UNDERSTANDING CARBON IN THE HISTORIC ENVIRONMENT

Case Study Extension

Addendum to 'Understanding Carbon in the Historic Environment: Scoping Report'

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Key Findings

This study compared the embodied and operational carbon emissions of three domestic refurbishments under three different levels of low-emissions intervention scenarios: 'Base-case' (do nothing); 'Refurbishment' (improve the performance of the existing building); and 'New-build' (demolish and rebuild the existing building to meet current building standards). It estimated their financial attractiveness to homeowners/investors using the savings-to-investment ratio (SIR) metric. In addition, it estimated the policy attractiveness of each scenario using marginal abatement cost (MAC). Two reference study periods (RSPs) were assessed: 60 and 120 years. This report should be read in conjunction with 'Understanding Carbon in the Historic Environment: Scoping Report'. Some key findings from this additional work are described below.

1. The Base-case scenario has highest life cycle carbon emissions for both RSPs. In two of the three case studies Refurbishment is estimated to provide the highest cumulative carbon savings.
2. In total, all three refurbishments saved 212 tonnes of carbon dioxide equivalents compared to the Base-cases over a 60-RSP. In the case of the New-build scenario, this saving was 197 tCO_2e.
3. For both the 60- and 120-year RSPs, the Refurbishment scenario outperformed the New-build option for two of the three case studies in terms of life cycle carbon emissions. One case study did not perform as well as the others due to the fact that the energy-efficient refurbishment measures employed were not as deep as those in the other case studies. Low emissions retrofits must therefore be carefully designed and implemented in order to compete with New-build alternatives.
4. The Refurbishment scenario results in the lowest cumulative emissions for both 2030 and 2050 policy target years.
5. The Refurbishment scenario performed best in term of SIR ratio and MAC for all case studies under these study assumptions. It therefore offers the best value-for-money both to the homeowner/investor and the taxpayer. This is due to the fact that a deep energy-efficient refurbishment can achieve close to the same operational carbon emissions' reductions for significantly lower carbon and capital costs due to the reuse of the existing structure.
6. The use of wood-based products such as woodfibre insulation board in refurbishment resulted in lower embodied emissions than conventional alternatives. The use of such low carbon/carbon negative materials can therefore be used to lower overall life cycle emissions of a building.

1 Case Studies

1.1 Scope

For the purpose of this addendum case study report, data for three completed energy refurbishment projects were obtained for analysis:

1. Mid-terrace, two storey dwelling built between 1900-1910 ('1900s')
2. Semi-detached, two storey dwelling building during the 1970s ('1970s')
3. Detached, two storey dwelling built during the 1990s ('1990s')

The three buildings are located within Manchester, Lancaster and Chorley.

The three case studies were analysed according to the methodology outlined in Section 3 of the original *Understanding Carbon in the Historic Environment* report. The following sections provide results on the life cycle carbon emissions, savings-to-investment ratios and marginal abatement costs for different reference study periods and internal building temperatures. The relative carbon, economic and policy performances of the different building refurbishment options are also presented.

The intention of these case studies was to estimate the relative life cycle carbon emissions of refurbishment works that were carried out at each dwelling, not to verify the suitability of these works or to provide guidance on the energy refurbishment of traditional and historic buildings.

1.2 Retrofit Scenarios: Base-case, Refurbishment and New-build

The life cycle carbon emissions of the following three case studies were assessed against the Base-case and New-build.

The *Base-case* represents the case study building before any energy efficiency upgrades or material changes are made. As no material changes are being made to the Base-case, the embodied emissions are zero. The operation of the building continues as normal, and by modelling the current energy use and sources, an estimate can be made of the amount of carbon the building can be expected to emit over a specified period of time if no improvements are made to the building fabric.

The *Refurbishment* scenario takes into account all of the building upgrades which have been specified by the designers for each of the case studies. These typically involve significant improvements in the thermal performances of walls, roofs, windows and floors, plus air-tightness measures. In all cases it is assumed that heating systems have been upgraded to include modern condensing gas boilers. Lighting systems are completely upgraded to LEDs.

The *New-build* is based on an actual residential building that is currently under construction and has been designed to meet current building regulations and standards. The dwelling is representative of new residential construction in the UK, with concrete block cavity walls and high levels of insulation in the walls, roof and ground floor slab. The modelling of life cycle carbon emissions for the New-build starts with the construction of the building, which includes the embodied emissions of any structure that was demolished on that site, the embodied emissions of the new structure, and the operational emissions for a specified period of time after construction (referred to as the reference study period – RSP).

The embodied and operational emissions are modelled for all scenarios. Embodied emissions result mainly from materials manufacturing, construction and maintenance. Data are largely from relevant product declarations and databases such as the Inventory of Carbon and Energy (ICE). Operational emissions result from the heating and lighting of the dwellings. Fabric and ventilation heat losses are estimated in accordance with BS EN ISO 13790 and combined with published fuel carbon dioxide emissions factors. See *Understanding Carbon in the Historic Environment* for a detailed description of the study methodology.

It should be noted that to calculate the life cycle carbon emissions of maintenance (windows, boilers and roofs/gutters) for each building case (Base-case, Refurbishment and New-build), the same emissions factors were used for each building element across the three different building cases.

The relative emissions and economic performances of the different scenarios are presented for each case study in sections 1.3 – 1.5.

1.3 Mid-terrace Refurbishment, Manchester ('1900s')

1.3.1 Background

This two-storey, mid-terrace brick building was constructed between 1900 and 1910 and is composed of solid brick masonry walls and an insulated cavity wall. The solid brick walls were insulated internally with 40 mm woodfibre board, while 40 mm mineral wool was added to the roof. The boiler was upgraded to a modern condensing gas boiler.

A mechanical ventilation and heat recovery (MVHR) unit was also installed and airtightness membranes were added to reduce air permeability. The existing chimney was filled using clay aggregates and capped with chimney caps to improve the airtightness of the house.

The solid floor was insulated with a 20 mm load bearing insulation board to address any thermal bridges. Other thermal bridges were addressed with woodfibre board and plasterboard.

1.3.2 Building Option Inputs

Key inputs to the life cycle carbon emissions model are summarised in Table 1 for each of the building cases: Base-case, Refurbishment and New-build.

Table 1. Key inputs to the life cycle carbon emissions model for the 1900s case study.

1900s			
Building option	**Base-case**	**Refurbished**	**New-build**
Assumed climate	Finnigley	Finnigley	Finnigley
Year built	1900	1900, refurbished 2018	2018
Building height	2-storey	2-storey	2-storey
Floor area (m2)	60.54	60.54	64.54
Summary of works	None	Energy efficient retrofit of the existing dwelling including woodfibre and mineral wool insulation (wall, attic, floor) and draughtproofing, modern gas boiler installed.	Complete demolition of the existing dwelling and its replacement with typical new domestic building using cavity blockwork, PIR insulation, timber floors, triple glazing, pitched roof.
Structure	Load-bearing masonry	Load-bearing masonry	Load-bearing masonry
Envelope	Solid brick; PVC windows	Internally-insulated solid brick; PVC windows maintained	Insulate cavity wall; triple glazing
Glazing (%)	17	17	17
Heating system (efficency)	Gas-fired (80%)	Gas-fired (90%)	Gas-fired (90%)
Window R-value (m2-K/W)	0.37	0.38	0.63
Wall R-value (m2-K/W)	0.83	2.39	6.25
Roof R-value (m2-K/W)	5.41	7.52	9.09

Life cycle costs comprise building, operational and maintenance costs. Building costs included the capital costs of construction and, where necessary, site clearance (for New-build only). Operational costs include all energy-related space heating and lighting costs. Maintenance costs include scheduled replacements of windows (30 year intervals), roofing (100 year) and boilers (20 year). Building costs were based on reported refurbishment costs (£35,816) and estimated new-build costs (£94,913) and adjusted to the base (2018) year of analysis. Operational (energy) costs were based on the simulated energy use and average 2018 domestic energy prices (*Average unit costs and fixed costs for gas for GB regions*, 2019; *Average variable unit costs and fixed costs for electricity for UK regions*, 2019).

Table 2. Average 2018 domestic energy prices (Average unit costs and fixed costs for gas for GB regions, 2019; Average variable unit costs and fixed costs for electricity for UK regions, 2019).

	Unit Cost (£/kWh)	**Fixed Cost** (£/year)
Gas	0.0365	84.60
Electricity	0.1490	82.55

1.3.3 Emissions Results

The construction-related embodied carbon emissions were estimated to be 4.15 tCO_2e (6.4% of total emissions) and 16.9 tCO_2e (23.1% of total emissions) for the Refurbishment and New-build (including demolition) respectively. The demolition emissions associated with the New-build made up 4.8% of its total 60-year RSP emissions. There are no embodied emissions for the Base-case as the carbon embedded in the existing fabric has already been spent and has no consequence on current and future emissions. The operational emissions for the Refurbishment and New-build scenarios accounted for 93.6% and 72.0% of the total emissions respectively. Annual operational energy end use was estimated to be 9,953kWh, 5,240kWh and 3,923kWh for the Base-case, Refurbishment and New-build respectively.

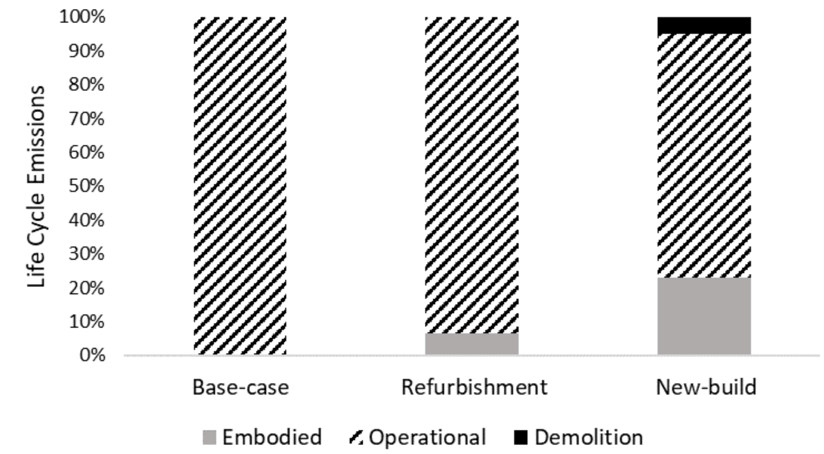

Figure 1. The percentage of embodied, operational and demolition emissions of total emissions associated with the Base-case, Refurbishment and New-build within the 60-year RSP. The embodied emissions of the New-build in the graph exclude the demolition emissions to show the percentage of demolition emissions separately.

