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 currently causes 2% of UK territorial greenhouse gas (GHG) emissions. The UK government aims to increase the number of new homes in England by almost a third to reach 300,000 new homes per year by the mid-2020s. This contradicts the government's commitment to zero emissions in 2050. In this paper, for a first time upfront embodied carbon cost (cradle-to-handover) to deliver domestic properties in the UK by 2050 was quantified. For this purpose a bottom-up analysis modelling 7 domestic buildings typologies for 2018 was used. The use of materials for each typology represents current UK practice. The analysis in this paper include possible interventions to reduce upfront embodied carbon cost in domestic building sector. The results show that maintaining today's emissions, the remaining 2050 carbon budget (160 $MtCO_{2e}$) will be spend by 2036. If today's living floor area per capita (37.5m^2) is maintained in 2050, for commonly used technologies and today's low demolition rates, new construction could end by 2035 with cumulative upfront embodied carbon by 2050 of 88 $MtCO_{2e}$. It is possible to reach absolute zero in 2050 if the living floor area per capita do not exceed the EU average (40.5 m^2) with the cumulative upfront embodied carbon of 160 $MtCO_{2e}$. These emissions will double if we add 355,000 new homes each year by 2050 (300,000 in England). We found that significant upfront 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.

1. Introduction

In 2008, the UK accepted by legislation a greenhouse gas (GHG) emissions reduction of 80 per cent by 2050, compared to 1990 levels. However, this target was made even more ambitious in 2019 when the UK became the first major economy to commit to a 'net zero' target [1]. In April 2021, the UK announced to set in law 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).

One fifth of current UK annual territorial GHG emissions (out of 454 $MtCO_{2e}$) 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 estimates between 17.0 [4] and 18.5 $MtCO_{2e}$ [5]. New domestic buildings accounted for between 9.4 - 8.9 $MtCO_{2e}$, respectively. These emissions include material extraction, manufacturing and production, construction activities and distribution of materials - cradle-to-handover emissions according to BS EN 15643-1:2010 [6] or upfront embodied carbon according to [7].

Moving towards net-zero operational energy buildings, the embodied carbon connected to materials will approach 100% of total emissions [8, 9], and therefore 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 which advocates for Building Regulations to mandate reporting of embodied carbon [15]. This initiative was mainly driven by the construction industry. Just before the 26^{th} 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 to explore a maximum level of embodied carbon for new builds in the future [16].

In 2018 there were approximately 28.7 million dwellings with an overall floor area of approximately 2.6 billion m^2 [17]. Historically, there has been a clear correlation between population change and change in domestic building stock in the UK [17, 18]. Based on current trends, we can predict that the domestic building stock will grow 11% to reach almost 2.9 billion m^2 in 2050 (Figure 1). The delivery of these buildings is directly related to emissions from materials and construction processes (cradle-to-handover). If these emissions remain as they are today, the share of upfront embodied emissions from UK building construction will increase to 50% (out of 19 $MtCO_{2e}$) of the total UK emissions allowed by the Climate Change Committee's recommended "Balanced Net Zero" Pathway i2045 (in this paper used as "Balanced UK Net Zero Pathway"[19].

Existing UK Roadmaps which aim for net-zero by 2050 rely heavily on technologies that are not commercially ready yet, such as carbon capture and storage (CCS). 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, so the UK

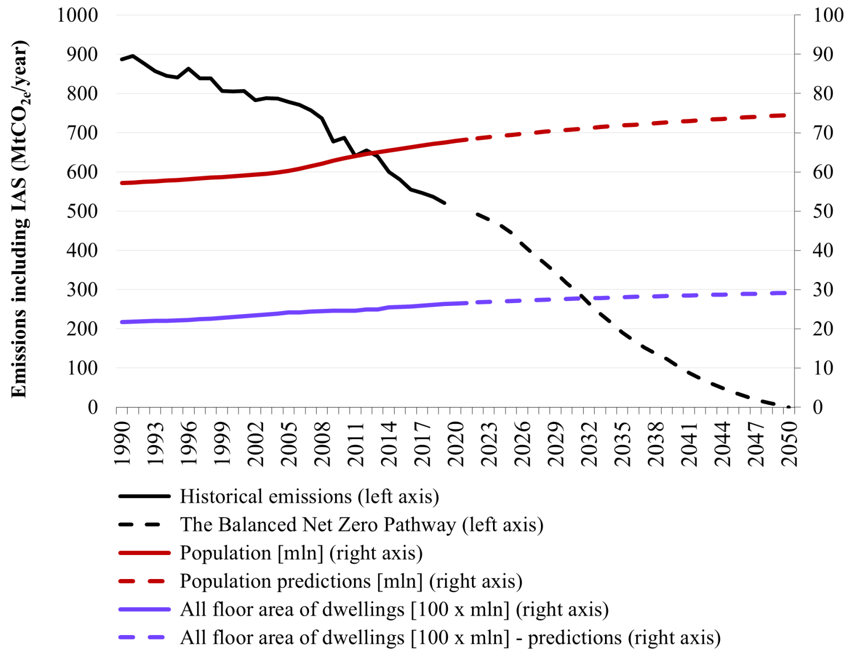


Figure 1: UK historical and the Balanced UK Net Zero Pathway (left axis) [19] and UK and floor area of dwellings predictions (right axis) [17, 18]

government's forecast is highly optimistic. 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 a reduction of the number of new buildings delivered. The work that includes embodied carbon from materials as well operational emissions for the English building stock prediction by 2050 was done by Serrenho et al. [21]. However the study was limited only to masonry cavity walls with concrete blocks and reinforced concrete flat slabs. Analysed by Serrenho et al. [21] wall technology is used in approximately 80% of new one and two family new houses as well as low rise residential buildings. Unlike to flat slabs, the most common material to construct floors in these buildings is timber followed by precast concrete slabs (e.g. Hollowcore) [22, 4]. Their study includes foundation, roof, windows and doors - elements to deliver a shell and core of the buildings. Embodied carbon was also limited to cradle-to-gate emissions (only material extraction, manufacturing and production of materials). This exclude delivery of materials and construction processes. Serrenho et al. [21] 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 current practice in UK construction. This analysis include calculations of upfront embodied carbon emissions (cradle-to-handover) for new domestic and non-domestic buildings for superstructure, substructure, façade, doors, windows and wall finishes. For 2018, Drewniok et al. [4] analysed use of concrete, steel sections (hot rolled), fabricated sections (from steel sheet), steel reinforcing bar (rebar), cold rolled steel sections (made from steel sheet), steel sheet (steel deck), aluminum sections (extruded aluminum), aluminium sheet, structural timber, clay products, glass, stone products, gypsum plaster, plasterboard, PVC and glass. This study however present only a snap-shot for 2018 and does not model future predictions.

