Wood in Construction in the UK: An Analysis of Carbon Abatement Potential

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The BioComposites Centre have 30 years' experience in research and development for the timber and wood based panels industry. Specialising in industry-facing research, the Centre also provides consultancy, product development and technical support for companies in timber, natural fibre composites, bio-based materials and biopolymer sectors.

JCH Industrial Ecology Limited is an environmental consultancy specialising in analysing and quantifying the environmental impacts associated with materials production, use and disposal. Professor Callum Hill has been researching and publishing in the area of renewable and sustainable materials for nearly 25 years and has written two text books, six book chapters and over 200 research publications in this field. He is currently a visiting researcher at the Norwegian Institute for Bioeconomy Research and a Global Expert at the InnoRenew Centre of Excellence in Slovenia.

Dr Andrew Norton is Director of Renuables Ltd, an environmental consultancy specialising in Life Cycle Assessment based analysis. He has provided LCA and Carbon Footprinting advice to many major international companies and government bodies over the last 20 years and has also worked on the development of many bio-derived and composite materials as well as renewable energy systems. He was a Technical Secretariat to the EC DG Environment for the PEF pilot studies and remains a BSI technical committee member and represents CEI-Bois on the CEN/TC 350 standardisation committee.

Colin Price researches as Colin Price Free-lance Academic Services. He has worked on the economics of carbon fluxes since 1990, with many journal articles on the subject. His books include "Time, Discounting and Value", which examines valuation of future costs and benefits, environmental as well as financial ones. He has been awarded the Gold Medal for Scientific Achievement by the International Union of Forest Research Organizations.

Wood in Construction in the UK: An Analysis of Carbon Abatement Potential

The Committee on Climate Change (CCC) appointed a team led by the BioComposites Centre at Bangor University to undertake a research project into the greenhouse gas (GHG) abatement potential of increasing the use of timber in construction in the UK. The main objective was to develop a detailed understanding of the emissions savings that could be achieved at an individual unit level and an economy wide level through greater use of timber framed techniques as well as newer engineered wood products. The methodology, analysis and findings of the project are presented here.

This analysis has informed the CCC's 2018 report, *Biomass in a low-carbon economy* which provides an up-to-date assessment of the role of biomass and bioenergy in decarbonising the UK's economy and meeting carbon budgets.

Findings

Main findings

For the building types studied, timber systems have potential to contribute to GHG abatement by reducing embodied carbon and by storing sequestered carbon.

At the individual building level, the reduction in embodied emissions for **substituting timber frame for masonry is approx. 20%**. A greater reduction (~60%) is seen for CLT and concrete structures.

The level of carbon stored at a building-scale is approx. 50% higher for timber frame than masonry, or significantly higher for CLT (approx. 400% the concrete structure).

Scenarios with high growth in timber construction up to 2050 showed total embodied emissions are 0.8-1.0 Mt CO_2e p.a. lower and sequestered carbon is 1.0-1.3 Mt CO_2e p.a. higher compared with the no growth counterfactual. Because of low levels of demolition activity, the total stock of carbon stored within buildings grows under all scenarios, with net annual additions under the highest growth in wood in construction scenario ~75% higher than under no growth.

These carbon savings can be made at negligible abatement cost, due to approximate cost parity with counterfactual construction systems.

The embodied carbon of typical UK residential buildings was compared for different construction systems. A timber framed house had a lower embodied carbon (reduced by 1.7-3.2 t carbon dioxide equivalents (CO_2e)) compared with a functionally-equivalent masonry house. In addition, the timber framed houses also stored 2.0-4.2 t CO_2e more sequestered carbon in the structural elements than a masonry house.

In comparing concrete framed and cross laminated timber (CLT) apartment blocks a greater differential was seen, with a 12.8 to 18.0 t CO_2e reduction per flat in embodied carbon of the structure, and an increase of 12.4 to 17.3 t CO_2e stored sequestered carbon.

Looking at construction scenarios in the residential sector to 2050, **moderate and high levels of timber usage deliver more GHG abatement than scenarios with low levels of timber usage**.

For high building rate and high timber usage scenarios, we estimate that high timber usage (270,000 new homes each year using timber frame and CLT systems) would result in (net) storage of sequestered carbon of around 3 Mt CO_2e p.a. in 2050. This is 1.3 Mt CO_2e p.a. higher than scenarios with no growth in timber use.

For embodied carbon, a moderate growth in timber usage (135,000 timber homes p.a.) leads to a 0.20 to 0.38 Mt CO_2e saving p.a. by 2050. The high growth scenarios lead to a reduction of 0.48 to 1.00 Mt CO_2e p.a. The lower end of these ranges assumes ambitious decarbonisation in the cement and masonry sectors.

Within the non-residential sector, potential for increased use of wood in construction is significant as uptake of timber systems in large buildings is currently very low. A high-level projection to 2050 indicates that significant reductions in embodied emissions compared to comparable concrete and steel systems is possible, from 0.3 to 1.5 Mt CO_2e p.a. by 2050 under different scenarios. This would be accompanied by 0.5 to 2.3 Mt CO_2e stored sequestered carbon, under low and high timber growth.

Analysis of the origin of timber and construction materials indicated that **between 86 and 92% of the GHG abatement achieved by increasing timber usage could be attributed to UK carbon accounts**.

Quantification of embodied carbon at a building level offers a useful tool to compare structures and designs, and optimise use of materials. Recording the sequestered carbon stored in a building would recognise of the size of the building products pool of sequestered carbon, and its potential to deliver a carbon storage effect.

Context

The use of timber in construction is growing in the UK. According to the Structural Timber Association (STA) timber frame systems represented over a quarter of all UK housing starts in 2016, increasing by almost 9% over the previous year, compared with 3.6% growth in non-timber frame systems.[1] In addition, engineered wood products, such as Cross Laminated Timber (CLT) and glulam, are now facilitating a new generation of larger timber buildings in the UK and many countries around the world, including industrial and commercial buildings.

Much of the wood used in construction is sawn timber produced in sawmills using high quality logs from coniferous forests. Market forces will generally direct this timber to the highest value uses and it would not normally be expected for this resource to be used for energy. Other wood products used in construction, notably wood based panels, are generally made from lower quality small roundwood[2] and from sawmill offcuts and shavings – materials which can potentially be used for bioenergy in different contexts. Neither the sawn softwood, nor the wood-based panels, can be manufactured from forestry residues, i.e. branches, stumps, etc. According to the Forestry Commission, about a third of the sawn timber and half of the wood-based panels consumed in the UK in 2015 were supplied from UK forests.[3]

There is a recognised need to reduce carbon emissions within construction to contribute to national GHG abatement targets. This has been evident in the drive to improve energy efficiency of new buildings, retrofit of existing buildings and more general efficiency gains in delivery of construction projects, such as reduction of waste. The target of the *Construction Sector Deal* is a 50% reduction of carbon emissions by 2025,[4] which will require sustained effort to reduce both operational and embodied carbon.

The GHG abatement benefits from using timber in construction are delivered by two separate effects. The first is the *substitution* of high embodied carbon products such as steel and concrete. This requires the life-cycle emissions of timber construction systems to be lower than those of masonry or steel-based systems on a functional equivalence (like-for-like) basis.[5] The second effect is the *sequestration* and long-term storage of 'biogenic' carbon in the timber products themselves. For this to represent genuine abatement the timber used must be sourced from sustainably managed forests with stable or growing carbon stocks.

In 2011 the CCC concluded that it is more beneficial to use sustainably-sourced wood biomass for long-lived construction applications (where this is possible) than for bioenergy.[6] This finding was informed by analysis undertaken by Pöyry that compared the GHG impact of timber and non-timber construction products, considering both substitution and sequestration effects.[7] The new research presented in this report aims to update this previous analysis to reflect the latest evidence, to address methodological limitations and to take a more in-depth look at the potential GHG abatement impacts of increasing the use of timber construction in the UK.

Scope

The analysis presented here is focussed primarily on a detailed assessment of the residential sector. However it is estimated that only ~10% of the UK's annual sawn timber and wood-based panel consumption can be attributed to new housing, with a further ~10% to new non-residential structures and

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[1] STA (2017) *Annual survey of UK structural timber markets. Market report 2016*

[2] Small roundwood is a class of logs with top diameter between 7cm to 14cm, which are generated during forest thinning and harvesting operations

[3] Forestry Commission Scotland (2016) *Sustainable construction timber: Sourcing and specifying local timber*

[4] HM Government (2018) https://www.gov.uk/government/publications/construction-sector-deal

[5] Comparisons are made based on construction system (including all necessary material elements), not between individual elements of a single material.

[6] CCC (2011) *Bioenergy Review*

[7] Pöyry (2011) *Alternative uses of biomass in decarbonising industry*

~40% to work on existing buildings.[8] Thus this study also considers new build in the non-residential sector, albeit at a higher level of analysis. The analysis covers 'structural' timber elements such as panels, joists, cassettes and trusses used in wall, floor and roof elements, as well as timber cladding, and excludes 'decorative' elements such as joinery, fitted furniture, and windows or doors. All timber within this study was assumed to be from sustainably managed forests, traded legally in the UK.

According to the UK Green Building Council 'embodied' GHG emissions (those caused by the extraction, manufacture, transportation, assembly, maintenance, demolition and disposal of the products and elements in an asset) can account for over half of the overall carbon footprint of a building across its lifetime.[9] [10] The operational phase of buildings is also a major contributor, principally from water and energy use during the building's lifetime. Carbon emissions directly relating to construction and demolition phases account for only a small portion of overall lifecycle emissions – a few percent at most.[10]

For this study, the main analytical focus (and quantitative output) is embodied and sequestered carbon associated with the 'capital' phase of new buildings.[11] However the methodological approach used[12] also allows the assumption to be made that emissions associated with operational carbon will be equivalent in the pairs of archetypes, i.e. equal energy efficiency in service.[13] It was also assumed that maintenance and demolition inputs would be broadly equivalent.[14] The intention is that our estimates of the GHG emissions savings associated with using timber in construction clearly indicate trends in embodied carbon, and broadly indicate overall lifecycle savings for buildings of matching functional unit. It is acknowledged that in the context of an individual building, site and design factors will mean that savings may deviate from the numbers presented here; however, the materials substitution effects will remain similar.

Methodology

The detailed analysis of abatement from timber use in the *residential* sector comprised two parts:

<u>Individual dwellings – unit level</u>

The embodied emissions and sequestered carbon associated with timber-based construction systems and 'traditional' construction systems were compared for eight different housing archetypes. This involved developing high-level designs and material quantity estimates based on common floor plans and equivalent levels of thermal performance.[15] Thus the comparison between timber and traditional systems is on a functional equivalence basis with operational emissions during the lifetime of each archetype assumed to

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[8] Robson et al. (2014) Carbon sequestered in UK forest products and wood based panels in construction. *International Wood Products Journal* 5:139-145.

[9] 'Embodied carbon' is also sometimes referred to as Global Warming Potential (GWP), which assesses all of the greenhouse gases, referred to as CO_2e or carbon dioxide equivalents.

[10] UKGBC (2017) *Embodied carbon: developing a client brief*

[11] This was considered from "cradle to factory gate", i.e. under A1 to A3 of an EN 15978 assessment of a building.

[12] The functional unit was single matched dwellings (in timber framed or masonry structures) with identical floor plan, and matching wall, roof and glazed areas. The same principle was applied to CLT and concrete framed structures.

