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Modelling the embodied carbon cost of UK domestic building construction: Today to 2050

Michał P. Drewniok[a], Cyrille F. Dunant[c], Julian M. Allwood[c], Tim Ibell[b], Will Hawkins[b]

[a] *School of Civil Engineering, Faculty of Engineering and Physical Sciences, University of Leeds, Leeds*
[b] *Department of Architecture and Civil Engineering, University of Bath, Bath, UK*
[c] *Department of Engineering, University of Cambridge, Cambridge, UK*

Abstract

The construction of new domestic properties contributes 2% of UK territorial greenhouse gas (GHG) emissions. The UK government aims to increase construction of new homes in England by almost a third, to 300,000 per year by the mid-2020s, whilst simultaneously reducing emissions in line with its net zero 2050 commitment. In this paper, for the first time, the upfront embodied carbon cost of constructing domestic properties in the UK by 2050 is quantified. A bottom-up analysis modelling seven domestic building typologies was used, with the material use for each based on current UK practice. Possible interventions to reduce the embodied carbon cost are then analysed. The results show that maintaining today's levels of construction will use the remaining 2050 carbon budget apportioned to house building (160 $MtCO_{2e}$) by 2036, and cause a substantial increase in domestic floor area per capita. However, construction could reduce and cease entirely by 2035 without reducing today's living floor area per capita (37.5m^2), resulting in a substantially reduced cumulative embodied carbon of 88 $MtCO_{2e}$ by 2050. Increasing living floor area per capita to the EU average of 40.5 m^2, can be achieved within the carbon budget and with zero emissions by 2050. In contrast, increasing house building to government targets will result in double the cumulative emissions than the budget allows.

A number of carbon reduction interventions were then investigated. It was found that of to 75% embodied carbon savings can be achieved by simultaneously changing the typology share, increasing material efficiency, increasing conversion from non-residential buildings and increasing the use of timber for structural purposes.

Keywords: embodied carbon cost, embodied carbon budget, UK domestic building stock, mitigation strategies, building materials

1. Introduction

The UK has some of the world's most ambitious greenhouse gas (GHG) reduction targets. in 2009, it became the first major economy to commit to a 'net zero' 2050 target [1]. In April 2021, the UK announced the world's most ambitious climate change target, cutting emissions by 78% by 2035 compared to 1990 levels, including international aviation and shipping emissions [2] (Figure 1).

Of current UK annual territorial GHG emissions (454 $MtCO_{2e}$), one fifth are caused by building operation [3], 90% of which are from domestic buildings. Direct emissions needed to construct new buildings in the UK in 2018 was estimated between 17.0 [4] and 18.5 $MtCO_{2e}$ [5], with domestic buildings accounting for 9.4 and 8.9 $MtCO_{2e}$ respectively. This includes material extraction, manufacturing and production, construction activities and distribution of materials - known as "cradle-to-handover emissions" in BS EN 15643-1:2010 [6] or "upfront embodied carbon" in a recent report on terminology in carbon assessments [7].

As building move towards net-zero operational energy, the proportion of embodied carbon will approach 100% total emissions [8, 9], so it is crucial to minimise embodied carbon over the building life to achieve net zero UK construction in 2050 [10, 11, 12, 13, 14]. For this reason, in 2021 a proposal was launched advocating for Building Regulations to mandate reporting of embodied carbon [15]. This initiative was mainly driven by the construction industry. Just before the 26th UN Climate Change Conference of the Parties (COP26) in Glasgow, the UK Government recognised the importance in reporting on embodied carbon in buildings and infrastructure, and committed to explore a maximum level of embodied carbon for new buildings in the future [16].

In 2018, there were approximately 28.7 million dwellings in the UK, with an overall floor area of approximately 2.6 billion m^2 [17]. Historically, there has been a clear correlation between the UK population change and the change in domestic building stock [17, 18]. Based on anticipated population trends, we can predict that the domestic building stock will grow 11% to reach almost 2.9 billion m^2 by 2050 (Figure 1). The delivery of these buildings is directly related to emissions from materials and construction processes. If these emissions remain as they are today, the share of emissions from domestic building construction will increase to 50% of the total UK emissions allowed by the Climate Change Committee's recommended "Balanced Net Zero" Pathway in 2045 (19 $MtCO_{2e}$) [19], referred to in this paper as the "Balanced UK Net Zero Pathway".

Existing UK Roadmaps which aim for net-zero by 2050 rely heavily on technologies that are not commercially ready, such as carbon capture and storage (CCS). For example, according to "The Sixth Carbon Budget - The UK's path to Net Zero" published by the Climate Change Committee in December 2020 [19], a fifth of current emissions will be removed in 2050 using underdeveloped technologies.

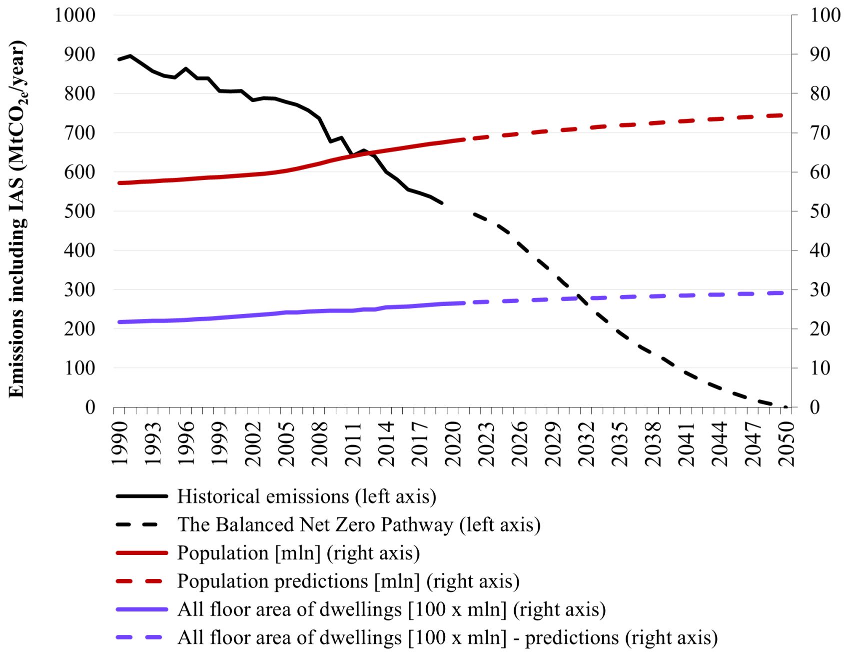

Figure 1: UK historical and the Balanced UK Net Zero Pathway (left axis) [19] and UK and floor area of dwellings predictions (right axis) [17, 18]

Therefore, a holistic strategy and policy along the supply chain which can place resource efficiency at the heart of industrial strategy is crucial in achieving decarbonisation targets [20]. Possible resource efficiency strategies in domestic buildings may include increased structural efficiency, technological change, increased conversion from non-domestic stock, or even approaches aimed at reducing total demand.