To deliver new construction in 2018 in the UK, almost 90% by mass and 66% of upfront embodied emissions in 2018 were from materials that use cement as a binder [4]. These are identified as hard to decarbonise because around 50–60% of its production emissions are from the chemical decomposition of the raw materials, called ‘process’ emissions [23]. This means that emissions reductions techniques, such as alternative fuels and energy efficiency can only impact part of the industry’s emissions, requiring industry-specific solutions to be developed to address the rest. Shanks et al. [24] assessed that the domestic building sector consumed approximately 4.6 Mt out of 13.0 Mt of cementitious materials in 2014, delivering approximately 177,000 new builds in the UK [17]. Since then, cement consumption in the UK has increased by 2.2 Mt reaching 15.2 Mt with 250 thousand new builds in the UK [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.

If, based on “The Sixth Carbon Budget - The UK’s path to Net Zero” [19], the Government’s goal is to achieve near-zero emissions for all cement production by 2040 [19] without highly optimistic CCS technology, the cement production as we know today should stop by this date in the UK (currently 80% of cement sales in the UK is from domestic production [25]). Current practice does not allow to reach zero carbon construction by 2050. UK concrete industry’s GHG emissions are likely to exceed Government targets. To meet these, carbon sequestration is required [26].

Since 2016, annual net additional dwellings in England increased by 12% reaching 236 thousands, whereas new build completions increased by 17% reaching 209 thousands [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 [27], 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. [28]. The main driver was to reduce

[1] England - scaled up by population

affordability pressures for low and middle incomes and first buyers [29]. The increase in the supply of new housing is in contradiction with the goals to reduce (upfront) carbon emissions as to deliver 300,000 new homes, material consumption needs to increase by 50% compared to 2016. Also, boosting supply 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. Raising the rate of supply will do little to bring prices down, and will instead result in a growing number of vacant properties [30].

In this paper an analysis of different scenarios for UK domestic properties demand to 2050 was conducted. Scenarios include commonly used technologies, differs in the annual net additions, demolition rates as well as change in typologies share. This paper analyses consequences of the permanent occupation of vacant and second homes on upfront embodied carbon and increase in conversion from office, agricultural, storage and light industrial to residential flats.

This enables to find the cumulative carbon cost for different scenarios and allows to compare them to the UK carbon budget bu 2050. This study used bottom-up analysis of material use in UK construction used by Drewniok at al. [4] to find upfront embodied carbon for 2018.

2. Background

2.1. Existing domestic building stock [17]

Over the last 50 years English dwelling building stock was between 83-84% of the UK domestic building stock. At the same time English population was 83-84% of the UK population [17, 18], therefore there is a good correlation between population and building stock in England and UK (Figure 2). This study covers and analyses the UK territory. When the data for the UK was unavailable, statistics for England, English and Wales or Great Britain were used and then scaled by population to cover UK.

The average usable floor area out of 28.7m dwellings [17] in the UK is 94m^2, and is 3 m^2 higher than in 2008. English Housing Survey (EHS) [17] distinguishes seven main domestic properties typologies. Relative proportions of those typologies in UK housing stock, average floor area as well as share of typologies in annual net additions is included in Table 1.

2.2. Annual domestic building completion, conversion and demolition [17]

Terrace houses have the largest share in annual additions to the domestic building stock followed by semi-detached houses and low rise purpose build flat (up to 6 storeys). The lowest share in annual additions are high rise purpose build flats with more than 6 floors (Table 1).

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

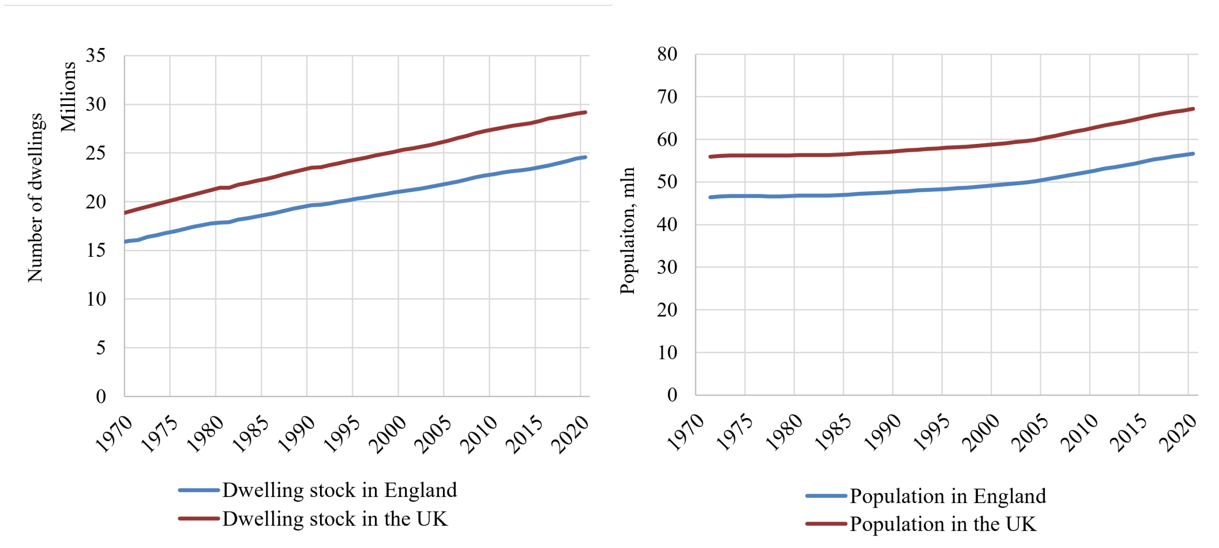


Figure 2: English and UK housing stock 1970 – 2019 – left, population of England and UK – right [17, 18]

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

Typology	Average floor area 2008 [m^2]	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)

thousand to 9 thousand (Figure 3), which is the lowest reported in this period. Serrenho at al. [31] assessed the average lifetime for dwellings in England at 52 years. Nevertheless, due to the very low demolition rate, the life expectancy of domestic buildings in the UK is increasing quite significantly.

