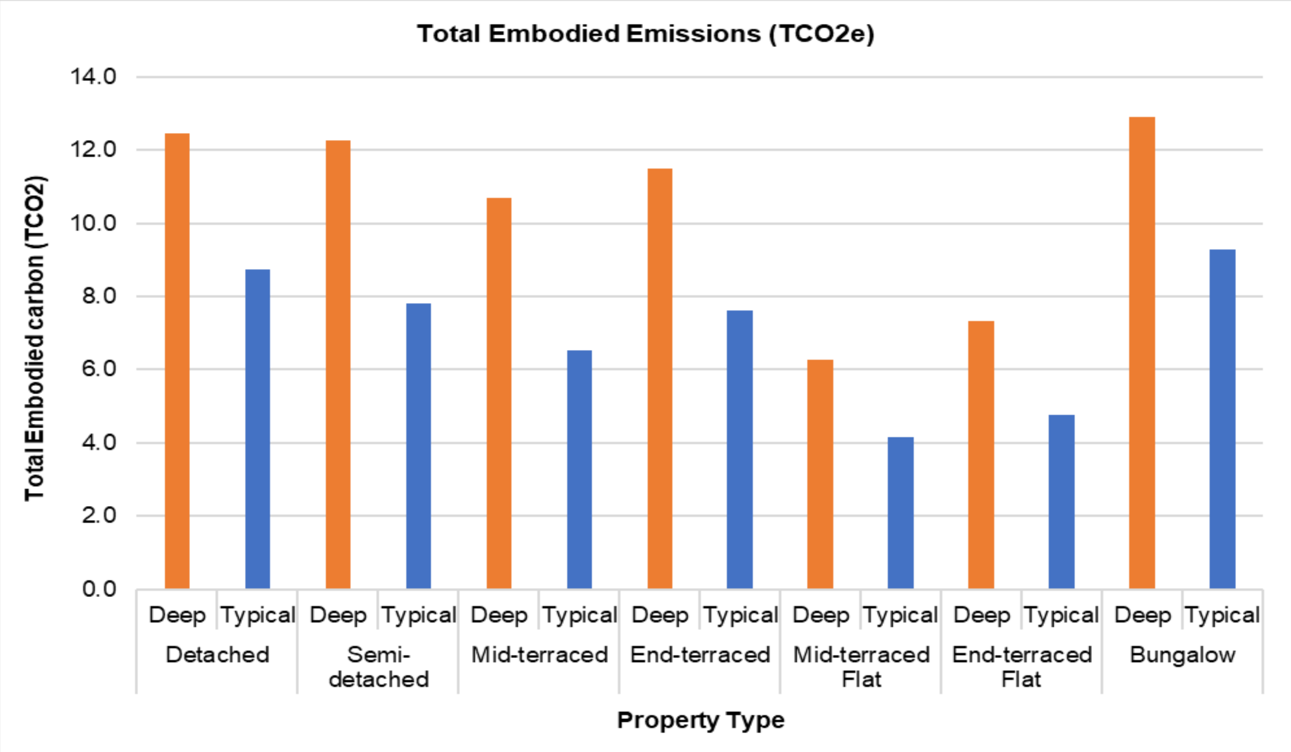


Figure 40: Total Embodied Emissions - All House Types (TCO_2e)

5.2 Summary

For the specific house type, the typical retrofit scenario achieves approximately 70% of the emissions generated by the deep retrofit, which is in line with the findings of the generic house type study. For the bungalow, a typical retrofit will emit approximately 173.7kgCO_2e/m² compared to 241.0kgCO_2e/m² for the deep scenario. Considering all house types, the Global Warming Potential (GWP) per square meter of the property is highest for bungalows. This is driven primarily by the increased quantum of PV at 28m^2 compared to 10m^2 for the other property types. Another factor is the high heat loss perimeter surface area, when compared as a ratio to internal floor area. The total embodied carbon emissions of 12.9tonnes and 9.3tonnes for the deep and typical scenarios respectively, are considerably higher than other property types, as illustrated in Table 45.

For the specific house type, renewable energy is the largest contributor to embodied emissions across both retrofit scenarios. Considering the typical scenario, renewable energy accounts for 73.5kgCO_2e/m² or 40% of embodied emissions. The standardisation of HVAC equipment across all property types, results in a comparable total embodied carbon impact, although, on a square-metre basis, emissions are higher.

For the deep retrofit scenario specifically, EPS Floor Insulation within the bungalow emerged as one of the most carbon-intensive additions, contributing 35.8kgCO_2e/m² to the overall emissions. This compares to 26.5kgCO_2e/m² for the Spacetherm Aerogel insulation in the detached house type (generic scenario). This method of floor insulation is less effective in reducing embodied emissions. Additionally, it requires the ground floor level to be altered significantly which can be costly and time consuming.

In conclusion, for the bungalow, implementing a typical retrofit results in a saving of roughly 28% in embodied carbon, compared to the deep retrofit scenario. A deep retrofit results in 12.9tonnes of

CO_2e whereas a typical retrofit generates 9.3tonnes of CO_2e. This additional 3.6tonnes of CO_2e is what must be saved in operational carbon emissions over the lifetime of the property to make the deep retrofit scenario worth pursuing.

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6 Lifetime Capital Cost of Retrofit

In this Section, the Lifetime Capital Cost of deep and typical retrofit is estimated. In general, the assumptions made within this Section align with the materials, specifications, and quantities as set out within Section 2.3 (Building Fabric Optimisation) and Sections 3 and 5 (Embodied Carbon Calculation).

6.1 Assumptions

General

All cost estimations include labour, calculated on a day rate based on the property type and associated floor area. The Reference Study Period (RSP) used within the data analysis is 20-years, which aligns with Section 3.1 (Methodology and Assumptions).

All estimations are VAT exclusive.

Building Fabric Optimisation

For External Wall Insulation (EWI), the build-up includes 230mm of Rockwool External Wall Dual Density Slab, with a Fibreglass Mesh, EWI Premium Dual Basecoat Adhesive, and EWI-075 Silicone Render. For loft insulation, 400mm of Knauf Loft roll 44 has been assumed. For the specific house type, the EWI build-up includes a reduced insulation thickness of 150mm, due to the improved base-build fabric performance.

The application of EWI to both the typical and deep retrofit scenarios results in improvements to air tightness. Additionally, loft hatch strips, letter box and keyhole draft excluders, external door storm guard draft strips and external window calking has been assumed, to improve air tightness to the specified levels.

For deep retrofit, replacement triple glazing is assumed, including adhesives and seals. External window caulking is therefore excluded. For ground floor insulation, the deep retrofit includes 40mm of Spacetherm Aerogel Insulation, finished with 3mm of chipboard and secured with adhesives, nails, and tape. For the specific house type, a different ground floor build up has been assumed due to the age of the property (see Section 4). Therefore, the ground floor insulation strategy assumed for the deep retrofit scenario assumes the removal of the existing screed and EPS insulation and replacement with a like-for-like alternative at an increased thickness of 230mm. The ground floor insulation strategy results in an increased floor level of approximately 200mm. Cost allowances have been made for adjustments to doors, thresholds, and ceilings.

Building fabric measures are assumed to have a life expectancy of 60-years. No system replacements are assumed during the life cycle.

Low-Carbon Heating

A 5kW Mitsubishi Ecodan air-to-water heat pump has been assumed, with a 200L DHW tank suitable for dwellings with 2-3 person occupancy. Both typical and deep retrofit scenarios assume retention of existing radiators, with only minor adjustments to connections and pipework.

It has been established that the introduction of Mechanical Ventilation with Heat Recovery (MVHR) has a negligible impact on energy reduction. That said, the introduction of EWI and other fabric improvements will impact internal humidity levels; increasing the risk of moisture-related fabric defects. The modelling therefore assumes the introduction of decentralised Mechanical Extract Ventilation (dMEV), which will be demand-controlled to automatically activate according to internal humidity and temperature levels.

Low carbon heating measures are assumed to have a life expectancy of 20-years. No system replacements are assumed during the life cycle.

Renewable Energy Generation

For the detached, semi-detached, and terraced house-types, 5no. Jinko Tiger Neo 440Wp solar panels have been assumed. For the specific house type, 14no. solar panels have been assumed. The capital cost estimations include all system elements including inverter, wiring and connection equipment, monitoring console, and roof mounting. For the ground and first floor flats, it has been assumed that a shared 5no. panel array serves both dwellings.

Renewable energy generation measures are assumed to have a life expectancy of 20-years. No system replacements are assumed during the life cycle.

Incurred Costs

Incurred costs relate to surveys and enabling work, contractor preliminary costs (3%), contractor overhead and profit (8%), and risk allowance (8%). All cost estimations are inclusive of incurred costs.

Enabling works to Roof and Eaves

An additional sum of £3,000 was allocated to account for potential works required to the roof or eaves, ensuring that the insulation could be installed to the appropriate standards. This provision was made to address any structural adjustments or repairs necessary to facilitate proper installation and long-term performance of the insulation system.

6.2 Lifetime Capital Costs

The Lifetime Capital Cost estimations within this Section align with the specifications, materials, and quantities used within the OneClick LCA embodied carbon model, for the associated property type. Costs are taken from supplier data where possible. For incurred costs and other elements where supplier data is not available, benchmark data has been applied from domestic retrofit projects completed in the UK during 2024. Where relevant, costs include end-of life-system replacement, as specified within Section 6.1.

Typical Retrofit – Generic

Within Table 50, the Lifetime Capital Cost for typical retrofit has been estimated, for the generic property types. Further detail and pricing breakdown can be made available upon request.

Table 50 – Lifetime Capital Cost for typical retrofit (generic property types)

	Description	Unit	Quantity	Rate (£/Unit)	Total
Detached	EWI & Air Tightness	m2	159.00	£174.66	Inc. Below
	Loft Insulation	m2	57.60	£20.94	Inc. Below
	Building Fabric Optimisation Sub-Total (Exc. VAT)				£35,632.65
	Low-Carbon Heating Systems Sub-Total (Exc. VAT)				£12,199.52
	Renewable Energy Generation Sub-Total (Exc. VAT)				£7,968.24

	Combined Total (Exc. VAT)				£55,800.41
Semi-Detached	Description	Unit	Quantity	Rate (£/Unit)	Total
	EWI & Air Tightness	m2	112.00	£174.66	Inc. Below
	Loft Insulation	m2	48.70	£20.94	Inc. Below
	Building Fabric Optimisation Sub-Total (Exc. VAT)				£25,494.28
	Low-Carbon Heating Systems Sub-Total (Exc. VAT)				£12,288.86
	Renewable Energy Generation Sub-Total (Exc. VAT)				£8,026.59
	Total (Exc. VAT)				£45,809.72
Mid-Terrace	Description	Unit	Quantity	Rate (£/Unit)	Total
	EWI & Air Tightness	m2	72.90	£174.66	Inc. Below
	Loft Insulation	m2	53.20	£20.94	Inc. Below
	Building Fabric Optimisation Sub-Total (Exc. VAT)				£17,301.72
	Low-Carbon Heating Systems Sub-Total (Exc. VAT)				£12,396.37
	Renewable Energy Generation Sub-Total (Exc. VAT)				£8,096.81
	Total (Exc. VAT)				£37,794.91
End Terrace	Description	Unit	Quantity	Rate (£/Unit)	Total
	EWI & Air Tightness	m2	118.50	£174.66	Inc. Below
	Loft Insulation	m2	53.20	£20.94	Inc. Below
	Building Fabric Optimisation Sub-Total (Exc. VAT)				£26,983.10
	Low-Carbon Heating Systems Sub-Total (Exc. VAT)				£12,273.32
	Renewable Energy Generation Sub-Total (Exc. VAT)				£8,016.44
	Total (Exc. VAT)				£47,272.86
Mid-Terrace Flat	Description	Unit	Quantity	Rate (£/Unit)	Total
	EWI & Air Tightness	m2	51.70	£174.66	Inc. Below
	Loft Insulation	m2	22.90	£20.94	Inc. Below
	Building Fabric Optimisation Sub-Total (Exc. VAT)				£12,045.35
	Low-Carbon Heating Systems Sub-Total (Exc. VAT)				£14,230.35
	Renewable Energy Generation Sub-Total (Exc. VAT)				£8,139.49
	Total (Exc. VAT)				£34,208.64
End Terrace Flat	Description	Unit	Quantity	Rate (£/Unit)	Total
	EWI & Air Tightness	m2	63.00	£174.66	Inc. Below
	Loft Insulation	m2	28.00	£20.94	Inc. Below
	Building Fabric Optimisation Sub-Total (Exc. VAT)				£14,581.22
	Low-Carbon Heating Systems Sub-Total (Exc. VAT)				£14,142.17
	Renewable Energy Generation Sub-Total (Exc. VAT)				£8,109.17
	Total (Exc. VAT)				£36,677.65

Typical Retrofit – Specific (Bungalow)

Within Table 51, the Lifetime Capital Cost for typical retrofit has been estimated, for the specific property type. Further detail and pricing breakdown can be made available upon request.

Table 51 - Lifetime Capital Cost for typical retrofit (specific property type)

	Description	Unit	Quantity	Rate (£/Unit)	Total
Bungalow (Specific)	EWI & Air Tightness	m2	86.70	£137.90	Inc. Below
	Loft Insulation	m2	57.80	£20.94	Inc. Below
	Building Fabric Optimisation Sub-Total (Exc. VAT)				£16,354.11
	Low-Carbon Heating Systems Sub-Total (Exc. VAT)				£12,323.44
	Renewable Energy Generation Sub-Total (Exc. VAT)				£14,190.41
	Combined Total (Exc. VAT)				£42,867.96

Deep Retrofit – Generic

Within Table 52, the Lifetime Capital Cost for deep retrofit has been estimated, for the generic property types. Further detail and pricing breakdown can be made available upon request.

Table 52 - Lifetime Capital Cost for deep retrofit (generic property types)

	Description	Unit	Quantity	Rate (£/Unit)	Total
Detached	EWI & Air Tightness	m2	159.00	£155.80	Inc. Below
	External Windows & Doors	m2	14.97	£389.29	Inc. Below
	Loft Insulation	m2	57.60	£20.94	Inc. Below
	Ground Floor Insulation	m2	48.70	£447.50	Inc. Below
	Building Fabric Optimisation Sub-Total (Exc. VAT)				£68,980.36
	Low-Carbon Heating Systems Sub-Total (Exc. VAT)				£12,091.39
	Renewable Energy Generation Sub-Total (Exc. VAT)				£7,897.61
	Combined Total (Exc. VAT)				£88,969.37
Semi-Detached	Description	Unit	Quantity	Rate (£/Unit)	Total
	EWI & Air Tightness	m2	112.0	£155.80	Inc. Below
	External Windows & Doors	m2	15.00	£389.29	Inc. Below
	Loft Insulation	m2	48.70	£20.94	Inc. Below
	Ground Floor Insulation	m2	48.70	£447.50	Inc. Below
	Building Fabric Optimisation Sub-Total (Exc. VAT)				£58,928.37
	Low-Carbon Heating Systems Sub-Total (Exc. VAT)				£12,128.48
	Renewable Energy Generation Sub-Total (Exc. VAT)				£7,921.84
	Combined Total (Exc. VAT)				£78,978.68
Mid-Terrace	Description	Unit	Quantity	Rate (£/Unit)	Total
	EWI & Air Tightness	m2	72.90	£155.80	Inc. Below
	External Windows & Doors	m2	16.40	£389.29	Inc. Below
	Loft Insulation	m2	53.20	£20.94	Inc. Below
	Ground Floor Insulation	m2	50.30	£447.50	Inc. Below
	Building Fabric Optimisation Sub-Total (Exc. VAT)				£52,344.72
	Low-Carbon Heating Systems Sub-Total (Exc. VAT)				£12,158.43
	Renewable Energy Generation Sub-Total (Exc. VAT)				£7,941.40
	Combined Total (Exc. VAT)				£72,444.55
End Terrace	Description	Unit	Quantity	Rate (£/Unit)	Total
	EWI & Air Tightness	m2	118.50	£155.80	Inc. Below
	External Windows & Doors	m2	16.40	£389.29	Inc. Below
	Loft Insulation	m2	53.20	£20.94	Inc. Below
	Ground Floor Insulation	m2	50.30	£447.50	Inc. Below
	Building Fabric Optimisation Sub-Total (Exc. VAT)				£61,891.85
	Low-Carbon Heating Systems Sub-Total (Exc. VAT)				£12,116.59
	Renewable Energy Generation Sub-Total (Exc. VAT)				£7,914.07
	Combined Total (Exc. VAT)				£81,922.51
Mid-Terrace Flat	Description	Unit	Quantity	Rate (£/Unit)	Total
	EWI & Air Tightness	m2	51.70	£155.80	Inc. Below
	External Windows & Doors	m2	9.10	£389.29	Inc. Below
	Loft Insulation	m2	22.90	£20.94	Inc. Below
	Ground Floor Insulation	m2	28.00	£447.50	Inc. Below
	Building Fabric Optimisation Sub-Total (Exc. VAT)				£31,997.08
	Low-Carbon Heating Systems Sub-Total (Exc. VAT)				£7,033.89
	Renewable Energy Generation Sub-Total (Exc. VAT)				£8,072.49
	Combined Total (Exc. VAT)				£46,921.73
End Terrace Flat	Description	Unit	Quantity	Rate (£/Unit)	Total
	EWI & Air Tightness	m2	63.00	£155.80	Inc. Below
	External Windows & Doors	m2	9.10	£389.29	Inc. Below
	Loft Insulation	m2	28.00	£20.94	Inc. Below

	Ground Floor Insulation	m2	34.00	£447.50	Inc. Below
				Building Fabric Optimisation Sub-Total (Exc. VAT)	£37,750.21
				Low-Carbon Heating Systems Sub-Total (Exc. VAT)	£6,986.19
				Renewable Energy Generation Sub-Total (Exc. VAT)	£8,031.63
				Combined Total (Exc. VAT)	£52,636.83

Deep Retrofit – Specific (Bungalow)

Within Table 53, the Lifetime Capital Cost for typical retrofit has been estimated, for the specific property type. Further detail and pricing breakdown can be made available upon request.

Table 53 - Lifetime Capital Cost for deep retrofit (specific property type)

	Description	Unit	Quantity	Rate (£/Unit)	Total
Bungalow (Specific)	EWI & Air Tightness	m2	86.70	£137.90	Inc. Below
	External Windows & Doors	m2	11.90	£389.29	Inc. Below
	Loft Insulation	m2	57.80	£20.94	Inc. Below
	Ground Floor Insulation	m2	53.50	£184.18	Inc. Below
				Building Fabric Optimisation Sub-Total (Exc. VAT)	£37,704.76
				Low-Carbon Heating Systems Sub-Total (Exc. VAT)	£12,206.73
				Renewable Energy Generation Sub-Total (Exc. VAT)	£14,056.01
				Combined Total (Exc. VAT)	£63,967.49

6.3 Summary

Typical Retrofit

Within

Figure 41, a comparison of Lifetime Capital Cost is provided for the typical retrofit scenario.