Current studies on the decarbonisation of the built environment have primarily focused on existing building stocks at building, precinct and city levels [21, 22, 23, 24]. Some studies conducted at the national level are static analyses that do not allow assessments or comparisons over time [25, 26, 27].

Only a few studies have explored mitigation strategies on a national level. For the the residential building stock in the U.S., Hu [28] found that, while the progressive scenario produces a carbon emission reduction of 42%, it still exceeds the carbon budget for a 1.5°C pathway. They found that single-family detached houses (SDs) are the top contributor to embodied carbon in the U.S., and small multifamily houses are the most carbon-intense. They suggest questioning the need for building new SDs, and their appropriate size. They indicate that the focus should be on creating a regulatory environment that can promote less carbon-intense materials but also replacing embodied carbon-intensive buildings with low-embodied carbon materials. They also found that exterior walls contribute the most carbon emissions across all building types. Mitigation pathways for Australia's built environment was studied by Allen et al. [29], who found it possible to reduce total emissions towards net-zero by 2050 under suitable policy settings. With ambitious policies and rigorous life-cycle and lifetime management, it would even be possible to achieve a net-negative emissions by 2050 by accounting for a carbon sequestration in timber buildings at a large scale. However, they conclude that there is no 'silver bullet' to reach net-zero, so a combination of measures are required.

Serrenho et al. [30] have predicted the embodied and operational emissions in the English housing stock to 2050 and found that progress in the use of low carbon materials in construction and the deployment of zero-operational carbon buildings at scale would not be enough to deliver a reduction of emissions of the scale. To achieve the goals they propose to improve building standards for both new and pre-existing construction, and reduce the demand for floor area per capita by promoting flexible design of buildings, house sharing or telecommuting. Embodied carbon in this study was limited only to one structural system – masonry cavity walls with concrete blocks and reinforced concrete flat slabs. This wall technology is used in approximately 80% of new one and two family new houses, as well as only in low rise residential buildings [4], and the most common material used to construct floors in these buildings is timber followed by precast concrete slabs (e.g. Hollowcore), rather than flat slabs [31, 4]. The embodied carbon was also limited to cradle-to-gate emissions (only material extraction, manufacturing and production of materials), excluding the delivery of materials and construction processes. Serrenho et al. [30] did not analyse conversion from non-domestic stock as well as resource efficiency strategies and therefore this analysis does not include variety of possible intervention to meet Net UK Zero targets in construction.

Drewniok et al. [4] analysed the embodied carbon of current (2018) UK construction, including the superstructure, substructure, façade, doors, windows and wall finishes of domestic and non-domestic buildings. This is, however, only a snap-shot for 2018 and does not model future predictions. According to Drewniok et al. [4], 66% of upfront embodied emissions in current UK construction arise from materials that use cement as a binder. These are considered hard to decarbonise, since around 50–60% of their production emissions are from the chemical decomposition of the raw materials [32], where emissions reductions techniques, such as alternative fuels and energy efficiency are not effective. Shanks et al. [33] calculated that the UK domestic building sector consumed approximately 4.6 Mt out of 13.0 Mt of cementitious materials in 2014, delivering approximately 177,000 new builds [17]. Since then, cement consumption in the UK has increased by 2.2 Mt, reaching 15.2 Mt with 250,000 new builds [17][1]. Drewniok et al [4] found that in 2018, 4.6 Mt out of 11.7 Mt cement alone was used to deliver new domestic properties.

No studies modelling embodied carbon by 2050 to deliver domestic properties in the UK have been

[1] England - scaled up by population

previously done.

If, as described in the Climate Change Committee's "The Sixth Carbon Budget" [19], the Government's goal is to achieve near-zero emissions for all cement production by 2040 [19] without highly optimistic CCS technology, then bulk cement production as we know today should stop by this date (currently 80% of cement sales in the UK is from domestic production [34]). On this assumption, current practice does not allow to reach zero carbon construction by 2050, and thus the UK concrete industry's GHG emissions are likely to exceed Government targets, or require considerable carbon sequestration [35].

Since 2016, annual net additions of dwellings in England has increased by 12% reaching 236,000, whereas new build completions increased by 17% to 209,000 [17]. Following The National Housing Federation (NHF) and Crisis from Heriot-Watt University that identified *"a need for 340,000 homes each year to 2031"* in England [36], to deliver these buildings material consumption needs to double compared to 2016. In 2015, the UK Government set out an ambition to deliver 1 million net additions to the housing stock by the end of 2020 in England. Since 2019 the ambition of the Government is to deliver 300,000 new homes (net additions) a year by the mid-2020s [37]. The main driver was to reduce affordability pressures for low and middle incomes and first time buyers [38]. This commitment appears to be in direct contradiction to carbon reduction goals [30], although questions remain over whether this quantity of home can be delivered with reduced emissions.

In this paper, for the first time, an embodied carbon analysis of UK domestic building construction to 2050 is conducted, based on a bottom-up analysis of material use in UK construction for 2018 presented by Drewniok at al. [4]. Various scenarios are explored, including technology variations, typology share, demolition rates as well as total construction rates (and the associated floor area per capita). This paper also investigates the consequences of permanent occupation of vacant and second homes on upfront embodied carbon, and increases in conversion from office, agricultural, storage and light industrial to residential flats. For each scenario, the cumulative carbon costs is compared to the UK's carbon budget to 2050.

2. Background

2.1. The existing UK domestic building stock

Over the last 50 years, England has represented 83-84% of the total UK domestic building stock, precisely the same proportion as population [17, 18]. Taking advantage of this correlation, when data for the UK is unavailable, this study scales statistics for England, England and Wales, or Great Britain by population to cover the UK where necessary.