Figure 2 shows the estimated life cycle carbon emissions for each building scenario for different reference study periods. Year 0 represents embodied construction emissions only (i.e. no operational emissions). In all cases, life cycle carbon emissions increase with the reference study period due to ongoing fuel consumption and maintenance. The Base-case results in the highest emissions for reference study periods 60-120 years due to the carbon impact associated with its high space-heating fuel use. New-build emissions increase at the lowest rate, but they start with higher construction emissions in Year 0. Nonetheless, they are slightly lower (7%) than Refurbishment life cycle emissions for a 60-year RSP; this gap has increased after 120 years.

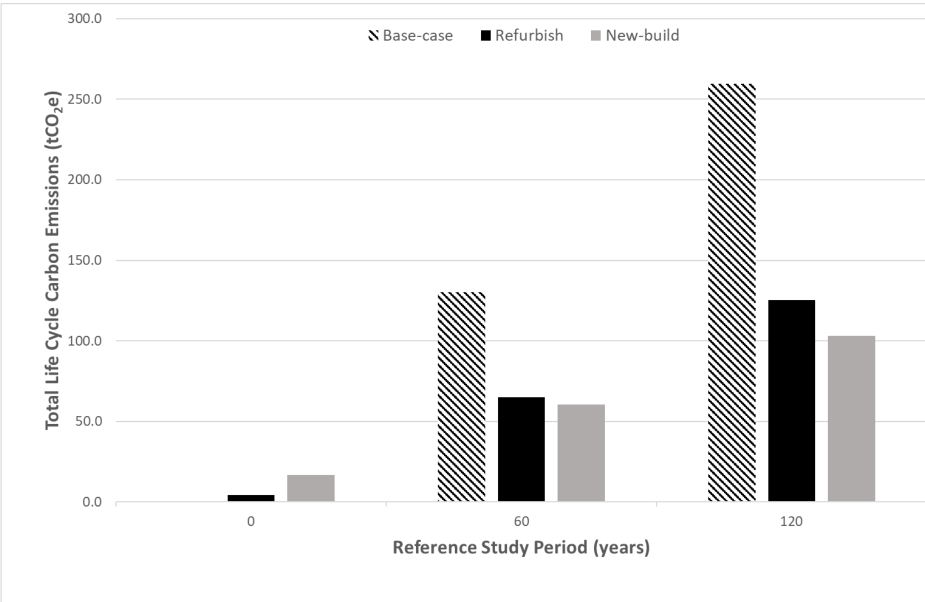

Figure 2. Estimated life cycle carbon emissions for each building case for different reference study periods (internal temperature of 21°C)

Table 3 shows the emissions for the three building cases for a reference study period of 60 years and an internal temperature of 21°C expressed both in conventional tCO_2e and alternative measures: litres of petrol (Ecoscore, 2019), metres squared of carbon dioxide sequestered by British oak forest in one year (Morison *et al.*, 2012) and miles driven by an average 2018 British car (The Society of Motor Manufacturers and Traders, 2019).

Table 3. Alternative measures of life cycle carbon emissions for the 1990s Refurbishment assuming a 21°C internal temperature and a 60 year reference study period.

Design Option	**Carbon** (tCO_2e)	**Petrol** (litres)	**Oak Woodland** (m^2)	**Car Use** (miles)
Base-case	130	29,950	4,818	522,966
Refurbish	65	14,945	2,404	260,965
New-build	60	13,887	2,234	242,479

Given that government policy has set carbon reduction targets for 2030 and 2050, it is worth noting the emissions performances of the different building cases on these dates. Assuming a start date Jan 1st 2020 (i.e. refurbishment or new building construction would happen on this date, as well as the operation of all building scenarios), by 2030 the cumulative carbon emissions for the Base-case, Refurbishment and New-build would be 22, 14 and 24 tCO_2e respectively; the equivalent figures in 2050 would be 66, 35 and 40 tCO_2e. The refurbishment would therefore be the best policy option in this regard.

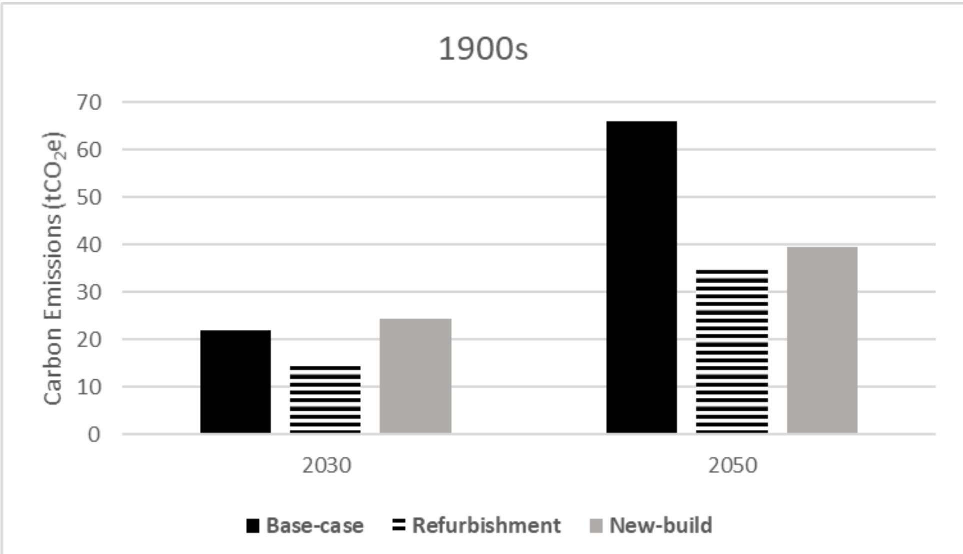

Figure 3. The estimated 2030 and 2050 emissions of the Base-case, Refurbishment and New-build.

Figure 4 (a-b) shows the life cycle carbon emissions for each case for 60- and 120-year reference study periods broken down by embodied, heating and lighting emissions. This illustrates that embodied energy is an important life cycle carbon emissions component for the New-build scenario, particularly for the 60-year reference study period where it accounts for 28% of all emissions.

(a-d) shows the cumulative life cycle carbon emissions for the scenarios over the first 100 years of operation. Each figure represents a different internal temperature ranging from 21°C down to 18°C in 1°C increments. The figures illustrate the time periods after which the New-build begins to outperform the Base-case and Refurbishment (indicated by where lines of cumulative emissions for the different scenarios cross). It can be seen that the carbon emissions of the Base-case exceeds the New-build 13-16 years after construction depending on the internal temperature assumption; between 49 and 60 years are required before the Refurbishment exceeds that of the New-build (see Table 4 for exact results).

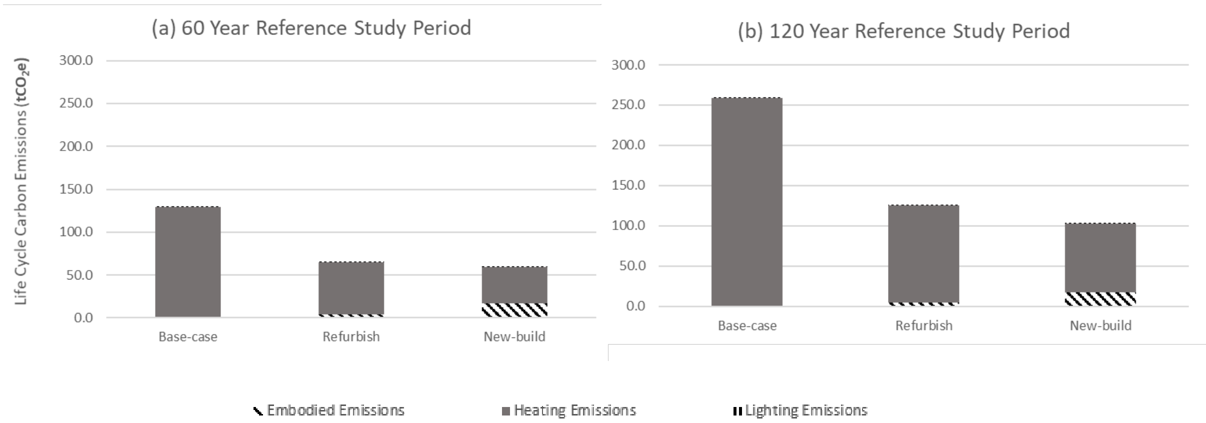

Figure 4 (a-b). Life cycle carbon emissions for each case for 60- and 120- year reference study periods broken down by embodied, heating and lighting emissions
(internal temperatures of 21°C)