[13] Variations in occupational carbon emissions between different studies are acknowledged, however in a study by the NHBC (2011, NF34, *Operational and embodied carbon in new build housing: a reappraisal*) variation in occupational carbon per square metre were -0.01 to +0.05 tCO_2e for a Code Level 4 home (25% saving on 2006 building regulations). In the light of continued changes in fabric performance of both timber framed and masonry systems, and a wide range of occupant behaviour effects in predicting operational emissions, the assumption of equivalence allowed the focus of the study to remain on the capital carbon.

[14] i.e. that the energy and materials required for maintaining the building envelope will be similar (e.g. repointing a brick facing on a timber framed building will use as much mortar as repointing the brick on a masonry house, and be required at similar intervals), and energy inputs during demolition and reclamation of materials will be approximately equivalent. Sequestered carbon at demolition was handled in a separate analysis.

[15] Thermal performance requirements for buildings are set out in Part L of the Building Regulations for England and Wales (equivalent information for Scotland is provided in Technical Handbooks, and in Technical Booklets for Northern Ireland). One measure is the U-value for the wall, roof and other elements. Within the study the archetypes were designed to match performance at the current U-values within England. Glazed area of walls was identical in timber framed and masonry structures, providing matching G-values.

be equal across construction systems. Both the timber framed and the masonry structures were assumed to have an equal probability of delivering a service life of 100 years, based on an industry standard design life of 60 years [16].

Table E1: Description of housing archetypes

Archetype	Size	Internal area (m^2)	Traditional construction system	Timber-based construction system
Detached house	4-bedroom	117.0	Masonry	Timber frame
End terrace	3-bedroom	84.4	Masonry	Timber frame
Mid terrace	3-bedroom	84.4	Masonry	Timber frame
Bungalow	2-bedroom	58.5	Masonry	Timber frame
Low-rise flat (3 storey block)	2-bedroom	70.1	Masonry	Timber frame
Low-rise flat (3 storey block)	1-bedroom	50.0	Masonry	Timber frame
Mid-rise flat (6 storey block)	2-bedroom	70.1	Concrete frame	CLT
Mid-rise flat (6 storey block)	1-bedroom	50.0	Concrete frame	CLT

Figure E1: Floor plan used to develop the 4-bedroom detached house archetype

For each archetype, embodied emissions were calculated for the extraction and production stage of the lifecycle, covering modules A1-A3 as set out in European Standard BS EN 15804[17] (i.e. cradle to factory gate). Embodied emissions are reported in tonnes of CO_2 equivalent (t CO_2e). Where possible, data on the current emissions intensities of different building materials were taken from the relevant Environmental Product Declaration (EPD), or from other representative data sources where this was not possible. The

[16] The project team recognise that different construction systems assign 'design lives' when calculating loadings within structural elements. However, these have little influence on the true service life achieved by a building in practice, which is defined by long and medium term changes in urban planning (e.g. creating new roads), risk factors (e.g. fire, flood) and occupant change of circumstance (extension, remodelling). Demolition rate of all construction types was considered in a separate stage of the analysis.

[17] BS EN 15804:2012+A1:2013 Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products

sequestered carbon data has been separated out from the embodied carbon data for all wood products, and is used in a separate analysis.[18]

To examine how these embodied emissions might reduce over time, different decarbonisation scenarios were explored in the economy-wide analysis (below). Two adjusted emissions intensities datasets were prepared based on percentage reduction of the current EPD reported values. The first scenario assumes that grid electricity is fully decarbonised and attainable energy efficiency measures have been applied in all sectors by 2050 ('Decarb. Grid (2050)' in Table E2). The second scenario applied stronger reduction factors, based on stated sector ambitions.[19] Here several sectors utilise CCS or CCU[20] schemes in order to address CO_2 emissions (such as CO_2 arising from fossil fuel use and chemical reactions during manufacture), or more ambitious refit of infrastructure to switch fuel or electrify (e.g. the brick sector). These are ambitious rates of decarbonisation, and are reliant on investment in CCS infrastructure at a national level ('Ambitious decarb. (2050)', Table E2).

Table E2: Emissions intensities and data sources used for different construction materials (* decarbonised values derived by expert judgement including reference to published sector strategy documents)

Material	Data source	Emissions intensities (kg CO_2e/kg) Current	Decarb. Grid (2050)*	Ambitious decarb. (2050)*	Sequestered CO_2 [21]
Sawn wood	Wood for Good EPD	0.189	0.100	0.100	-1.598
CLT	Stora Enso EPD	0.318	0.239	0.191	-1.555
Wood-based panels	OSB Kronoply Gmbh EPD	0.128	0.073	0.064	-1.593
Plasterboard	Gyproc Wallboard EPD	0.251	0.211	0.201	-0.072
Fibre insulation	Knauf glass wool EPD	1.162	0.997	0.465	0
PUR insulation	PUR average (Hill et al 2018[22])	2.900	2.728	0.870	0
Brick	BRE UK brick EPD	0.158	0.142	0.071	0
AAC block	BRE AAC EPD, IBU EPD	0.280	0.256	0.112	0
Cement mortar	CAPEM GB	0.204	0.187	0.122	0
Reinforced concrete	Average UK, BRE and MPA	0.295	0.232	0.177	0
Fibre cement cladding	Rockwool Rockpanel EPD	1.752	1.507	0.876	0

Economy wide level

An Excel-based model was developed to explore the abatement impact of different scenarios for timber based construction in the UK to 2050. The results of this model are not disaggregated to identify the impact on the UK GHG accounts versus other countries;[23] rather they represent total direct impacts on the global

[18] This approach is in line with the proposed amendments to Product Environmental Footprint (PEF) and EN15804, spring 2019.

[19] DECC-BEIS (2015) https://www.gov.uk/government/publications/industrial-decarbonisation-and-energy-efficiency-roadmaps-to-2050

[20] CCS (Carbon Capture and Storage) refers to schemes where CO_2 generated by industrial processes is captured and stored under pressure, often within geological systems. CCU (Carbon Capture and Use) refers to industrial CO_2 captured from one process and re-used in a different process, avoiding the emission of that CO_2 to the atmosphere.

[21] Carbon sequestered during growth of biomass is retained in the product throughout the service life. Recarbonation of concrete was not included in this study as the concrete materials (foundations, interior structural frame) had limited exposure to the relative humidity necessary for it to occur during service life.

[22] Hill C., Norton A. and Dibdiakova J. (2018) A comparison of the environmental impacts of different categories of insulation materials. *Energy and Buildings* 162:12-20.

[23] Construction uses materials which have already been manufactured, and their CO_2 emissions accounted at the manufacturing stage

climate regardless of where emissions (or abatement) actually occurs.[24] A high-level calculation to do this was carried out separately and is presented later.

The model is focused on new build (rather than existing housing stock) and has a high-level representation of the type of new units built in the UK each year: detached, semi-detached & end-terraced, mid-terraced, bungalows and flats. The amount of new build and the proportion of each type of unit built to 2050 can be varied according to the scenario. Overall abatement is calculated by drawing on the unit level analysis discussed above.

The model base year is 2018. Current house-building activity was assumed to be 190,000 new starts p.a.[25] and the split between different unit types was based on data from the NHBC.[26] For the current split between different construction systems, data from the Structural Timber Association (STA) were used, indicating 28% of all UK housing starts were timber frame in 2016.[27] There are no reliable data currently available on the amount of new starts built using engineered wood systems, so a very small proportion was assumed (0.3% of flats) drawing on the judgement of the Bangor project team.[28]

Table E3: Unit types and percentages of new build assumed for the model base year (2018)

Unit type in model	Percentage of base year new build	Percentage of houses with timber frame in this unit type
Detached	27%	7.6%
Semi-detached and end-terraced	23%	6.4%
Mid-terraced	17%	4.8%
Bungalows	2%	0.6%
Flats	31%	8.7%
Total (as % of all new build)	**100%**	**28%**

To develop overall timber construction scenarios to 2050, different rates of house-building activity and different levels of timber frame and engineered wood activity were explored. These scenarios are not intended to represent predictions of future activity, but rather to provide a range of possible futures against which to evaluate GHG abatement potentials.

Rates of house-building activity – A '*low*' house-building activity scenario is based on an annual increase of 1% p.a. (resulting in around 261,200 new units p.a. by 2050); and a '*high*' activity scenario achieves 4% p.a. growth to 2025 and 1% p.a. thereafter, resulting in the Government's ambition of 300,000 new units p.a. by 2044.[29] Within each of these building rates, the percentage share of detached, semi-detached, mid-terraced houses, bungalows and flats was constant for all years studied.

Levels of timber construction activity – A number of scenarios were explored here, including:[30]

- *No growth* – where the number of timber framed and CLT units built each year to 2050 remains the same as the 2018 reference year. This was 53,200 timber framed dwellings, and 177 CLT flats.

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24 Indirect market-mediated impacts are not considered.

25 Based on an average of 2016-17 levels. There were 195,960 new housing starts in the UK in 2017, and 186,850 in 2016 (National Statistics Live Table 211). The net increase in total housing stock in 2015/16 was 190,000 (this includes conversions and change of use)

26 NHBC (2017) *NHBC New Home Statistics Review 2016*

27 It is known that there is a difference between reported % timber frame from the STA and NHBC figures, relating to differences in sample population and reporting stage. The STA units recorded by members are compared with national housing starts data, while NHBC registered builders report building type, but cover only approx. 80% of house building activity. Many of the housing starts not included in the NHBC figure are self-build, which is known to use a high proportion of timber frame and SIPs systems.

28 The assumption of CLT units as 0.3% of flats (i.e. ~0.093% of total housing starts) is a conservative estimate, representing typical activity early in this decade. The figure in 2018 is likely to be higher than this.

29 When the number of housing conversions and change of use is considered, this scenario would lead to 300,000 homes per year considerably sooner, in approx. 2028.

30 All scenarios assume that no high-rise blocks of flats (over 10 stories) are built using timber construction systems.

- *Business as Usual (BAU) growth* – where timber frame and engineered wood systems make up the same proportion of new build[31] as they do today (meaning an increase in the actual number of units).
- *Moderate growth* – where timber frame systems contribute 35% of new build by 2025 and 40% by 2050, with engineered wood systems remaining a minor contributor, reaching 5% by 2050.
- *High growth* – where timber construction increases to a very high level, with timber frame reaching 40% of new build by 2025 and 80% by 2050 and engineered wood systems increase at 10% p.a. to 2027 then 20% p.a. from 2027.

The moderate growth scenario reflects growth under conditions where policy preference for an increase in wood in construction and reduction in embodied emissions is an aspiration and driven by supporting a shift at an industry level. The high growth scenario is intended to reflect a stronger set of policy drivers, leading to a relatively rapid ramp up in market share of both timber framed and CLT construction, including some pump-priming or business support to establish a UK-based CLT supply chain alongside imports.