The average usable floor area out of 28.7m dwellings [17] in the UK is 94m^2, 3m^2 higher than in 2008. The English Housing Survey (EHS) [17] distinguishes seven main domestic property typologies, the

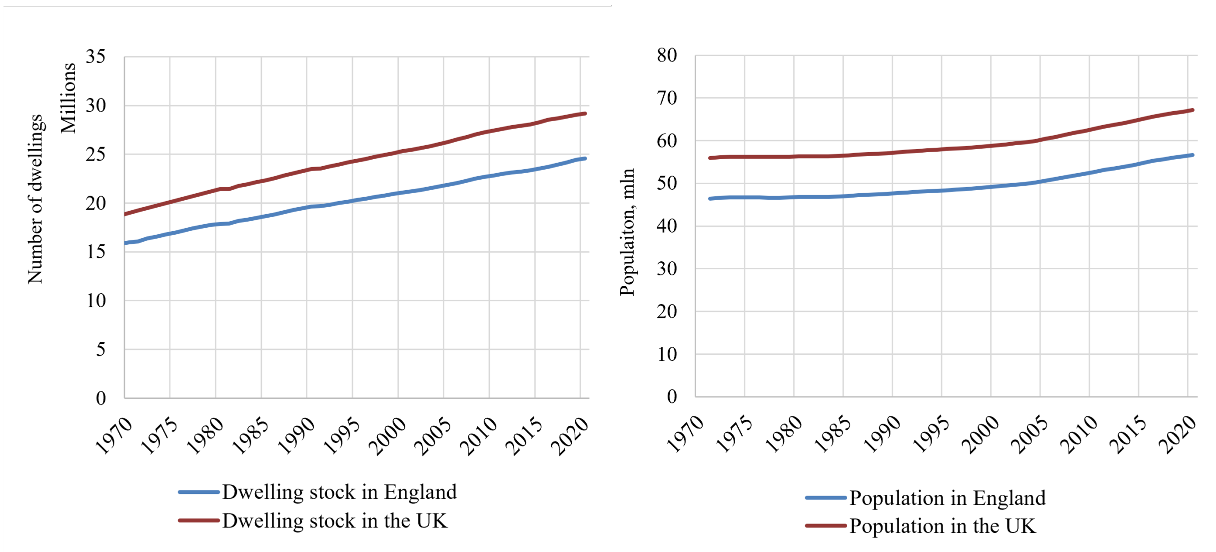

Figure 2: English and UK housing stock 1970 – 2019 – left, population of England and UK – right [17, 18]

relative proportions of which are included in Table 1, along with average floor areas and the share of net annual additions. The EHS distinguishes low rise flats as having up to six storeys, and high rise over six.

Table 1: Average floor area in m^2 per domestic property typology in England, the share in the domestic building stock and the share of annual additions.

Typology	Average floor area 2008 [m^2]	Average floor area 2018 [m^2]	Change [%]	Typology share in domestic building stock [% share by number]	Typology share of annual additions[1] [% share by number]
End-terrace	83	89	6%	10%	17%
Mid-terrace	82	88	6%	18%	17%
Semi-detached	92	97	5%	25%	31%
Detached	147	149	1%	17%	14%
Bungalow	76	77	1%	9%	2%
Converted flat	69	66	-5%	4%	10%
Purpose built flat, low rise	56	7	4%	15%	8%
Purpose built flat, high rise	59	61	3%	2%	1%

[1] 5 years average (2013-2018)

2.2. Annual domestic building completion, conversions and demolitions

Terraced houses have the largest share in annual additions to the domestic building stock followed by semi-detached houses and low rise purpose built flats. The lowest share in annual additions are high rise flats (Table 1).

Between 2012 and 2019, net annual additions in the UK increased from 144,000 to 250,000, and the number of properties that changed in use from office, agricultural, storage and light industrial to residential (conversion) increased from 22,000 to 42,000. Since 2006, demolition decreased from 26,000 to 9,000

(Figure 3), which is the lowest reported in this period. Serrenho at al. [30] assessed the average lifetime for dwellings in England at 52 years. Due to very low demolition rate, the life expectancy of domestic buildings in the UK is increasing over the time.

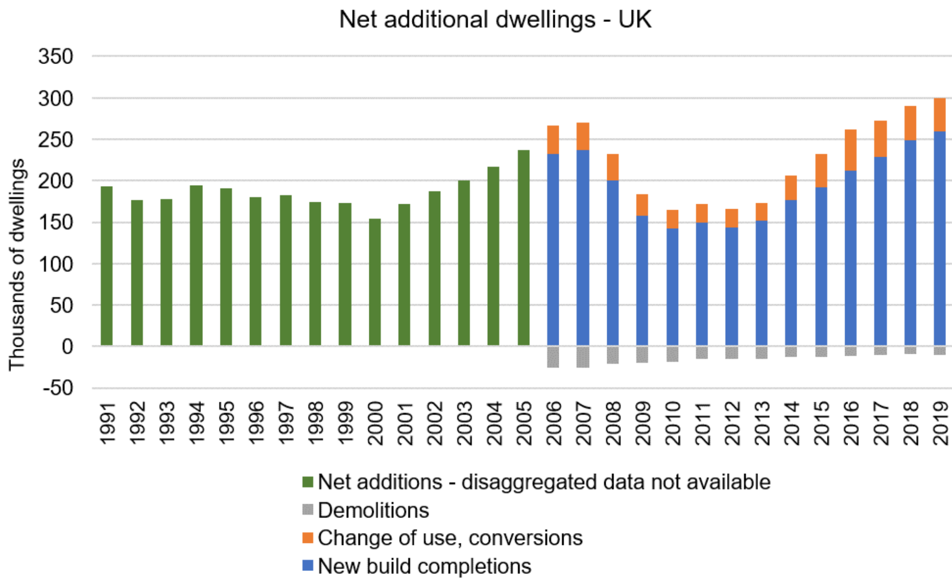

Figure 3: Annual net additions to the UK domestic building stock (England - scaled up by population to UK) [17]

2.3. *Vacant buildings and second homes*

According to the Live Tables on dwelling stocks published by the Ministry of Housing, Communities & Local Government (MHCLG), there were 634,000 vacant dwellings in England in 2018. These include long-term empty homes which have been unoccupied and substantially unfurnished for over six months, as well as dwellings undergoing major structural repairs for up to 12 months [39]. Scaling this by population, we can expect approximately 750,000 vacant dwellings currently in the UK, representing 2.7% of the UK building stock (Figure 4). This figure has varied between 700-930,000 over the last 15 years.

Second homes are defined as properties used by family/friends as holiday home, let to others as a holiday let, or for occupation while working away from home [17]. In 2018, 772,000 households in England owned a total of 783,000 second homes, of which 495,000 were in the UK. Scaling this figure by population, we estimate 588,000 second homes in the UK in 2018: 2% of the of the UK domestic building stock (Figure 4). The main reasons for having second homes are “to use as a holiday home or weekend cottage”, with a share of 39%, and “as a long-term investment and/or source of income”, with a 35% share [17].