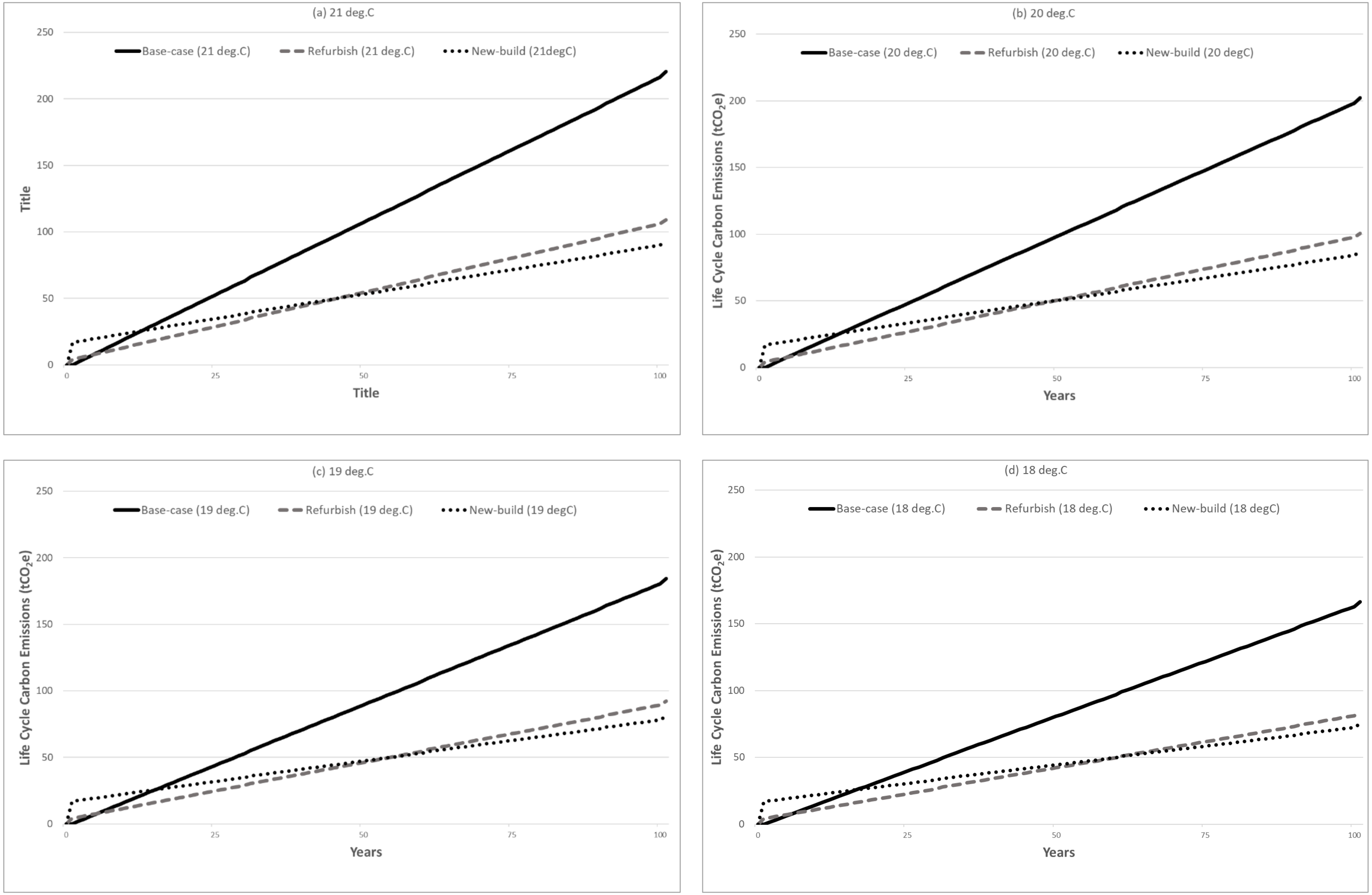

Figure 5 (a-d). Cumulative life cycle carbon emissions with different internal temperature assumptions.

Table 4. Time periods (years highlighted) after which the New-build outperforms the Base-case and Refurbishment for different internal temperatures.

	Internal Temperature (degC)			
	21	*20*	*19*	*18*
Base Case	13	13	15	16
Refurbish	49	49	54	60

Table 5 shows the differences between cumulative New-build and Refurbishment emissions (where positive results indicate higher Refurbishment emissions) for both 60- and 120-year RSPs under different internal temperatures. It shows that life cycle emissions for Refurbishment always exceed those for New-build under all temperature assumptions and RSPs. The difference, however, is very small for lower internal temperatures.

Table 5. Differences in New-build and Refurbishment life cycle carbon emissions (tCO_2e) using different reference study periods and internal temperature assumptions (negative indicates that Refurbishment is lower than New-build).

		Internal Temperature (degC)			
		21	*20*	*19*	*18*
RSP (yrs)	*60*	7	4	3	2
	120	27	23	20	17

1.3.4 Financial Results

Table 6 shows the savings-to-investment-ratios (SIR) for the Refurbishment and New-build for both RSPs and summarises their sensitivities to different discount rates. Here the SIR is given by the life cycle energy savings divided by the total investment in refurbishment or a new building. A positive SIR exceeding a ratio of 1 indicates that a project is financially viable at the relevant discount rate, i.e. the total life cycle savings (through lower energy bills) are greater than the total additional costs (mainly construction or refurbishment). It can be seen that no SIR exceeds 1 for either scenario. The best result is obtained for the Refurbishment scenario with a 0% discount rate after 120 years and Refurbishment always gives a better financial result than New-build. Given that discount rates of 5-10% are normally used in this type of analysis, these results indicate no building case is financially viable for a private investor and would require subvention to incentivise investment. The wide range of results show that the SIR is very sensitive both to the discount rate chosen and the reference study period. In reality, however, economic decisions are made by individuals based on time frames lower than 60 years – typically of between 5 and 20 years. However, this analysis shows that SIRs will always be less than one in this period, indicating that financial incentives are required to break even. The higher SIR for Refurbishment indicates that it would require a lower subvention than New-build to make it financially attractive.

Table 6. Savings-to-investment-ratios (SIR) for the Refurbishment and New-build for different discount rates. An SIR of greater than 1 indicates it is financially attractive.

Scenario	Discount Rate	Reference Study Period (years)	
		60	120
Refurbish	0.0%	0.43	0.86
New-build	0.0%	0.19	0.37
Refurbish	2.5%	0.22	0.27
New-build	2.5%	0.10	0.12
Refurbish	5.0%	0.14	0.14
New-build	5.0%	0.06	0.06
Refurbish	7.5%	0.09	0.10
New-build	7.5%	0.04	0.04
Refurbish	10.0%	0.07	0.07
New-build	10.0%	0.03	0.03

Marginal abatement cost (MAC) measures the total additional life cycle financial cost of an intervention per tonne of carbon saved and may be used by policymakers to identify where the best opportunities lie for carbon abatement in an economy. A positive MAC indicates that there is a cost in reducing carbon emissions, whereas a negative MAC indicates that financial savings would be achieved when investing in the new technology. It can be seen in Figure 6 that there are substantial abatement costs associated with the New-build scenario which were estimated to be 1,107 and 381 £/tCO_2e for the 60- and 120-year RSPs respectively. The corresponding Refurbishment MACs of 313 and 37 £/tCO_2e are substantially lower. For the purposes of comparison, the *Report of the High-Level Commission on Carbon Prices* (2017) estimated carbon prices will need to be in the region of US$40–80 (£32.8-65.6)/t$CO_2$e by 2020 and US$50–100 (£41-82)/tCO_2e by 2030 to meet the goals of the Paris Agreement. Carbon costs below these may therefore be attractive to policymakers. The MAC results for this case study indicate that Refurbishment is more cost-effective in reducing life cycle emissions; however, it would currently only be attractive when viewed over a very long time-frame. Any reductions in refurbishment capital costs, for example through lower VAT rates, would improve MAC results.

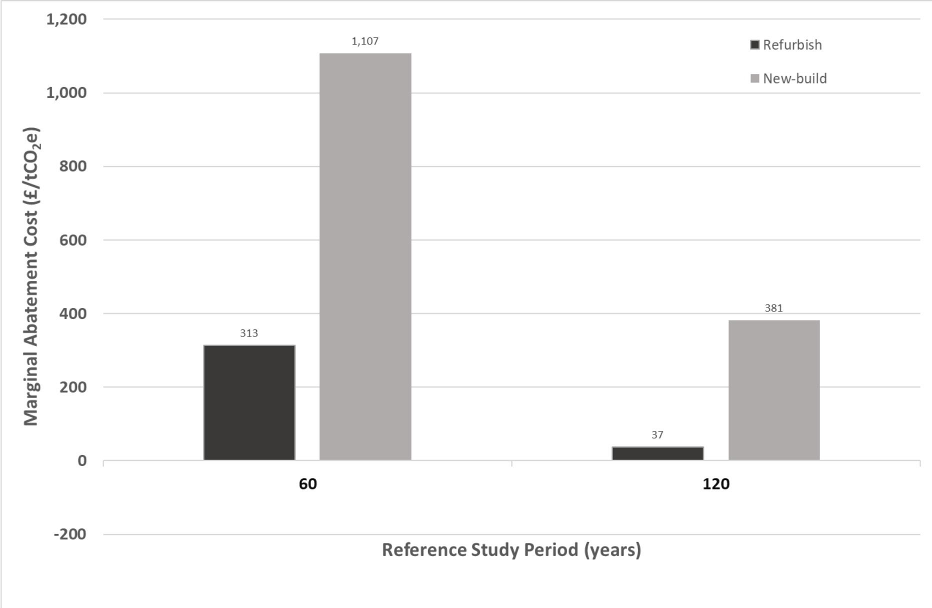

Figure 6. Marginal abatement costs (MAC) for the Refurbishment and New-build.

1.3.5 Internal Temperature Scenario

Using the life cycle assessment models developed, it is possible to investigate a number of scenarios which combine different input values for key variables. One such scenario was developed to take account of the fact that poorly-insulated buildings (e.g. the Base-case scenario) tend to be operated at lower ambient temperatures and that highly-insulated buildings (e.g. refurbished or newly-built) may be operated at higher temperatures (often referred to as 'comfort taking' or 'the rebound effect') (BRE Group, 2013). For these reasons the following internal temperature scenario was investigated:

- Base-case: 18°C
- Refurbishment: 19°C
- New-build: 21°C

These temperatures are not meant to reflect perceived thermal comfort, merely the temperature at which refurbished buildings and new buildings might operate. It should also be noted that buildings refurbished to a high standard of energy efficiency are likely to be operated at higher temperatures after retrofit.

The carbon emissions for this scenario (referred to as 'Scenario_18-19-21) are presented in Figure 7 up to 100 years. The Refurbishment marginally outperforms New-build in terms of emissions up to an RSP of 93 years; thereafter the New-build emissions are lower than the Refurbishment. The figure can be compared to the results in Figure 2, which shows emissions for all building cases operating at an assumed 21°C internal temperature. Here, the emissions for the Base-case fall somewhat compared to the Refurbishment and New-build, and Refurbishment emissions fall slightly relative to New-build. This Scenario_18-19-21 assumptions result in longer time periods until the New-build outperforms both Base-case and Refurbishment in terms of carbon emissions. Under Scenario_18-19-21, the New-build outperforms the Base-case and Refurbishment after 19 and 105 years respectively, as compared to 13-16 years and 49-60 years for scenarios with the same internal temperatures (Table 7).