Table E4: Numbers of new timber units built by 2050 in the timber construction scenarios

House building activity	Timber construction activity	Timber frame units p.a. in 2050	Engineered wood units p.a. in 2050	Non timber system units p.a. in 2050
Low: ~261,200 new units p.a. by 2050	No growth	53,200	177	207,843
	BAU growth	73,142	243	187,835
	Moderate growth	106,290	4,049	150,881
	High growth	180,634	38,060	42,527
High: ~ 320,600 new units p.a. by 2050	No growth	53,200	177	267,247
	BAU growth	89,775	298	230,551
	Moderate growth	130,462	4,970	185,192
	High growth	221,716	48,703	50,209

An increase in the use of timber cladding is treated separately from these timber construction scenarios, as timber cladding can be applied to the external walls of buildings regardless of the underlying construction system. Current use of timber cladding on new build is estimated to be between 37.5 and 60 thousand cubic metres p.a., however the majority of this is on non-residential buildings. In terms of new-build housing, there is large region-to-region variation,[32] but it is unlikely that timber cladding exceeds 5% of total wall area. We explore this increasing to 25% of new residential wall area by 2050 (below).

Non-residential sector timber growth – Analysis of abatement potential from timber construction in the *non-residential* sector was less detailed than analysis of the house-building activity described above. This sector comprises a wide variety of building types with greater use of steel and concrete framed structures. This diversity, along with less readily available datasets, means that estimating abatement potential to 2050 is both more challenging and speculative, and only a high-level assessment was possible within the scope of this study.

Our methodology used a case-study approach to estimate broad levels of timber usage per m^2 of floor space for engineered wood buildings in the following five sectors: office, retail, industrial, hospitality and health. Together these sectors represent around 70% of total energy use in the UK's non-domestic sector.[33] These per m^2 timber usage figures were used to derive abatement estimates based on current emissions intensities – we have not attempted to estimate abatement potential based on future emissions intensities.

[31] A value of 28% timber framed homes was used, based on STA statistics for 2016.

[32] One current trend in some regions is to use a decorative quantity of timber cladding to provide visual interest and character within housing developments, these typically may use up to 10% of wall area.

[33] BEIS (2016) *Building Energy Efficiency Survey*

Our estimates are based on existing examples and available literature, as well as the expert judgement of the Bangor project team. They should be treated as indicative figures only.

Using available high level data for buildings with timber, steel, concrete or other structures,[34] and an estimated split of timber structures between timber framed, CLT and glulam framed (40:10:50), it was possible to derive approximate current structural timber usage within this sector. To project forwards to 2050, the growth of each timber sector (timber framed, CLT, glulam) was estimated based on trends derived from recent publicity, journal articles and industry reports. Low growth, high growth and business as usual scenarios were considered. The highest growth was anticipated within CLT, and moderate growth within timber framed and glulam structures. As this calculation was derived on timber usage per m^2 floor area, it was not possible to perform a detailed substitution analysis (i.e. on the types and amounts of materials displaced by timber), however indicative values were derived using published figures for comparative emissions of steel, concrete hybrid and CLT buildings[35].

Domestic sector GHG savings

Unit level

Based on current emissions intensities, we estimate that timber frame construction systems have **embodied emissions that are 1.7-3.2 t CO_2e lower per unit than counterfactual masonry construction systems**. The upper end of this range represents the detached house archetype and lower end the bungalow archetype. In addition**, sequestered carbon in timber frame systems is 2.0-4.2 t CO_2e more per unit than masonry equivalents.**

If timber cladding is also included, the GHG abatement increases further[36]. For the detached house archetype replacing brick cladding with timber cladding gives an *additional* reduction of 5.6 t CO_2e in embodied emissions and an increase of 2.1 t CO_2e in sequestered carbon.[37]**.**

The results shown in Figures E2 and E3 provide a number of additional insights. First, timber frame systems still have significant levels of embodied carbon emissions, despite the savings they offer compared to masonry counterfactuals. This is primarily because timber frame systems still use concrete for building foundations[38] and in most cases brick as the exterior wall cladding. This underlies the importance of future reductions in the emissions intensities of these materials, regardless of future levels of timber construction. Second, masonry systems still use significant amounts of timber for floor and roof systems (i.e. joists and trussed rafters). This means that even these systems store a substantial amount of sequestered carbon. This reflects the long-standing historical use of timber as a construction material in the UK and implies that not all of the sequestered carbon associated with timber frame systems can be regarded as additional. Building level analysis of embodied carbon and sequestered carbon presents a useful tool for encouraging a shift towards lower carbon buildings.

[34] BCSA (2016) *Annual Review 2015-2016*. www.steelconstruction.org
[35] TRADA Exova (2017) *Cross-laminated timber: Design and performance*
[36] Note that cladding is included as an example, but excluded from the carbon flux calculations due to a difference between expected replacement interval of cladding (~30 years) and the building design life and service life. Repointing of masonry was also excluded.
[37] This is for the LCA stages A1-A3. Consideration of potential maintenance for brick (repointing of mortar) and maintenance of replacement of cladding have not been addressed.
[38] For some systems timber framed buildings can require smaller foundations than the masonry equivalent, as a result of the lighter weight of the superstructure, e.g. in the low-rise apartment block archetype.

Figure E2: Embodied emission estimates for the 4-bedroom detached house archetype (based on current emissions intensities) (structural elements only)

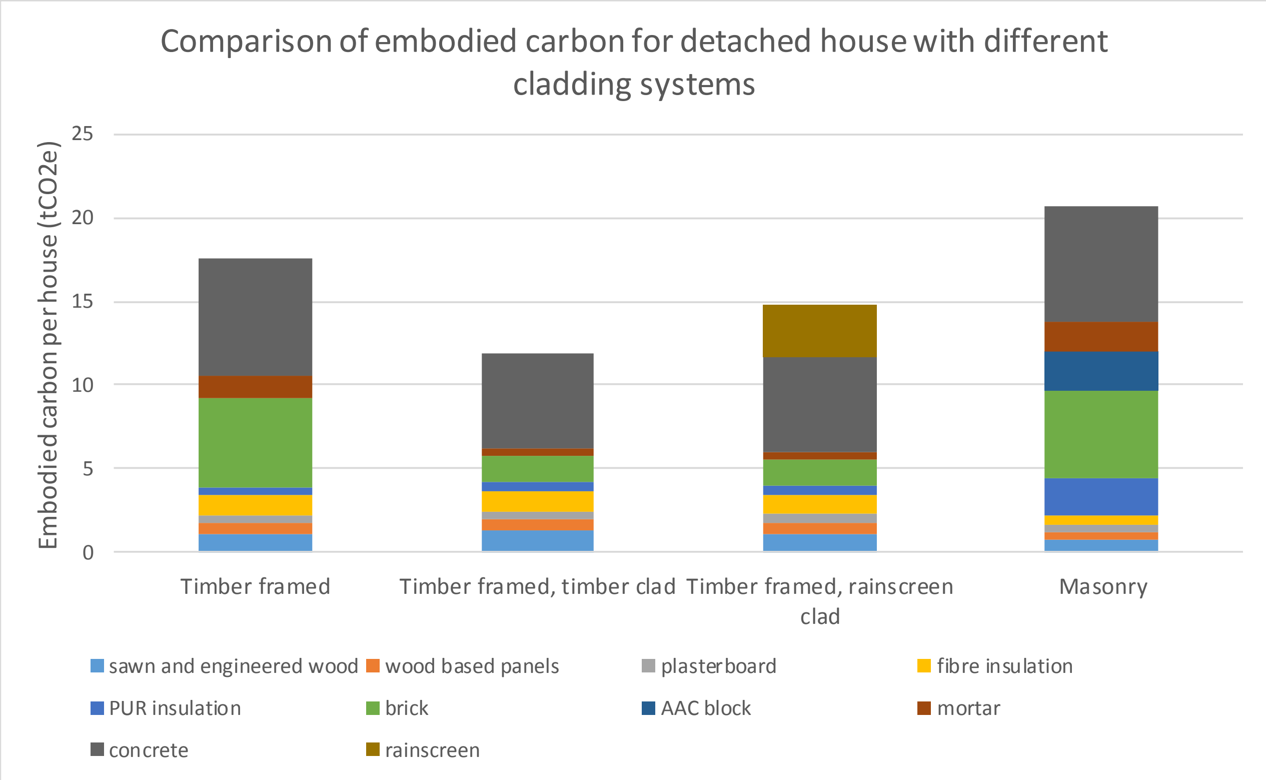


Figure E3: Sequestered carbon estimates for the 4-bedroom detached house archetype (structural elements only)

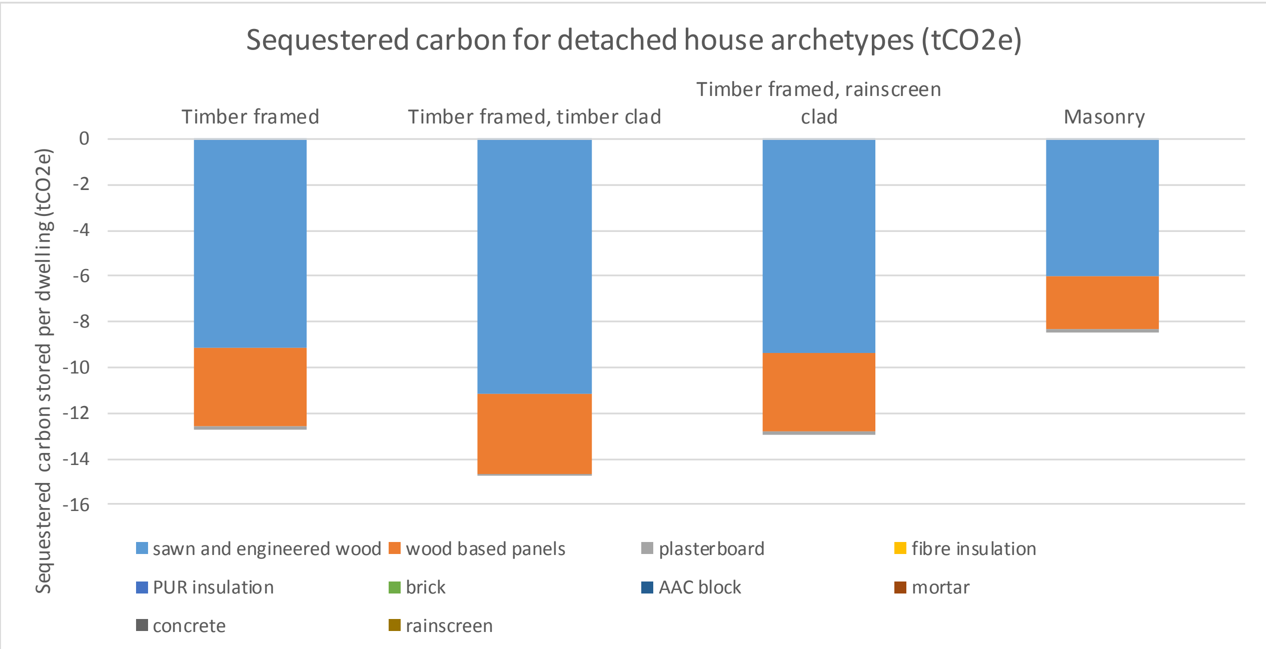
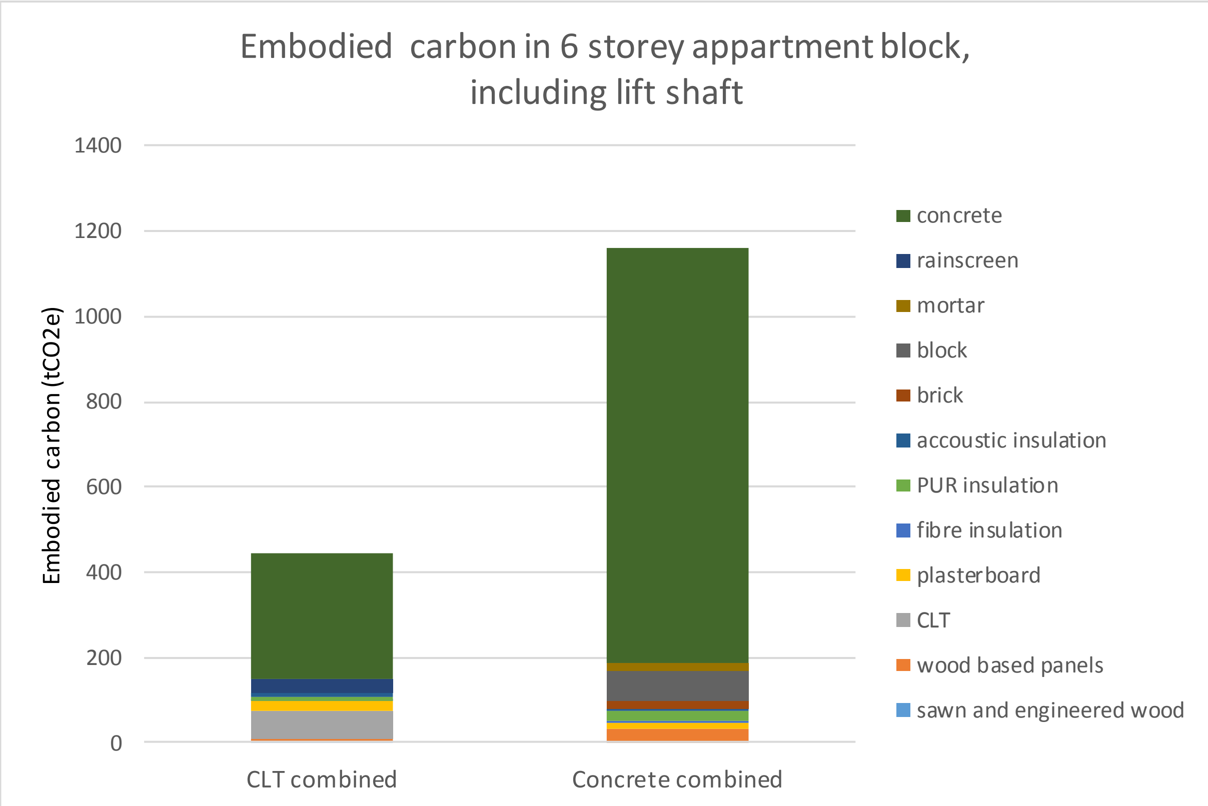