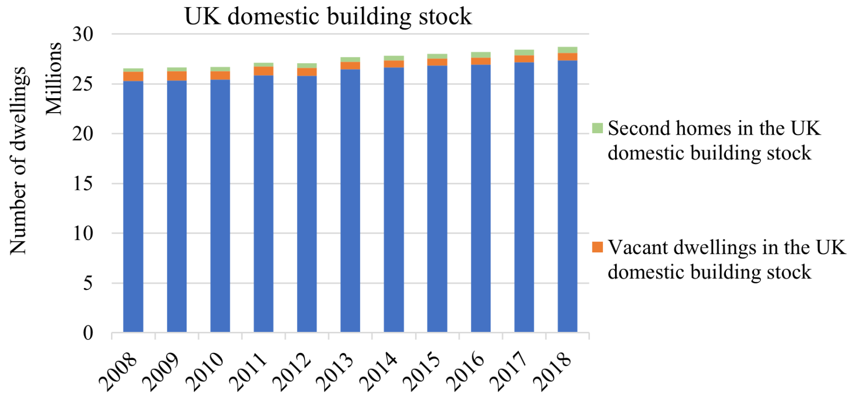

Figure 4: The share of vacant dwellings and second homes in the UK domestic building stock [17].

2.4. Floor area per capita

Floor area per capita can be calculated using various methodologies. One approach is to divide the total dwelling stock floor area by population. In this case, the total floor area can be found by multiplying all dwellings by the average floor area per dwelling. This methodology was used by Serrenho at al. [30], who found that the average floor area of domestic buildings per capita in England in 2013 was 38.8 m^2. Jiang et al. [40] used the same method and found similar results. Another approach is to assess the occupied floorspace (living floor area, excluding vacant properties). Using this approach, Gleeson [41] found that between 1996 and 2018 the floorspace per person in England rose from 34.8 m^2 to 38.1 m^2, with very little change in the last decade. The main focus was on the space available per person, so it was less meaningful to include space in vacant homes in this measure. Therefore, the average floorspace per person in an area or among a particular group was calculated as the average space per (occupied) dwelling divided by the average household size.

The differences in these these two approaches are presented in Figure 5. This figure also highlights the actual (living) floor area that excludes both vacant and second homes, which was 37.5m^2 per capita in 2018. This approach is adopted in this paper for further analysis.

3. Methodology

3.1. Materials and upfront embodied carbon to deliver domestic properties based on current UK practice

The material intensity to deliver domestic buildings in the UK in 2018 was taken from Drewniok at al. [4]. This study modelled the building typologies listed in the English Housing Survey (EHS) [17] (Table 1) using a bottom-up approach, and therefore represents current housing trends. The height of the analysed single family houses (except bungalows) was assumed as 2 storeys. The identified properties had either 2, 3 or 4 bedrooms (Table 2 and Supporting Information, SI, Section 3 [42]).

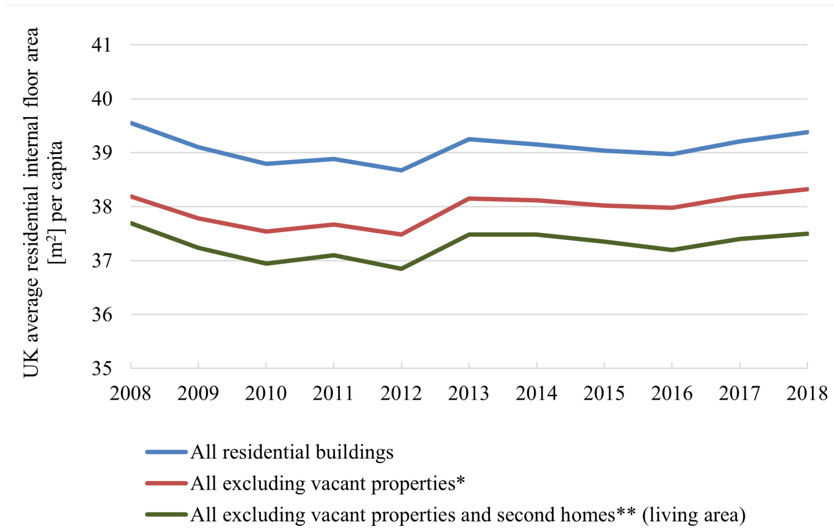

Figure 5: UK average residential internal floor area. Building stock, vacant properties and second homes are shown according to [17], population [18]. The floor area of domestic stock was calculated based on the average floor area of seven different typologies for England and scaled by population to the UK. The floor area of vacant and second homes was calculated using the number of properties and average floor area of English domestic building stock and scaled up by population to UK figures. The data for second homes in 2011 and 2014-2017 was unavailable - for these years values were chosen to match to the UK building stock trend.
* long-term empty homes which have been unoccupied and substantially unfurnished for over six months as well as well as dwellings undergoing major structural repairs for up to 12 months.
** properties used by family/friends as holiday home, let to others as a holiday let, for occupation while working away from home[17].

Table 2: Model buildings used for analysis by Drewbiok et al. [4]

Typology	**Code**	**Model buildings**	**Floor area (GIA)** m^2
End-terrace	E-T	3 bedroom	79
Mid-terrace	M-T	3 bedroom	79
Semi-detached	S-D	3 bedroom	94
Detached	D	4 bedroom	132
Bungalow	B	3 bedroom	76
Converted flats	C-F	2 bedroom	62
Purpose built flat low rise up to 4 storeys	LRF<4	2 bedroom	62
Purpose built flat low rise up to 6 storeys	4≤LRF≤6	2 bedroom	62
Purpose built flat high rise up to 10 storeys	7≤HRF≤10	2 bedroom	62
Purpose built flat high rise above 10 storeys	HRF>10	2 bedroom	62

For each case study, based on the layout, the material intensity of the substructure, structure, roof, partitions, cladding, walls and ceiling finishes (e.g. plaster), windows and doors was calculated. In this study MEP was not included. For conversion from office, agricultural, storage and light industrial to residential flats, it was assumed that foundations and upper floors are reused, the structural system (load bearing walls, frame) is reused at 50% and all other elements are replaced with new. The overall material intensity for the modelled typologies, including waste from construction processes, represent weighted averages of commonly used construction materials and technologies in the UK (SI, Section 3, Table 3.1).

The upfront embodied carbon in Drewniok at al. [4] is defined as the greenhouse gas (GHG) emissions associated with materials and construction processes up to practical completion (cradle-to-handover, Modules A1-A5, [43, 44, 7]), and are presented here in Figure 6. All upfront carbon coefficients are listed in the SI, Section 12, Table 32.