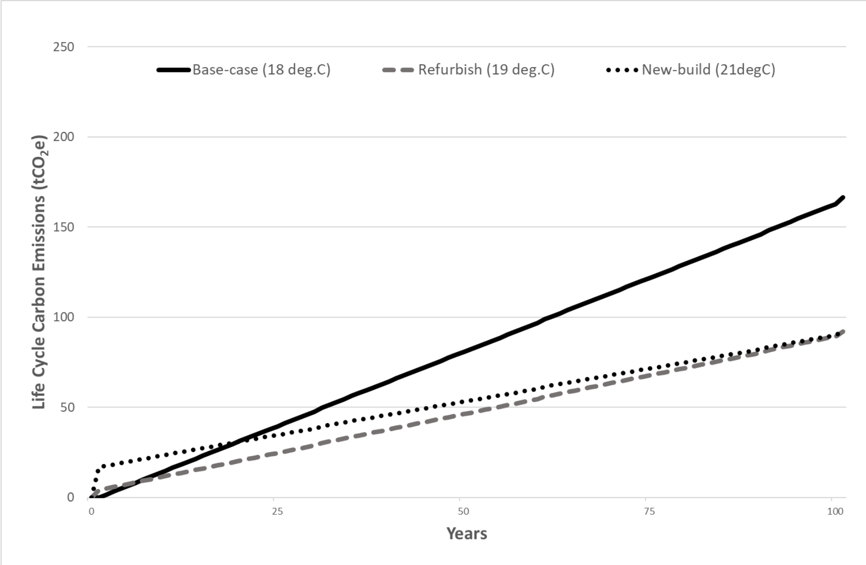

Figure 7. Estimated life cycle carbon emissions for each building case for different reference study periods assuming different internal temperatures, 18, 19 and 21 °C

Table 7. Time periods (years in yellow) after which the New-build outperforms the Base-case and Refurbishment for different internal temperatures.

	Internal Temperature (degC)				
	21	*20*	*19*	*18*	Scenario 18-19-21
Base Case	13	13	15	16	19
Refurbish	49	49	54	60	105

1.4 Semi-detached Refurbishment, Lancaster ('1970s')

1.4.1 Background

The 1970s semi-detached dwelling is composed of solid brick masonry walls and cavity walls. The cavity walls had already been insulated with expanded polystyrene (EPS) beads. Woodfibre was added to these walls internally to reduce the U-value of the walls further. Some of the brick walls were also insulated internally with woodfibre insulation. The rest of the solid walls were left with no insulation, but no reason was provided for this. Mineral wool insulation was used on the horizontal surfaces of the main loft. The MVHR ducting works were insulated using a closed-cell flexible elastomeric foam (FEF) insulation which also acts as a vapour barrier.

The floors were insulated using EPS and oriented strand board (OSB). An under-floor heating system was also installed. Existing oak floorboards were removed and 75% of them were re-used when laying the new floor.

New over sills were added to the doors and windows and the front door was replaced.

A heat pump was installed as the heating source. For comparability with the other case studies, however, it was assumed within this study that a high efficiency gas boiler was installed instead of a heat pump.

1.4.2 Building Option Inputs

The key inputs to the life cycle carbon emissions model are summarised for each of the building cases: Base Case, Refurbishment and New-Build in Table 8.

Table 8. Key inputs for the life cycle carbon emissions model for the 1970s case study.

1970s			
Building option	**Base-case**	**Refurbished**	**New-build**
Assumed climate	Finnigley	Finnigley	Finnigley
Year built	1970	1970, refurbished 2018	2018
Building height	2-storey	2-storey	2-storey
Floor area (m2)	110.9	110.9	110.9
Summary of works	None	Energy efficient retrofit of the existing dwelling including woodfibre insulation (wall, attic, floor) and draughtproofing, underfloor heating installed, modern boiler installed.	Complete demolition of the existing dwelling and its replacement with typical new domestic building using cavity blockwork, PIR insulation, timber floors, triple glazing, pitched roof.
Structure	Load-bearing masonry	Load-bearing masonry	Load-bearing masonry
Envelope	Solid brick; PVC windows	Internally-insulated solid brick and cavity walls; single glazed sash windows with secondary glazing, PVC windows kept	Insulate cavity wall; triple glazing
Glazing (%)	26	26	26
Heating system (efficency)	Gas-fired (80%)	Gas-fired (90%)	Gas-fired (90%)
Window R-value (m2-K/W)	0.61	0.63	0.63
Wall R-value (m2-K/W)	1.81	4.33	6.25
Roof R-value (m2-K/W)	2.25	7.69	9.09

Life cycle costs comprise both building, operational and maintenance costs. Building costs included the capital costs of construction and, where necessary, site clearance (i.e. for New-build). Operational costs include all energy-related space heating and lighting costs. Maintenance costs include scheduled replacements of windows (30 year), roofing (100 year) and boilers (20 year). Building costs were based on reported refurbishment costs (£62,130) and estimated New-build costs (£113,129) and converted to base year (2018) prices. Operational (energy) costs were based on the simulated energy use and average 2018 domestic energy prices (*Updated Energy and Emissions Projections 2018*, 2019).

1.4.3 Emissions Results

The construction-related embodied carbon emissions were estimated to be 2.55 tCO_2e (4% of total emissions) and 16 tCO_2e (21.6% of total emissions) for the Refurbishment and New-build (including demolition). There are no embodied emissions for the Base-case as the carbon embedded in the existing fabric has already been spent and has no consequence on current and future emissions. The demolition emissions associated with the new build accounted for 2.7% of life cycle emissions, assuming a 60-year RSP. The operation emissions for the Refurbishment and New-build accounted for 96% and 78.4% of total emissions respectively. Annual operational energy use was estimated to be 9,646kWh, 5,218kWh and 4,933Wh for the Base-case, Refurbishment and New-build.

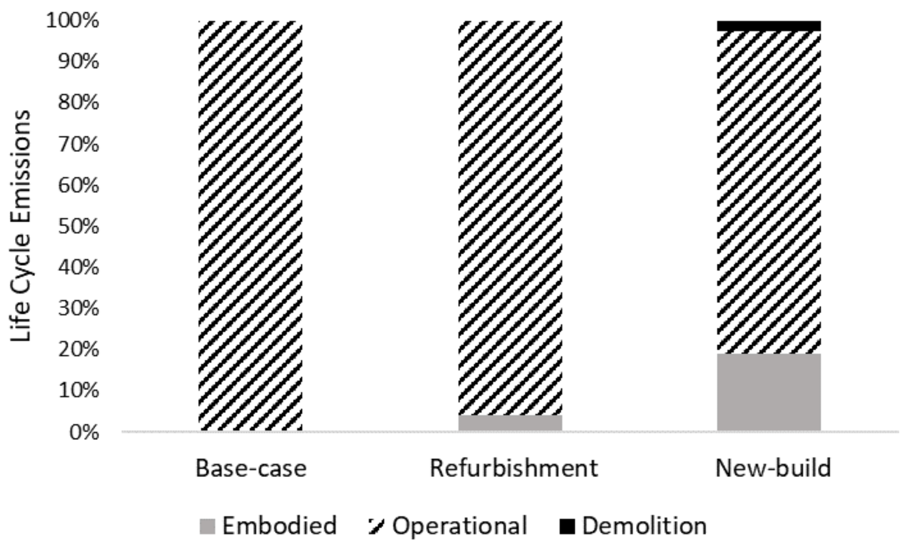

Figure 8. The percentage of embodied, operational and demolition emissions of total emissions associated with the Base-case, Refurbishment and New-build within the 60-year RSP. The embodied emissions of the New-build in the graph exclude the demolition emissions to show the percentage of demolition emissions separately.

Figure 9 shows the estimated life cycle carbon emissions for each building scenario for different reference study periods. Life cycle carbon emissions increase with the RSP due to emissions related to fuel consumption and maintenance. Results for an RSP of zero years represent the construction-related embodied emissions for each scenario. The New-build has the highest emissions, followed by the Refurbishment, while the Base-case has no embodied emissions. The Base-case results in the highest cumulative emissions for reference study periods 60-120 years which are dominated by emissions from fuel used in space heating. Refurbishment emissions are lowest for these RSPs, while New-build are marginally higher.

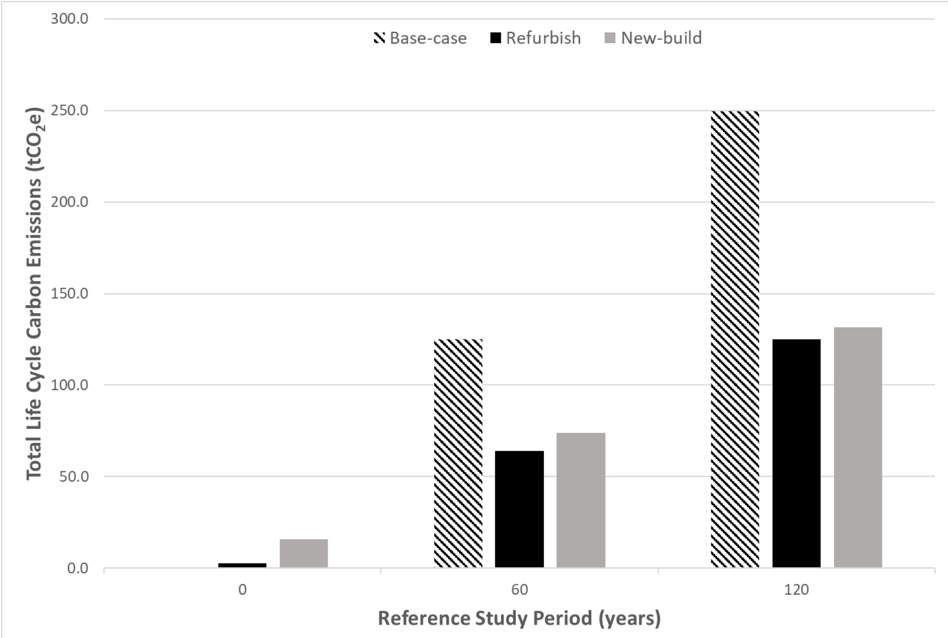

Figure 9. Estimated life cycle carbon emissions for each building case for different reference study periods (internal temperature of 21°C)

Table 9 shows the emissions for the three building cases for a reference study period of 60 years and an internal temperature of 21°C expressed as: carbon dioxide equivalent, litres of petrol (Ecoscore, 2019), metres squared of carbon dioxide sequestered by British oak forest in one year (Morison *et al.*, 2012) and miles driven by an average 2018 British car (The Society of Motor Manufacturers and Traders, 2019).

Table 9. Alternative measures of life cycle carbon emissions for the Refurbishment assuming a 21°C internal temperature and a 60 year reference study period.

Design Option	**Carbon** (tCO_2e)	**Petrol** (litres)	**Oak Woodland** (m^2)	**Car Use** (miles)
Base-case	125	28,783	4,630	502,581
Refurbish	64	14,711	2,367	256,879
New-build	74	17,003	2,735	296,898

In relation to emissions in the 2030 and 2050 government policy target years, the 2030 life cycle carbon emissions for the Base-case, Refurbishment and New-build are 21, 13 and 26 tCO_2e respectively; the equivalent figures in 2050 are 64, 34 and 46 tCO_2e. Based on these figures, the Refurbishment scenario would best help reach policy targets for both years.