2.3. Vacant buildings and second homes [17]

According to the Live Tables on dwelling stock 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. Scaling this up by population, we can expect approximately 750 thousand vacant dwellings in the UK and find that over the last 15 years

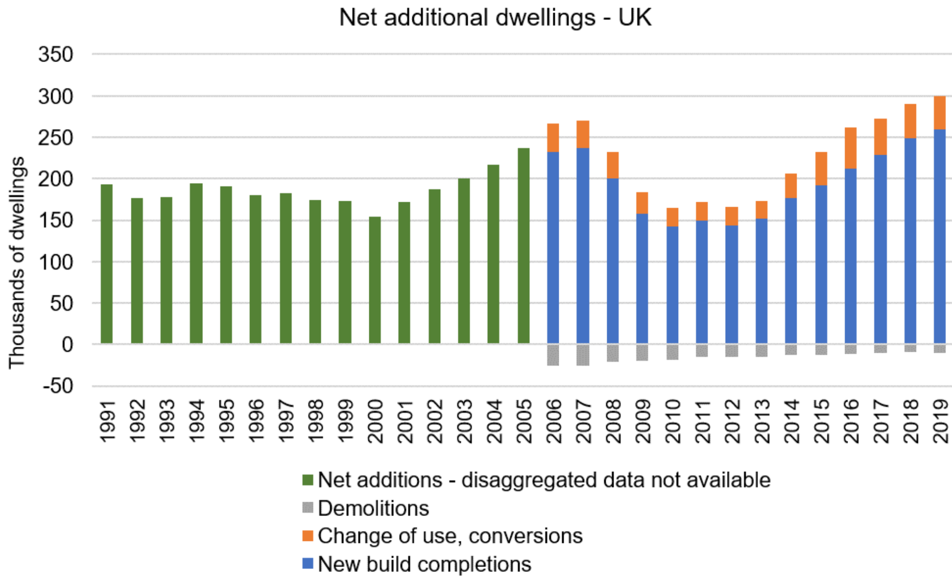


Figure 3: Annual net additions to the UK domestic building stock (England - scaled up by population to UK) [17]

vacant dwellings in the UK varied between 700 – 930 thousand. In 2018 vacant dwellings in the UK were 2.7% of the UK building stock (Figure 4).

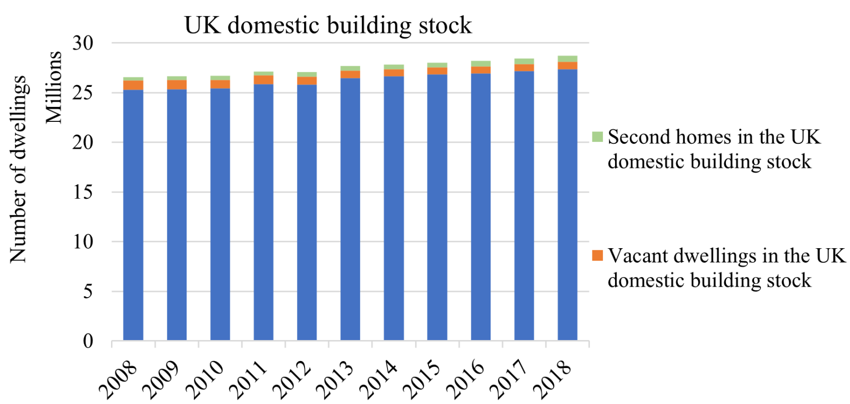


Figure 4: Vacant dwellings and second homes share in the UK domestic building stock [17].

Second homes are defined as properties used by family/friends as holiday home, let to others as a holiday let, for occupation while working away from home, rented or other. In 2018, 772,000 households in England had in total 783,000 owned second homes. Of these, 495,000 were in the UK. Scaling this figure by population, we have 588 thousand 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].

2.4. Floor area per capita

Floor area per capita can be calculated using various methodologies. Calculations can be made by dividing all dwelling stock floor area by population. In this case all available domestic properties floor area can be found by multiplying all dwellings and an average floor area of dwellings. This methodology was used by Serrenho at al. [31] who found that the average floor area of domestic buildings per capita in England in 2013 was 38.8 m^2. Jiang et al. [32] used the same method and found similar results. Another way is to assess the occupied floorspace (living floor area, excluding vacant properties. Using this approach, Gleeson [33] found that between 1996 and 2018 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 and it was less meaningful to include space in vacant homes in this measure. Therefore 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.

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 37.5 m^2 per capita in 2018. This approach is used 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]. The study modelled the building typologies listed in the English Housing Survey (EHS) [17] (Table 1) and represented current housing trends. The height of the analysed single and to family houses (except bungalows) was assumed as 2 storeys (ground floor and upper floor) [17]. The EHS [17] distinguishes low rise buildings (up to 6 storeys) and high rise residential buildings (above 6 storeys). Drewniok at al. [4] split residential buildings category into 2-4 (LRF<4) and 5-6 (4≤LRF≤6) storeys for low rise buildings and 7-10 (7≤HRF≤10) and above 10 (HRF>10) for high rise residential buildings. This was due to the differences in the technologies used for different heights of residential buildings. The identified properties had either 2, 3 or 4 bedrooms (Table 2 and Supporting Information, SI, Section 1 [34]).

For each case study, based on the layout, material intensity of the substructure, structure, roof, partitions, cladding, walls and ceiling finishes (e.g. plaster), windows and doors was calculated. Drewniok at al. [4] assumed that 20% of single and double family houses and 30% of multi-storey buildings have retaining walls. For residential properties assumed 5% material provision for shared space (shared entrance space, corridors, maintenance rooms, service rooms). For conversion from office, agricultural, storage and light

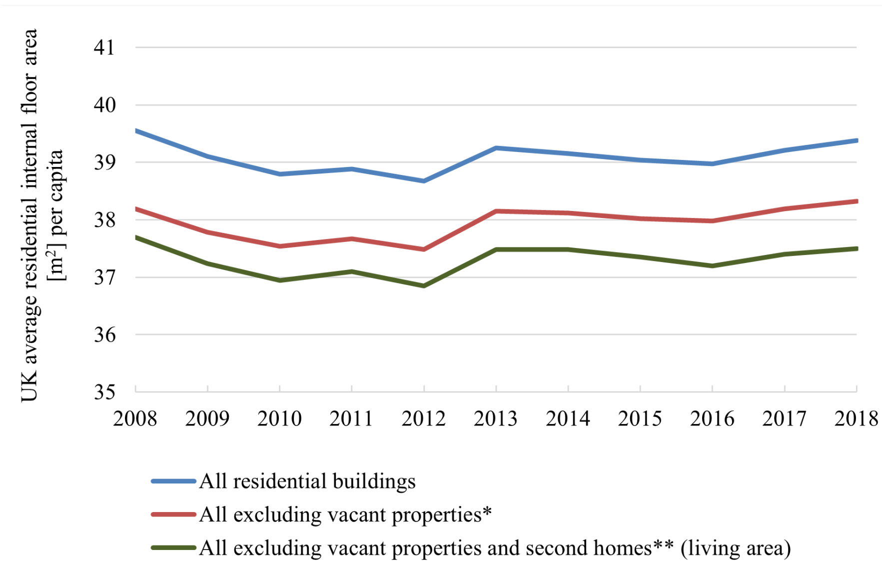


Figure 5: UK average residential internal floor area. Building stock, vacant properties and second homes are according to [17], population [18]. Floor area of domestic stock was calculated based on the average floor area of seven different typologies for England and scaled up by population to UK figures. 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, rented or other.