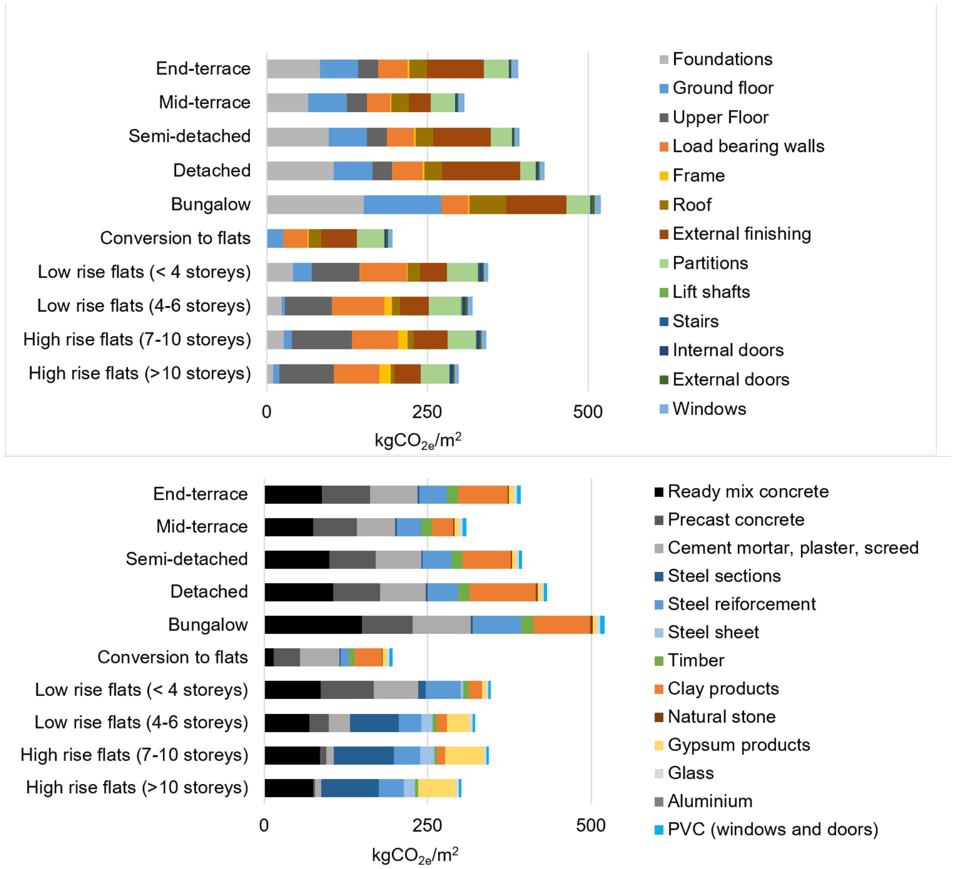

Figure 6: Upfront carbon per m^2 of GIA for average UK domestic building typologies by end use (top) and material (bottom), for 2018 [4].

Drewniok at al. [4] found that the upfront embodied carbon to deliver approximately 250,000 new builds and 37,000 converted properties in 2018 in the UK was almost 9.5 $MtCO_{2e}$. 20% of these emissions were associated with substructure (foundations), 20% with external finishes (of which 95% was in the cavity wall outer skin), 16% with ground floors, 14% with load bearing walls, 9% with partitions and 6% with roofs. The most carbon intensive materials were ready mix concrete 22%, concrete blocks 17%, bricks 16%, and steel rebar for concrete 11%. Cementitious structural materials including concrete, precast concrete, concrete blocks, (excluding steel reinforcement) in total 44% of the upfront embodied carbon, whereas timber was only 3%.

3.2. *Future domestic building predictions*

Based on a projected UK population increase of 10% to 74 million by 2050 [18], the building stock might be expected to increase accordingly to 2.9bn m^2 (Figure 7), if a constant floor area per capita 39.3 m^2 (living floor area 37.5 m^2) as found in Section 2.4, Figure 5 is maintained. This approach was used by Serrenho at al. [30] to describe baseline for their analysis. Nevertheless, the pace of change of domestic building stock may vary depending on on the amount of new property completions, demolition rates, and the number of conversions from non-domestic properties. Serrenho et al. [30] considered changes in new completions and demolition rates, and modelled an increase in floor area to 50.4 m^2 and decrease to 27.1 m^2 compared to 38.8 m^2 in 2013. For comparison, the average residential floor area in Europe is approximately 40 m^2 per capita [45], and is similar in most other OECD member countries [40]).

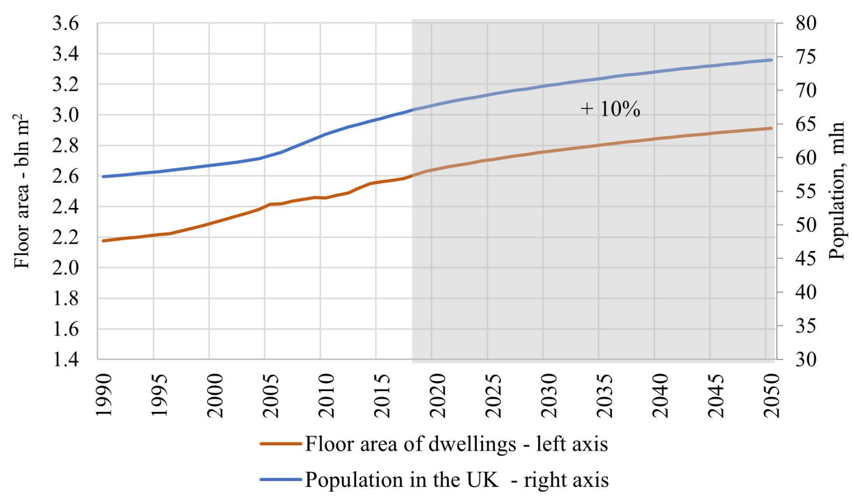

Figure 7: Domestic building stock prediction by floor area. Domestic building stock pre-2018 according to [17, 18], pre-2018 and post-2018 population prediction according to [18]

Based on the upfront domestic building embodied carbon found by Drewniok at al. [4], this study analyses future carbon emissions in two parts:

Part 1 - Demand side impacts Including assessment of the impact of the annual net additions and changes in living space per capita, maintaining the same construction practices as today.

Part 2 - Supply side impacts Including assessment of the impact of the demolition rate, the share of sub-typologies, the share of technologies and the change in the number of conversions.

3.3. *Part 1 - The impact of net additions and living space per capita*

This section investigates four options differing in annual net additions and living floor area per capita. These include: increasing net additions to government targets of 300,000 per year in England [37] (355,000 in the UK), and maintaining this to 2050 (Option I); maintaining current 2018 net addition levels (Option II); a reduction of net additions to zero by 2050 (Option III); and finally a scenario which gives a similar floor area per capita in 2050 to that of 2018 (Option IV). These are summarised in Table 3.