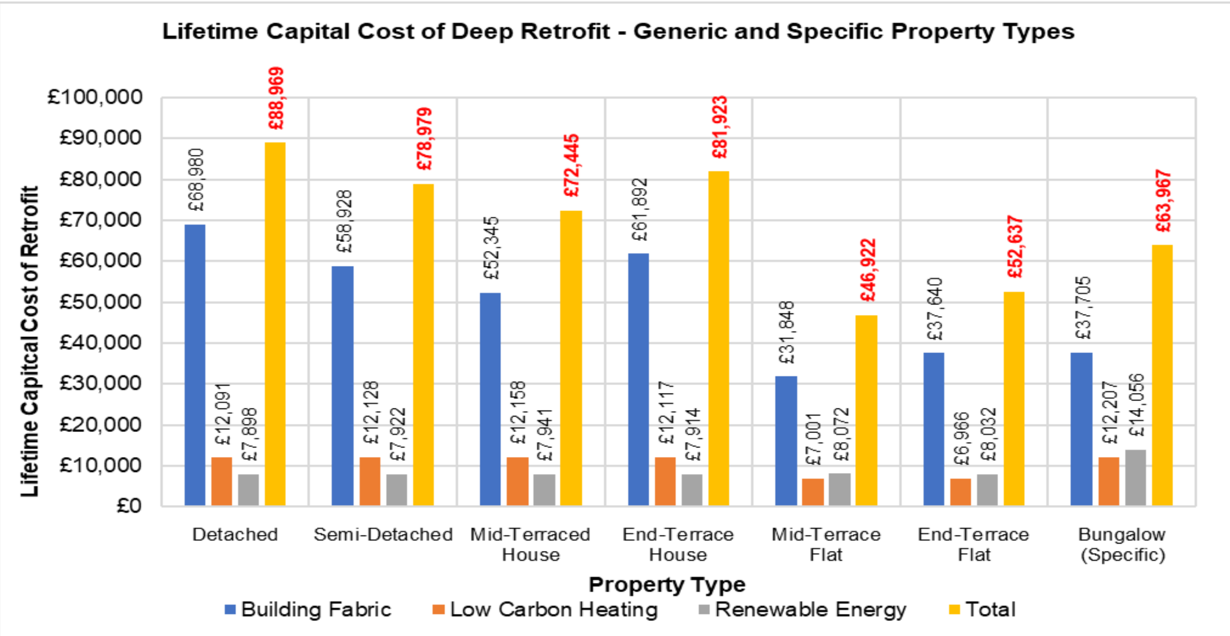
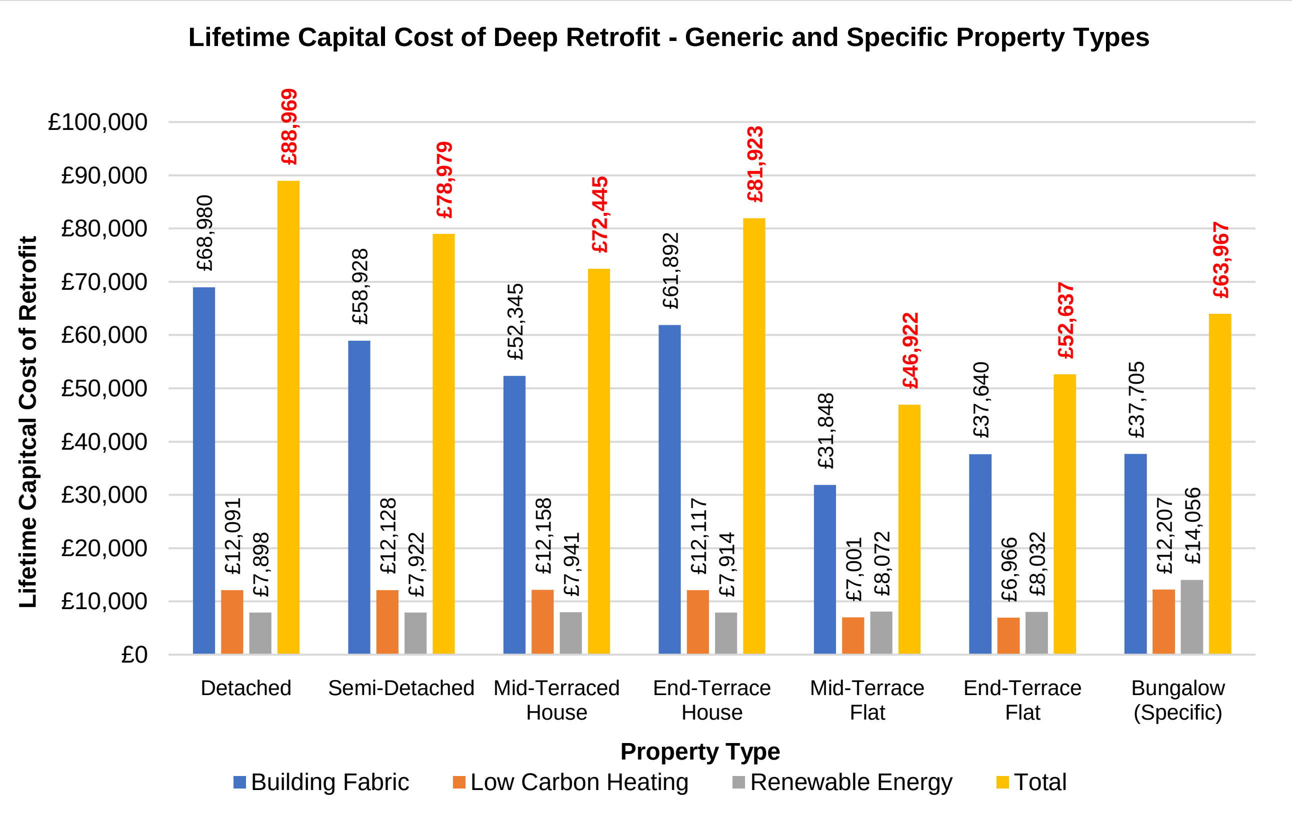


Figure 41 – Lifetime Capital Cost of typical retrofit, generic and specific property type.

Discussion
▪ For the detached, semi-detached, mid-terrace, end-terrace, and bungalow, the same heating system has been specified. Therefore, the Low Carbon Heating costs are aligned for these property types. ▪ For the detached, semi-detached, mid-terrace, and end-terrace properties, the same quantum of solar PV has been specified. Therefore, the Renewable Energy costs are aligned. ▪ The detached, semi-detached, mid-terrace, and end-terrace properties have an internal floor area of 90m². For these property types, the Lifetime Capital Cost for typical retrofit ranges from between £37,794 to £55,900 (Exc. VAT), or between £421/m² and £621/m² (GIA). ▪ The bungalow has an internal floor area of 54m². The Lifetime Capital Cost of typical retrofit for the bungalow is £42,867 or £801/m² (GIA). ▪ The mid-and-end-terraced flats have an internal floor area of 51m² and 62m², respectively. The Lifetime Capital Cost ranges from £34,208 to £36,377 (Exc. VAT), or between £535/m² and £575/m² (GIA). ▪ The variation in Lifetime Capital Cost is primarily driven by the surface area of heat loss perimeter walls and the associated quantity of external wall insulation.

Deep Retrofit

Within Figure *42*, a comparison of Lifetime Capital Cost is provided for the deep retrofit scenario.



Discussion

- For the detached, semi-detached, mid-terrace, end-terrace, and bungalow, the same heating system has been specified. Therefore, the Low Carbon Heating costs are aligned for these property types.
- For the detached, semi-detached, mid-terrace, and end-terrace properties, the same quantum of solar PV has been specified. Therefore, the Renewable Energy costs are aligned.
- The detached, semi-detached, mid-terrace, and end-terrace properties have an internal floor area of 90m^2. For these property types, the Lifetime Capital Cost for deep retrofit ranges from between £88,969 to £72,444 (Exc. VAT), or between £989/m^2 and £803/m^2 (GIA).
- The bungalow has an internal floor area of 54m^2. The Lifetime Capital Cost of typical retrofit for the bungalow is £63,967 or £1,195/m^2 (GIA).
- The mid-and-end-terraced flats have an internal floor area of 51m^2 and 62m^2, respectively. The Lifetime Capital Cost ranges from £42,680 to £49,166 (Exc. VAT), or between £839/ m^2 and £793/m^2 (GIA).
- The variation in Lifetime Capital Cost is primarily driven by the surface area of heat loss perimeter walls and the associated quantity of external wall insulation.
- The increase in Lifetime Capital Cost when compared to the typical retrofit scenario, is due to the introduction of ground floor insulation and new external windows and doors.

7 Net Lifetime Cost of Retrofit

The Net Lifetime Cost of a retrofit project is the Lifetime Capital Cost of the works, less the Lifetime Cost Savings. For example, consider a retrofit project that has a Lifetime Capital Cost of £30,000 – this includes all material and labour costs, incurred costs (enabling works, surveys, contractor overhead and profit, preliminaries, and risk allowances), and maintenance and replacement costs over the Reference Study Period (RSP). Over a 20-year RSP, the retrofit project results in £20,000 of energy bill savings. The Net Lifetime Cost of the installation is therefore £10,000. Where the Lifetime Cost Savings are higher than the Lifetime Capital Cost, the retrofit project results in a Net Lifetime Cost saving.

Within this Section the Net Lifetime Cost of retrofit is determined, using the annual energy costs taken from Sections 2.4 and 4.4, and the Lifetime Capital Cost data from Section 6. Both the typical and deep retrofit scenarios have been analysed according to the following Retrofit Stages:

- Retrofit Stage 1: Building Fabric Optimisation
- Retrofit Stage 2: Low-Carbon Heating Systems
- Retrofit Stage 3: Renewable Energy Generation

7.1 Assumptions

Energy Tariff Projections

There are no definitive projections for future UK Gas and Electricity price caps over the long term, as price forecasting is inherently complex and subject to numerous variables. Future energy prices are influenced by factors such as global fuel markets, geopolitical events, regulatory changes, infrastructure investments, and shifts in energy demand due to electrification and decarbonisation efforts. Given this uncertainty, we have chosen to use the current gas and electricity price caps in our modelling assumptions. As of October to December 2024, the price cap for Electricity is 24.50p per kWh and 6.24p per kWh for Gas. The daily standing charges currently sit at 60.99p and 31.66p for Electricity and Gas respectively (OFGEM, 2024). This approach ensures that our analysis is based on reliable and transparent data rather than speculative projections, which could be subject to significant revisions.

7.2 Net Lifetime Cost of Retrofit

Typical Retrofit – Generic

Within Table 54, the Net Lifetime Cost for typical retrofit has been estimated, for the generic property types.

Table 54 – Net Lifetime Cost for typical retrofit (generic property types)

Property Type	Retrofit Stage	Annual Cost of Energy (£/year)		Financial Savings (£)		Lifetime Capital Cost	Net Lifetime Cost
		Before	After	Annum	Lifetime	(£)	(£)
Detached	Base Case	£2,049.74	£2,049.74	£0.00	£0.00	£0.00	£0.00
	1.Building Fabric	£2,049.74	£1,626.47	£423.27	£8,465.43	£35,632.65	£27,167.21
	2.Low-Carbon Heating	£1,626.47	£1,480.86	£145.61	£2,912.26	£12,199.52	£9,287.26
	3.Renewable Energy	£1,480.86	£1,137.20	£343.66	£6,873.23	£7,968.24	£1,095.01
	Totals (Exc. VAT)			£912.55	£18,250.92	£55,800.41	£37,549.49

Semi Detached	Base Case	£2,131.88	£2,131.88	£0.00	£0.00	£0.00	£0.00
	1.Building Fabric	£2,131.88	£1,810.64	£321.25	£6,424.95	£25,494.28	£19,069.32
	2.Low-Carbon Heating	£1,810.64	£1,442.25	£368.39	£7,367.78	£12,288.86	£4,921.08
	3.Renewable Energy	£1,442.25	£1,096.97	£345.28	£6,905.57	£8,026.59	£1,121.02
	Totals (Exc. VAT)			£1,034.92	£20,698.30	£45,809.72	£25,111.42
Mid Terrace House	Base Case	£2,277.96	£2,277.96	£0.00	£0.00	£0.00	£0.00
	1.Building Fabric	£2,277.96	£1,665.61	£612.36	£12,247.12	£17,301.72	£5,054.59
	2.Low-Carbon Heating	£1,665.61	£1,812.88	-£147.28	-£2,945.56	£12,396.37	£15,341.94
	3.Renewable Energy	£1,812.88	£1,467.43	£345.45	£6,909.00	£8,096.81	£1,187.81
	Totals (Exc. VAT)			£810.53	£16,210.56	£37,794.91	£21,584.35
End Terrace House	Base Case	£2,408.22	£2,408.22	£0.00	£0.00	£0.00	£0.00
	1.Building Fabric	£2,408.22	£1,709.42	£698.81	£13,976.10	£26,983.10	£13,007.00
	2.Low-Carbon Heating	£1,709.42	£1,817.51	-£108.10	-£2,161.95	£12,273.32	£14,435.27
	3.Renewable Energy	£1,817.51	£1,472.06	£345.45	£6,909.00	£8,016.44	£1,107.44
	Totals (Exc. VAT)			£936.16	£18,723.15	£47,272.86	£28,549.71
Mid Terrace Flat	Base Case	£1,763.10	£1,763.10	£0.00	£0.00	£0.00	£0.00
	1.Building Fabric	£1,763.10	£1,403.42	£359.67	£7,193.47	£12,114.17	£4,920.70
	2.Low-Carbon Heating	£1,403.42	£1,214.45	£188.98	£3,779.55	£7,155.83	£3,376.28
	3.Renewable Energy	£1,214.45	£869.51	£344.94	£6,898.71	£8,250.85	£1,352.14
	Totals (Exc. VAT)			£893.59	£17,871.73	£27,520.84	£9,649.11
End Terrace Flat	Base Case	£1,915.95	£1,915.95	£0.00	£0.00	£0.00	£0.00
	1.Building Fabric	£1,915.95	£1,543.45	£372.50	£7,450.06	£14,671.43	£7,221.37
	2.Low-Carbon Heating	£1,543.45	£1,363.95	£179.50	£3,590.02	£7,114.83	£3,524.82
	3.Renewable Energy	£1,363.95	£1,019.01	£344.94	£6,898.71	£8,203.58	£1,304.87
	Totals (Exc. VAT)			£896.94	£17,938.79	£29,989.85	£12,051.06

NOTE: Data rounded to two decimal places – for accurate data see data source: Develeco BBC Data

Typical Retrofit – Specific (Bungalow)

Within Table 55, the Net Lifetime Cost for typical retrofit has been estimated, for the specific property type.

Table 55 - Net Lifetime Cost for typical retrofit (specific property type)

Property Type	Retrofit Stage	Annual Cost of Energy (£/year)		Financial Savings (£)		Lifetime Capital Cost (£)	Net Lifetime Cost (£)
		Before	After	Annum	Lifetime		
Bungalow (Specific)	Base Case	£1,615.13	£1,615.13	£0.00	£0.00	£0.00	£0.00
	1.Building Fabric	£1,615.13	£1,416.08	£199.04	£3,980.87	£16,354.11	£12,373.24
	2.Low-Carbon Heating	£1,416.08	£1,290.91	£125.17	£2,503.40	£12,323.44	£9,820.04
	3.Renewable Energy	£1,290.91	£376.18	£914.73	£18,294.64	£14,190.41	-£4,104.23
	Totals (Exc. VAT)			£1,238.95	£24,778.91	£42,867.96	£18,089.05

Deep Retrofit – Generic

Within Table 56, the Net Lifetime Cost for deep retrofit has been estimated, for the generic property types.

Table 56 - Net Lifetime Cost for deep retrofit (generic property types)

Property Type	Retrofit Stage	Annual Cost of Energy (£/year)		Financial Savings (£)		Lifetime Capital Cost (£)	Net Lifetime Cost (£)
		Before	After	Annum	Lifetime		
Detached	Base	£2,049.74	£2,049.74	£0.00	£0.00	£0.00	£0.00
	1.Building Fabric	£2,049.74	£1,477.81	£571.93	£11,438.67	£68,980.36	£57,541.70

	2.Low-Carbon Heating	£1,477.81	£1,272.12	£205.69	£4,113.82	£12,091.39	£7,977.57
	3.Renewable Energy	£1,272.12	£928.46	£343.66	£6,873.23	£7,897.61	£1,024.38
			Totals (Exc. VAT)	£1,121.29	£22,425.72	£88,969.37	£66,543.65
Semi-Detached	Base Case	£2,131.88	£2,131.88	£0.00	£0.00	£0.00	£0.00
	1.Building Fabric	£2,131.88	£1,659.65	£472.24	£9,444.74	£58,928.37	£49,483.63
	2.Low-Carbon Heating	£1,659.65	£1,230.74	£428.91	£8,578.16	£12,128.48	£3,550.32
	3.Renewable Energy	£1,230.74	£885.46	£345.28	£6,905.57	£7,921.84	£1,016.27
			Totals (Exc. VAT)	£1,246.42	£24,928.47	£78,978.68	£54,050.21
Mid Terrace House	Base	£2,277.96	£2,277.96	£0.00	£0.00	£0.00	£0.00
	1.Building Fabric	£2,277.96	£1,526.06	£751.90	£15,038.03	£52,344.72	£37,306.69
	2.Low-Carbon Heating	£1,526.06	£1,526.06	£0.00	-£0.04	£12,158.43	£12,158.47
	3.Renewable Energy	£1,526.06	£1,180.61	£345.45	£6,909.00	£7,941.40	£1,032.40
			Totals (Exc. VAT)	£1,097.35	£21,946.99	£72,444.55	£50,497.56
End Terrace House	Base	£2,408.22	£2,408.22	£0.00	£0.00	£0.00	£0.00
	1.Building Fabric	£2,408.22	£1,541.74	£866.48	£17,329.60	£61,891.85	£44,562.25
	2.Low-Carbon Heating	£1,541.74	£1,543.58	-£1.84	-£36.76	£12,116.59	£12,153.35
	3.Renewable Energy	£1,543.58	£1,198.13	£345.45	£6,909.00	£7,914.07	£1,005.07
			Totals (Exc. VAT)	£1,210.09	£24,201.84	£81,923.51	£57,720.67
Mid Terrace Flat	Base	£1,763.10	£1,763.10	£0.00	£0.00	£0.00	£0.00
	1.Building Fabric	£1,763.10	£1,292.30	£470.80	£9,415.91	£31,848.11	£22,432.20
	2.Low-Carbon Heating	£1,292.30	£1,090.26	£202.05	£4,040.92	£7,001.14	£2,960.22
	3.Renewable Energy	£1,090.26	£745.32	£344.94	£6,898.71	£8,072.49	£1,173.78
			Totals (Exc. VAT)	£1,017.78	£20,355.54	£42,680.73	£26,566.19
End Terrace Flat	Base	£1,915.95	£1,915.95	£0.00	£0.00	£0.00	£0.00
	1.Building Fabric	£1,915.95	£1,334.57	£581.38	£11,627.62	£37,639.50	£26,011.88
	2.Low-Carbon Heating	£1,334.57	£1,130.53	£204.03	£4,080.69	£6,965.70	£2,885.01
	3.Renewable Energy	£1,130.53	£785.60	£344.94	£6,898.71	£8,031.63	£1,132.92
			Totals (Exc. VAT)	£1,130.35	£22,607.02	£49,167.83	£30,029.82

Deep Retrofit – Specific (Bungalow)

Within Table 57, the Net Lifetime Cost for typical retrofit has been estimated, for the specific property type.

Table 57 - Net Lifetime Cost for deep retrofit (specific property type)

Property Type	**Retrofit Stage**	**Annual Cost of Energy (£/year)**		**Financial Savings (£)**		**Lifetime Capital Cost (£)**	**Net Lifetime Cost (£)**
		Before	**After**	**Annum**	**Lifetime**		
Bungalow (Specific)	Base	£1,615.13	£1,615.13	£0.00	£0.00	£0.00	£0.00
	1.Building Fabric	£1,615.13	£1,304.09	£311.04	£6,220.78	£37,704.76	£31,483.98
	2.Low-Carbon Heating	£1,304.09	£1,165.03	£139.06	£2,781.11	£12,206.73	£9,425.62
	3.Renewable Energy	£1,165.03	£250.30	£914.73	£18,294.64	£14,056.01	-£4,238.63
			Totals (Exc. VAT)	£1,364.83	£27,296.53	£63,967.49	£36,670.96

7.3 Summary

Typical Retrofit

Within Figure 43, a comparison of Net Lifetime Cost is provided for the typical retrofit scenario.