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

industrial to residential flats, Drewniok at al. [4] assumed that foundations and upper floors are reused, structural system (load bearing walls, frame) are reused in 50% and the the rest elements are as new.

For each element, separately, Drewniok at al. [4] assigned material allowance for shape irregularity in line with [35], 10-15% for floors and roofs, 5-20% for foundations, ground floor, and partitions, 5-10% load bearing walls. Detailed list of assumed material allowances are included in Section 4 included in SI.

Drewniok at al. [4] in their work included waste rate for each material separately. Depending on material, waste rate was assumed between 1-23% (SI, Section 8, Table 28). Overall material intensity for modelled by Drewniok at al. [4] typologies include weighted shares of commonly used in the UK technologies (SI, Section 1, Table 1.1). Detailed material assumptions are included in SI, Section 1.1.

Upfront embodied carbon in this study is defined as the greenhouse gas (GHG) emissions associated with materials and construction processes up to practical completion (cradle-to-handover, Modules A1-A5, [36, 37, 7]). Each module for each material was assumed separately. The Inventory of Carbon and Energy (ICE), V3.0 BETA [38] was used as the main source for Module A1-A3. If materials were not listed in the ICE [38], A1-A3 were assumed from suitable available Environmental Product Declarations (EPDs). For end products such as windows and doors, relevant EPDs were used. Module A4 (transport) was calculated individually for each material based on road haulage (average laden). Module A5 (construction activities) includes emissions from the transportation the waste away from site for reuse or recycling (SI, Section 8, Table 28). All upfront carbon coefficients are listed in SI, Section 9, Table 29. Upfront carbon for analysed by Drewniok et al. [4] sub-typologies per m^2 is presented on Figure 6.

Drewniok at al. in [4] found total material intensity and upfront embodied carbon for new domestic properties delivered in 2018 in the UK. Within the analysed boundaries Drewniok at al. in [4] found that the upfront embodied carbon to deliver approximately 250 thousand new builds and 37 thousand converted properties in 2018 in the UK was almost 9.5 $MtCO_{2e}$. 20% of these emissions were connected to substructure (foundations), 20% to external finishes (of which 95% was in the cavity wall outer skin), 16% to ground floors, 14% to load bearing walls, 9% to partitions and 6% to roof. 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 by approximately 10% to 74 million by 2050 [18], it is expected the building stock to increase accordingly to 2.9 billion m^2 (Figure 7). This maintains a constant floor area per capita (37.5 m^2 as found in Section 2.4). This approach was used by Serrenho at al. [31] 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 completion, demolition rates, and the number of conversions from non-domestic properties. The analysis based on changes in new completions and demolition was included in Serrenho at al. [31]. They modelled 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 [39] (this applies also for most other OECD member countries [32]). Similar approach

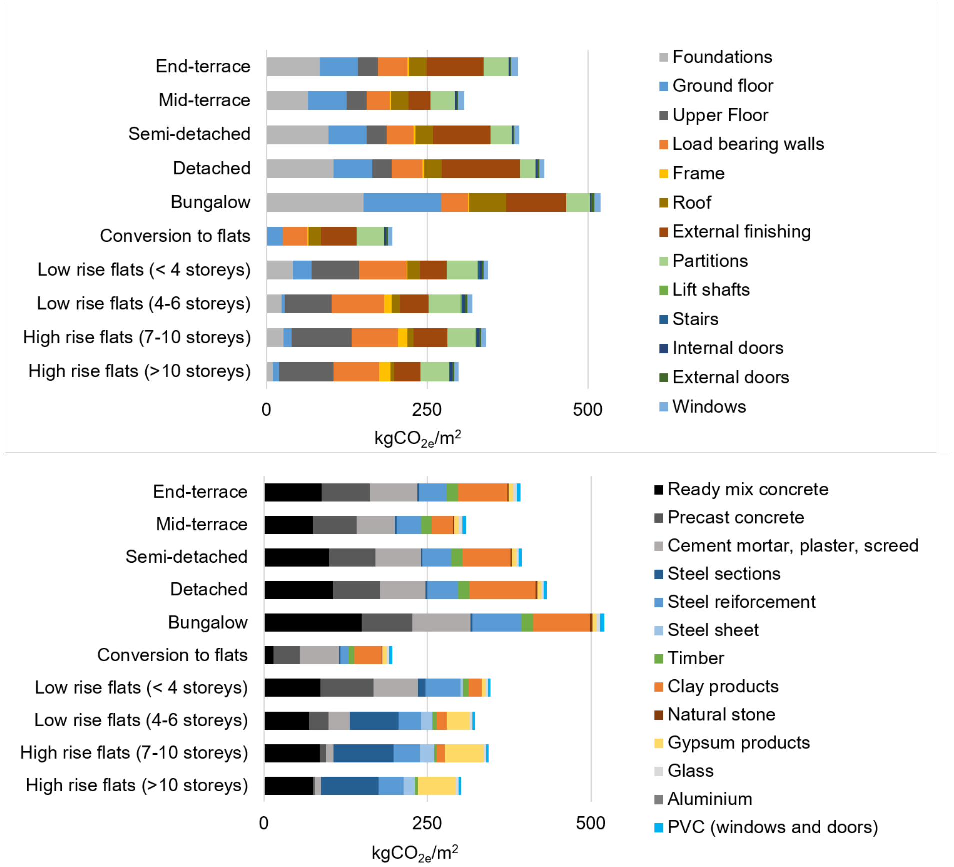


Figure 6: Upfront carbon per m^2 of GIA for analysed building typologies by end use (top) and material (bottom) [4]

was used in this study.