Figure E4: Embodied emissions for mid-rise apartment block archetype (6 storeys, 48 flats) (based on current emissions intensities) (structural elements only)



Abatement from engineered timber systems (CLT was assumed here) in mid-rise apartment blocks was calculated against a concrete framed counterfactual, again using current emissions intensities (Figure E4). Based on analysis at the apartment block level (subsequently apportioned to individual units) we estimate that **1 and 2 bed CLT flats have embodied emissions savings of 12.8 t CO_2e and 18.0 t CO_2e respectively, and additional storage of sequestered carbon of 12.4 t CO_2e and 17.3 t CO_2e**.

Thus, we calculate that total per unit abatement for engineered wood systems has the potential to be substantially higher than for timber frame systems (Table E5). The main reason for this is that CLT systems use more timber (increasing sequestered carbon) and displace more counterfactual materials (lowering embodied emissions) than timber framed systems. In addition, efficiency gains in concrete foundations (which are required in all construction systems) can be seen most prominently in the design of the low and medium rise flats (in timber-frame or CLT archetypes respectively), compared to masonry or concrete frame equivalents. This is due to weight reduction in the superstructure for the wood archetypes, reducing the required groundwork and concrete consumption. Industry case studies such as Dalston Lane, London,[39] demonstrate this weight saving in practice.[40]

[39] https://www.bkstructures.co.uk/case-studies/dalston-lane, https://www.theb1m.com/video/dalston-lane-the-worlds-largest-timber-building

[40] It is reported that an extra three storeys were possible at Dalston Lane due the weight saving offered by choice of CLT. The concrete option for the site would have had 106 flats, while the CLT structure delivered 121 flats.

Table E5: Summary of estimated per unit GHG abatement from timber construction systems (structural elements only), based on current emissions intensities

	Embodied emissions (tCO_2e)		Sequestered carbon (tCO_2e)	
Archetype	**Per unit**	**Difference vs counterfactual**	**Per unit**	**Difference vs counterfactual**
Detached house, masonry	20.72	--	-8.47	--
Detached house, timber frame	17.55	-3.17	-12.70	-4.23
Detached house, timber frame & clad	11.90	-8.82	-14.77	-6.30
Semi-detached, masonry	15.81	--	-5.64	--
Semi-detached, timber frame	12.83	-2.98	-8.88	-3.24
Mid-terraced, masonry	13.57	--	-5.65	--
Mid-terraced, Timber frame	11.60	-1.97	-8.72	-3.07
Bungalow, masonry	15.46	--	-4.13	--
Bungalow, timber frame	13.72	-1.74	-6.47	-2.34
1B Flat (low-rise), masonry	8.79	--	-2.86	--
1B Flat (low-rise), timber-framed	6.61	-2.18	-4.87	-2.01
2B Flat (low-rise), masonry	12.33	--	-4.01	--
2B Flat (low-rise), timber-framed	9.27	-3.06	-6.83	-2.82
1B Flat (medium rise), concrete frame	20.71	--	-3.04	--
1B Flat (medium rise), CLT	7.89	-12.82	-15.47	-12.43
2B Flat (medium rise), concrete frame	29.03	--	-4.36	--
2B Flat (medium rise), CLT	11.06	-17.97	-21.68	-17.32

Economy-wide

- The situation in 2018

For the model base year (2018) total embodied emissions for residential new build across the UK are estimated at 3.04 Mt CO_2e and sequestered carbon at 1.25 Mt CO_2e. This assumes 190,000 new units, of which 28% are timber frame and 0.3% of flats were CLT apartments in mid-rise blocks.[41] Within the model a portion of mid-rise apartments were reserved in concrete framed[42] construction to represent the high-rise sector.[43]

A comparison with a hypothetical alternative base year where no new units are built using timber construction systems reveals the level of abatement already being delivered by timber construction. In this hypothetical scenario, embodied emissions are estimated at 3.185 Mt CO_2e p.a. (0.145 Mt CO_2e p.a. higher than the actual model base year) and sequestered carbon is estimated at 1.080 Mt CO_2e p.a. (0.187 Mt CO_2e p.a. lower than the model base year). Thus, we estimate that the current level of timber construction in the UK **already contributes a reduction of embodied emissions of 145 kt CO_2e p.a., and 187 kt CO_2e p.a. storage of sequestered carbon.**

- Timber cladding in 2018

No timber cladding was used in the reference year BAU scenario (reference scenario), so to explore the impact of timber cladding we undertook an additional area-based analysis of timber cladding for 2018. This demonstrated some small additional potential for reducing embodied emissions.[44] The replacement interval of cladding products is typically shorter than the service life of the building, e.g. 25-30 years. For this reason, cladding was investigated as a case study, not within the model scenarios.

[41] No timber cladding was used in the base year; all timber framed, masonry and concrete framed structures used brick for exterior walls. A fibre-cement rainscreen cladding product was used for CLT structures, due to the nature of this building material. Timber cladding is considered within a separate analysis.

[42] A minimum of 4562 apartments in concrete; derived from analysis of multi-dwelling units by Siemens (2014).

[43] This sector currently utilises steel and concrete framed systems, and was excluded from this study.

[44] It should be noted that in practice a wide range of cladding products are used, especially within mid- and high-rise structures. The embodied carbon values of these alternatives were not the focus of this report.

For a scenario where 10% of the available exterior wall area of all residential new build used timber cladding, in place of brick facing, a reduction in embodied carbon was seen (35 kt CO_2e). This relates to the large weight of bricks replaced by a small weight of wood, and the relatively higher and lower GWP values for embodied carbon within each material.

Substitution of 25% of the building area resulted in a **2.9% reduction in total embodied carbon** for the building materials. While replacement interval will alter the embodied emissions reduction, the lower emissions per unit of timber cladding would still result in a reduction of total embodied carbon, even after four replacement events in a 120 year service life.

Economy-wide future scenarios

Looking to 2050, our estimates for the overall level of abatement delivered by timber construction vary according to the rate of housebuilding activity, the level of timber construction activity and changes in emissions intensities. All scenarios exclude timber cladding unless explicitly stated.[45]

- *If future emissions intensities remain the same as today*

The greatest abatement from timber construction is seen in scenarios where future emissions intensities are assumed to remain unchanged from today, because counterfactual materials such as cement and brick continue to be made via carbon intensive manufacturing processes.

Using this assumption, we estimate that scenarios with high growth in timber construction **total embodied emissions are 0.8-1.0 Mt CO_2e p.a. lower and sequestered carbon is 1.0-1.3 Mt CO_2e p.a. higher compared with the no growth counterfactual** (for low and high rates of building activity respectively). This represents an 18-19% reduction in embodied carbon, and a 59-64% increase in stored sequestered carbon.

Table E6: Summary of estimated overall annual GHG abatement by 2050 for different timber construction scenarios (structural elements only), based on low overall rates of building activity (261,000 p.a.) and current emissions intensities

Timber construction activity scenario (excludes timber cladding)	Embodied carbon (Mt CO_2e p.a. in 2050)		Sequestered carbon (Mt CO_2e entering the built environment pool[46] p.a. in 2050)	
	Total for all new build units	Difference vs no growth baseline	Total for all new build units	Difference vs no growth baseline
No growth	4.24	---	-1.66	---
BAU growth	4.18	-0.06	-1.72	-0.06
Moderate growth	3.95	-0.29	-1.88	-0.22
High growth	3.46	-0.78	-2.64	-0.98

Table E7: Summary of estimated overall annual GHG abatement by 2050 for different timber construction scenarios (structural elements only), based on high overall rates of building activity (321,000 p.a.) and current emissions intensities

Timber construction activity scenario (excludes timber cladding)	Embodied carbon (Mt CO_2e p.a. in 2050)		Sequestered carbon (Mt CO_2e entering the built environment pool p.a. in 2050)	
	Total for all new build units	Difference vs no growth baseline	Total for all new build units	Difference vs no growth baseline
No growth	5.23	---	-2.00	---
BAU growth	5.13	-0.10	-2.11	-0.11
Moderate growth	4.85	-0.38	-2.31	-0.31
High growth	4.23	-1.00	-3.27	-1.27

[45] Timber cladding was treated as a sensitivity analysis, due to the different maintenance interval, so was excluded from all primary scenarios of house-building activity.

[46] In a stocks and flows approach to carbon accounting the built environment can be defined as a pool of stored sequestered carbon within the biogenic materials, i.e. timber, wood-based panels etc.