In each case, the same 2018 demolition rate, share of sub-typologies and share of technologies are assumed. The analysis also accounts for decarbonisation of key construction materials, per unit produced, based on literature evidence. The reduction rates are summarised in Table 5, and consider Carbon Capture and Storage (CCS) technologies and the use of hydrogen as being unlikely, due to their current lack of development at significant scale.

Table 3: Change in net additions and floor area per capita - Part 1

Options	Living floor area per capita in 2050 [m^2]	Net additions	Demolition rate	Technology share
Option I	48.0	increase to 355,000[1] by 2025 and constant by 2050	Constant 5 year average Table 4	current practice
Option II	45.0	constant, 2018 level until 2050	Constant 5 year average	current practice
Option III	40.5	a reduction to 0 by 2050	Constant 5 year average Table 4	current practice
Option IV	37.5	adjusted to get assumed living floor area per capita	Constant 5 year average Table 4	current practice

[1] follows the UK Government plan to deliver 300,000 new homes a year (net additions) by the mid-2020s. in England [37] - this number scaled up to cover the UK

Table 4: Share of net additions - average for five years from 2013-2018 [17]

	share of net additions by number	share of net additions by floor area used for demolitions
E-T	16.6%	16.5%
M-T	16.9%	16.7%
S-D	28.5%	31.1%
D	8.9%	14.9%
B	2.1%	1.8%
CF	14.7%	10.9%
LR<6	9.3%	6.1%
4≤LRF≤6	2.3%	1.5%
7≤HRF≤10	0.5%	0.3%
HRF>10	0.1%	0.0%

3.4. Part 2 - The impact of demolition rate, typology and technology share, and conversions

This section tests the effects of demolition rates, typology and technology share, and conversion rates to find interventions that yield the greatest embodied carbon savings. Constant 2020 level of net

Table 5: Material carbon reduction by 2050

Material	Carbon reduction by 2050	Scope	Source
Cementitious materials	36%	◦ efficiency in concrete production (electrification) ◦ savings in cement and binders ◦ savings in clinker production ◦ de-carbonisation of electricity	[46]
Steel	36%	◦ change to bioenergy ◦ electrification ◦ change the technology performance, ◦ shift to other fuel shift	[47]
Aluminium	76%	◦ zero carbon electricity ◦ increase energy efficiency ◦ 100% scrap collection ◦ direct emissions reduction	[48]
Timber	47%	◦ grid decarbonisation	[49]
Plasterboard	16%	◦ grid decarbonisation	[49]
PVC (plastic)	31%	◦ new processes (ready to use only)	[50]

additions was assumed (business as usual, Option II included in **Part 1**). Five different Scenarios were considered (Table 6). The *Higher* scenario includes a significant increase in the demolition of vacant domestic buildings, which is now permitted by the General Permitted Development approved in August 2020 (England) (Amendment) (No. 3) Order 2020 [51].

Table 6: Impact of different interventions on upfront embodied carbon by 2050

Scenario	Variables	Notes
Higher	◦ current demolition rate ◦ demolition of all vacant properties by 2050 ◦ current practice	current demolition (12,000 / year, 1.1 million m^2/year) demolition of all 753,300 properties with floor area of 69.3m m^2 by 2050
Baseline	◦ current demolition rate ◦ current practice	equivalent to the Option II from a Table 3 demolition of 12,000 (approx. 1.1 million m^2) properties per year
Low	◦ reduction of demolition to zero by 2050 ◦ occupy of all vacant buildings by 2050 ◦ current practice	demolition from 12,000 (approx. 1.1 million m^2) to zero by 2050, use of all vacant buildings by 2050 (2018, 753,324 buildings, approx. 69.3 million m^2)
Lower	◦ reduction of demolition to zero by 2050 ◦ change in typology share ◦ current practice	demolition as in Low scenario, reduce the share of one and two family houses by a half, increase conversions by 70%*, increase a share of low rise residential by a factor of three and increase a share of high rise residential properties by nine times
Lowest	◦ reduction of demolition to zero by 2050 ◦ change in typology share ◦ change in technology ◦ increase in efficiency	demolition and typology share as in Lower scenario, this option assumes increase in use of timber for structural purposes in one and two family houses, low rise residential buildings as well as conversions.

*Scenario Lower includes simulation where by 2050 approximately 80 million m^2 of office, industrial and other buildings floor area will be converted for domestic purposes (35% of 2018 office buildings floor area, 10% industrial and 10% other buildings [52]). This makes approximately 2.7 million m^2/y by 2050, 70% increase compared to 2018.

4. Results

4.1. Part 1 - Demand side impacts

Figure 8 (top) presents the change in living floor area per capita in the UK and number of net additions for the four options in Table 4. The bottom part of Figure 8 shows the annual upfront embodied carbon cost to deliver these, with and without decarbonisation of material production (solid line and dashed line, respectively). The graph also includes the total UK emissions under the Balanced UK Net Zero Pathway [19] (red dashed line), which reaches zero by 2050.

Maintaining the current demolition rate, reducing net additions to zero by 2050 (Option III) still results in a greater living floor area per capita than 2018, increasing by 2 m^2 to 40.5 m^2, close to the current EU average. Taking into account material carbon reduction, this option would be responsible for 3% share of The Balanced UK Net Zero Pathway in 2045 (green lines on Figure 8), with a cumulative upfront embodied carbon of 160 $MtCO_{2e}$ by 2050.

If the 2018 living floor area per capita is maintained in 2050 (37.5 m^2) and having current rates of demolition, then new additions must decline to zero by 2035, with carbon emissions following accordingly (Option IV, grey lines). In this case, the cumulative upfront embodied carbon by 2050, including material carbon reduction, drops by almost a half, to 88.4 $MtCO_{2e}$.

Maintaining 2018 net additions to 2050, with current demolition rates (Option II, orange line), increases the living floor area per capita to 45 m^2, today's average residential floor area in Germany [40]. Given the reduction in material carbon footprint, it will have 18% share of The Balanced UK Net Zero Pathway (orange lines on Figure 8) with a cumulative upfront embodied carbon by 2050 of 250 $MtCO_{2e}$.

Following the UK Government plan to deliver 300,000 homes a year by the mid-2020s in England (355,000 in the UK), and maintaining this to 2050 (Option I, dark red line), increased the living floor area by 10 m^2 in 2050 to 48 m^2, the current average for Nordic countries [45]. In this scenario, in 2045 the emissions to deliver domestic buildings will reach 25% of the Balanced UK Net Zero Pathway (including material carbon reduction). The cumulative upfront embodied carbon by 2050 will double compared to Option III, reaching (320 $MtCO_{2e}$).