Based on upfront embodied carbon form domestic buildings found by Drewniok at al. [4], an analysis of future carbon emissions was conducted. This was done in two steps:

Step 1 assessment of the impact of the annual domestic properties net additions and changes in living space per capita on upfront embodied carbon by 2050

Step 2 assessment of the impact of the in the demolition rate, share of sub-typologies, share of technologies and change in the number of conversions on upfront embodied carbon by 2050, maintaining the same living space per capita

3.3. The impact of the annual domestic properties net additions and changes in living space per capita on upfront embodied carbon by 2050

In this part, four options differing in annual net additions and living floor area per capita, but keeping the same 2018 demolition rate, share of sub-typologies and share of technologies were analysed (Table 3).

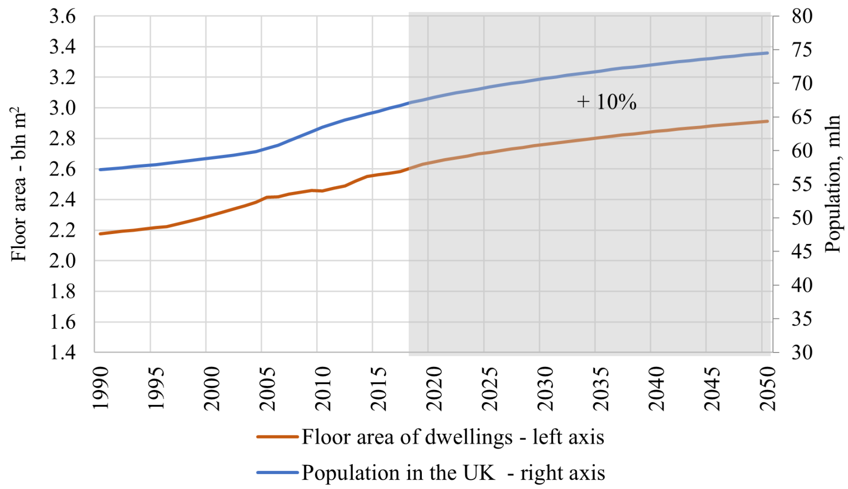


Figure 7: Domestic building stock prediction by floor area. Domestic building stock pre-2018 according to [17, 18], pre-2018 and post-2018 population prediction according to [18]

These options included the same living floor area per capita found for 2018, an increase of 2 m^2 reaching the EU average, an increase to 45 m^2, similar to residential floor area in Germany [32] and approaching the average residential floor are for the Nordic countries - 48 m^2 [39].

The analysis in this step also includes decarbonisation rates for key materials used in construction. They are based on literature sources and summarised in Table 5. This reduction excludes Carbon Capture and Storage (CCS) technologies and the use of hydrogen, as these technologies are not yet developed at scale. The decarbonisation rate also excludes interventions that are not dependent on the material manufacturer, such as material efficiency.

For the **Step 2**, Option II was considered as a Baseline Scenario (living floor area similar to residential floor area in Germany [32]).

Table 3: Change in net additions and floor area per capita - Step 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 thousands new homes a year (net additions) by the mid-2020s. in England [28] - 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. The impact of the in the demolition rate, share of sub-typologies, share of technologies and change in the number of conversions on upfront embodied carbon by 2050

In this part, five different Scenarios were considered (Table 6). As a Baseline, Option II from **Step 1** was adopted (see Table 3).

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	[40]
Steel	36%	∘ change to bioenergy ∘ electrification ∘ change the technology performance, ∘ shift to other fuel shift	[41]
Aluminium	76%	∘ zero carbon electricity ∘ increase energy efficiency ∘ 100% scrap collection ∘ direct emissions reduction	[42]
Timber	47%	∘ grid decarbonisation	[43]
Plasterboard	16%	∘ grid decarbonisation	[43]
PVC (plastic)	31%	∘ new processes (ready to use only)	[44]

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

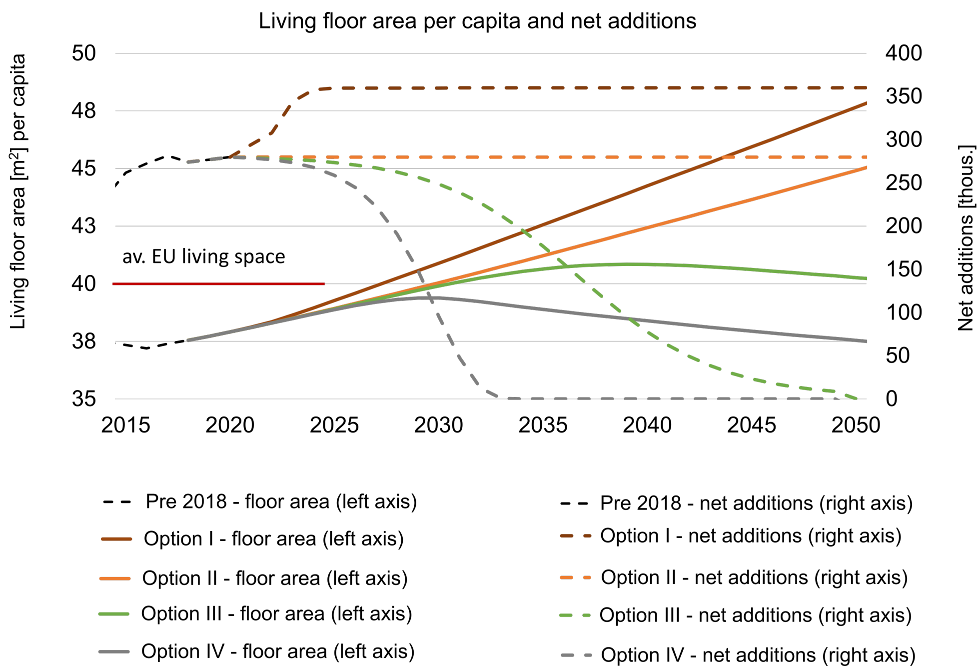
Scenario	Variables	Notes
Higher	∘ current demolition rate ∘ demolition of all vacant properties by 2050 ∘ current practice	current demolition (12 thousand / year, 1.1 million m^2/year) demolition of all 753.3 thousand properties with floor area of 69.3 million m^2 by 2050
Baseline	∘ current demolition rate ∘ current practice	equivalent to the Option II from a Table 3 demolition of 12 thousand (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 thousand (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 [45]). This makes approximately 2.7 million m^2/y by 2050, 70% increase compared to 2018.