Figure E5: Total annual <u>embodied emissions</u> from residential new build (structural elements) in the UK for a high rate of construction activity scenario, assuming <u>current</u> emissions intensities

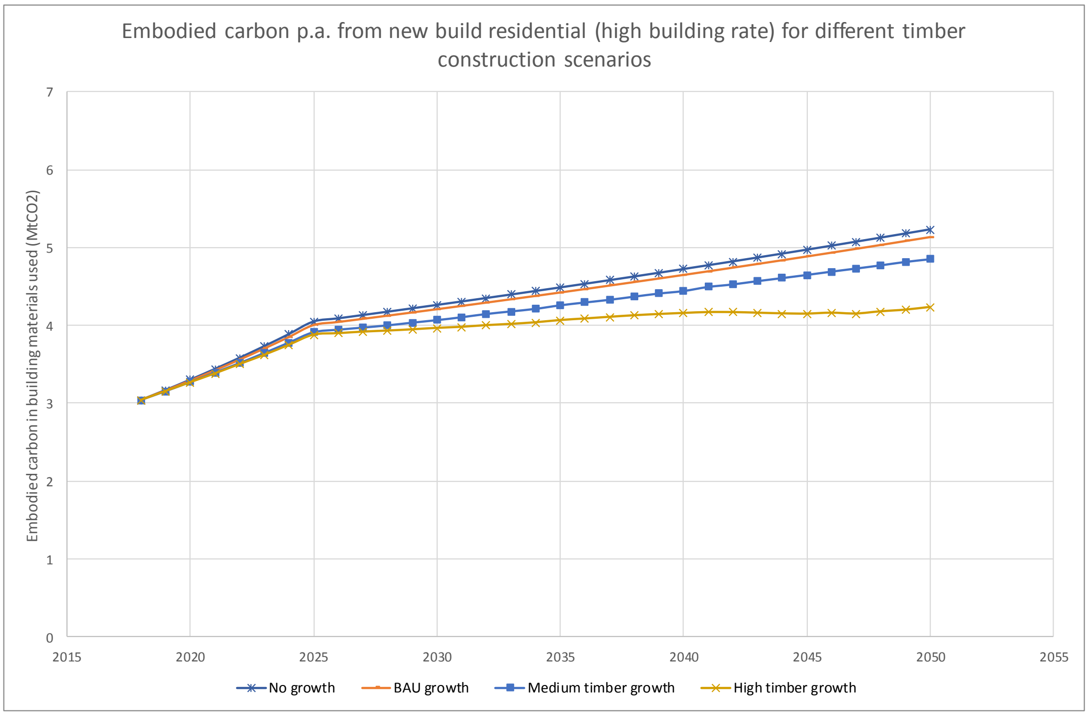
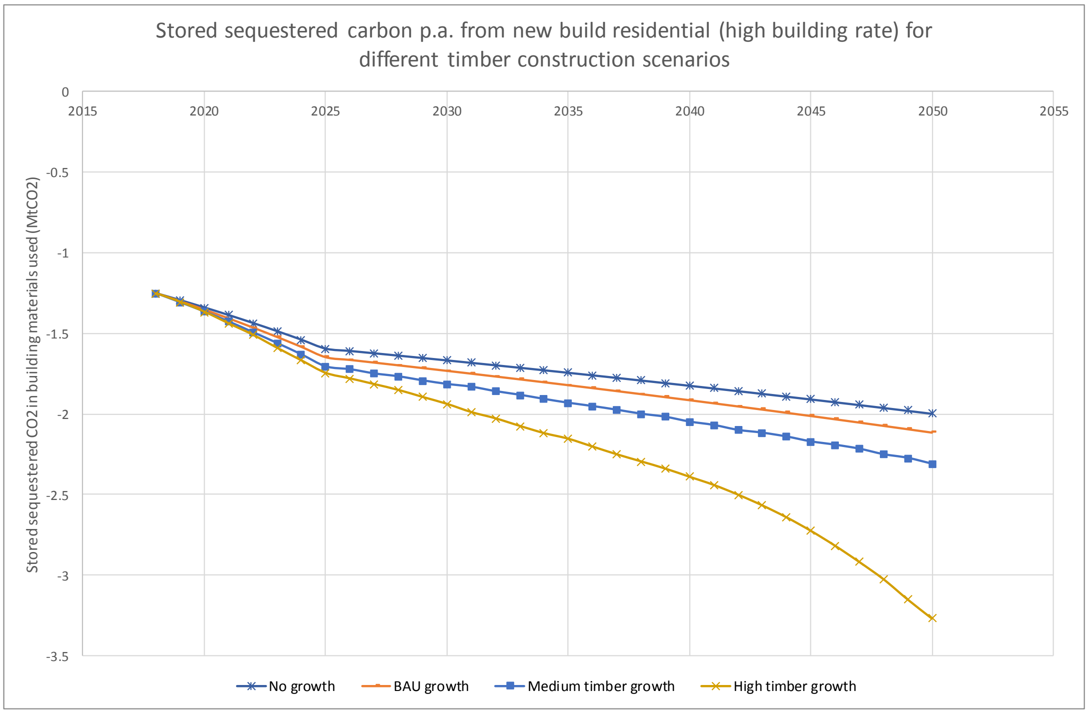


Figure E6: Total annual <u>sequestered carbon</u> in residential new build (structural elements) in the UK for a high rate of construction activity scenario



When calculating sequestered carbon at the economy-wide level it is necessary to take account of the fact that whilst additional carbon is entering the 'sequestered carbon pool' through timber in construction, it is also leaving this same pool when houses are demolished.

Further analysis was undertaken to consider the effect of demolition of houses in each year, to quantify carbon flux into the pool of stored carbon within building products. Timber within both masonry and timber framed structures was considered. Overall, we found that wood generated by demolition of houses remained smaller than the storage of sequestered carbon associated with no growth, BAU, and medium and high timber growth scenarios. This indicates that the pool of stored carbon is expanding and a carbon flux into the built environment can be accounted per year.

The demolition analysis indicated that 0.095 Mt CO_2e would be released due to oxidation[47] of the removed structural timber of the dwellings demolished in 2018, rising to an estimated 0.177 Mt CO_2e in 2050.[48] After adjusting for demolition timber, **the total sequestered carbon per annum in 2050 was -1.48 to -1.82 Mt CO_2e for the no growth scenarios** (under low and high building rates), and **-2.46 to -3.09 Mt CO_2e for the high timber growth scenarios** under low and high building rates respectively.

It should also be noted that this wood removed during demolition represents a potential biomass energy resource.[49] The available material per year arising was 0.06 Mt, rising to 0.11 Mt in 2050. This wood could also be cascaded through the forest products value chain.[50]

- <u>*If future emissions intensities reduce in line with ongoing decarbonisation efforts*</u>

The same scenarios were considered for the year 2050 using the two different decarbonisation scenarios described above. This investigated whether the contribution of timber construction to GHG abatement would occur at a lower level in scenarios where **future emissions intensities reduce** over time.

The first decarbonisation scenario explored was a **decarbonised electricity grid** with simple energy-efficiency-based reductions. This achieved a 19 to 21% reduction in embodied carbon for the different timber scenarios presented. Here the benefit of an additional shift towards timber-based construction systems remained clearly visible with a reduction of 0.91 Mt CO_2e for the high growth timber scenario.

The second decarbonisation scenario explored was the decarbonised electricity grid, energy efficiency measures, **with additional sector specific reductions** such as electrification (brick manufacture) and CCS or CCU (chemical industry and cement industry[51]). There was an estimate of the trickle-down effect of e.g. reduction in the chemical industry reducing GWP values for glues or additives within other products such as wood-based panels.

If this second 'deep-decarbonisation' scenario were achieved, with each sector achieving their maximum technology scenarios, many of which rely on extensive use of CCS and CCU technologies, then a significant reduction of embodied carbon is seen. This is an overall reduction of 48.6 to 57.3% compared to the 2018 emissions basis. In this scenario, the effect of high timber use still reduces embodied carbon by an additional 0.48 Mt CO_2e compared with the no growth scenario.

Thus overall, timber construction still delivers GHG abatement even when other sectors (e.g. cement and brick) achieve ambitious levels of decarbonisation. The quantity of stored sequestered carbon was not altered by either level of industry-based decarbonisation.

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[47] Demolition timber was assumed to be incinerated on removal without energy recovery, as a worst case scenario to ensure that net carbon flux values were not over-estimated.

[48] For simplicity of analysis, the worst-case scenario was considered at demolition, i.e. all waste wood was burnt after removal from the buildings, with zero recycling rate and with no energy recovery. In practice higher recycling rates would therefore reduce the effects demonstrated here (i.e. leaving a relatively larger net sequestered carbon for that year's activity).

[49] Recycled wood infrastructure for collection, sorting and transport to energy facilities has improved within the past decade. The Wood Recyclers Association reports a large growth of recovered wood supplied to bioenergy markets. https://woodrecyclers.org/

[50] The cascading use of wood from planks into secondary products such as wood based panels can extend service life of biogenic materials. Multiple cascading steps can occur before ultimate return of CO_2 to the atmosphere when burning with energy recovery.

[51] The suitability of each sector for decarbonisation was derived after review of the sector decarbonisation roadmaps, and with consideration of many factors including the type of product, manufacture process, and concentration of CO_2 generated. Concentrated CO_2 emissions present greater options for CCS than dilute CO_2 atmospheres.

While the high levels of decarbonisation shown in Table E8 set a target for 2050, they cannot be achieved without investment. Many of the industry decarbonisation roadmaps[52] highlight the need for large national-level investment in the CCS infrastructure. The distance into the future also places significant uncertainty on the attainment of these reductions.

Table E8: Annual embodied emissions values by 2050 for different timber construction scenarios (high overall building activity), based on different decarbonisation scenarios (structural elements only)

Timber construction scenario (excludes timber cladding)	2018 emissions intensities (Mt CO_2e in 2050, %)		Decarbonised electricity grid (MtCO_2e in 2050, %)		Decarbonised grid with additional sector specific reductions (MtCO_2e, %)	
	Total for all new build units	Difference vs no growth baseline	Total for all new build units	Difference vs no growth baseline	Total for all new build units	Difference vs no growth baseline
No growth	5.23	---	4.27	---	2.69	---
BAU growth	5.13	-0.10	4.15	-0.12	2.64	-0.05
Moderate growth	4.85	-0.38	3.90	-0.37	2.49	-0.20
High growth	4.23	-1.00	3.36	-0.91	2.21	-0.48

<u>Timber cladding sensitivity analysis</u>

Considering the potential of timber cladding in 2050, an example using 10% and 25% of the external wall area for the 2050 mix of houses demonstrated that this **offers a reduction in embodied emissions of up to 150 kt CO_2e on the high building rate scenario** using 2018 emission levels (Table E9). These comparisons were made between the clad examples and the no growth scenario as reference case. This equated to a 2.9% reduction in embodied emissions (150 kt CO_2e), and a 3.1% increase in sequestered carbon (62 ktCO_2e) in the high growth 25% timber cladding example. The percentage reductions were similar for the low building rate scenario under 25% timber cladding.

Table E9. Reduction in embodied carbon for timber cladding compared to the no growth reference case, in the 2050 year (t CO_2e, 2018 emissions values)

	Embodied		Sequestered	
	Total for new build	change vs reference	Total for new build	change vs reference
Low building rate reference 2050	4,235,922	---	-1,658,170	---
10% cladding	4,187,032	-48,890	-1,678,469	-20,299
25% cladding	4,113,697	-122,225	-1,708,917	-50,747
High building rate reference 2050	5,231,883	---	-1,996,700	---
10% cladding	5,171,875	-60,008	-2,021,615	-24,915
25% cladding	5,081,863	-150,020	-2,058,987	-62,287

When the timber cladding case study was considered under the two decarbonisation scenarios, it was found that a GHG abatement effect was still possible via this route. The 25% timber cladding by exterior wall area option presented a 141.8 kt CO_2e emissions reduction under the grid decarbonisation scenario, or a 75.3 kt CO_2e emissions reduction under the ambitious decarbonisation scenarios (Table E10).