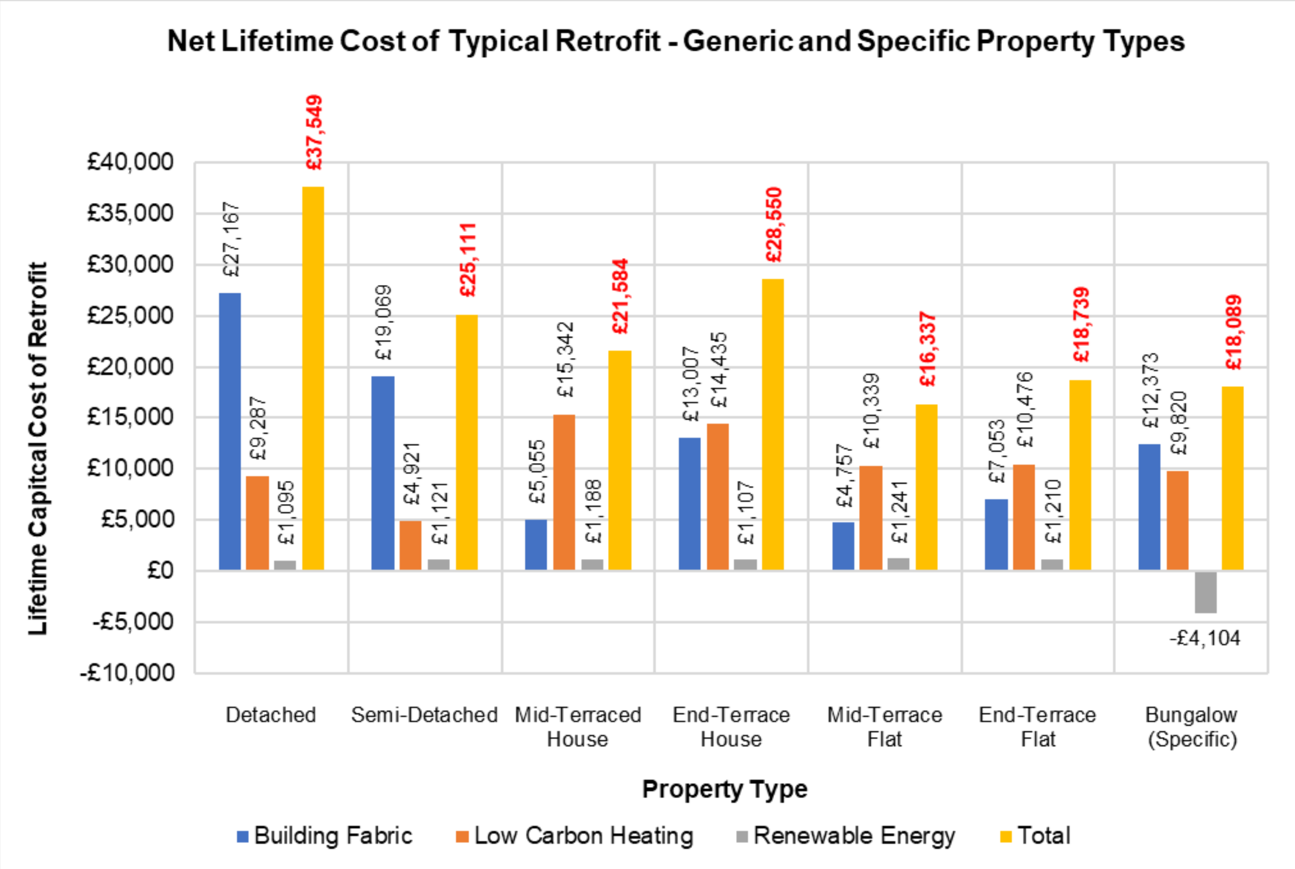


Figure 43 – Net Lifetime Cost of typical retrofit, generic and specific property types

Discussion

- For all property types with the exception of the bungalow, Renewable Energy installations do not provide a Net Lifetime Cost saving, over the 20-year RSP.
- Only the bungalow sees a net lifetime saving from PV.
- For all property types, the building fabric upgrades do not result in a Net Lifetime Cost saving, which is driven by the surface area of heat loss perimeter walls.
- The detached, semi-detached, mid-terrace, and end-terrace properties have a Net Lifetime Cost of between £21,584 and £37,549
- The bungalow has a Net Lifetime Cost of £18,089.
- The mid-and-end-terraced flats both result in a Net Lifetime Cost of between £12,096 and £15,269 over a 20-year RSP.

Deep Retrofit

Within

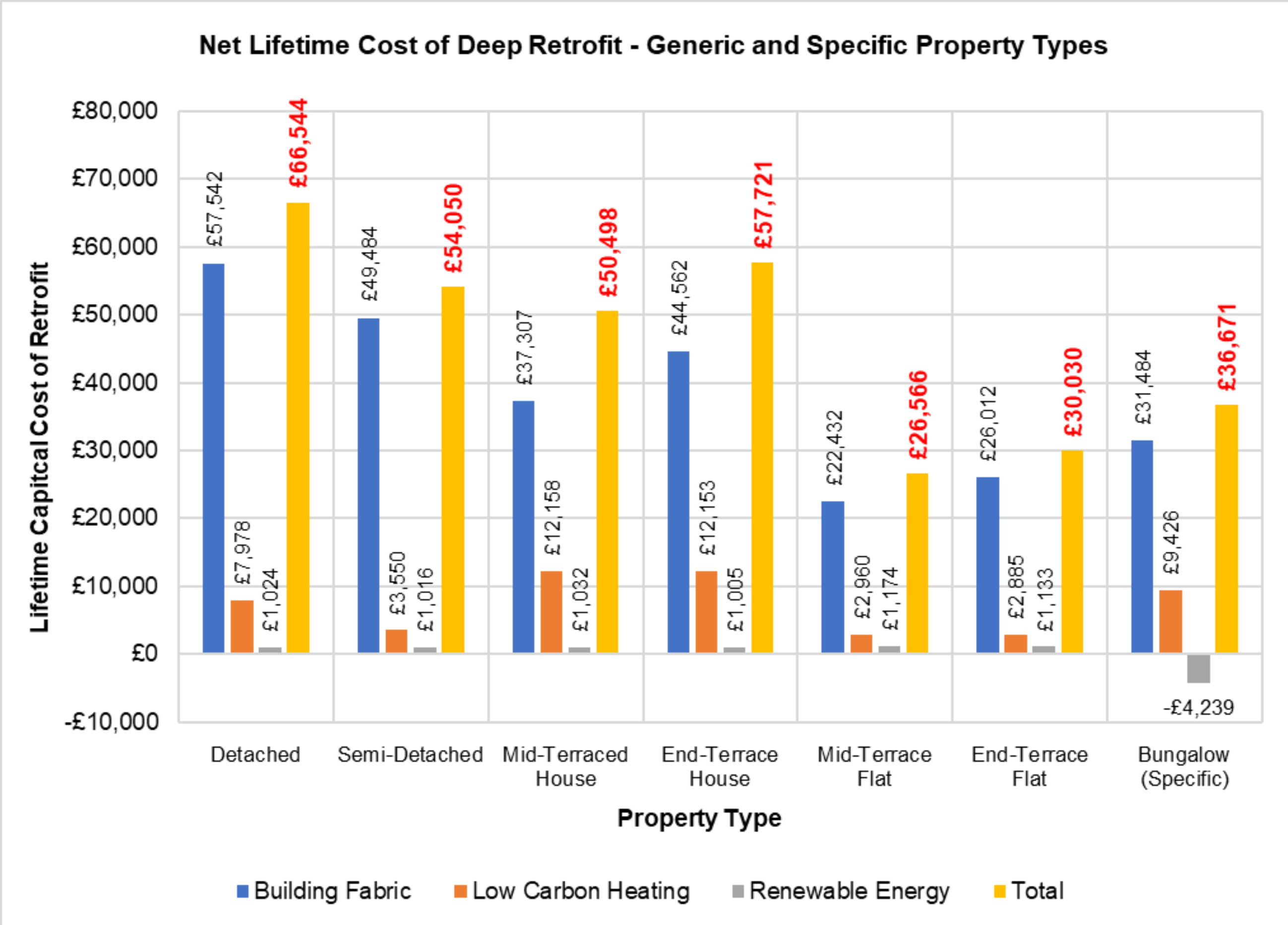


Figure 44, a comparison of Net Lifetime Cost is provided for the deep retrofit scenario.

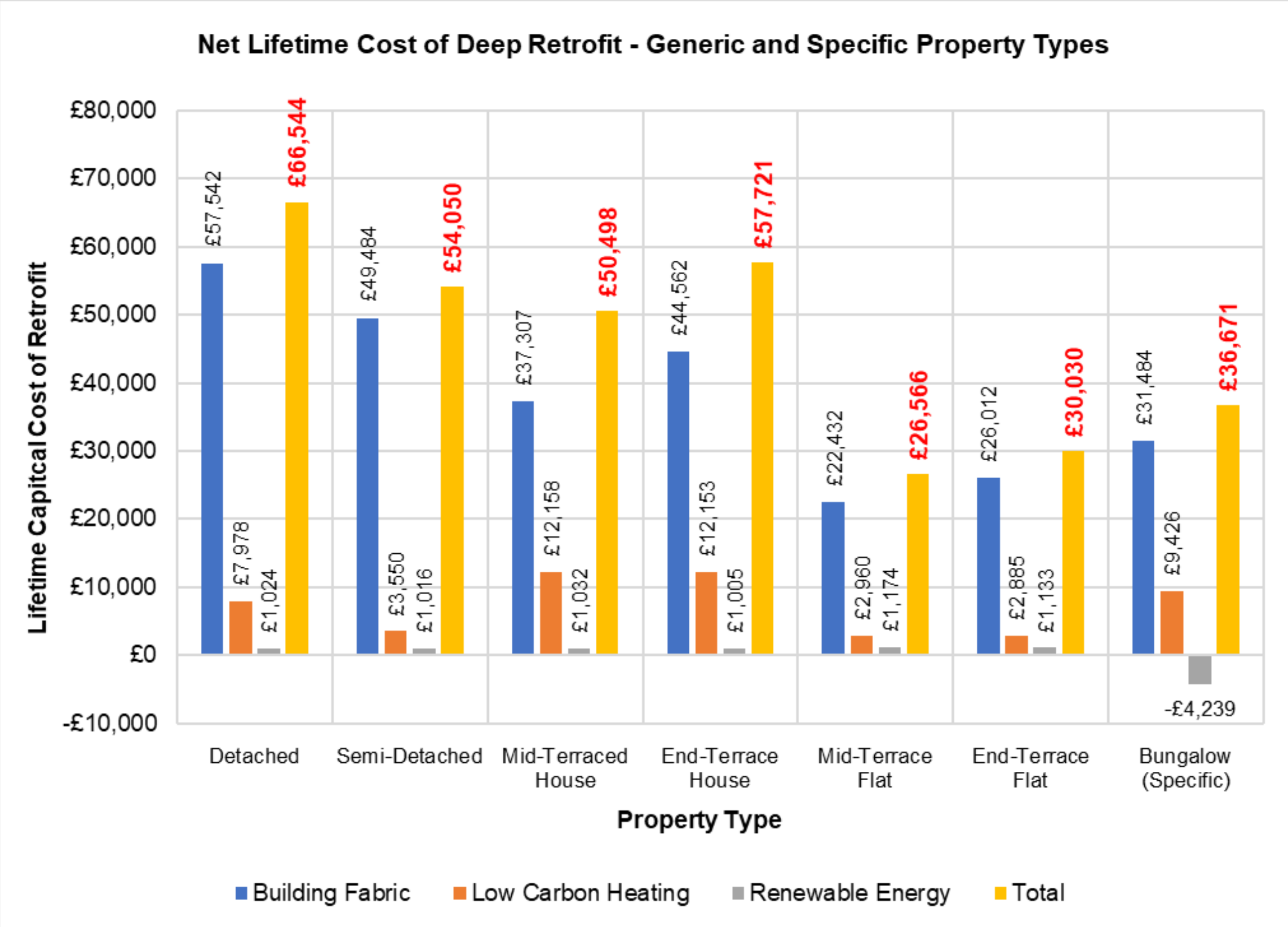


Figure 44 – Net Lifetime Cost of deep retrofit, generic and specific property types

Discussion

- For all property types with the exception of the bungalow, Renewable Energy installations do not provide a Net Lifetime Cost saving, over the 20-year RSP.
- Only the bungalow sees a net lifetime saving from PV due to the increased quantum and associated energy cost savings.
- With the deep retrofit scenario, there are no Net Lifetime Cost savings associated with the building fabric upgrades. This is driven by the introduction of ground floor insulation and window replacement, which have a high-cost impact.
- The detached, semi-detached, mid-terrace, and end-terrace properties have a Net Lifetime Cost of between £50,498 and £66,544.
- The bungalow has a Net Lifetime Cost of £36,671.
- The mid-and-end-terraced flats both result in a Net Lifetime Cost saving of between £22,325 and £26,560 over a 20-year RSP.

8 Carbon-Cost Effectiveness

This Section considers the Carbon Cost Effectiveness (CCE) of retrofit. CCE is a way of measuring the cost per tonne of Carbon Dioxide equivalent that is removed from the atmosphere over the lifetime of a project, as a result of a retrofit installation. CCE is measured in £/tCO_2e and requires base case or 'pre-retrofit' carbon emission data, so that carbon reductions can be determined. A retrofit project with a Net Lifetime Cost of £100,000 that results in a Net Lifetime Carbon Reduction of 200tonnes over its lifetime (20-years) would have a CCE of £500/tCO_2e.

The CCE calculation methodology proposed by the Retrofit Academy is used within this Section. Figure 45 provides a graphical representation of the calculation.

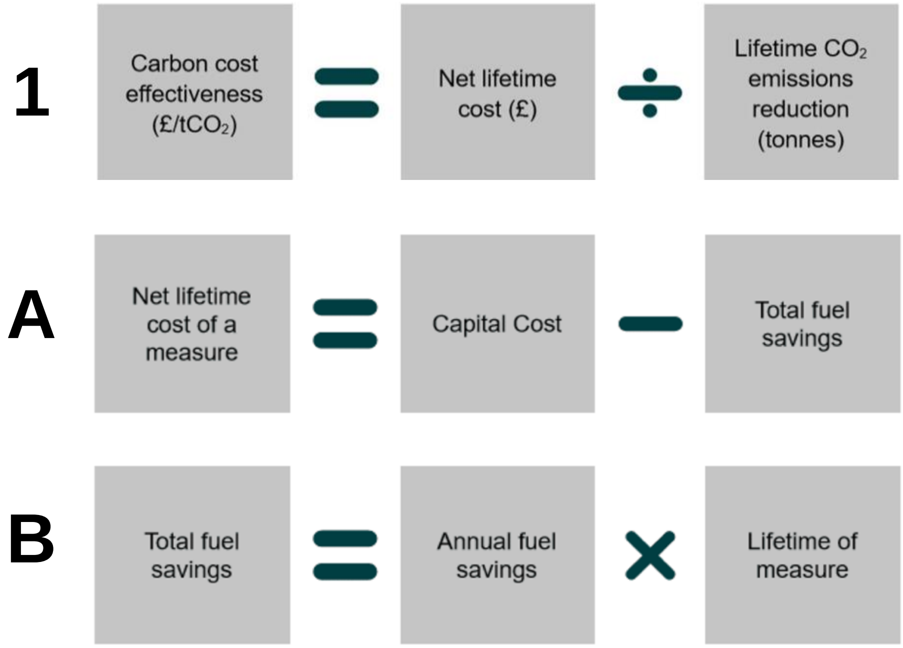


Figure 45 – Retrofit Academy simplified methodology for calculating Carbon Cost Effectiveness (Rickaby, 2020)

8.1 Assumptions

Carbon Intensity of Electricity

There are clear projections indicating that the carbon intensity of the UK electricity grid will decrease significantly over the next 20 years, reflecting the nation's ongoing transition to low-carbon energy sources and the decarbonisation of the power sector. While general trends and targets are outlined in the UK's decarbonisation strategy, the 'Valuation of Energy Use and Greenhouse Gas Emissions for Appraisal' publication provides detailed, government-endorsed projections for the carbon intensity of electricity generation (GOV, 2023).Therefore, we have chosen to use the projected data from this source and applied these values over the Reporting Service Period (RSP) of 20 years. Projected grid carbon intensity figures until 2045 are detailed in

Table *58*.

Table 58 – Grid Carbon Intensity Projections (GOV, 2023)

Year	Factor ($kgCO_2e/kWh$)	Year	Factor ($kgCO_2e/kWh$)	Year	Factor ($kgCO_2e/kWh$)
2025 (FHS Aligned)	0.086	2032	0.033	2039	0.017
2026 (FHS Aligned)	0.086	2033	0.026	2040	0.016
2027	0.073	2034	0.021	2041	0.015
2028	0.063	2035	0.020	2042	0.015
2029	0.054	2036	0.020	2043	0.009
2030	0.049	2037	0.018	2044	0.008
2031	0.042	2038	0.018	2045	0.008

Carbon Intensity of Gas

There are no specific projections for the carbon intensity of the UK's domestic gas supply over the next 20 years. The UK's decarbonisation strategy primarily focuses on reducing overall greenhouse gas emissions and transitioning to low-carbon energy sources, rather than providing detailed projections for the carbon intensity of specific fuels like natural gas. The International Energy Agency (IEA) offer detailed data on current emissions and discuss trends in carbon intensities, but they do not provide specific projections for the carbon intensity of UK natural gas over the next 20 years. We have therefore taken the FHS Fuel Factor of 0.214$kgCO_2e/kWh$ as set out within the Home Energy Model and used this value over the RSP of 20 years (DofE, 2023).

8.2 Net Lifetime Carbon Reduction

To complete the CCE calculation, the Net Lifetime Carbon Reduction must be determined. The Net Lifetime Carbon Reduction is calculated by deducting the Whole Life Embodied Carbon (Sections 3 and 5) from the Whole Life Operational Carbon Savings (Sections 2.4 and 4.4).

Typical Retrofit – Generic

Table 59, the Net Lifetime Carbon Reduction for typical retrofit has been estimated, for the generic property types.

Table 59 – Net Lifetime Carbon Reduction of typical retrofit (generic property types)

Property Type	Retrofit Stage	Operational Carbon Emissions ($kgCO_2e/year$)		Operational Carbon Savings ($kgCO_2e$)		Whole Life Embodied Carbon ($kgCO_2e$)	Net Lifetime Carbon Reduction ($kgCO_2e$)
		Before	After	Avg. Year	Lifetime		
Detached	Base	3,169.53	3,169.53	0.00	0.00	0.00	0.00
	1.Building Fabric	3,169.53	1,717.92	1,451.60	29,032.10	5,775.35	23,256.74
	2.Low-Carbon Heating	1,717.92	178.93	,1538.99	30,779.74	1,610.92	29,168.82
	3.Renewable Energy	178.93	130.06	48.87	977.44	1,338.86	-361.42
	Totals			3,039.46	60,789.27	8,725.13	52,064.14
	Base	2,731.78	2,731.78	0.00	0.00	0.00	0.00

Semi Detached	Building Fabric	2,731.78	1,630.06	1,101.71	22,034.30	4,870.21	17,164.08
	Low-Carbon Heating	1,630.06	173.44	1,456.62	29,132.35	1,610.92	2,7521.43
	Renewable Energy	173.44	124.34	49.10	982.03	1,338.86	-356.83
	Totals			2,607.43	52,149.68	7,819.99	44,328.69
Mid Terrace House	Base	3,830.18	3,830.18	0.00	0.00	0.00	0.00
	1.Building Fabric	3,830.18	1,730.11	2,100.07	4,2001.35	3,560.18	38,441.17
	2.Low-Carbon Heating	1,730.11	226.15	1,503.96	30,079.21	1,610.92	28,468.29
	3.Renewable Energy	226.15	177.02	49.13	982.52	1,338.86	-356.34
	Totals			3,653.15	73,063.09	6,509.96	66,553.12
End Terrace House	Base	4,276.90	4,276.90	0.00	0.00	0.00	0.00
	1.Building Fabric	4,276.90	1,880.36	2,396.54	47,930.86	4,674.37	43,256.50
	2.Low-Carbon Heating	1,880.36	226.81	1,653.55	33,071.03	1,610.92	31,460.11
	3.Renewable Energy	226.81	177.68	49.13	982.52	1,338.86	-356.34
	Totals			4,099.22	81,984.42	7,624.15	74,360.27
Mid Terrace Flat	Base	2,706.59	2,706.59	0.00	0.00	0.00	0.00
	1.Building Fabric	2,706.59	,1473.10	1,233.50	24,669.92	2,084.97	22,584.95
	2.Low-Carbon Heating	1,473.10	141.05	1,332.05	26,640.96	726.27	2,5914.69
	3.Renewable Energy	141.05	91.99	49.05	981.06	1,338.86	-357.80
	Totals			2,614.60	52,291.94	4,150.10	48,141.85
End Terrace Flat	Base	3,174.50	3,174.50	0.00	0.00	0.00	0.00
	1.Building Fabric	3,174.50	1,897.00	1,277.49	25,549.89	2,539.43	23,010.46
	2.Low-Carbon Heating	1,897.00	162.31	1,734.70	34,693.93	884.65	33,809.28
	3.Renewable Energy	162.31	113.25	49.05	981.06	1,338.86	-357.80
	Totals			3,061.24	61,224.87	4,762.94	56,461.93

NOTE: Data rounded to two decimal places – for accurate data see data source: Develeco BBC Data

Typical Retrofit – Specific (Bungalow)

Within Table 60, the Net Lifetime Carbon Reduction for typical retrofit has been estimated, for the specific property type.