4. Results

4.1. Change in net additions and floor area per capita

Figure 8 (top) presents change in the living floor area per capita in the UK and number of net additions for analysed four options. Bottom part of Figure 8, the annual upfront embodied carbon cost to deliver these, with and without decarbinisation 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).



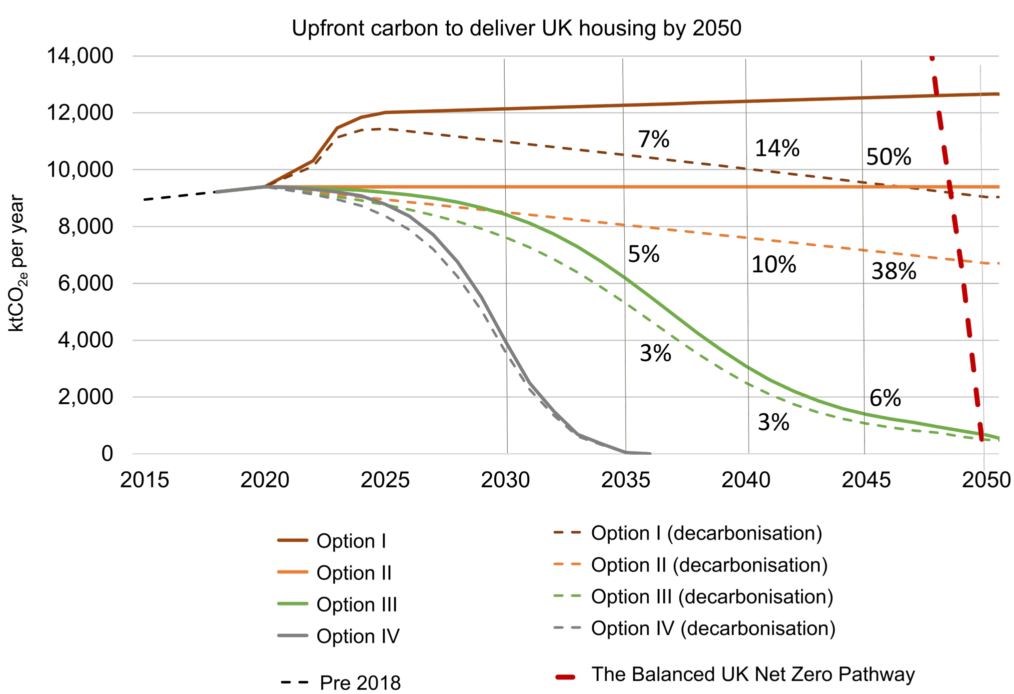


Figure 8: Options to deliver domestic properties by 2050. Top - living floor area in the UK and number of net additions for each option, bottom - upfront carbon for analysed options. Living floor area in the UK excludes vacant a properties and second homes.

Maintaining the current demolition rate, if we reduce net additions to zero by 2050 (Option III, green lines), we still get a greater living floor area per capita compared to 2018. In this case it increases by 2 m^2, reaching 40.5 m^2, close to the current EU average. Taking into account material carbon reduction, this option will be responsible for 6% share of The Balanced UK Net Zero Pathway in 2045 (green lines on Figure 8) with cumulative upfront embodied carbon by 2050 of 160 $MtCO_{2e}$. If we keep the same floor area per capita in 2050 as in 2018 (37.5 m^2), maintaining current rates of demolition, new additions must decline to zero by 2035, with carbon emissions following accordingly (Option IV, grey lines). Cumulative upfront embodied carbon by 2050, including material carbon reduction, drops by almost a half, to 88.4 $MtCO_{2e}$. Keeping constant 2018 net additions by 2050 with current demolition rates (Option II, orange line), we can expect an increase in living floor area per capita to 45 m^2, today's average residential floor area in Germany [32]. Given the reduction in material carbon footprint it will have 38% share of The Balanced UK Net Zero Pathway (orange lines on Figure 8) with cumulative upfront embodied carbon by 2050 of 250 $MtCO_{2e}$. Following the UK Government plan to deliver 300 thousands homes a year by the mid-2020s in England (355 thousand in the UK) and keeping this level until 2050 (Option I, dark red line), we can expect an increase in living floor area by 10 m^2 in 2050 to 48 m^2, the current average residential floor are for Nordic countries [39]. In this scenario, in 2045 the emissions to deliver domestic buildings will reach 48% of the Balanced UK Net Zero Pathway (including material carbon reduction). The cumulative upfront embodied carbon by 2050 will double compared to Option III with the EU average living floor area per capita in 2050 (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, living floor area in 2050 could reach 42.1 and 39.1 m^2, respectively.

4.2. Constant net additions and floor area per capita

Further analysis presented on Figure 9 includes Option II as a Baseline scenario (see Table 6). The main assumption was to keep the same net additions and living floor area per capita by 2050, amounting to 45 m^2 (cumulative upfront embodied carbon by 2050 including material carbon reduction 250 $MtCO_{2e}$). For today's material carbon intensity it is possible to reach 25% upfront carbon reduction compared to 2018 (Figure 6, Low and Lower scenarios). For material carbon reduction we can reach almost 50% with 145 $MtCO_{2e}$ of cumulative upfront embodied carbon by 2050.

The main interventions to reach this reduction are either

- to occupy all vacant buildings by 2050 (Low scenario), or

- to change the share of typologies with increasing the share of low and high rise residential properties, and increase conversion from non-domestic buildings (Lower scenario)

For both of these scenarios, savings could reach even 63% if by 2050 all second homes are used for living purposes (approximately 115 $MtCO_{2e}$ of cumulative upfront embodied carbon by 2050).

The highest, 70%, savings with an additional 10% for material decarbonisation was found if, in addition to changing the share of typologies and increase conversion, we increase the use of timber and increase material efficiency. Use of timber frame resisting systems are also beneficial as they are commonly used alongside natural insulation systems such us hemp, cork and sheep's wool. Even with almost 80% upfront carbon reduction (50 $MtCO_{2e}$ of cumulative upfront embodied carbon by 2050), this scenario will still have between 15-20% 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 (allowed by Country Planning Order 2020, No. 3), we can expect an increase in upfront embodied carbon by 16%, reaching 56% share of The Balanced UK Net Zero Pathway by 2045 and with 300 $MtCO_{2e}$ of cumulative upfront embodied carbon by 2050 (solid red line).