[52] DECC/BEIS (2015) https://www.gov.uk/government/publications/industrial-decarbonisation-and-energy-efficiency-roadmaps-to-2050

In the ambitious decarbonisation scenario, the emissions reduction presented by altering the cladding system on 25% of building area still presented a 2.8% emissions saving. Stored sequestered carbon remained unchanged by decarbonisation.

Table E10. For high building rate scenario in 2050, the embodied emissions associated with timber cladding, compared with the reference no timber growth scenario (using 2050 level emissions)

	Embodied carbon In the grid decarbonisation scenario ($MtCO_2e$)		**Embodied carbon In the ambitious decarbonisation scenario ($MtCO_2e$)**	
	Total for new build	**change vs reference**	**Total for new build**	**change vs reference**
Reference 2050	4,266,011	---	2,693,012	---
10% cladding	4,209,308	-56,703	2,662,895	-30,117
25% cladding	4,124,253	-141,758	2,617,719	-75,293

Abatement costs

Overall, non-commercially sensitive comparisons of timber frame systems with counterfactuals on a 'like-for-like' basis are not readily available. We have identified one recent publicly available study[53] indicating broadly equivalent costs of construction between timber framed and masonry systems. This finding was backed up by Bangor's conversations with industry stakeholders. A cost analysis of the archetypes used in this study was conducted by Currie & Brown for the CCC. This analysis also supports the assumption of cost parity as broadly correct. A small increase was seen in materials cost for timber framed, and a reduction in cost for timber-clad timber framed dwellings (Table E11)[54].

Table E11. Comparison of cost per dwelling, as prepared by Currie & Brown.

	Detached house	**Reduction compared to masonry**	**Semi-detached house**	**Reduction compared to masonry**
Masonry structure	£157,950	---	£121,800	---
Timber-framed structure	£158,891	+0.59%	£122,365	+0.46%
Timber-framed structure with timber cladding	£155,868	-1.32%	£120,551	-1.02%

In addition, the comparison between CLT and concrete was investigated, and a publicly available study was found which showed that the relative cost of CLT compared with concrete frame had decreased.[55] This indicated a price difference of 0.12% between the two systems. Differences in structural details between the Alinea report and the flat archetypes within this study prevented direct use of the cost model, and a wide range of suppliers and systems may lead to variability. As a result, a difference of 5% was considered by the project team[56]; however abatement cost was low, potentially £129 per tonne of CO_2e abated under a differential as high as 5%.

Conversations with stakeholders indicated that current rapid investment in CLT manufacturing capability in many locations within Europe is addressing demand. It is expected that this increased availability is likely to allow price to decrease within the near future, reducing variability across suppliers. Future concrete costs

[53] Rider Levett Bucknall (2018) *Construction cost comparison report – affordable housing: timber & masonry*.

[54] These figures exclude site preliminaries and overheads, which are typically lower for timber framed systems.

[55] Alinea Knowledge (2017) Residential Timber Cost Model. For *Building Magazine*, June 2017.

[56] Differences in cost of build may vary with local factors, quality of build and other aspects. A differential of 5% was considered to over-estimate any cost difference seen in practice, and derive a maximum abatement cost.

are currently expected to be stable; however, if ambitious decarbonisation were undertaken by the cement industry costs could double in the longer term.[57]

Based on the assumption of equivalent capital costs, and equal operational costs due to the archetype variants meeting the same thermal standards, the study concluded that a zero cost of abatement for timber framed housing could be assumed. The picture for engineered wood is more difficult to predict, given the much lower market share and the emerging nature of the technology. The cost difference of 5% is likely to overestimate abatement cost in many cases, and is expected to fall over time as supply chains scale up.

Non-residential sector GHG savings

A high-level analysis was conducted based on floor area of non-residential units per year[58] and for a 3.5% currently reported floor area for timber structures compared to other structural systems[59]. This allowed estimation of current timber and engineered wood product consumption on a floor area basis.

The non-residential floor area currently reported as using timber-based systems, was allocated on a 40:10:50 percent basis, between timber frame, CLT and glulam structures (estimated values). This approximation was based on established use of timber framed systems in hospitality and office structures; the recently emerging use of CLT in schools and similar buildings; and the long-established use of glulam and related products in halls, stadiums and retail premises.

Using timber consumption per square metre data for typical structures,[60] it was calculated that in 2018, timber and engineered wood consumption in non-residential applications lay between 14.3 to 25.7 kt in total. Within this figure, an estimated 3.7 to 6.6 kt p.a. was in timber framed, 4.7 to 5.5 kt p.a. was in CLT structures, and glulam and related products used between 5.9 and 13.7 kt p.a.

Table E12. Estimation of timber usage (air dry tonnes[61]) within current timber non-residential structures[62], used to derive embodied emissions (tCO_2e) and stored sequestered carbon (tCO_2e) for timber structures, and for counterfactual steel hybrid and concrete systems.

	Timber and engineered wood material used (t p.a.)	Stored sequestered carbon, timber system (t CO_2e p.a.)	Embodied emissions, timber system (t CO_2e p.a.)	Embodied emissions, steel hybrid system (t CO_2e p.a.)	Embodied emissions, concrete system (t CO_2e p.a.)
Timber framed non-residential	3,700 to 6,600	-5,800 to 10,200			
CLT non-residential	4,700 to 5,500	-7,300 to 8,500			
Glulam non-residential	5,900 to 13,700	-9,100 to 21,200			
Total	**14,300 to 25,700**	**-22,200 to -40,000**	**6,900 to 12,400**	**19,000 to 34,200**	**17,900 to 32,300**
i.e. abatement relative to alternative				12,200 to 21,900	11,100 to 19,900

[57] WSP, Parsons-Brinkerhoff and DNV-GL (2015) *Industrial Decarbonisation Roadmaps and Energy Efficiency Roadmaps to 2050: Cement.*

[58] VOA (2016) *Non-domestic rating: business floorspace*

[59] BCSA (2016) *Annual Review 2015-2016*. www.steelconstruction.org. Data released since the study was completed showed that timber structures had a 5% share of floor area in 2017-18.

[60] Timber per square metre was derived from literature sources, industry contacts and values derived during the residential analysis, where similarities in design exist.

[61] Timber quantities were calculated air dry, reflecting the typical moisture content in service in the building, and the moisture content when sold into construction applications, a value of 18% moisture was assumed.

[62] Values are for the mean additional non-residential floor area per year, but actual floor area delivered fluctuates between ~0.5 and 28 million m^2 per year.

For these timber usage values, based on carbon emissions data within a TRADA and Ramboll study[63], a comparison with concrete framed and a steel concrete hybrid system was extrapolated (Table E12). This analysis showed that the total annual embodied carbon for the engineered wood structures could be 6.9 to 12.4 kt CO_2e, and the abatement provided by these timber structures compared to steel or concrete alternatives was **between 11 and 20 ktCO_2e**.

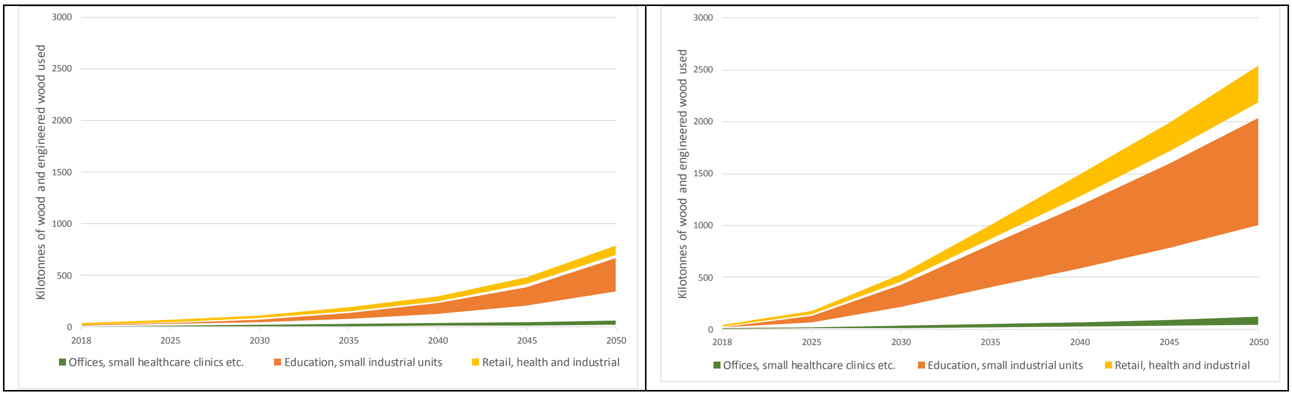
To address the potential for wood in construction to expand within the non-residential sector, each category of timber buildings was subjected to growth on a variable percentage basis year on year to 2050. The growth rate in the business as usual scenario was assumed to be 1% for total floor area, and for all timber building categories. The low growth scenario used initial growth rates of 6% for timber framed and glulam, and 15% for CLT structures. The high growth rate initially used 10% for timber framed, 40% for CLT and 15% for glulam, slowing steadily over time to 5% for each category by 2050. The high growth rate scenario reflects a very strong policy steer towards increased wood in construction, possibly via a legislative rather than market led route.

Table E13. Wood used in non-residential structures in 2050 under different growth scenarios (air dry kt) (structural elements only)

	BAU non-residential		**Low growth non residential**		**High growth non-residential**	
	% of structures	**Total timber (kt)**	**% of structures**	**Total timber (kt)**	**% of structures**	**Total timber (kt)**
Timber framed: Offices, small healthcare, hospitality	1.2 to 1.4	5.1 to 9.0	5.6 to 6.6	60-70	10 to 12	43 to 76
CLT: Education, small industrial units, offices	0.3 to 0.31	6.4 to 6.6	13 to 15	256 to 322	41 to 48	885 to 1,033
Glulam: Retail, health, industrial, and public buildings	1.5 to 1.75	8.0 to 18.8	7.0 to 8.2	755 to 881	28 to 33	152 to 354
Total wood in 2050	**3.0 to 3.5**	**19.6 to 34.4**	**26 to 30**	**338 to 452**	**80 to 93**	**1,080 to 1,462**

Key data for the categories of timber building are presented in Table E13. The ranges of potential timber consumption per grouping within the low and high timber growth scenarios are shown in Figure E8.

Figure E8: Projected annual timber consumption (air dry kilotonnes) under (a) low growth and (b) high growth scenarios for non-residential structures, per structural method, timber framed (green), CLT (orange), glulam (yellow).



[63] Data referenced within TRADA Exova (2017) *Cross-laminated timber: design and performance*.

The wood usage values were used to derive approximate building level embodied carbon values, using the same conversion factor as above (Table E14). This estimate indicated that in 2050 a reduction in embodied emissions of 261 to 385 kt CO_2e could be related to timber in non-residential timber buildings under the low growth scenario, and between 836 and 1,245 kt CO_2e for the high growth scenario (2018 emission levels). In addition, the timber structures could include between 525 and 703 kt CO_2e, or 1,680 to 2,275 kt CO_2e of stored sequestered carbon, under low and high growth rates respectively.