Table 60 - Net Lifetime Carbon Reduction of typical retrofit (specific property type)

Property Type	**Retrofit Stage**	**Operational Carbon Emissions ($kgCO_2e$/year)**		**Operational Carbon Savings ($kgCO_2e$)**		**Whole Life Embodied Carbon ($kgCO_2e$)**	**Net Lifetime Carbon Reduction ($kgCO_2e$)**
		Before	**After**	**Avg. Year**	**Lifetime**		
Bungalow (Specific)	Base	1,971.20	19,71.20	0.00	0.00	0.00	0.00
	Building Fabric	1,971.20	1,288.58	682.62	13,652.34	3,691.53	9,960.82
	Low-Carbon Heating	1,288.58	151.92	1,136.66	22,733.16	1,668.14	21,065.02
	Renewable Energy	151.92	21.84	130.08	2601.66	3,931.86	-1,330.20
	Totals			1,949.36	38,987.17	9,291.52	29,695.65

Deep Retrofit – Generic

Within Table 61, the Net Lifetime Carbon Reduction for deep retrofit has been estimated, for the generic property types.

Table 61 - Net Lifetime Carbon Reduction of deep retrofit (generic property types)

Property Type	Retrofit Stage	Operational Carbon Emissions ($kgCO_2e$/year)		Operational Carbon Savings ($kgCO_2e$)		Whole Life Embodied Carbon ($kgCO_2e$)	Net Lifetime Carbon Reduction ($kgCO_2e$)
		Before	After	Avg. Year	Lifetime		
Detached	Base	3,169.53	3,169.53	0.00	0.00	0.00	0.00
	1.Building Fabric	3,169.53	1,208.09	1,961.44	39,228.77	9513.14	29715.63
	2.Low-Carbon Heating	1208.09	149.25	1,058.84	21,176.76	1,592.39	19,584.37
	3.Renewable Energy	149.25	100.38	48.87	977.44	1,338.86	-361.42
	Totals			3,069.15	61,,382.96	12444.39	48,938.57
Semi-Detached	Base Case	2,731.78	2,731.78	0.00	0.00	0.00	0.00
	Building Fabric	2,731.78	1,112.24	1,619.53	32,390.61	8,920.16	23,470.45
	Low-Carbon Heating	1,112.24	143.36	968.88	19,377.60	2,003.48	17,374.12
	Renewable Energy	143.36	94.26	49.10	982.03	1343.30	-361.26
	Total			2,637.51	52,750.25	12,266.93	40,483.32
Mid Terrace House	Base	3,830.18	3,830.18	0.00	0.00	0.00	0.00
	1.Building Fabric	3,830.18	1,251.54	2,578.64	51,572.72	7,742.52	43,830.19
	2.Low-Carbon Heating	1,251.54	185.36	1,066.18	21,323.62	1,592.39	19,731.23
	3.Renewable Energy	185.36	136.24	49.13	982.52	1,338.86	-356.34
	Totals			3,693.94	73,878.86	10,673.77	63,205.09
End Terrace House	Base	4,276.90	4,276.90	0.00	0.00	0.00	0.00
	1.Building Fabric	4,276.90	1,305.32	2,971.58	59,431.65	8,556.90	50,874.75
	2.Low-Carbon Heating	1,305.32	187.85	1,117.47	22,349.36	1,592.39	20,756.97
	3.Renewable Energy	187.85	138.73	49.13	982.52	1,338.86	-356.34
	Totals			4,138.18	82,763.54	11,488.15	71,275.38
Mid Terrace Flat	Base	2,706.59	2,706.59	0.00	0.00	0.00	0.00
	1.Building Fabric	2,706.59	1,092.00	1,614.59	32,291.74	4,173.96	28,117.78
	2.Low-Carbon Heating	1,092.00	123.39	968.62	19,372.36	750.15	1,8622.21
	3.Renewable Energy	123.39	74.33	49.05	981.06	1,338.86	-357.80
	Totals			2,632.26	52,645.16	6,262.97	46,382.19
End Terrace Flat	Base	3,174.50	3,174.50	0.00	0.00	0.00	0.00
	1.Building Fabric	3,174.50	1,180.66	1,993.84	39,876.76	5,084.20	34,792.56
	2.Low-Carbon Heating	1,180.66	129.11	1,051.55	21,030.92	913.74	20,117.18
	3.Renewable Energy	129.11	80.06	49.05	981.06	1,338.86	-357.80
	Totals			3,094.44	61,888.74	7336.80	54551.94

Deep Retrofit – Specific (Bungalow)

Within Table 62, the Net Lifetime Carbon Reduction for typical retrofit has been estimated, for the specific property type.

Table 62 - Net Lifetime Carbon Reduction of deep retrofit (specific property type)

Property Type	**Retrofit Stage**	**Operational Carbon Emissions ($kgCO_2e$/year)**		**Operational Carbon Savings ($kgCO_2e$)**		**Whole Life Embodied Carbon ($kgCO_2e$)**	**Net Lifetime Carbon Reduction ($kgCO_2e$)**
		Before	**After**	**Avg. Year**	**Lifetime**		
Bungalow (Specific)	Base	1971.20	1971.20	0.00	0.00	0.00	0.00
	Building Fabric	1971.20	904.49	1066.70	21334.09	7367.72	13966.37
	Low-Carbon Heating	904.49	134.02	770.47	15409.44	1592.39	13817.06
	Renewable Energy	134.02	3.94	130.08	2601.66	3931.86	-1330.20
	Total			1967.26	39345.20	12891.97	26453.23

8.3 Carbon Cost Effectiveness: Results

The last step in the CCE calculation is to divide the Net Lifetime Cost of retrofit by the Net Lifetime Carbon Reduction. This will provide a CCE metric in pounds per tonne of carbon saved, over the lifetime of the project. The CCE results will facilitate an understanding as to the most cost-effective retrofit measures, from a carbon reduction standpoint.

Typical Retrofit – Generic

Within Table 63, the Carbon Cost Effectiveness for typical retrofit has been estimated, for the generic property types.

Table 63 – Carbon Cost Effectiveness of typical retrofit (generic property types)

Property Type	Retrofit Stage	**Net Lifetime Carbon Reduction ($kgCO_2e$)**	**Net Lifetime Cost (£)**	**Carbon Cost Effectiveness (£/tCO_2e)**
Detached	Base	0.00	£0.00	N/A
	1.Building Fabric	23,256.74	£27,167.21	£1,168.14
	2.Low-Carbon Heating	29,168.82	£9,287.26	£318.40
	3.Renewable Energy	-361.42	£1,095.01	Not Effective
	Totals	52,064.14	£37,549.49	£721.22
Semi Detached	Base	0.00	£0.00	N/A
	Building Fabric	17,164.08	£19,069.32	£1,111.00
	Low-Carbon Heating	27,521.43	£4,921.08	£178.81
	Renewable Energy	-356.83	£1,121.02	Not Effective
	Totals	44,328.69	£25,111.42	£566.48
Mid Terrace House	Base	0.00	£0.00	N/A
	1.Building Fabric	38,441.17	£5,054.59	£131.49
	2.Low-Carbon Heating	28,468.29	£15,341.94	£538.91
	3.Renewable Energy	-356.34	£1,187.81	Not Effective

	Totals	66,553.12	£21,584.35	£324.32
End Terrace House	Base	0.00	£0.00	N/A
	1.Building Fabric	43,256.50	£13,007.00	£300.69
	2.Low-Carbon Heating	31,460.11	£14,435.27	£458.84
	3.Renewable Energy	-356.34	£1,107.44	Not Effective
	Totals	74,360.27	£28,549.71	£383.94
Mid Terrace Flat	Base	0.00	£0.00	N/A
	1.Building Fabric	22,584.95	£4,920.70	£217.88
	2.Low-Carbon Heating	25,914.69	£3,376.28	£130.28
	3.Renewable Energy	-357.80	£1,352.14	Not Effective
	Totals	48,141.85	£9,649.11	£200.43
End Terrace Flat	Base	0.00	£0.00	N/A
	1.Building Fabric	23,010.46	£7,221.37	£313.83
	2.Low-Carbon Heating	33,809.28	£3,524.82	£104.26
	3.Renewable Energy	-357.80	£1,304.87	Not Effective
	Totals	56,461.93	£12,051.06	£213.44

Typical Retrofit – Specific (Bungalow)

Within Table 64, the Carbon Cost Effectiveness for typical retrofit has been estimated, for the specific property type.

Table 64 - Carbon Cost Effectiveness of typical retrofit (specific property type)

Property Type	Retrofit Stage	**Net Lifetime Carbon Reduction ($kgCO_2e$)**	**Net Lifetime Cost (£)**	**Carbon Cost Effectiveness (£/tCO_2e)**
Bungalow (Specific)	Base	0.00	£0.00	N/A
	Building Fabric	9,960.82	£12,373.24	£1,242.19
	Low-Carbon Heating	21,065.02	£9,820.04	£466.18
	Renewable Energy	-1,330.20	-£4,104.23	Not Effective
	Totals	29,695.65	£18,089.05	£609.15

Deep Retrofit – Generic

Within Table 65, the Carbon Cost Effectiveness for deep retrofit has been estimated, for the generic property types.

Table 65 - Carbon Cost Effectiveness of deep retrofit (generic property types)

Property Type	**Retrofit Stage**	**Net Lifetime Carbon Reduction ($kgCO_2e$)**	**Net Lifetime Cost (£)**	**Carbon Cost Effectiveness (£/tCO_2e)**
Detached	Base	0.00	£0.00	N/A
	1.Building Fabric	29,715.63	£57,541.70	£1,936.41
	2.Low-Carbon Heating	19,584.37	£7,977.57	£407.34
	3.Renewable Energy	-361.42	£1,024.38	Not Effective
	Totals	48,938.57	£66,543.65	£1,359.74

Semi-Detached	Base Case	0.00	£0.00	N/A
	Building Fabric	23,470.45	£49,483.63	£2,108.34
	Low-Carbon Heating	17,374.12	£3,550.32	£204.35
	Renewable Energy	-361.26	£1,016.27	Not Effective
	Total	40,483.32	£54,050.21	£1,335.12
Mid Terrace House	Base	0.00	£0.00	N/A
	1.Building Fabric	43,830.19	£37,306.69	£851.16
	2.Low-Carbon Heating	19,731.23	£12,158.47	£616.20
	3.Renewable Energy	-356.34	£1,032.40	Not Effective
	Totals	63,205.09	£50,497.56	£798.95
End Terrace House	Base	0.00	£0.00	N/A
	1.Building Fabric	50,874.75	£44,562.25	£875.92
	2.Low-Carbon Heating	20,756.97	£12,153.35	£585.51
	3.Renewable Energy	-356.34	£1,005.07	Not Effective
	Totals	71,275.38	£57,720.67	£809.83
Mid Terrace Flat	Base	0.00	£0.00	N/A
	1.Building Fabric	28,117.78	£22,432.20	£797.79
	2.Low-Carbon Heating	18,622.21	£2,960.22	£158.96
	3.Renewable Energy	-357.80	£1,173.78	Not Effective
	Totals	46,382.19	£26,566.19	£572.77
End Terrace Flat	Base	0.00	£0.00	N/A
	1.Building Fabric	34,792.56	£26,011.88	£747.63
	2.Low-Carbon Heating	20,117.18	£2,885.01	£143.41
	3.Renewable Energy	-357.80	£1,132.92	Not Effective
	Totals	54,551.94	£30,029.82	£550.48

Deep Retrofit – Specific (Bungalow)

Within Table 66, the Carbon Cost Effectiveness for typical retrofit has been estimated, for the specific property type.

Table 66 - Carbon Cost Effectiveness of deep retrofit (specific property type)

Property Type	Retrofit Stage	Net Lifetime Carbon Reduction ($kgCO_2e$)	Net Lifetime Cost (£)	Carbon Cost Effectiveness ($£/tCO_2e$)
Bungalow (Specific)	Base	0	£0	N/A
	Building Fabric	13,966	£31,484	£2,254.27
	Low-Carbon Heating	13,817	£9,426	£682.17
	Renewable Energy	-1,330	-£4,239	Not Effective
	Total	26,453	£36,671	£1,386.26

8.4 Summary

Typical Retrofit

Within Figure 46, a comparison of Carbon Cost Effectiveness is provided for the typical retrofit scenario.

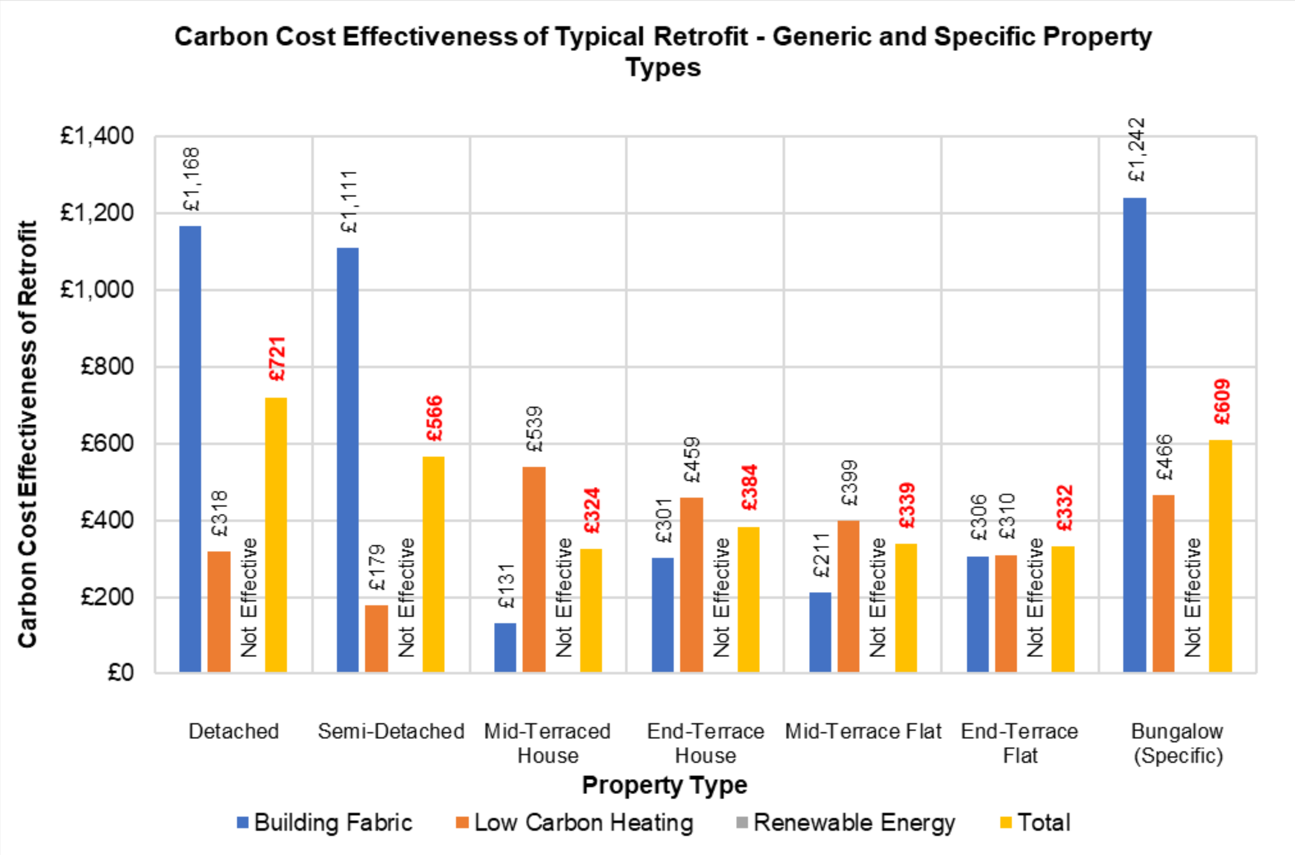


Figure 46 – Carbon Cost Effectiveness of typical retrofit, generic and specific property types

Discussion

- All property types, under both the typical and deep retrofit scenarios, result in a Net Lifetime Carbon Reduction. Therefore, it can be concluded that over a 20-year RSP, these measures are 'effective' at reducing Net Lifetime Carbon, when sequenced in accordance with the assumptions.
- In all property types, renewable energy installations result in neither a Net Lifetime Cost saving, or a Net Lifetime Carbon Saving. The Carbon Cost Effectiveness for renewables is therefore not effective for these property types.
- For all properties, building fabric upgrades result in a Net Lifetime Cost whilst also all seeing a Net Lifetime Carbon Reduction.
- For the detached and semi-detached properties, the low carbon heating upgrades result in a Carbon Cost Effectiveness of between £318/tCO_2e and £1179/tCO_2e respectively.
- For the mid-terraced house and end-terraced house, the low carbon heating upgrades result in a Carbon Cost Effectiveness of between £539/tCO_2e and £459/tCO_2e respectively. For the low carbon heating, this is the highest CCE of all of the generic property types.

- For the mid-terraced and end-terraced flats, the low carbon heating upgrades result in a Carbon Cost Effectiveness of between £399/tCO_2e and £310/tCO_2e respectively.
- For the bungalow, the low carbon heating upgrades result in a Carbon Cost Effectiveness of £466/tCO_2e.
- Considering total Carbon Cost Effectiveness, the detached and semi-detached properties, and the mid-terrace and end-terrace houses, result in a total CCE of between 721/tCO_2e and 566/tCO_2e, over the RSP.
- The mid-terrace and end-terrace flats result in a total CCE of between £339/tCO_2e. and -£332/tCO_2e, over the RSP.
- The bungalow results in a CCE of between 609/tCO_2e, over the RSP. This high CCE figure is driven by the increased quantity of solar applied to the bungalow, which hasn't begun to pay off effectively after just 20 years.

Deep Retrofit

Within Figure 47, a comparison of Carbon Cost Effectiveness is provided for the deep retrofit scenario.