If all today's vacant buildings are occupied, the living floor area will increase by 1 m^2, and by another 0.6 m^2 if all second homes located in the UK are used for long term occupation (ignoring any upfront embodied carbon cost this may incur). This means that for the lowest upfront embodied carbon option, Option III and Option IV, the living floor area in 2050 could reach 42.1 and 39.1 m^2, respectively.

4.2. Part 2 - Supply side impacts

Figure 9 shows the impact of supply-side interventions, as summarised in Table 6, which each feature Option II for their underlying demand baseline (business as usual, a constant rate of house building).

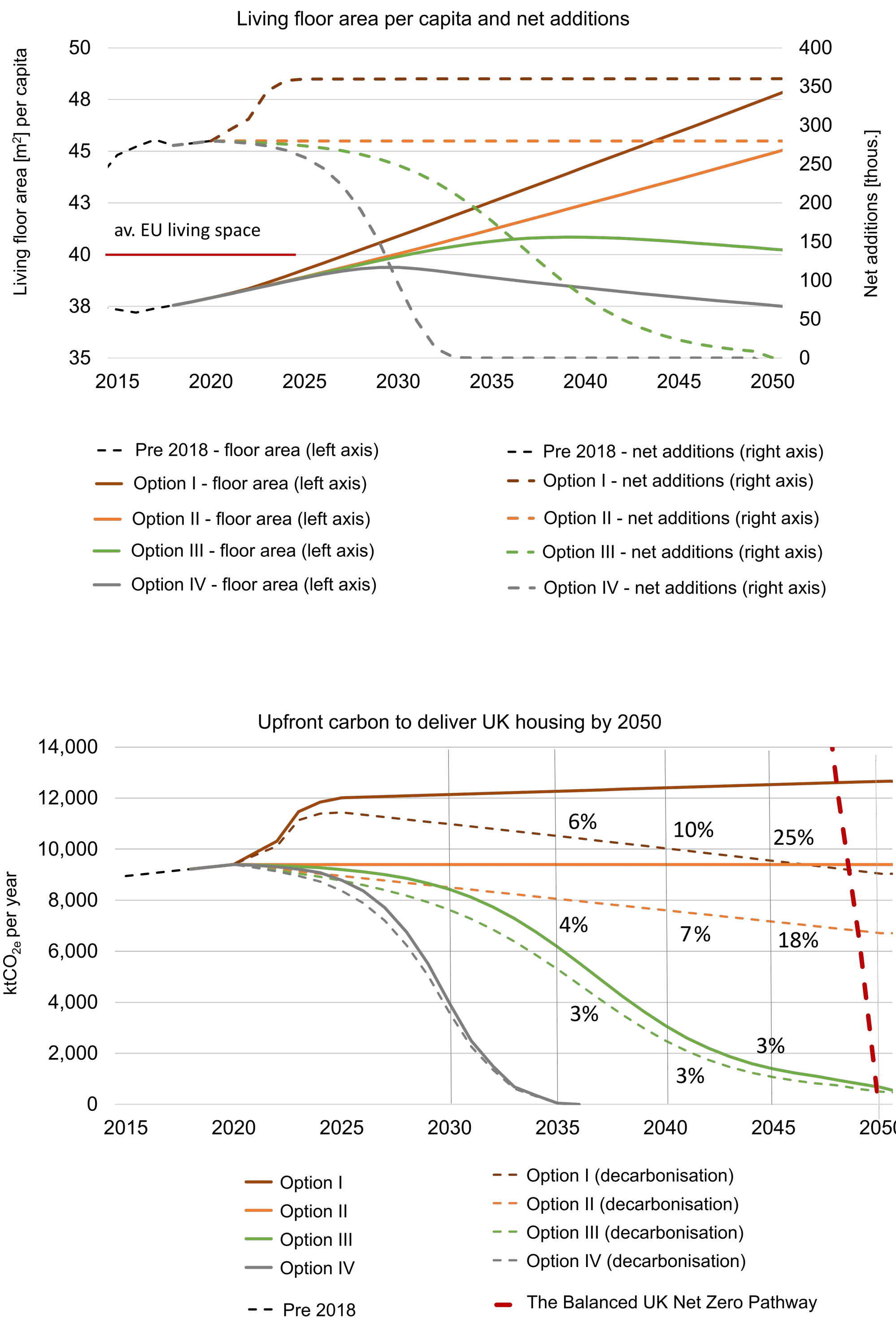

Figure 8: Options to deliver domestic properties by 2050. Top - living floor area in the UK and number of net additions for each option, bottom - upfront carbon for analysed options. Living floor area in the UK excludes vacant a properties and second homes.

Analysis include material decarbonisation strategies included in Table 5. Material carbon reduction strategies allow the business as usual (Baseline, orange line) to reduce embodied carbon by 28% compared to 2018 with 250 $MtCO_{2e}$ of cumulative upfront embodied carbon by 2050, and a share of 18% of the Balanced UK Net Zero Pathway in 2045.

We currently have a low annual residential demolition rate, so the embodied carbon reduction from less demolition is around 2%. The interventions that can bring up to 50% of embodied carbon reduction are:

- change of typology share with an increase in the share of low and high rise residential properties, and an increase in conversion from non-domestic buildings – *Lower scenario*, or
- occupy all vacant buildings by 2050 – *Low scenario*

For *Lower scenario* and *Low scenario* we could expect 220 $MtCO_{2e}$ of cumulative upfront embodied carbon by 2050 and a share of 15% of the Balanced UK Net Zero Pathway in 2045. For both these scenarios (*Lower scenario* and *Low scenario*), savings could reach 63% if by 2050 all second homes are used for living purposes.

The highest, 75%, savings was found if, in addition to changing the share of typologies and increasing conversion, we increase the use of timber and increase material efficiency (*Lowest scenario*). The use of timber frame structures are also beneficial as they are commonly used alongside natural insulation systems such us hemp, cork and sheep's wool. Even with 75% upfront carbon reduction (180 $MtCO_{2e}$ of cumulative upfront embodied carbon by 2050), this scenario will still have 10% of The Balanced UK Net Zero Pathway in 2045.

Keeping a constant 2018 demolition rate and replacing all vacant buildings with well-designed new residential units (*Higher scenario*) – allowed by Country Planning Order 2020, No. 3) [51], in 2050 we can expect similar upfront embodied carbon as in 2018, reaching 25% share of The Balanced UK Net Zero Pathway by 2045 and with 390 $MtCO_{2e}$ of cumulative upfront embodied carbon by 2050 (solid red line).