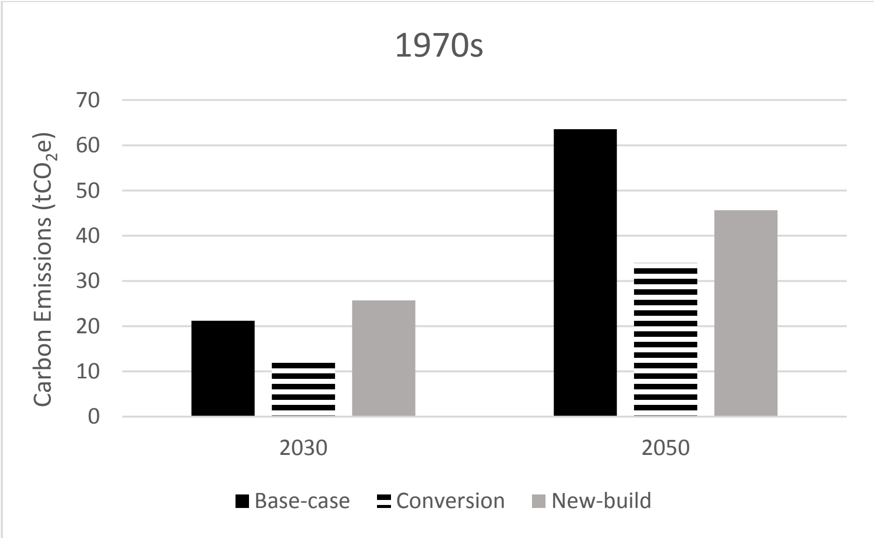

Figure 10. The estimated 2030 and 2050 emissions of the Base-case, Refurbishment and New-build.

Figure 11 (a-b) shows the life cycle carbon emissions for each case for the 60- and 120- year reference study periods broken down by embodied, heating and lighting emissions. This illustrates that operational emissions dominate, but that embodied emissions are most significant for the New-build over shorter life spans.

Figure 12 (a-d) shows the cumulative life cycle carbon emissions for the three building cases over 60 years, with each figure representing a different internal temperature ranging from 21^{o}C to 18^{o}C. It can be seen that the carbon emissions of the Base-case exceed the New-build 16-19 years after construction, depending on the internal temperature assumption. Cumulative New-build emissions always exceed Refurbishment over the 100-year period shown in the Figure. It is estimated to take 106-287 years before cumulative Refurbishment emissions exceed those of New-build, depending on internal temperature assumptions (see Table 10 for exact results).

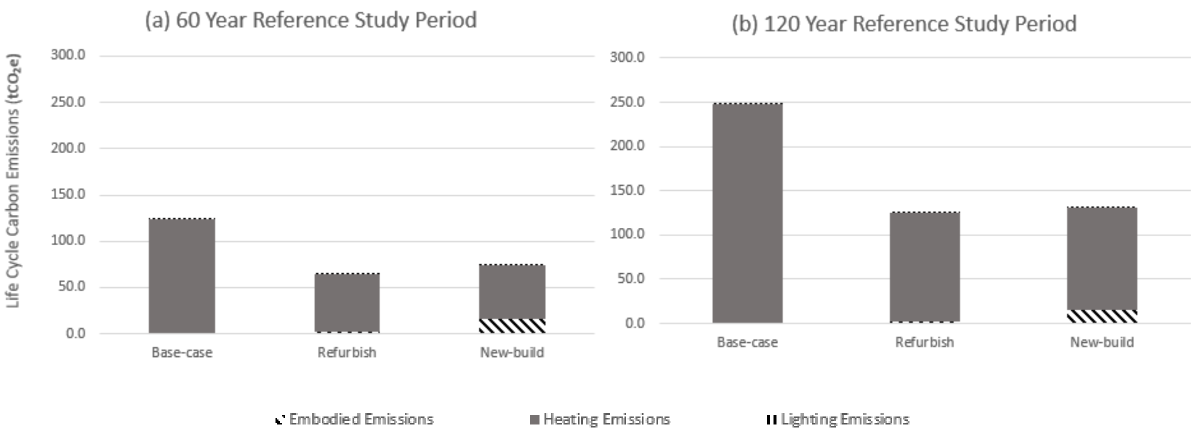

Figure 11 (a-b). Life cycle carbon emissions for each case for 60- and 120- year reference study periods broken down by embodied, heating and lighting emissions (internal temperature of 21°C)

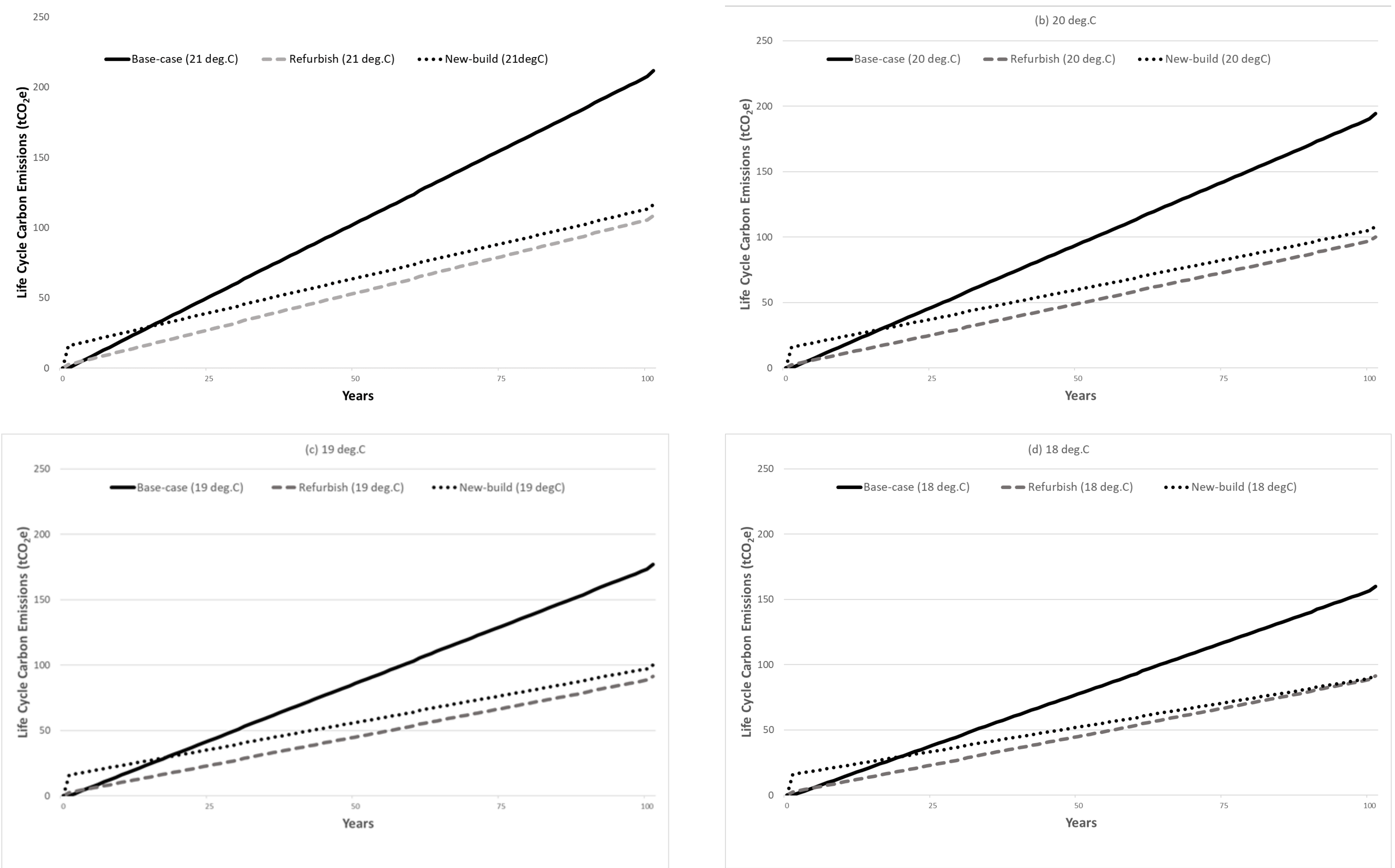

Figure 12 (a-d). Cumulative life cycle carbon emissions with different internal temperature assumptions

Table 10. Time periods (years in yellow) after which the New-build outperforms the Base-case and Refurbishment for different internal temperatures.

	Internal Temperature (degC)			
	21	*20*	*19*	*18*
Base Case	16	16	17	19
Refurbish	287	287	283	106

Table 11 below shows the differences in New-build and Refurbishment life cycle carbon emissions for 60- and 120-year RSPs under different internal temperature assumptions. Negative values indicate that Refurbishment emissions are lower than New-build. Refurbishment emissions are lower than New-build under almost all temperature assumptions for both RSPs; New-build emissions are only slightly lower in the case of an 18 degree internal temperature for a 120-year RSP.

Table 11. Differences in New-build and Refurbishment life cycle carbon emissions (shades of red) using different reference study periods and internal temperature assumptions (negative indicates that Refurbishment is lower than New-build).

		Internal Temperature (degC)			
		21	*20*	*19*	*18*
RSP (yrs)	*60*	-10	-13	-11	-6
	120	-7	-9	-8	2

1.4.4 Financial Results

Table 12 shows the savings-to-investment-ratios (SIR) for the Refurbishment and New-build for different discount rates. A positive SIR exceeding a ratio of 1 indicates that a project is financially viable. It can be seen that no scenario meets this criterion. The best-performing SIR of 0.5 is for the Refurbishment scenario with a discount rate of 0% after 120 years.

Table 12. Savings-to-investment-ratios (SIR) for the Refurbishment and New-build for different discount rates. An SIR of greater than 1 indicates it is financially attractive.

Scenario	**Discount Rate**	**Reference Study Period (years)**	
		60	**120**
Refurbish	0.0%	0.25	0.50
New-build	0.0%	0.14	0.29
Refurbish	2.5%	0.13	0.16
New-build	2.5%	0.07	0.09
Refurbish	5.0%	0.08	0.08
New-build	5.0%	0.04	0.05
Refurbish	7.5%	0.05	0.05
New-build	7.5%	0.03	0.03
Refurbish	10.0%	0.04	0.04
New-build	10.0%	0.02	0.02

Marginal abatement costs are presented in Figure 13 where it can be seen that there are substantial abatement costs associated with both the Refurbishment and New-build scenarios which are 1,894 and 764 £/tCO_2e respectively for the 60-year RSP. These fall to 685 and 250 £/tCO_2e for 120 year. These MACs remain high, however, when compared to those quoted in the *Report of the High-Level*

Commission on Carbon Prices (2017). Here, estimated carbon prices will need to be in the region of US$40–80/t$CO_2$e by 2020 and US$50–100/tCO_2e by 2030 to meet the goals of the Paris Agreement.