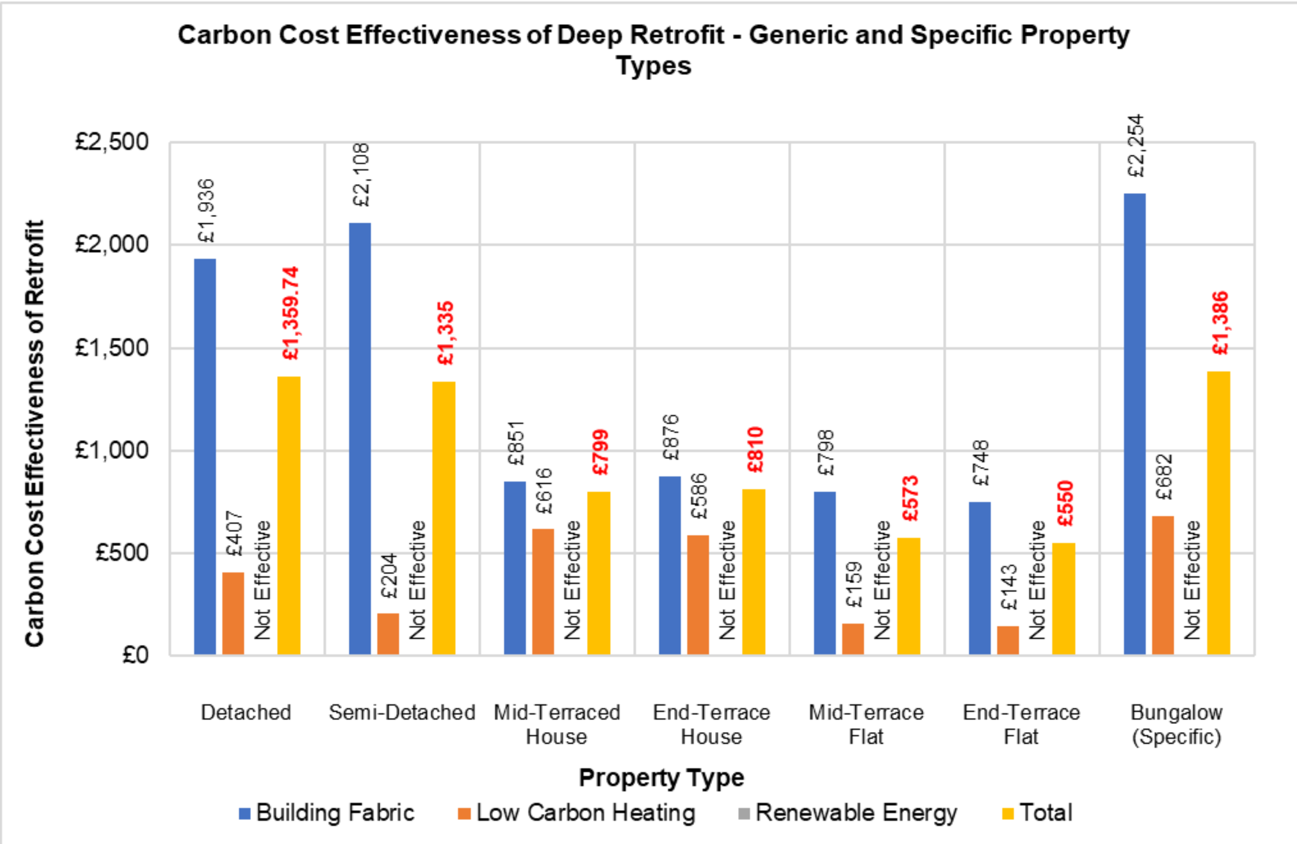


Figure 47 – Carbon Cost Effectiveness of deep retrofit, generic and specific property types

Discussion

- All property types, under both the typical and deep retrofit scenarios, result in a Net Lifetime Carbon Reduction. Therefore, it can be concluded that over a 20-year RSP, these measures are ‘effective’ at reducing Net Lifetime Carbon, when sequenced in accordance with the assumptions.
- In all property types, renewable energy installations result in neither a Net Lifetime Cost saving, or a Net Lifetime Carbon Saving. The Carbon Cost Effectiveness for renewables is therefore not effective for these property types.
- For the detached and semi-detached properties, the building fabric improvements result in a CCE rate of between £1,936/tCO_2e and £2,108/tCO_2e, which is the highest amongst the property types.
- For the flats, the building fabric upgrades result in a CCE rate of between £748/tCO_2e and £798/tCO_2e, which is the lowest of all property types for this Retrofit Stage. This is driven by the low quantity of heat loss perimeter walls and the reduced quantity of ground floor insulation required, when applied as a ratio across both flats.
- For the bungalow, the building fabric upgrades result in a CCE rate of £2,254/tCO_2e.
- For the detached and semi-detached properties, the low carbon heating upgrades result in a Carbon Cost Effectiveness of between £407/tCO_2e and £204/tCO_2e respectively.
- For the mid-terraced house and end-terraced house, the low carbon heating upgrades result in a Carbon Cost Effectiveness of between £616/tCO_2e and £586/tCO_2e respectively.
- For the mid-terraced and end-terraced flats, the low carbon heating upgrades result in a Carbon Cost Effectiveness of between £159/tCO_2e and £143/tCO_2e respectively. For the low carbon heating, this is the lowest CCE of all property types, which is driven by the fact that the flats share a single ASHP.
- For the bungalow, the low carbon heating upgrades result in a Carbon Cost Effectiveness of £682/tCO_2e. For the low carbon heating, this is the highest CCE of all property types.
- Considering total Carbon Cost Effectiveness, the detached and semi-detached properties, and the mid-terrace and end-terrace houses, result in a total CCE of between 1359/tCO_2e and 799/tCO_2e, over the RSP.
- The mid-terrace and end-terrace flats result in a total CCE of between £573/tCO_2e. and £550/tCO_2e respectively, over the RSP.
- The bungalow results in a CCE of between £1,386/tCO_2e, over the RSP.

9 Broxtowe Housing: Decarbonisation Roadmap

Within this Section, the key data outputs from this technical report are summarised, to provide strategic guidance for Broxtowe Borough Council.

9.1 House Type Analysis

Within this sub-section, the key outputs and results are summarised per house type.

Detached House

General

- Floor area: 89.9
- Bedrooms: 2
- Occupancy: 3
- For the detached house the following material quantities were assumed for the typical retrofit scenario:
  - 57.6m^2 of Rockwool loft insulation at 400mm thickness
  - 159m^2 of external wall insulation, consisting of Rockwool insulation at 230mm thickness, adhesive basecoat, fibreglass mesh, and silicone render
  - Mitsubishi Ecodan 5kW + 200L Packaged Cylinder
  - 5 Jinko Tiger Neo 440Wp Solar Panels
- For the detached house the following additional material quantities were assumed for the deep retrofit scenario:
  - 57.6m^2 of Spacetherm Aerogel ground floor insulation at 40mm thickness and 3mm chipboard flooring
  - 9.3m^2 of triple glazed PVC window area (openable)
  - 5.7m^2 of solid UPVC external door area
- Excluding the flats, the assumed quantity of Low Carbon Heating and PV remains consistent across all generic property types. The only varying factors being the material quantities for fabric improvements. As a result, in this analysis, the house type geometry is the primary factor influencing cost and carbon outcomes.

Typical Retrofit

- Upfront Capital Cost: £55,800
  - Building Fabric: £35,633
  - Low-Carbon Hating: £12,200
  - Renewable Energy: £7,968
- Annual Energy Savings: £913
- Payback Period: 61 years
- Lifetime Financial Savings: £18,251
- Net Lifetime Cost: £37,549
- Embodied Carbon Emissions (20-Year): 8.7tCO_2e
- Operational Carbon Emissions (20-Year): 2.6tCO_2e
- Whole Life Carbon Emissions (20-Year): 11.3tCO_2e
- Operational Carbon Savings: 60.7tCO_2e
- Net Lifetime Carbon Reduction: 52.0tCO_2e
- Carbon Cost Effectiveness: £721 per tonne of CO_2e saved

Deep Retrofit

- Upfront Capital Cost: £88,969
  - Building Fabric: £68,980
  - Low-Carbon Hating: £12,091
  - Renewable Energy: £7,898
- Annual Energy Savings: £1,121
- Payback Period: 79 years
- Lifetime Financial Savings: £22,426

- Net Lifetime Cost: £66,544
- Embodied Carbon Emissions (20-Year): 12.4tCO_2e
- Operational Carbon Emissions (20-Year): 2tCO_2e
- Whole Life Carbon Emissions: 14.5tCO_2e
- Operational Carbon Savings: 61.3tCO_2e
- Net Lifetime Carbon Reduction: 48.9tCO_2e
- Carbon Cost Effectiveness: £1,359 per tonne of CO_2e saved

Discussion

- A Typical Retrofit has a Lifetime Capital Cost of £55,800 compared to £88,969 for Deep Retrofit. The increase of £33,169 or 59% represents the additional cost of implementing enhanced measures such as new floor insulation, new windows and doors, and improved air tightness.
- A Typical Retrofit results in annual energy savings of £913, compared to £1,121 for Deep Retrofit.
- Deep Retrofit costs £33,169 more than Typical Retrofit for increased annual savings of £208. This equates to a payback period of 159 years for the additional capital investment.
    - Retrofit Stage 1 (Building Fabric) represents 64% of the total cost for Typical Retrofit (at £35,633) and increases to 78% for Deep Retrofit.
    - Retrofit Stage 2 (Low-Carbon Heating) represents 22% of the total Capital Cost for Typical Retrofit (at £12,200) and 14% for Deep Retrofit.
    - Retrofit Stage 3 (Renewable Energy) represents 14% of the total Capital Cost for Typical Retrofit (at £7,968) and 9% for Deep Retrofit.
- Considering payback periods at each Retrofit Stage, based on the energy bill savings:
    - Typical Retrofit would result in a payback period of 61 years for Stage 1 (Building Fabric), 61 years for Stage 2 (Low-Carbon Heating), and 17 years for Stage 3 (Renewable Energy). Combined, this gives a financial payback of 61 years.
    - Deep Retrofit would result in a payback period of 96 years for Stage 1 (Building Fabric), 47 years for Stage 2 (Low-Carbon Heating), and 18 years for Stage 3 (Renewable Energy). Combined, this yields a financial payback of 79 years.
- For Typical Retrofit, the Embodied Carbon emissions over 20 years are 8.7tCO_2e compared to 12.4tCO_2e for Deep Retrofit. The increase of 3.7tCO_2e is associated with the enhanced building fabric measures.
- The Operational Carbon associated with Typical Retrofit is 2.6tCO_2e compared to 2.0tCO_2e for Deep Retrofit. The additional saving of 0.6tCO_2e for Deep Retrofit is attributed to these enhanced measures.
- For this property type, Deep Retrofit results in 3.7tCO_2e more embodied carbon emissions than Typical Retrofit, but only achieves operational carbon savings of 0.6tCO_2e. Therefore, shifting from Typical to Deep Retrofit results in a net increase in Whole Life Carbon of approximately 3.2tCO_2e.
- Over 20 years, a Typical Retrofit achieves a Net Whole Life Carbon Reduction of 52,100kgCO_2e compared to 48,900kgCO_2e for Deep Retrofit. Considering the breakdown per Retrofit Stage:
    - Retrofit Stage 1 (Building Fabric) represents 45% of the Net Lifetime Carbon Savings for Typical Retrofit, compared to 61% for Deep Retrofit.
    - Retrofit Stage 2 (Low-Carbon Heating) represents 56% of the Net Lifetime Carbon Savings for Typical Retrofit, compared to 40% for Deep Retrofit.
    - Retrofit Stage 3 (Renewable Energy) represents –1% of the Net Lifetime Carbon Savings for both the Typical and Deep Retrofit scenarios.
- For this house type, it can be concluded that the increased building fabric measures between Typical and Deep Retrofit are not cost-effective in terms of financial payback.

- It can be concluded that Low-Carbon Heating is the single most impactful measure in terms of Net Lifetime Carbon Reduction, driven by the shift from gas to electricity.
- It can be concluded that solar is not effective in reducing Whole Life Carbon, as the upfront embodied carbon is higher than the operational carbon savings over a 20-year period.
- Considering Carbon Cost Effectiveness, Typical Retrofit costs less and achieves more Whole Life Carbon Savings than Deep Retrofit; the cost per tonne of carbon saved is £721/tCO_2e for Typical Retrofit compared to £1,359/tCO_2e for Deep Retrofit.

Semi-Detached House

General

- Floor area: 89.7
- Bedrooms: 2
- Occupancy: 3
- For the detached house the following material quantities were assumed for the typical retrofit scenario:
    - 48.7m^2 of Rockwool loft insulation at 400mm thickness
    112m^2 of external wall insulation, consisting of Rockwool insulation at 230mm thickness, adhesive basecoat, fibreglass mesh, and silicone render
    - Mitsubishi Ecodan 5kW + 200L Packaged Cylinder
    - 5 Jinko Tiger Neo 440Wp Solar Panels
- For the detached house the following additional material quantities were assumed for the deep retrofit scenario:
    - 48.7m^2 of Spacetherm Aerogel ground floor insulation at 40mm thickness and 3mm chipboard flooring
    - 9.3m^2 of triple glazed PVC window area (openable)
    - 5.7m^2 of solid UPVC external door area
- Excluding the flats, the assumed quantity of Low Carbon Heating and PV remains consistent across all generic property types. The only varying factors being the material quantities for fabric improvements. As a result, in this analysis, the house type geometry is the primary factor influencing cost and carbon outcomes.

Typical Retrofit

- Upfront Capital Cost: £45,810
    - Building Fabric: £25,494
    - Low-Carbon Hating: £12,289
    - Renewable Energy: £8,027
- Annual Energy Savings: £1,035
- Payback Period: 44 years
- Lifetime Financial Savings: £20,698
- Net Lifetime Cost: £25,111
- Embodied Carbon Emissions (20-Year): 7.8tCO_2e
- Operational Carbon Emissions (20-Year): 2.5tCO_2e
- Whole Life Carbon: 10.3tCO_2e
- Operational Carbon Savings: 52.1tCO_2e
- Net Lifetime Carbon Reduction: 44.3tCO_2e
- Carbon Cost Effectiveness: £566 per tonne of CO_2e saved

Deep retrofit

- Upfront Capital Cost: £78,979
    - Building Fabric: £58,928
    - Low-Carbon Hating: £12,128
    - Renewable Energy: £7,922
- Annual Energy Savings: £1,246
- Payback Period: 63 years
- Lifetime Financial Savings: £24,928
- Net Lifetime Cost: £54,050
- Embodied Carbon Emissions (20-Year): 12.3tCO_2e
- Operational Carbon Emissions (20-Year): 1.9tCO_2e
- Whole Life Carbon: 14.2tCO_2e
- Operational Carbon Savings: 52.7tCO_2e
- Net Lifetime Carbon Reduction: 40.4tCO_2e
- Carbon Cost Effectiveness: £1,335 per tonne of CO_2e saved

Discussion

- A Typical Retrofit has a Lifetime Capital Cost of £45,810 compared to £78,979 for Deep Retrofit. The increase of £33,169 or 72% represents the additional cost of implementing new floor insulation, new windows and doors, and improved air tightness measures.
- A Typical Retrofit results in annual energy savings of £1,035, compared to £1,246 for Deep Retrofit.
- Deep Retrofit costs £33,169 more than Typical Retrofit for increased annual savings of £211. This equates to a payback period of 157 years for the increased capital investment.
    - Retrofit Stage 1 (Building Fabric) represents 56% of the total cost, at £25,494. This increases to 75% for Deep Retrofit.
    - Retrofit Stage 2 (Low-Carbon Heating) represents 27% of the total Capital Cost for Typical Retrofit and 15% for Deep Retrofit.
    - Retrofit Stage 3 (Renewable Energy) represents 18% of the total Capital Cost for Typical Retrofit and 10% for Deep Retrofit.
- Considering payback periods at each Retrofit Stage, based on the energy bill savings:
    - Typical Retrofit would result in a payback period of 61 years for Stage 1 (Building Fabric), 61 years for Stage 2 (Low-Carbon Heating), and 17 years for Stage 3 (Renewable Energy). Combined financial payback 44 years.
    - Deep Retrofit would result in a payback period of 96 years for Stage 1 (Building Fabric), 47 years for Stage 2 (Low-Carbon Heating), and 18 years for Stage 3 (Renewable Energy). Combined financial payback 63 years.
- For Typical Retrofit, the Embodied Carbon emissions over 20 years are 7.8tCO_2e compared to 12.3tCO_2e for Deep Retrofit. The increase of 4.5tCO_2e is associated with the enhanced building fabric measures.
- The Operational Carbon associated with Typical Retrofit is 2.5tCO_2e compared to 1.9tCO_2e for Deep Retrofit. The increased saving of 0.6tCO_2e for Deep Retrofit is associated with the enhanced building fabric measures.
- For this property type, Deep Retrofit results in 4.5tCO_2e more embodied carbon emissions than the Typical Retrofit, but only results in operational carbon savings of 0.6tCO_2e. Therefore, improving the retrofit strategy from Typical to Deep results in a net increase in Whole Life Carbon of 3.9tCO_2e.
- Over 20 years, a Typical Retrofit achieves a Net Whole Life Carbon Reduction of 44,300kgCO_2e compared to 40,400kgCO_2e for Deep Retrofit. Considering the breakdown per Retrofit Stage:

- Retrofit Stage 1 (Building Fabric) represents 47% of the Net Lifetime Carbon Savings for Typical Retrofit, compared to 58% for Deep Retrofit.
  - Retrofit Stage 2 (Low-Carbon Heating) represents 51% of the Net Lifetime Carbon Savings for Typical Retrofit, compared to 43% for Deep Retrofit.
  - Retrofit Stage 3 (Renewable Energy) represents –1% of the Net Lifetime Carbon Savings for both the Typical and Deep Retrofit scenarios.
- For this house type, it can be concluded that the increased building fabric measures between Typical and Deep Retrofit are not cost-effective, in terms of financial payback.
- It can be concluded that Low-Carbon Heating is the single most impactful measure, in terms of Net Lifetime Carbon Reduction. This is driven by the shift to electricity from gas.
- It can be concluded that solar is not effective in reducing Whole Life Carbon. This is because the upfront embodied carbon is higher than the operational carbon savings, over a 20-year period.
- From a Whole Life Carbon Reduction perspective, it can be concluded that Typical Retrofit is more effective than Deep Retrofit for this property type.
- Considering Carbon Cost Effectiveness, Typical Retrofit costs less and results in more Whole Life Carbon Savings than Deep Retrofit. Therefore, the cost per tonne of carbon saved for Typical Retrofit is lower, at £566/tCO_2e compared to £1,335/tCO_2e for Deep Retrofit.

Mid-Terrace House

General

- Floor area: 8*9.7*
- Bedrooms: 3
- Occupancy: 4
- For the detached house the following material quantities were assumed for the typical retrofit scenario:
  - 50.3m^2 of Rockwool loft insulation at 400mm thickness
  - 72.9m^2 of external wall insulation, consisting of Rockwool insulation at 230mm thickness, adhesive basecoat, fibreglass mesh, and silicone render
  - Mitsubishi Ecodan 5kW + 200L Packaged Cylinder
  - 5 Jinko Tiger Neo 440Wp Solar Panels
- For the detached house the following additional material quantities were assumed for the deep retrofit scenario:
  - 50.3m^2 of Spacetherm Aerogel ground floor insulation at 40mm thickness and 3mm chipboard flooring
  - 10.7m^2 of triple glazed PVC window area (openable)
  - 5.7m^2 of solid UPVC external door area
- Excluding the flats, the assumed quantity of Low Carbon Heating and PV remains consistent across all generic property types. The only varying factors being the material quantities for fabric improvements. As a result, in this analysis, the house type geometry is the primary factor influencing cost and carbon outcomes.

Typical Retrofit

- Upfront Capital Cost: £37,795
  - Building Fabric: £17,302
  - Low-Carbon Hating: £12,396

- Renewable Energy: £8,097
- Annual Energy Savings: £811
- Payback Period: 47 years
- Lifetime Financial Savings: £16,211
- Net Lifetime Cost: £21,584
- Embodied Carbon Emissions (20-Year): 6.5tCO_2e
- Operational Carbon Emissions (20-Year): 3.5tCO_2e
- Whole Life Carbon: 10.0tCOe
- Operational Carbon Savings: 73.1tCO_2e
- Net Lifetime Carbon Reduction: 66.6tCO_2e
- Carbon Cost Effectiveness: £324 per tonne of CO_2e saved

Deep Retrofit

- Upfront Capital Cost: £72,445
  - Building Fabric: £52,345
  - Low-Carbon Hating: £12,158
  - Renewable Energy: £7,922
- Annual Energy Savings: £1,097
- Payback Period: 66 years
- Lifetime Financial Savings: £21,947
- Net Lifetime Cost: £50,498
- Embodied Carbon Emissions (20-Year): 10.7tCO_2e
- Operational Carbon Emissions (20-Year): 2.7tCO_2e
- Whole Life Carbon: 13.4tCO_2 e
- Operational Carbon Savings: 73.9tCO_2e
- Net Lifetime Carbon Reduction: 63.2tCO_2e
- Carbon Cost Effectiveness: £798 per tonne of CO_2e saved

Discussion

- A Typical Retrofit has a Lifetime Capital Cost of £37,795 compared to £72,445 for Deep Retrofit. The increase of £34,650 (approximately 92%) represents the additional cost of implementing enhanced measures such as improved building fabric.
- A Typical Retrofit results in annual energy savings of £811, compared to £1,097 for Deep Retrofit.
- Deep Retrofit costs £34,650 more than Typical Retrofit for increased annual savings of £286. This equates to a payback period of approximately 121 years for the additional capital investment.
  - Retrofit Stage 1 (Building Fabric) represents 46% of the total cost for Typical Retrofit (at £17,302) and increases to 72% for Deep Retrofit (at £52,345).
  - Retrofit Stage 2 (Low-Carbon Heating) represents 33% of the total Capital Cost for Typical Retrofit (at £12,396) and 17% for Deep Retrofit (at £12,158).
  - Retrofit Stage 3 (Renewable Energy) represents 21% of the total Capital Cost for Typical Retrofit (at £8,097) and 11% for Deep Retrofit (at £7,922).
- Considering payback periods at each Retrofit Stage, based on the energy bill savings:
  - Typical Retrofit would result in a payback period of approximately 55 years for Stage 1 (Building Fabric), 55 years for Stage 2 (Low-Carbon Heating), and 15 years for Stage 3 (Renewable Energy), yielding a combined financial payback of 47 years.
  - Deep Retrofit would result in a payback period of approximately 80 years for Stage 1, 45 years for Stage 2, and 18 years for Stage 3, yielding a combined financial payback of 66 years.