Table E14. Stored sequestered carbon and embodied carbon for non-residential buildings in 2050 under different growth scenarios, showing the emissions abated relative to steel and concrete alternatives (structural elements only)

	Stored sequestered carbon, timber system (kt CO_2e p.a.)	**Embodied emissions, timber system (kt CO_2e p.a.)**	**Embodied emissions, steel hybrid system (kt CO_2e p.a.)**	**Abatement relative to steel (kt CO_2e p.a.)**	**Embodied emissions, concrete system (kt CO_2e p.a.)**	**Abatement relative to concrete (kt CO_2e p.a.)**
BAU	-31 to -54	9.5 to 16.6	26 to 46	-17 to -29	25 to 43	-15 to -27
Low growth	-525 to -703	163 to 218	450 to 603	-287 to -385	424 to 568	-261 to -350
High growth	-1,680 to -2,275	521 to 705	1,440 to 1,950	-919 to -1,245	1,357 to 1,837	-836 to -1,132

Impact on UK carbon accounts

The construction sector falls within Scope 3 of the Greenhouse Gas Protocol, and accounting is covered by the Corporate Value Chain standard[64] for the purposes of calculating the UK net carbon account. Therefore, the embodied carbon figures calculated on a per dwelling basis within this study, or multiplied to national level scenarios, are useful tools in understanding materials and structural choices, but do not map directly onto the UK's national carbon accounts. Emissions from the manufacture of most construction products is already accounted for within the EU ETS component of national accounts[65] (e.g. via cement industry or chemicals industry), and in some cases within the non-traded emissions component (for example the biomass-based elements such as timber).

EPD data, such as used in this study, supports building-level embodied carbon calculations, promoting good decision-making at the building level. It also allows design decisions within the construction sector to keep pace with the shift in environmental profile of the materials used, as reported in EPDs now, and as revised over time to reflect decarbonisation or efficiency within manufacture.

To gain insight into the potential effect of the changes outlined on the UK national carbon accounts, a simple analysis was conducted. This was applied to the residential sector scenarios presented in this report. A share of each product was attributed to UK manufacture or import, based on estimated current market share (Table E15). These data were used to highlight overriding trends.

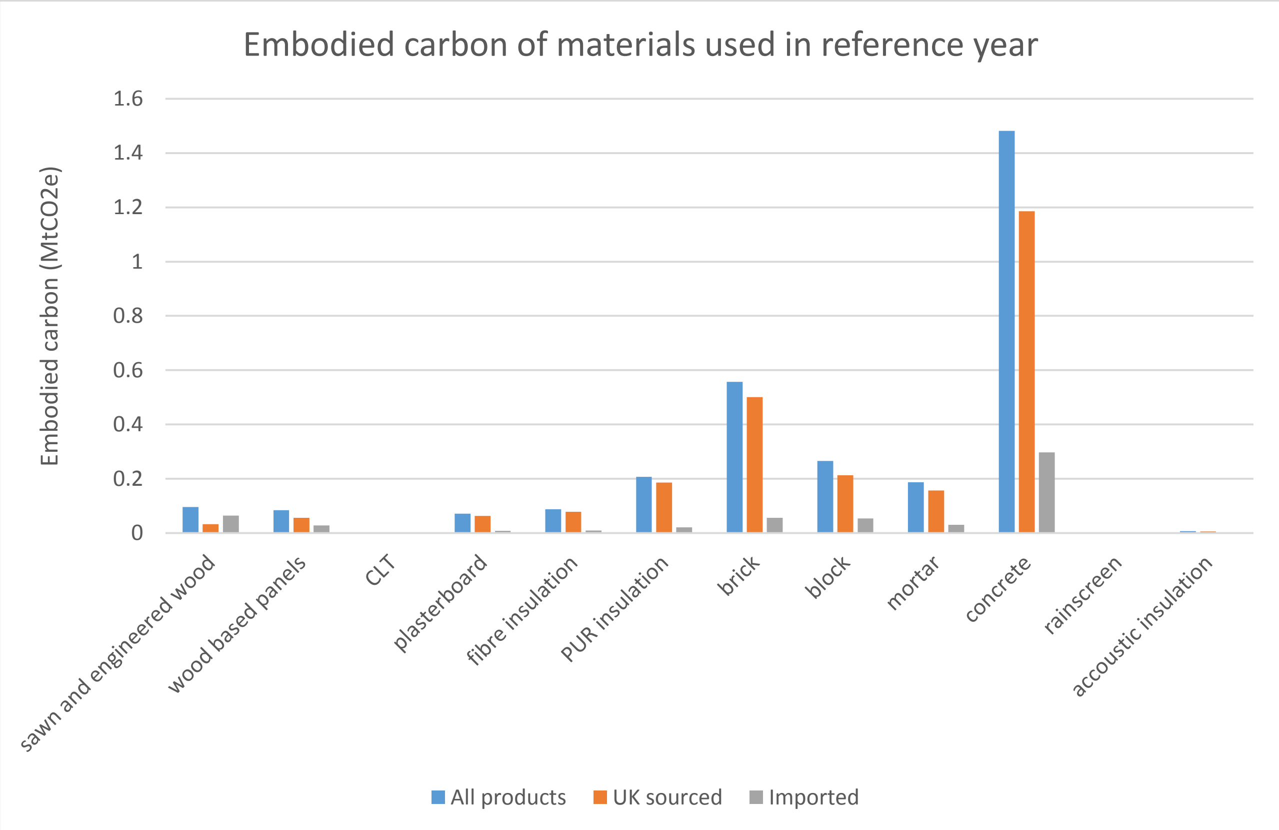
For the 2018 reference year, the approximate split of embodied carbon currently attributed to UK manufacturing is 81% (2.48 Mt CO_2e), and 19% (0.56 Mt CO_2e) attributable to imports. The split within the different materials categories is shown in Figure E8.

[64] https://ghgprotocol.org/standards/scope-3-standard
[65] This carbon is accounted in the nation where the manufacture occurs.

Table E15. Split between UK manufacture and import used in UK carbon accounts, estimations

	Est. UK manufacture	Est. import
Sawn wood	33%	67%
CLT	0%	100%
Wood-based panels	67%	33%
Plasterboard	89%	11%
Inorganic insulation	90%	10%
PUR insulation	90%	10%
Brick	90%	10%
AAC block	80%	20%
Cement mortar	84%	16%
Reinforced concrete	80%	20%
Fibre-cement cladding	50%	50%

Figure E8. Total embodied carbon (2018 reference year) by material type, and the embodied carbon attributable to UK carbon accounts vs. imported products where embodied carbon is accounted elsewhere (structural elements only).



For each of the different timber growth scenarios (under the low house-building rate) the change in percentage split in 2050 was also calculated, based on 2018 emissions values[66]. Total emissions reduction under moderate growth of timber systems to 2050 reduced the emissions of both UK and imported materials, resulting in only minor change of the split between emissions of domestically produced and imported materials. Under high growth of timber systems, the carbon emissions of UK materials were reduced to 79.5% of total.

Within the 2050 emissions, the proportion of additional GHG abatement achieved by UK rather than imported sources (relative to the no growth baseline) is 92% in the BAU scenario, is 86% in the moderate

[66] Note that the percentage of material imported in all material categories is likely to change by 2050, so figures are indicative only

timber growth scenario and 91% within the high timber growth scenario. These proportions vary due to the profile of components displaced, and their manufacturing location.

When stored sequestered carbon is considered, the increase is greatest under the BAU scenario (with 50% of additional sequestered carbon being attributed to UK accounts). In the moderate and high timber growth scenarios the additional sequestered carbon due to UK forests is 27% and 13% respectively. It is complexities such as these, relating to origin of timber and selection of system boundaries, which have led to the long-running discussion about how to account for the wood products pool in national carbon accounts.[67] Consideration of carbon fluxes into and out of the UK forestry pool were not part of this study.

It is clear from the above examples that all scenarios retain a significant UK emission of carbon relating to manufacture of primary building products. These examples represented the housebuilding sector only, but the dominance of UK-based manufacture of concrete and steel elements used within large non-residential structures is likely to mean that the majority of emissions from the non-residential sector are also attributed to UK carbon accounts.

Impact on bioenergy feedstock availability

The wood used within the various scenarios was analysed to determine the type and quantity of raw material which would be required by the forest products industry to support this house-building activity. The data were converted to oven dry tonnes[68] to allow use of the data within the CCC's wider biomass resource modelling. Sawlogs would be unlikely to enter the bioenergy market, whereas the small roundwood which is used within wood-based panels manufacture is under demand from several potential markets, including bioenergy, but also fencing, pallets and similar uses.

Feedstock requirements for the structural elements of the residential scenarios are reported in Table E16 and E17 for low and high building rate scenarios respectively. These values exclude timber used in cladding, as the default archetypes were brick-faced. The projected timber requirements fell within the Forestry Commission's predicted softwood availability[69] for each time period.

Table E16: Summary of feedstock requirement for sawn wood, engineered wood, CLT and wood-based panels within the low building rate model under different timber building scenarios (structural elements only). (M odt = million oven dry tonnes) all values are per annum representative of that time period.

Period	No growth		Business as Usual		TF medium growth		TF high and CLT high	
	Sawlog weight (M odt)	SRW wt (M odt)	Sawlog weight (M odt)	SRW wt (M odt)	Sawlog weight (M odt)	SRW wt (M odt)	Sawlog weight (M odt)	SRW wt (M odt)
2018-22	0.880	0.264	0.882	0.264	0.893	0.266	0.896	0.267
2023-27	0.918	0.276	0.928	0.278	0.967	0.283	0.995	0.290
2028-32	0.958	0.288	0.975	0.292	1.036	0.298	1.115	0.315
2033-37	1.001	0.301	1.025	0.307	1.108	0.314	1.258	0.343
2038-42	1.045	0.315	1.077	0.323	1.181	0.330	1.427	0.362
2043-47	1.092	0.330	1.132	0.339	1.257	0.345	1.709	0.371
2048-2050	1.131	0.342	1.178	0.353	1.329	0.359	2.065	0.371

[67] The IPCC 2006 rules provide four methodologies alongside the default option, to address carbon storage within the built environment, however benefits vary considerably with national economy and business factors, as discussed by Hashimoto (2008) *Environmental Science and Policy* **11**:756-771.

[68] All weight data presented for timber in this document is on an air-dry basis unless otherwise specified. This is the moisture content of wood in service, i.e. approx. 18% moisture content for structural timbers. To compare with biomass weights reported for bioenergy purposes, an oven dry basis was used, i.e. 0% moisture content.

[69] Forestry Commission Softwood Availability Forecasts (published 2014, 2016)

Table E17: Summary of feedstock requirement for sawn wood, engineered wood, CLT and wood-based panels within the high building rate model under different timber building scenarios (structural elements only). (M odt = million oven dry tonnes) all values are per annum representative of that time period.