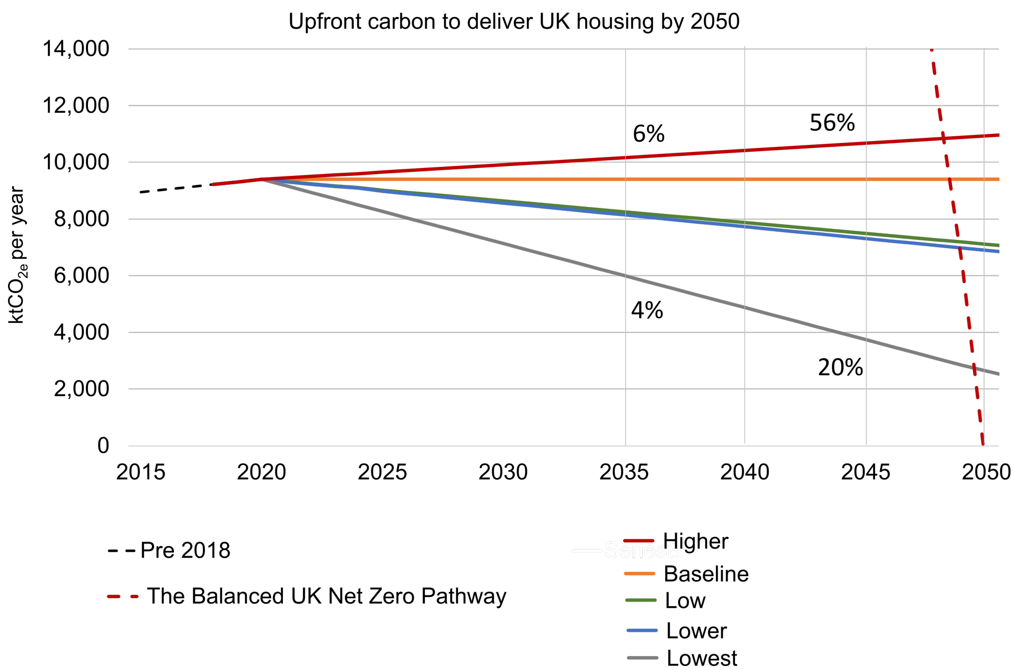


Figure 9: Interventions to minimise upfront carbon for analysed scenarios.

5. Discussion

In this study, we assessed the upfront embodied carbon to deliver a shell and core of domestic properties in the UK. The scope included foundation, roof, windows and doors, as well as finishing of walls and ceilings. 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 $MtCO_{2e}$) mainly due to increase of new additions. Assuming that the goal is to reach absolute zero in 2050, rather than net zero, from 2021 to 2050 we could "use" approximately 160 $MtCO_{2e}$ of remaining upfront embodied carbon budget from the supply of domestic buildings. Maintaining today's embodied carbon emissions from delivering domestic buildings, we will use this budget in 16 years, by 2036. However, using existing lower carbon technologies, we can significantly reduce upfront carbon cost to deliver future domestic needs.

It is not possible to achieve absolute zero if we do not reduce the number of new additions to the building stock. With a gradual reduction number of net additions from today, by 2050 we will sill increase living floor area per capita by 2 m^2, to the current EU level. This will increase a further 1 m^2 if vacant buildings are occupied. This analysis was made assuming current, low demolition rates. Due to prolonging the buildings life strategies in the UK - refurbishments, conservation of existing buildings, it seems to be unlikely that the demolition of domestic buildings will increase dramatically. A threat to this could be the General Permitted Development approved in August 2020 (England) (Amendment) (No. 3) Order 2020. The Order allows the demolition of vacant residential blocks and replacing these with well-designed new residential units. The Order also guide that the 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 stated in this study, if all vacant residential buildings are replaced, upfront carbon emissions can increase by 16% compared to 2018. If we combine this with the Government's goal to deliver 1 million net additions to the housing stock by the end of 2020s in England, we will spend the remaining upfront embodied carbon budget by 2030.

The Government 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"* [29]. 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. Raising the rate of supply will do little to bring prices down, and will instead result in a growing number of vacant properties [30]. 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 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 per m^2 for different properties by 10-15%. These aspects are at 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 various future scenarios for delivering domestic properties in the UK by 2050 were analysed. The paper suggests possible interventions to minimise upfront embodied carbon. As a result, 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 to increase.
- Maintaining today's emissions, the remaining 2050 carbon budget will be spend in 16 years, by 2036.
- The current net rate of new domestic properties far exceeds population growth, so the living flpor area per capita is increasing.
- Even if we reduce building to zero by 2050, we will still have more floor area per capita than we do now.
- The impact of occupying vacant properties is quite significant.
- 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.

7. Supplementary information

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

8. Acknowledgements

This work was supported by EPSRC programme grant 'UKFIRES' Ref. EP/S019111/1; A part of this study was supported by EPSRC grant 'TransFIRe' Ref. EP/V054627/1

References

[1] The Climate Change Act 2008 (2050 Target Amendment) Order 2019, No. 1056. Legal rule or regulation, The UK Government, 2019.

[2] Department for Business, Energy & Industrial Strategy, Prime Minister's Office, The Rt Hon Kwasi Kwarteng MP, The Rt Hon Alok Sharma MP, and The Rt Hon Boris Johnson MP. UK enshrines new target in law to slash emissions by 78% by 2035. https://bit.ly/3lhUn0r, 2021. Press Release.

[3] Final UK greenhouse gas emissions national statistics. Government document, BEIS, 2021.

[4] M.P. Drewniok, J.M.Cruz Azevedo, C.F. Dunant, J.M. Allwood, J.M. Cullen, T. Ibell, and W. Hawkins. Mapping material use and embodied carbon in UK construction. *Resources, Conservation and Recycling - submitted 29/06/2022, preprint available under the link: https://doi.org/10.31224/2441*.

[5] Net Zero Whole Life Carbon Roadmap. Technical report.

[6] BS EN 15643:2010 - Sustainability of construction works. Sustainability assessment of buildings. General framework, October 2010.

[7] Anderson J., Bagenal George C., Bowles L., Desai K., Drewniok M.P., Edwards M., J. Giesekam, Hamot M., Hopkins B., Smith M., Sturgis S., and Wyatt S. Improving consistency in whole life carbon assessment and reporting, carbon definitions for the built environment, buildings and infrastructure. Report, WLCN, LETI, RIBA, 2021.

[8] T. Ibn-Mohammed, R. Greenough, S. Taylor, L. Ozawa-Meida, and A. Acquaye. Operational vs. embodied emissions in buildings—a review of current trends. *Energy and Buildings*, 66:232 – 245, 2013.