- For Typical Retrofit, the Embodied Carbon emissions over 20 years are 6.5tCO_2e compared to 10.7tCO_2e for Deep Retrofit. The increase of 4.2tCO_2e is associated with the enhanced building fabric measures.
- The Operational Carbon associated with Typical Retrofit is 3.5tCO_2e compared to 2.7tCO_2e for Deep Retrofit. The additional saving of 0.8tCO_2e for Deep Retrofit is attributed to these measures.
- For this property type, Deep Retrofit results in 4.2tCO_2e more embodied carbon emissions than Typical Retrofit, but only achieves operational carbon savings of 0.8tCO_2e. Therefore, shifting from Typical to Deep Retrofit results in a net decrease in Whole Life Carbon Reduction of approximately 3.4tCO_2e.
- Over 20 years, a Typical Retrofit achieves a Net Whole Life Carbon Reduction of 66,600kgCO_2e compared to 63,200kgCO_2e for Deep Retrofit. Considering the breakdown per Retrofit Stage:
  - Retrofit Stage 1 (Building Fabric) represents 58% of the Net Lifetime Carbon Savings for Typical Retrofit, compared to 69% for Deep Retrofit.
  - Retrofit Stage 2 (Low-Carbon Heating) represents 43% of the Net Lifetime Carbon Savings for Typical Retrofit, compared to 31% for Deep Retrofit.
  - Retrofit Stage 3 (Renewable Energy) represents –1% of the Net Lifetime Carbon Savings for both the Typical and Deep Retrofit scenarios.
- For this house type, it can be concluded that the increased building fabric measures between Typical and Deep Retrofit are not cost-effective in terms of financial payback.
- It can be concluded that Low-Carbon Heating is the single most impactful measure in terms of Net Lifetime Carbon Reduction, driven by the shift from gas to electricity.
- It can be concluded that solar is not effective in reducing Whole Life Carbon, as the upfront embodied carbon is higher than the operational carbon savings over a 20-year period.
- Considering Carbon Cost Effectiveness, Typical Retrofit costs less and achieves more Whole Life Carbon Savings than Deep Retrofit; therefore, the cost per tonne of carbon saved for Typical Retrofit is £324/tCO_2e compared to £798/tCO_2e for Deep Retrofit.

End-Terrace House

General

- Floor area: 89.7
- Bedrooms: 3
- Occupancy: 4
- For the detached house the following material quantities were assumed for the typical retrofit scenario:
  - 50.3m^2 of Rockwool loft insulation at 400mm thickness
  - 118.5m^2 of external wall insulation, consisting of Rockwool insulation at 230mm thickness, adhesive basecoat, fibreglass mesh, and silicone render
  - Mitsubishi Ecodan 5kW + 200L Packaged Cylinder
  - 5 Jinko Tiger Neo 440Wp Solar Panels
- For the detached house the following additional material quantities were assumed for the deep retrofit scenario:
  - 50.3m^2 of Spacetherm Aerogel ground floor insulation at 40mm thickness and 3mm chipboard flooring
  - 10.7m^2 of triple glazed PVC window area (openable)
  - 5.7m^2 of solid UPVC external door area

- Excluding the flats, the assumed quantity of Low Carbon Heating and PV remains consistent across all generic property types. The only varying factors being the material quantities for fabric improvements. As a result, in this analysis, the house type geometry is the primary factor influencing cost and carbon outcomes.

Typical Retrofit

- Upfront Capital Cost: £47,273
    - Building Fabric: £26,983
    - Low-Carbon Hating: £12,273
    - Renewable Energy: £8,016
- Annual Energy Savings: £936
- Payback Period: 30 years
- Lifetime Financial Savings: £18,723
- Net Lifetime Cost: £28,550
- Embodied Carbon Emissions (20-Year): 7.6tCO_2e
- Operational Carbon Emissions (20-Year): 3.6tCO_2e
- Whole Life Carbon: 11.2tCO_2e
- Operational Carbon Savings: 82.0tCO_2e
- Net Lifetime Carbon Reduction: 74.4tCO_2e
- Carbon Cost Effectiveness: £383 per tonne of CO_2e saved

Deep Retrofit

- Upfront Capital Cost: £81,923
    - Building Fabric: £61,892
    - Low-Carbon Hating: £12,117
    - Renewable Energy: £7,914
- Annual Energy Savings: £1,210
- Payback Period: 67 years
- Lifetime Financial Savings: £24,202
- Net Lifetime Cost: £57,721
- Embodied Carbon Emissions (20-Year): 11.5tCO_2e
- Operational Carbon Emissions (20-Year): 2.8tCO_2e
- Whole Life Carbon: 14.3tCO_2e
- Operational Carbon Savings: 82.8tCO_2e
- Net Lifetime Carbon Reduction: 71.3tCO_2e
- Carbon Cost Effectiveness: £809 per tonne of CO_2e saved

Discussion

- A Typical Retrofit has a Lifetime Capital Cost of £47,273 compared to £81,923 for Deep Retrofit. The increase of £34,650 (approximately 73%) represents the additional cost of implementing enhanced measures such as improved building fabric.
- A Typical Retrofit results in annual energy savings of £936, compared to £1,210 for Deep Retrofit.
- Deep Retrofit costs £34,650 more than Typical Retrofit for increased annual savings of £274. This equates to a payback period of approximately 126 years for the additional capital investment.
    - Retrofit Stage 1 (Building Fabric) represents 57% of the total cost for Typical Retrofit (at £26,983) and increases to 76% for Deep Retrofit (at £61,892).

- Retrofit Stage 2 (Low-Carbon Heating) represents 26% of the total Capital Cost for Typical Retrofit (at £12,273) and 15% for Deep Retrofit (at £12,117).
- Retrofit Stage 3 (Renewable Energy) represents 17% of the total Capital Cost for Typical Retrofit (at £8,016) and 10% for Deep Retrofit (at £7,914).

- Considering payback periods at each Retrofit Stage, based on the energy bill savings:
  - Typical Retrofit would result in a payback period of approximately 40 years for Stage 1 (Building Fabric), 40 years for Stage 2 (Low-Carbon Heating), and 15 years for Stage 3 (Renewable Energy), yielding a combined financial payback of 30 years.
  - Deep Retrofit would result in a payback period of approximately 70 years for Stage 1 (Building Fabric), 45 years for Stage 2 (Low-Carbon Heating), and 18 years for Stage 3 (Renewable Energy), yielding a combined financial payback of 67 years.
- For Typical Retrofit, the Embodied Carbon emissions over 20 years are 7.6tCO_2e compared to 11.5tCO_2 e for Deep Retrofit. The increase of 3.9tCO_2e is associated with the enhanced building fabric measures.
- The Operational Carbon associated with Typical Retrofit is 3.6tCO_2e compared to 2.8tCO_2e for Deep Retrofit. The additional saving of 0.8tCO_2e for Deep Retrofit is attributed to these measures.
- For this property type, Deep Retrofit results in 3.9tCO_2e more embodied carbon emissions than Typical Retrofit, but only achieves additional operational carbon savings of 0.8tCO_2e. Therefore, shifting from Typical to Deep Retrofit results in a net decrease in Whole Life Carbon Reduction of approximately 3.1tCO_2e.
- Over 20 years, a Typical Retrofit achieves a Net Whole Life Carbon Reduction of 74,400kgCO_2e compared to 71,300kgCO_2e for Deep Retrofit. Considering the breakdown per Retrofit Stage:
  - Retrofit Stage 1 (Building Fabric) represents 58% of the Net Lifetime Carbon Savings for Typical Retrofit, compared to 71% for Deep Retrofit.
  - Retrofit Stage 2 (Low-Carbon Heating) represents 42% of the Net Lifetime Carbon Savings for Typical Retrofit, compared to 29% for Deep Retrofit.
  - Retrofit Stage 3 (Renewable Energy) represents –1% of the Net Lifetime Carbon Savings for both the Typical and Deep Retrofit scenarios.
- For this house type, it can be concluded that the increased building fabric measures between Typical and Deep Retrofit are not cost-effective in terms of financial payback.
- It can be concluded that Low-Carbon Heating is the single most impactful measure in terms of Net Lifetime Carbon Reduction, driven by the shift from gas to electricity.
- It can be concluded that solar is not effective in reducing Whole Life Carbon, as the upfront embodied carbon is higher than the operational carbon savings over a 20-year period.
- Considering Carbon Cost Effectiveness, Typical Retrofit costs less and achieves more Whole Life Carbon Savings than Deep Retrofit; therefore, the cost per tonne of carbon saved for Typical Retrofit is £383/tCO_2e compared to £809/tCO_2e for Deep Retrofit.

Mid Terrace Flat

General

- Floor area: 50.9
- Bedrooms: 2

- Occupancy: 3
- For the detached house the following material quantities were assumed for the typical retrofit scenario:
    - 50.9m^2 of Rockwool loft insulation at 400mm thickness
    - 51.7m^2 of external wall insulation, consisting of Rockwool insulation at 230mm thickness, adhesive basecoat, fibreglass mesh, and silicone render
    - Mitsubishi Ecodan 8kW + 150L Packaged Cylinder (Shared between flats)
    - 5 Jinko Tiger Neo 440Wp Solar Panels
- For the detached house the following additional material quantities were assumed for the deep retrofit scenario:
    - 50.3m^2 of Spacetherm Aerogel ground floor insulation at 40mm thickness and 3mm chipboard flooring
    - 7.3m^2 of triple glazed PVC window area (openable)
    - 1.8m^2 of solid UPVC external door area
- Excluding the flats, the assumed quantity of Low Carbon Heating and PV remains consistent across all generic property types. The only varying factors being the material quantities for fabric improvements. As a result, in this analysis, the house type geometry is the primary factor influencing cost and carbon outcomes.

Typical Retrofit

- Upfront Capital Cost: £27,521
    - Building Fabric: £11,951
    - Low-Carbon Hating: £7,156
    - Renewable Energy: £8,139
- Annual Energy Savings: £894
- Payback Period: 31 years
- Lifetime Financial Savings: £17,872
- Net Lifetime Cost: £9,649
- Embodied Carbon Emissions (20-Year): 4.2tCO_2e
- Operational Carbon Emissions (20-Year): 1.8tCO_2e
- Whole Life Carbon: 6.0tCO_2e
- Operational Carbon Savings: 52.3tCO_2e
- Net Lifetime Carbon Reduction: 48.1tCO_2e
- Carbon Cost Effectiveness: £200 per tonne of CO_2e saved

Deep Retrofit

- Upfront Capital Cost: £46,922
    - Building Fabric: £31,848
    - Low-Carbon Hating: £7,001
    - Renewable Energy: £8,072
- Annual Energy Savings: £1,018
- Payback Period: 46 years
- Lifetime Financial Savings: £20,356
- Net Lifetime Cost: £26,566
- Embodied Carbon Emissions (20-Year): 6.3tCO_2e
- Operational Carbon Emissions (20-Year): 1.5tCO_2e
- Whole Life Carbon: 7.8tCO_2e
- Operational Carbon Savings: 52.6tCO_2e
- Net Lifetime Carbon Reduction: 46.3tCO_2e

- Carbon Cost Effectiveness: £573 per tonne of CO_2e saved

Discussion

- A Typical Retrofit has a Lifetime Capital Cost of £27,521 compared to £46,922 for Deep Retrofit. The increase of £19,401 (approximately 70%) represents the additional cost of implementing enhanced measures such as improved building fabric, optimized low-carbon heating, and upgraded renewable energy systems.
- A Typical Retrofit results in annual energy savings of £894, compared to £1,018 for Deep Retrofit.
- Deep Retrofit costs £19,401 more than Typical Retrofit for increased annual savings of £124. This equates to a payback period of approximately 157 years for the additional capital investment.
    - Retrofit Stage 1 (Building Fabric) represents 43% of the total cost for Typical Retrofit (at £11,951) and increases to 68% for Deep Retrofit (at £31,848).
    - Retrofit Stage 2 (Low-Carbon Heating) represents 26% of the total Capital Cost for Typical Retrofit (at £7,156) and 15% for Deep Retrofit (at £7,001).
    - Retrofit Stage 3 (Renewable Energy) represents 30% of the total Capital Cost for Typical Retrofit (at £8,139) and 17% for Deep Retrofit (at £8,072).
- Considering payback periods at each Retrofit Stage, based on the energy bill savings:
    - Typical Retrofit would result in a payback period of approximately 35 years for Stage 1 (Building Fabric), 35 years for Stage 2 (Low-Carbon Heating), and 12 years for Stage 3 (Renewable Energy). Combined, this yields a financial payback of 31 years.
    - Deep Retrofit would result in a payback period of approximately 55 years for Stage 1 (Building Fabric), 40 years for Stage 2 (Low-Carbon Heating), and 15 years for Stage 3 (Renewable Energy). Combined, this yields a financial payback of 46 years.
- For Typical Retrofit, the Embodied Carbon emissions over 20 years are $4.2tCO_2e$ compared to $6.3tCO_2e$ for Deep Retrofit. The increase of $2.1tCO_2e$ is associated with the enhanced building fabric measures.
- The Operational Carbon associated with Typical Retrofit is $1.8tCO_2e$ compared to $1.5tCO_2e$ for Deep Retrofit. The additional saving of $0.3tCO_2e$ for Deep Retrofit is attributed to these measures.
- For this property type, Deep Retrofit results in $2.1tCO_2e$ more embodied carbon emissions than Typical Retrofit, but only achieves operational carbon savings of $0.3tCO_2e$. Therefore, shifting from Typical to Deep Retrofit results in a net decrease in Whole Life Carbon Reduction of approximately $1.8tCO_2e$.
- Over 20 years, a Typical Retrofit achieves a Net Lifetime Carbon Reduction of $48{,}100kgCO_2e$ compared to $46{,}300kgCO_2e$ for Deep Retrofit. Considering the breakdown per Retrofit Stage:
    - Retrofit Stage 1 (Building Fabric) represents 47% of the Net Lifetime Carbon Savings for Typical Retrofit, compared to 61% for Deep Retrofit.
    - Retrofit Stage 2 (Low-Carbon Heating) represents 54% of the Net Lifetime Carbon Savings for Typical Retrofit, compared to 40% for Deep Retrofit.
    - Retrofit Stage 3 (Renewable Energy) represents –1% of the Net Lifetime Carbon Savings for both the Typical and Deep Retrofit scenarios.
- For this property type, it can be concluded that the increased building fabric measures between Typical and Deep Retrofit are not cost-effective in terms of financial payback.
- It can be concluded that Low-Carbon Heating is the single most impactful measure in terms of Net Lifetime Carbon Reduction, driven by the shift from gas to electricity.
- It can be concluded that solar is not effective in reducing Whole Life Carbon, as the upfront embodied carbon is higher than the operational carbon savings over a 20-year period.

- Considering Carbon Cost Effectiveness, Typical Retrofit costs less and achieves more Whole Life Carbon Savings than Deep Retrofit; therefore, the cost per tonne of carbon saved for Typical Retrofit is £200/tCO_2e compared to £573/tCO_2e for Deep Retrofit.

End Terrace Flat

General

- Floor area: 62.0
- Bedrooms: 2
- Occupancy:3
- For the detached house the following material quantities were assumed for the typical retrofit scenario:
  - 62.0m^2 of Rockwool loft insulation at 400mm thickness
  - 63.0m^2 of external wall insulation, consisting of Rockwool insulation at 230mm thickness, adhesive basecoat, fibreglass mesh, and silicone render
  - Mitsubishi Ecodan 8kW + 150L Packaged Cylinder (Shared between flats)
  - 5 Jinko Tiger Neo 440Wp Solar Panels
- For the detached house the following additional material quantities were assumed for the deep retrofit scenario:
  - 62.0m^2 of Spacetherm Aerogel ground floor insulation at 40mm thickness and 3mm chipboard flooring
  - 8.1m^2 of triple glazed PVC window area (openable)
  - 1.8m^2 of solid UPVC external door area
- Excluding the flats, the assumed quantity of Low Carbon Heating and PV remains consistent across all generic property types. The only varying factors being the material quantities for fabric improvements. As a result, in this analysis, the house type geometry is the primary factor influencing cost and carbon outcomes.

Typical Retrofit

- Upfront Capital Cost: £29,990
  - Building Fabric: £14,503
  - Low-Carbon Hating: £7,115
  - Renewable Energy: £8,109
- Annual Energy Savings: £897
- Payback Period: 33 years
- Lifetime Financial Savings: £17,939
- Net Lifetime Cost: £12,051
- Embodied Carbon Emissions (20-Year): 4.8tCO_2e
- Operational Carbon Emissions (20-Year): 2.3tCO_2e
- Whole Life Carbon: 7.1tCO_2e
- Operational Carbon Savings: 61.2tCO_2e
- Net Lifetime Carbon Reduction: 56.5tCO_2e
- Carbon Cost Effectiveness: £213 per tonne of CO_2e saved

Deep Retrofit

- Upfront Capital Cost: £52,637
  - Building Fabric: £37,640

- Low-Carbon Hating: £6,966
  - Renewable Energy: £8,032
- Annual Energy Savings: £1,130
- Payback Period: 47 years
- Lifetime Financial Savings: £22,607
- Net Lifetime Cost: £30,030
- Embodied Carbon Emissions (20-Year): 7.3tCO_2e
- Operational Carbon Emissions (20-Year): 1.6tCO_2e
- Whole Life Carbon: 8.9tCO_2e
- Operational Carbon Savings: 61.9tCO_2e
- Net Lifetime Carbon Reduction: 54.6tCO_2e
- Carbon Cost Effectiveness: £550 per tonne of CO_2e saved

Discussion

- A Typical Retrofit has a Lifetime Capital Cost of £29,990 compared to £52,637 for Deep Retrofit. The increase of £22,647 or approximately 76% represents the additional cost of implementing enhanced measures such as improved building fabric, optimized low-carbon heating, and upgraded renewable energy systems.
- A Typical Retrofit results in annual energy savings of £897, compared to £1,130 for Deep Retrofit.
- Deep Retrofit costs £22,647 more than Typical Retrofit for increased annual savings of £233. This equates to a payback period of approximately 97 years for the additional capital investment.
  - Retrofit Stage 1 (Building Fabric) represents 48% of the total cost for Typical Retrofit (at £14,503) and increases to 72% for Deep Retrofit (at £37,640).
  - Retrofit Stage 2 (Low-Carbon Heating) represents 24% of the total Capital Cost for Typical Retrofit (at £7,115) and 13% for Deep Retrofit (at £6,966).
  - Retrofit Stage 3 (Renewable Energy) represents 27% of the total Capital Cost for Typical Retrofit (at £8,109) and 15% for Deep Retrofit (at £8,109)—noting a slight rounding adjustment for consistency.
- Considering payback periods at each Retrofit Stage, based on the energy bill savings:
  - Typical Retrofit would result in a payback period of approximately 46 years for Stage 1 (Building Fabric), 46 years for Stage 2 (Low-Carbon Heating), and 13 years for Stage 3 (Renewable Energy), yielding a combined financial payback of 33 years.
  - Deep Retrofit would result in a payback period of approximately 72 years for Stage 1, 35 years for Stage 2, and 14 years for Stage 3, yielding a combined financial payback of 47 years.
- For Typical Retrofit, the Embodied Carbon emissions over 20 years are 4.8tCO_2e compared to 7.3tCO e for Deep Retrofit. The increase of 2.5tCO_2e is associated with the enhanced building fabric measures.
- The Operational Carbon associated with Typical Retrofit is 2.3tCO_2e compared to 1.6tCO_2e for Deep Retrofit. The increased saving of 0.7tCO_2e for Deep Retrofit is attributed to these measures.
- For this property type, Deep Retrofit results in 2.5tCO_2e more embodied carbon emissions than Typical Retrofit, but only achieves operational carbon savings of 0.7tCO_2e. Therefore, improving the retrofit strategy from Typical to Deep results in a net decrease in Whole Life Carbon Reduction of approximately 1.8tCO_2e.
- Over 20 years, a Typical Retrofit achieves a Net Lifetime Carbon Reduction of 56.5tCO_2e compared to 54.6tCO_2e for Deep Retrofit. Considering the breakdown per Retrofit Stage:
  - Retrofit Stage 1 (Building Fabric) represents 41% of the Net Lifetime Carbon Savings for Typical Retrofit, compared to 64% for Deep Retrofit.