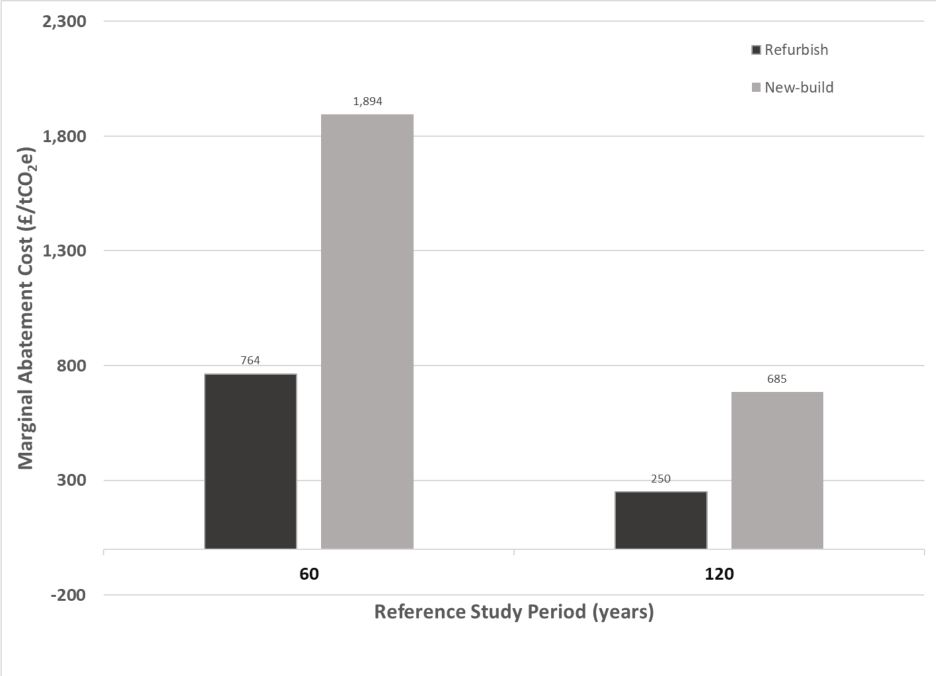

Figure 13. Marginal abatement costs (MAC) for the Refurbishment and New-build.

1.4.5 Internal Temperature Scenario

The carbon emissions for the Scenario_18-19-21 are presented in Figure 14 for the 60- and 120- year RSPs. Under these assumptions, the Refurbishment is the best performer in terms of life cycle carbon emissions for all RSPs studied.

Figure 14 can be compared to Figure 9, where it can be seen that the emissions for the Base-case fall slightly compared to the Refurbishment and New-build, and Refurbishment emissions fall relative to New-build. This results in longer time periods until the New-build outperforms the Base-case in terms of carbon emissions. Table 13 shows these time periods and it can be seen under Scenario_18-19-21, the New-build outperforms the Base-case after 26 years, as compared to 16-19 years when comparing both scenarios using same internal temperatures. Under the 18-19-21 Scenario, cumulative Refurbishment emissions are always lower than New-build for the time periods studied.

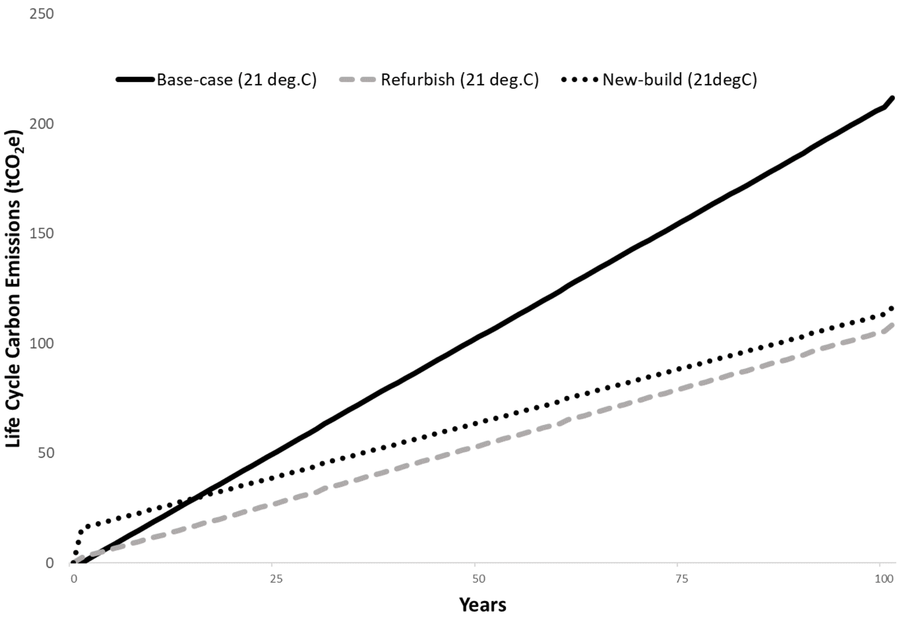

Figure 14. Estimated life cycle carbon emissions for each building case for different reference study periods (internal temperature of 21°C)

Table 13. Time periods (years in yellow) after which the New-build outperforms the Base-case and Refurbishment for different internal temperatures.

	Internal Temperature (degC)				
	21	*20*	*19*	*18*	Scenario 18-19-21
Base Case	16	16	17	19	26
Refurbish	287	287	283	106	n/a

1.5 Detached Refurbishment, Chorley ('1990s')

1.5.1 Background

The 1990s detached dwelling is composed of cavity and solid concrete walls. The main cavity walls had previously been insulated with 40 mm blown mineral wool within the cavity, then an additional 40 mm woodfibre board insulation was installed internally as part of the refurbishment. The minor cavity wall also already had some PIR insulation but 75mm PIR was added during the refurbishment. The house has a garage extension composed of single skin concrete blocks which were insulated with both woodfibre board and Expanded Polystyrene (EPS). The existing loft insulation consisted of mineral and sheep's wool and was not altered.

Cellular glass insulation was used to address thermal bridges at the front door threshold. The other thermal bridge between the kitchen floor and wall was treated with aerogel insulation. The domestic hot water pipes were insulated with pipe lagging.

The front door and most windows were replaced. An MVHR unit was installed and air-tightness membranes were added to the ceilings, walls and reveals. Expanded polystyrene (EPS) and a damp-proof membrane were installed in the solid floor of the office.

1.5.2 Building Option Inputs

The key inputs to the life cycle carbon emissions model are summarised for each of the building cases: Base Case, Refurbishment and New-Build in Table 14.

Table 14. Key inputs for the life cycle carbon emissions model for the 1990s case study.

1990s			
Building option	**Base-case**	**Refurbished**	**New-build**
Assumed climate	Finnigley	Finnigley	Finnigley
Year built	1990	1990, refurbished 2018	2018
Building height	2-storey	2-storey	2-storey
Floor area (m2)	198.14	198.14	198.14
Summary of works	None	Energy efficient retrofit of the existing dwelling including insulation (wall, attic, floor), draught proofing, window and door replacements	Complete demolition of the existing dwelling and its replacement with typical new domestic building using cavity blockwork, PIR insulation, timber floors, triple glazing, pitched roof.
Structure	Load-bearing masonry	Load-bearing masonry	Load-bearing masonry
Envelope	Solid brick; unknown type of windows	Internally-insulated cavity and solid concrete walls; Double glazed, timber frame windows	Insulate cavity wall; triple glazing
Glazing (%)	16	16	16
Heating system (efficency)	Gas-fired (80%)	Gas-fired (90%)	Gas-fired (90%)
Window R-value (m2-K/W)	0.31	0.83	0.63
Wall R-value (m2-K/W)	2.13	5.95	6.25
Roof R-value (m2-K/W)	8.13	7.58	9.09

Life cycle costs comprise both building, operational and maintenance costs. Building costs included the capital costs of construction and, where necessary, site clearance (i.e. for New-build). Operational costs include all energy-related space heating and lighting costs. Maintenance costs include scheduled replacements of windows (30 year), roofing (100 year) and boilers (20 year). Building costs were based on reported Refurbishment costs (£54,353) and estimated New-build costs (£174,324). These costs were adjusted for inflation where relevant. Operational (energy) costs were based on the simulated energy use and average 2018 domestic energy prices (*Updated Energy and Emissions Projections 2018*, 2019).

1.5.3 Emissions Results

The construction-related embodied carbon emissions were estimated to be 1.3 tCO_2e (1.4% of total 60-year emissions) and 18.8 tCO_2e (17%) for the Refurbishment and New-build scenarios respectively (including demolition). There are no embodied emissions for the Base-case as the carbon embedded in the existing fabric has already been spent and has no consequence on current and future emissions. The demolition emissions associated with the New-build accounted for 4.4% of total 60-year RSP emissions. The operational emissions for the Refurbishment and New-build accounted for 98.6% and 83% of total emissions respectively. Annual operational energy use was estimated to be 14,379 kWh, 8,856 kWh and 7,792 kWh for the Base-case, Refurbishment and New-build scenarios respectively.

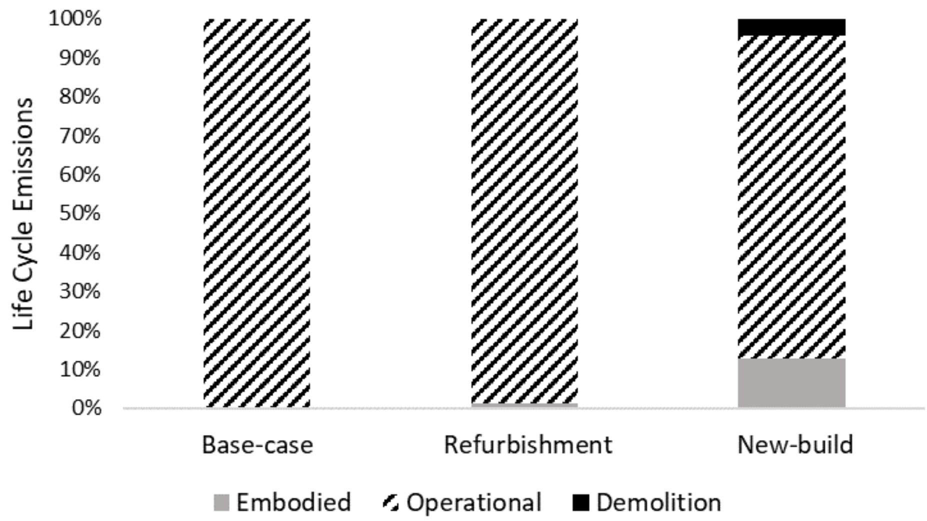

Figure 15. The percentage of embodied, operational and demolition emissions of total emissions associated with the Base-case, Refurbishment and New-build within the 60-year RSP. The embodied emissions of the New-build in the graph exclude the demolition emissions to show the percentage of demolition emissions separately.