[9] M.C. Moynihan and J.M. Allwood. Utilization of structural steel in buildings. *Proc. R. Soc. A*, 470(2168):20140170, August 2014.

[10] G. Hammond and C. Jones. Inventory of carbon & energy (ice) version 2.0. *University of Bath*, 19:20, 2011.

[11] F. Pomponi and A. Moncaster. Embodied carbon mitigation and reduction in the built environment – what does the evidence say? 181:687–700, 2016-10-01.

[12] A. Akbarnezhad and J. Xiao. Estimation and minimization of embodied carbon of buildings: A review. 7(1):5, 2017-03.

[13] F. Pomponi, A. Moncaster, and C. De Wolf. Furthering embodied carbon assessment in practice: Results of an industry-academia collaborative research project. *Energy and Buildings*, 167:177–186, 2018.

[14] J. Orr, M.P. Drewniok, I. Walker, T. Ibell, A. Copping, and S. Emmitt. Minimising energy in construction: Practitioners' views on material efficiency. *Resources, Conservation and Recycling*, 140:125 – 136, 2018.

[15] J. Giesekam, W. Arnold, T. den Dekker, J. Godefoy, and Sturgis S. Part Z - A proposed amendment to UK Building Regulations 2010.

[16] Net Zero Strategy: Build Back Greener, 2021.

[17] English housing survey, household data. [data collection]. uk data service. sn: 8669.

[18] UN. Probabilistic Population Projections Rev. 1 based on the World Population Prospects 2019 rev. 1. Report, United Nations, Department of Economic and Social Affairs, Population Division, 2019.

[19] The Sixth Carbon Budget, The UK's path to Net Zero. Report, Committee on Climate Change, 2020.

[20] J. Allwood, J. Azevedo, A. Clare, Ch. Cleaver, J.M. Cullen, C.F. Dunant, T. Fellin, W. Hawkins, I. Horrocks, P. Horton, et al. Absolute Zero: Delivering the UK's climate change commitment with incremental changes to today's technologies. 2019.

[21] A.C. Serrenho, M.P. Drewniok, C.F. Dunant, and J.M. Allwood. Testing the greenhouse gas emissions reduction potential of alternative strategies for the English housing stock. *Resources, Conservation and Recycling*, 144:267–275, 2019.

[22] S. Nicol, C. Beer, and C. Scott. *The Age and Construction of English Homes: A Guide to Ageing the English Housing Stock*. BRE, 2014.

[23] P. Van den Heede and N. De Belie. Environmental impact and life cycle assessment (LCA) of traditional and 'green'concretes: Literature review and theoretical calculations. *Cement and Concrete Composites*, 34(4):431–442, 2012.

[24] W. Shanks, C.F. Dunant, Michał P. Drewniok, R.C. Lupton, A. Serrenho, and Julian M. Allwood. How much cement can we do without? Lessons from cement material flows in the UK. *Resources, Conservation and Recycling*, 141:441 – 454, 2019.

[25] Annulal cementitious 2001 onwards. Mineral Product Associacion (MPA) Available from https://bit.ly/3ztc2Xi.

[26] A. Mullholland, C. Ackerman, P. Astle, M.P. Drewniok, A. Dunster, A. Hibbert, R. Inman, R. Kershaw, B. Martin, C. McCague, C. Price, and G. Thompson. Low carbon concrete routemap - setting the agenda for a path to net zero. Report, Institution of Civil Engineers, The Green Construction Board, The Low Carbon Concrete Group, 2022.

[27] G. Bramley. Housing supply requirements across Great Britain: for low-income households and homeless people. *NHF and Crisis, London*, 2018.

[28] W. Wilson, C. Barton, and L. Smith. Tackling the under-supply of housing in England. *Briefing paper*, 7671, 2018.

[29] Oral evidence: MHCLG Housing Prices, HC 830. Available from https://bit.ly/3AfKi9W.

[30] I. Mulheirn. Tackling the uk housing crisis: is supply the answer. *UK Collaborative Centre for Housing Evidence*, 2019.

[31] A.C. Serrenho, M.P. Drewniok, C.F. Dunant, and J.M. Allwood. Testing the greenhouse gas emissions reduction potential of alternative strategies for the english housing stock. 144:267–275, 2019-05-01.

[32] Yi Jiang, Da Yan, Shan Hu, Siyue Guo, Ying Cui, and Chen Peng. *China Building Energy Use 2016*. 12 2016.

[33] J. Gleeson. An analysis of housing floorspace per person - Housing Research Note 6. Report, GLA Housing and Land, 2019.

[34] M.P. Drewniok, J.M. Cruz Azevedo, C.F. Dunant, and W. Hawkins. Mapping material use and modelling the embodied carbon in UK construction [Dataset]. University of Leeds, DOI https://doi.org/10.5518/1176, 2022.

[35] C. F. Dunant, M.P. Drewniok, J.J. Orr, and J.M. Allwood. Good early stage design decisions can halve embodied co2 and lower structural frames' cost. *Structures*, 33:343–354, 2021.

[36] BS EN 15978:2011 - Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method, 30 November 2011.

[37] BS EN 15804:2012+A1:2013 - Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products, 30 November 2011.

[38] Inventory of Carbon & Energy - ICE, v3.0 beta - 9 August 2019. Circular Ecology Ltd, http://www.circularecology.com.

[39] P. Pajakkala. The living conditions in the Nordic countries are the world's top class - why building of new dwellings is still the most intensive in Europe. Available from https://bit.ly/3jGSQAA, 2018.

[40] Concrete future - The GGCA 2050 Cememt and Concrete Industry Roadmap for Net Zero Concrete. Available from https://bit.ly/2XvNLDi.

[41] Iron and steel sector direct co2 emission reductions in the Sustainable Development Scenario by mitigation strategy, 2019-2050. Available from https://bit.ly/3G3pPs7.

[42] Aluminium sector greenhouse gas pathways to 2050. Available from https://bit.ly/3n4ORyx.

[43] Wood in Construction in the UK: An Analysis of Carbon Abatement Potential. Extended Summary. Published as an annex to the Committee on Climate Change report" Biomass in a low-carbon economy". 2019.

[44] MaterialEconomics. Industrial transformation 2050: Pathways to net-zero emissions from EU Heavy Industry. 2019.

[45] Non-domestic rating: stock of properties including business floorspace. Available from https://bit.ly/3kzswcm, 2019.