Period	No growth		Business as Usual		TF medium growth		TF high and CLT high	
	Sawlog weight (M odt)	SRW wt (M odt)	Sawlog weight (M odt)	SRW wt (M odt)	Sawlog weight (M odt)	SRW wt (M odt)	Sawlog weight (M odt)	SRW wt (M odt)
2018-22	0.926	0.278	0.937	0.281	0.949	0.282	0.952	0.283
2023-27	1.082	0.326	1.119	0.335	1.167	0.341	1.201	0.349
2028-32	1.147	0.347	1.196	0.358	1.271	0.365	1.369	0.387
2033-37	1.199	0.363	1.257	0.377	1.360	0.385	1.544	0.421
2038-42	1.254	0.380	1.322	0.396	1.450	0.405	1.751	0.444
2043-47	1.311	0.398	1.389	0.416	1.543	0.424	2.097	0.455
2048-2050	1.359	0.412	1.445	0.433	1.632	0.440	2.546	0.455

Technical and perception barriers

Several topics were discussed with stakeholders relating to technical or perceived barriers to the use of wood in construction. These issues included fire safety of timber structures, indoor air quality issues and thermal performance.

Fire performance

Most dwellings in the UK already contain a significant quantity of timber, as we shown in the dwelling level analysis of masonry homes. Timber framed systems have been in use in the UK for several decades, and are widespread in other regions such as Scandinavia and North America. While there may be a perception of fire risk, all new build structures in the UK must meet strict levels of fire performance and maintain structural integrity in the case of fire[70]. Both timber framed and CLT buildings have been shown to perform at or above the requirements of the Building Regulations Part B when designed according to the principles of Eurocode 5[71].

- In timber framed systems, the use of non-combustible internal panels such as plasterboard governs performance, and manufacturers select thickness, grade, fixings to achieve the required fire resistance.
- In mass timber structures such as CLT and glulam the design approach includes the use of non-combustible finishes, as well as exposed timber elements where design calculations demonstrate that structural integrity of these elements will be retained, in the case of fire. The formation of a char layer on the surface of mass timber elements provides highly predictable performance, allowing designers to adjust element dimensions to provide the levels of performance specified by the National Annex to Eurocode 5.

Guidance, training and publications are available for industry practitioners from bodies such as TRADA and the STA relating to both timber framed and CLT buildings[72] [73] [74].

The risk of fire spread in the case of a fire occurring is controlled by the building design. Care should be taken in modifying or altering a timber frame structure, to ensure that the fire safe envelope of the

[70] Building Regulations Approved Document B: Fire Safety https://www.gov.uk/government/publications/fire-safety-approved-document-b Note that parts 1 and 2 were amended in December 2018 following the Hackitt enquiry.
[71] STA (2014) *Structural Timber Engineering Bulletin 7*; Eurocode 5: Design of timber structures (BS EN 1995-1-1:2004+A2:2014)
[72] Training module on Fire performance, https://www.trada.co.uk/academic/structural-characteristics-of-timber/fire-performance/
[73] https://www.trada.co.uk/publications/wood-information-sheets/fire-performance-of-timber-frame-dwellings/
[74] Competency programme for timber frame designers includes fire prevention https://www.structuraltimber.co.uk/professional-development/timber-frame-workbooks-design-gold-level

structure is retained after any alterations. Similarly, airtightness, moisture barriers and other design details may be compromised if work is undertaken without necessary care or understanding of the structural system. Poor workmanship, or removal of cavity barriers, fire stops or finishes could compromise the performance. The responsibility for maintaining the performance of the building after occupancy was highlighted in the Hackitt report, with a need for a chain of responsibility throughout the construction process and into the service life[75]. Guidelines to prevent loss of functional performance during routine maintenance, renovations and remodelling of buildings are required.

A separate issue which concerns the timber frame sector is fires on construction sites, prior to the completion of the structure. The Structural Timber Association has worked closely with chief fire officers and other parties to develop clear guidance for the sector on best practice to avoid or minimise this risk during construction[76]. The Construction (Design and Management) Regulations 2015 were introduced to address this,[77] resulting in improved site working practices, such as scheduling of the phases of erecting adjacent structures.

Thermal efficiency

High levels of thermal efficiency can be achieved in both timber framed and CLT buildings. The systems can both be used to deliver the required U-values at an element level, or energy efficiency of the whole structure[78]. This is typically achieved by thermal insulation efficiency, and the low thermal coefficient required for timber. The thermal dynamics of these buildings is different, but equally predictable to traditional structures.

The new generation of buildings with high levels of thermal efficiency have been the focus of several studies to observe the efficiency delivered in practice, versus the predicted performance. Projects such as the Building Performance Evaluation Programme[79] have revealed the performance gap between designed and as built performance, but identified actions which are being fed back into improved systems and working practices to improve delivery. An issue which has also been observed in some systems used to deliver the new levels of energy efficiency, is overheating during summer heatwaves.[80] An industry-wide project investigated this complex issue in depth, and recommended steps for ongoing research and reviewed the many approaches to designing building to minimise this effect.[81]

One aspect which is frequently discussed, but in practice a complex topic, is thermal mass[82]. This may be harnessed within buildings to reduce the peaks and troughs in energy demand. A cooling effect can be achieved when designed correctly[83]. Concrete and stone buildings are frequently cited as having excellent thermal mass, and CLT also has a thermal mass component, which can be enhanced by design decisions. However, in the majority of housing stock the use of plasterboard decouples the thermal mass element from the occupied area. It should be noted that thermal mass does require provision of night time cooling if it is to regulate overheating. It is therefore only one element of building design for energy efficiency,

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[75] MHCLG (2018) Independent Review of Building Regulations and Fire Safety: final report https://www.gov.uk/government/publications/independent-review-of-building-regulations-and-fire-safety-final-report

[76] STA (2017) 16 steps to fire safety. The STA's Site Safe Policy is mandatory for all STA members.

[77] Construction (Design and Management) Regulations http://www.hse.gov.uk/construction/cdm/2015/index.htm

[78] The premise of the embodied and sequestered carbon analysis in timber framed and masonry dwellings was that both methods were investigated at a level which would deliver equal thermal performance, in line with current building regulations part L.

[79] Innovate UK (2016) Building Performance Evaluation Programme: Findings from Domestic Projects. PDF download from https://www.gov.uk/government/publications/low-carbon-homes-best-strategies-and-pitfalls

[80] NHBC (2012) Overheating in new homes: A review of the evidence. NHBC Foundation Report NF 46.

[81] ZCH/BRE (2016) *Solutions to Overheating in Homes: Evidence Review*.

[82] Stakeholders commented that engineering design tools to properly calculate and predict thermal mass effects are frequently inaccurate or insufficient, additional research would be needed to accurately harness thermal mass effects.

[83] Delivery of cooling is one of several proposed mechanisms to regulate summer overheating, however requires adequate ventilation or alternative provision of 'coolth' to avoid residual build up during heatwaves. This is discussed in ZCH/BRE (2016) *Solutions to Overheating in Homes: Evidence Review*.

alongside consideration of orientation, glazed area, shading and ventilation, and not a pre-requisite in efficiently insulated buildings.

Air quality

Indoor air quality (IAQ) has been highlighted by various bodies[84] since the toughening of standards relating to airtightness of dwellings during the revisions of Building Regulations in the 1990-2000s. Continued review or monitoring of the effects of airtightness on IAQ is equally required in all new construction methods which meet these targets. It is increasingly recognised that while airtightness reduces the air changes per hour and decreases heat energy consumption, if not carefully controlled it may lead to build up of VOCs, and to elevated humidity, leading to potential mould or bacterial colonisation. All of these factors can lead to health-related issues; some are short-lived, others chronic.

In buildings with very high airtightness, mechanical ventilation and heat recovery systems are frequently specified. Reports from post-occupancy assessments of a range of the new generation buildings have highlighted several issues in this area[85], including the need to consider occupant lifestyle and behaviour when specifying MVHR systems, provision of information to occupants, and further investigation of delivered performance versus modelled values. Evidence is still emerging from the most recent generation of high energy efficiency and high airtightness buildings, for example addressing the performance gap, and feeding back into ongoing development of best practice in all structural systems. This process should be supported with research funding, as the issue cuts across all building structural methods, and relates to design details and occupant behaviour.

Conclusions & key messages

Increasing the quantity of wood used in construction presents a significant opportunity to reduce GHG emissions. While reduction of embodied carbon within buildings can be achieved through various measures, an increase in stored sequestered carbon can only be achieved by increased use of biomass-based materials such as timber.

Considering the residential sector alone, the total **additional** annual abatement resulting from the high UK timber construction scenarios compared to a no growth counterfactual is **~2.2 Mt CO_2e p.a**. Approximately half of this comes from a reduction in embodied emissions and half from an increase in sequestered carbon. If timber cladding is used on a quarter of the available external wall area, this figure is increased to **~2.4 Mt CO_2e p.a.**

Once future reductions in the emissions intensity of building products is taken into account, the annual emissions can fall by ~1Mt CO_2e (for energy efficiency and decarbonisation of the grid mix), or ~2Mt CO_2e (for high levels of decarbonisation, including CCS and CCU in cement and chemical sectors). However, **the use of timber still contributes a reduction in each of the decarbonisation scenarios**, namely an additional reduction of 0.9 Mt CO_2e in the grid decarbonisation scenario, and a 0.5 Mt CO_2e reduction under ambitions decarbonisation scenario.

Not all this abatement would be attributable to the UK's GHG accounts. A proportion of the embodied emissions associated with construction materials relates to materials produced overseas. This includes the timber elements, where much of the sawn timber, and all CLT, currently used in construction is grown overseas, whereas a high proportion of wood-based panels are manufactured in the UK. The results varied with scenario. A high-level estimate for moderate timber growth suggests that **86% of the emissions**

[84] UK GBC (2016) *Health and wellbeing in homes*; UK GBC (2018) *Healthy housebuilding: making 300,000 new homes a year better places to live*.
[85] Innovate UK (2016) *Building Performance Evaluation Programme: Findings from Domestic Projects*. https://www.gov.uk/government/publications/low-carbon-homes-best-strategies-and-pitfalls

savings achieved would be attributable to UK carbon budgets, while **91% of emissions savings** would be attributable to the UK under high timber growth scenarios.

This project also highlights the need to consider the full profile of materials used in the building structure. For example, timber framed buildings still utilise concrete foundations, and masonry buildings utilise a reasonable volume of timber in flooring and roofing. As a result, building-level embodied carbon calculations are needed. At the individual building level, the reduction in embodied emissions for **substituting timber frame for masonry is approx. 20%**. A greater reduction (~60%) is seen for CLT and concrete structures. Overall, this points to the need for significant decarbonisation efforts in the sectors that produce key construction materials, regardless of the amount of future timber based construction.

Considering the non-residential sector, only broad estimation of current and future substitution potential was possible. However, given the current low market penetration of timber structural systems within this sector (estimate 3.5% by floor area) there is considerable scope for large emissions reductions to be achieved, given suitable incentives. With low growth, reaching 26-30% timber buildings (by area) by 2050, 0.3-0.4 Mt CO_2e emissions abatement was indicated, alongside an increase of 0.5-0.7 Mt CO_2e in stored carbon. For the high growth scenario (80-93% timber buildings in 2050) an increase of 0.8-1.2 Mt CO_2e emissions abatement and a 1.7-2.3 MtCO_2e increase in stored carbon were predicted. There is a large range of structural combinations possible to achieve the necessary range of building types and requirements in this sector.

Quantification of embodied carbon at a building level offers a useful tool to compare structures and designs, and to optimise use of materials or choice of supplier. As the manufacturing industries decarbonise, the reduced embodied carbon of their construction products can then be recognised in the decreased embodied carbon per dwelling. In addition, recording the sequestered carbon stored in a building would recognise of the size of the building products pool of sequestered carbon, and its potential to deliver a carbon storage effect.