Figure 16 shows the estimated life cycle carbon emissions for each building case for different reference study periods. Life cycle carbon emissions increase with the RSP due to emissions related to fuel consumption and maintenance. The Base-case results in the highest emissions for reference study periods 60-120 years which are dominated by emissions from fuel used in space heating. Refurbishment emissions are lowest for both the 60- and 120-year reference periods; New-build has 10% higher cumulative emissions for a 60-year RSP, falling to 1.7% in year 120.

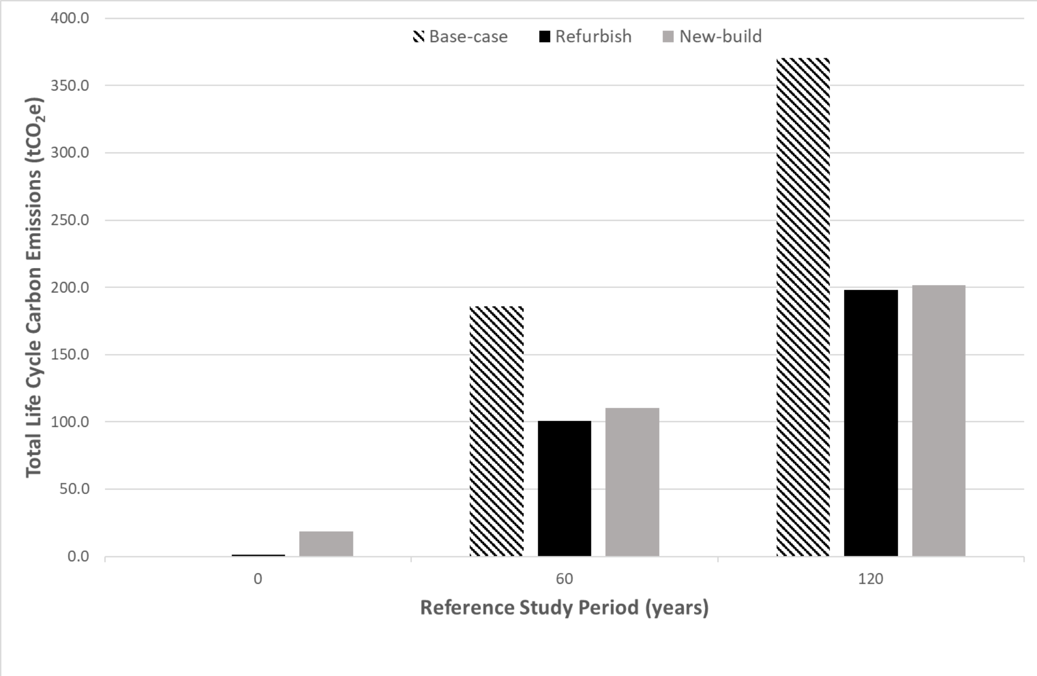

Figure 16. Estimated life cycle carbon emissions for each building case for different reference study periods (internal temperature of 21°C)

Table 15 shows the emissions for the three building cases for a reference study period of 60 years and an internal temperature of 21°C expressed as: carbon dioxide equivalent, litres of petrol (Ecoscore, 2019), metres squared of carbon dioxide sequestered by British oak forest in one year (Morison *et al.*, 2012) and miles driven by an average 2018 British car (The Society of Motor Manufacturers and Traders, 2019).

Table 15. Alternative measures of life cycle carbon emissions for the Refurbishment assuming a 21°C internal temperature and a 60 year reference study period.

Design Option	**Carbon** (tCO_2e)	**Petrol** (litres)	**Oak Woodland** (m^2)	**Car Use** (miles)
Base-case	186	42,747	6,877	746,414
Refurbish	100	23,113	3,718	403,587
New-build	110	25,378	4,083	443,126

The 2030 life cycle carbon emissions for the Base-case, Refurbishment and New-build are 32, 19 and 34 tCO_2e respectively; the equivalent figures in 2050 are 94, 52 and 65 tCO_2e. Based on these figures, the Refurbishment would best help reach policy targets for both years.

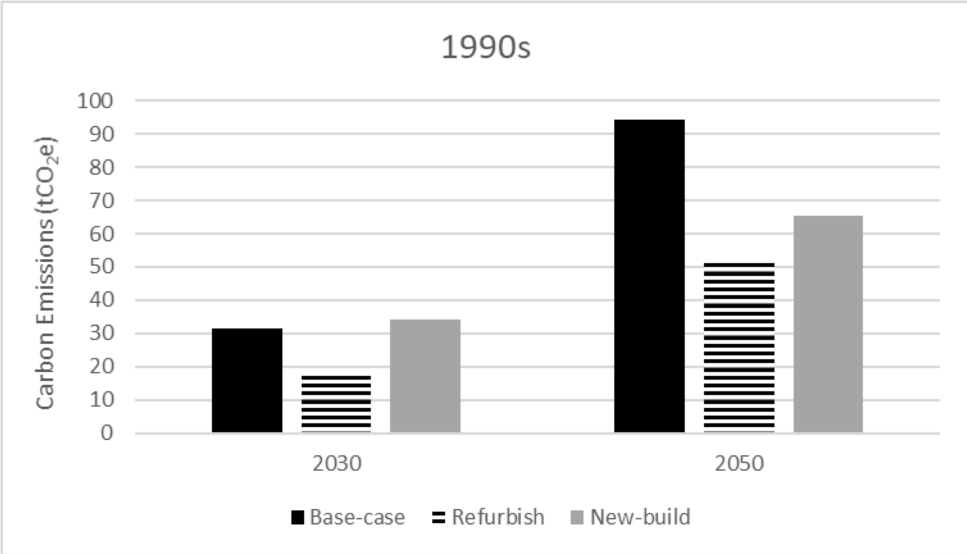

Figure 17. The estimated 2030 and 2050 emissions of the Base-case, Refurbishment and New-build.

Figure 18 (a-b) shows the life cycle carbon emissions for each case for the 60- and 120- year reference study periods broken down by embodied, heating and lighting emissions. This illustrates that operational emissions dominate, but that embodied emissions are most significant for the New-build over shorter life spans.

Figure 19 (a-d) shows the cumulative life cycle carbon emissions for the three building cases over 60 years. Each figure represents a different internal temperature ranging from 21°C to 18°C. It can be seen that the carbon emissions of the Base-case exceeds the New-build 13-16 years after construction, depending on the internal temperature assumption; it is estimated to take 165-201 years before the Refurbishment exceeds that of the New-build (see Table 16 for exact results), well beyond the maximum 60-year RSP considered in this study.

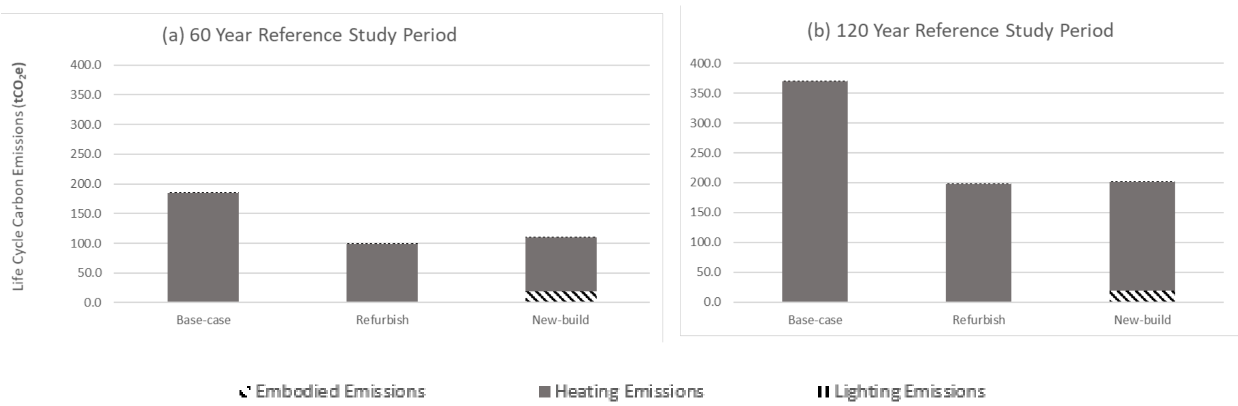

Figure 18 (a-b). Life cycle carbon emissions for each case for the 60- and 120- year reference study periods broken down by embodied, heating and lighting emissions (internal temperature of 21°C)