- Retrofit Stage 2 (Low-Carbon Heating) represents 60% of the Net Lifetime Carbon Savings for Typical Retrofit, compared to 37% for Deep Retrofit.
- Retrofit Stage 3 (Renewable Energy) represents –1% of the Net Lifetime Carbon Savings for both the Typical and Deep Retrofit scenarios.

- For this property type, it can be concluded that the increased building fabric measures between Typical and Deep Retrofit are not cost-effective in terms of financial payback.
- It can be concluded that Low-Carbon Heating is the single most impactful measure in terms of Net Lifetime Carbon Reduction, driven by the shift from gas to electricity.
- It can be concluded that solar is not effective in reducing Whole Life Carbon, as the upfront embodied carbon is higher than the operational carbon savings over a 20-year period.
- Considering Carbon Cost Effectiveness, Typical Retrofit costs less and achieves more Whole Life Carbon Savings than Deep Retrofit; therefore, the cost per tonne of carbon saved for Typical Retrofit is £213/tCO_2e compared to £550/tCO_2e for Deep Retrofit.

Bungalow (Specific)

General

- Floor area: 53.0
- Bedrooms: 3
- Occupancy:4
- For the detached house the following material quantities were assumed for the typical retrofit scenario:
  - 57.8m^2 of Rockwool loft insulation at 400mm thickness
  - 86.7m^2 of external wall insulation, consisting of Rockwool insulation at 230mm thickness, adhesive basecoat, fibreglass mesh, and silicone render
  - Mitsubishi Ecodan 5kW + 200L Packaged Cylinder
  - 14 Jinko Tiger Neo 440Wp Solar Panels
- For the detached house the following additional material quantities were assumed for the deep retrofit scenario:
  - 53.5m^2 of Spacetherm Aerogel ground floor insulation at 40mm thickness and 3mm chipboard flooring
  - 8.7m^2 of triple glazed PVC window area (openable)
  - 3.6m^2 of solid UPVC external door area

Typical Retrofit

- Upfront Capital Cost: £42,868
  - Building Fabric: £16,354
  - Low-Carbon Hating: £12,323
  - Renewable Energy: £14,190
- Annual Energy Savings: £1,239
- Payback Period: 35 years
- Lifetime Financial Savings: £24,779
- Net Lifetime Cost: £18,083
- Embodied Carbon Emissions (20-Year): 9.2tCO_2e
- Operational Carbon Emissions (20-Year): 0.4tCO_2e
- Whole Life Carbon: 9.7tCO_2e
- Operational Carbon Savings: 29.7tCO_2e
- Net Lifetime Carbon Reduction: 21.0tCO_2e

- e Carbon Cost Effectiveness: £609 per tonne of CO_2e saved

Deep Retrofit

- Upfront Capital Cost: £63,967
  - Building Fabric: £37,705
  - Low-Carbon Hating: £12,207
  - Renewable Energy: £14,056
- Annual Energy Savings: £1,365
- Payback Period: 47 years
- Lifetime Financial Savings: £27,297
- Net Lifetime Cost: £36,671
- Embodied Carbon Emissions (20-Year): 12.9tCO_2e
- Operational Carbon Emissions (20-Year): 0.1tCO_2e
- Whole Life Carbon: 13.0tCO_2e
- Operational Carbon Savings: 39.3tCO_2e
- Net Lifetime Carbon Reduction: 26.5tCO_2e
- Carbon Cost Effectiveness: £1386 per tonne of CO_2e saved

Discussion

- A Typical Retrofit has a Lifetime Capital Cost of £42,868 compared to £63,967 for Deep Retrofit. The increase of £21,099 or approximately 49% represents the additional cost of implementing enhanced measures such as improved building fabric, optimized low-carbon heating, and upgraded renewable energy systems.
- A Typical Retrofit results in annual energy savings of £1,239, compared to £1,365 for Deep Retrofit.
- Deep Retrofit costs £21,099 more than Typical Retrofit for increased annual savings of £126. This equates to a payback period of approximately 167 years for the additional capital investment.
  - Retrofit Stage 1 (Building Fabric) represents 38% of the total cost for Typical Retrofit (at £16,354) and increases to 59% for Deep Retrofit (at £37,705).
  - Retrofit Stage 2 (Low-Carbon Heating) represents 29% of the total Capital Cost for Typical Retrofit (at £12,323) and 19% for Deep Retrofit (at £12,207).
  - Retrofit Stage 3 (Renewable Energy) represents 33% of the total Capital Cost for Typical Retrofit (at £14,190) and 22% for Deep Retrofit (at £14,056).
- Considering payback periods at each Retrofit Stage, based on the energy bill savings:
  - Typical Retrofit would result in a payback period of approximately 48 years for Stage 1 (Building Fabric), 48 years for Stage 2 (Low-Carbon Heating), and 15 years for Stage 3 (Renewable Energy), yielding a combined financial payback of 35 years.
  - Deep Retrofit would result in a payback period of approximately 70 years for Stage 1, 40 years for Stage 2, and 16 years for Stage 3, yielding a combined financial payback of 47 years.
- For Typical Retrofit, the Embodied Carbon emissions over 20 years are 9.2tCO_2e compared to 12.9tCO_2e for Deep Retrofit. The increase of 3.7tCO_2e is associated with the enhanced building fabric measures.
- The Operational Carbon associated with Typical Retrofit is 0.4tCO_2e compared to 0.1tCO_2e for Deep Retrofit. The additional saving of 0.3tCO_2e for Deep Retrofit is attributed to these measures.
- For this property type, Deep Retrofit results in 3.7tCO_2e more embodied carbon emissions than Typical Retrofit, but achieves operational carbon savings that are 0.3tCO_2e greater.

Therefore, improving the retrofit strategy from Typical to Deep results in a net increase in Whole Life Carbon Reduction of approximately 5.5tCO_2e.

- Over 20 years, a Typical Retrofit achieves a Net Lifetime Carbon Reduction of 29.7tCO_2e compared to 26.5tCO_2e for Deep Retrofit. Considering the breakdown per Retrofit Stage:
    - Retrofit Stage 1 (Building Fabric) represents 34% of the Net Lifetime Carbon Savings for Typical Retrofit, compared to – for Deep Retrofit.
    - Retrofit Stage 2 (Low-Carbon Heating) represents 71% of the Net Lifetime Carbon Savings for Typical Retrofit, compared to – for Deep Retrofit.
    - Retrofit Stage 3 (Renewable Energy) represents –4% of the Net Lifetime Carbon Savings for Typical Retrofit, compared to – for Deep Retrofit.
- For this property type, it can be concluded that the increased building fabric measures between Typical and Deep Retrofit are not cost-effective in terms of financial payback.
- It can be concluded that Low-Carbon Heating is the single most impactful measure in terms of Net Lifetime Carbon Reduction, driven by the shift from gas to electricity.
- It can be concluded that solar is not effective in reducing Whole Life Carbon, as the upfront embodied carbon is higher than the operational carbon savings over a 20-year period.
- Considering Carbon Cost Effectiveness, Typical Retrofit costs less and achieves more Whole Life Carbon Savings than Deep Retrofit; therefore, the cost per tonne of carbon saved for Typical Retrofit is £213/tCO_2e compared to £550/tCO_2e for Deep Retrofit.

9.2 Energy Bills

As highlighted throughout this report, the cost of energy increases significantly following ASHP installation, unless Fabric First principles are followed. To demonstrate this, Figure 48 and Figure 49 show the impact of electric heating on annual energy bills.

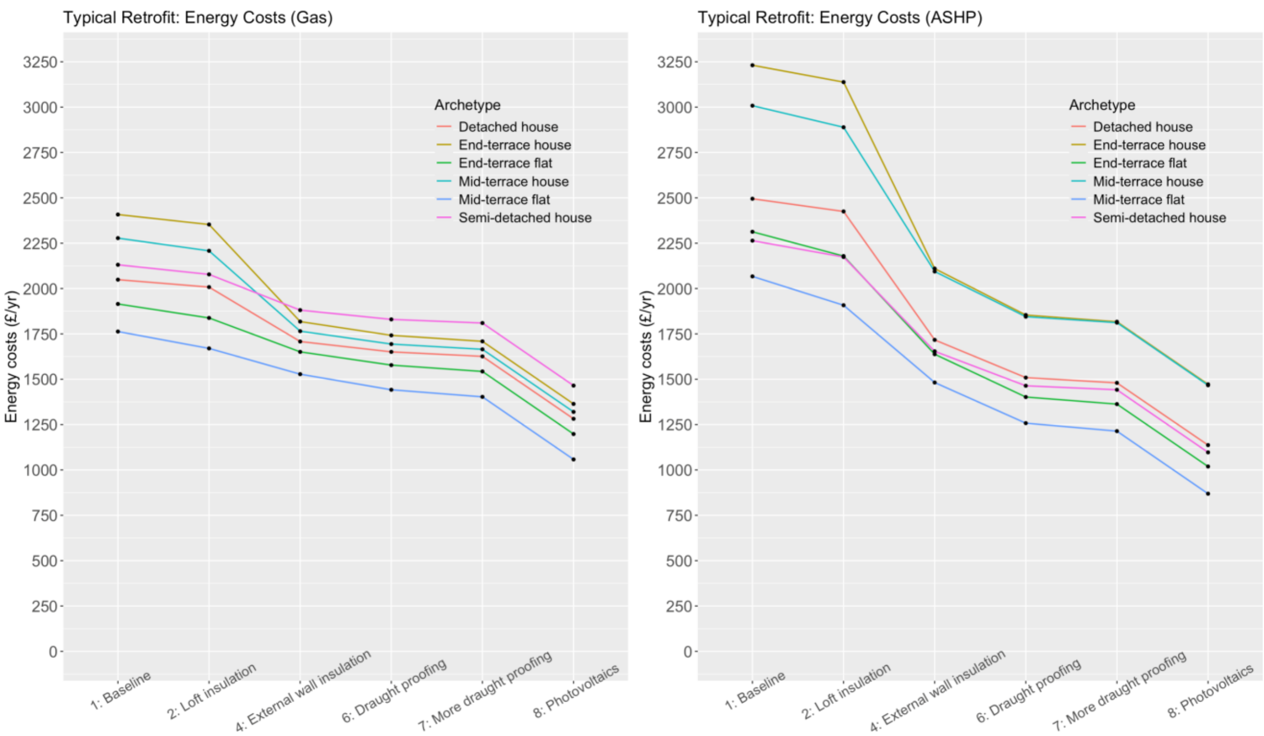


Figure 48 - Comparison of annual energy costs for deep retrofit, between gas (left) and ASHP heating (right)

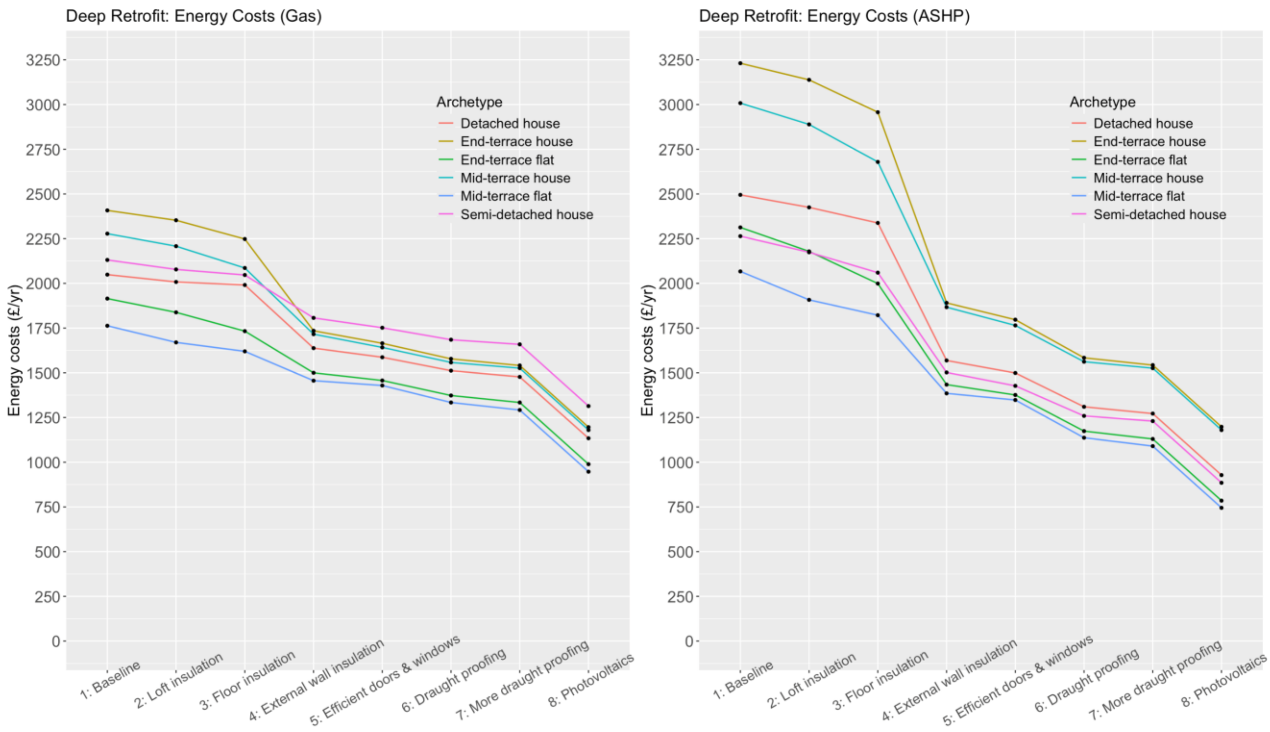


Figure 49 - Comparison of annual energy costs for deep retrofit, between gas (left) and ASHP heating (right)

Across all property types, energy bills increase by between 17%-34% per year, if an ASHP is installed with no fabric improvements. The equates to an increase of between £305 and £824 per year or between £6k and £16k over a 20-year period, depending on the house type.

Table 67 considers the annual reduction in energy bills, following the installation of loft insulation and EWI, with an electric heating system.

Table 67: Analysis of annual energy bills before and after loft and EWI optimisation, with ASHP heating

Annual Energy Cost Analysis			
House Type	Pre-Retrofit (Base) – Gas	Optimised (Loft & EWI) – Electricity	Reduction (%)
Detached	£2,050	£1,717	16%
Semi-Detached	£2,132	£1,655	22%
Mid-Terrace	£2,278	£2,094	8%
End-Terrace	£2,408	£2,111	12%
Mid-Terrace Flat	£1,763	£1,483	16%
End-Terrace Flat	£1,916	£1,639	14%

Table 67 shows that, for every house type, the annual energy bills consistently fall by between 8% and 22% compared to the pre-retrofit scenario. It is vital that Broxtowe Borough Council do not recommend or implement retrofit strategies that will result in increased energy bills for the occupiers. This would worsen household financial pressures and would adversely impact fuel poverty levels within the Borough.

9.3 Recommendations

Unless otherwise stated, the statements within this Section are true for both Generic and Specific house types.

- A Fabric First approach is recommended, for reasons set out at Sections 1.4, 1.5, 1.6, and 9.2. A primary driver for this is to ensure that energy bills for occupiers do not increase, as a result of heating electrification.
- To avoid unintended consequences, it is recommended that Broxtowe Borough Council (BBC) follow PAS 2035 best practice principles for retrofit. This includes the specification of External Wall Insulation, for reasons set out at Section 1.6.
- It can be concluded that increasing the fabric measures from Typical to Deep Retrofit is not cost-effective, in terms of financial payback.
- From a Whole Life Carbon Reduction perspective, it can be concluded that Typical Retrofit is more effective than Deep Retrofit.
- Considering Carbon Cost Effectiveness, Typical Retrofit consistently costs less and results in more Whole Life Carbon Savings than Deep Retrofit.
- It can be concluded that External Wall Insulation is the single most impactful fabric improvement measure, in terms of energy demand reduction and impact on household energy bills.
- In accordance with a Fabric First approach, we recommend that BBC implement Typical Retrofit – Stage 1, across their portfolio. In summary, this consists of:
    - Loft insulation
    - External wall insulation
- As highlighted, improving the fabric further than this (via windows, doors, and ground floor insulation) is neither cost effective nor carbon effective, when assessed over a 20-year period.
- Assuming that PAS2035 principles are followed, we can be confident that a Typical Retrofit (Stage 1) will result in the following outcomes:
    - Each property will be free from building defects.
    - Each property will be warmer and more comfortable, with associated health benefits.
    - Each property, still heated by gas, will require between 12% - 24% less to be spent on energy bills annually.
    - The fabric and thermal performance of each property will have been improved sufficiently to comply with BUS funding for electric heating upgrades.
- The cost for Typical Retrofit Stage 1 is estimated to be between £11,590 and £35,633, depending on the property type. This is the estimated Capital Cost for loft insulation and EWI, and other allowances set out at Section 6.1.
- It is recommended that BBC investigate potential funding schemes to meet the initial upfront investment for Typical Retrofit Stage 1 fabric improvements. Potential schemes that would be suitable include:
    - Energy Company Obligation (ECO) (OFGEM, 2025).
    - Warm Homes: Social Housing Fund (DofESNZ, 2024).
    - Great British Insulation Scheme (GBIS) (DofESNZ, 2023) .
- It can be concluded that Low Carbon Heating is the single most impactful measure, in terms of Net Lifetime Carbon Reduction. This is driven by the shift to electricity from gas.
- Low Carbon Heating installations are anticipated to cost between £12,200 - £14,118 per property.
- Following the implementation of Typical Retrofit Stage 1, the fabric and thermal performance of each property will have been improved sufficiently to ensure that, post Retrofit Stage 2 (Low Carbon Heating), the energy bills will be between 8%-22% lower than the pre-retrofit scenario.
- We recommend that following Stage 1, BBC implement Typical Retrofit Stage 2 (Low Carbon Heating). We can be confident that this will result in the following outcomes:

    - Treated properties will become 'Net Zero ready' (see Section 1.5).
    - Generic properties will emit between 94%-95% less operational carbon emissions, equating to between 51tonnes and 81tonnes saved per property over a 20-year period.
    - The specific property type (bungalow) will emit approximately 92% less operational carbon emissions, equating to approximately 36tonnes over a 20-year period.
    - Energy bills for occupants will not increase.
    - ASHP installations will perform optimally based on improved fabric performance.
- Subject to the agreed funding strategy and the level of funding available, there are likely to be financial efficiencies associated with implementing Retrofit Stage 1 and 2 in combination.
- It is recommended that BBC investigate potential funding schemes to meet the initial upfront investment for Typical Retrofit Stage 2 low carbon heating upgrades. Potential schemes that would be suitable include:
    - Energy Company Obligation (ECO) (OFGEM, 2025).
    - Warm Homes: Social Housing Fund (DofESNZ, 2024).
    - Boiler Upgrade Scheme (BUS) (DofESNZ, 2022).
- Solar installations are consistently not effective in reducing Whole Life Carbon. This is because the embodied carbon is higher than the operational carbon savings, over a 20-year period.
- Solar installations result in the most attractive financial payback, compared to fabric and low carbon heating improvements.
- It is not recommended that BBC invest in Retrofit Stage 3 (Renewable Energy), since the there is a negative Whole Life Carbon impact over a 20-year period. Occupiers should be made aware of the potential benefits in relation to their energy bills, should they wish to invest.

9.4 Social Housing: Projections

Within this section, estimated projections are provided for Social Housing within Broxtowe Borough Council, in relation to aggregated retrofit costs and carbon savings.

9.4.1 Housing Quantity

As reported in previous sections (see Section 1.8), social housing accounts for around 14% (n=5,157) of Broxtowe's entire stock.
Table *68* and

Table 69 provide more granular social housing information. First,
Table *68* provides a basic cross-tabulation of property type versus building form, while

Table 69 presents energy efficiency statistics per property-build type of interest (detached, semi-detached, mid- and end-terrace houses, flats and detached bungalows). Note that the number of observations reduces to 4,914 in
Table *68* as built form information was not available for ~250 properties.