5. Discussion

It was found that upfront emissions increased by 2% to deliver domestic buildings in 2020, compared to 2018 (from 9.4 $MtCO_{2e}$ to 9.6 $MtCO_{2e}$).

Reaching absolute zero emissions in 2050 apportioned to house building (linear approximation from 2018 to 2050) we could "use" approximately 160 $MtCO_{2e}$ (remaining upfront embodied carbon budget from the supply of domestic buildings). Maintaining today's domestic buildings net additions, including envisaged strategies for the decarbonisation of building materials, we will use this budget in 16 years,

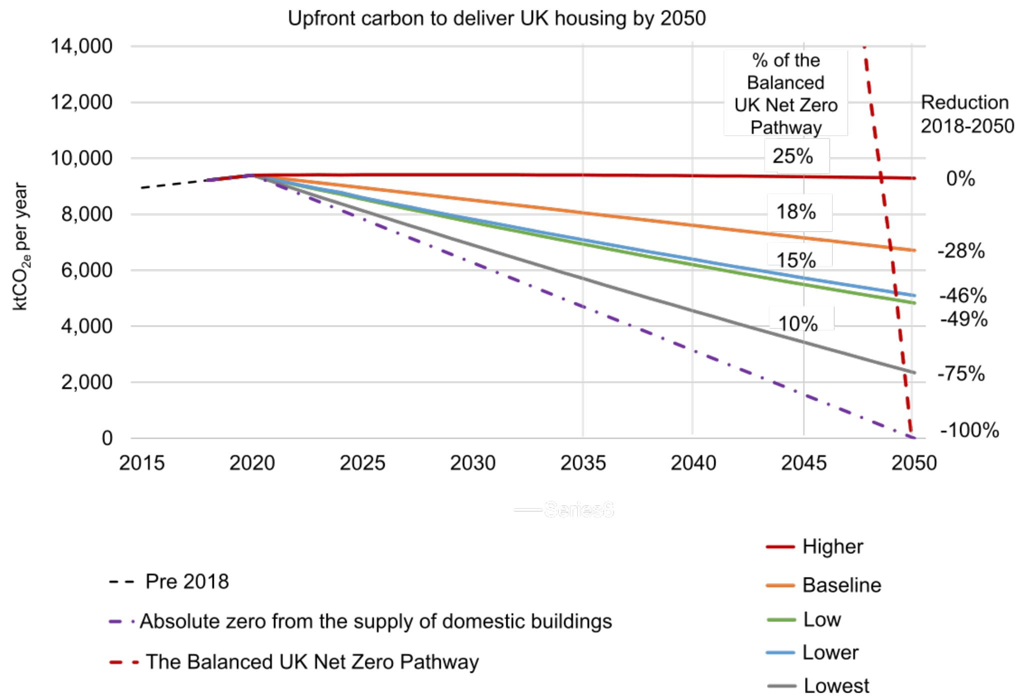

Figure 9: Interventions to minimise upfront carbon for analysed scenarios.

by 2036. By changing the share of typologies, increasing conversion, increasing the use of timber and increasing material efficiency, we will use this budget by 2039.

This analysis suggests that it is not possible to eliminate emissions without the number of new additions to the building stock reaching zero. With a gradual reduction number of net additions from today, the 2050 living floor area per capita will still increase by 2 m^2 to the current EU level. This will increase by a further 1 m^2 if vacant buildings are occupied. This analysis was made assuming current demolition rates. Due to ongoing efforts to prolonging building life in the UK - refurbishments, conservation of existing buildings - it seems to be unlikely that the demolition of domestic buildings will increase significantly. A threat to this could be the General Permitted Development approved in August 2020 (England) (Amendment) (No. 3) Order 2020 [51]. The Order allows the demolition of vacant residential blocks and replacing these with well-designed new residential units. The Order also stipulates that builders no longer need a normal planning application to demolish and rebuild vacant and redundant residential and commercial buildings if they are rebuilt as homes. As shown in Figure 9, replacing vacant residential buildings combined with with the Government's goal to deliver 1 million net additions to the housing stock by the end of 2020s in England (355,000 in the UK) will result in spending the remaining upfront embodied carbon budget by 2030. The Government's justification for increasing new homes additions is to reduce affordability pressures especially *"for the nurse, the teacher, and those on low and middle incomes, and particularly for* *those trying to get on the housing ladder for the first time"* [38]. Nevertheless, boosting supply and does not offer a solution to the affordability crisis, since a shortage of housing did not contribute to house price increases between 1996 and 2018 [53]. Raising the rate of supply will do little to bring prices down, and will instead result in a growing number of vacant properties [53]. What is also important, more than a third of second homes in the UK are for a long-term investment or source of income [17]. This increases the price of domestic properties, both new and second-hand.

This analysis includes only the substructure, superstructure, partitions, finishing walls and ceilings (plaster), windows and doors. The calculations do not include either mechanical, electrical and plumbing services, external works or painting. Including these can increase the upfront carbon for different properties by 10-15% [54] [55]. These aspects are the scope of authors future research. This study does not include operational emissions from new and existing buildings. This aspect as well as housing needs without transgressing national climate and biodiversity goals will be investigated further by the authors.

6. Conclusions

This paper analyses various future scenarios for delivering domestic properties in the UK by 2050, and explores possible interventions to minimise upfront embodied carbon. The main conclusions are as follows:

- The upfront embodied carbon (cradle-to-handover) of house building is set to become an increasingly significant share of UK emissions if current construction rates continue.
- Maintaining today's emissions, the remaining 2050 carbon budget apportioned to house building will be spent in 16 years, by 2036.
- The current net rate of new domestic properties far exceeds population growth, so the living floor area per capita is increasing.
- Even if rates of house building reduce to zero by 2050, the floor area per capita will still be greater in 2050 than it is today.
- The impact of occupying vacant properties can bring up to 45% embodied carbon savings by 2050.
- The potential impact of changing housing typologies and increasing the number of conversions is also quite significant, similar to occupying vacant properties.
- The impact of using the best currently available technology is very significant, and should be the primary focus of policies to reduce embodied carbon in construction.

7. Supplementary information

Supplementary Information for this study is available from the University of Leeds at https://doi.org/10.5518/1176.

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9. Contribution

MPD the lead in writing the manuscript, conceptual ideas and proof outline, methodology, modeling. All authors were engaged on the conceptual ideas. WH, CFD verified analytical methods, WH, CFD interpretation of the results, proofreading of the manuscript, visualization, review & editing.

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