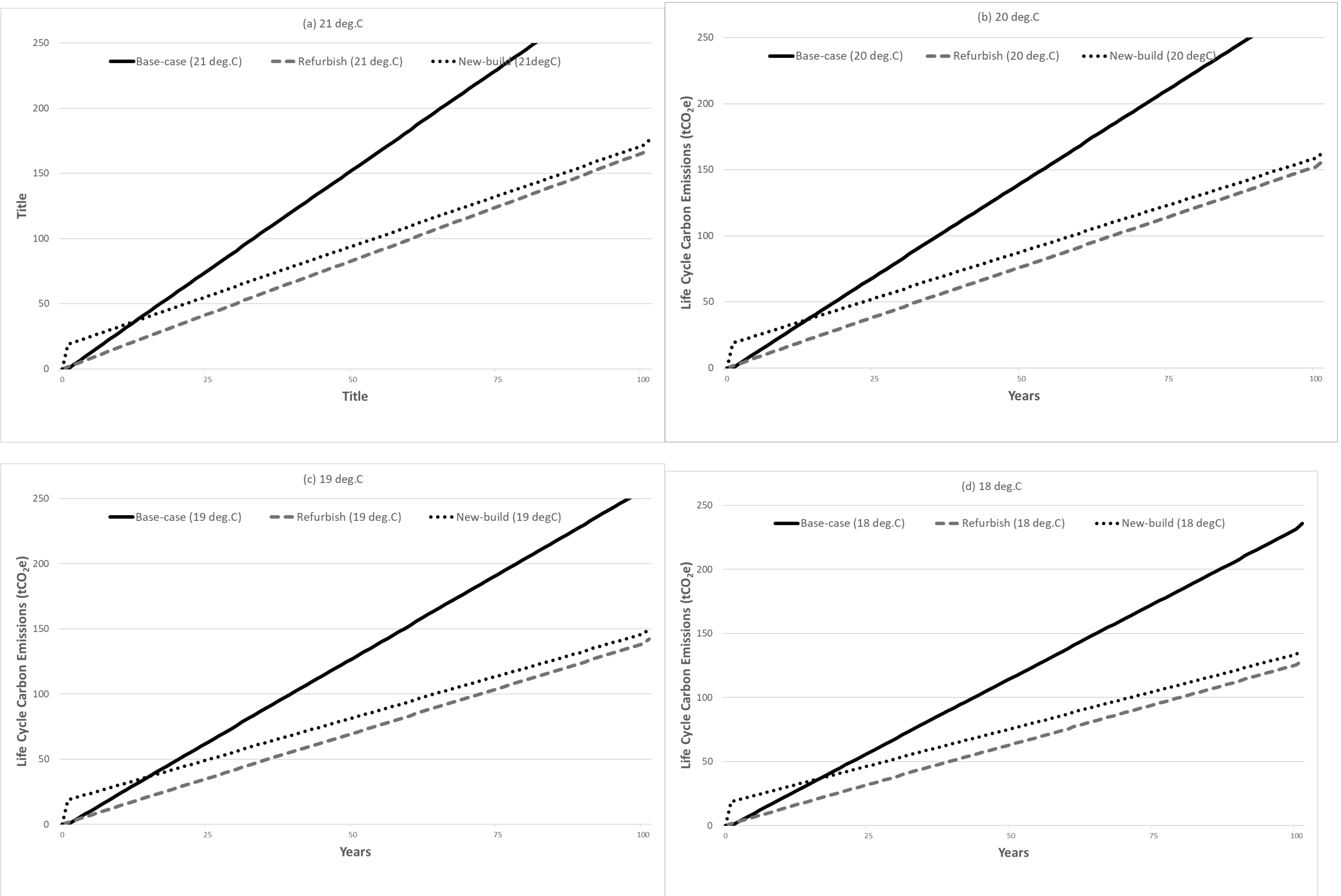

Figure 19 (a-d). Cumulative life cycle carbon emissions with different internal temperature assumptions

Table 16. Time periods (years in yellow) after which the New-build outperforms the Base-case and Refurbishment for different internal temperatures.

	Internal Temperature (degC)			
	21	*20*	*19*	*18*
Base Case	13	13	14	16
Refurbish	165	165	181	201

Table 17 below shows the differences in New-build and Refurbishment life cycle carbon emissions using different reference study periods and internal temperature assumptions. Negative values indicate that Refurbishment emissions are lower than New-build. Cumulative Refurbishment emissions are lower than New-build for all internal temperatures and RSPs considered in this analysis.

Table 17. Differences in New-build and Refurbishment life cycle carbon emissions (shades of red) using different reference study periods and internal temperature assumptions (negative indicates that Refurbishment is lower than New-build).

		Internal Temperature (degC)			
		21	*20*	*19*	*18*
RSP (years)	*60*	-10	-12	-11	-11
	120	-3	-4	-6	-7

1.5.4 Financial Results

Table 12 shows the savings-to-investment-ratios (SIR) for the Refurbishment and New-build for different discount rates. A positive SIR exceeding a ratio of 1 indicates that a project is financially viable. It can be seen that no scenario meets this criterion. Refurbishment always either outperforms or equals New-build, with the best performing option being Refurbishment with a 0% discount rate and a 120-year RSP, which gives an SIR of 0.65.

Table 18. Savings-to-investment-ratios (SIR) for the Refurbishment and New-build for different discount rates. An SIR of greater than 1 indicates it is financially attractive.

Scenario	**Discount Rate**	**Reference Study Period (years)**	
		60	**120**
Refurbish	0.0%	0.32	0.65
New-build	0.0%	0.14	0.27
Refurbish	2.5%	0.17	0.20
New-build	2.5%	0.07	0.09
Refurbish	5.0%	0.10	0.11
New-build	5.0%	0.04	0.04
Refurbish	7.5%	0.07	0.07
New-build	7.5%	0.03	0.03
Refurbish	10.0%	0.05	0.05
New-build	10.0%	0.02	0.02

Marginal abatement costs are presented in Figure 20 where it can be seen that New-build is significantly higher than Refurbishment. For an RSP of 60 years, New-build and Refurbishment MACs are estimated to be 1,996 £/tCO_2e and 431 £/tCO_2e respectively. These decrease as RSP increases since the cumulative carbon savings increase. The lowest MAC of 111 £/tCO_2e is Refurbishment for a 120-year RSP. For the purposes of comparison, the *Report of the High-Level Commission on Carbon Prices* (2017) estimated carbon prices will need to be in the region of US$40–80/t$CO_2$e by 2020 and US$50–100/tCO_2e by 2030 to meet the goals of the Paris Agreement.

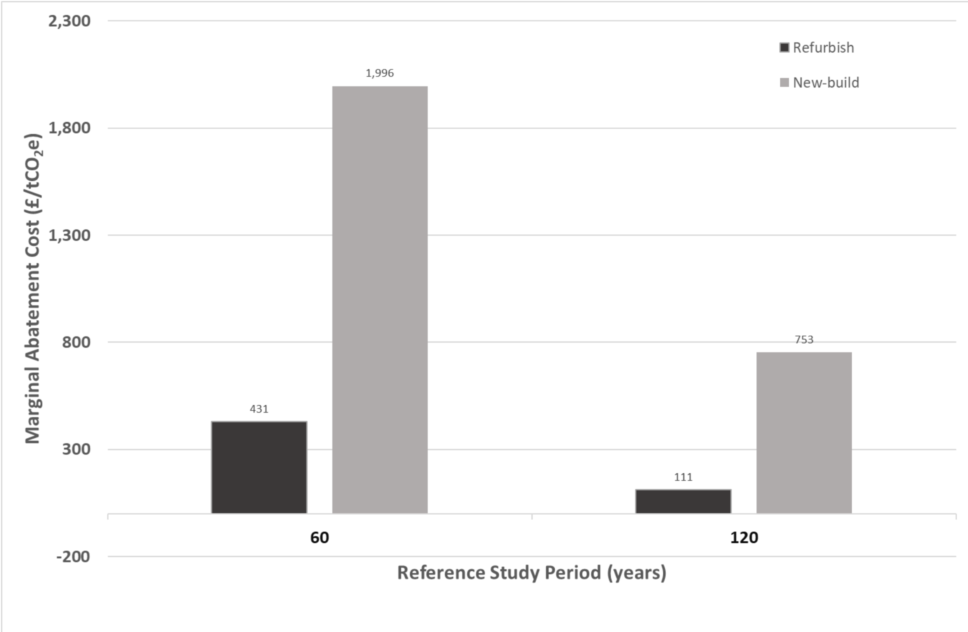

Figure 20. Marginal abatement costs (MAC) for the Refurbishment and New-build.

1.5.5 Internal Temperature Scenario

The carbon emissions for the Scenario_18-19-21 are presented in Figure 21 for the different reference study periods, from 60 to 120 years. Under these assumptions, Refurbishment improves as the best performer in terms of life cycle carbon emissions for all RSPs excepting zero years.

Figure 21 can be compared to Figure 9, where it can be seen that the emissions for the Base-case fall slightly compared to the Refurbishment and New-build, and Refurbishment emissions fall relative to New-build. This results in longer time periods until the New-build outperforms the Base-case and Refurbishment in terms of carbon emissions. Table 19 shows these time periods and it can be seen under Scenario_18-19-21, New-build outperforms Base-case after 23 years, as compared to 13-16 years when comparing both scenarios using same internal temperatures. Under the 18-19-21 Scenario, cumulative Refurbishment emissions are always lower than New-build over the timespan considered.

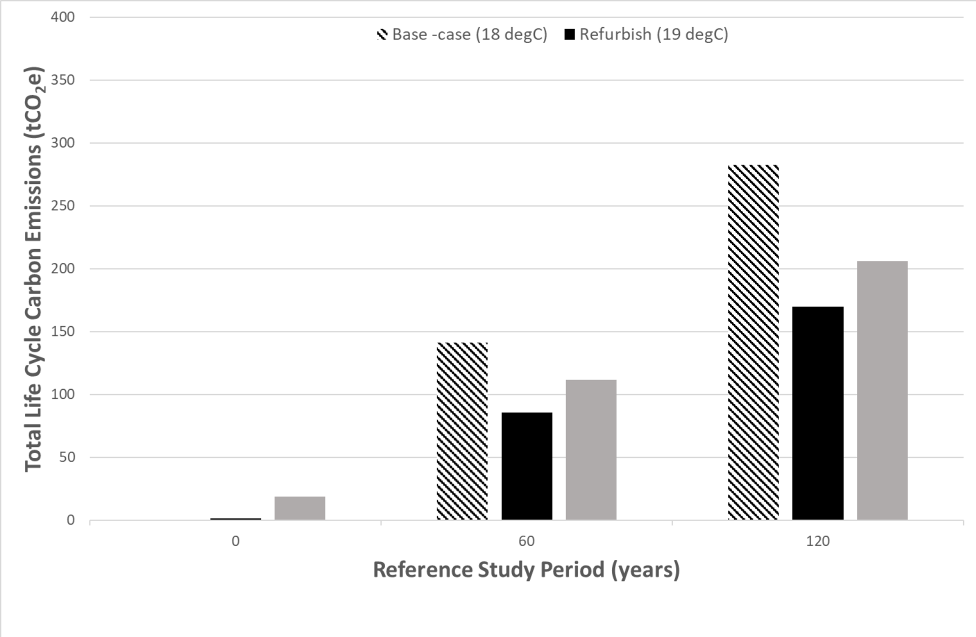

Figure 21. Estimated life cycle carbon emissions for each building case for different reference study periods (internal temperature of 21°C)

Table 19. Time periods (years in yellow) after which the New-build outperforms the Base-case and Refurbishment for different internal temperatures.

	Internal Temperature (degC)				
	21	*20*	*19*	*18*	Scenario 18-19-21
Base Case	13	13	14	16	23
Refurbish	165	165	181	201	n/a