Table 68: Property type versus building form in Broxtowe for social housing (n=4,914)

	Detached	Semi-detached	Mid-Terrace	End-Terrace	Total
Bungalow	128 (2.60)	291 (5.92)	122 (2.48)	137 (2.79)	678 (13.80)
House	33 (0.67)	763 (15.53)	628 (12.78)	453 (9.22)	1,877 (38.20)
Flat	NA	NA	NA	NA	2,061 (41.94)

Maisonette	64 (1.30)	152 (3.09)	35 (0.71)	47 (0.96)	298 (6.06)
Total	**670**	**2,036**	**1,293**	**915**	**4,914**

Table 69 - Energy efficiency characteristics for socially rented houses, flats and detached bungalows, disaggregated by building form (% EPC A–C versus D–G within property-build type in parentheses

Property type	**Building form**	**EPC A–C**	**EPC D–G**	**Median SAP**
Houses (n=1877)	*Detached*	6 (18.18)	27 (81.82)	63
	Semi-detached	278 (36.44)	485 (63.56)	67
	Mid-terrace	351 (55.89)	277 (44.11)	69
	End-terrace	188 (41.50)	265 (58.50)	67
Flats (n=2061)	*All flats*	1,693 (74.32)	585 (25.68)	73
Bungalows (n=128)	*Detached*	15 (11.72)	113 (88.28)	66

Table 70 projects the total quantity of Social Housing in Broxtowe, according to property type. As shown, the seven property types analysed within this report represent 57% of all Social Housing within the Borough.

Table 70: Quantity of Social Housing per property type within Broxtowe Borough Council

Property Type	**Generic/Specific**	**Actual Data**	**%**	**Projected**
Detached	Generic	33	1%	35
Semi-Detached	Generic	763	16%	801
Mid-Terraced House	Generic	628	13%	659
End-Terraced House	Generic	453	9%	475
Mid-Terraced Flat	Generic	508	10%	533
End-Terraced Flat	Generic	278	6%	292
Detached Bungalow	Specific	128	3%	134
Total (Exc. Other)		**2,791**	**57%**	**2,929**
Other Property Types		2,123	43%	2,228
Total		**4,914**	**100%**	**5,157**

9.4.2 Capital Costs

Fabric Improvement Measures

Using the projected quantities set out within Table 70, Table 71 estimates the total Capital Cost to implement the recommended Retrofit Stage 1 (Fabric Improvement) measures.

Table 71: Projected costs for Typical Retrofit Stage 1 (Fabric Improvement) – Social housing

Typical Retrofit - Stage 1 (Fabric Improvement)			
Property Type	**Quantity**	**Capital Cost**	**Total**
Detached	35	£35,632.65	£1,234,025.14
Semi-Detached	801	£25,494.28	£20,414,051.42
Mid-Terraced House	659	£17,301.72	£11,402,782.74
End-Terraced House	475	£26,983.10	£12,827,795.91

Mid-Terraced Flat	533	£12,114.17	£6,458,317.26
End-Terraced Flat	292	£14,671.43	£4,280,350.77
Detached Bungalow (Specific)	134	£16,354.11	£2,196,842.20
Total (Exc. Other)	**2,929**		**£58,814,165.44**
Other Property Types	2,228	Exc.	Exc.

- The seven property types represent 57% of the total number of social housing properties in Broxtowe.
- The projected cost to implement Typical Retrofit Stage 1 Fabric Improvement across 2,929 social housing properties in Broxtowe, is approximately £58.8m.
- This projected cost does not account for potential available funding, which is discussed in previous sections.
- For EWI and loft insulation, Broxtowe Borough Council should be able to access at least £7,500 per social housing property (DofESNZ, 2024). This represents £22.0m or 37% of the total cost.

Low Carbon Heating Measures

Using the projected quantities set out within Table 70, Table 72 estimates the total Capital Cost to implement the recommended Retrofit Stage 2 (Low Carbon heating) measures.

Table 72: Projected costs for Typical Retrofit Stage 2 (Low Carbon Heating) – Social housing

Typical Retrofit - Stage 2 (Low Carbon Heating)			
Property Type	**Quantity**	**Cost**	**Total**
Detached	35	£12,199.52	£422,492.17
Semi-Detached	801	£12,288.86	£9,840,064.83
Mid-Terraced House	659	£12,396.37	£8,169,890.96
End-Terraced House	475	£12,273.32	£5,834,749.29
Mid-Terraced Flat	533	£7,155.83	£3,814,920.59
End-Terraced Flat	292	£7,114.83	£2,075,733.43
Bungalow (Specific)	134	£12,323.44	£1,655,404.17
Total (Exc. Other)	**2,929**		**£31,813,255.45**
Other Property Types	2,228	Exc.	Exc.

- The seven property types represent 57% of the total number of social housing properties in Broxtowe.
- The projected cost to implement Typical Retrofit Stage 2 Low Carbon Heating across 2,929 social housing properties in Broxtowe, is approximately £31.8m.
- This projected cost does not account for potential available funding, which is discussed in previous sections.
- For Low Carbon Heating, Broxtowe Borough Council should be able to access £7,500 per social housing property (DofESNZ, 2022). This represents approximately £22m, or 70% of the total cost of low carbon heating.

9.4.3 Carbon Savings

Fabric Improvement Measures

Using the projected quantities set out within Table 70, Table 73 estimates the total Net Lifetime Carbon Savings following the implementation of Retrofit Stage 1 (Fabric Improvement) measures.

Table 73: Projected carbon savings for Typical Retrofit Stage 1 (Fabric Improvement) – social housing

Property Type	Quantity	Net Lifetime Carbon Reductions	
		Per Property (tCO_2e)	**Total (tCO_2e)**
Detached	35	23	805
Semi-Detached	801	17	13,744
Mid-Terraced House	659	38	25,335
End-Terraced House	475	43	20,564
Mid-Terraced Flat	533	23	12,041
End-Terraced Flat	292	23	6,713
Detached Bungalow (Specific)	134	10	1,338
Total (Exc. Other)	**2,929**		**80,540**
Other Property Types	2,228	Exc.	Exc.

- The seven property types represent 57% of the total number of social housing properties in Broxtowe.
- Implementing Typical Retrofit Stage 1 Fabric Improvement across 2,929 social housing properties will result in approximately 80,540tonnes of CO_2e saved, over a 20-year period.
- On average, a mature tree absorbs roughly 21kg of CO_2e per year (Viessmann, 2022). 80,540tonnes of CO_2e therefore equates to the carbon absorbed by roughly 3.8million mature trees in one year. This translates to an area of roughly 35km^2, similar in size to the city of Tamworth.

Low Carbon Heating Measures

Using the projected quantities set out within Table 70, Table 74 estimates the total Net Lifetime Carbon Savings following the implementation of Retrofit Stage 1 (Fabric Improvement) measures.

Table 74: Projected carbon savings for Typical Retrofit Stage 2 (Low Carbon Heating) – social housing

Property Type	Quantity	Net Lifetime Carbon Reductions	
		Per Property (tCO_2e)	**Total (tCO_2e)**
Detached	35	29	1,010
Semi-Detached	801	28	22,037
Mid-Terraced House	659	28	18,762
End-Terraced House	475	31	14,956
Mid-Terraced Flat	533	26	13,816
End-Terraced Flat	292	34	9,864
Detached Bungalow (Specific)	134	21	2,830
Total (Exc. Other)	**2,929**		**83,275**
Other Property Types	2,228	Exc.	Exc.

- The seven property types represent 57% of the total number of social housing properties in Broxtowe.
- Implementing Typical Retrofit Stage 2 Low Carbon Heating across 2,929 social housing properties will result in approximately 83,275tonnes of CO_2e saved, over a 20-year period.
- On average, a mature tree absorbs roughly 21kg of CO_2e per year (Viessmann, 2022). 83,275tonnes of CO_2e therefore equates to the carbon absorbed by roughly 4 million mature trees in one year. This translates to an area of roughly 38km^2, similar in size to the town of Cambridge.

9.5 Combined Total: Projections

Within this section, estimated projections are provided for all properties within Broxtowe Borough Council, in relation to aggregated retrofit costs and carbon savings.

9.5.1 Housing Quantity

As reported in previous sections (see Section 1.8), there are a total of 36,993 properties in Broxtowe Borough Council. Table 75 highlights that the seven property types analysed within this technical report represent 86% of the total number of properties in Broxtowe.

Table 75: Property type and quantity in Broxtowe (n=36,993)

Typical Retrofit - Stage 1 (Fabric Improvement)		
Property Type	**Quantity**	**%**
Detached	7,607	21%
Semi-Detached	11,105	30%
Mid-Terraced House	4,559	12%
End-Terraced House	3,111	8%
Mid-Terraced Flat	1,324	4%
End-Terraced Flat	951	3%
Detached Bungalow (Specific)	3,016	8%
Total (Exc. Other)	**31,673**	**86%**
Other	5,320	14%
Total	**36,993**	**100%**

9.5.2 Capital Costs

Fabric Improvement Measures

Using the projected quantities set out within Table 75, Table 76 estimates the total Capital Cost to implement the recommended Retrofit Stage 1 (Fabric Improvement) measures.

Table 76: Projected costs for Typical Retrofit Stage 1 (Fabric Improvement) – total

Typical Retrofit - Stage 1 (Fabric Improvement)			
Property Type	**Quantity**	**Cost**	**Total**
Detached	7,607	£35,632.65	£271,057,548.51
Semi-Detached	11,105	£25,494.28	£283,113,937.59
Mid-Terraced House	4,559	£17,301.72	£78,878,531.90
End-Terraced House	3,111	£26,983.10	£83,944,427.50
Mid-Terraced Flat	1,324	£12,114.17	£16,039,161.81
End-Terraced Flat	951	£14,671.43	£13,952,534.40

Detached Bungalow (Specific)	3,016	£16,354.11	£49,323,995.67
Total (Exc. Other)	**31,673**		**£796,310,137.40**
Other Property Types	5,320	Exc.	Exc.

- The seven property types represent 86% of the total number of properties in Broxtowe.
- The projected cost to implement Typical Retrofit Stage 1 Fabric Improvement across 31,673 properties in Broxtowe, is approximately £796m.
- This projected cost does not account for potential available funding, which would be subject to the occupier and property tenure type.

Low Carbon Heating Measures

Using the projected quantities set out within Table 75, Table 77 estimates the total Capital Cost to implement the recommended Retrofit Stage 2 (Low Carbon heating) measures.

Table 77: Projected costs for Typical Retrofit Stage 2 (Low Carbon Heating) – Total

Typical Retrofit - Stage 2 (Low Carbon Heating)			
Property Type	**Quantity**	**Cost**	**Total**
Detached	7,607	£12,199.52	£92,801,748.98
Semi-Detached	1,1105	£12,288.86	£136,467,741.93
Mid-Terraced House	4,559	£12,396.37	£56,515,064.72
End-Terraced House	3111	£12,273.32	£38,182,295.11
Mid-Terraced Flat	1,324	£7,155.83	£9,474,314.47
End-Terraced Flat	9,51	£7,114.83	£6,766,207.65
Bungalow (Specific)	3,016	£12,323.44	£37,167,507.21
Total (Exc. Other)	**31,673**		**£377,374,880.08**
Other Property Types	5,320	Exc.	Exc.

- The seven property types represent 86% of the total number of properties in Broxtowe.
- The projected cost to implement Typical Retrofit Stage 2 Low Carbon Heating across 31,673 properties in Broxtowe, is approximately £377m.
- This projected cost does not account for potential available funding, which is discussed in previous sections.
- For Low Carbon Heating, Broxtowe Borough Council should be able to access £7,500 per property. This represents approximately £238m, or 63% of the total cost of low carbon heating.

Combined

Using the projected quantities set out within Table 75, Table 78 estimates the total Capital Cost to implement both the Retrofit Stage 1 and 2 measures.

Table 78: Projected costs for Combined Typical Retrofit Stage 1 & 2 – Total

Typical Retrofit - Combined Stage 1 and Stage 2			
Property Type	**Quantity**	**Cost**	**Total**
Detached	7,607	£47,832.17	£363,859,297.49
Semi-Detached	11,105	£37,783.13	£419,581,679.53
Mid-Terraced House	4,559	£29,698.09	£135,393,596.62
End-Terraced House	3,111	£39,256.42	£122,126,722.61

Mid-Terraced Flat	1,324	£19,270.00	£25,513,476.28
End-Terraced Flat	951	£21,786.27	£20,718,742.05
Bungalow (Specific)	3,016	£28,677.55	£86,491,502.89
Total (Exc. Other)	**31,673**		**£1,173,685,017.47**
Other Property Types	5,320	Exc.	Exc.

- The projected cost to implement Typical Retrofit - Combined Stage 1 and Stage 2 across 31,673 properties in Broxtowe is approximately £1.17bn.
- This projected cost does not account for potential available funding, which is discussed in previous sections.

9.5.3 Carbon Savings

Fabric Improvement Measures

Using the projected quantities set out within Table 75, Table 79 estimates the total Net Lifetime Carbon Savings following the implementation of Retrofit Stage 1 (Fabric Improvement) measures.

Table 79: Projected carbon savings for Typical Retrofit Stage 1 (Fabric Improvement) – Total

Property Type	**Quantity**	**Net Lifetime Carbon Reductions**	
		Per Property (tCO_2e)	**Total (tCO_2e)**
Detached	7,607	23	176,914
Semi-Detached	11,105	17	19,0607
Mid-Terraced House	4,559	38	175,253
End-Terraced House	3,111	43	134,571
Mid-Terraced Flat	1,324	23	29,902
End-Terraced Flat	951	23	21,883
Detached Bungalow (Specific)	3,016	10	30,042
Total (Exc. Other)	**31,673**		**759,173**
Other Property Types	5,320	Exc.	Exc.

- The seven property types represent 86% of the total number of properties in Broxtowe.
- Implementing Typical Retrofit Stage 1 Fabric Improvement across 31,673 properties will result in approximately 759,173tonnes of CO_2e saved, over a 20-year period.
- On average, a mature tree absorbs roughly 21kg of CO_2e per year (Viessmann, 2022). 759,173tonnes of CO_2e therefore equates to the carbon absorbed by roughly 36.2million mature trees in one year. This translates to an area of roughly 345km^2, similar in size to the Isle of Wight.

Low Carbon Heating Measures

Using the projected quantities set out within Table 75, Table 80 estimates the total Net Lifetime Carbon Savings following the implementation of Retrofit Stage 1 (Fabric Improvement) measures.

Table 80: Projected carbon savings for Typical Retrofit Stage 2 (Low Carbon Heating) – total

Property Type	**Quantity**	**Net Lifetime Carbon Reductions**	
		Per Property (tCO_2e)	**Total (tCO_2e)**
Detached	7,607	29	221,887

Semi-Detached	11,105	28	305,625
Mid-Terraced House	4,559	28	129,787
End-Terraced House	3,111	31	97,872
Mid-Terraced Flat	1,324	26	34,311
End-Terraced Flat	951	34	32,153
Detached Bungalow (Specific)	3,016	21	63,532
Total (Exc. Other)	**31,673**		**885,168**
Other Property Types	5,320	Exc.	Exc.

- The seven property types represent 86% of the total number of properties in Broxtowe.
- Implementing Typical Retrofit Stage 2 Low Carbon Heating across 31,673 properties will result in approximately 885,168tonnes of CO_2e saved, over a 20-year period.
- On average, a mature tree absorbs roughly 21kg of CO_2e per year (Viessmann, 2022). 885,168tonnes of CO_2e therefore equates to the carbon absorbed by roughly 42.1million mature trees in one year. This translates to an area of roughly 402km^2, similar to the size to the County of Rutland.

Combined

Using the projected quantities set out within Table 75, Table 81 estimates the total Net Lifetime Carbon Savings following the implementation of the combined Retrofit Stage 1 and 2 measures.

Table 81: Projected carbon savings for Combined Typical Retrofit Stage 1 & 2 – total

Property Type	Quantity	Net Lifetime Carbon Reductions (tCO2e)	
		Per Property (tCO2e)	Total (tCO2e)
Detached	7,607	52	398,801
Semi-Detached	11,105	45	496,233
Mid-Terraced House	4,559	67	305,040
End-Terraced House	3,111	75	232,443
Mid-Terraced Flat	1,324	48	64,214
End-Terraced Flat	951	57	54,036
Detached Bungalow (Specific)	3,016	31	93,574
Total (Exc. Other)	**31,673**		**1,644,341**
Other	0	Exc.	Exc.

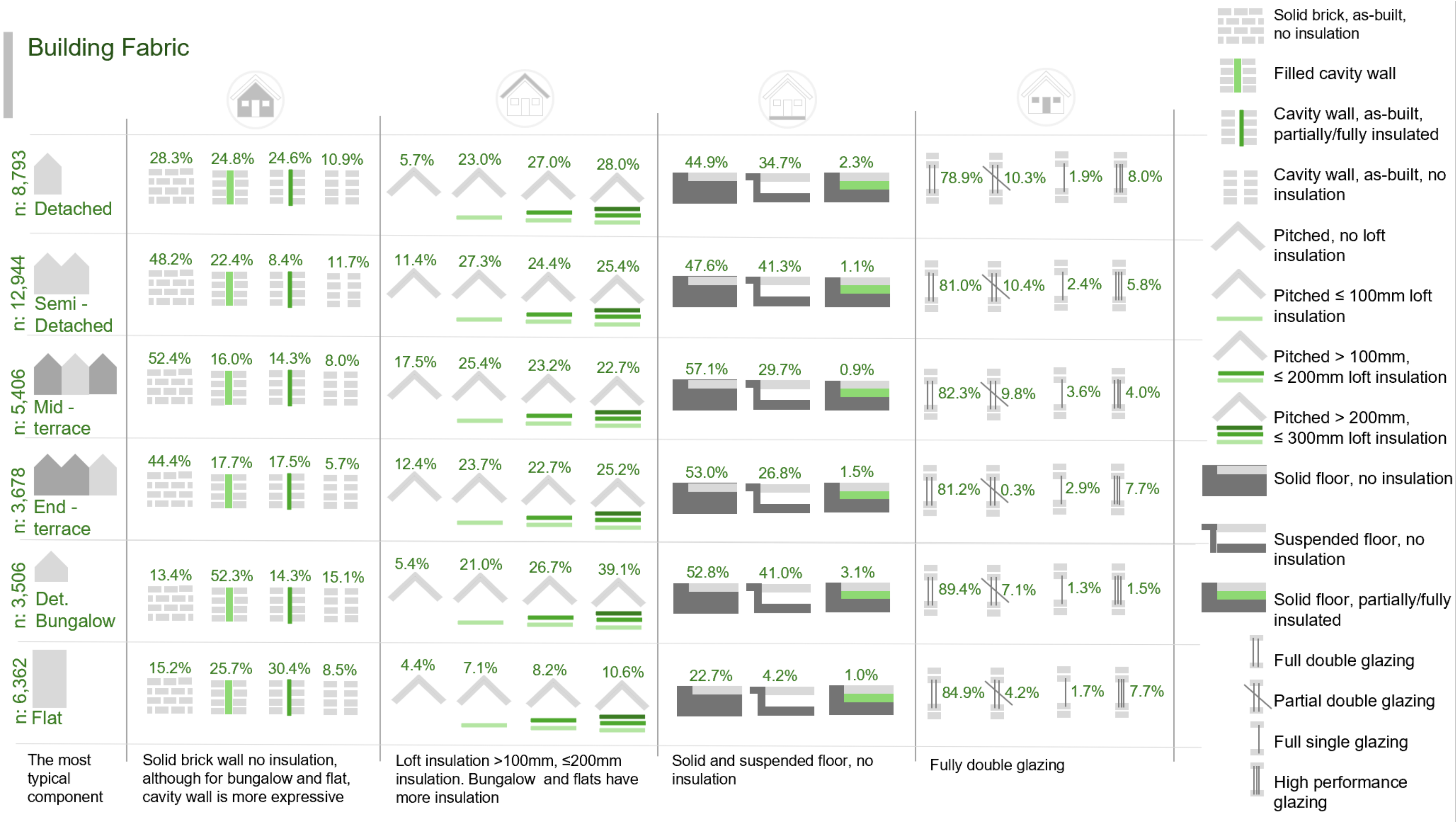
- Implementing Typical Retrofit – Combined Stage 1 and Stage 2 across 31,673 properties will result in approximately 1,644,341 tonnes of CO_2e saved over a 20-year period.
- On average, a mature tree absorbs roughly 21 kg of CO_2e per year (Viessmann, 2022). 1,644,341 tonnes of CO_2e therefore equates to the carbon absorbed by roughly 78.3 million mature trees in one year. This translates to an area of roughly 748 km^2, which is almost double the size of the Isle of Wight (380.7 km^2).

10 Appendices

This section contains any appendix cross-referenced in the report.

10.1 Appendix A: Building Fabric

Typical building fabric breakdown



10.2 Appendix B: Embodied Carbon Data Exports

Data spreadsheet to be made available on request.

11 References

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